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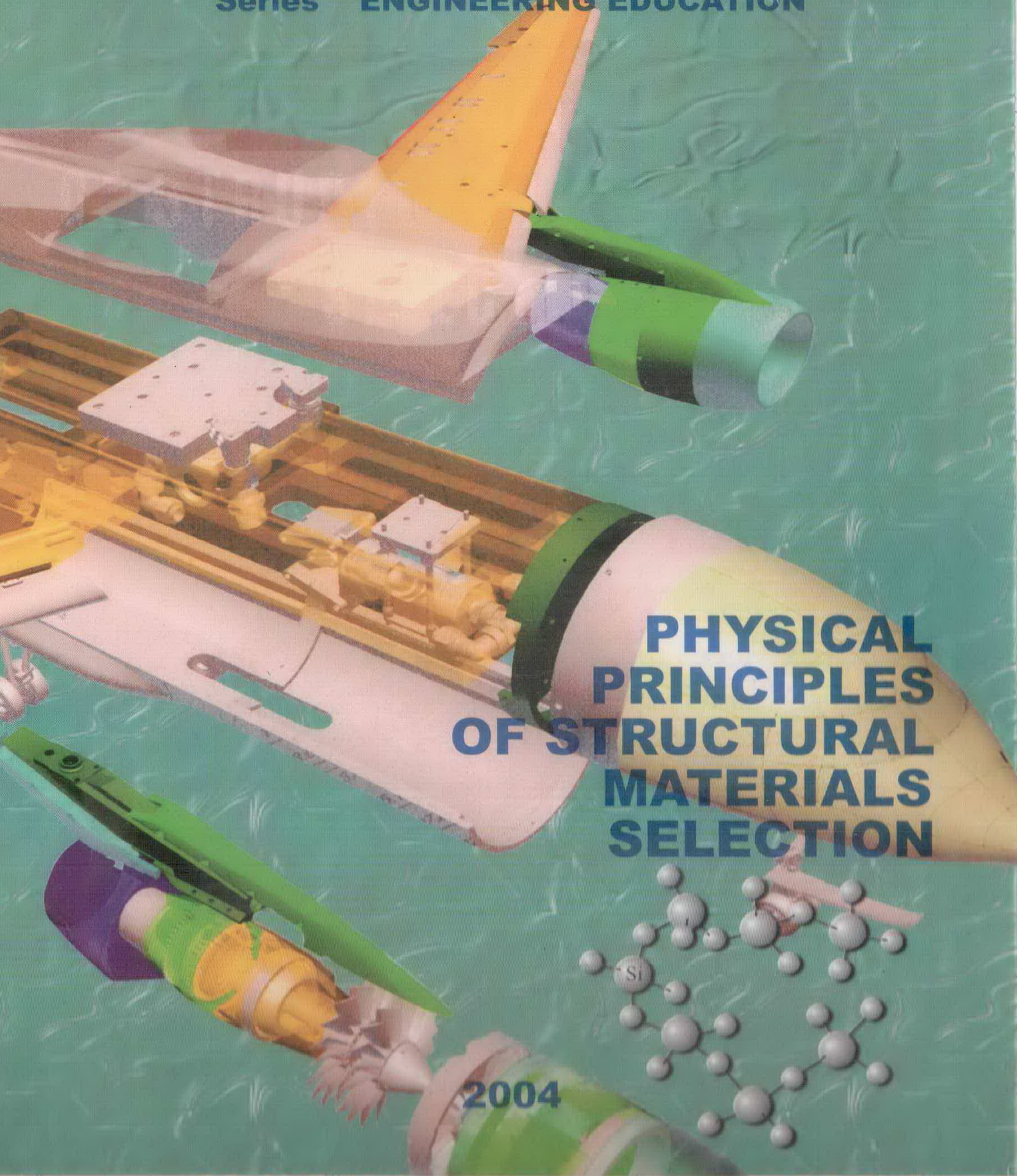

PHYSICAL PRINCIPLES OF STRUCTURAL MATERIALS SELECTION

2004

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Devoted to the 75-th anniversary of the National Aerospace University
“Kharkiv Aviation Institute”

Recommended
by the Ministry of Education and Science of Ukraine
as teaching aid
for students of higher technical educational institutions

Sealed by the Ministry of Education and Science of Ukraine
(letter № 14/182-2288.1 dated 21.10.05)

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
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NATIONAL AEROSPACE UNIVERSITY
“KHARKIV AVIATION INSTITUTE”

Series ENGINEERING EDUCATION

PHYSICAL PRINCIPLES OF STRUCTURAL MATERIALS SELECTION

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Kharkiv 2004

УДК: 620.22 (075.8)
UDK: 620.22 (075.8)

Фізичні принципи вибору конструкційних матеріалів/ Я.С. Карпов, В.Ф. Деменко, П.П. Лепіхін, О.Г. Попова, В.Т. Сікульський, А.О. Таран, І.М. Тараненко, Т.А. Ястремська. – Навч. посібник. – Харків: Нац. аерокосм. ун-т “Харк. авіац. ін-т”, 2004. – 403 с.

Physical Principles of Structural Materials Selection/ Ya. Karpov, V. Demenko, P. Lepikhin, O. Popova, V. Sikulskiy, A. Taran, I. Taranenko, T. Jastremska. – Textbook. – Kharkiv: National Aerospace University “Kharkiv Aviation Institute”, 2004. – 403 p.

ISBN 966-662-118-5

Посібник містить основні теоретичні відомості з теорії будови речовини та фізики твердого тіла, необхідні для вивчення спектра функціональних властивостей конструкційних матеріалів і методів керування ними. Розглянуто основні методи механічних випробувань конструкційних матеріалів. Фізико-механічні характеристики матеріалів використані для побудови критеріїв їх раціонального вибору при проектуванні машинобудівних конструкцій, зокрема в авіаційно-космічній галузі.

Для студентів, які навчаються за напрямами “Авіація та космонавтика” і “Інженерна механіка”.

Може бути використаний для здійснення підготовки з технічного перекладу при вивченні англійської мови у вищих технічних навчальних закладах, а також студентами, які навчаються за спеціальністю “Прикладна лінгвістика”.

Іл. 221. Табл. 60. Бібліогр.: 60 назв

The Textbook contains principal theoretical information on theory of matter structure and physics of solids, needed for study of wide range of structural materials functional properties as well as the methods how to handle them.

The authors considered the main methods of structural materials mechanical testing. Physical and mechanical characteristics of the materials used for development of the criteria of their rational selection in machine designing, in particular, in aerospace field.

The Textbook is intended for the students, who are trained in aerospace and mechanical engineering. It may be used for carrying out the technical translation preparation in learning English in higher educational technical institutions as well as for the students, who are trained in “Applied linguistics” specialty.

Illustrations 221. Tables. 60. Bibliographical references: 60 names

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ISBN 966-662-118-5

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PREFACE

The original goal of this text is to present materials information that a designer needs to know in order to select materials for the structure in engineering design based on physical principles of materials science. The designer must know not only something about all types of structural materials (plastics, metals and so on), their properties, their limitations, but how to specify them properly in engineering drawing or in design specifications.

Designer's understanding of the relationship between structure and properties provides the basis for both his/her selection of existing materials and his (her) development of new materials. A modern designer must be able to engineer the electronic and atomic structure of materials in order to produce miniaturized electronic and optical devices. By manipulating molecular structure, we have produced a vast spectrum of polymers capable of operating under extreme conditions including elevated temperatures of wear. Controlling microstructure has led to many new metal alloys and ceramics, including light weight aerospace alloys and ceramic superconductors. And we have played wizard, juggling the structure of composites to produce unique properties. The methods used to control the microstructure and macrostructure of materials are examined to find out the fact that by controlling the structure we in turn can control the mechanical properties. Before looking at the processes used to control the strengthening mechanisms, the mechanical testing of materials needs to be considered.

The results of mechanical tests are the mechanical properties of materials. They are used to produce effective material selection, which requires that a designer should be familiar with common materials systems and should be able to choose a repertoire of specific materials from the system as well as must know how to use a material effectively.

The modern method of material selection is discussed, using physically based relationships between chemical, physical and mechanical properties.

The text can serve, first, those students the course of engineering materials had been formally introduced to and who will not be involved in this field in future. Such students need a basic understanding of materials, the types of materials behavior so that they could appropriately select materials and, second, this text can introduce the science of materials, the types of materials available, and the application of materials by materials-oriented students in engineering. These students will go on studying the details of materials structure and properties in more advanced courses.

We believe that to read this text, a student must be sure to have sufficient exposure to chemistry, physics, and mathematics. The experience gained will be useful to provide students with fundamental knowledge in materials manufacturing, processing or selection.

Chapter 1 Origin of Materials Internal Structure

All engineers are involved with materials on a daily basis. We manufacture and process materials, design and construct components or structures using materials, select materials, analyze failures of materials, or simply hope the materials we are using perform adequately.

We are interested in improving the performance of the product we are designing or manufacturing. Electrical engineers want integrated circuits to perform properly, switches in computers to reach instantly , and insulators to withstand high voltages even under the most adverse conditions. Civil engineers wish to construct reliable structures that are resistant to corrosion. Petroleum and chemical engineers require drill bits or piping that *survive* in abrasive or corrosive conditions. Automotive engineers desire light weight yet strong and durable materials. Aerospace engineers demand light weight materials that perform well both at high temperatures and in the cold vacuum of outer space. Metallurgical, ceramic, and polymer engineers wish to produce and shape materials that are more economical and possess improved properties.

Each of developed products requires materials with specified characteristic such that (1) *the material can be processed into the final products satisfactorily and economically* and (2) *the products will behave appropriately in service*.

Since the engineer must specify the materials for TV sets, computers, suspension bridges, oil refineries, rocket motors, nuclear reactors, or supersonic transports he must have sufficient knowledge to select the optimum material for each applicant taking into account material availability, processing requirements, service demands, and the ever-important cost factor, in addition to the design specification which match the part to the system as a whole. Although experience provides the engineer with a starting point for selection of materials, and the property data found in handbooks will aid him, the skill of the engineer will be limited unless he understands the factors, which contribute to the properties of materials. Without this knowledge, a material is simply a "black box" and the engineer will have no conception of the material's limitations, or of possible modifications in materials selection and design.

The intent of this Chapter is to permit the student to become aware of the types of materials available, to understand their general behavior and capabilities, and to recognize the effects of the environment and service conditions on the materials performance.

1.1 Internal Structure of Materials

Materials engineering is based largely on the sciences of chemistry and physics. This text will assume that the reader has a general knowledge of these subjects. Since engineering materials involve many chemical terms, we shall preface our material discussions with a brief review of some of the more important chemical fundamentals and terms.

All materials obey the laws of physics and chemistry in their formation, reactions, and combinations. The smallest part of an element that retains the chemical properties of that element is the *atom.* Atoms are the building blocks for engineering materials. All *matter* is composed of atoms bonded together in different patterns and with different types of *bonds*.

As shown in the Figure 1.1, most substances that we deal with in industry and in everyday life can be categorized as *organic* or *inorganic*.

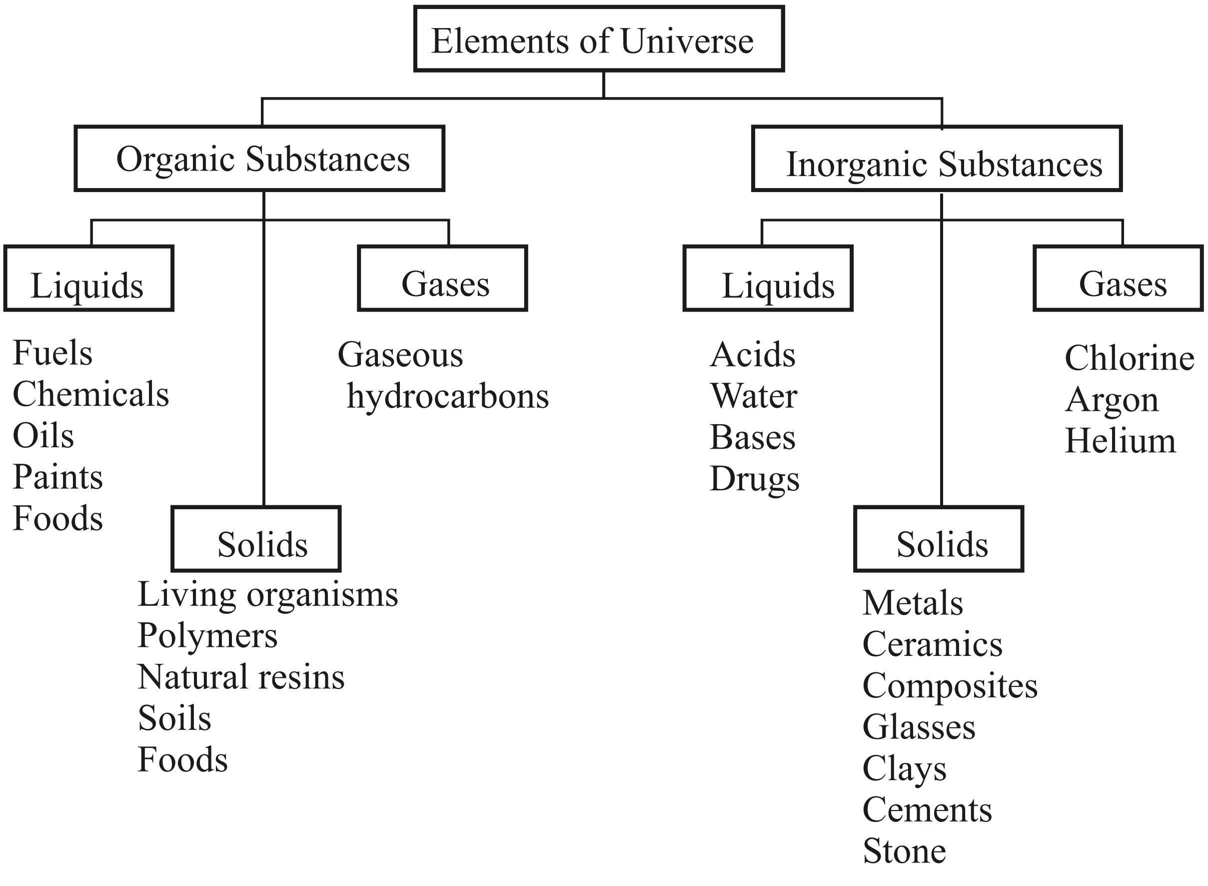


Figure 1.1 The elements are the building blocks for all materials

Organic materials contain the element *carbon* (and usually *hydrogen*) as a general part of their structure, and they are usually derived from living things. Petroleum products are organic; crude oil is really the residue of plants that lived millions of years ago and all plants and animals are organic in nature. Organic substances consist of not only carbon and hydrogen, but *oxygen*, and *nitrogen* also. *Inorganic* materials are those substances not derived from living things. Sand, rock, water, metals, and inert gases are inorganic materials. Chemistry as a science is usually separated into two fields based upon these two criteria. Some chemists specialize in organic chemistry; others specialize in inorganic chemistry. Metallurgists and ceramists deal primarily with inorganic substances. Plastic engineers, on the other hand, deal primarily with organic substances. The field of materials engineering deals with both areas.

In order to study engineering materials on a chronological basis, we shall review the list of basic ingredients that are used to make both organic and inorganic materials, the *elements*. An element is a pure substance that cannot be broken down by chemical means to a simpler substance. About 90 elements occur naturally in the earth's crust; some elements are unstable and occur as the result of *fission* or *fusion reactions*. Most chemistry texts list 104 elements, but inclusion of laboratory synthesized elements brings the total number of elements to about 114.

Many of these elements have little industrial importance, but it is important in engineering materials to recognize the names and chemical symbols for the more useful elements. Figure 1.2 shows a common version of the *periodic table*. This table lists elements on the basis of the differences in their *atomic structure*. An atomic structure is the first level of materials structure division:

- atomic structure,
- atomic arrangement,
- microstructure,
- macrostructure,

and we must first understand the atomic and crystal structures.

Atomic structure influences how the atoms are bounded together, which in turn help to categorize materials as *metals*, *semiconductors*, *ceramics*, and *polymers* and permits us to draw some general conclusions concerning the physical properties and mechanical behavior of these classes of materials.

1.1.1 Structure of the Atom

As you know from quantum theory an atom is composed of a *nucleus* surrounded by *electrons* (see Figure 1.3).

The nucleus contains *neutrons* and positively charged *protons* and thus carries a net positive charge. The negatively charged electrons are held to the nucleus by an electrostatic *attraction*. The *electrical charge q* carried by each electron and proton is 1.60×10^{-19} C. Because the numbers of electrons and protons in the atom are equal, the atom as a whole is electrically neutral.

The *atomic number* of an element is equal to the *number of electrons* or

Key:

element name
atomic number
symbol
atomic weight (mean relative mass)

Ia	IIa		IIIb	IVb	Vb	VIb	VIIb	VIIIb			Ib	IIb	IIIa	IVa	Va	VIa	VIIa	VIIIa
hydrogen **1** **H** 1.00794(7)																		helium **2** **He** 4.002602(2)
lithium **3** **Li** 6.941(2)	beryllium **4** **Be** 9.012182(3)												boron **5** **B** 10.811(7)	carbon **6** **C** 12.0107(8)	nitrogen **7** **N** 14.00674(7)	oxygen **8** **O** 15.9994(3)	fluorine **9** **F** 18.9984032(5)	neon **10** **Ne** 20.1797(6)
sodium **11** **Na** 22.989770(2)	magnesium **12** **Mg** 24.3050(6)												aluminium **13** **Al** 26.981538(2)	silicon **14** **Si** 28.0855(3)	phosphorus **15** **P** 30.973761(2)	sulfur **16** **S** 32.065(5)	chlorine **17** **Cl** 35.453(2)	argon **18** **Ar** 39.948(1)
potassium **19** **K** 39.0983(1)	calcium **20** **Ca** 40.078(4)		scandium **21** **Sc** 44.955910(8)	titanium **22** **Ti** 47.867(1)	vanadium **23** **V** 50.9415(1)	chromium **24** **Cr** 51.9961(6)	manganese **25** **Mn** 54.938049(9)	iron **26** **Fe** 55.845(2)	cobalt **27** **Co** 58.933200(9)	nickel **28** **Ni** 58.6934(2)	copper **29** **Cu** 63.546(3)	zinc **30** **Zn** 65.409(4)	gallium **31** **Ga** 69.723(1)	germanium **32** **Ge** 72.64(1)	arsenic **33** **As** 74.92160(2)	selenium **34** **Se** 78.96(3)	bromine **35** **Br** 79.904(1)	krypton **36** **Kr** 83.798(2)
rubidium **37** **Rb** 85.4678(3)	strontium **38** **Sr** 87.62(1)		yttrium **39** **Y** 88.90585(2)	zirconium **40** **Zr** 91.224(2)	niobium **41** **Nb** 92.90638(2)	molybdenum **42** **Mo** 95.94(1)	technetium **43** **Tc** [98]	ruthenium **44** **Ru** 101.07(2)	rhodium **45** **Rh** 102.90550(2)	palladium **46** **Pd** 106.42(1)	silver **47** **Ag** 107.8682(2)	cadmium **48** **Cd** 112.411(8)	indium **49** **In** 114.818(3)	tin **50** **Sn** 118.710(7)	antimony **51** **Sb** 121.760(1)	tellurium **52** **Te** 127.60(3)	iodine **53** **I** 126.90447(3)	xenon **54** **Xe** 131.293(6)
caesium **55** **Cs** 132.90545(2)	barium **56** **Ba** 137.327(7)	**57-70** *	lutetium **71** **Lu** 174.967(1)	hafnium **72** **Hf** 178.49(2)	tantalum **73** **Ta** 180.9479(1)	tungsten **74** **W** 183.84(1)	rhenium **75** **Re** 186.207(1)	osmium **76** **Os** 190.23(3)	iridium **77** **Ir** 192.217(3)	platinum **78** **Pt** 195.078(2)	gold **79** **Au** 196.96655(2)	mercury **80** **Hg** 200.59(2)	thallium **81** **Tl** 204.3833(2)	lead **82** **Pb** 207.2(1)	bismuth **83** **Bi** 20898038(2)	polonium **84** **Po** [209]	astatine **85** **At** [210]	radon **86** **Rn** [222]
francium **87** **Fr** [223]	radium **88** **Ra** [226]	**89-102** *	lawrencium **103** **Lr** [262]	rutherfordium **104** **Rf** [261]	dubnium **105** **Db** [262]	seaborgium **106** **Sg** [266]	bohrium **107** **Bh** [264]	hassium **108** **Hs** [269]	meitnerium **109** **Mt** [268]	darmstadtium **110** **Pt** 195.078(2)	unununium **111** **Uuu** [272]	ununbium **112** **Uub** [285]		ununquadium **114** **Uuq** [289]				

*lanthanoids	lanthanum **57** **La** 138.9055(2)	cerium **58** **Ce** 140.116(1)	praseodymium **59** **Pr** 140.90765(2)	neodymium **60** **Nd** 144.24(3)	promethium **61** **Pm** [145]	samarium **62** **Sm** 150.36(3)	europium **63** **Eu** 151.964(1)	gadolinium **64** **Gd** 157.25(3)	terbium **65** **Tb** 158.92534(2)	dysprosium **66** **Dy** 162.500(1)	holmium **67** **Ho** 164.93032(2)	erbium **68** **Er** 167.259(3)	thulium **69** **Tm** 168.93421(2)	ytterbium **70** **Yb** 173.04(3)
**actinoids	actinium **89** **Ac** [227]	thorium **90** **Th** 232.0381(1)	protactinium **91** **Pa** 231.03588(2)	uranium **92** **U** 238.02891(3)	neptunium **93** **Np** [237]	plutonium **94** **Pu** [244]	americium **95** **Am** [243]	curium **96** **Cm** [247]	berkelium **97** **Bk** [247]	californium **98** **Cf** [251]	einsteinium **99** **Es** [252]	fermium **100** **Fm** [257]	mendelevium **101** **Md** [258]	nobelium **102** **No** 173.04(3)

Figure 1.2 Periodic table of the elements

protons in each atom. Thus, an *iron* atom, which contains 26 electrons and 26 protons, has an atomic number of 26.

Most of the mass of the atom is contained within the nucleus. The mass of each proton and neutron is about 1.67×10^{-27} kg, but the mass of each electron is only 9.11×10^{-31} kg. The *atomic mass M* (in another words – *atomic weight*), which is equal to the average number of protons and neutrons in the atom, is the mass of the *Avogadro number* N_A of atoms. $N_A = 6.02\times10^{23}$ mol^{-1} is the number of atoms or molecules in a mole. An unit for atomic mass is the *atomic mass unit*, which is 1/12 the mass of *carbon* 12.

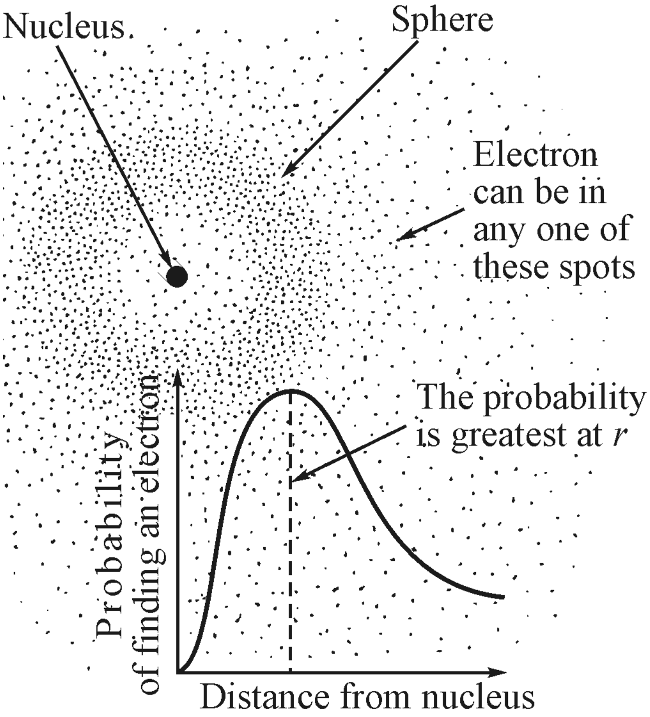


Figure 1.3 An atom described by quantum mechanics

Atoms of the same element that contain a different number of neutrons in the nucleus are called *isotopes* and thus have a different atomic mass. The atomic mass used for such an element is an average value of different isotopes and thus the atomic mass may not be a whole number.

To provide a basis for the solution of the problems we consider an examples at the end of each chapter. They introduce certain concepts which cannot be presented as efficiently in the text proper.

Example 1.1

In a collection of nickel atoms, 70% of the atoms contain 30 neutrons and 30% of the atoms contain 32 neutrons. The atomic number for nickel is 28. Calculate the approximate average atomic mass of nickel.

Answer

The atomic mass of the atoms containing 30 neutrons is $M =$ number of protons + number of neutrons =28+30=58. These atoms are the Ni^{58} isotope.

The atomic mass of the atoms containing 32 neutrons is $M = 28 + 32 = 60$, or the atomic mass of Ni^{60}.

The average atomic mass of nickel is

$$M \text{ of Ni} = (0.7)(M \text{ of Ni}^{58}) + (0.3)(M \text{ of Ni}^{60}) =$$
$$= (0.7)(58) + (0.3)(60) = 58.6.$$

1.1.2 Electronic Structure of the Atom

In accordance with the quantum theory electrons occupy discrete *energy levels* within the atom. Each electron possesses a particular energy, with no more than two electrons in each atom having the same energy. This also implies that there is a definite energy difference between each electron.

Quantum Numbers The energy level to which each electron belongs is determined by four *quantum numbers*. The number of possible energy levels is determined by the first three quantum numbers.

1. *The principal quantum number n* is assigned integral values 1, 2, 3, 4, 5, … , that refer to the *quantum shell* to which the electron belongs (Figure 1.4). Often the quantum shells are assigned a letter rather than a number; the shell for $n=1$ is designated *K*, for $n=2$ is *L*, for $n=3$ is *M*, and so on.

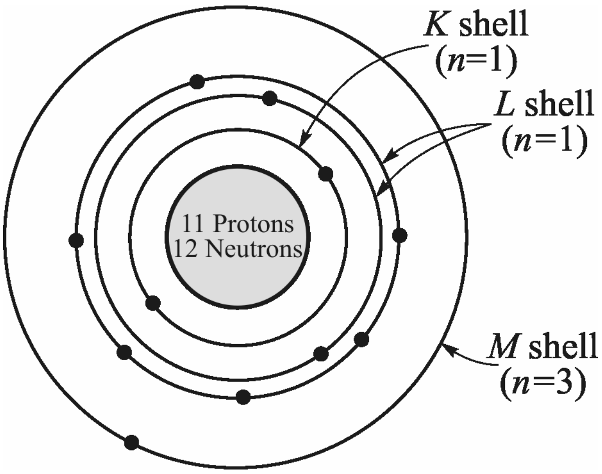


Figure 1.4 The atomic structure of *sodium*, atomic number 11, showing the *K*, *L*, and *M* quantum shells

2. The number of energy levels in each quantum shell is determined by the *azimuthal quantum number l* and the *magnetic quantum number m*. The azimuthal quantum numbers may also be assigned numbers: $l=0,\ 1,\ 2,\ \ldots\ ,\ n-1$. If $n=2$, then there are also two azimuthal quantum numbers, $l=0$ and $l=1$. The azimuthal quantum numbers are often designated by lowercase letters,

s for $l=0$, d for $l=2$,
p for $l=1$, f for $l=3$.

The magnetic quantum number m gives the number of *energy levels*, or *orbitals*, for each azimuthal quantum number. The total number of magnetic quantum numbers for each l is $2l+1$. The values for m are given by whole numbers between $-l$ and $+l$. For $l=2$, there are $2(2)+1=5$ magnetic quantum numbers, with values $-2, -1, 0, +1,$ and $+2$.

Example 1.2

Calculate the number of possible ortibals in the L shell, where $n=2$.

Answer

If $n=2$, then $l=0,1$.

For $l=0$, there are $2(0)+1=1$ magnetic quantum numbers, so $m=0$.

For $l=1$, there are $2(1)+1=3$ magnetic quantum numbers, so $m=-1,0,+1$.

Consequently, there are a total of four orbitals possible in the *L* shell.

3. The *Pauli exclusion principle* specifies that no more than two electrons, each with opposing *electronic spins*, may be present in each orbital. The *spin quantum number* m_s is assigned values +1/2 and –1/2 to reflect the different spins. Figure 1.5 shows the quantum numbers and energy levels for each electron in a sodium atom.

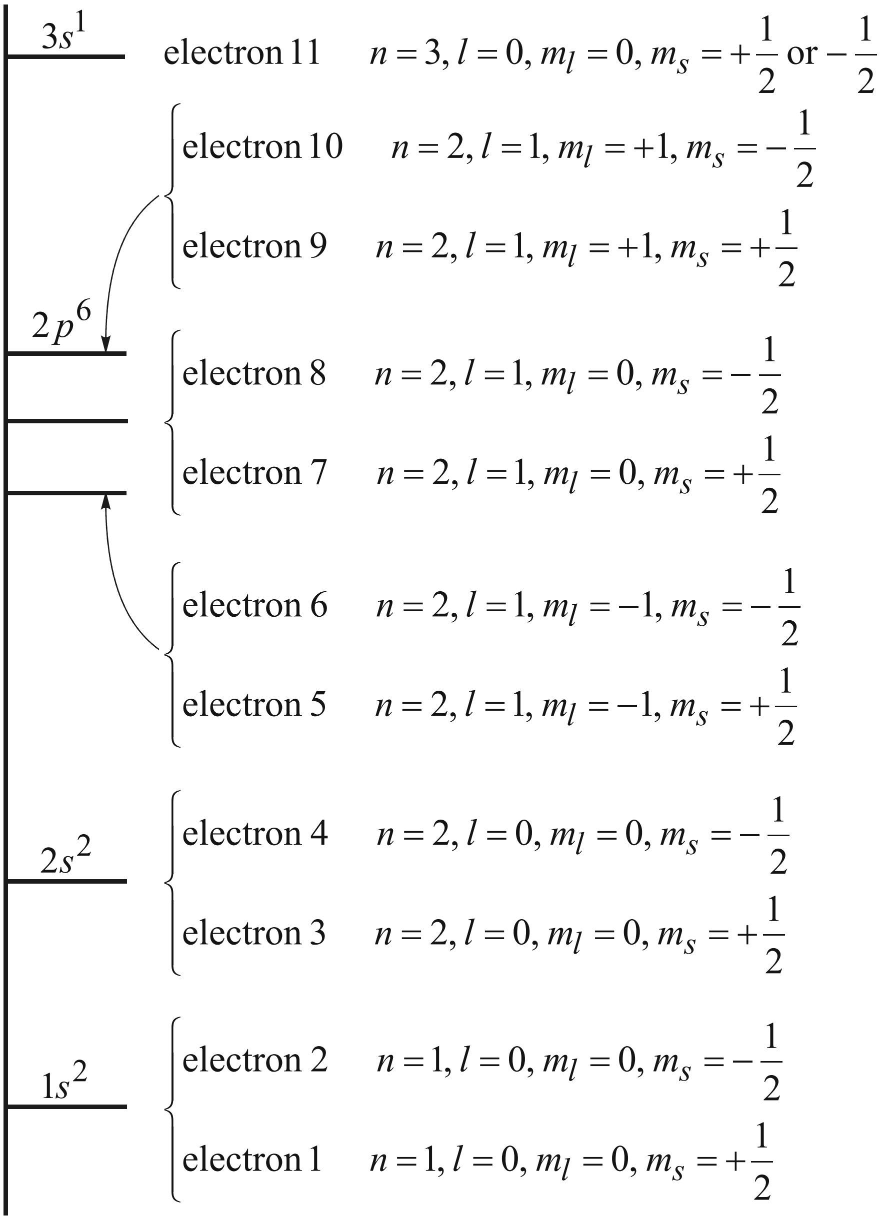


Figure 1.5 The complete set of quantum numbers for each of the 11 electrons in sodium

Example 1.3

Determine the maximum number of electrons in the *M* shell of an atom.

Answer

The principal quantum number for the M shell is $n=3$. If $n=3$, then $l=0, 1, 2$.

$$s \text{ level}, l=0, m=0, m_s=+1/2, -1/2 \qquad \text{2 electrons}$$

$$\left.\begin{aligned} p \text{ level}, l=1, m&=-1, m_s=+1/2, -1/2 \\ &=0, m_s=+1/2, -1/2 \\ &=+1, m_s=+1/2, -1/2 \end{aligned}\right\} \qquad \text{6 electrons}$$

$$\left.\begin{aligned} d \text{ level}, l=2, m&=-2, m_s=+1/2, -1/2 \\ &=-1, m_s=+1/2, -1/2 \\ &=0, m_s=+1/2, -1/2 \\ &=+1, m_s=+1/2, -1/2 \\ &=+2, m_s=+1/2, -1/2 \end{aligned}\right\} \qquad \text{10 electrons}$$

Thus, a total of 18 electrons may be present in the M shell.

If we continue the exercises in Examples 1.2 and 1.3, we could represent the maximum number of electrons in each energy shell by the pattern in Table 1.1.

Table 1.1 The pattern used to assign electrons to energy levels

		l=0 (s)	l=1 (p)	l=2 (d)	l=3 (f)	l=4 (g)	l=5 (h)
$n=1$	(K)	2					
$n=2$	(L)	2	6				
$n=3$	(M)	2	6	10			
$n=4$	(N)	2	6	10	14		
$n=5$	(O)	2	6	10	14	18	
$n=6$	(P)	2	6	10	14	18	22

The shorthand notation used to denote the electronic structure of an atom combines the numerical value of the principal quantum number, the lowercase letter notation for the azimuthal quantum number, and a superscript showing the number of electrons in each orbital. Thus, the shorthand notation for the electronic structure of *germanium*, which has an atomic number of 32, is

$$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 3p^2 .$$

The electronic configurations for the elements are represented in the Table 1.2.

Deviations from Expected Electronic Structures The orderly building up of the electronic structure is not always followed, particularly when the atomic number is large and the *d* and *f* levels begin to fill. For example, we would expect the

Table 1.2 The electronic configuration for the elements

Atomic Number	Element	*K*	*L*		*M*			*N*				*O*			*P*	
		1*s*	2*s*	2*p*	3*s*	3*p*	3*d*	4*s*	4*p*	4*d*	4*f*	5*s*	5*p*	5*d*	6*s*	6*p*
1	Hydrogen	1														
2	Helium	2														
3	Lithium	2	1													
4	Beryllium	2	2													
5	Boron	2	2	1												
6	Carbon	2	2	2												
7	Nitrogen	2	2	3												
8	Oxygen	2	2	4												
9	Fluorine	2	2	5												
10	Neon	2	2	6												
11	Sodium	2	2	6	1											
12	Magnesium	2	2	6	2											
13	Aluminum	2	2	6	2	1										
14	Silicon	2	2	6	2	2										
15	Phosphorus	2	2	6	2	3										
16	Sulfur	2	2	6	2	4										
17	Chlorine	2	2	6	2	5										
18	Argon	2	2	6	2	6										
19	Potassium	2	2	6	2	6		1								
20	Calcium	2	2	6	2	6		2								
21	Scandium	2	2	6	2	6	1	2								
22	Titanium	2	2	6	2	6	2	2								
23	Vanadium	2	2	6	2	6	3	2								
24	Chromium	2	2	6	2	6	5	1								
25	Manganese	2	2	6	2	6	5	2								
26	Iron	2	2	6	2	6	6	2								
27	Cobalt	2	2	6	2	6	7	2								
28	Nickel	2	2	6	2	6	8	2								
29	Copper	2	2	6	2	6	10	1								
30	Zinc	2	2	6	2	6	10	2								
31	Gallium	2	2	6	2	6	10	2	1							
32	Germanium	2	2	6	2	6	10	2	2							
33	Arsenic	2	2	6	2	6	10	2	3							
34	Selenium	2	2	6	2	6	10	2	4							
35	Bromine	2	2	6	2	6	10	2	5							
36	Krypton	2	2	6	2	6	10	2	6							
37	Rubidium	2	2	6	2	6	10	2	6			1				
38	Strontium	2	2	6	2	6	10	2	6			2				
39	Yttrium	2	2	6	2	6	10	2	6	1		2				
40	Zirconium	2	2	6	2	6	10	2	6	2		2				
41	Niobium	2	2	6	2	6	10	2	6	4		1				
42	Molybdenum	2	2	6	2	6	10	2	6	5		1				
43	Technetium	2	2	6	2	6	10	2	6	6		1				
44	Ruthenium	2	2	6	2	6	10	2	6	7		1				

Table 1.2 The electronic configuration for each of the elements (finished)

Atomic Number	Element	*K*	*L*		*M*			*N*				*O*			*P*	
		1*s*	2*s*	2*p*	3*s*	3*p*	3*d*	4*s*	4*p*	4*d*	4*f*	5*s*	5*p*	5*d*	6*s*	6*p*
45	Rhodium	2	2	6	2	6	10	2	6	8		1				
46	Palladium	2	2	6	2	6	10	2	6	10						
47	Silver	2	2	6	2	6	10	2	6	10		1				
48	Cadmium	2	2	6	2	6	10	2	6	10		2				
49	Indium	2	2	6	2	6	10	2	6	10		2	1			
50	Tin	2	2	6	2	6	10	2	6	10		2	2			
51	Antimony	2	2	6	2	6	10	2	6	10		2	3			
52	Tellurium	2	2	6	2	6	10	2	6	10		2	4			
53	Iodine	2	2	6	2	6	10	2	6	10		2	5			
54	Xenon	2	2	6	2	6	10	2	6	10		2	6			
55	Cesium	2	2	6	2	6	10	2	6	10		2	6		1	
56	Barium	2	2	6	2	6	10	2	6	10		2	6		2	
57	Lanthanum	2	2	6	2	6	10	2	6	10	1	2	6		2	
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	
71	Lutetium	2	2	6	2	6	10	2	6	10	14	2	6	1	2	
72	Hafnium	2	2	6	2	6	10	2	6	10	14	2	6	2	2	
73	Tantalum	2	2	6	2	6	10	2	6	10	14	2	6	3	2	
74	Tungsten	2	2	6	2	6	10	2	6	10	14	2	6	4	2	
75	Rhenium	2	2	6	2	6	10	2	6	10	14	2	6	5		
76	Osmium	2	2	6	2	6	10	2	6	10	14	2	6	6		
77	Iridium	2	2	6	2	6	10	2	6	10	14	2	6	9		
78	Platinum	2	2	6	2	6	10	2	6	10	14	2	6	9	1	
79	Gold	2	2	6	2	6	10	2	6	10	14	2	6	10	1	
80	Mercury	2	2	6	2	6	10	2	6	10	14	2	6	10	2	
81	Thallium	2	2	6	2	6	10	2	6	10	14	2	6	10	2	1
82	Lead	2	2	6	2	6	10	2	6	10	14	2	6	10	2	2
83	Bismuth	2	2	6	2	6	10	2	6	10	14	2	6	10	2	3
84	Polonium	2	2	6	2	6	10	2	6	10	14	2	6	10	2	4
85	Astatine	2	2	6	2	6	10	2	6	10	14	2	6	10	2	5
86	Radon	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6

electronic structure of iron, atomic number 26, to be

$$1s^2 2s^2 2p^6 3s^2 3p^6 \boxed{3d^8}.$$

However, from Table 1.2, we find that the actual structure is

$$1s^2 2s^2 2p^6 3s^2 3p^6 \boxed{3d^6 4s^2}.$$

The unfilled $3d$ level causes the magnetic behavior of iron. Many other examples of this behavior can be found in the Table 1.2.

Valence The *valence* of an atom is related to the *ability of the atom to enter into chemical combination* with other elements and is often determined by the number of electrons in the outermost combined *sp* level. Examples of the valence are

Mg: $1s^2 2s^2 2p^6 \boxed{3s^2}$ valence=2,

Al: $1s^2 2s^2 2p^6 \boxed{3s^2 3p^1}$ valence=3,

Ge: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} \boxed{4s^2 4p^2}$ valence=4.

The valence also depends on the nature of the chemical reaction. The electronic structure of *phosphorus* is

$1s^2 2s^2 2p^6 \boxed{3s^2 3p^1}$.

Phosphorus has the expected valence of five when it combines with oxygen. But the valence of phosphorus is only three – the electrons in the 3*p* level – when it reacts with hydrogen. *Manganese* may have a valence of 2, 3, 4, 6, or 7.

Atomic Stability If an atom has a valence of zero, no electrons enter into chemical reactions and the element is inert. An example is *argon*, which has the electronic structure

$1s^2 2s^2 2p^6 \boxed{3s^2 3p^6}$.

Other atoms also prefer to behave as if their outer *sp* levels are either completely full, with eight electrons, or completely empty. Aluminum with the electronic structure

$1s^2 2s^2 2p^6 \boxed{3s^2 3p^1}$

has three electrons in its outer *sp* level. An aluminum atom readily gives up its outer three electrons to empty the *3sp* level. The nature of the atomic bonding and the chemical behavior of aluminum is determined by the mechanism through which these three electrons interact with surrounding atoms.

On the other hand, chlorine, with an electronic structure

$1s^2 2s^2 2p^6 \boxed{3s^2 3p^5}$

contains seven electrons in the outer *3sp* level. The reactivity of chlorine is caused by its desire to fill its outer energy level by accepting an electron.

Electronegativity *Electronegativity* describes the tendency of an atom to gain an electron. Atoms with almost completely filled outer energy levels, like chlorine, are strongly electronegative and readily accept electrons. However, atoms with nearly empty outer levels, such as sodium

$1s^2 2s^2 2p^6 \boxed{3s^1}$

readily give up electrons and are strongly *electropositive.* High atomic number elements also have a low electronegativity; because the outer electrons are at a greater distance from the positive nucleus, electrons are not as strongly attracted to the atom. Electronegativities for some elements are shown in Figure 1.6

Example 1.4

Using the electronic structures, compare the electronegativities of *calcium* and *bromine*.

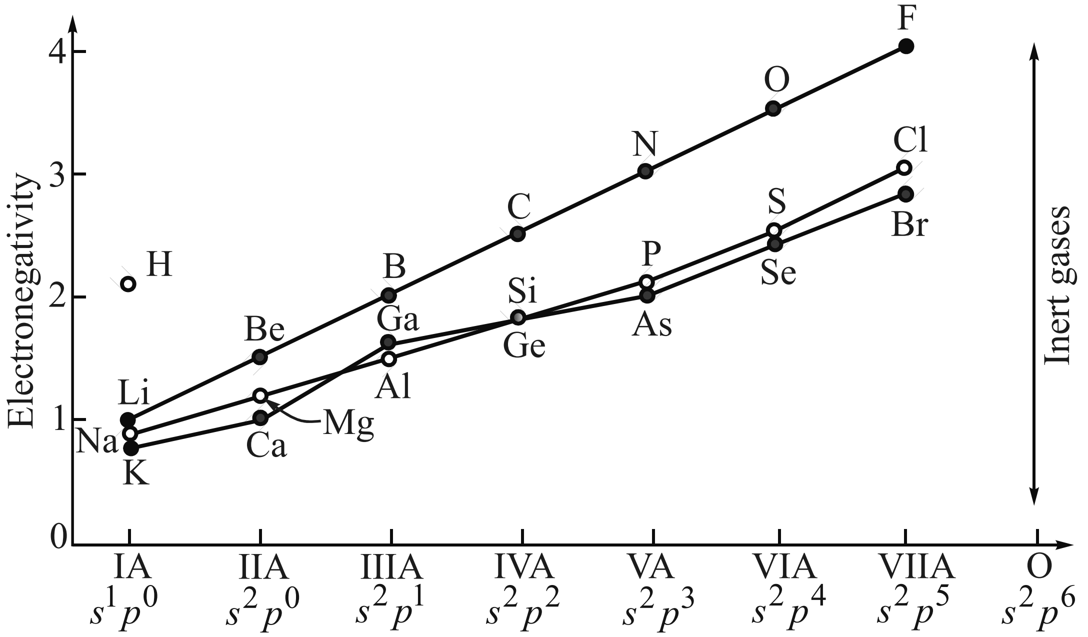


Figure 1.6 The electronegativies of selected chemical elements with respect to the position of the element in the periodic table

Answer

The electronic structures, obtained from Table 1.2, are

Ca: $1s^2 2s^2 2p^6\ 3s^2 3p^6 \boxed{4s^2}$,

Br: $1s^2 2s^2 2p^6\ 3s^2 3p^6 3d^{10} \boxed{4s^2 4p^5}$.

Calcium has two electrons in its outer 4*s* orbital and bromine has seven electrons in its outer 4*s*4*p* orbital. Calcium tends to give up electrons and is strongly electropositive, but bromine tends to accept electrons and is strongly electronegative.

1.1.3 Periodic Table

The properties of elements tend to be a periodic function of their atomic numbers. It is common practice to list the elements in the array shown in Figure 1.2, the *periodic table.* The construction of the periodic table is based on the electronic configuration of the elements. Consequently, the periodic table can give us the possibilities to study the behavior of the elements.

The atomic number of the elements increases horizontally in the table, and the vertical groupings are based on similarities in valence electron configurations and similarities in chemical and physical properties of the elements (see Figure 1.7).

The elements in group IA are called *alkali metals*; group IIA elements are *alkaline-earth metals*. The groups listed as *transition* elements are metals with a particular electron sub shell configuration (incompleted *subshell*). Groups IIIA, IVA, VA, and VIIA are mostly *nonmetals* (as shown by the heavy line in Figure 1.2), and

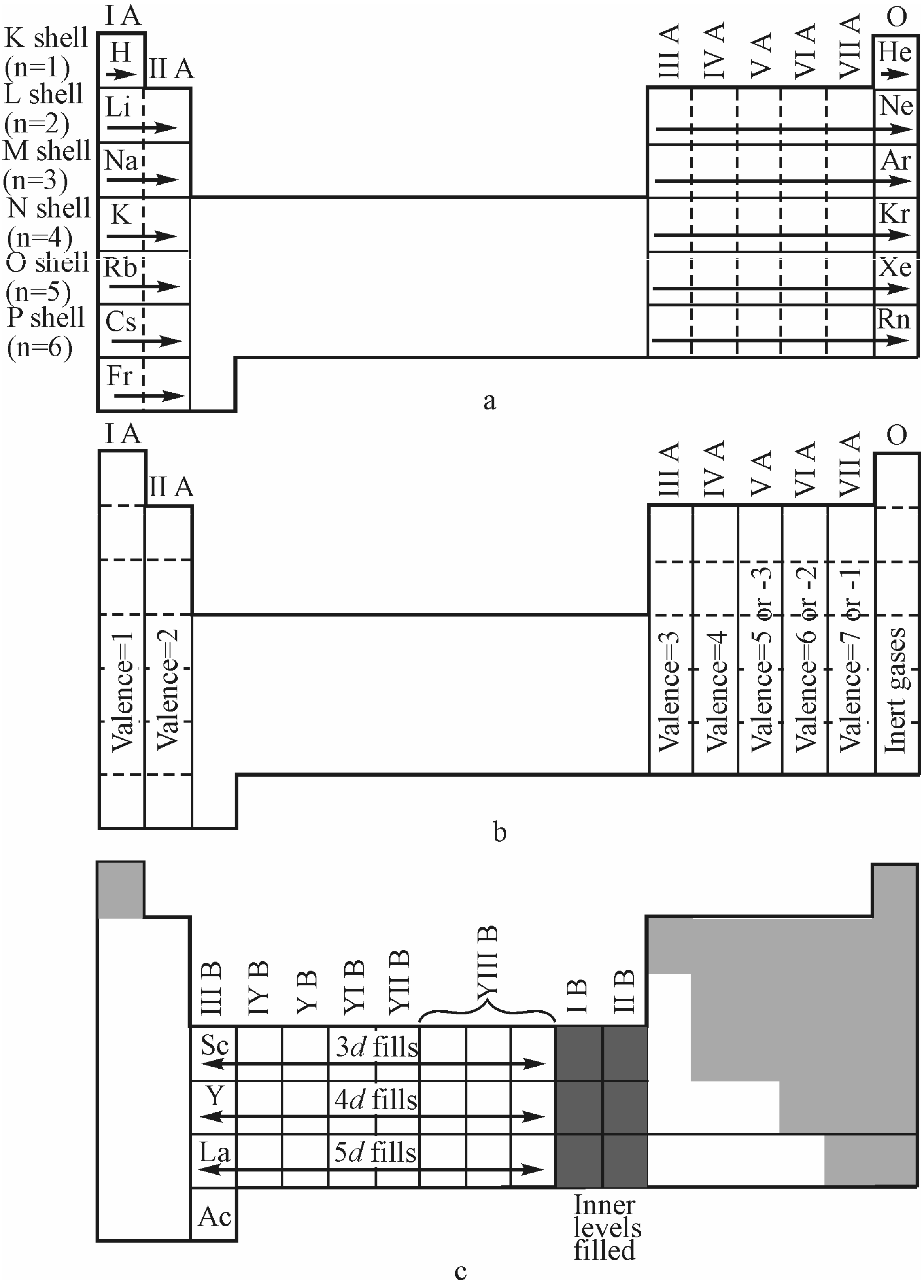


Figure 1.7 In the periodic table, (a) rows correspond to principal quantum numbers and show the change in electronegativity, (b) columns correspond to similar electronegativities, and (c) transition elements have partly filled inner energy levels. The lightly shaded regions in (c) denote nonmetallic elements

the elements in the last vertical grouping are *inert gases*. The groups of elements in the separate horizontal blocks, *lanthanide* series and *actinide* series, really belong in periods 6 and 7 respectively, but to list them in this way would make the table unbalanced in shape. The elements in each series behave the same chemically.

Another trend in the periodic listing of elements is that the atomic size of the elements becomes smaller in a period going from left to right on the table. The size of the elements in a particular family or group tends to increase going from top to bottom. The elements with atomic numbers greater than 92 do not occur in nature; they were produced by *nuclear reactions*. Thus there is no definite end to the periodic table. Elements with atomic numbers as high as 114 have been identified, but they are relatively unstable and some are even unnamed.

What is the significance of the periodic table in engineering materials? Foremost, it is the “dictionary” for the names and chemical symbols for the elements which are the building blocks for all engineering materials. The chemical symbols for the elements are used throughout subsequent discussions of materials and their processing. The family groupings indicate which elements behave similar. This can be important in selection problems solving. The atomic weight is the average weight of the common isotopes of a particular element. The atomic weight is an indicator of the *density* of an element. This is a physical property that can also used in selection. The simplified electron structure shown in Figure 1.2 shows the number of electrons in the various orbitals. The number at the bottom of the vertical column indicates the number of electrons in the valence shell. This number and the element grouping provide indicators of how a particular element might combine with other elements.

1.1.4 Atomic Bonding

There are four important mechanisms by which atoms are bonded in solids. In three of the four mechanisms, bonding is achieved when the atoms fill their outer *s* and *p* levels.

The Metallic Bond The metallic elements, which have a low valence, give up their valence electrons to form a “cloud” of electrons surrounding the atoms (Figures 1.3 and 1.8). Aluminum, for example, gives up its three valence electrons, leaving behind a core consisting of the nucleus and inner electrons. Since three negatively charged electrons are missing from this atom, the atom becomes an ion with a positive charge of three. The valence electrons, which are no longer associated with any particular atom, move freely within the electron cloud and become associated with several atom nuclei. The positively charged atom nuclei are held together by mutual attraction to the electron, thus producing the strong *metallic bond*.

Metallic bonds are *nondirectional*; the electrons holding the atoms together are not fixed in one position. When a metal is bent and the atoms attempt to change their relationship to one another, the direction of the bond merely shifts, rather than the bond breaking (Figure 1.9 (a)). This permits metals to have good *ductility* and to be deformed into useful shapes.

The metallic bond also allows metals to be good *electrical conductors*. Under the influence of an applied voltage, the valence electrons move (Figure 1.9 (b)), causing a current to flow if the circuit is complete. Other bonding mechanisms require much higher voltages to free the electrons from the bond.

The Covalent Bond Covalently bonded materials share electrons among two or more atoms. For example, a silicon atom, which has a valence of four, obtains eight electrons in its outer energy shell by sharing its electrons with four surrounding silicon atoms (Figure 1.10). Each instance of sharing represents one *covalent bond*; thus each silicon atom is bonded to four neighboring atoms by four covalent bonds.

To produce the covalent bonds the silicon atoms must be arranged so the bonds have a fixed *directional* relationship with one another. In the case of silicon, this arrangement produces a *tetrahedron,* with angles of about 109° between the covalent bonds (Figure 1.11). There is a much higher probability that electrons are located near these covalent bonds than elsewhere around the atom nucleus.

Although covalent bonds are very strong, materials bonded in this manner have poor ductility and poor electrical conductivity. When a silicon rod is bent, the bonds must break if the silicon atoms are to permanently change their relationships to one another. Furthermore, for an electron to move and carry a current, the covalent bond must be broken, requiring

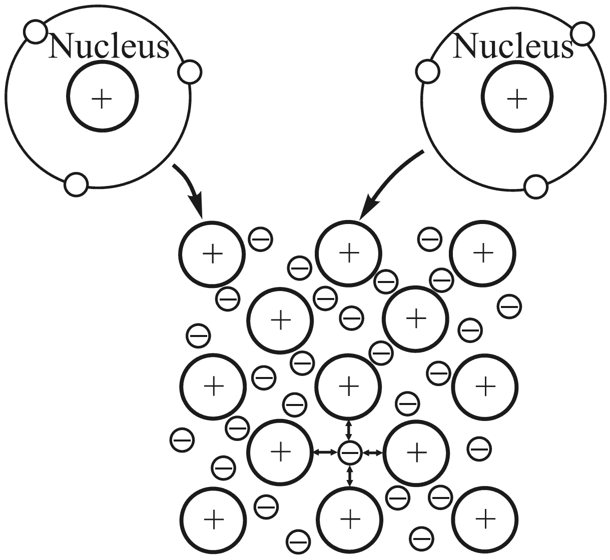


Figure 1.8 The metallic bond forms when atoms give up their valence electrons, which then form an electron “cloud”. The positively charged atom nuclei are bonded by mutual attraction to the negatively charged electrons

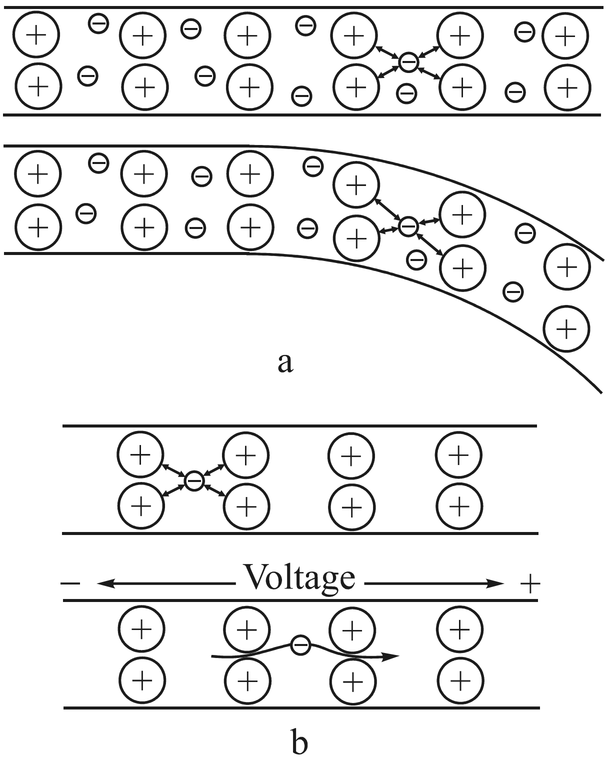


Figure 1.9 (a) Atoms joined by the metallic bond can shift their relative positions when the metal is deformed, permitting metals to have good ductility, (b) When a voltage is applied to a metal, the electrons in the electron “cloud” can easily move and carry a current

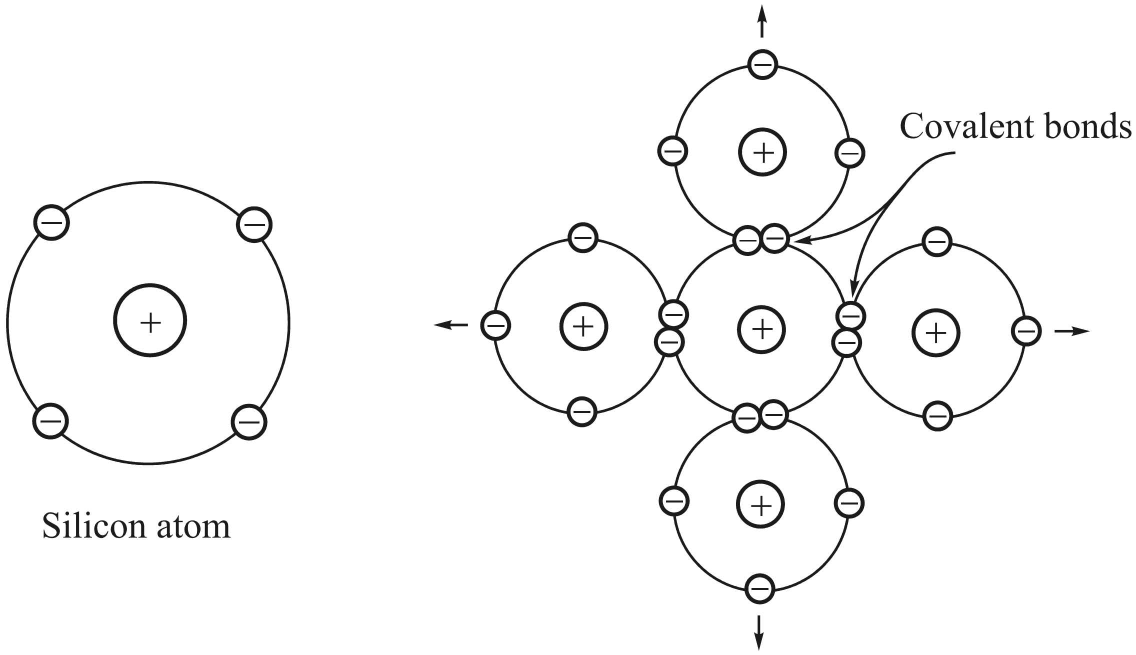


Figure 1.10 Covalent bonding requires that electrons be shared between atoms in such a way that each atom has its outer *sp* orbital filled. In silicon, with a valence of four, four covalent bonds must be formed

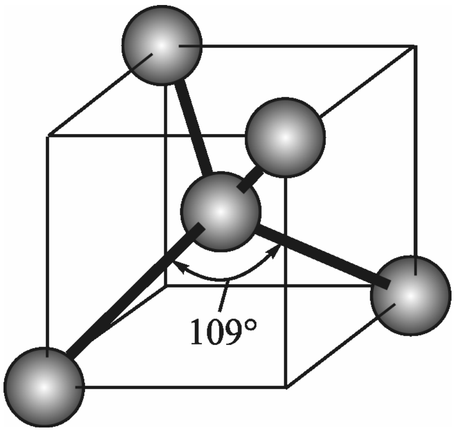


Figure 1.11 Covalent bonds are directional. In silicon, a tetrahedral structure is formed, with angles of about 109° required between each covalent bond

high temperatures or voltages.

Thus, covalently bonded materials are *brittle* rather than ductile and behave as electrical insulators instead of conductors. Many ceramic, semiconductor, and polymer materials are fully or partly bonded by covalent bonds, explaining why glass shatters when dropped and why bricks are good insulating.

Example 1.5

Describe how covalent bonding joins oxygen and silicon atoms in *silica* (SiO_2).

Answer

Silicon has a valence of four and shares electrons with four oxygen atoms, thus giving a total of eight electrons for each silicon atom. However, oxygen has a valence of six and shares electrons with two silicon atoms, giving oxygen a total of eight electrons.

Figure 1.12 shows one of the possible structures. As in silicon, a tetrahedral structure is produced.

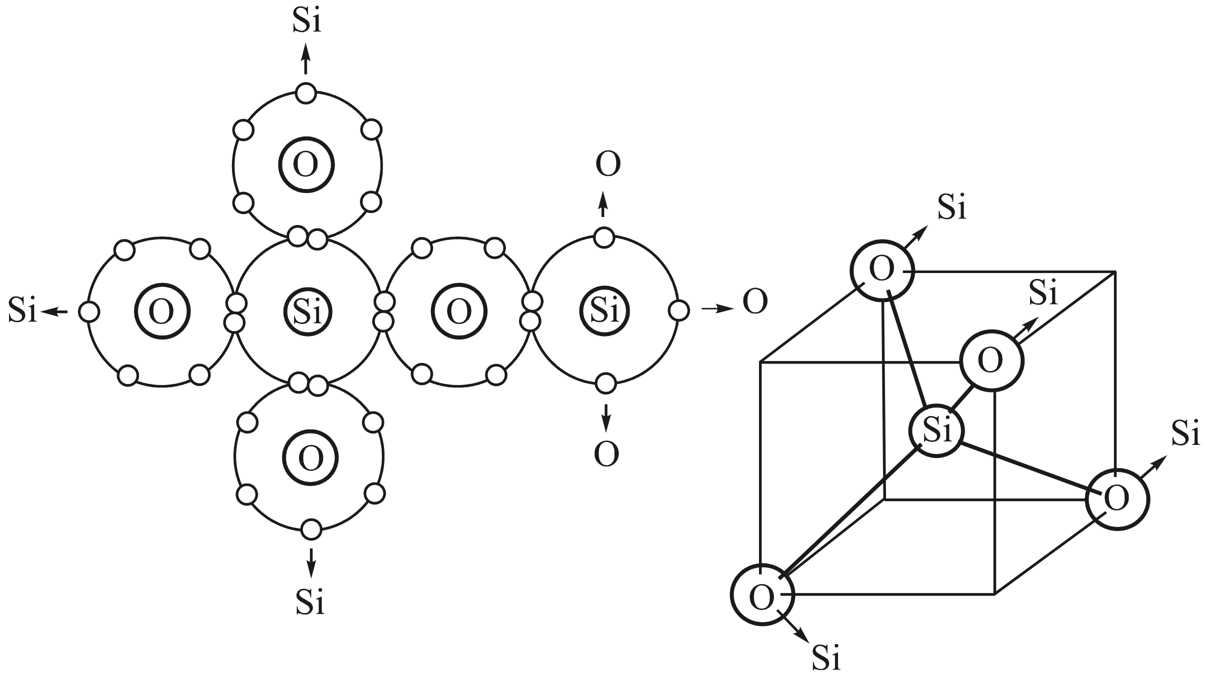


Figure 1.12 The tetrahedral structure of silica (SiO_2), which contains covalent bonds between silicon and oxygen atoms

The Ionic Bond When more than one type of atom is present in a material, one atom may donate its valence electrons to a different atom, filling the outer energy shell of the second atom. Both atoms now have filled (or empty) outer energy levels but both have acquired an electrical charge and *behave* as ions. The atom that contributes the electrons is left with a net positive charge and is a *cation,* while the atom that accepts the electrons acquires a net negative charge and is an *anion.* The oppositely charged ions are then attracted to one another and produce the *ionic bond.* For example, attraction between sodium and chloride ions (Figure 1.13) produces *sodium chloride*, or table salt, NaCl.

When a force is applied to a sodium chloride crystal, the electrical balance between the ions is upset. Partly for this reason, ionically bonded materials behave in a brittle manner. (A more detailed explanation for this brittle behavior will be offered in a later chapter.) Electrical conductivity is also poor; the electrical charge is transferred by the movement of entire ions (Figure 1.14), which do not move as easily as electrons.

Example 1.6

Describe the ionic bonding between *magnesium* and chlorine.

Answer

The electronic structures and valences are

Mg: $1s^2 2s^2 2p^6 \boxed{3s^2}$ valence=2,

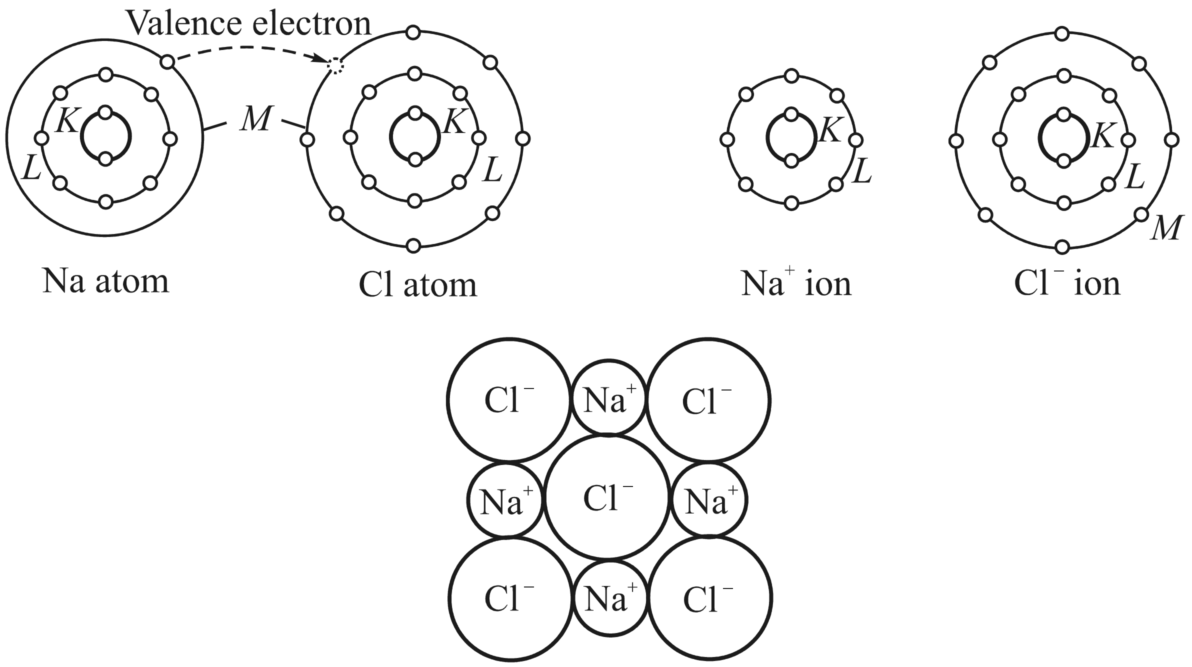


Figure 1.13 The ionic bond is created between two unlike atoms with different electronegativities. When sodium donates its valence electron to chlorine, each becomes an ion, attraction occurs, and the ionic bond is formed

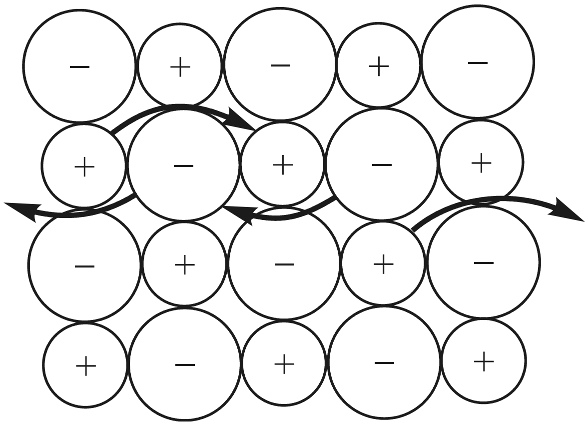


Figure 1.14 When a voltage is applied to an ionic material, entire ions must move to cause a current to flow. Ion movement is slow and the electrical conductivity is poor

Cl: $1s^2 2s^2 2p^6 \boxed{3s^2 3p^5}$ valence=7.

Each magnesium atom gives up its two valence electrons, becoming a Mg^{2+} ion. Each chlorine atom accepts one electron, becoming a Gl^- ion. To satisfy the ionic bonding, there must be twice as many chlorine atoms as magnesium atoms present, and a compound, $MgCl_2$, is formed.

Example 1.7

As a general rule, would you expect anions or cations to have the larger ionic radius?

Answer

Because the cation gives up its electron whereas the anion accepts an electron, we find that anions tend to be larger than cations.

Van der Waals Bonding Van der Waals bonds join molecules or groups of atoms by weak electrostatic attractions. Many plastics, ceramics, water, and other molecules are permanently *polarized;* that is, some portions of the molecule tend to be positively charged, while other portions are negatively charged. The electrostatic attraction between the positively charged regions of one molecule and the negatively charged regions of a second molecule weakly bond the two molecules together (Figure 1.15).

Van der Waals bonding is a *secondary bond,* but the atoms within the molecule or group of atoms are joined by strong covalent or ionic bonds. Heating water to the boiling point breaks the Van der Waals bonds and changes water to steam, but much higher temperatures are required to break the covalent bonds joining oxygen and hydrogen atoms together.

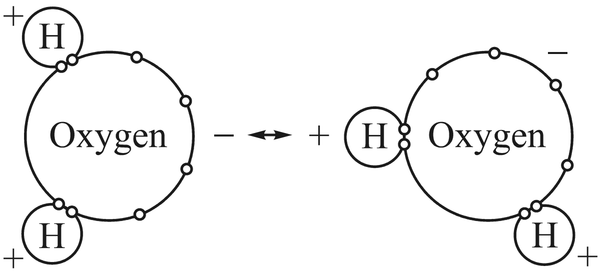


Figure 1.15 The Van der Waals bond is formed due to polarization of molecules or groups of atoms. In water, electrons in the oxygen tend to concentrate away from the hydrogen. The resulting charge difference permits the molecule to be weakly bonded to other water molecules

Van der Waals bonds can dramatically change the properties of materials. Since polymers normally have covalent bonds, we would expect *polyvinyl chloride* (PVC plastic) to be very brittle. However, polyvinyl chloride contains many long, chainlike molecules (Figure 1.16). Within each chain, bonding is covalent, but individual chains are bonded to one another by Van der Waals bonds. Polyvinyl chloride can be deformed significantly by breaking only the Van der Waals bonds as the chains slide past one another.

Mixed Bonding In most materials, bonding between atoms is a mixture of two or more types. *Iron*, for example, is bonded by a combination of metallic and covalent bonding. The directional nature of the covalent portion may prevent atoms in iron from packing as efficiently as we might expect.

Compounds formed from two or more metals (*intermetallic compounds*) may be bonded by a mixture of metallic and ionic bonds, particularly when there is a large difference in electronegativity between the elements. Because *lithium* has an electronegativity of 1.0 and aluminum has an electronegativity of 1.5, we would expect AlLi to have a combination of metallic and ionic bonding. On the other hand, because both *aluminum* and *vanadium* have electronegativities of 1.5, we would expect $A1_3V$ to be bonded primarily by metallic bonds.

Many ceramic and semiconducting compounds, which are combinations of metallic and nonmetallic elements, have a mixture of covalent and ionic bonding. As the electronegativity difference between the atoms increases, the bonding becomes more ionic. The fraction of bonding that is covalent can be estimated from the equation

$$\text{fraction covalent} = \exp(-0.25\Delta E^2), \qquad (1.1)$$

where ΔE is the difference in electronegativities.

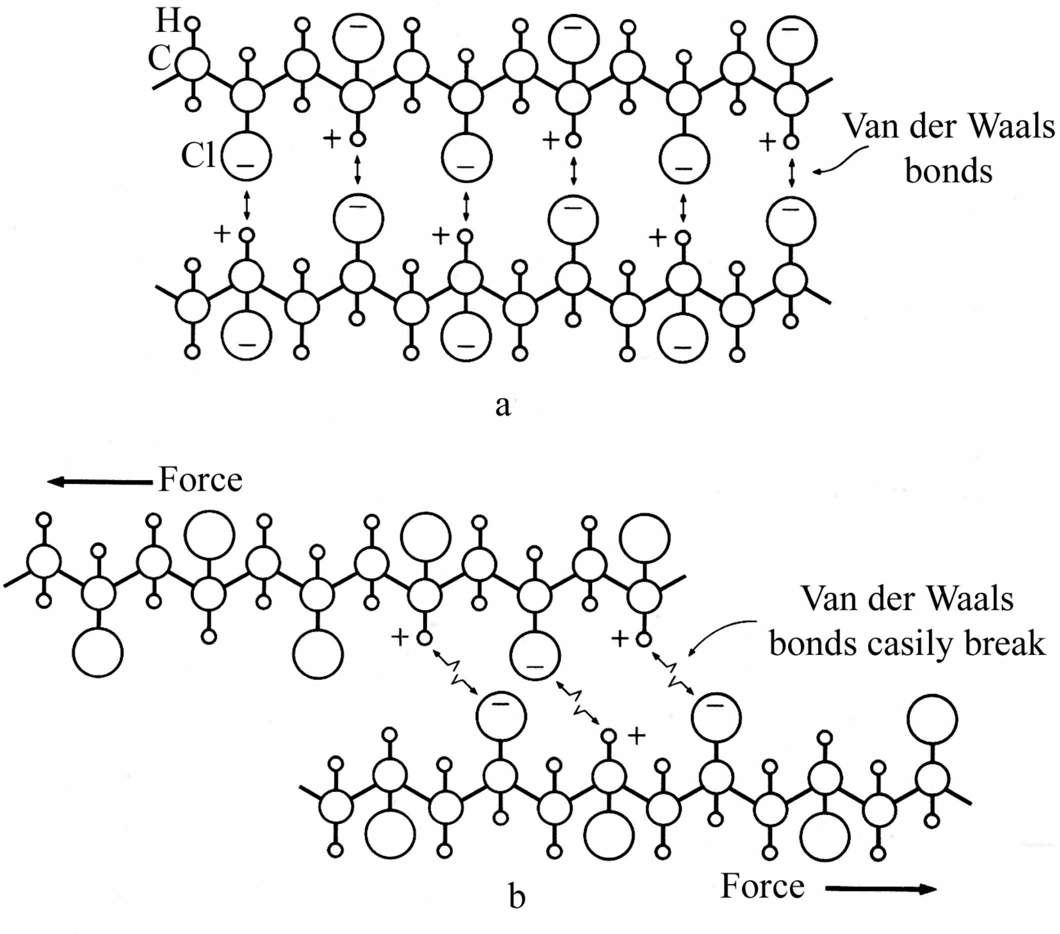


Figure 1.16 (a) In polyvinyl chloride, the chlorine atoms attached to the polymer chain have a negative charge and the hydrogen atoms are positively charged. The chains are weakly bonded by Van der Waals bonds, (b) When a force is applied to the polymer, the Van der Waals bonds are broken and the chains slide past one another

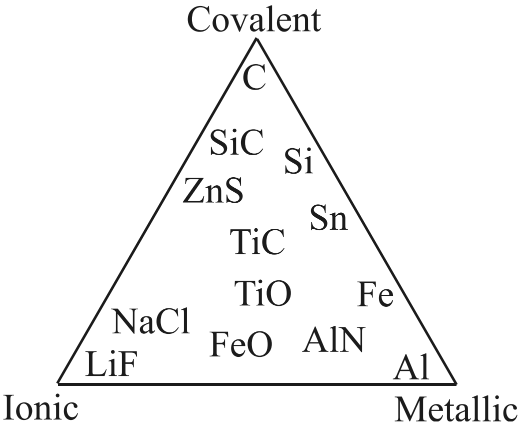


Figure 1.17 Bonding mixtures. Most materials possess a combination of bonds

The intermediate bond combinations are illustrated schematically in Figure 1.17.

Example 1.8

We used SiO_2 as an example of a covalently bonded material. What fraction of the bonding is covalent?

Answer

From Figure 1.6, which estimates the relationship between the electronegativities of materials and their position in the periodic table, we determine the electronegativity of silicon as 1.8 and that of oxygen as 3.5. The fraction of the bonding that is covalent is

$$\text{fraction covalent} = \exp(-0.25(3.5-1.8)^2) = \exp(-0.72) = 0.486\,.$$

Although the covalent bonding represents only about half of the bonding, the directional nature of these bonds plays an important role in the eventual structure of SiO_2.

1.1.5 Binding Energy and Interatomic Spacing

Interatomic spacing is the equilibrium distance between atoms and is caused by a balance between *repulsive* and *attractive* forces. In the metallic bond, for example, the attraction between the electrons and the atom nucleus is balanced by the repulsion between atom nuclei. Equilibrium separation occurs when the total energy of the pair of atoms is at a minimum, or when no net force is acting to either attract or repulse the atoms (Figure 1.18).

The interatomic spacing in a solid metal is equal to the atomic diameter, or twice the *atomic radius r.* We cannot use this approach for ionically bonded materials, however, since the spacing is the sum of the two different ionic radii. Atomic and ionic radii for the elements are listed in Appendix I.

The minimum energy in Figure 1.18 is the *binding energy,* or the energy required to create or break the bond. Consequently, materials having a high binding energy also have a high *strength* and a high *melting temperature*.

Ionically bonded materials have a particularly large binding energy, due to the large difference in electronegativities between the ions (Table 1.3); metals have lower binding energies, since the electronegativities of the atoms are similar.

Table 1.3 Binding energies for the four bonding mechanisms

Bond	Binding Energy (kJ/mol)
Ionic	630-1550
Covalent	520-1260
Metallic	105-840
Van der Waals	< 42

Other properties can be related to the force-distance and energy-distance expressions in Figure 1.18. For example, the *modulus of elasticity* of a material which is the amount that a material will stretch when a force is applied, is related to the slope of the force-distance curve (Figure 1.19). A steep slope, which correlates with a higher binding energy and a higher melting point, means that a greater force is required to stretch the bond; thus, the material has a high modulus of elasticity. In a similar manner, the *coefficient of thermal expansion,* which describes how much a material expands or contracts when its temperature is changed, can be related to the energy-distance curve. When the material is heated, additional energy is supplied to the material, causing the atoms to separate. When the binding energy is large, the additional energy causes a smaller change in the separation, or the material has a lower coefficient of thermal expansion.

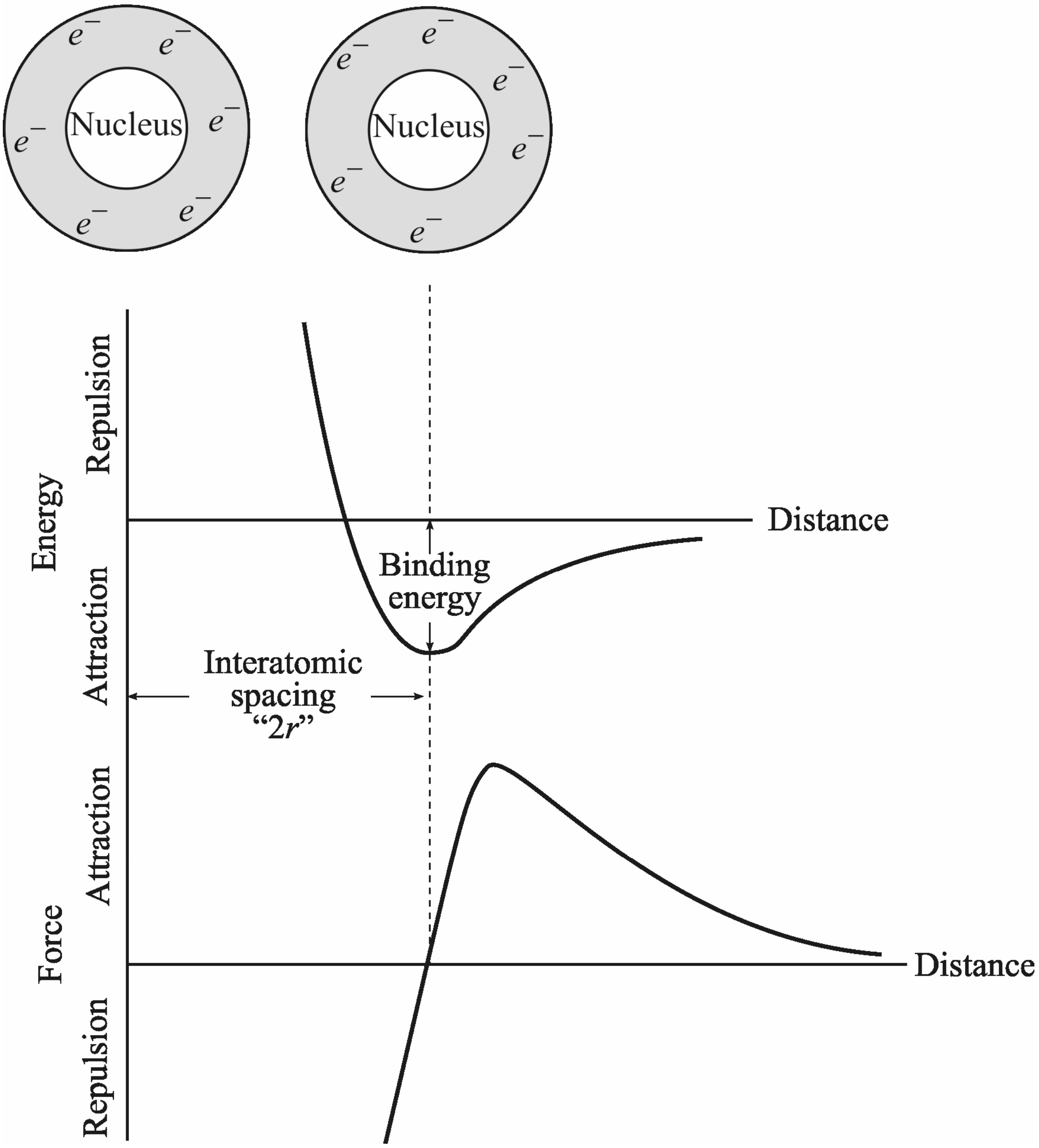


Figure 1.18 Atoms or Ions are separated by an equilibrium spacing that corresponds to the minimum energy of the atoms or ions (or when zero force is acting to repel or attract the atoms or ions)

As the result, the electronic structure of an atom may be characterized by examining the energy levels to which each electron is assigned by the four quantum numbers. The periodic table of the elements is constructed based on the electronic structure. The energies of the electrons play an important role in determining many of the physical properties of a material. We have found that the electronic structure plays an important role in determining the bonding between atoms, permitting us to assign general characteristics to each type of material. Metals have good ductility and electrical conductivity because of the metallic bond. Ceramics, semiconductors, and many polymers have poor ductility and electrical conductivity because of the covalent and ionic bonds. Van der Waals bonds are responsible for good ductility in certain polymers.

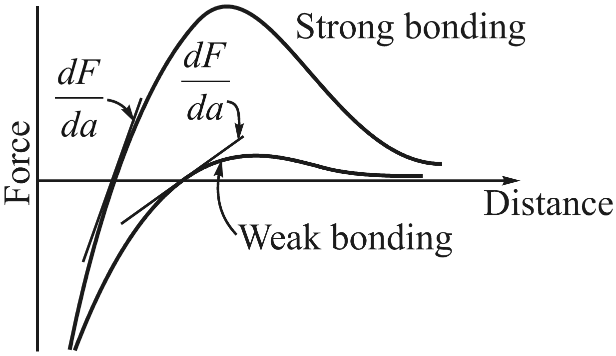


Figure 1.19 The force-distance curve for two materials, showing the relationship between atomic bonding and the modulus of elasticity. A steep *dF/da* slope gives a high modulus

1.2 Atomic Arrangement

Some of the chemical elements are used as engineering materials in their “pure” elemental state. Many metals fall into this category; *beryllium*, *titanium*, *copper*, *gold*, *silver*, *platinum*, *lead*, *mercury*, and many of the *refractory metals* (W, Ta, Mo, Hf) are used to make industrial items. Many metals are used in the “pure” state for electroplating durable goods, tools, and electrical devices: Cr, Ni, Cd, Sn, Zn, Os, Re, Rh. In the nonmetal category, carbon is used in industrial applications for motor brushes, wear parts, and in the cubic form as diamond for tools. The inert gases are other nonmetals that are used in the elemental form for industrial applications for protective atmospheres and the like.

A larger percentage of engineering materials utilize the elements in combined forms, in *alloys* (a metal combined with one or more other elements), in *compounds* (chemically combined elements with definite proportions of the component elements), and to a smaller degree, in *mixtures* (a physical blend of two or more substances). These combinations of the elements can be *solids*, *liquids*, or *gases*. Our discussions will concentrate on elements combined to make solids. Many solids are compounds formed by chemical reactions. The smallest part of a compound that still retains the properties of that compound is the *molecule.* Usually, molecules contain various atoms with definite ratios of one atom to the other (Figure 1.20):

H_2O – a water molecule formed by two hydrogen atoms and one oxygen atom.

Gases often form molecules with like atoms.

All chemical reactions must be balanced. The number of atoms in the re-

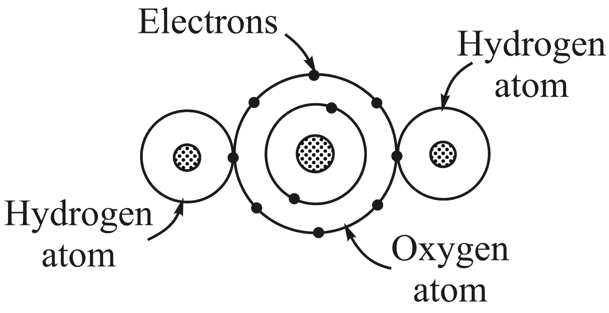


Figure 1.20 Water molecule

acting species must equal the number of atoms in the reaction products.

There are many laws of chemistry and physics controlling chemical bonding and the tendencies for bonding, which are used in materials development. The studying of an *atomic arrangement* is the second step in the understanding of our possibilities in further materials forming, because not only bonds but atomic arrangement also play an important role in determining the microstructure and behavior of a solid material. In metals, some arrangements permit exceptional ductility, whereas others permit exceptional strength. Certain physical properties of ceramics rely on the atomic arrangement; transducers used to produce the electrical signal in a stereo record player rely on an atomic arrangement that produces a permanent displacement of electrical charge within the material. The diverse behavior of polymers, such as rubber, polyethylene, and epoxy, is caused by differences in the atomic arrangement.

We will study typical atomic arrangements in *perfect solids* and develop the nomenclature used to characterize this arrangement. But only after that we will be prepared to investigate how *imperfections* in the atomic arrangement permit us to understand the sources of solid materials strength and deformation.

1.2.1 Short-Range Order Versus Long-Range Order

If we neglect imperfections in materials, there are three levels of atomic arrangement (Figure 1.21).

No Order In gases such as argon, the atoms have *no order*; argon atoms randomly fill up the space to which the gas is confined.

Short-Range Order A material displays short-range order if the special arrangement of the atoms extends only to the atom's nearest neighbors. Each water molecule in steam has a *short-range order* due to the covalent bonds between the hydrogen and oxygen atoms; that is, each oxygen atom is joined to two hydrogen atoms, forming an angle of about 104.5° between the bonds. However, the water molecules have no special arrangement but instead randomly fill up the space available to them.

A similar situation exists in ceramic glasses. In Example 1.5, we described the tetrahedral structure in silica, which satisfies the requirement that four oxygen atoms be covalently bonded to each silicon atom. Because the oxygen atoms must form angles of about 109° to satisfy the directionality requirements of the covalent bonds, a short-range order results. However, the tetrahedral units may be joined together in a random manner.

Polymers also display short-range atomic arrangements and, in fact, may closely resemble the silica glass structure. Polyethylene is composed of chains of carbon atoms, with two hydrogen atoms attached to each carbon. Because carbon has a valence of four and the carbon and hydrogen atoms are bonded covalently, a *tetrahedral* structure is again produced (Figure 1.22). The tetrahedral units can be joined

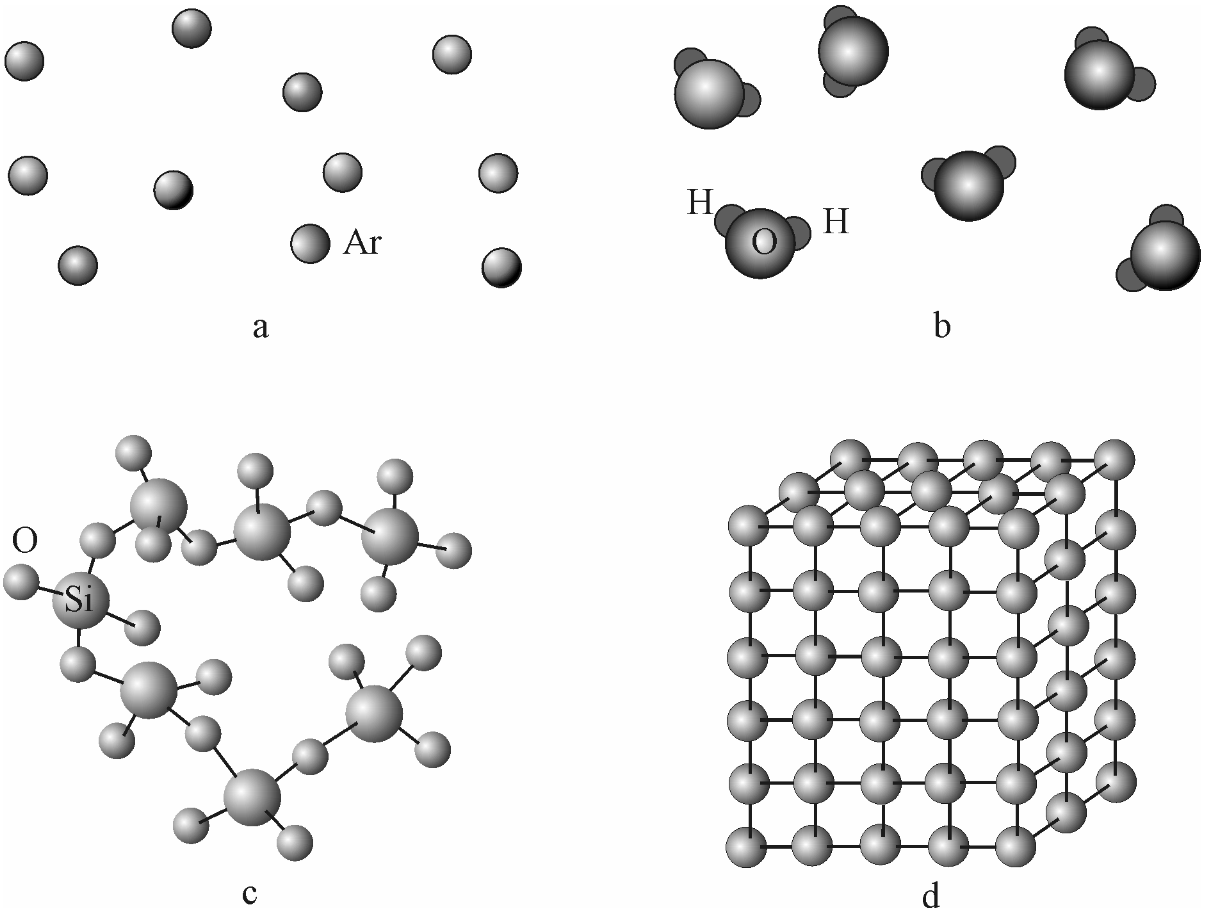


Figure 1.21 The levels of atomic arrangement in materials, (a) Inert gases have no regular ordering of atoms, (b) and (c) Some materials, including steam and glass, have ordering only over a short distance, (d) Metals and many other solids have a regular ordering of atoms that extends through the material

together *in a random manner* to produce the polymer chains.

Ceramics and polymers having only this short-range order are often characterized as *amorphous* materials. *Glasses,* which form in both ceramic and polymer systems, are amorphous materials often having good strength and stiffness and unique physical properties but brittle behavior. Semiconductors may also possess only short-range order.

Long-Range Order Metals, semiconductors, many ceramics, and even some polymers have a *crystalline* structure in which the atoms also display *long-range order*; the special atomic arrangement extends through-

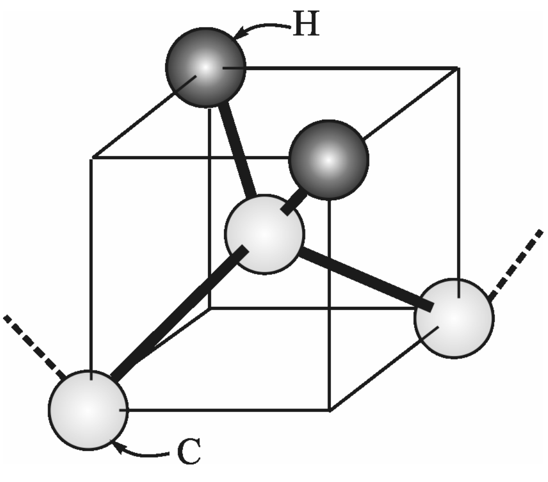


Figure 1.22 The *tetrahedral* structure in polyethylene

out the entire material. The atoms form a regular repetitive, three-dimensional pattern, or *lattice*. The lattice is a collection of points, called *lattice points*, which are arranged in a periodic pattern so that the surroundings of each point in the lattice are identical. One or more atoms are associated with each lattice point. Consequently, each atom has both a short-range order, since the surroundings of each lattice point are identical and a long-range order, since the lattice extends periodically throughout the entire material.

The lattice differs from material to material in both *shape* and *size*, depending on the *size of the atoms* and the *type of bonding* between the atoms. The *crystal structure* of a material the size, shape, and atomic arrangement within the lattice. Most metals and inorganic compounds have a crystalline structure.

Solids that do not have a repetitive three-dimensional pattern of atoms were called *amorphous*. The dictionary definition of amorphous is “without form”.

Amorphous materials do not have a structure ordered enough to allow distinct diffraction patterns. It has been studied, however, that most amorphous materials have *short-range order*. For example, an amorphous material may consists of long chain molecules with a significant order between molecules making up molecular chains (short-range order), but there may be little order between the chains (*long-range*). From the property standpoint, amorphous materials have different solidification characteristics than crystalline materials, but this does not decrease their engineering properties.

1.2.2 Unit Cells

The *unit cell* is a subdivison of the crystalline lattice that still retains the overall characteristics of the entire lattice. The cells form a larger three-dimensional pattern named as lattice. A unit cell is shown in the lattice in Figure 1.23 by the heavy lines. By stacking identical unit cells, the entire lattice can be constructed.

We identify 14 types of unit cells, or *Bravais lattices,* grouped in seven *crystal structures* (Figure 1.24 and Table 1.4). *Lattice points* are located at the corners of the unit cells and, in some cases, at either faces or the center of the unit cell. Some of the characteristics of a lattice or unit cell will be considered in further.

When a crystalline solid starts to form from the molten or gaseous state, these cells will tend to stack in a three-dimensional array with each cell perfectly aligned and they will form a *crystal*. If many crystals are growing in a melt at the

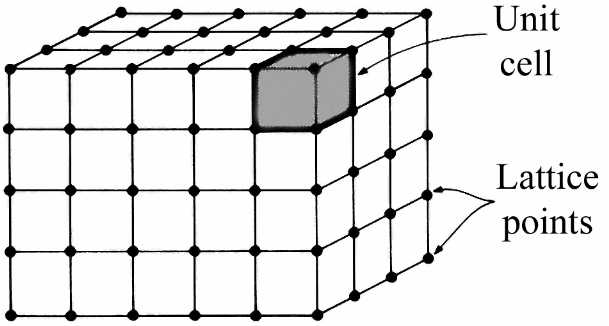


Figure 1.23 A lattice is a periodic array of points that define space. The unit cell (heavy outline) is a subdivision of the lattice that still retains the characteristics of the lattice

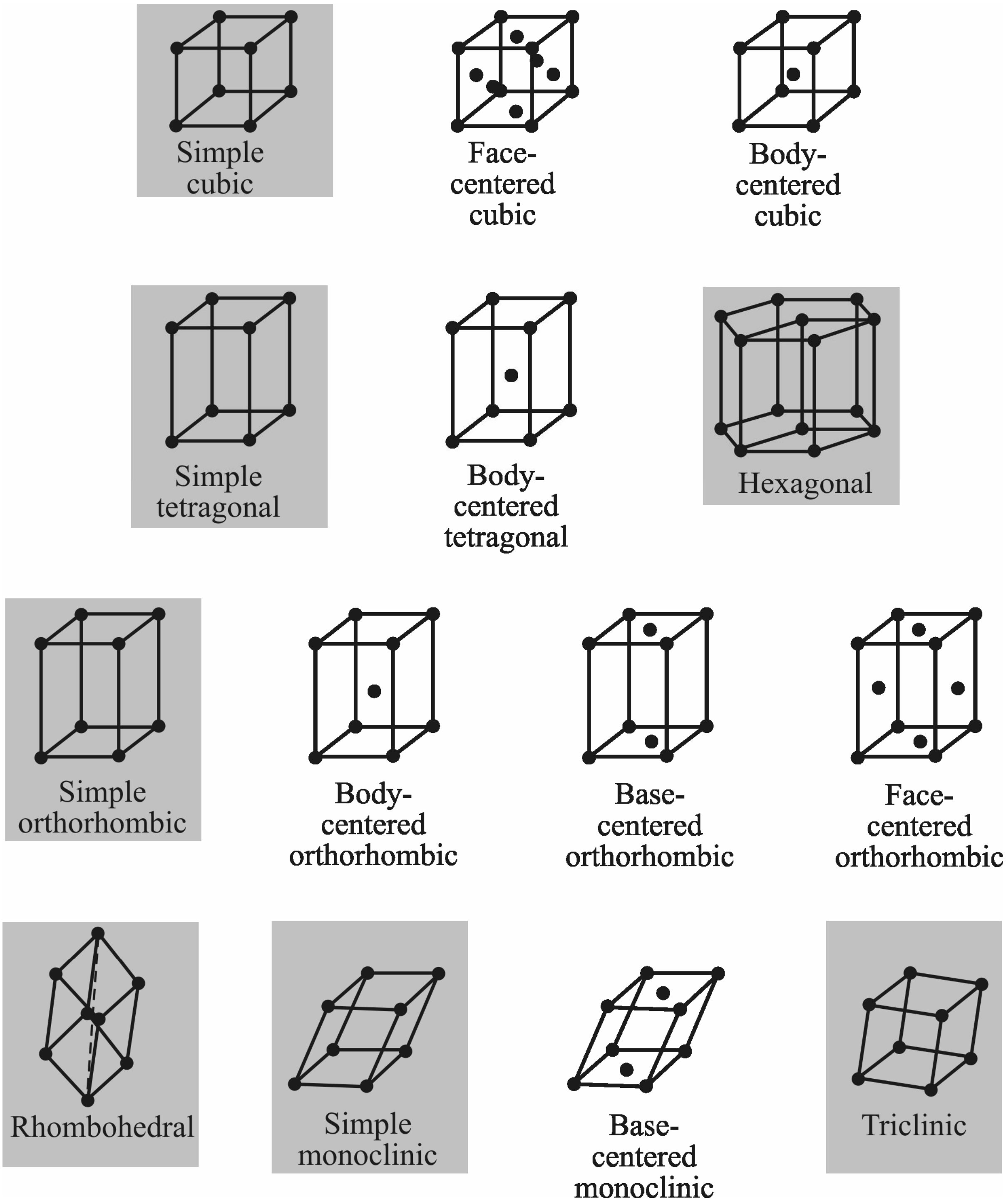


Figure 1.24 The seven crystal systems (heavy back) and 14 Bravais lattices. Characteristics of the crystal systems are summarized in Table 1.4

same time, the crystals will eventually meet and form *grains*. The junction of the crystallites is called *grain boundaries* (Figure 1.25).

The properties of crystalline materials are affected by the type of crystal structure (body-centered cubic – BCC, face-centered cubic – FCC, etc.), *the crystal or*

Table 1.4 Characteristics of the seven crystal systems

Structure	Axes	Angles between Axes
Cubic	$a = b = c$	All angles equal 90°
Tetragonal	$a = b \neq c$	All angles equal 90°
Orthorhombic	$a \neq b \neq c$	All angles equal 90°
Hexagonal	$a = b \neq c$	Two angles equal 90°. One angle equals 120°
Rhombohedral	$a = b = c$	All angles are equal and none equals 90°
Monoclinic	$a \neq b \neq c$	Two angles equal 90°. One angle (β) not equal to 90°
Triclinic	$a \neq b \neq c$	All angles are different and none equals 90°

grain size, and the strength of the bonds between atoms.

Crystallinity or lack of same is measured by X-ray or electron diffraction techniques. When a crystalline solid is exposed to a collimated beam of X-rays, the beam will be diffracted by the ordered planes of atoms, and the crystal cell size and location of atoms can be measured (see Figure 1.26). This is how the materials engineer knows what type of structure a solid has.

Lattice Parameter The *lattice parameters*, which describe the size and shape of the unit cell, include the dimensions of the sides of the unit cell and the angles between the sides (Figure 1.27). In a *cubic crystal system*, only the length of one of the sides of the cube is necessary to completely describe the cell (angles of 90° are assumed unless otherwise specified). This length, measured at room temperature, is the lattice parameter a_0. The length is often given in *angstrom* units or *nanometers*,

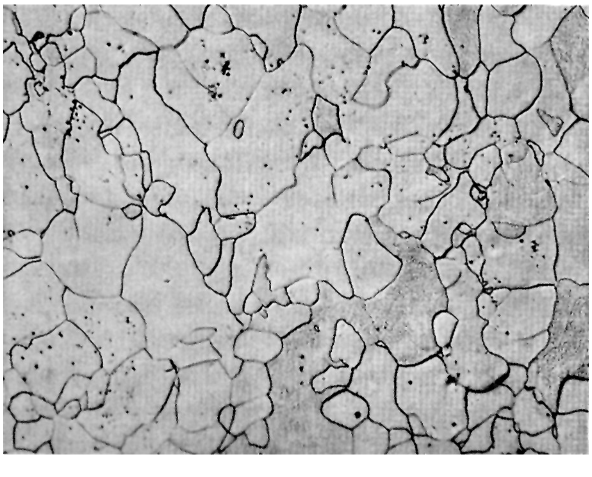


Figure 1.25 Microstructure of pure iron (×100). Dark areas are grain boundaries. Each grain is a crystal

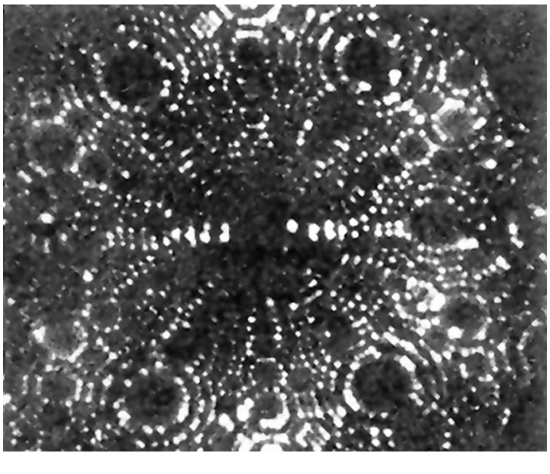
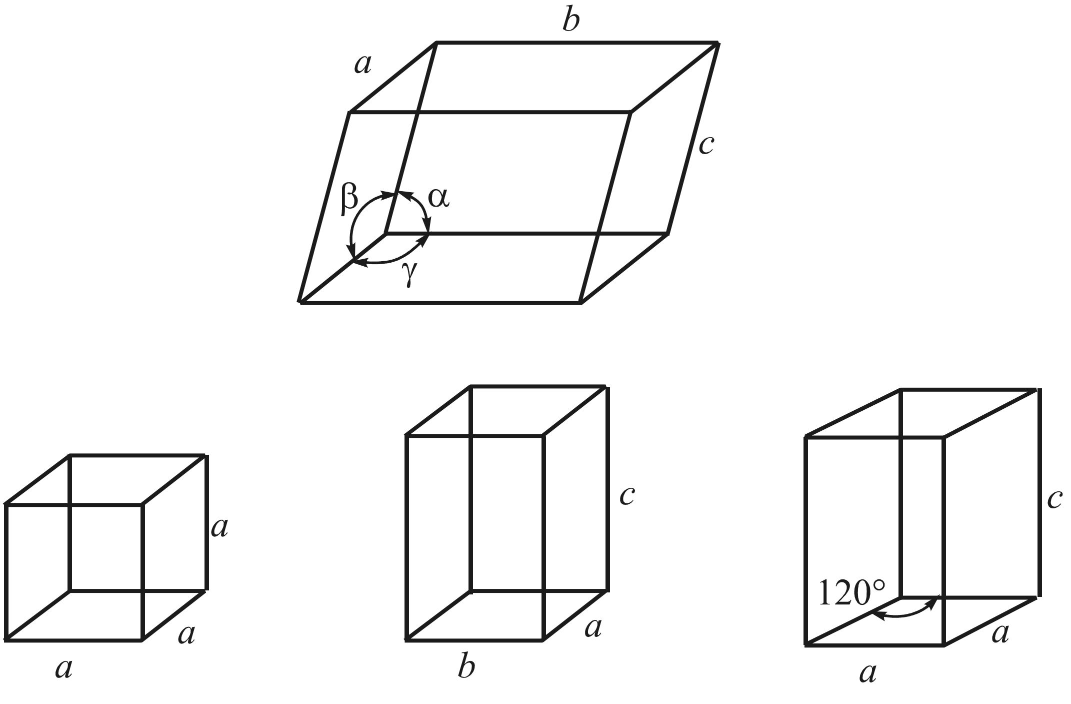


Figure 1.26 Crystal level (×1,300,000 (linear)). Each bright spot reveals the location of an atom in a crystal on a very sharply pointed tungsten cathode. Crystal possess specific atom arrangements



Cubic Orthorhombic Hexagonal

Figure 1.27 Definition of the lattice parameters and their use in three of seven crystal systems

where

1 angstrom (Å) $= 10^{-10}$ m,

1 nanometer (nm) $= 10^{-9}$ m = 10 Å.

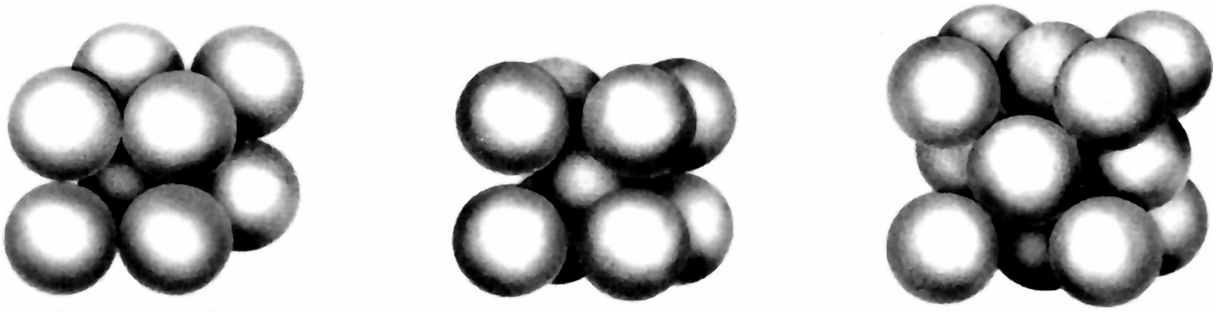
Several lattice parameters are required to define the size and shape of complex unit cells. For an *orthorhombic unit cell*, we must specify the imensions of all three sides of the cell, a_0, b_0, and c_0. *Hexagonal unit cells* require two dimensions, a_0 and c_0, and the angle of 120° between the a_0 axes. The most complicated cell, the *triclinic unit cell,* is described by three lengths and three angles.

Number of Atoms per Unit Cell A specific number of lattice points defines every unit cells. For example, the corners of the cells are easily identified, as they are body- and face-centered positions (see Figure 1.24). If we counted the number of lattice points belonging to each unit cell, we would admit the fact that lattice points may be shared by more than one unit cell. A lattice point at a corner of one unit cell is shared by seven adjacent unit cells; only 1/8 of each corner belongs to one particular cell. Thus, the number of lattice points from the corner positions in one unit cell is

$$\left(\frac{1}{8}\frac{\text{lattice point}}{\text{corner}}\right)\left(8\frac{\text{corners}}{\text{cell}}\right)=1\left(\frac{\text{lattice point}}{\text{unit cell}}\right).$$

Corners contribute 1/8 of a point, faces contribute 1/2, and body-centered positions contribute a whole point.

The number of atoms per unit cell is the product of the number of atoms per lattice point and the number of lattice points per unit cell. *In* most *metals*, *one atom is located at each lattice point*, so the number of atoms is equal to the number of lattice points. The structures of simple cubic (SC), face-centered cubic (FCC), and body-centered cubic (BCC) unit cells, with one atom per lattice point, are shown in Figure 1.28. In more complicated structures, particularly compounds and ceramic materials, several or even hundreds of atoms may be associated with each lattice point, forming very complex unit cells.



Simple cubic Body-centered cubic Face-centered cubic

Figure 1.28 The models for simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) unit cells, assuming only one atom per lattice point

Example 1.9

Determine the number of lattice points per cell in the cubic crystal systems.

Answer

In the SC unit cell, lattice points are located only at the corners of the cube:

$$\frac{\text{lattice point}}{\text{unit cell}} = (8 \text{ corners})\left(\frac{1}{8}\right) = 1 .$$

In BCC unit cells, lattice points are located at the corners and the center of the cube:

$$\frac{\text{lattice point}}{\text{unit cell}} = (8 \text{ corners})\left(\frac{1}{8}\right) + (1 \text{ center})(1) = 2 .$$

In FCC unit cells, lattice points are located at the corners and faces of the cube:

$$\frac{\text{lattice point}}{\text{unit cell}} = (8 \text{ corners})\left(\frac{1}{8}\right) + (6 \text{ faces})\left(\frac{1}{2}\right) = 4 .$$

Figure 1.29 shows the contribution that each lattice point makes to the individual unit cell.

Atomic Radius versus Lattice Parameter In simple structures, particularly those with only one atom per lattice point, we can calculate the relationship between the apparent *size of* the *atom* and the *size of* the *unit cell*. We must locate the direction in the unit cell along which atoms are in continuous contact. These are the *close-packed directions.* By geometrically determining the length of the direction relative to the lattice parameters, and then adding the number of atomic radii along this direction, we can determine the desired relationship.

Example 1.10

Determine the relationship between the atomic radius and the lattice parameter in SC, BCC, and FCC structures.

Answer

If we refer to Figure 1.30, we find that atoms touch along the edge of the cube in SC structures. The corner atoms are centered on the corners of the cube, so

$$a_0 = 2r\,. \tag{1.2}$$

In FCC structures, atoms touch along the face diagonal of the cube, which is $\sqrt{2}a_0$ in length. There are four atomic radii along this length – two radii from the face-centered atom and one radius from each corner, so

$$a_0 = \frac{4r}{\sqrt{2}}\,. \tag{1.3}$$

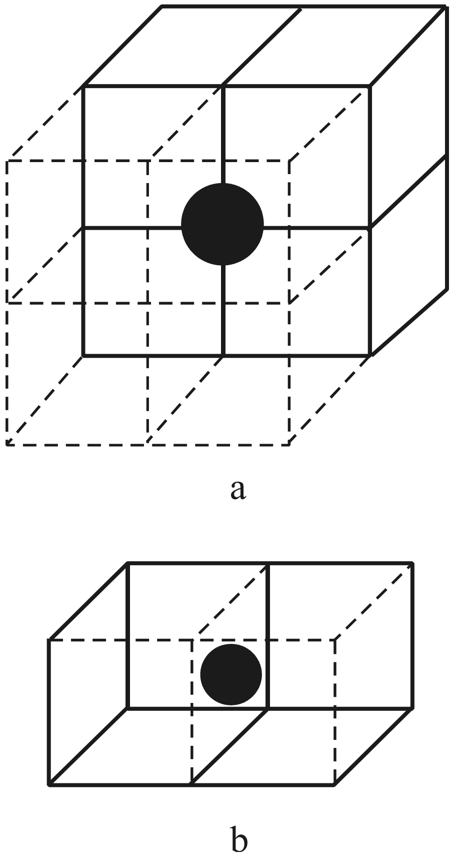


Figure 1.29 (a) Corner atoms are shared by eight unit cells, (b) Face-centered atoms are shared by two unit cells.

In BCC structures, atoms touch along the body diagonal, which is $\sqrt{3}a_0$ in length. There are two atomic radii from the center atom and one atomic radius from each of the corner atoms on the body diagonal, so

$$a_0 = \frac{4r}{\sqrt{3}}\,. \tag{1.4}$$

Example 1.11

The atomic radius of iron is 1.24 Å. Calculate the lattice parameters of BCC and FCC iron.

Answer

For BCC iron,

$$a_0 = \frac{4r}{\sqrt{3}} = \frac{(4)(1.24)}{\sqrt{3}} = 2.86\ \text{Å} = 2.86\times10^{-10}\ \text{m}.$$

For FCC iron,

$$a_0 = \frac{4r}{\sqrt{2}} = \frac{(4)(1.24)}{\sqrt{2}} = 3.51 \text{ Å} = 3.51\times10^{-10} \text{ m}.$$

Coordination Number The number of atoms touching a particular atom, or the number of nearest neighbors, is called the *coordination number*. It is the indication of how tightly atoms are packed together. In simple crystal structures containing only one atom per lattice point, we find that the atoms have a coordination number related to the lattice structure. By inspecting the unit cells in Figure 1.31, we see that each atom in the SC lattice has a coordination number of six, while each atom in the BCC lattice has eight nearest neighbors. In the FCC lattice each atom has a coordination number of 12, which is the theoretical maximum.

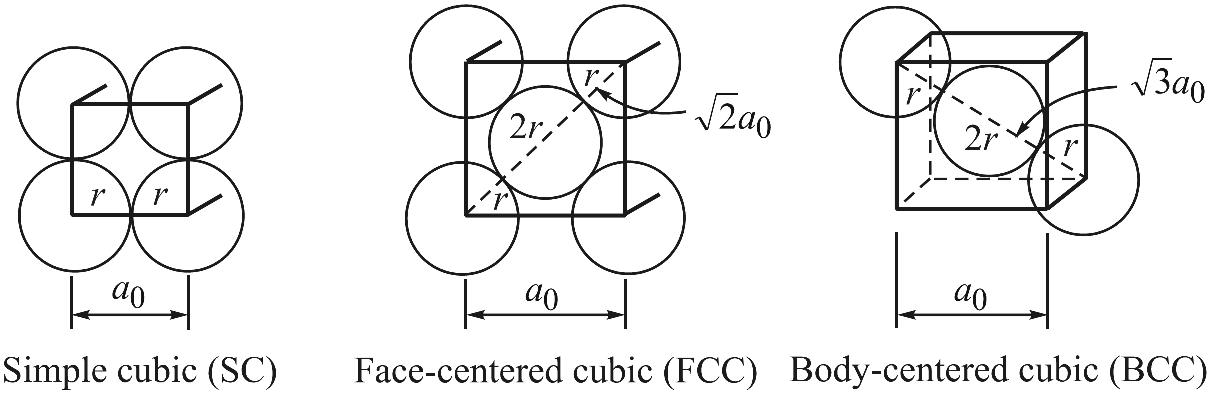


Figure 1.30 The relationship between the atomic radius and the lattice parameter in cubic systems (for Example 1.10)

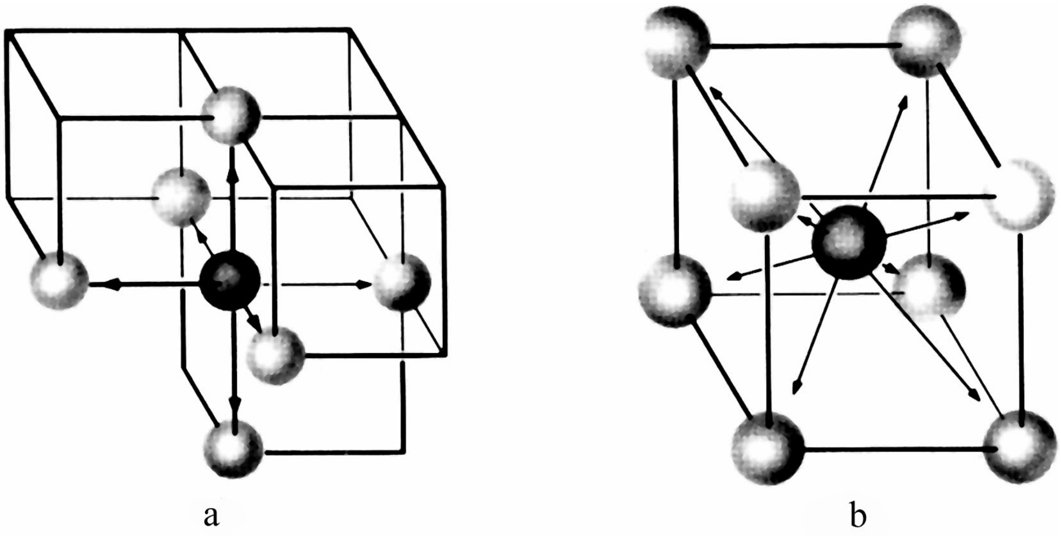


Figure 1.31 Illustration of coordination in SC and BCC unit cells. Six atoms touch each atom in SC, while the eight corner atoms touch the body-centered atom in BCC

Packing Factor The *packing factor* is the fraction of space occupied by atoms, assuming that atoms are hard spheres. The general expression for the packing factor is

$$\text{Packing factor} = \frac{\text{(number of atoms/cell)/(volume of each atom)}}{\text{volume of unit cell}}. \qquad (1.5)$$

Example 1.12

Calculate the packing factor for the FCC cell.

Answer

There are four lattice points per cell; if there is one atom per lattice point, there are also four atoms per cell. The volume of one atom is $4\pi r^3/3$ and the volume of the unit cell is a_0^3.

$$\text{Packing factor} = \frac{\text{(4 atoms/cell)}/(4\pi r^3/3)}{a_0^3}.$$

Since for FCC unit cells,

$$\text{Packing factor} = \frac{(4)/(4\pi r^3/3)}{(4r/\sqrt{2})^3} = 0.74.$$

In metals, the packing factor of 0.74 in the FCC unit cell is the most efficient packing possible. BCC cells have a packing factor of 0.68 and SC cells have a packing factor of 0.52. Materials may have low packing factors as a consequence of atomic bonding. Metals with only the metallic bond are packed as efficiently as possible. Metals with mixed bonding may have unit cells with less than the maximum packing factor. No common engineering metals have the SC structure, although this structure is found in ceramic materials.

Density The theoretical density of a metal can also be calculated using the properties of the crystal structure. The general formula is

$$\text{Density } \rho = \frac{\text{(atom/cell)(atomic mass of each atom)}}{\text{(volume of unit cell)(Avogadro number)}}. \qquad (1.6)$$

Example 1.13

Determine the density of BCC iron, which has a lattice parameter of 2.866 Å.

Answer

$$\text{Atoms/cell} = 2,$$

$$\text{Atomic mass} = 55.85.$$

$$\text{Volume of unit cell} = a_0^3 = (2.866\times10^{-10})^3 = 23.55\times10^{-30}\ \text{m}^3\text{/cell},$$

$$\text{Avogadro number } N_A = 6.02\times10^{23}\ \text{1/mole},$$

$$\rho = \frac{(2)(55.85)}{(23.55\times10^{-30})(6.02\times10^{23})} = 7.879\times10^{3}\ \text{kg/m}^3.$$

The measured density is 7.88×10^{3} kg/m^3. We will consider the discrepancy between the theoretical and measured density when we discuss imperfections in solids.

The Hexagonal Close-Packed Structure A special form of the hexagonal lattice, the hexagonal close-packed structure (HCP), is shown in Figure 1.32. The unit cell is the skewed prism, shown separately. The HCP structure has one lattice point per cell – one from each of the eight corners of the prism – but two atoms are associated with each lattice point. One atom is located at a corner, while the second atom is located within the unit cell.

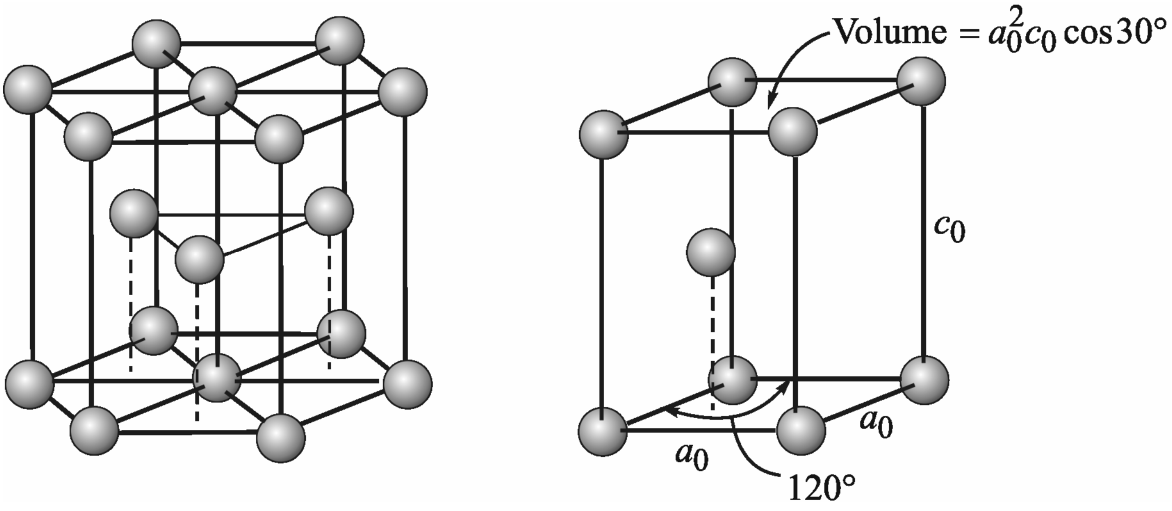


Figure 1.32 The hexagonal close-packed (HCP) lattice and its unit cell

In ideal HCP metals, the a_0 and c_0 axes are related by the ratio $c/a = 1.633$. Most HCP metals, however, have c/a ratios that differ slightly from the ideal value, due to mixed bonding. Because the HCP structure, like the FCC structure, has a very efficient packing factor of 0.74 and a coordination number of 12, a number of metals possess this structure. Table 1.5 summarize the characteristics of the most important crystal structures in metals.

1.2.3 Allotropic or Polymorphic Transformations

Materials that can have more than one crystal structure are called *allotropic* or *polymorphic.* The term *allotropy* is normally reserved for this behavior in pure elements, while polymorphism is a more general term. As follows from the Table 1.5 some metals, such as iron and titanium, have more than one crystal structure. At low temperatures iron has the BCC structure, but at higher temperatures iron transforms to an FCC structure. These transformations provide the basis for the *heat treatment* of steel and titanium.

Table 1.5 Characteristics of common metallic crystals

Structure	a_0 versus r	Atoms per Cell	Coordination Number	Packing Factor	Typical Metals
Simple cubic (SC)	$a_0 = 2r$	1	6	0.52	None
Body-centered cubic (BCC)	$a_0 = 4r\sqrt{3}$	2	8	0.68	Fe, Ti, W, Mo, Nb, Ta, K, Na, V, Cr, Zr
Face-centered cubic (FCC)	$a_0 = 4r\sqrt{2}$	4	12	0.74	Fe, Cu, Al, Au, Ag, Pb, Ni, Pt
Hexagonal close-packed (HCP)	$a_0 = 2r$ $c_0 = 1.633a_0$	2	12	0.74	Ti, Mg, Zn, Be, Co, Zr, Cd

Many ceramic materials, such as silica (SiO_2), also are polymorphic. A volume change may accompany the transformation during heating or cooling. This volume change may cause the material to crack and fail.

Example 1.14

Calculate the change in volume that occurs when BCC iron is heated and changed to FCC iron. At the transformation temperature the lattice parameter of BCC iron is 2.863 Å and the lattice parameter of FCC iron is 3.591 Å.

Answer

Volume of BCC $= a^3 = (2.863)^3 = 23.467$ Å^3.

Volume of FCC cell $= a^3 = (3.591)^3 = 46.307$ Å^3.

But the FCC unit cell contains four atoms and the BCC unit cell contains only two atoms. Two BCC unit cells with a total volume of $2(23.467) = 46.934$ Å^3 will contain four atoms. Thus the volume change is

$$\text{Volume change} = \frac{46.307 - 46.934}{46.934} \times 100 = -1.34\%.$$

This result indicates that iron contracts on heating.

1.2.4 Points, Directions, and Planes in Unit Cell

Coordinates of Points To locate certain points, such as atom positions, in the lattice or unit cell we must construct the right-handed coordinate system (see Figure 1.33). Distance is measured in terms of the number of lattice parameters we must move in each of the *x, y* and *z* coordinates to get from the origin to the point under consideration. The coordinates are written as the three distances, with commas separating the numbers.

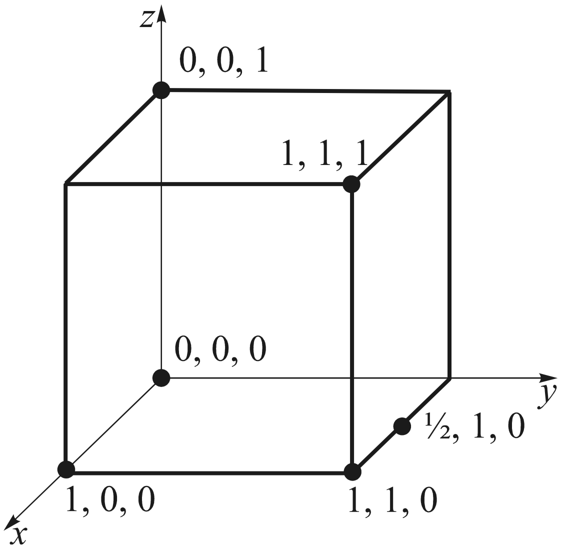


Figure 1.33 Coordinates of points in the unit cell. The numbers refer to numbers of lattice parameters

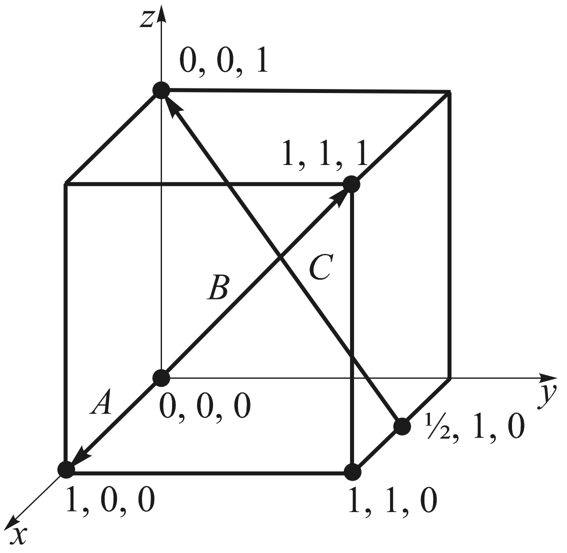


Figure 1.34 Crystallographic directions and coordinates required for Example 1.15

Directions in Unit Cell Certain directions in the unit cell are of particular importance. Metals deform, for example, in directions along which atoms are in closest contact. Properties of a material may depend on the direction in the crystal along which the property is measured. *Miller indices* for directions are the shorthand notation used to describe these directions. The procedure for finding the Miller indices for directions is as follows:

(a) Using a right-handed coordinate system, determine the coordinates of two points that lie on the direction.

(b) Subtract the coordinates of the "tail" point from the coordinates of the "head" point to obtain the number of lattice parameters traveled in the direction of each axis of the coordinate system.

(c) Clear fractions and/or reduce the results obtained from the subtraction to lowest integers.

(d) Enclose the numbers in square brackets [ ]. If a negative sign is produced, represent the negative sign with a bar over the number.

Example 1.15

Determine the Miller indices of directions *A, B,* and C in Figure 1.34.

Answer

Direction A

(a) Two points are 1, 0, 0, and 0, 0, 0;
(b) 1, 0, 0 – 0, 0, 0 = 1, 0, 0;
(c) No fractions to clear or integers to reduce;
(d) [100].

Direction B

(a) Two points are 1, 1, 1 and 0, 0, 0;
(b) 1, 1, 1 – 0, 0, 0 = 1, 1, 1;
(c) No fractions to clear or integers to reduce;
(d) [111].

Direction C

(a) Two points are 0, 0, 1 and 1/2, 1, 0;
(b) 0, 0, 1 – 1/2, 1, 0 = –1/2, –1, 1;
(c) 2 (–1/2, –1, 1)= –1, –2, 2;
(d) $[\bar{1}\bar{2}2]$.

Several points should be noted about the use of Miller indices for directions.

1. A direction and its negative are not identical; [100] is not equal to $[\bar{1}00]$. They represent the same line but opposite directions.

2. A direction and its multiple are identical; [100] is the same direction as [200]. We just forgot to reduce to lowest integers.

3. Certain groups of directions are equivalent; they have their particular indices primarily because of the way we construct the coordinates. For example, in a cubic system a [100] direction is a [010] direction if we redefine the coordinate system as shown in Figure 1.35. We may refer to groups of equivalent directions as *directions of a form*. The special brackets < > are used to indicate this collection of directions. All of the directions of the form <110> are shown in the Table 1.6.

Table 1.6 Directions of the form <110> in cubic systems

$$\langle 110\rangle = \begin{cases} [110] & [\bar{1}\bar{1}0] \\ [101] & [\bar{1}0\bar{1}] \\ [011] & [0\bar{1}\bar{1}] \\ [1\bar{1}0] & [\bar{1}10] \\ [10\bar{1}] & [\bar{1}01] \\ [01\bar{1}] & [0\bar{1}1] \end{cases}$$

Another way of characterizing equivalent directions is by the distance between lattice points along the direction. For example, we could examine the [110] direction in an FCC unit cell (Figure 1.36); if we start at the 0, 0, 0 location, the next lattice point is at the center of a face, or a 1/2, 1/2, 0 site. The dis-

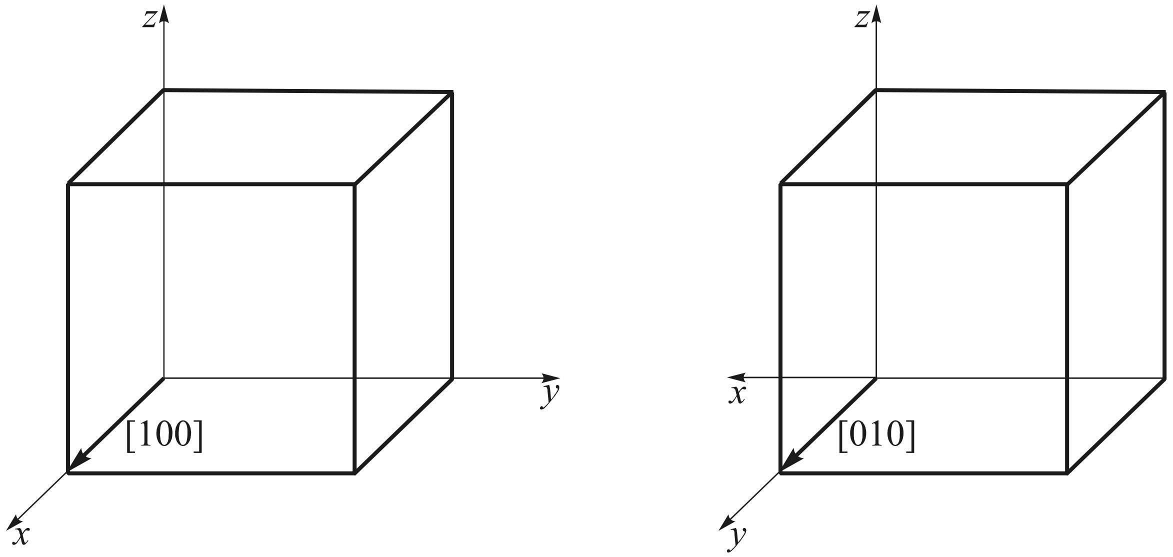


Figure 1.35 Equivalency of crystallographic directions of a form in cubic systems

tance between lattice points is therefore one-half of the face diagonal, or $\sqrt{2}a_0/2$. In copper, which has a lattice parameter of 3.6151×10^{-10} m, the *repeat distance* is 2.556×10^{-10} m.

The *linear density* is the number of lattice points per unit length along the direction. In copper, there are two repeat distances along the [110] direction in each unit cell; since this distance is $\sqrt{2}a_0 = 5.1125\times10^{-10}$ m, then

$$\text{Linear density} = \frac{2\text{ repeat distances}}{5.1125\times10^{-10}} = 390.0\times10^7 \text{ lattice points/m.}$$

It is necessary to note that the linear density is also the *reciprocal* of the repeat distance.

Finally, we could compute *the packing fraction* of a particular direction, or the fraction actually covered by atoms. For copper, in which one atom is located at each lattice point, this fraction is equal to the product of the linear density and twice the atomic radius. For FCC copper, the atomic radius $r = \sqrt{2}a_0/4 = 1.2781\times10^{-10}$ m. Therefore, the packing fraction is

$$\text{Packing fraction} = (\text{linear density})(2r) = (390\times10^7)(2)(1.2781\times10^{-10}) = 1.0.$$

In this case, atoms lie continuously along the [110] direction, as expected, since the [110] direction is close packed in FCC metals. All of the directions of the form $\langle 110\rangle$ in copper will have the same linear density and packing fraction.

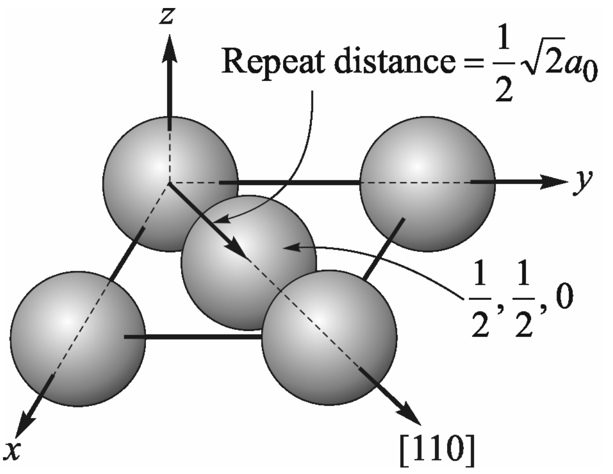


Figure 1.36 Determining the repeat distance, linear density, and packing fraction for a [110] direction in FCC copper

Example 1.16

Calculate the repeat distance, linear density, and packing fraction for the [111] direction in FCC copper.

Answer

If we start at the lattice point at 0, 0, 0, we do not encounter another lattice point until 1, 1, 1. This distance (Figure 1.37) is

$$\text{Repeat distance} = \sqrt{3}a_0 = \sqrt{3}(3.6151\times10^{-10}) = 6.262\times10^{-10}.$$

The linear density is the reciprocal of the repeat distance, or

$$\text{Linear density} = \frac{1}{6.262\times10^{-10}} = 1.597\times10^9 \text{ lattice points/m.}$$

The packing fraction is the linear density times 2r, or

$$\text{Packing fraction} = (1.597\times10^{9})(2)(1.278\times10^{-10}) = 0.408.$$

The linear density and packing fraction are lower than along the [110] direction because the [111] direction is not close packed.

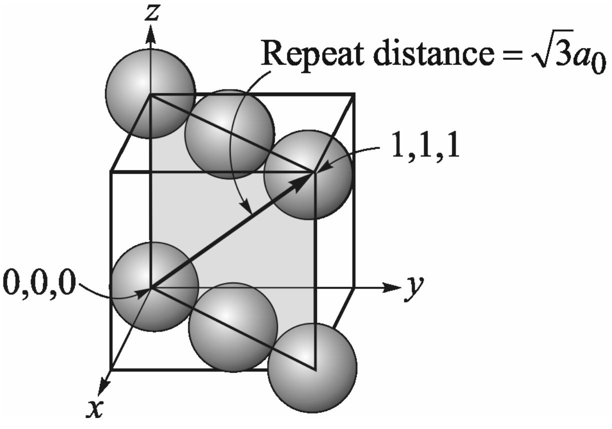


Figure 1.37 Determining the repeat distance, linear density, and packing fraction for a [111] direction in FCC copper (Example 1.16)

Planes in the Unit Cell Certain planes of atoms in a crystal are significant; for example, metals deform along planes of atoms that are most tightly packed together. Miller indices can be used as a shorthand notation to identify these important planes, as described in the following procedure.

(a) Identify the points at which the plane intercepts the *x, y,* and *z* coordinates in terms of the number of lattice parameters. If the plane passes through the origin, the origin of the coordinate system must be moved!

(b) Take reciprocals of these intercepts.

(c) Clear fractions but do not reduce to lowest integers.

(d) Enclose the resulting numbers in parentheses ( ). Again, negative numbers should be written with a bar over the number.

Example 1.17

Determine the Miller indices of planes *A, B,* and *C* in Figure 1.38.

Answer

Plane A

(a) $x=1,\ y=1,\ z=1;$

(b) $\frac{1}{x}=1,\ \frac{1}{y}=1,\ \frac{1}{z}=1;$

(c) No fractions to clear;

(d) (1 1 1).

Plane B

(a) The plane never intercepts the *z* axis, so $x=1,\ y=2$, and $z=\infty$;

(b) $\frac{1}{x}=1,\ \frac{1}{y}=\frac{1}{2},\ \frac{1}{z}=0;$

(c) Clear fractions: $\frac{1}{x}=2,\ \frac{1}{y}=1,\ \frac{1}{z}=0;$

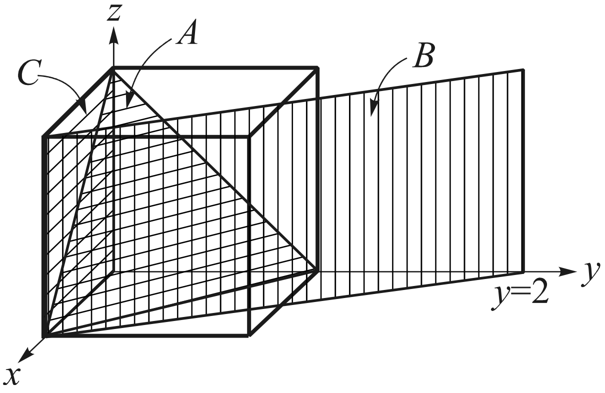


Figure 1.38 Crystallographic planes and intercepts for Example 1.17

(d) (2 1 0).

Plane C

(a) We must move the origin since the plane passes through 0, 0, 0. Let's move the origin one lattice parameter in the *y*-direction. Then $x = \infty$, $y = -1$, and $z = \infty$;

(b) $\frac{1}{x} = 0$, $\frac{1}{y} = -1$, $\frac{1}{z} = 0$;

(c) No fractions to clear;

(d) $(0\bar{1}0)$.

It is important to note several aspects of the Miller indices for planes.

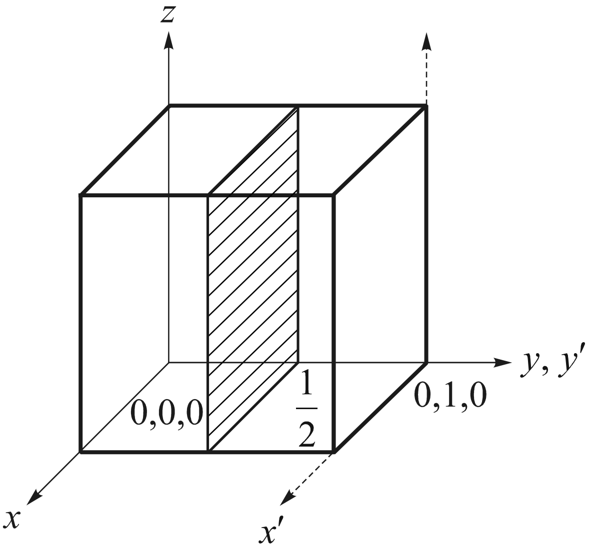


Figure 1.39 A plane and its negative are identical

Aspect 1. Planes and their negatives are identical (this was not the case for directions). As an example, consider Figure 1.39. The shaded plane has the indices (020) if the *x, y,* and *z* coordinates are used but has the indices $(0\bar{2}0)$ if the x', y', and z' coordinates are used. But we are considering the same plane! Therefore, $(020) = (0\bar{2}0)$.

Aspect 2. Planes and their multiples are not identical (again, this is the opposite of what we found for directions). We can show this by defining planar densities and planar packing fractions. *The planar density* is the number of atoms per unit area whose centers lie on the plane; *the packing fraction* is the fraction of that plane actually covered by these atoms. Example 1.18 shows how these can be calculated.

Example 1.18

Calculate the planar density and planar packing fraction for the (010) and (020) planes in simple cubic *polonium*, which has a lattice parameter of 3.34×10^{-10} m.

Answer

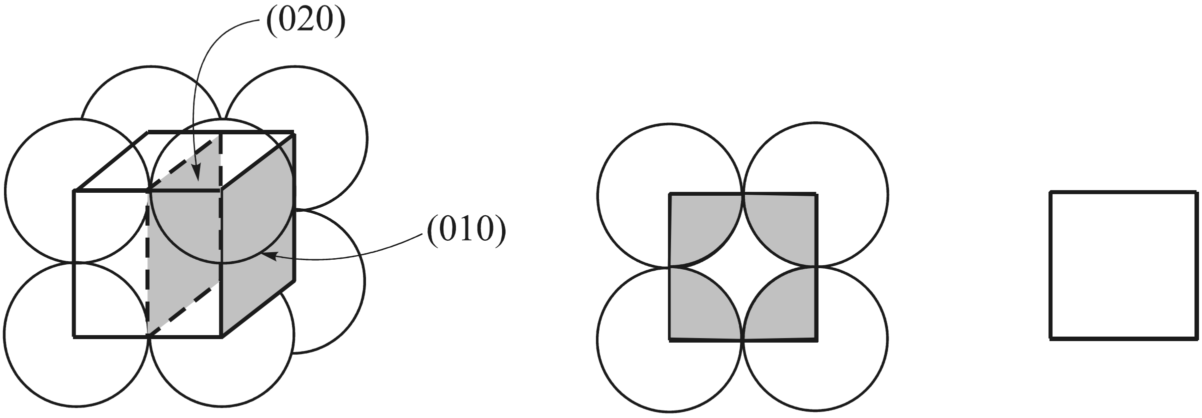
The two planes are drawn in Figure 1.40. On the (010) plane, atoms are centered at each corner of the cube face, with 1/4 of each atom actually in the face of the unit cell. Thus, the total atoms in each face is one. The planar density is

$$\text{Planar density } (010) = \frac{\text{atoms per face}}{\text{area of face}} = \frac{1 \text{ atoms per face}}{(3.34\times10^{-10})^2} = 8.96\times10^{18} \text{ atoms/m}^2.$$

The planar packing fraction is given by

$$\text{Packing fraction } (010) = \frac{\text{area of atoms per face}}{\text{area of face}} = \frac{(1 \text{ atoms})(\pi r^2)}{(a_0)^2} = \frac{\pi r^2}{(2r)^2} = 0.79.$$

However, no atoms are centered on the (020) planes. Therefore, the planar density and the planar packing fraction are both zero. The (010) and (020) planes are not equivalent.



(010) (020)

Figure 1.40 The planar densities of the (010) and (020) planes in SC unit cells are not identical (see Example 1.18)

Aspect 3. In each unit cell, *planes of a form* represent groups of equivalent planes that have their particular indices because of the orientation of the coordinates. We represent these groups of similar planes with the notation { }. The planes of the form {110} in cubic systems are shown in Table 1.7.

Aspect 4. In cubic systems, a direction that has the same indices as a plane is perpendicular to that plane. Figure 1.41 shows a unit cell containing a (100) plane and a [100] direction and clearly indicates this property. Be attentive, this is not always true for non-cubic cells.

Table 1.7 Planes of the form {110} in cubic systems

$$\{110\} = \begin{cases} (110) \\ (101) \\ (011) \\ (1\bar{1}0) \\ (10\bar{1}) \\ (01\bar{1}) \end{cases}$$

Close-Packed Planes and Directions In examining the relationship between atomic radius and lattice parameter, we looked for *close-packed directions*, where atoms are in continuous contact. We can now assign Miller indices to these close-packed directions, as shown in Table 1.8.

Table 1.8 Close-packed planes and directions

Structure	Directions	Planes
SC	<100>	None
BCC	<111>	None
FCC	<110>	{111}
HCP	<100>, <110>	(0001), (0002)

We can also examine FCC and HCP unit cells more closely and discover that there is at least one set of close-packed planes in each. A close-packed plane is shown in Figure 1.42. Notice that a hexagonal arrangement of atoms is produced in two dimensions. The close-packed planes are easy to find in the HCP unit cell; they are the (0001) and (0002) planes of the HCP structure and are given the special name *basal planes.* In fact, we can build up an HCP unit cell by stacking together close-packed planes in an ... *ABABAB ... stacking sequence* (Figure 1.42). Atoms on plane *B,* the (0002) plane, fit into the valleys between atoms on plane *A,* the bottom (0001) plane. If another plane identical in orientation to plane *A* is placed in the valleys of plane *B,* the HCP structure is created. Notice that all of the possible close-packed planes are parallel to one another. Only the basal planes – (0001) and (0002) – are close packed.

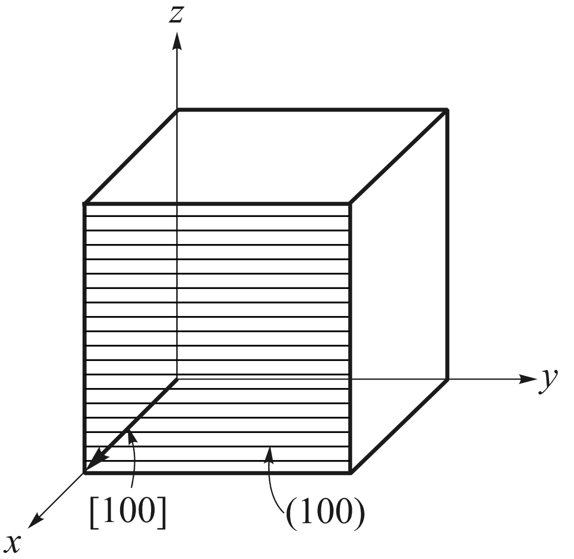


Figure 1.41 A direction in a cubic unit cell is perpendicular to a plane with the same indices

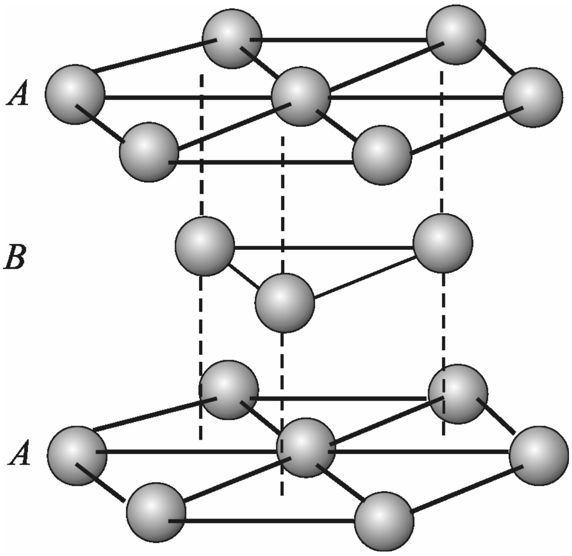


Figure 1.42 The *ABABAB* stacking sequence of close-packed planes produces the HCP structure

We can easily determine the coordination number of the atoms in the HCP structure from Figure 1.42. We find that the center atom in a basal plane is touched by six other atoms in the same plane. Three atoms in a lower plane and three atoms in an upper plane also touch the same atom. The coordination number is 12.

In the FCC structure, close-packed planes are of the form {111} (Figure 1.43). When stacking parallel (111) planes, atoms in plane *B* fit over valleys in plane *A* and atoms in plane C fit over valleys in both planes *A* and *B.* The fourth plane fits direct-

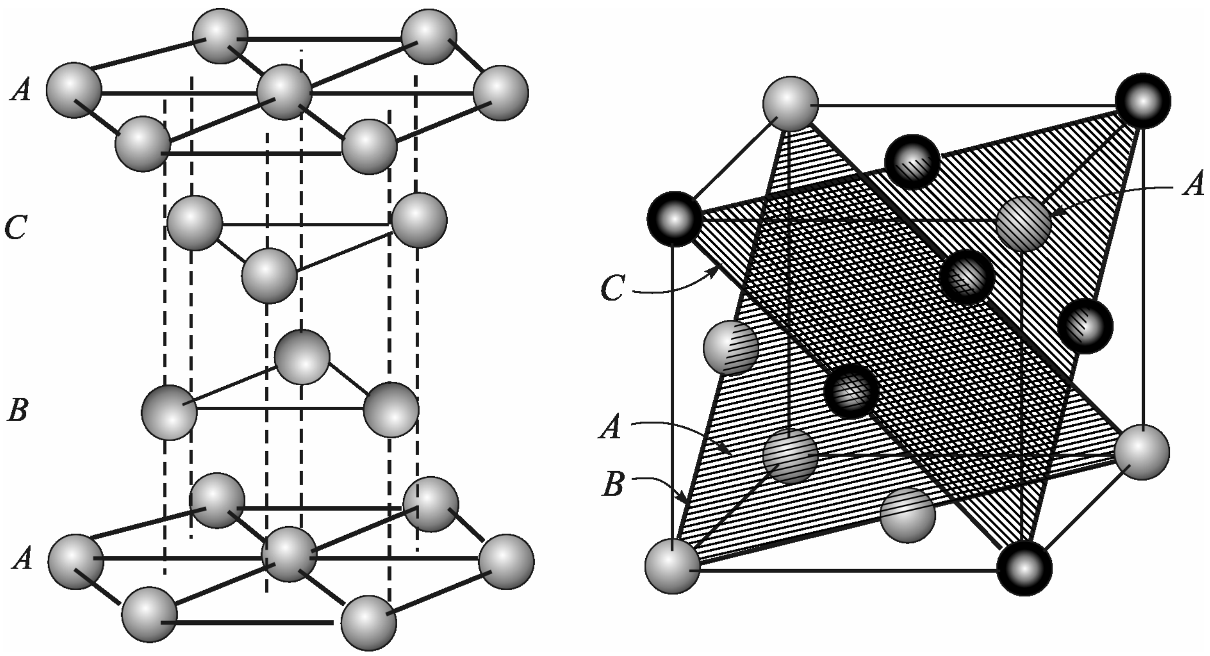


Figure 1.43 The *ABCABCABC* stacking sequence of close-packed planes produces the FCC structure

ly over atoms in plane *A*. Consequently, a stacking sequence ... *ABCABCABC* ... is produced using the (111) plane. Again we find that each atom has a coordination number of 12.

Unlike the HCP unit cell, there are four sets of nonparallel close-packed planes – (111), $(11\bar{1})$, $((1\bar{1}1))$, and $((\bar{1}11))$ – in the FCC cell. This difference between the FCC and HCP unit cells – the presence or absence of intersecting close-packed planes – significantly affects the behavior of metals with these structures.

Anisotropic Behavior Because of differences in atomic arrangement in the planes and directions within a crystal, the *properties* also *vary with direction*. A material is *anisotropic* if its properties depend on the crystallographic direction along which the property is measured. If the properties are identical in all directions, the crystal is *isotropic*. The anisotropic behavior of the modulus of elasticity is illustrated in Table 1.9 for several materials. A few materials, including *tungsten* (W), are isotropic.

Interplanar Spacing The distance between two adjacent parallel planes of atoms with the same Miller indices is called the *interplanar spacing* d_{hkl}. The interplanar spacing in cubic materials is given by the general equation

$$d_{hkl} = \frac{a_0}{\sqrt{h^2 + k^2 + l^2}}, \tag{1.7}$$

where a_0 is the lattice parameter and h, k, and l represent the Miller indices of the adjacent planes being considered.

Table 1.9 Variation of modulus of elasticity (x 10^{11} Pa) with crystal direction

Material	[100]	[111]	Random
Al	0.63	0.76	0.69
Cu	0.68	1.92	1.25
Fe	1.32	2.79	2.07
Nb	1.52	0.81	1.03
W	4.08	4.08	4.08
MgO	2.45	3.36	3.10
NaCl	0.43	0.32	0.37

Example 1.19

Calculate the distance between adjacent (111) planes in gold, which has a lattice parameter of 4.0786 Å.

Answer

$$d_{111} = \frac{4.0786}{\sqrt{1^2+1^2+1^2}} = \frac{4.0786}{\sqrt{3}} = 2.355 \text{ Å}.$$

1.2.5 Interstitial Sites

In any of the crystal structures, there are small holes between the usual atoms into which smaller atoms could be placed. These locations are called *interstitial sites.* The interstitial sites are often partly filled; small *impurity atoms*, for instance, may be located in these positions. In some cases, we intentionally add small atoms to create metal alloys; this is the case when small carbon atoms are added to iron to produce steels. Finally, the structure of many ceramic materials can be understood by utilizing these interstitial sites. For instance, in ionically bonded compounds, cations may be located at normal lattice points, while anions may be inserted into the interstitial positions.

An atom, when placed into an interstitial site, will touch two or more of the usual atoms in the unit cell. Therefore, these interstitial atoms will have a coordination number equal to the number of atoms it is touching. The Figure 1.44 shows the interstitial locations for the SC, FCC, BCC, and HCP structures. The *cubic interstitial site*, with a coordination number of eight, occurs in the SC structure. *Octahedral interstitial sites* give a coordination number of six, while *tetrahedral sites* give a coordination number of four. Examples of the octahedral and tetrahedral positions in BCC, FCC, and HCP unit cells are shown in the figure. As an example, the octahedral sites in BCC unit cells are located at faces of the cube; a small atom placed in the octahedral site will touch the four atoms at the corners of the face, the atom in the center of the unit cell, plus another atom at the center of the adjacent unit cell, giving

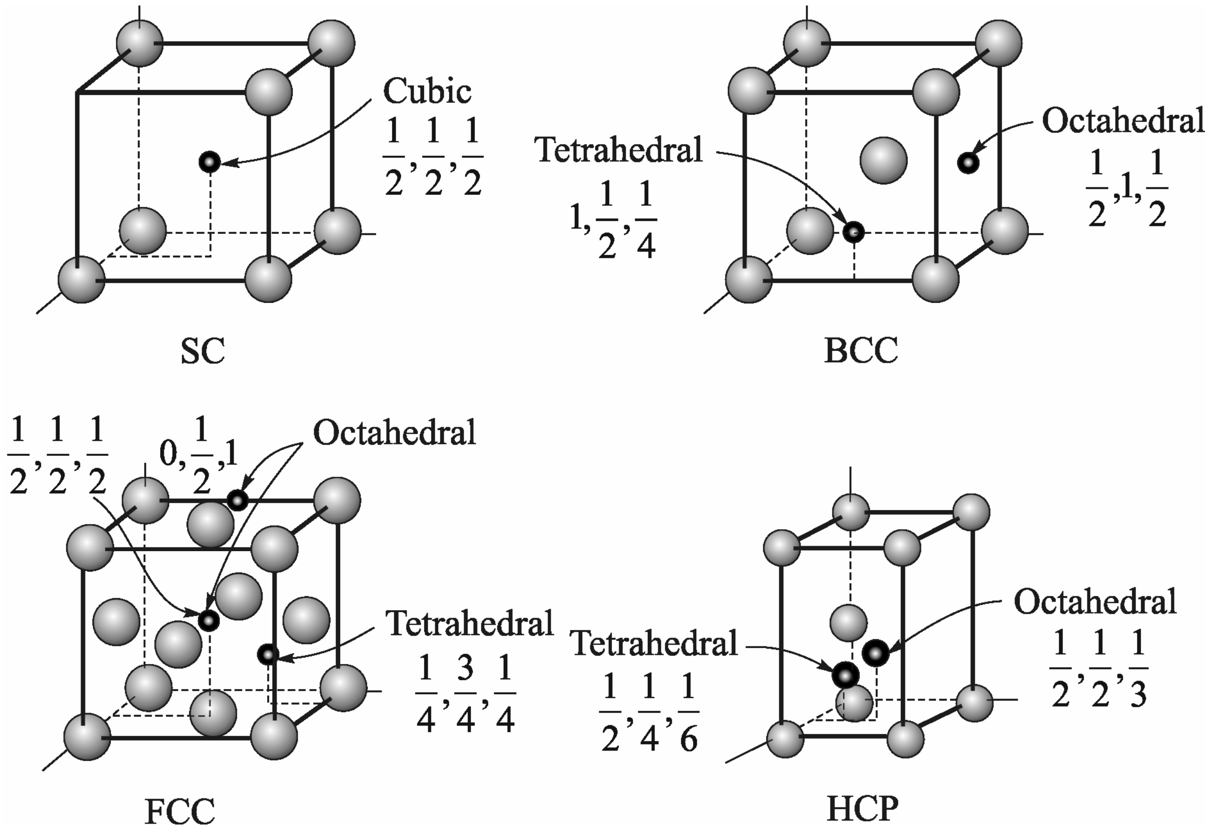


Figure 1.44 The location of the interstitial sites in common unit cells. Only representative sites are shown

a coordination number of six. In FCC unit cells, octahedral sites occur at the center of each edge of the cube as well as in the center of the unit cell.

Example 1.20

Write the coordinates for all of the tetrahedral interstitial sites in the FCC crystal structure.

Answer

$$\text{Tetrahedral sites: } \begin{array}{llll} \frac{1}{4},\frac{1}{4},\frac{1}{4} & \frac{1}{4},\frac{1}{4},\frac{3}{4} & \frac{3}{4},\frac{1}{4},\frac{1}{4} & \frac{3}{4},\frac{1}{4},\frac{3}{4} \\ \frac{1}{4},\frac{3}{4},\frac{1}{4} & \frac{1}{4},\frac{3}{4},\frac{3}{4} & \frac{3}{4},\frac{3}{4},\frac{1}{4} & \frac{3}{4},\frac{3}{4},\frac{3}{4} \end{array}$$

Example 1.21

Calculate the number of octahedral sites that uniquely belong to one FCC unit cell.

Answer

The octahedral sites include the 12 edges of the unit cell, with the coordinates

$$\begin{array}{llll} \frac{1}{2},0,0 & \frac{1}{2},1,0 & \frac{1}{2},0,1 & \frac{1}{2},1,1 \\ 0,\frac{1}{2},0 & 1,\frac{1}{2},0 & 1,\frac{1}{2},1 & 0,\frac{1}{2},1 \\ 0,0,\frac{1}{2} & 1,0,\frac{1}{2} & 1,1,\frac{1}{2} & 0,1,\frac{1}{2} \end{array}$$

plus the center position, $\frac{1}{2},\frac{1}{2},\frac{1}{2}$. Each of the sites on the edge of the unit cell is shared between four unit cells, so only $\frac{1}{4}$ of each site belongs uniquely to each unit cell. Therefore, the number of sites belonging uniquely to each cell is

$$(12\text{ edges})\left(\frac{1}{4}\text{ per cell}\right)+1\text{ center location}=4\text{ octahedral sites}.$$

We can calculate the size of each interstitial site in terms of the size of atoms at the regular lattice positions. Example 1.21 shows how the radius of the interstitial site is related to the atom size for the cubic and octahedral sites.

Example 1.21

Calculate the radius of an atom that will just fit into (a) the cubic site and (b) the octahedral site. The radius of the atoms in the normal lattice positions is *R*.

Answer

(a) Figure 1.45 (a) shows the arrangement of the atoms when the smaller atom just fits into the center of a cube.

$$2R+2r=2R\sqrt{3},$$

$$r=\sqrt{3}R-R=(\sqrt{3}-1)\cdot R,$$

$$\frac{r}{R}=0.732.$$

(b) Figure 1.45 (b) shows the arrangement of the atoms when the smaller atom just fits into the center of an octahedron.

$$2R+2r=2R\sqrt{2},$$

$$r=\sqrt{2}R-R=(\sqrt{2}-1)\cdot R,$$

$$\frac{r}{R}=0.414.$$

Interstitial atoms whose radii are slightly larger than the radius of the interstitial site may enter that site, pushing the surrounding atoms slightly apart. However, atoms whose radii are smaller than the radius of the hole are not allowed to fit into the interstitial site, or the ion will “rattle” around in the site. If the interstitial atom

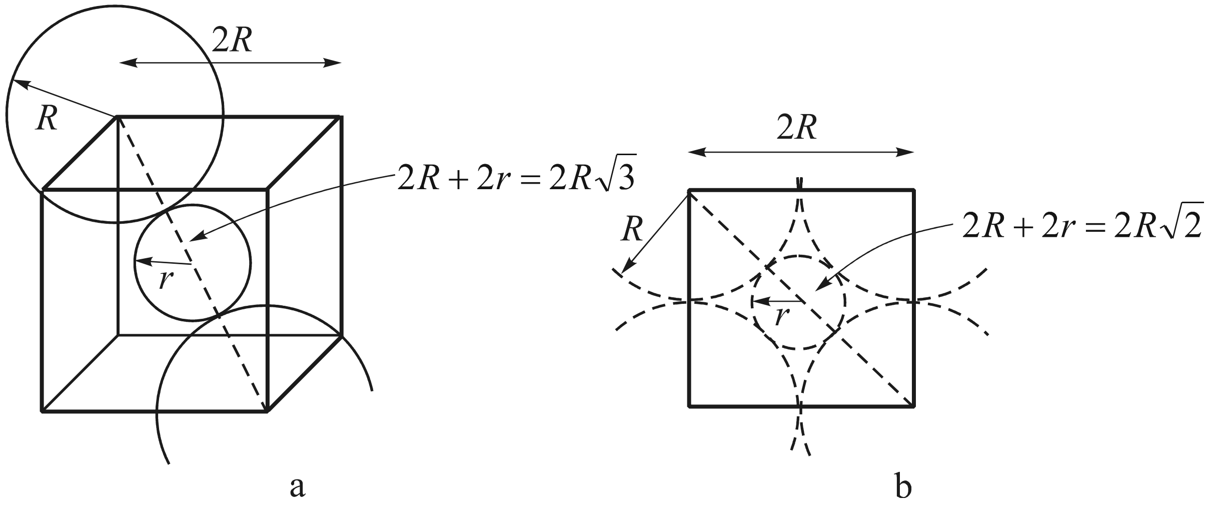


Figure 1.45 Illustration for Example 1.21 to determine the radius of an interstitial site for (a) a cubic hole and (b) an octahedral hole

becomes too large, it prefers to enter a site having a larger coordination number (Table 1.10). Therefore, an atom whose radius ratio is between 0.225 and 0.414 will enter a tetrahedral site; if its radius is somewhat larger than 0.414, it will enter an octahedral site instead. When atoms have the same size, as in pure metals, the radius ratio is one and the coordination number is 12, which is the case for metals with the FCC and HCP structures.

Example 1.22

Determine the expected coordination number for each ion in NiO.

Answer

From Appendix D, the ionic radii are

$$r_{\mathrm{Ni}} = 0.69\ \text{Å} \qquad r_{\mathrm{O}} = 1.32\ \text{Å}$$

$$\frac{r_{\mathrm{Ni}}}{r_{\mathrm{O}}} = \frac{0.69}{1.32} = 0.523\,.$$

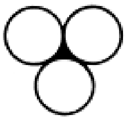
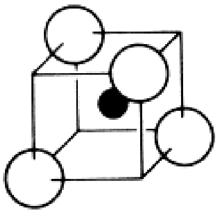
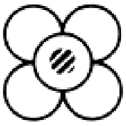
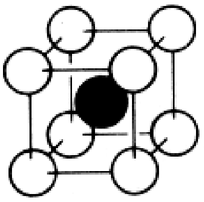
From Table 1.10, we find that the coordination number should be six, since $0.414 < 0.523 < 0.732$.

1.2.6 Ionic Crystals

Many ceramic materials contain ionic bonds between the negatively charged anions and the positively charged cations. These ionic materials must have crystal structures that assure electrical neutrality yet permit ions of different sizes to be efficiently packed.

Electrical Neutrality If the charges on the anion and the cation are identical, the ceramic compound has the formula *AX,* and the coordination number for each ion is identical to assure a proper balance of charge. As an example, each cation may be

Table 1.10 The coordination number and the radius ratio

Coordination Number	Location of Interstitial	Radius Ratio	Representation
2	Linear	0 – 0.155	
3	Corners of triangle	0.155 – 0.225	
4	Corners of tetrahedron	0.225 – 0.414	
6	Corners of octahedron	0.414 – 0.732	
8	Corners of cube	0.732 – 1.000	

surrounded by six anions, while each anion is in turn surrounded by six cations. However, if the valence of the cation is + 2 and that of the anion is – 1, then twice as many anions must be present, and the formula is of the form AX_2. The structure of the AX_2 compound must assure that the coordination number of the cation is twice the coordination number of the anion. For example, each cation may have 8 anion nearest neighbors, while only 4 cations will touch each anion.

Cesium Chloride and Sodium Chloride Structures as the Examples of Ionic Crystals The crystal structures of the ionically bonded compounds often can be described by placing the cations at the normal lattice points of a unit cell, with the anions then located at one or more of the interstitial sites described in Section 1.2.5. The ratio of the sizes of the ionic radii of the anion and cation influences both the manner of packing and the coordination number (Table 1.10).

Cesium chloride (CsCl) is simple cubic, with the “cubic” interstitial site filled by the Cl anion (Figure 1.46). The radius ratio, $r_{Cs}/r_{Cl} = 1.67/1.81 = 0.92$, dictates that cesium chloride have a coordination number of eight. We can characterize the structure as a simple cubic structure with two ions – one Cs and one Cl – associated with each lattice point. This structure is possible when the anion and the cation have the same valence.

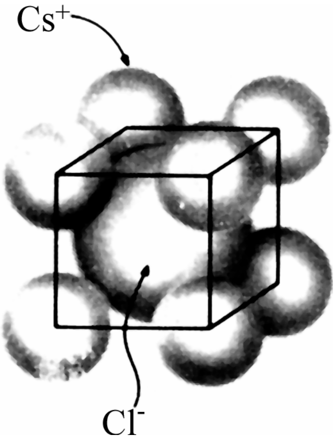


Figure 1.46 The cesium chloride structure, an SC unit cell with two ions per lattice point

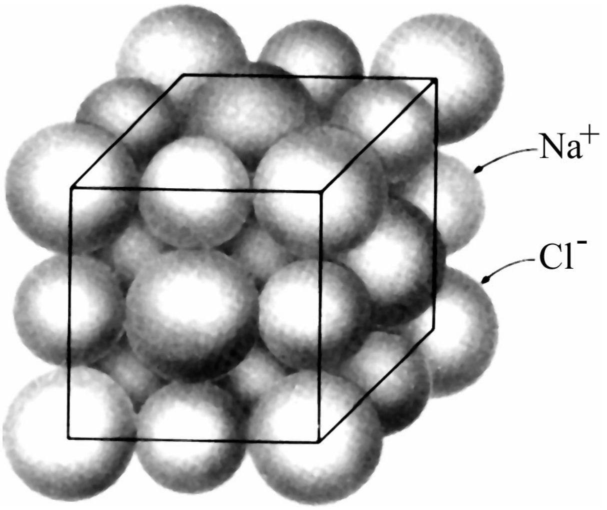


Figure 1.47 The sodium chloride structure, an FCC unit cell with two ions per lattice point

In *sodium chloride* (NaCl) the radius ratio for sodium and chloride ions is $r_{\text{Na}}/r_{\text{Cl}} = 0.97/1.81 = 0.536$; the sodium ion has a charge of + 1, while the chloride ion has a charge of – 1. Therefore, based on the charge balance and radius ratio, each anion and cation must have a coordination number of six. The FCC structure, with Na cations at FCC positions and Cl anions at the four octahedral sites, will satisfy these requirements (Figure 1.47). We can also consider this structure to be FCC with two ions – one Na and one Cl – associated with each lattice point. Many ceramics, including MgO, CaO, and FeO, have this structure.

1.2.7 Covalent Structures

Covalently bonded materials frequently must have complex structures in order to satisfy the directional restraints imposed by the bonding.

Diamond Cubic Structure Elements such as silicon, germanium, and carbon in its diamond form are bonded by four covalent bonds and produce a tetrahedron (Figure 1.48). The coordination number for each silicon atom is only four, due to the nature of the covalent bonding.

As these tetrahedral groups are combined, a large cube can be constructed [Figure 1.48 (b)]. This large cube contains eight smaller cubes that are the size of the tetrahedral cube; however, only four of the cubes contain tetrahedra. The large cube is the *diamond cubic,* or DC, unit cell. The lattice is a special FCC structure. The atoms on the corners of the tetrahedral cubes provide atoms at each of the regular FCC lattice points. However, four additional atoms are present within the DC unit cell from the atoms in the center of the tetrahedral cubes. We can describe the DC lattice as an FCC lattice with two atoms associated with each lattice point. Therefore, there must be eight atoms per unit cell.

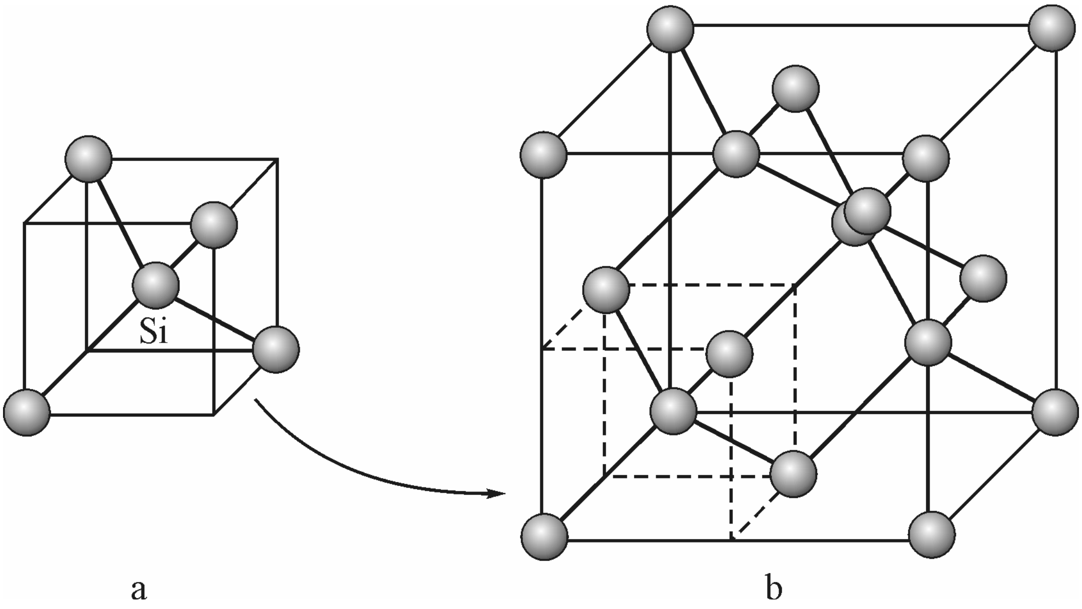


Figure 1.48 (a) Tetrahedron and (b) the diamond cubic (DC) unit cell. This open structure is produced because of the requirements of covalent bonding

Example 1.23

Determine the packing factor for DC silicon.

Answer

We find that atoms touch along the body diagonal of the cell (Figure 1.49). Although atoms are not present at all locations along the body diagonal, there are voids that have the same diameter as atoms. Consequently,

$$\sqrt{3}a_0 = 8r\,.$$

$$\text{Packing factor} = \frac{(8\ \text{atoms/cell})(4/3\pi r^3)}{a_0^3} = \frac{(8)(4/3\pi r^3)}{(8r/\sqrt{3})^3} = 0.34\,.$$

Crystalline Silica In a number of its forms, *silica*, or SiO_2, has a crystalline ceramic structure which is partly covalent and partly ionic. Figure 1.50 shows the crystal structure of one of the forms of silica, *β-cristobalite*, which is a complicated FCC structure. The ionic radii of silicon and oxygen are 0.42 Å and 1.32 Å, respectively, so the radius ratio is $r_{\text{SiO}} / r_{\text{O}} = 0.318$ and the coordination number is four.

Crystalline Polymers A number of polymers may form a crystalline structure. The dashed lines in Figure 1.51 outline the unit cell for the lattice of *polyethylene*. Polyethylene is obtained by joining C_2H_4 molecules together to produce long polymer chains that form an orthorhombic unit cell. Some polymers, including *nylon*, can have several polymorphic forms.

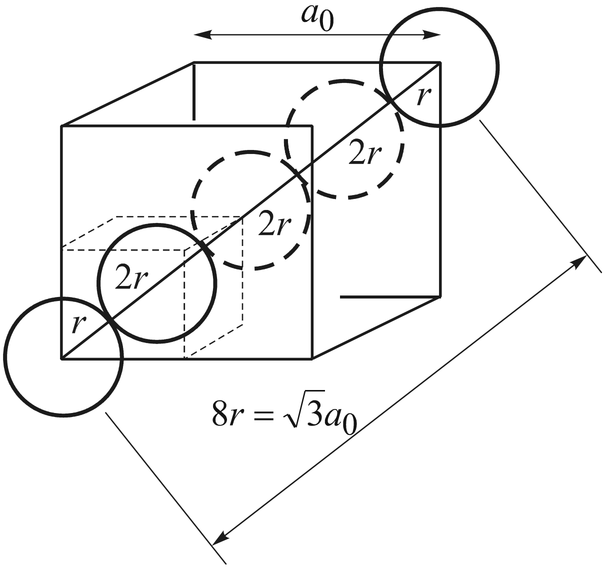


Figure 1.49 Determining the relationship between lattice parameter and atomic radius in diamond cubic

As the result of atomic arrangement examination we pay the reader's attention to the following. All atoms in solids are arranged with either a short-range or long-range order. Amorphous materials, such as glasses as well as many polymers, have only a short-range order, determined primarily by the restrictions of covalent bonding. Crystalline materials, including metals and many ceramics, have both a long-and short-range order. The long-range periodicity in these materials is described by the crystal structure.

In metals, the crystal structure is closely related to the general mechanical properties of the material. FCC structured metals are normally soft and ductile, BCC structured metals are much stronger, and HCP structured metals tend to be relatively brittle. The differences in materials behaviors are linked with the role of crystal structure in mechanical deformation.

Any crystal structure becomes more complicated when atoms arranged at interstitial sites in a unit cell. Many ceramic structures can be interpreted in this way.

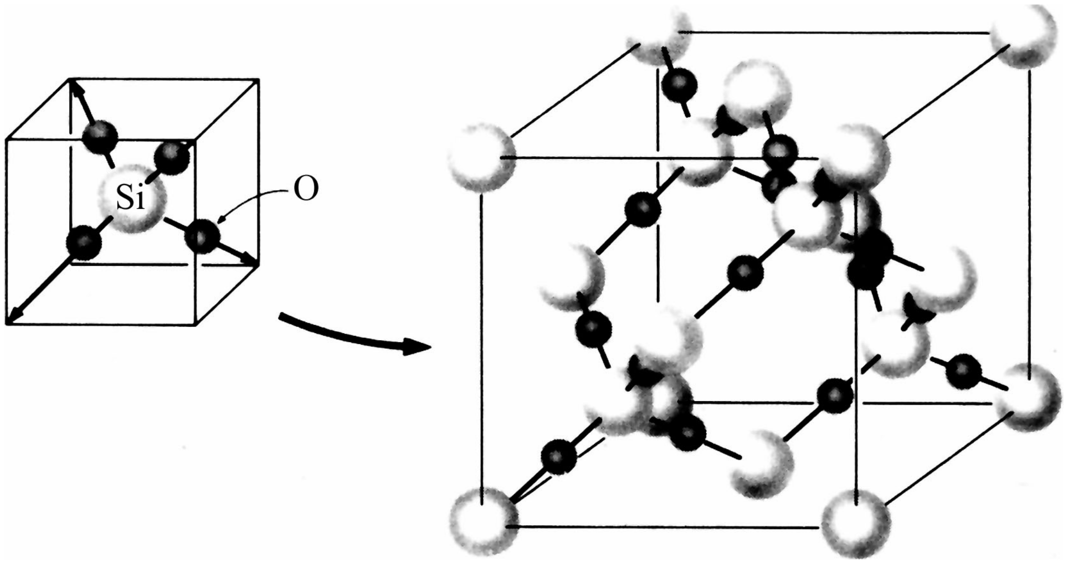


Figure 1.50 The silicon-oxygen tetrahedra and their combination to form the β-cristobalite form of silica

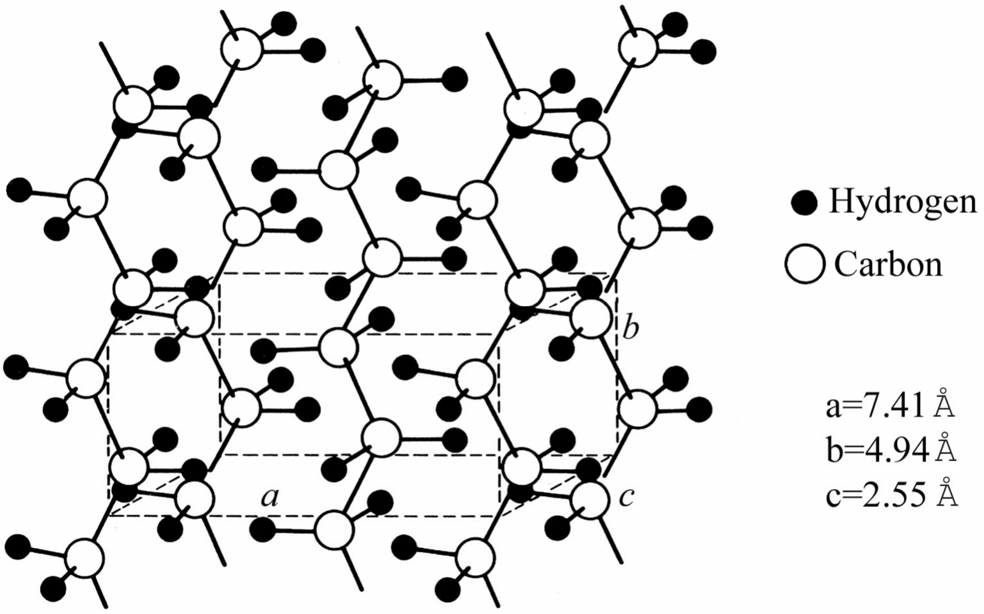


Figure 1.51 The unit cell of crystalline polyethylene

1.3 Imperfections in the Atomic Arrangement

All materials contain imperfections in the arrangement of the atoms which influence on the behavior of the material. By controlling lattice imperfections we create stronger metals and alloys, more powerful magnets, improved transistors and solar cells, glassware of striking colors, and many other materials of practical importance.

We will introduce three basic types of lattice imperfections – *point defects*, *line defects* (*or dislocations*), *surface defects*. We must remember, however, that these imperfections represent only defects in the perfect atomic arrangement and should not suggest that the material itself is defective. Indeed, these “defects” are intentionally added to produce a desired set of mechanical and physical properties. We can control these defects through *alloying*, *heat treatment*, or *processing techniques* to produce improved engineering materials.

1.3.1 Dislocations

When crystalline solids are subjected to loads on the atomic scale resulting from external forces, there is a tendency to pull the atoms apart. If the external efforts are not very powerful we have so called *elastic deformation* of a solid body, which disappears after the removal of external forces. More powerful external loading leads to *plastic deformation* and as the result of loading we observe the *failure* of different types (ductile, brittle and their combinations, Figure 1.52).

In plastic deformation *atomic slipping* in crystals is the primary mechanism.

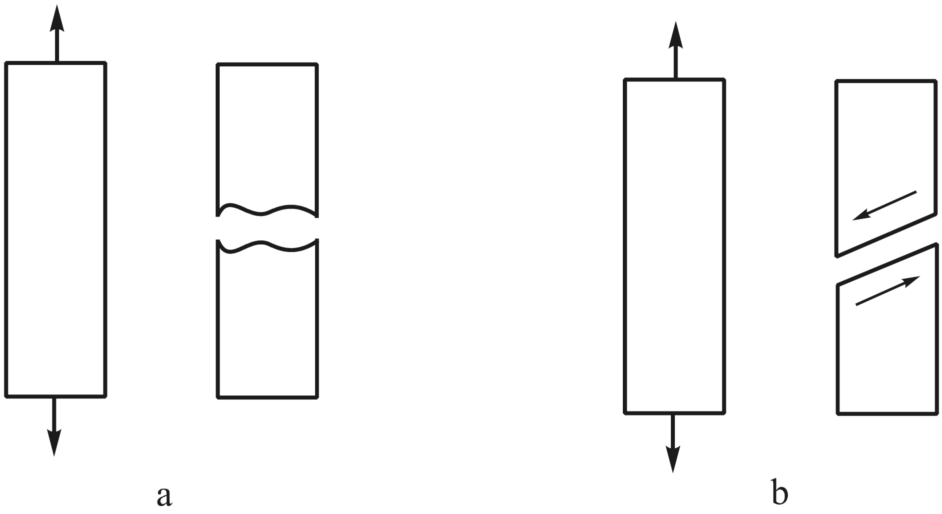


Figure 1.52 Cleavage failure of brittle crystalline materials

The slipping in the lattice primarily occurs along the most close-packed directions. But in order to have a slip made by simultaneous group movement of the atoms arranged in slip plane we would need a stress hundreds time exceeding the actual slip stress. A great discrepancy between theoretical and actual strength of materials is caused by availability of numerous lattice defects within crystals. And a relatively easy movement of atoms along the slip planes may be explained by availability of *dislocations* which may be referred to as linear defects of crystalline structure.

In 1934 G.J. Taylor, E. Orovan, and M. Polanyi were the first, who declared that it was possible the *movable defects* should be available in solids lattice. Their motion is the primary mechanism of plastic deformation which is caused in this case by a rather low stress than it was theoretically needed. These movable imperfections were called “dislocations” (in latinic dislocation equals to displacement). Their *movability* is the primary term in *dislocation theory*, which investigates the mechanisms of crystal solids deformation.

Dislocations are *line imperfections* in a perfect lattice. We can identify two types of dislocations – the *screw dislocation* and the *edge dislocation*. The screw dislocation (Figure 1.53-1.55) can be illustrated by cutting partway through a perfect crystal, then skewing the crystal one atom spacing. If we followed a crystallographic plane one revolution around the axis on which the crystal was skewed, traveling equal atom spacing in each direction, we would finish one atom spacing below our starting point. The vector required to complete the loop and return us to our starting point is the *Burgers vector* **b**. If we continued our rotation, we would trace out a spiral path. The axis, or line, around which we trace out this path is the screw dislocation. We see that the Burgers vector is parallel to the screw dislocation.

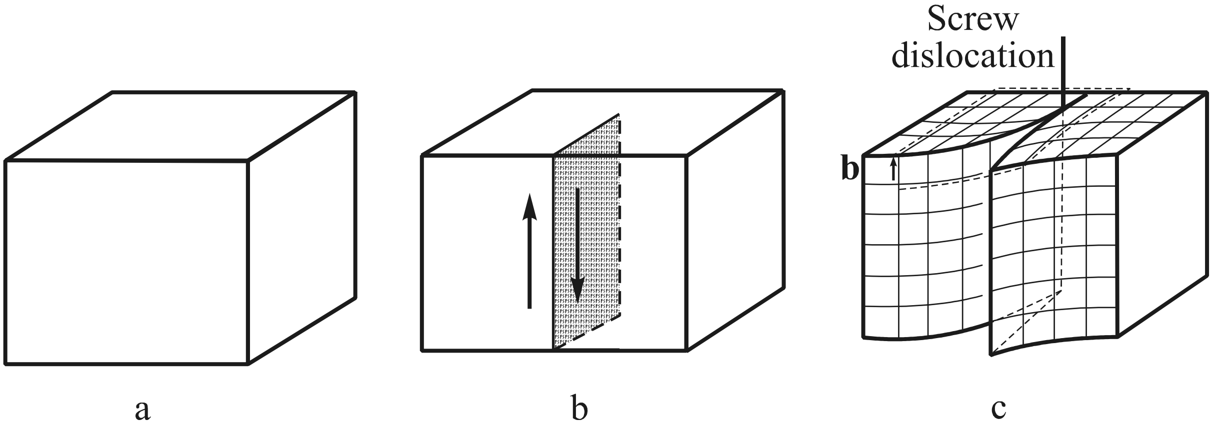


Figure 1.53 The perfect crystal (a) is cut and sheared one atom spacing, (b) and (c). The line along which shearing occurs is a screw dislocation. A Burgers vector **b** is required to close a loop of equal atom spacings around the screw dislocation

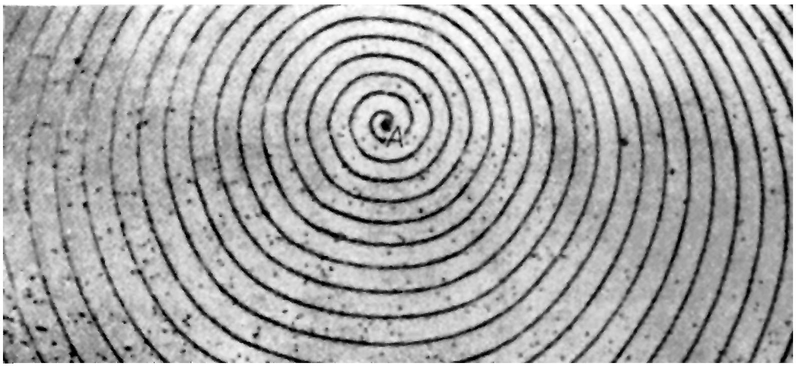


Figure 1.54 Screw dislocation in silicon carbide (SiC) (×60)

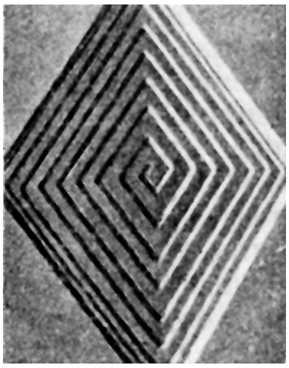


Figure 1.55 The helicoidal growth as the result of screw dislocation in paraffin crystal surface

An edge dislocation (Figure 1.56, 1.57) can be illustrated by slicing partway through a perfect crystal, spreading the crystal apart, and partly filling the cut with an *extra plane* of atoms. The bottom edge of this inserted plane represents the edge dislocation. If we describe a clockwise loop around the edge dislocation by going an equal number of atom spacings in each direction, we would finish one atom spacing from our starting point. The vector that is required to complete the loop is again the Burgers vector. In this case, the Burgers vector is perpendicular to the edge dislocation. By introducing the dislocation , the atoms above the dislocation line are squeezed too closely together, while the atoms below the dislocation are stretched too far apart. The perfection of the lattice has been destroyed by the presence of the dislocation.

From the Figure 1.56 more simple definition of the edge dislocation may be done: it is the *extra half plane* of atoms.

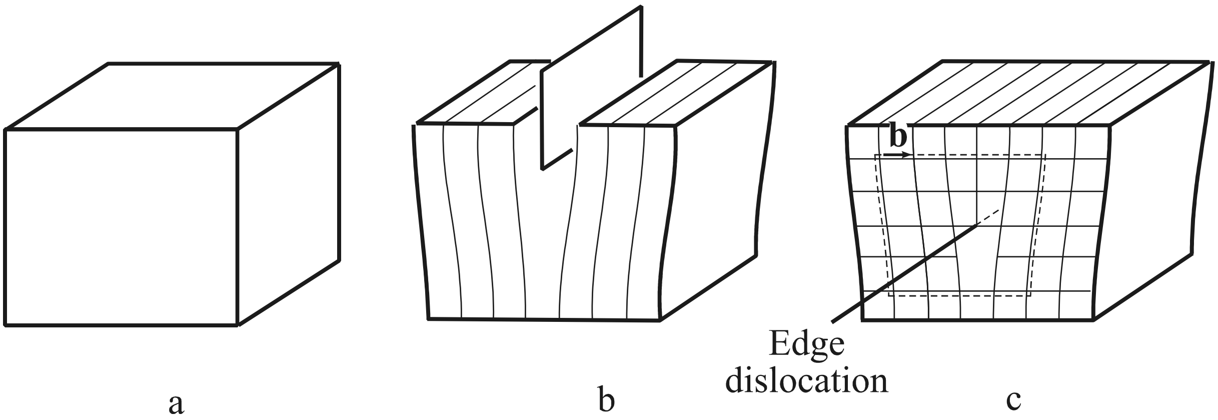


Figure 1.56 The perfect crystal in (a) is cut and an extra plane of atoms is inserted (b). The bottom edge of the extra plane is an edge dislocation (c). A Burgers vector **b** is required to close a loop of equal atom spacings around the edge dislocation

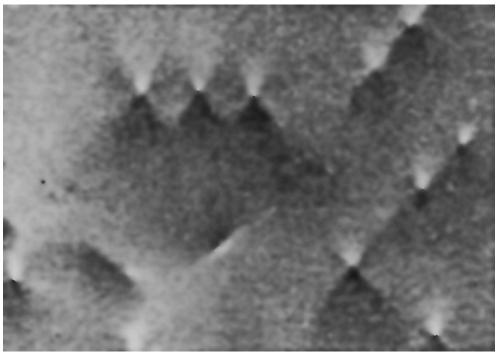


Figure 1.57 An appearance of an edge dislocation on the material surface

Example 1.24

Suppose we have a BCC structure with a lattice parameter of 4.0 Å that contains the dislocation shown in Figure 1.58. Determine the direction and length of the Burgers vector.

Answer

The clockwise loop around the dislocation is closed by the vector **b**. Because **b** is perpendicular to the (222) planes, the Miller indices of direction **b** must be [222] or, reducing to lowest integers, [111]. The length of **b** is the distance between two adjacent (222) planes. From Equation,

$$d_{hkl} = \frac{a_0}{\sqrt{h^2 + k^2 + l^2}}$$

receive

$$d_{222} = \frac{a_0}{\sqrt{h^2 + k^2 + l^2}} = \frac{4}{\sqrt{2^2 + 2^2 + 2^2}} = 1.155 \text{ Å}.$$

The Burgers vector is a [111] direction that is 1.155 Å in length.

We could translate the Burgers vector from the loop to the edge dislocation, as shown in Figure 1.59. After this translation, we find that the Burgers vector and the edge dislocation define a *plane* in the lattice. The Burgers vector and the plane are helpful in explaining how materials deform.

One rather important question must be answered: where do dislocations from? Dislocations can be produced by *crystal mismatch* in solidification. They can be introduced by acting stresses in a plastic deformation; they can occur by *phase*

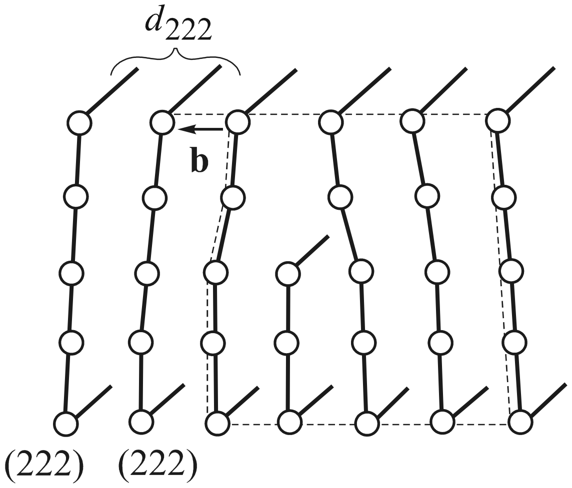


Figure 1.58 The Burgers vector for Example 1.24 is perpendicular to the (222) planes and has a length equal to the interplanar spacing between (222) planes

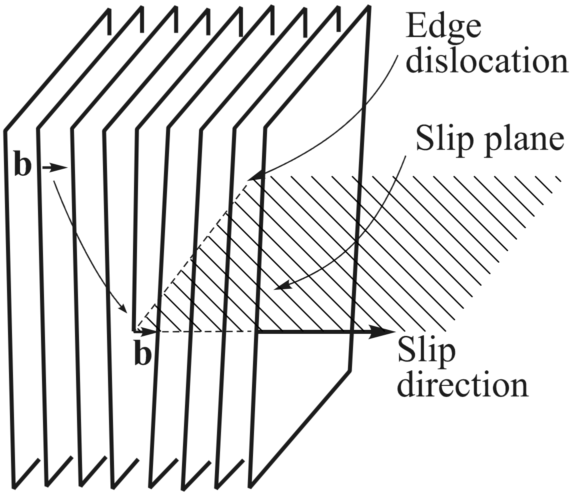


Figure 1.59 After the Burgers vector is translated from the loop to the dislocation line, a plane is defined

transformations that cause atomic mismatch; or they can be caused by the atomic mismatch effects of adding *alloy elements*.

1.3.2 Dislocations Movement

All dislocations have a very important feature which consists of relatively *light movability* at rather low stresses.

In plastic deformation not only available dislocations move. The great number of new dislocations create. Due to the dislocations density increase the materials strength grows. Materials strengthening occurring because of dislocation redundancy may be explained by their mutual obstacles in moving and therefore impede the plastic deformation. Therefore the examination of the dislocation movement is a primarily important problem to establish the relationship between its indices and deformation parameters of deformed materials.

When a shear force acting in the direction of the Burgers vector is applied to a crystal containing a dislocation, the dislocation can move by breaking the bonds between the atoms in one plane. The cut plane is shifted slightly to establish bonds with the original partial plane of atoms. This causes the dislocation to move one atom spacing to the side, as shown in Figure 1.60. If this process continues, the dislocation moves through the crystal until a step is produced on the exterior of the crystal (Figure 1.61). The crystal has now been deformed. If dislocations could be continually introduced into one side of the crystal and moved along the same path through the crystal, the crystal would eventually be cut in half.

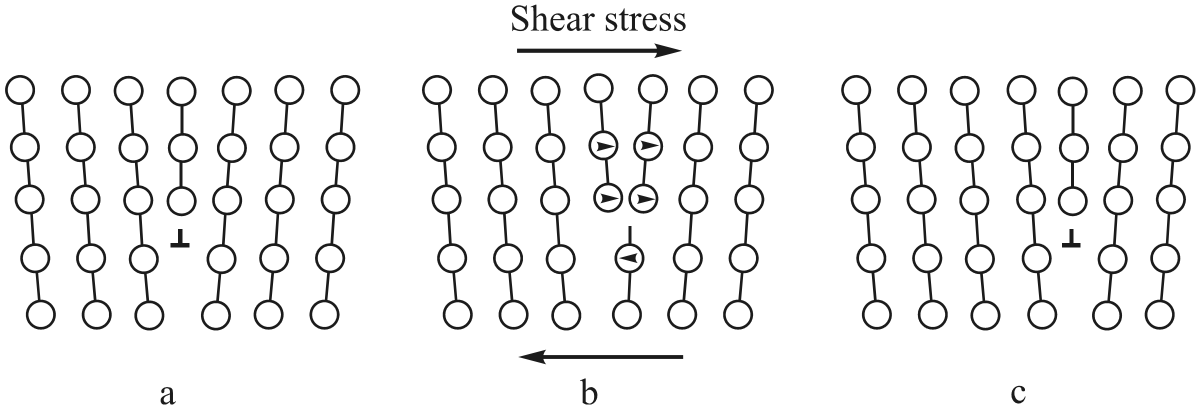


Figure 1.60 When a shear force is applied to the dislocation in (a), the atoms are displaced (b), until the dislocation moves one Burgers vector in the slip direction (c)

The process by which a dislocation moves and causes a metal to deform is called *slip.* The direction in which the dislocation moves, the *slip direction,* is the direction of the Burgers vector for edge dislocations. During slip the edge dislocation sweeps out the plane formed by the Burgers vector and the dislocation; this plane is called the *slip plane* (see Figures 1.59, 1.62). The combination of slip direction and slip plane is the *slip system.* A screw dislocation produces the same result; the dislocation moves in a direction perpendicular to the Burgers vector, although the crystal deforms in a direction parallel to the Burgers vector.

During slip, the dislocation moves from one set of surroundings to an identical set of surroundings. To do this with the least expenditure of energy, the dislocation will move the shortest possible distance – in a direction in which the repeat distance is small or the linear density is large. *The close-packed directions* satisfy this criterion and are therefore the *usual slip directions*. In addition, slip occurs between planes of atoms that are particularly smooth (so there are smaller "hills and valleys" on the surface) and far apart. Planes of atoms having a high planar density fulfill this requirement. Therefore, the slip planes are typically close-packed planes or those as closely packed as possible. The most common slip systems in metals are summarized in Table 1.11.

Example 1.25

Calculate the length of the Burgers vector in copper.

Answer

Copper is FCC with a lattice parameter of 3.615×10^{-10} m. The close-packed directions, or the directions of the Burgers vector, are of the form <110>. The repeat distance along the <110> directions is one-half the face diagonal, since lattice points are located at corners and centers of faces.

$$\text{Face diagonal} = \sqrt{2}a_0 = (\sqrt{2})(3.615\times10^{-10}) = 5.1125\times10^{-10}\ \text{m}.$$

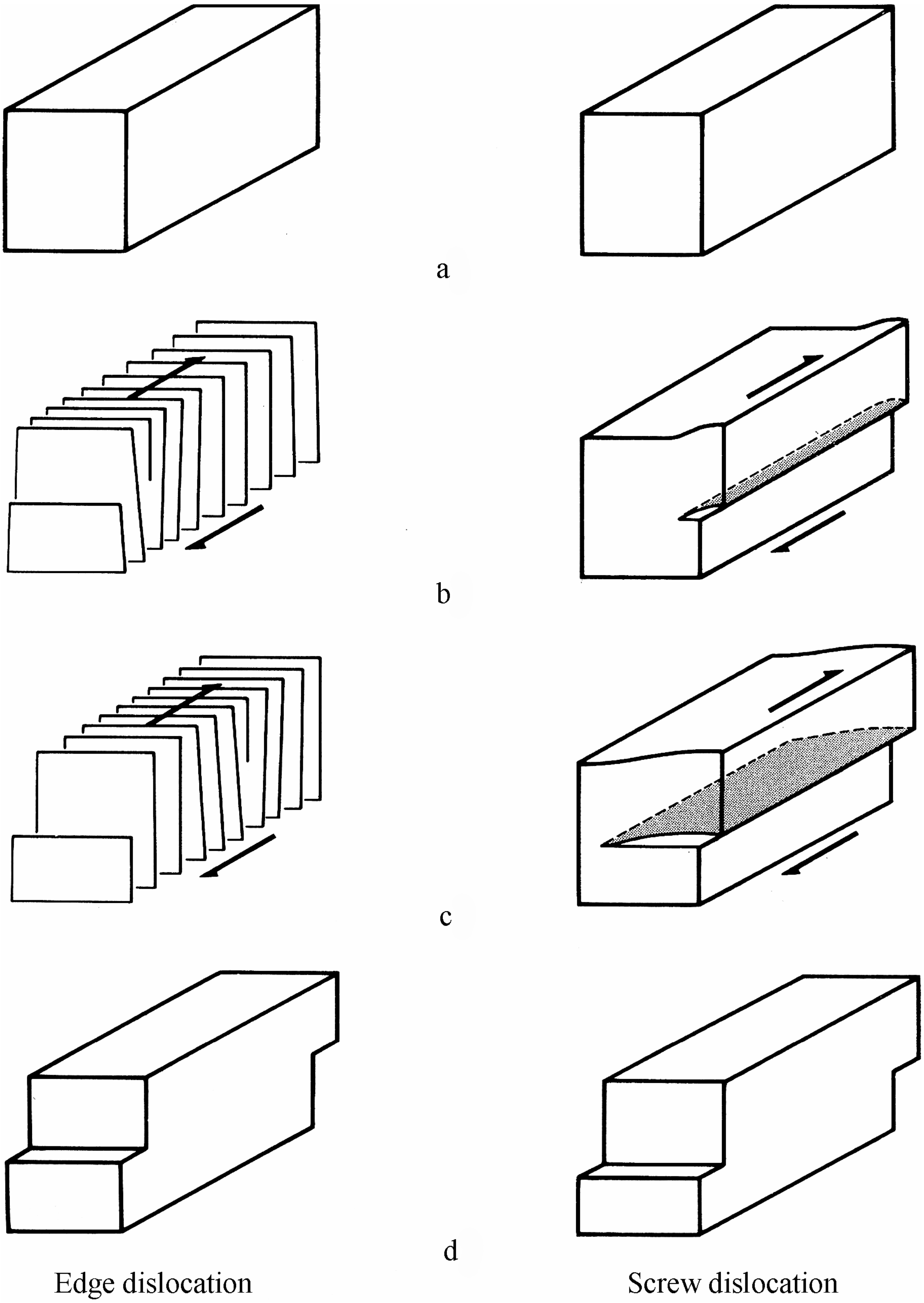


Figure 1.61 A shear force acting on a dislocation introduced into a perfect crystal (a) causes the dislocation to move through the crystal until a step is created (d). The crystal is now deformed

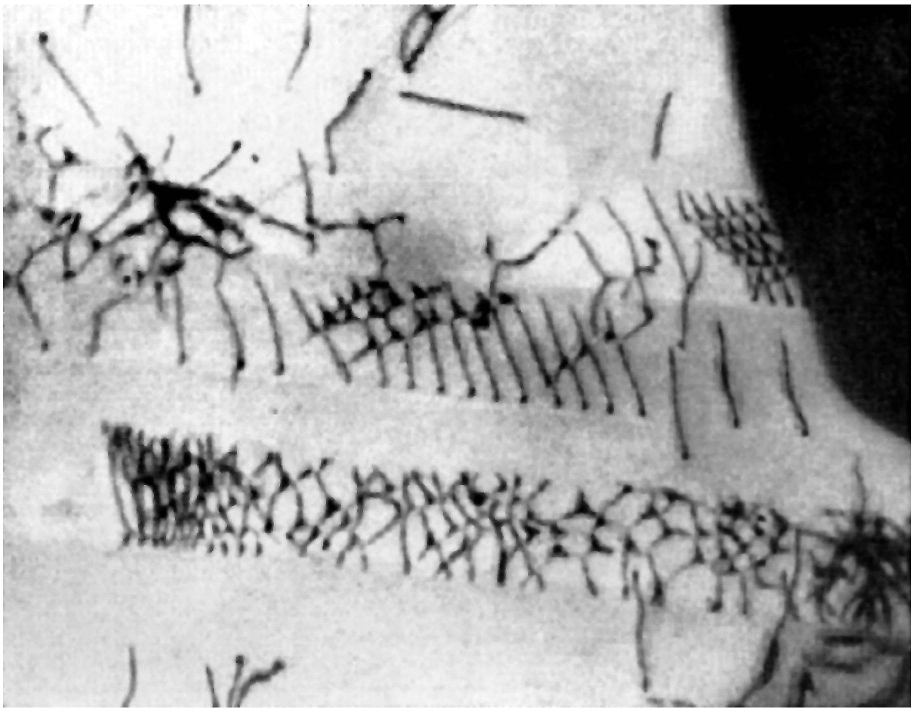


Figure 1.62 Dislocations and their slipping in stainless steel after tensile loading (strain ε=0.1) (×40,000)

Table 1.11 Slip planes and directions in metallic structures

Crystal Structure	Slip Plane	Slip Direction
BCC	{110} {112} {123}	<111>
FCC	{111}	<110>
HCP	(0001) $\left.\begin{array}{l}\{11\bar{2}0\}\\ \{10\bar{1}0\}\\ \{10\bar{1}1\}\end{array}\right\}*$	<100> <110>

(*) These planes are active in some metals and alloys or at elevated temperatures

The length of the Burgers vector, or the repeat distance, is

$$|\mathbf{b}| = \frac{1}{2}(5.1125\times10^{-10}) = 2.5563\times10^{-10} \text{ m.}$$

Example 1.26

The planar density of the (112) plane in BCC iron is 9.94×10^{-18} atoms/m^2.

Calculate (a) the planar density of the (110) plane and (b) the interplanar spacings for both the (112) and (110) planes. On which type of plane would slip normally occur?

Answer

The lattice parameter of BCC iron is 2.866×10^{-10} m. The (110) plane is shown in Figure 1.63, with the portion of the atoms lying within the unit cell being shaded. Note that one-fourth of the four corner atoms plus the center atom lie within an area of a_0 times $\sqrt{2}a_0$. The planar density is

$$\text{Planar density (110)} = \frac{\text{atoms}}{\text{area}} = \frac{2}{\sqrt{2}(2.866 \times 10^{-10})^2} = 1.72 \times 10^{-19} \text{ atoms/m}^2 .$$

The interplanar spacings are

$$d_{110} = \frac{2.866 \times 10^{-10}}{\sqrt{1^2 + 1^2 + 0}} = 2.0266 \times 10^{-10} \text{ m,}$$

$$d_{112} = \frac{2.866 \times 10^{-10}}{\sqrt{1^2 + 1^2 + 2^2}} = 1.17 \times 10^{-10} \text{ m.}$$

The planar density and interplanar spacing of the (110) plane are larger than those for the (112) plane; therefore, the (110) plane would be the preferred slip plane.

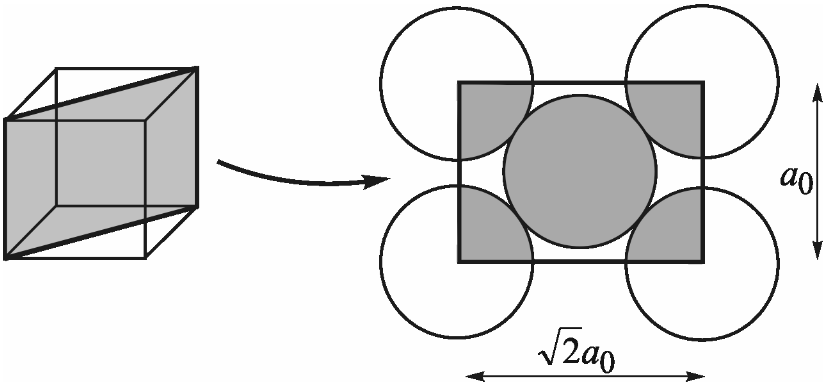


Figure 1.63 The atom locations on a (110) plane in a BCC unit cell (Example 1.26)

1.3.3 Dislocation Density and Materials Properties

Although slip can occur in some ceramics and polymers, the slip process is particularly helpful to us in understanding the mechanical behavior of metals. First, slip explains why really the strength of metals is much lower than the value predicted from the metallic bond. If we had to break an iron bar by breaking all of the metallic bonds across the cross section, as shown in Figure 1.64, we would have to exert a force of several thousands megapascals. Instead, we could deform the bar by causing slip, during which only a tiny fraction of all the metallic bonds need be broken at any one time. Perhaps a force of only 100 MPa would be required to deform the iron bar by slip.

Second, slip provides *ductility* in metals. If no dislocations were present, the iron bar would be brittle; metals could not be shaped by the various metal working processes, such as *forging*, into useful shapes

Third, we control the mechanical properties of a metal or alloy by interfering with the movement of dislocations. An obstacle introduced into the crystal prevents a dislocation from slipping unless we apply higher forces. If we are to apply a higher force, the metal appears to be stronger.

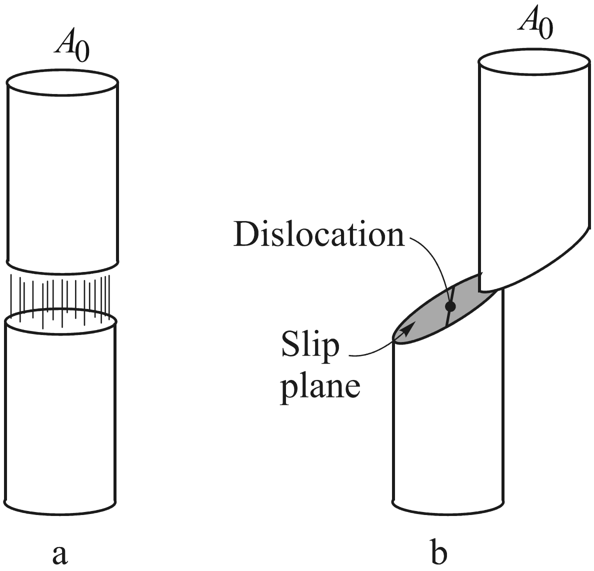


Figure 1.64 Without dislocations (a), a material would fail by breaking all of the bonds across the surface A_0. However, when a dislocation slips (b), bonds are only broken along the line of the dislocation

Enormous numbers of dislocations are found in materials. The *dislocation density,* or total length of dislocations per unit volume, is usually used to represent the amount of dislocations present. Dislocation densities of 10^{10} m/m^3 are typical of the softest metals, while densities up to 10^{16} m/m^3 can be achieved by deforming the material. Figure 1.65 – 1.68 shows dislocations at a very high magnification.

Example 1.27

A typical dislocation density in soft copper is 10^{10} m/m^3. If the dislocations in 1.0 kg of copper were placed end to end, how many miles of dislocation would be available?

Answer

The density of copper is 8.93×10^3 kg/m^3. Therefore

$$\text{Volume of copper} = \frac{1.0}{8.93\times10^3} = 0.112\times10^{-3}\ \text{m}^3.$$

$$\text{Length} = 0.112\times10^{-3}\cdot10^{10} = 1.12\times10^6 = 1120\ \text{km}$$

unidirectional force F to a metal specimen with the cross sectional area A_0 which is one single crystal (Figure 1.69). We can orient the slip plane and slip direction to the applied force by defining the angles λ and ϕ. λ is the angle between the slip direction and the applied force and ϕ is the angle between the normal to the slip plane and the applied force. In order for the dislocation to move in its slip system, a shear force acting in the slip direction must be produced by the applied force. This resolved shear force F_r is given by

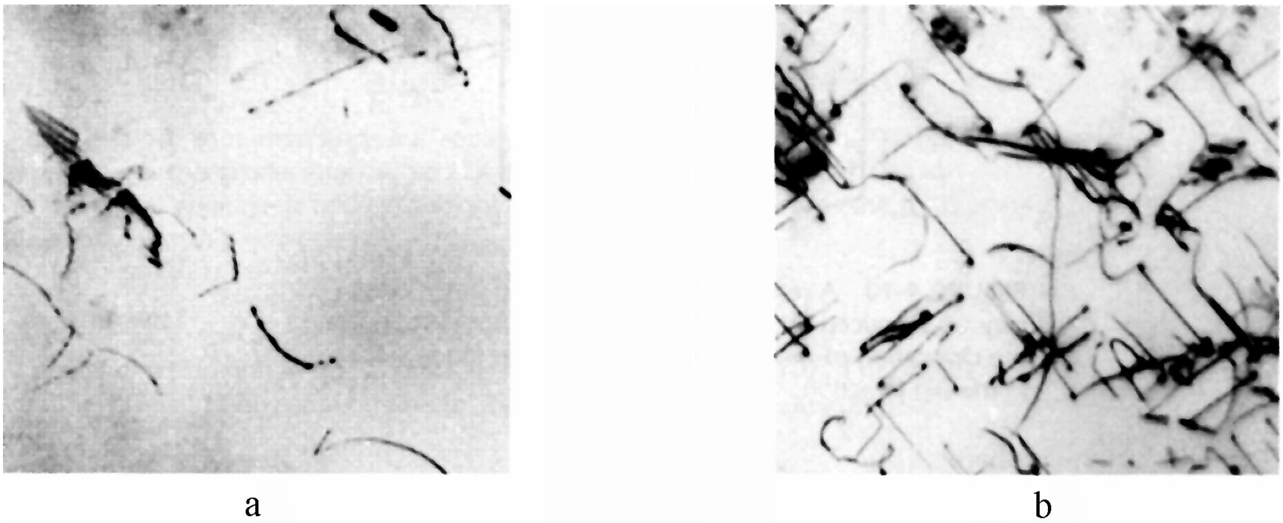

a
b

Figure 1.65 Electron photomicrographs of dislocations in Ti_3Al. (a) Dislocation pileups (× 36,500), (b) dislocation network (×15,750)

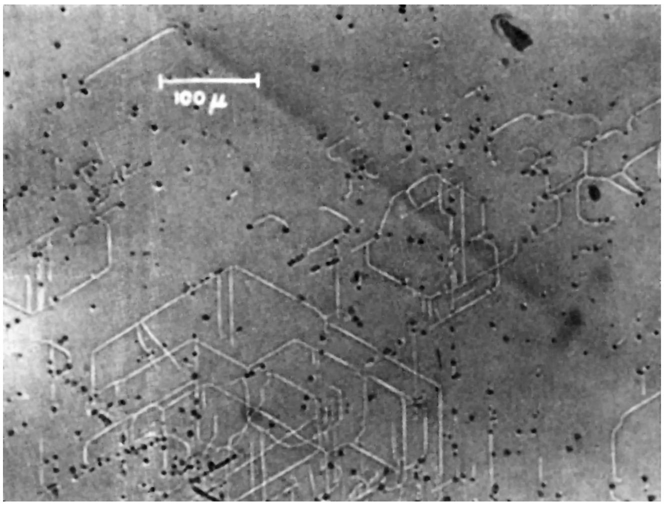


Figure 1.66 Dislocation loops, parallel to (111) plane in silicon after etching (100 μ = 100 micrometers)

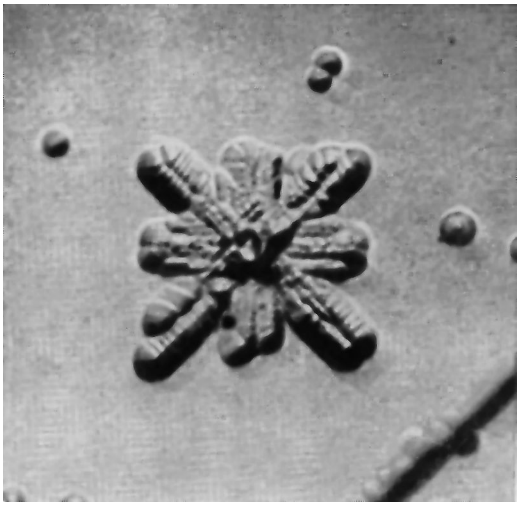


Figure 1.67 Rosette of dislocation near a indentation in MgO (×500)

$$F_r = F\cos\lambda .$$

If we divide the equation by the area of the slip plane, $A = A_0 / \cos\phi$, we obtain *Schmid's law*

$$\tau_r = \sigma\cos\phi\cos\lambda , \tag{1.8}$$

where

$$\tau_r = \frac{F_r}{A} = \text{ resolved shear stress in the slip direction,}$$

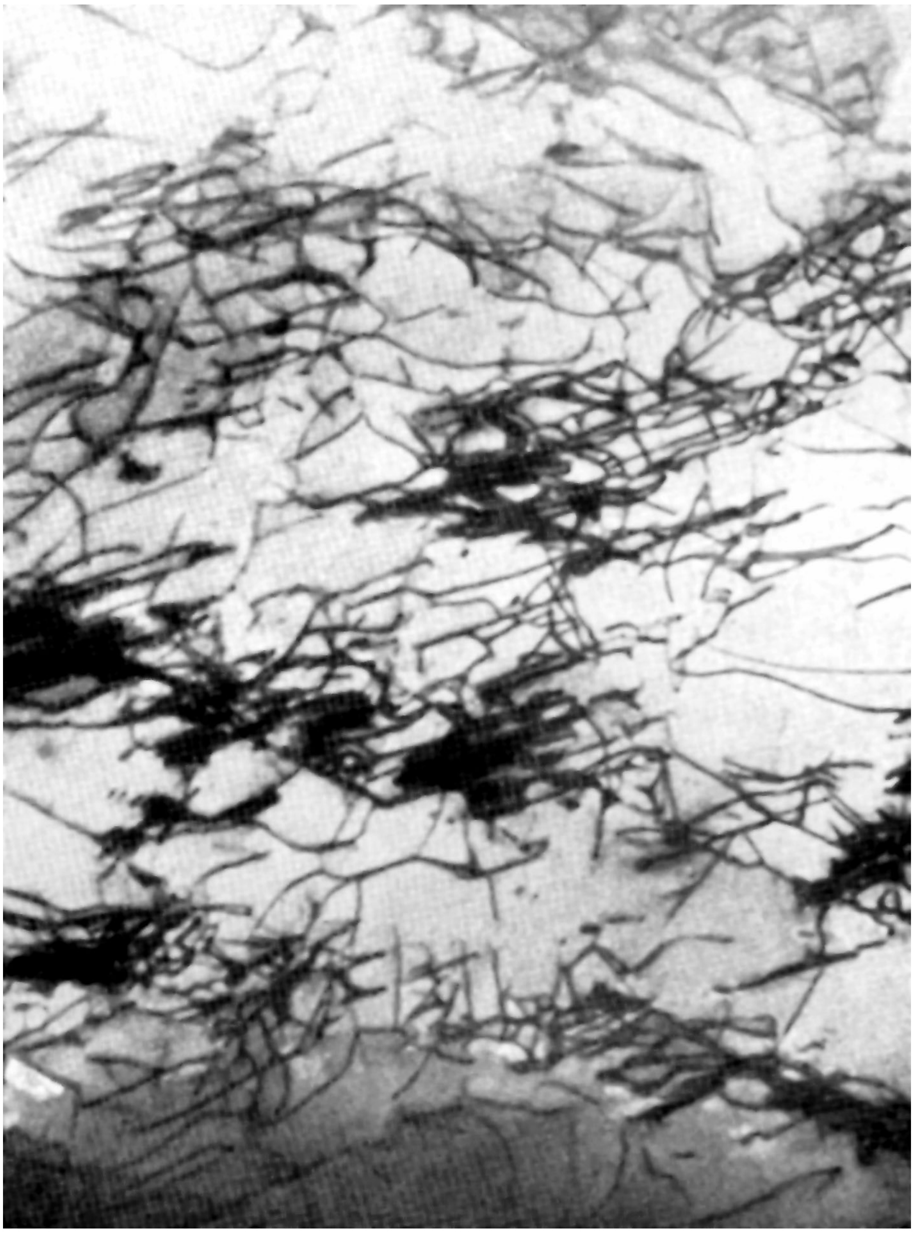


Figure 1.68 Dislocation network in stainless steel after tensile loading (× 30,000)

$$\sigma = \frac{F}{A_0} = \text{unidirectional stress applied to the example.}$$

Example 1.28

Suppose the slip plane is perpendicular to the applied stress σ, as in Figure 1.70. Then, $\phi = 0°$, $\lambda = 90°$, $\cos\lambda = 0$, and therefore $\tau_r = 0$. Even if the applied stress σ is enormous, no resolved shear stress develops along the slip direction and the dislocation cannot move. Slip cannot occur if the slip system is oriented so that either λ or ϕ is 90°.

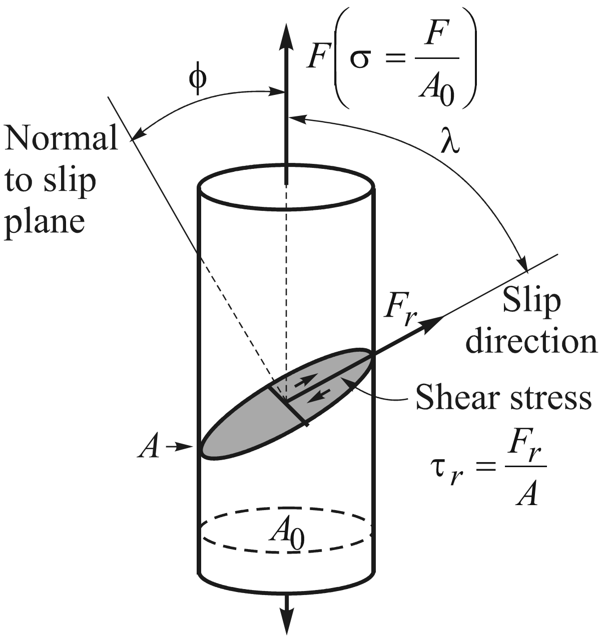


Figure 1.69 A resolved shear stress τ may be produced on a slip system, causing the dislocation to move on the slip plane in the slip direction

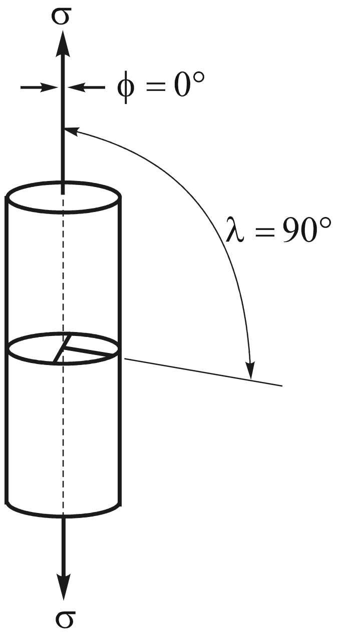


Figure 1.70 When the slip plane is perpendicular to the applied stress σ, the angle λ is 90° and no shear stress is resolved

Example 1.29

Calculate the resolved shear stress on the (111) $[\bar{1}01]$ slip system if a stress of 70 MPa is applied in the [001] direction of an FCC unit cell (see Figure 1.71).

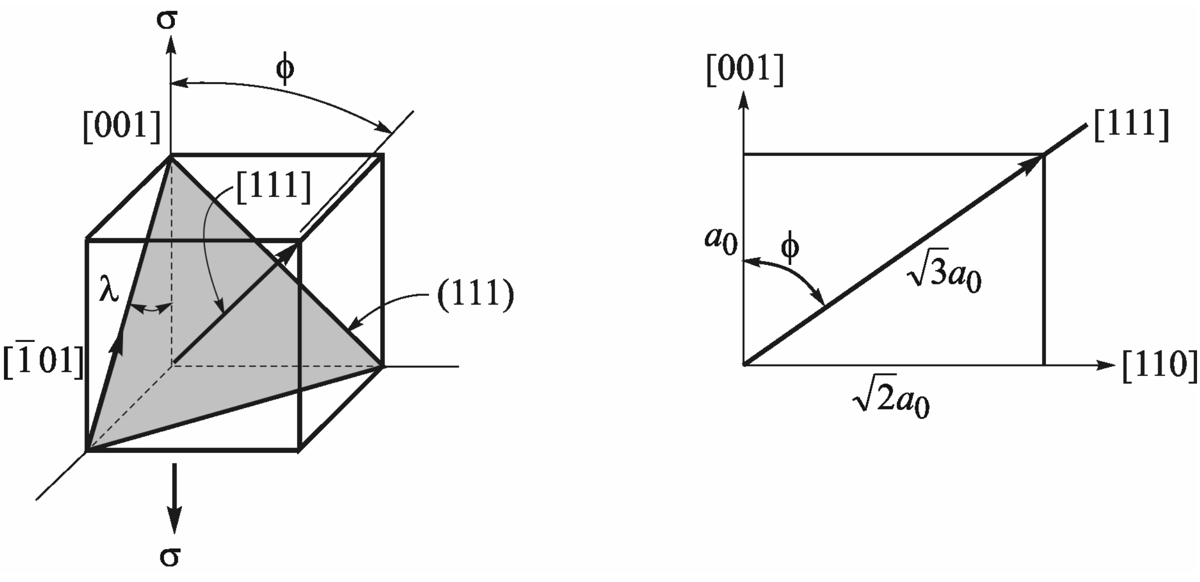


Figure 1.71 A normal stress σ is applied in the [001] direction of the unit cell. This produces an angle λ of 45° to the $[\bar{1}01]$ slip direction and an angle ϕ of 54.76° to the normal to the (111) plane (see Example 1.29)

Answer

It is clear from the drawing that $\lambda = 45°$ and $\cos\lambda = 0.707$. The normal to the (111) plane must be the $[111]$ direction. We can then calculate that

$$\cos\phi = \frac{1}{\sqrt{3}} = 0.577 \quad \text{or} \quad \phi = 54.76°,$$

$$\tau_r = \sigma\cos\lambda\cos\phi = (70)(0.707)(0.577) = 28.6\,\text{MPa}.$$

The *critical resolved shear stress* τ_{cr} is the shear stress required to break enough metallic bonds in order for slip to occur. Thus slip occurs, causing the metal to deform, when the applied stress produces a resolved shear stress that equals the critical resolved shear stress:

$$\tau_r = \tau_{cr}. \qquad (1.9)$$

This value is the materials constant. It depends on the temperature (Figure 1.72).

We have to admit that the value of σ is not a useless. In spite of its low influence the τ_{cr} value, this stress is used to calculate the materials tensile strength.

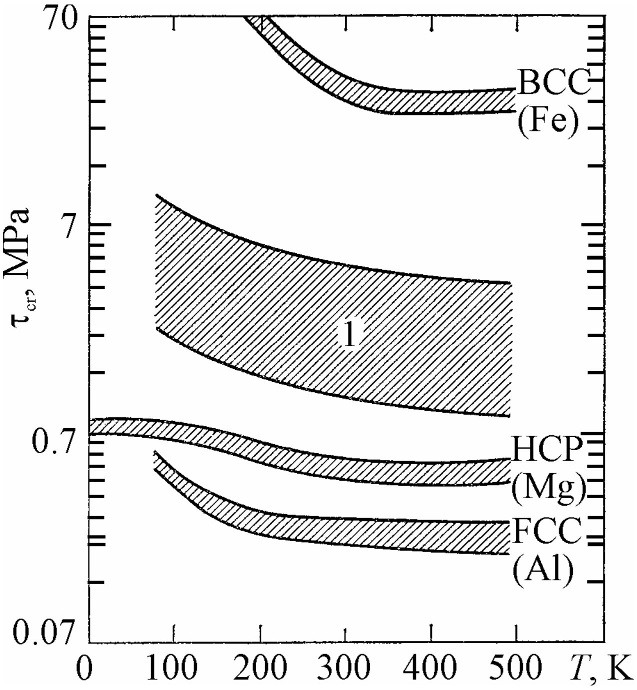


Figure 1.72 Critical resolved shear stress versus temperature for different classes of materials. (1) solids with ionic bonding, which have the same structure as NaCl

Example 1.30

Consider a slip system in which $\lambda = 70°$ and $\phi = 30°$. Slip is found to begin when a stress of 35 MPa is applied. Calculate the critical resolved shear stress.

Answer

$$\tau_{cr} = \tau_r \text{ when slip begins,}$$

$$\tau_{cr} = \sigma\cos\lambda\cos\phi = (35\times10^6)(\cos70°)(\cos30°) = 10.4\,\text{MPa}.$$

1.3.4 Influence of Crystal Structure

Schmid's law is used to compare the properties of metals having BCC, FCC, and HCP crystal structures. Table 1.12 lists three important factors that we can examine. Do not forget, that this discussion describes the behavior of nearly perfect single crystals. Real engineering materials are seldom single crystals and are never quite perfect.

Table 1.12 Summary of factors affecting slip in metallic structures

Factor	FCC	BCC	HCP
Critical resolved shear stress (MPa)	0.35 … 0.7	35.0 … 70.0	0.35 … 0.7 (for HCP metals with c/a=1.633)
Number of slip systems	12	48	3*
Cross-slip	Can occur	Can occur	Cannot occur*
Summary of properties	Ductile	Strong	Relatively brittle

*By alloying or heating to elevated temperatures, additional slip systems are active in HGP metals, permitting cross-slip to occur and thereby improving ductility.

Critical Resolved Shear Stress If the critical resolved shear stress in a metal is very high, the applied stress σ must also be high in order for τ_r to equal τ_{cr}. If σ is large, the metal must have a high strength! In FCC metals, which have close-packed planes, the critical resolved shear stress is low, about 0.35 to 0.7 MPa in a perfect crystal; FCC metals are expected to have low strength. On the other hand, BCC crystal structures contain non-close-packed planes. Dislocations must move on nonclose-packed planes, such as {110}, {112}, and {123} planes. Now we must exceed a higher critical resolved shear stress, on the order of 70 MPa in perfect crystals, before slip occurs; therefore, BCC metals tend to have high strength.

We would expect the HPC metals, because they contain close-packed planes, to have low critical resolved shear stresses. In fact, in HCP metals such as zinc that have a *c/a* ratio greater than or equal to the theoretical ratio of 1.633, the critical resolved shear stress is less than 0.7 MPa, just as in FCC metals. However, in HCP titanium, the *c/a* ratio is less than 1.633; the close-packed planes are spaced too closely together. Slip now occurs on planes such as $(10\bar{1}0)$, or the faces of the hexagon, and the critical resolved shear stress is then as great as or greater than in BCC metals.

Example 1.31

Calculate the *c/a* ratios for HCP zinc and titanium and determine the likely slip processes in each. Will zirconium behave more like zinc or titanium?

Answer

First of all we must know the lattice parameters of these metals:

Zinc: $$\frac{c}{a} = \frac{4.9470}{2.6648} = 1.856\,.$$

Titanium: $$\frac{c}{a} = \frac{4.6831}{2.9503} = 1.587\,.$$

Zirconium: $\frac{c}{a}=\frac{5.1477}{3.2312}=1.593$.

The *c/a* ratio for zinc is greater than 1.633; slip is expected to occur primarily on basal planes, with low critical resolved shear stresses. Both titanium and zirconium have *c/a* ratios less than ideal; high critical resolved shear stresses are expected for each.

Number of Slip Systems If at least one slip system is oriented to give the angles λ and ϕ near 45°, then τ_r equals τ_{cr} at low applied stresses. Ideal HCP metals possess only one set of parallel close-packed planes, the (0001) planes, and three close-packed directions, giving three slip systems. Consequently, the probability of the close-packed planes and directions being oriented with λ and ϕ near 45° is very low. The HCP crystal may fail in a brittle manner without a significant amount of slip.

However, in HCP metals with a low *c/a* ratio, or when HCP metals are properly alloyed, or when the temperature is increased, other slip systems become active, making these metals less brittle than expected.

On the other hand, FCC metals contain four nonparallel close-packed planes of the form {111} and three close-packed directions of the form <110> within each plane, giving a total of 12 slip systems. At least one slip system is favorably oriented for slip to occur at low applied stresses, causing FCC metals to have low strength but high ductility.

Finally, BCC metals have as many as 48 slip systems that are nearly close packed. Several slip systems are always properly oriented for slip to occur – in fact, there are too many possible slip systems. Dislocations moving on one slip plane may interfere with movement of dislocations on other active slip planes. This interference leads to high strength in BCC metals yet still permits at least some ductility as well.

Cross-Slip Suppose a dislocation moving on one slip plane encounters an obstacle and is blocked from further movement. The dislocation can shift to a second intersecting slip system, also properly oriented, and continue to move. This is called *cross-slip* (Figure 1.73). In many HCP metals, no cross-slip can occur because the slip planes are parallel, not intersecting. Therefore, the HCP metals tend to remain brittle. Fortunately, additional slip systems become active when HCP metals are alloyed or heated, thus improving ductility. Cross-slip is possible in both FCC and BCC metals because a number of intersecting slip systems is present. Cross-slip consequently helps maintain ductility in these metals.

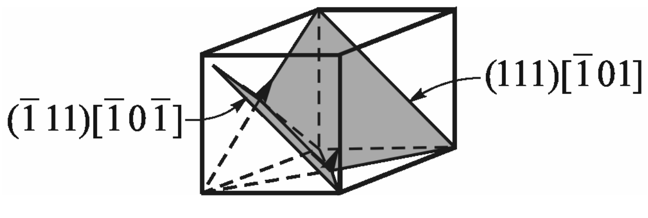


Figure 1.73 Cross-slip of a dislocation from a $(\bar{1}11)\,[\bar{1}0\bar{1}]$ system to a $(111)\,[\bar{1}01]$ system in an FCC crystal

As the result the most significant

characteristics of the three important crystal structures in single crystals of metals are: FCC metals are ductile, BCC metals are strong, and HCP metals are relatively brittle. These general conclusions still tend to be followed even in real engineering metals and alloys which are not single crystals.

Dislocations are more difficult to move in ionic and covalent materials. In covalent materials, such as silicon, the directionality of the bonds prevents easy movement of dislocations. Consequently, silicon behaves in a rather brittle manner.

In ionic materials, including most ceramics, dislocations are present and are observed to move. However, movement of a dislocation disrupts the charge balance around the anions and cations, requiring that bonds between anions and cations be broken. During slip, ions with a like charge must also pass close together, causing repulsion. Finally, the repeat distance along the slip direction, or the Burgers vector, is larger than in metals. Consequently, slip is much more difficult and ceramic materials normally display brittle behavior.

1.3.5 Point Defects

Point defects are localized disruptions of the lattice involving one or possibly several atoms. These imperfections, shown in Figure 1.74, may be introduced by movement of the atoms when they gain energy by heating, during processing of the material, by introduction of impurities, or intentionally through alloying.

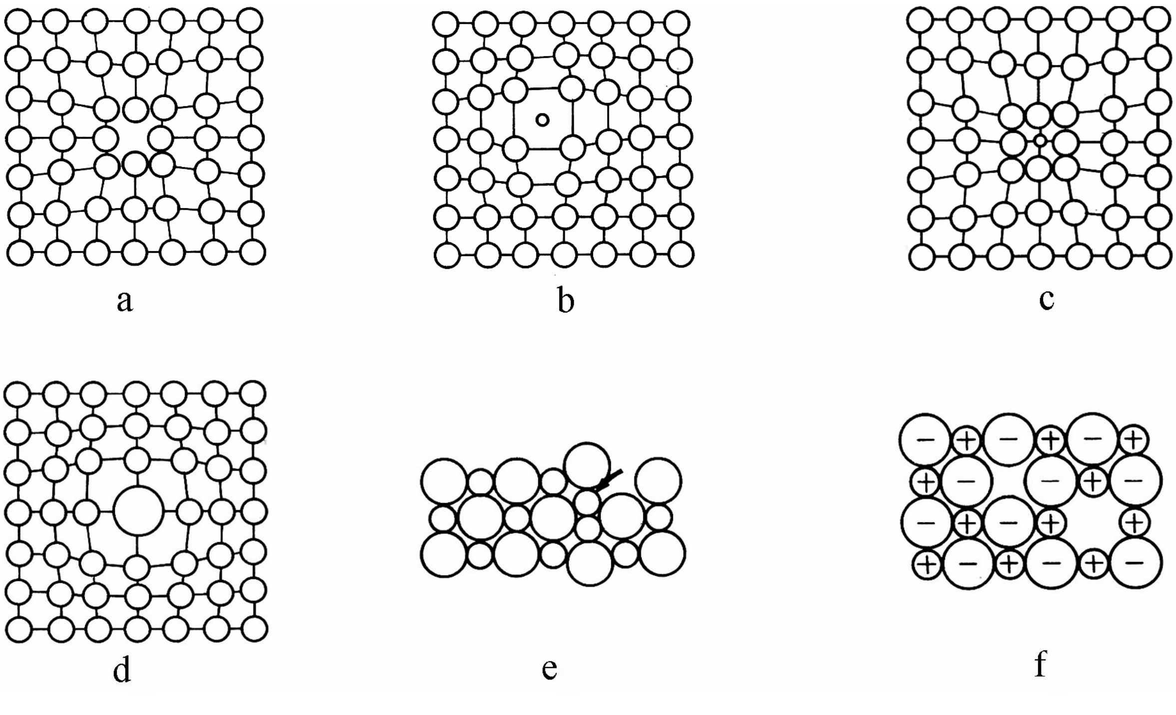


Figure 1.74 Point defects: (a) vacancy, (b) interstitial atom, (c) small substitutional atom, (d) large substitutional atom, (e) Frenkel defect, and (f) Schottky defect. All of these defects disrupt the perfect arrangement of the surrounding atoms

Vacancies A *vacancy* is produced when an atom is missing from a normal site. Vacancies are introduced into the crystal during solidification, at high temperatures, or as a consequence of radiation damage. At room temperature, very few vacancies are present (Example 1.32), but this number increases exponentially as we increase the temperature:

$$n_V = n\exp\left(-\frac{Q}{RT}\right), \tag{1.10}$$

where n_V is the number of vacancies per m^3; n is the number of lattice points per m^3; Q is the energy required to produce a vacancy, in J/mole; R is the gas constant, $8.315\,\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$; and T is the temperature in kelvin. Due to the large thermal energy near the melting temperature, there may be as many as one vacancy per 1000 lattice points.

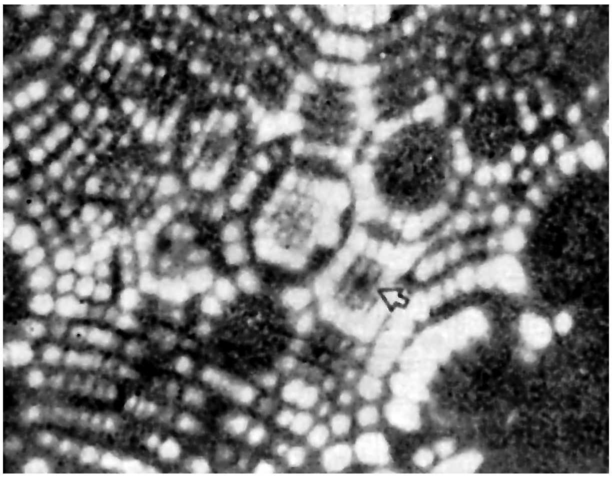


Figure 1.75 Vacancy in the (202) plane in platinum crystal ($\times 10^7$)

Example 1.32

Calculate the number of vacancies per cubic meter and the number of vacancies per copper atom when copper is at (a) room temperature and (b) 1084°C (just below the melting temperature). About 20,000 cal/mole are required to produce a vacancy in copper.

Answer

The lattice parameter of FCC copper is 3.6151×10^{-10} m. The number of copper atoms or lattice points per m^3 is

$$n = \frac{4\ \text{atoms/cell}}{(3.6151\times 10^{-10})^3} = 8.47\times 10^{28}\ \text{copper atoms/m}^3.$$

(a) At room temperature, $T = 25 + 273 = 298$ K.

$$n_V = (8.47\times 10^{28})\exp\left(\frac{-20{,}000\cdot 4.1868}{(8.315)(298)}\right) = 1.815\times 10^{14}\ \text{vacancies/m}^3.$$

$$\frac{n_V}{n} = \frac{1.815\times 10^{14}}{8.47\times 10^{28}} = 2.14\times 10^{-15}.$$

(b) Just below the melting temperature, $T = 1084 + 273 = 1357$ K.

$$n_V = (8.47\times 10^{28})\exp\left(\frac{-20{,}000\cdot 4.1868}{(8.315)(1357)}\right) = 5.09\times 10^{25}\ \text{vacancies/m}^3.$$

$$\frac{n_V}{n} = \frac{5.09\times10^{25}}{8.47\times10^{28}} = 6.0\times10^{-4}.$$

It is necessary to note the tremendous increase in the number of vacancies as the temperature increases.

Interstitial and Substitutional Defects An *interstitial defect* is formed when an extra atom is inserted into the lattice structure at a site which is not a normal lattice point. A *substitutional defect* is introduced when an atom is replaced by a different type of atom. The substitutional atom remains at the original normal lattice point. Both interstitial and substitutional defects are present in materials as impurities and may also be intentionally introduced as alloying elements. The number of these defects is usually independent of temperature. Both again distort the surrounding lattice structure.

An *interstitialcy* is created when an atom identical to those at the normal lattice points is located in an interstitial position. Because this involves a great deal of distortion of the lattice, it is relatively rare.

Imperfection Pairs A *Frenkel defect* is a vacancy-interstitial pair formed when an ion jumps from a normal lattice point to an interstitial site, leaving behind a vacancy. A *Schottky defect* is a pair of vacancies in an ionically bonded material. In this case, both an anion and a cation must be missing from the lattice if electrical neutrality is to be preserved in the crystal.

A final important point defect occurs when an ion of one charge replaces an ion of a different charge. This might be the case when an ion with a valence of +2 replaces an ion with a valence of +1 (Figure 1.76). In this case, an extra positive charge is introduced into the structure. To maintain a charge balance, one solution would be to create a vacancy where a +1 cation normally would be located.

Point defects disturb the perfect arrangement of the surrounding atoms. When a vacancy or a small substitutional atom is present, the surrounding atoms collapse

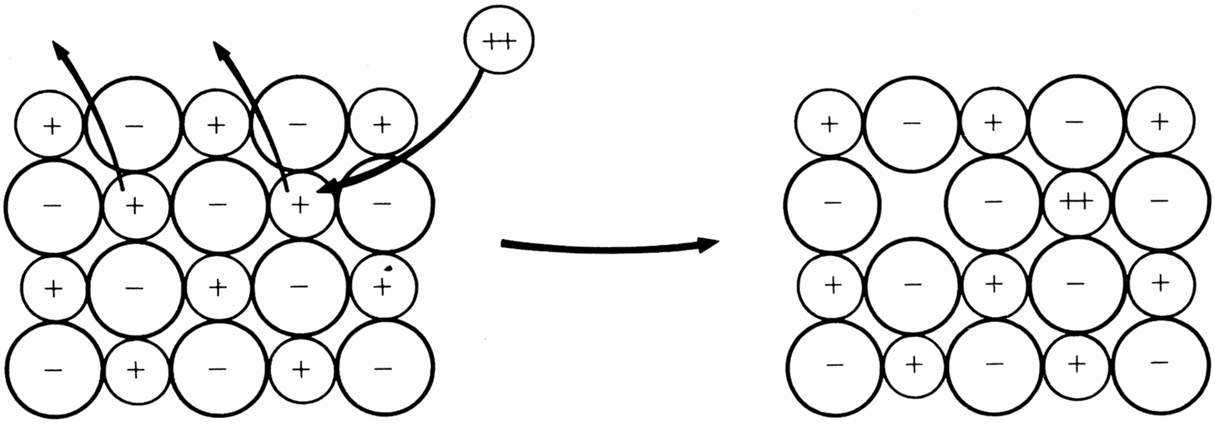


Figure 1.76 When a divalent atom replaces a monovalent cation, a second monovalent cation may also be removed, creating a vacancy

towards the point defect, stretching the bonds between the surrounding atoms and producing a tensile stress field. An interstitial, interstitialcy, or large substitutional atom pushes the surrounding atoms together, producing a compressive stress field. In either case, the effect is widely spread, extending perhaps hundreds of atom spacing from the actual point defect. A dislocation moving through the general vicinity of a point defect encounters a lattice in which the atoms are not at their equilibrium positions. This disruption requires that a higher stress be applied to force the dislocation past the defect, therefore increasing the strength of the metal.

Example 1.33

Iron has a measured density of 7.87×10^3 kg/m^3. The lattice parameter of BCC iron is 2.866 Å. Calculate the percentage of vacancies in pure iron.

Answer

From Equation (1.5)

$$\text{Density } \rho = \frac{\text{(atoms/cell)(atomic mass of each atom)}}{\text{(volume of unit cell)(Avogadro number)}}.$$

If $\rho = 7.87\times10^3$ kg/m^3 obtain

$$\text{atoms/cell} = \frac{(7.87\times10^3)(2.866\times10^{-10})(6.02\times10^{23})}{(55.85\times10^{-3})} = 1.998.$$

There should be 2 atoms/cell in a perfect BCC iron crystal. Thus, the difference must be due to the presence of vacancies.

$$\text{Vacancies} = \frac{2-1.988}{2}\times100 = 0.1\%.$$

Example 1.34

In FCC iron, carbon atoms are located at interstitial sites with coordinates $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$, whereas carbon atoms enter interstitial sites at 0, $\frac{1}{2}$, $\frac{1}{4}$ in BCC iron. The lattice parameter is 3.571 Å for FCC iron and 2.866 Å for BCC iron. Carbon atoms have a radius of 0.71 Å. Would we expect a greater distortion of the lattice by an interstitial carbon atom for FCC or BCC iron?

Answer

In the FCC crystal structure, the $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$ site is surrounded by four iron atoms in a tetrahedral arrangement. From Table 1.9, we know that the minimum radius ratio for fourfold coordination is

$$\frac{r(\text{interstitial})}{r(\text{iron atom})} = 0.225,$$

$$r(\text{interstitial}) = (0.225)\left(\frac{\sqrt{2}a_0}{4}\right) = \frac{(0.225)(\sqrt{2})(3.571)}{4} = 0.284\ \text{Å}.$$

In the BCC iron, the 0, $\frac{1}{2}$, $\frac{1}{4}$ site is shown in Figure 1.77:

$$R(\text{iron atom}) = \frac{\sqrt{3}a_0}{4} = \frac{\sqrt{3}(2.866)}{4} = 1.241\ \text{Å},$$

$$\left(\frac{1}{2}a_0\right)^2 + \left(\frac{1}{4}a_0\right)^2 = (r+R)^2,$$

$$(r+R)^2 = 2.566,$$

$$r(\text{interstitial}) = 1.602 - 1.241 = 0.361\ \text{Å}.$$

The carbon atom, 0.71 Å, is larger than either interstitial site. A compressive field is developed, which in this case will be larger in the FCC lattice than in the BCC lattice. Carbon atoms will likely disrupt slip more in the FCC iron.

1.3.6 Surface Defects

Surface defects are the boundaries, or planes, that separate a material into regions, each region having the same crystal structure but different orientations.

Material Surface The exterior dimensions of the material represent surfaces at which the lattice abruptly ends. Each atom at the surface no longer has the proper coordination number; atomic bonding is disrupted and may even be incomplete. The exterior surface may also be very rough, may contain tiny notches, and may be much more reactive than the bulk of the material.

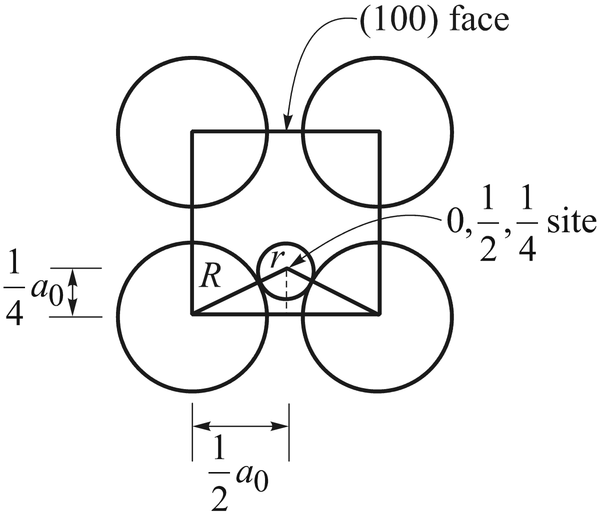


Figure 1.77 The location of the 0, $\frac{1}{2}$, $\frac{1}{4}$ interstitial site in BCC metals, showing the arrangement of the normal atoms and the interstitial atom

Grain Boundaries The microstructure of metals and many other solid materials consists of many grains. As you remember a *grain* is a portion of the material within which the arrangement of the atoms is identical. However, the orientation of the atom arrangement, or crystal structure, is different for each adjoining grain. Three grains are shown schematically in Figure 1.78; the lattice in each grain is identical but the lattices are oriented differently.

The photomicrograph of a single crystal of Al_2O_3 (Figure 1.79) represents the size, shape, and orientation of the crystalline grains.

As you see from Figures 1.78 and 1.79 a *grain boundary* is the surface that separates the individual grains and is a narrow zone in which the atoms are not properly spaced. The atoms are too close at some locations in the grain boundary, causing a region of compression, while in other areas the atoms are too far apart, causing a region of tension.

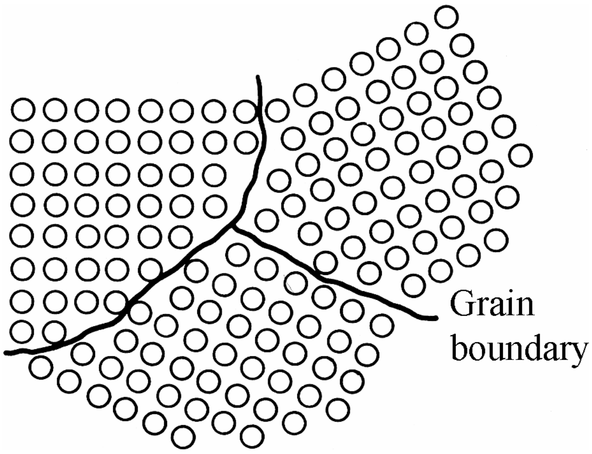


Figure 1.78 The atoms near the boundaries of the three grains do not have an equilibrium spacing or arrangement

One method of controlling the properties of a material which will be considered further is by *controlling the grain size*. By reducing the grain size, we increase the number of grains and hence increase the amount of grain boundary. Any dislocation moves only a short distance before encountering a grain boundary, and the strength of the metal is increased. The *Hall-Petch equation* relates the grain size to the yield strength of the metal:

$$\sigma_y = \sigma_0 + Kd^{-1/2}, \qquad (1.11)$$

where σ_y is the yield strength or the stress at which the material permanently deforms, d is the average diameter of the grains, and σ_0 and K are constants for the metal. Figure 1.80 shows this relationship in steel. Any engineer must know how the grain size can be controlled through solidification, alloying, and heat treatment.

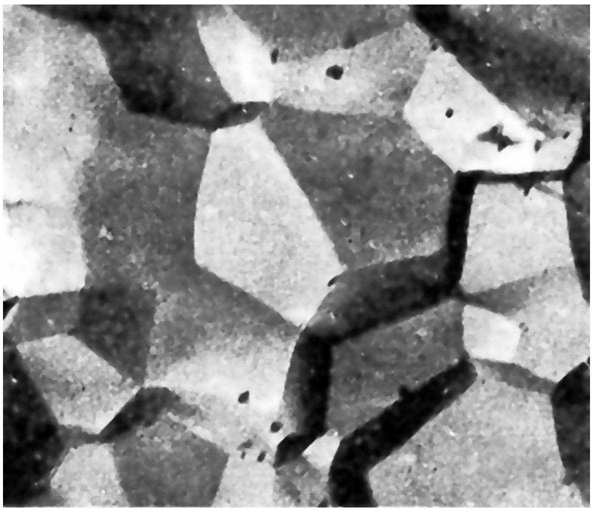


Figure 1.79 Microstructure level of internal structure of Al_2O_3 single crystal. Each area of this photomicrograph, magnified [×5000 (linear)], is a single crystal of Al_2O_3 containing about 1012 oxygen atoms plus two-thirds that number of aluminum atoms. Properties may be altered by changing the size, shape, orientation, or composition of the crystalline grains which comprise a microstructure

One technique by which grain size is specified is the *ASTM* (American Society for Testing & Materials) *grain size number*. The number of grains per square inch is determined from a photograph of the metal taken at magnification × 100 (Figure 1.81). The number of grains per square inch N is entered into Equation (1.12) and the ASTM grain size number n is

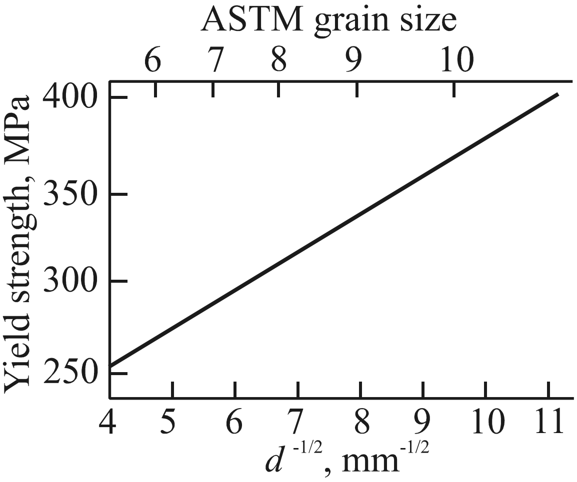


Figure 1.80 The effects of grain size on the yield strength of a steel at room temperature

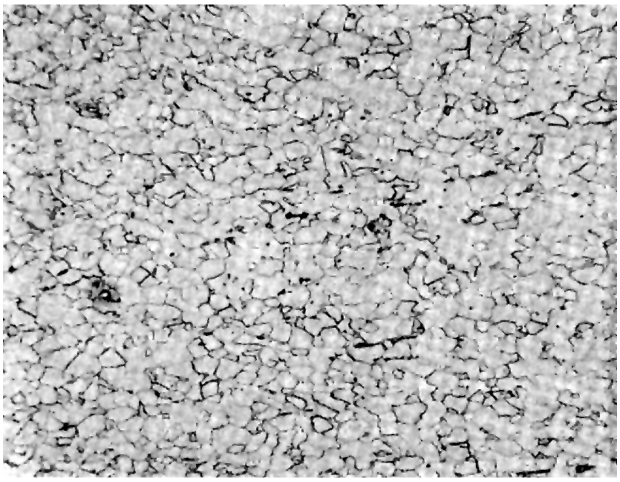


Figure 1.81 Photomicrograph showing the grain structure of nickel (× 100)

calculated:

$$N = 2n^{-1}. \tag{1.12}$$

A large ASTM number indicates many grains, or a fine grain size, and correlates with high strengths.

Example 1.35

Suppose we count 16 grains per square inch at magnification × 100 in a photomicrograph of a metal. Determine the ASTM grain size number.

Answer

$$N = 16 = 2n^{-1},$$
$$\log 16 = (n-1)\log 2,$$
$$1.204 = (n-1)(0.301),$$
$$n = 5.$$

Example 1.36

Suppose we count 16 grains per square inch in a photomicrograph taken at magnification × 250. What is the ASTM grain size number?

Answer

If we count 16 grains per square inch at magnification × 250, we must have at magnification × 100

$$N = \left(\frac{250}{100}\right)^2 (16) = 100 = 2n^{-1},$$
$$\log 100 = (n-1)\log 2,$$
$$2 = (n-1)(0.301),$$
$$n = 7.64.$$

Small Angle Grain Boundaries A *small angle grain boundary* is an array of dislocations that produces a small misorientation between the adjoining lattices (Figure 1.82 and 1.83). Because the energy of the surface is less than that at a regular grain boundary, the small angle grain boundaries are not as effective in blocking slip. Small angle boundaries formed by edge dislocations are called *tilt boundaries* and those caused by screw dislocations are called *twist boundaries.*

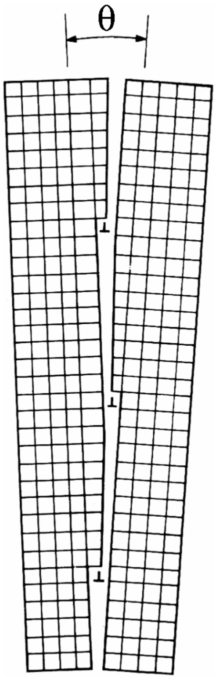


Figure 1.82 The small angle grain boundary is produced by an array of dislocations, causing an angular mismatch θ between the lattices on either side of the boundary

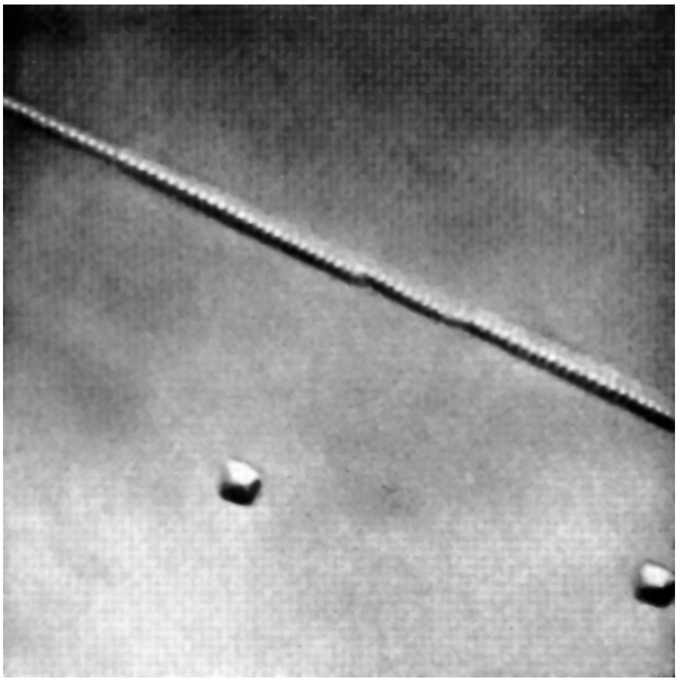


Figure 1.83 The small angle grain boundary in germanium

Example 1.37

Determine the angle θ across a small angle grain boundary in copper when the dislocations in the boundary are 1000 Å apart.

Answer

The grains are tilted one Burgers vector in each direction every 1000 Å. The Burgers vector in FCC copper is [110], so the length of the Burgers vector is the repeat distance in the [110] direction, or d_{110}:

$$d_{110} = \frac{a_0}{\sqrt{h^2 + k^2 + l^2}} = \frac{3.615}{\sqrt{2}} = 2.557 \text{ Å},$$

$$\sin\frac{\theta}{2}=\frac{2.557}{1000}=0.002557\,,$$
$$\theta=0.293^\circ\,.$$

Stacking Faults *Stacking faults* occur in FCC metals and represent an error in the stacking sequence of close-packed planes. Normally, a stacking sequence of *ABCABCABC* is produced in a perfect FCC lattice. But suppose the following sequence is produced:

$$ABC\underbrace{ABAB}CABC.$$

In the portion of the sequence indicated, a type *A* plane is shown where a type *C* plane would normally be located. This small region, which has an HCP stacking sequence instead of the FCC stacking sequence, represents a stacking fault. Stacking faults interfere with the slip process.

Twin Boundaries and Twinning A *twin boundary* is a plane across which there is a special mirror image misorientation of the lattice structure (Figure 1.84). Twins can be produced when a shear force, acting along the twin boundary, causes the atoms to shift out of position. Twinning occurs during deformation or heat treatment of certain metals. The twin boundaries interfere with the slip process and increase the strength of the metal. Movement of twin boundaries can also cause a metal to deform. Figure 1.84 shows that the formation of a twin has changed the shape of the metal.

The effectiveness of the surface defects in interfering with the slip process can be judged from the surface energies (Table 1.13). The high-energy grain boundaries are mucb more effective in blocking dislocations than either stacking faults or twin boundaries.

1.3.7 Methods of the Slip Process Controlling for Materials Strengthening

In a perfect crystal, the fixed, repeated arrangement of the atoms gives the lowest possible energy within the crystal. Any imperfection in the lattice raises the internal energy at the location of the imperfection. The local energy is increased because near the imperfection, the atoms either are squeezed too closely together (compression) or are forced too far apart (tension).

Strain Hardening Dislocations (l*inear defect*) *disrupt the perfection* of the lattice. In Figure 1.85, the atoms below the dislocation line at point *B* are compressed, while the atoms above dislocation *B* are too far apart. If dislocation *A* moves to the right and passes near dislocation *B,* dislocation *A* encounters a region where

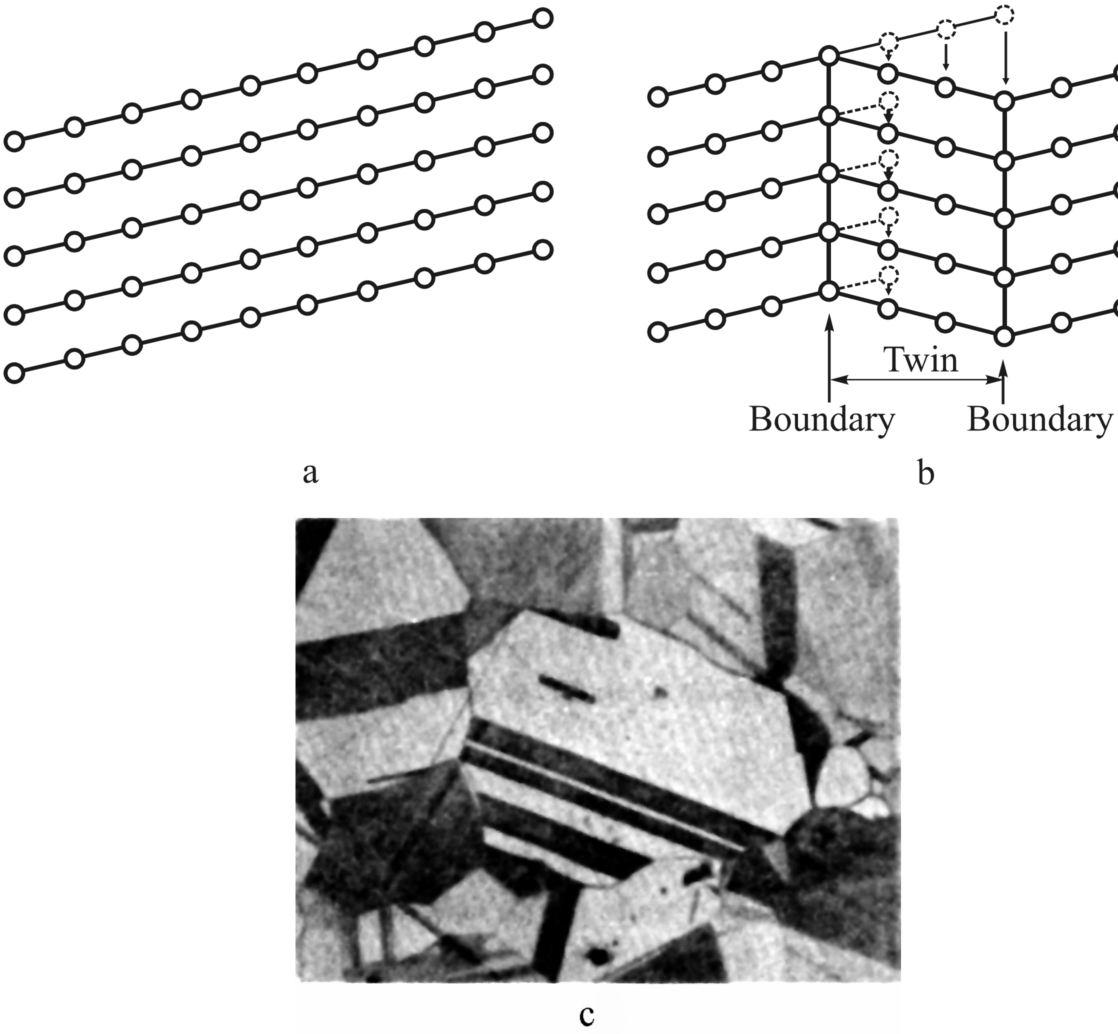


Figure 1.84 Application of a stress to the perfect crystal (a) may cause a displacement of the atoms (b), causing the formation of a twin. Note that the crystal has deformed as a result of twinning, (c) A photomicrograph of twins within a grain of brass (×250)

Table 1.13 Energies of surface imperfections in selected metals*

Energies of surface imperfections, J/m^2	Al	Cu	Pt	Fe
Stacking fault energy	0.2	0.075	0.095	–
Twin boundary energy	0.12	0.045	0.195	0.19
Grain boundary energy	0.625	0.645	1.0	0.78

*Stacking faults do not occur in BCC metals such as iron.

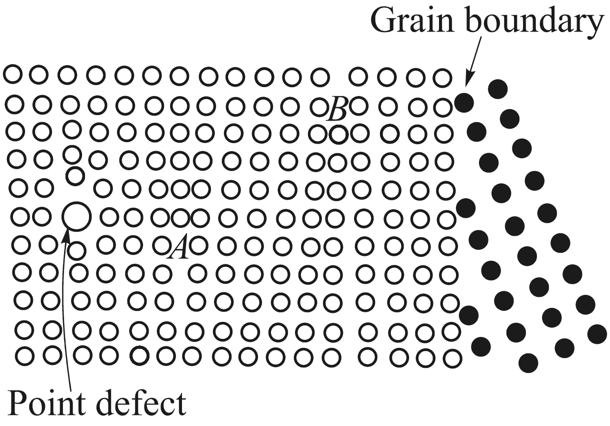


Figure 1.85 If the dislocation at point *A* moves to the left, it is blocked by the point defect. If the dislocation moves to the right, it interacts with the disturbed lattice near the second dislocation at point *B.* If the dislocation moves further to the right, it is blocked by a grain boundary

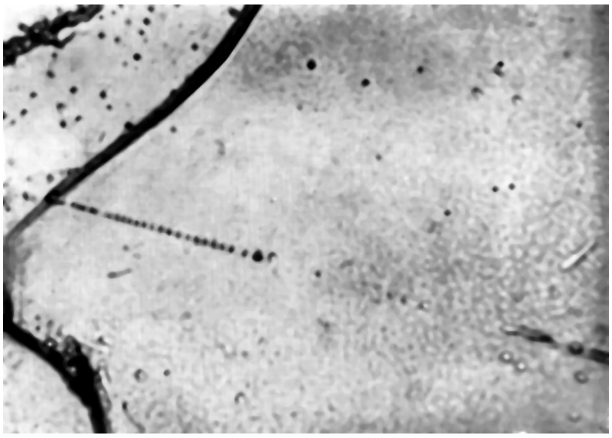


Figure 1.86 Dislocation pileups along the grain boundary in α–brass (×2000)

the atoms are not properly arranged. Higher stresses are required to keep the second dislocation moving; consequently, the metal must be stronger. The more dislocations that are present in the lattice, the more likely it is that any one dislocation will be blocked. Therefore, *increasing the number of dislocations increases the strength of the material*. This effect in called as *strain hardening.*

Solid Solution Strengthening Any of the *point defects* also *disrupt the perfection of the lattice*. If dislocation *A* moves to the left, it encounters a disturbed lattice caused by the point defect; higher stresses are needed to continue slip of the dislocation. By intentionally introducing substitutional or interstitial atoms, we can cause the material to become stronger by *solid solution strengthening.*

Grain Size Strengthening *Surface imperfections* such as grain boundaries *disturb the lattice too*. If dislocation *B* moves to the right, it encounters a grain boundary and is blocked. By increasing the number of grains, or reducing the grain size, *grain size strengthening* is achieved (Figure 1.86).

All these strengthening mechanisms are used for real strengthening of metals. If you want to strength the metal by solid solution strengthening you must add “impurity” atoms to a pure metal to make an alloy.

If the atoms of the alloying element are significantly larger than the atoms of the host metal, these large atoms can impede the motion of dislocations and thus strengthen the metal (Figure 1.87 (a)). Mechanical working strengthens metals by multiplication of dislocations. The dislocations interact with each other and with such the grain boundaries, and thus movement of individual dislocations becomes difficult and the metal is strengthened (Figure 1.87 (b)).

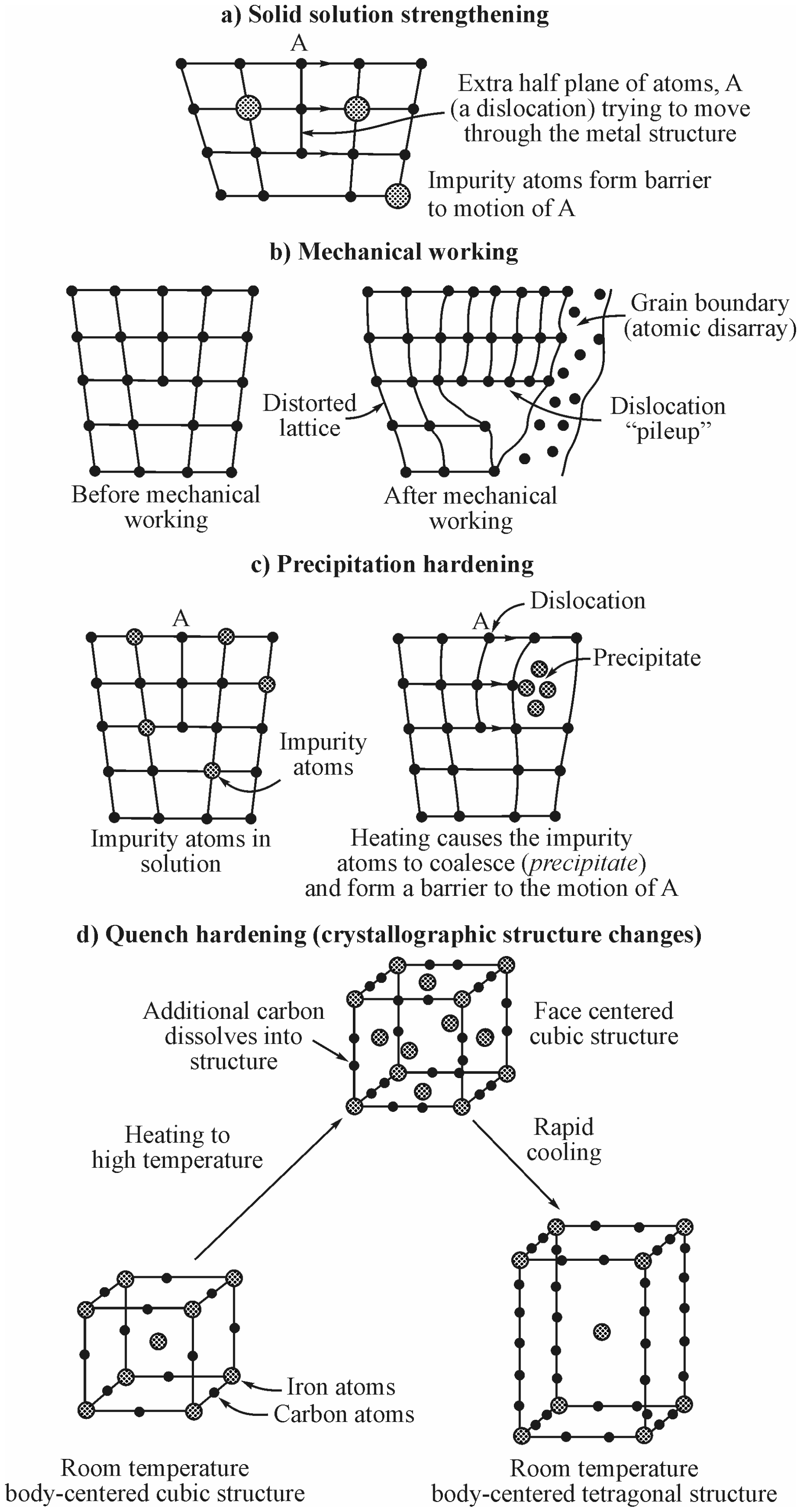


Figure 1.87 Strengthening mechanisms in metals

Precipitation hardening is used to strengthen many nonferrous metals. By choosing a suitable alloying element, it is possible by heat treating techniques to get alloying elements to agglomerate within the metal lattice. The agglomerated alloy element atoms create atomic mismatches and strains that serve as barriers to dislocation motion and thus strengthen the metal (Figure l.87 (c)). The final and most industrially important strengthening mechanism in metals is *quench hardening* (Figure 1.87 (d)). Quench hardening is a heat treating process used to induce atomic strains into a metal lattice. The strains are produced by quench induced *"trapping"* of solute atoms into the lattice. The trapped atoms actually change the atomic spacing. The distorted lattice and the action of the quenched-in solute atoms impedes dislocation motion and thus strengthens the metal.

We have found that the deformation of a metal can be explained in terms of the movement of certain lattice imperfections, namely dislocations, by a mechanism known as slip. The ease with which slip occurs depends first on the type of crystal structure and second on the number of other imperfections in the lattice. Based on this analysis, FCC metals should be ductile but weak, BCC metals should be strong with moderate ductility, and HCP metals should be relatively brittle with moderate strength. We can strengthen any of these structures by introducing larger numbers of lattice imperfections.

1.4 Atom Movement in Materials

Diffusion is the movement of atoms within a material. Atoms move:

- to eliminate concentration differences and produce a homogeneous, uniform composition;
- as the result of external forces application;
- after voltage application.

In fact, atoms even move about randomly in pure metals when no external forces are applied or no concentration differences exist.

Movement of atoms is required for many of the treatments *that we perform* on materials. Diffusion is required for the heat treatment of metals, the manufacture of ceramics, the solidification of materials, the manufacture of transistors and solar cells, and even the electrical conductivity of many ceramic materials.

We will focus our efforts on investigation of the diffusion of atoms in solid materials to examine the diffusion motive power and general laws.

1.4.1 Stability of Atoms and the Arrhenius Equation

We showed that imperfections could be introduced into the lattice of a crystal. However, these imperfections, and indeed even the normal atoms in their lattice positions, are not stable or at rest. Instead, the atoms possess some thermal energy, and there is the possibility that they may move. For instance, an atom may move from a normal lattice point to occupy a nearby vacancy. An atom may move from one interstitial site to another. Vacancies or interstitialcy atoms may be created. Atoms may jump across a grain boundary, permitting the grain boundary to move.

The ability of atoms and imperfections to move is related to the temperature, or thermal energy, possessed by the atoms. Both theory and experiment have shown that the rate of movement is related to temperature or thermal energy by the *Arrhenius* equation

$$\text{Rate} = c_0 \exp\left(-\frac{Q}{RT}\right) \tag{1.13}$$

where c_0 is a constant, R is the gas constant ($8.315\ \text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), T is the absolute temperature (K), and Q the *activation energy* (J/mol) required to cause the imperfection to move. This equation is derived from a statistical analysis of the probability that the atoms will have the extra energy Q needed to cause movement. The rate is related to the number of atoms that move.

We can rewrite the equation by taking natural logarithms of both sides:

$$\ln(\text{rate}) = \ln(c_0) - \frac{Q}{RT}. \tag{1.14}$$

By plotting ln(rate) of some reaction versus $1/T$ (Figure 1.88), the slope of the curve will be $-Q/R$, and consequently Q can be calculated. The constant c_0 is the intercept when $1/T$ is zero. One of the important application of the Arrhenius equation is the diffusion of atoms in a material. It is the general equation of diffusion.

Example 1.38

Suppose that interstitial atoms are found to move from one site to another at the rates of 5×10^8 jumps/s at 500° C and 8×10^{10} jumps/s at 800° C. Calculate the activation energy Q for the process.

Answer

Figure 1.88 represents the data on a $\ln(\text{rate})$ versus $1/T$ plot; the slope of this curve, as calculated in the figure, gives $Q/R = 14{,}000\ \text{K}$. As the result $Q = 114$ kJ/mol.

1.4.2 Diffusion Mechanisms

Even in absolutely pure solid materials, atoms move from one lattice position to another. This process, known as *self-diffusion*, can be detected by using radioactive tracers. Although self-diffusion occurs continually in all materials, the effect on the material's behavior is not significant.

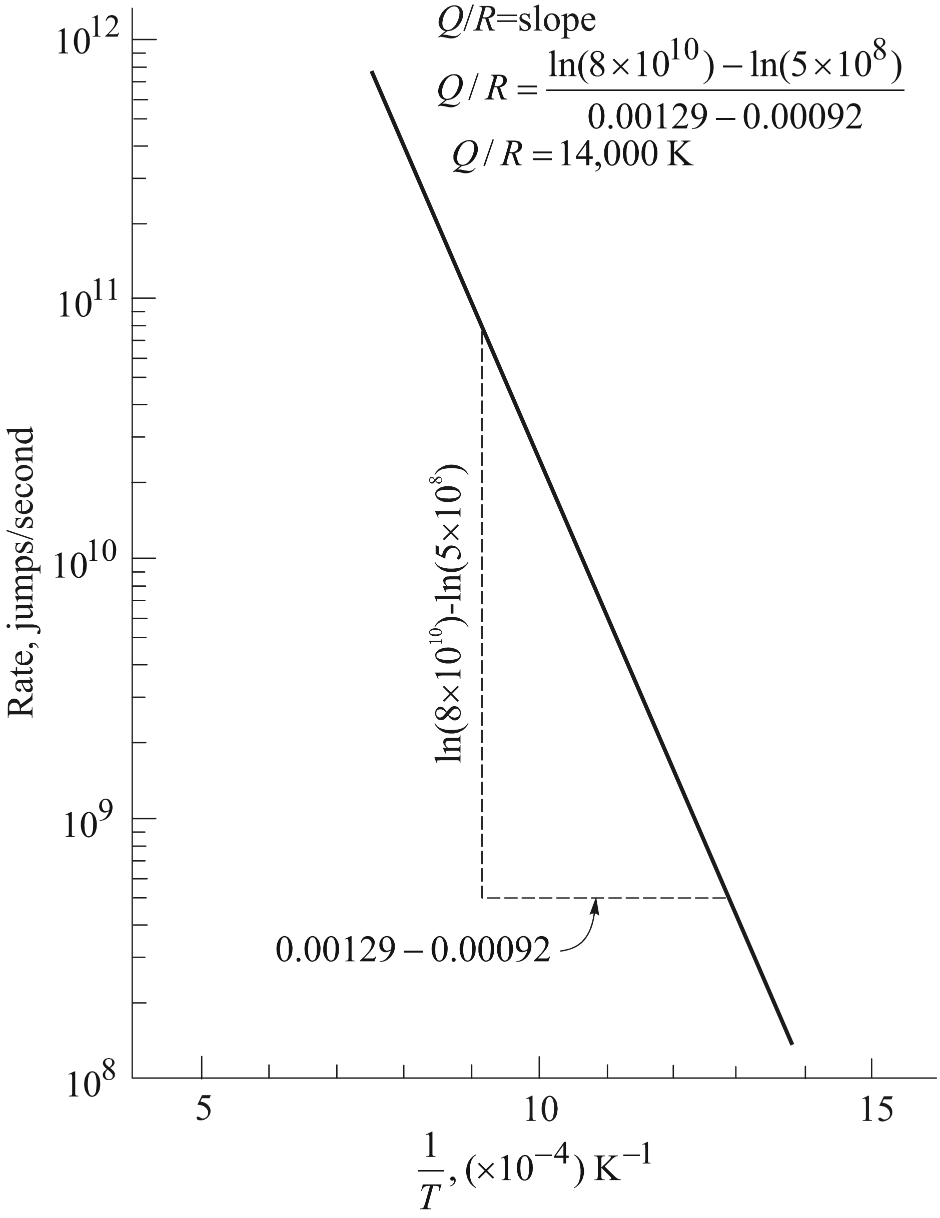


Figure 1.88 The Arrhenius plot of ln (rate) versus 1/*T* can be used to determine the activation energy required for a reaction

Diffusion of unlike atoms in materials also occurs. If a nickel sheet is bonded to a copper sheet, nickel atoms gradually diffuse into the copper and copper atoms migrate into the nickel. Again, the nickel and copper atoms eventually are uniformly distributed (Figure 1.89).

There are several mechanisms by which atoms diffuse (Figure 1.90).

Vacancy Diffusion In self-diffusion and diffusion involving substitutional atoms, an atom leaves its lattice site to fill a nearby vacancy (thus creating a new vacancy at the original lattice site). As diffusion continues, we have a counter-current flow of atoms and vacancies.

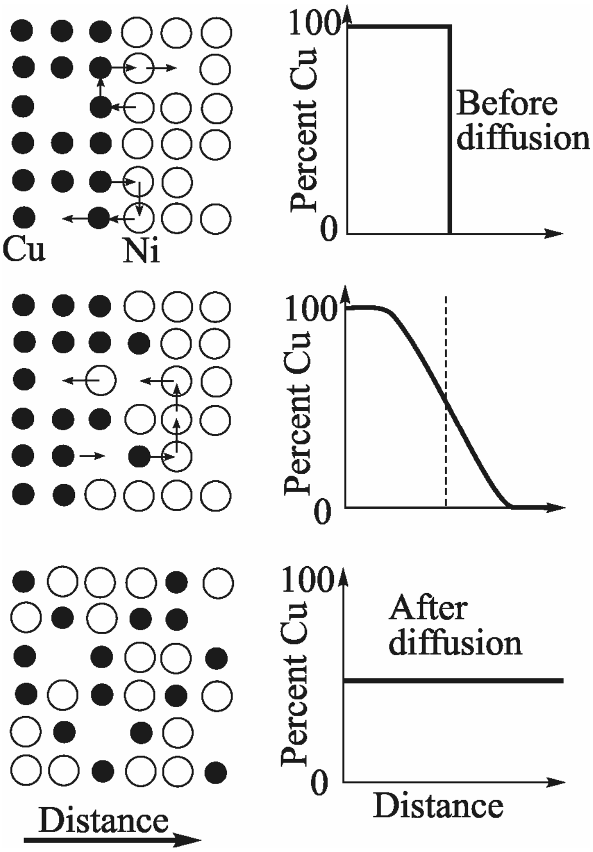


Figure 1.89 Diffusion of copper atoms into nickel. Eventually, the copper atoms are randomly distributed throughout the nickel

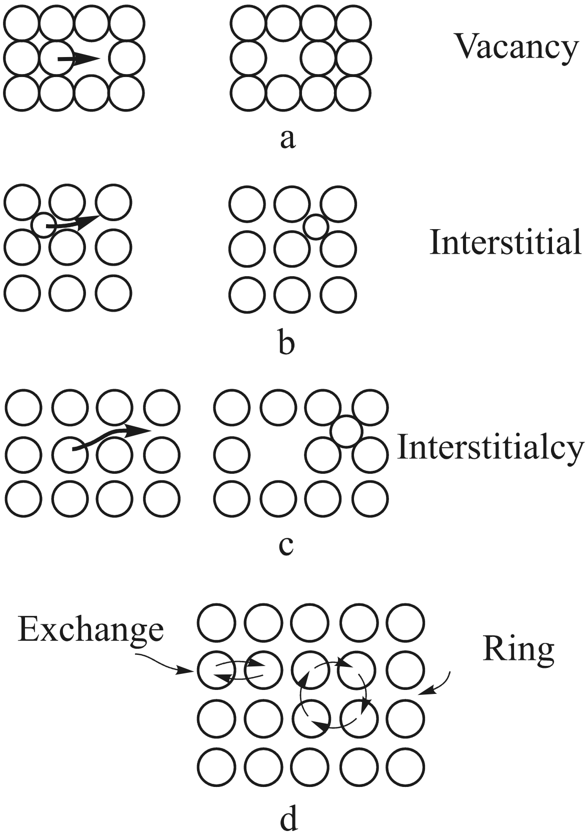


Figure 1.90 Diffusion mechanisms in materials: (a) vacancy or substitutional atom diffusion, (b) interstitial diffusion, (c) interstitialcy diffusion, and (d) exchange and ring diffusion

Interstitial Diffusion When a small interstitial atom is present in the crystal structure, the atom moves from one interstitial site to another. No vacancies are required for this mechanism to work.

Interstitialcy and Exchange Diffusion Sometimes a substitutional atom leaves its normal lattice site and enters an interstitial position. This *interstitialcy* diffusion mechanism is uncommon because the atom does not easily fit into the small interstitial site. Atoms also move by a simple *exchange* mechanism or by a *ring* mechanism. However, the vacancy and interstitial mechanisms appear to be responsible for diffusion in most cases.

1.4.3 Activation Energy for Diffusion

A diffusing atom must push apart the surrounding atoms to reach its new site. To do this, energy must be supplied to force the atom to its new position. This is shown schematically for vacancy and interstitial diffusion in Figure 1.91. The atom is originally in a low-energy, relatively stable location. In order to move to a new location, the atom must pass over an *energy barrier*. The energy barrier is the *activa-*

tion energy Q. Heat supplies the atom with the energy needed to exceed this barrier.

Normally less energy is required to squeeze an interstitial atom past the surrounding atoms; consequently, activation energies are lower for interstitial diffusion than for vacancy diffusion. Typical values for activation energies are shown in Table 1.14; a low activation energy indicates easy diffusion.

Table 1.14 Diffusion data for selected metals

Diffusion Couple	Q, cal/mol	Q, J/mol	$D_0 \times 10^{-4}$, m²/s
Interstitial diffusion			
C in FCC iron	32,900	138,180	0.23
C in BCC iron	20,900	87,780	0.011
N in FCC iron	34,600	145,320	0.0034
N in BCC iron	18,300	76,860	0.0047
H in FCC iron	10,300	43,260	0.0063
H in BCC iron	3,600	15,120	0.0012
Self-diffusion			
Au in Au	43,800	183,960	0.13
Al in Al	32,200	135,240	0.10
Ag in Ag	45,000	189,000	0.80
Cu in Cu	49,300	207,060	0.36
Fe in FCC iron	66,700	280,140	0.65
Pb in Pb	25,900	108,780	1.27
Pt in Pt	67,600	283,920	0.27
Mg in Mg	32,200	135,240	1.0
Zn in Zn	21,800	91,560	0.1
Ti in HCP Ti	22,900	96,180	0.4
Fe in BCC iron	58,900	247,380	4.1
Heterogeneous diffusion			
Ni in Cu	57,900	243,180	2.3
Cu in Ni	61,500	258,300	0.65
Zn in Cu	43,900	184,380	0.78
Ni in FCC iron	64,000	268,800	4.1
Au in Ag	45,500	191,100	0.26
Ag in Au	40,200	168,840	0.072
Al in Cu	39,500	165,900	0.045

1.4.4 Rate of Steady Diffusion (Fick's First Law)

The rate at which atoms diffuse in a material can be measured by the *diffusive flux J,* which is defined as the number of atoms passing through a plane of unit area per unit time (Figure 1.92). *Fick's first law* explains the net flux of atoms,

$$J = -D\frac{\Delta c}{\Delta x} \tag{1.15}$$

where J is the diffusive flux (atoms/m^2·s), D is the diffusivity or *diffusion coefficient* (m^2/s), and $D = D_0 \exp\left(-\frac{Q}{RT}\right)$ (see 1.15). $\Delta c / \Delta x$ is the *concentration gradient* (atoms/m^3·m). Several factors affect the flux of atoms during diffusion.

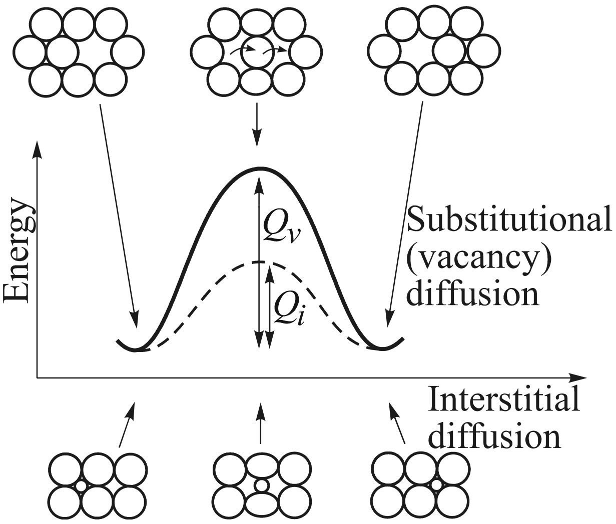


Figure 1.91 As atoms squeeze past one another during diffusion, a high energy is required. This energy is the activation energy Q. Generally more energy is required for a substitutional atom than for an interstitial atom

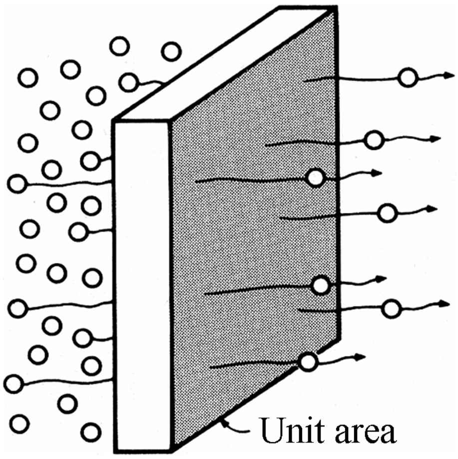


Figure 1.92 The flux during diffusion is defined as the number of atoms passing through a plane of unit area per unit time

Concentration Gradient The concentration gradient shows how the composition of the material varies with distance; Δc is the difference in concentration over the distance Δx (Figure 1.93). We should note that the flux is initially high when the concentration gradient is high and gradually decreases as the gradient is reduced.

Example 1.39

One way to manufacture transistors, which amplify electrical signals, is to diffuse impurity atoms into a semiconductor material such as silicon. Suppose a silicon wafer 0.001 m thick, which originally contains one phosphorus atom for every 10,000,000 Si atoms, is treated so that there are 400 P atoms for every 10,000,000 Si atoms at the surface. Calculate the concentration gradient (a) in atomic percent/m and (b) in atoms/m^3·m. The lattice parameter of silicon is 5.4307 Å.

Answer

First, let's calculate the initial and surface compositions in atomic percent:

$$c_i = \frac{1\text{ P atoms}}{10{,}000{,}000\text{ atoms}} \times 100 = 0.00001 \text{ at \% P},$$

$$c_s = \frac{400\text{ P atoms}}{10{,}000{,}000\text{ atoms}} \times 100 = 0.004 \text{ at \% P},$$

$$\frac{\Delta c}{\Delta x} = \frac{0.00001 - 0.004\text{ at \% P}}{0.001\text{ m}} = -3.99 \text{ at \% P/m}.$$

To find the gradient in terms of atoms/m^3·m, we must find the volume of the unit cell:

$$V_{cell} = (5.4307 \times 10^{-10})^3 = 1.6 \times 10^{-28} \text{ m}^3\text{/cell}.$$

The volume occupied by 10,000,000 Si atoms, which are arranged in a DC structure with 8 atoms/cell, is

$$V = \frac{10{,}000{,}000\text{ atoms}}{8\text{ atoms/cell}}(1.6 \times 10^{-28}\text{ m}^3\text{/cell}) = 2 \times 10^{-22}\text{ m}^3.$$

The compositions in atoms/m^3 are

$$c_i = \frac{1\text{ P atoms}}{2 \times 10^{-22}\text{ m}^3} = 0.005 \times 10^{24}\text{ P atoms/m}^3,$$

$$c_s = \frac{400\text{ P atoms}}{2 \times 10^{-22}\text{ m}^3} = 2 \times 10^{24}\text{ P atoms/m}^3,$$

$$\frac{\Delta c}{\Delta x} = \frac{0.005 \times 10^{24} - 2 \times 10^{24}\text{ P atoms/m}^3}{0.001\text{ m}} = -1.995 \times 10^{27}\text{ P atoms/m}^3 \cdot \text{m}.$$

Example 1.40

A thick-walled pipe 0.03 m in diameter contains a gas including 0.5×10^{26} N atoms per m^3 on one side of a 0.00001 m-thick iron membrane. The gas is continuously introduced to the pipe. The gas on the other side of the membrane contains 1×10^{24} N atoms per m^3. Calculate the total number of nitrogen atoms passing through the iron membrane at 700° C if the diffusion coefficient for nitrogen in iron is 4×10^{-11} m^2/s.

Answer

$$c_1 = 0.5 \times 10^{26}\text{ N atoms/m}^3 = 50 \times 10^{24}\text{ N atoms/m}^3,$$

$$c_2 = 1 \times 10^{24}\text{ N atoms/m}^3,$$

$$\Delta c = (1 - 50) \times 10^{24} = -49 \times 10^{24}\text{ N atoms/m}^3,$$

$$\Delta x = 0.00001 \text{ m}.$$

$$J = -D\frac{\Delta c}{\Delta x} = -\left(4\times10^{-11}\,\frac{\text{m}^2}{\text{s}}\right)\left(\frac{-49\times10^{24}\text{ N atoms/m}^3}{0.00001\,\text{m}}\right),$$

$$J = 1.96\times10^{20}\text{ N atoms/m}^2\cdot\text{s}.$$

$$\text{Total atoms/s} = JA = J\left(\frac{\pi}{4}d^2\right) = (1.96\times10^{20})\left(\frac{\pi}{4}\right)(0.03)^2 = 1.39\times10^{17}\text{ atoms/s}.$$

Obviously, if the gas on the high nitrogen side of the membrane were not continuously replenished, that side would soon be depleted of nitrogen atoms.

Temperature versus the Diffusion Coefficient The diffusion coefficient D is related to temperature by an Arrhenius equation

$$D = D_0 \exp\left(\frac{-Q}{RT}\right). \qquad (1.16)$$

where Q is the activation energy (J/mol), R is the gas constant ($8.315\ \text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), and T is the absolute temperature (K). D_0 is a constant for a given diffusion system. Typical values for D_0 are given in Table 1.14, while the temperature dependence of D is shown in Figure 1.94 for several materials.

When the temperature of a material increases, the diffusion coefficient and the flux of atoms increase as well. At higher temperatures, the thermal energy supplied to the diffusing atoms permits the atoms to overcome the activation energy barrier and more easily move to new lattice sites. At low temperatures, often below about 0.4 times the absolute melting temperature of the material, diffusion is very slow and may not be significant. For this reason, the heat treatment of metals and the processing of ceramics are done *at high temperatures*, where atoms move rapidly to complete reactions or to reach equilibrium conditions.

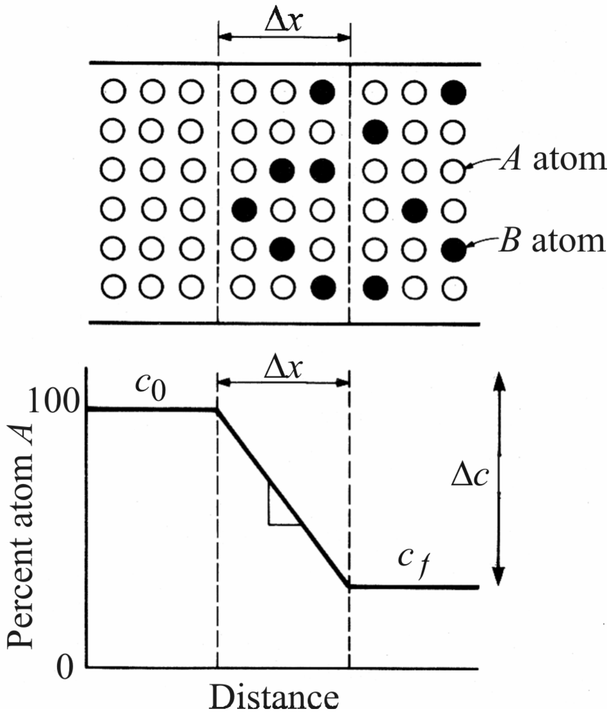


Figure 1.93 Illustration of the concentration gradient

Example 1.41

The diffusion coefficient for aluminum in copper is found to be $2.5\times10^{-24}\ \text{m}^2/\text{s}$ at 200° C and $3.1\times10^{-17}\ \text{m}^2/\text{s}$ at 500° C. Calculate the activation energy for the diffusion of aluminum in copper.

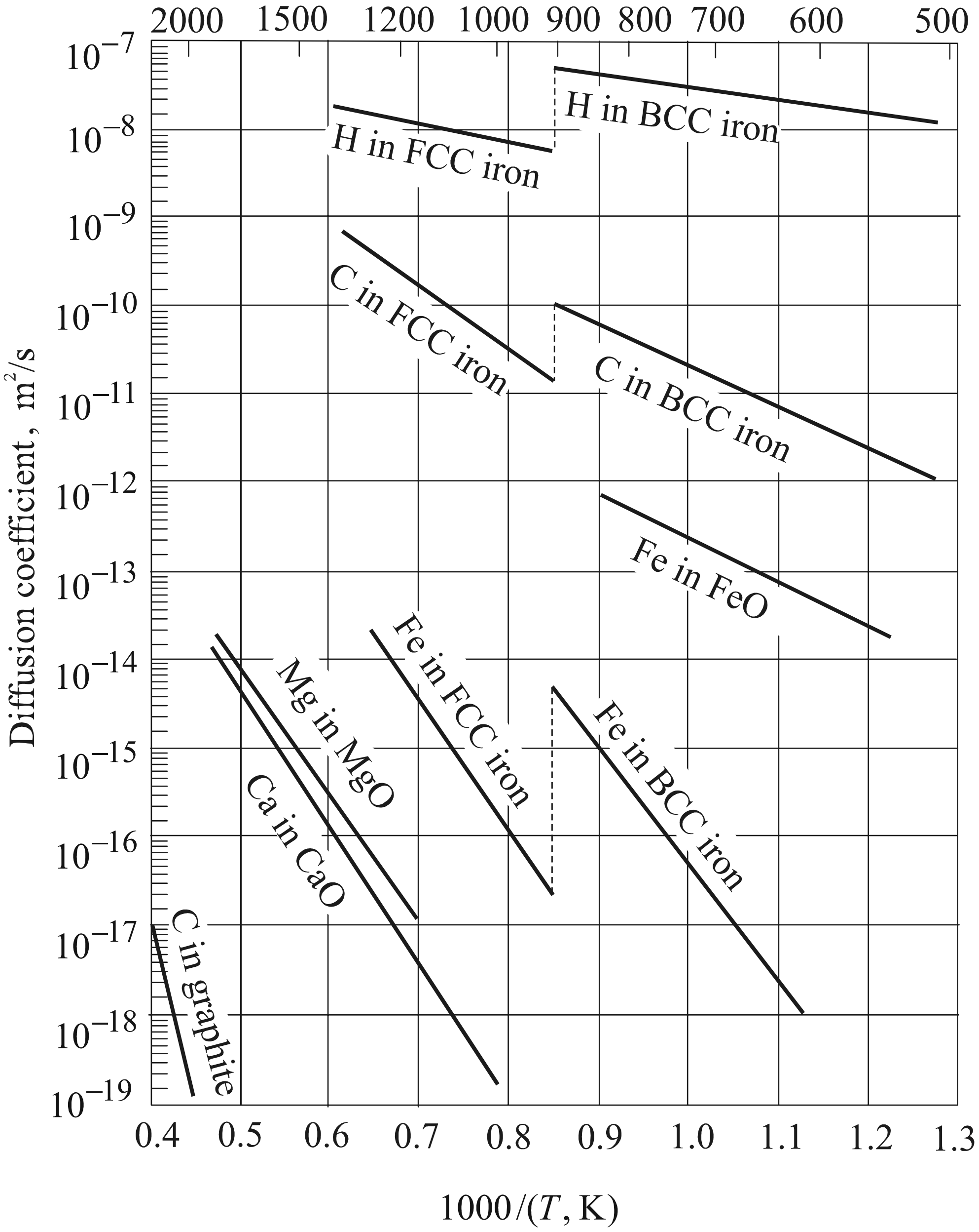


Figure 1.94 The diffusion coefficient *D* as a function of reciprocal temperature for several metals and ceramics. In this Arrhenius plot, *D* represents the rate of the diffusion process

Answer

Let's make a ratio between the diffusion coefficients at the two temperatures, 200° C=473 K and 500° C=773 K.

$$\frac{D_{773}}{D_{473}} = \frac{D_0 \exp\left(\frac{-Q}{(8.315)(773)}\right)}{D_0 \exp\left(\frac{-Q}{(8.315)(473)}\right)} = \frac{3.1\times 10^{-17}}{2.5\times 10^{-24}},$$

$$\exp\left[Q\left(\frac{-1}{773}-\frac{-1}{473}\right)\left(\frac{1}{987}\right)\right]=1.24\times10^{7},$$

$$\exp(0.0004129Q)=1.24\times10^{7},$$

$$0.0004129Q=\ln(1.24\times10^{7})=16.33,$$

$$Q=39{,}600\ \text{cal/mol} = 166{,}320\ \text{J/mol}.$$

Activation Energy and Diffusion Mechanism As you remember, a small activation energy Q increases the diffusion coefficient and flux, since less thermal energy is required to overcome the smaller activation energy barrier. Interstitial diffusion, with a low activation energy, usually occurs faster than vacancy, or substitutional, diffusion.

Activation energies are usually lower for atoms diffusing through open crystal structures compared with close-packed crystal structures. The activation energy for carbon diffusing in FCC iron is 138,180 J/mol, but is only 87,780 J/mol for carbon diffusing in BCC iron.

Activation energies are also lower for diffusion of atoms in materials with a low melting temperature (Figure 1.95) and are usually lower for small substitution atoms compared with larger atoms.

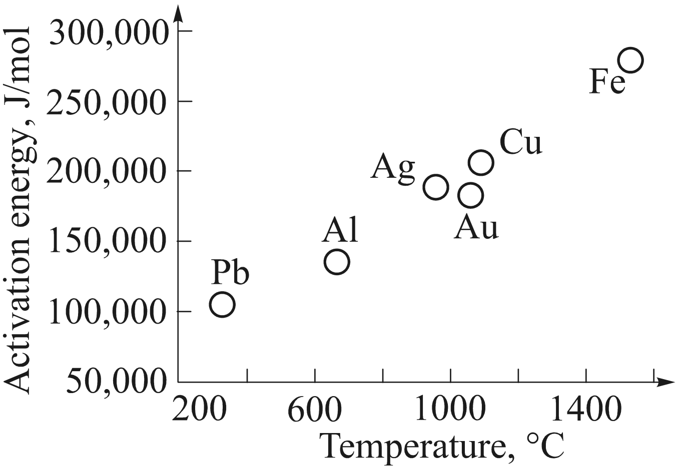


Figure 1.95 The activation energy for self-diffusion increases as the melting point of the metal increases

Example 1.42

Compare the diffusion coefficients for hydrogen and nickel in FCC iron at 1000°C and explain the difference.

Answer

From Table 1.14, at $T=1000°\text{ C}=1273\text{ K}$.

$$D_{\text{H}}=(0.0063\times10^{-4})\exp\left(\frac{-43{,}260}{RT}\right)=(0.0063\times10^{-4})\exp\left[\frac{-43{,}260}{(8.315)(1273)}\right]=$$

$$=(0.0063\times10^{-4})\exp(-4.07)=(0.0063\times10^{-4})(0.017)=1.07\times10^{-8}\ \text{m}^2/\text{s}.$$

$$D_{\mathrm{Ni}} = (4.1\times 10^{-4})\exp\left(\frac{-268{,}800}{RT}\right) = (4.1\times 10^{-4})\exp\left[\frac{-268{,}800}{(8.315)(1273)}\right] =$$

$$= (4.1\times 10^{-4})\exp(-25.3) = (4.1\times 10^{-4})(1.03\times 10^{-11}) = 4.2\times 10^{-15}\ \mathrm{m^2/s}.$$

Because hydrogen is a tiny interstitial atom and nickel is a larger substitutional atom, the activation energy for diffusion of hydrogen in iron is small and the rate of diffusion is seven orders of magnitude greater than that of nickel.

Example 1.43

Compare the diffusion coefficients of carbon in BCC and FCC iron at the allotropic transformation temperature of 910° C and explain the difference.

Answer

From Table 1.14, at $T = 910°\ \mathrm{C} = 1183\ \mathrm{K}$,

$$D_{\mathrm{C}}(\mathrm{BCC}) = (0.011\times 10^{-4})\exp\left[\frac{-87{,}780}{(8.315)(1183)}\right] = (0.011\times 10^{-4})\exp(-8.89) =$$

$$= (0.011\times 10^{-4})(1.38\times 10^{-4}) = 1.52\times 10^{-2}\ \mathrm{m^2/s}.$$

$$D_{\mathrm{C}}(\mathrm{BCC}) = (0.23\times 10^{-4})\exp\left[\frac{-138{,}180}{(8.315)(1183)}\right] = (0.23\times 10^{-4})\exp(-14.00) =$$

$$= (0.23\times 10^{-4})(8.31\times 10^{-7}) = 1.91\times 10^{-3}\ \mathrm{m^2/s}.$$

Diffusion is faster in the BCC iron than in the FCC iron, even at the same temperature, because the packing factor of BCC structures is less than that of FCC structures.

1.4.5 Time of Diffusion

It is evident, that the diffusion occurs in time because the unit for diffusive flux includes the time: it is atoms/m^2·s. If a large number of atoms must diffuse to produce a uniform structure, long times may be required, even at high temperatures. Times for heat treatments may be reduced by using higher temperatures or by making the *diffusion distances* (related to Δx) as small as possible.

The role of diffusion in materials using is not simple. We know, that some rather remarkable structures and properties are obtained if we prevent diffusion. Steels quenched rapidly from high temperatures to prevent diffusion form nonequilibrium structures which provide the basis for sophisticated heat treatments.

1.4.6 Types of Diffusion

In *volume* diffusion, the atoms move through the crystal from one lattice or interstitial site to another. Because of the surrounding atoms, the activation energy is large and the rate of diffusion is relatively slow.

However, atoms can also diffuse along boundaries, interfaces, and surfaces in the material. Atoms diffuse more easily by *grain boundary diffusion* because the atom packing is poor in the grain boundaries. Because atoms can more easily squeeze their way through the disordered grain boundary, the activation energy is low. *Surface diffusion* is still easier. Consequently, the activation energy is lower and the diffusion coefficient is higher for grain boundary and surface diffusion (Table 1.15).

Table 1.15 The effect of the type of diffusion for thorium in tungsten and for self-diffusion in silver

Diffusion Type	Diffusion Coefficient, 10^{-4} m^2/s	
	Thorium in Tungsten	Silver in Silver
Surface	0.47 exp (–278,880/*RT*)	0.068 exp (–37,380/*RT*)
Grain boundary	0.74 exp (–378,000/*RT*)	0.24 exp (–95,550/*RT*)
Volume	1.00 exp (–504,000/*RT*)	0.99 exp (–191,940/*RT*)

Example 1.44

Consider a diffusion couple set up between pure tungsten and a tungsten-1 at % thorium alloy. After several minutes of exposure at 2000° C, a transition zone of 0.0001 m thickness is established. What is the flux of thorium atoms at this time if diffusion is due to (a) volume diffusion, (b) grain boundary diffusion, and (c) surface diffusion?

Answer

The lattice parameter of BCC tungsten is about 3.165 Å. Thus, the number of tungsten atoms/m^3 is

$$\frac{\text{W atoms}}{\text{m}^3} = \frac{2\ \text{atoms/cell}}{(3.165\times10^{-10})^3\ \text{m}^3/\text{cell}} = 6.3\times10^{28}\,.$$

In the tungsten-1 at % thorium alloy, the number of thorium atoms is

$$c_{\text{Th}} = (0.0001)(6.3\times10^{28}) = 6.3\times10^{26}\ \text{Th atoms/m}^3\,.$$

In the pure tungsten, the number of thorium atoms is zero. Thus, the concentration gradient is

$$\frac{\Delta c}{\Delta x}=\frac{0-6.3\times10^{26}}{0.0001\,\mathrm{m}}=-6.3\times10^{30}\ \text{Th atoms/m}^3\cdot\mathrm{m}.$$

a) Volume diffusion

$$D=1.0\times10^{-4}\exp\left(\frac{-504{,}000}{(2273)(8.315)}\right)=2.89\times10^{-16}\ \mathrm{m^2/s}.$$

$$J=-D\frac{\Delta c}{\Delta x}=-(2.89\times10^{-16})(-6.3\times10^{30})=18.2\times10^{14}\ \text{Th atoms/m}^2\cdot\mathrm{s}.$$

b) Grain boundary diffusion

$$D=0.74\times10^{-4}\exp\left(\frac{-378{,}000}{(2273)(8.315)}\right)=1.64\times10^{-13}\ \mathrm{m^2/s}.$$

$$J=-(1.64\times10^{-13})(-6.3\times10^{30})=10.3\times10^{17}\ \text{Th atoms/m}^2\cdot\mathrm{s}.$$

c) Surface diffusion

$$D=0.47\times10^{-4}\exp\left(\frac{-278{,}880}{(2273)(8{,}315)}\right)=1.9\times10^{-11}\ \mathrm{m^2/s}.$$

$$J=-(1.9\times10^{-11})(-6.3\times10^{30})=12\times10^{19}\ \text{Th atoms/m}^2\cdot\mathrm{s}.$$

1.4.7 Fick's Second Law and Nonsteady Diffusion

Fick's second law, which describes the dynamic, or nonsteady state, diffusion of atoms, is the differential equation $dc/dt=D(d^2c/dx^2)$, whose solution depends on the boundary conditions for a particular situation. One solution is

$$\frac{c_s-c_x}{c_s-c_0}=erf\left(\frac{x}{2\sqrt{Dt}}\right) \qquad (1.17)$$

where c_s is a constant concentration of the diffusing atoms at the surface of the material, c_0 is the initial uniform concentration of the diffusing atoms in the material, and c_x is the concentration of the diffusing atom at location x below the surface after time t. These concentrations are illustrated in Figure 1.96. The function erf is the *error function* and can be evaluated from Figure 1.97.

The solution to Fick's second law permits us to calculate the concentration of one diffusing species near the surface of the material *as a function of time and distance*, provided that the diffusion coefficient D remains constant and the concentrations of the diffusing atom at the surface c_s and within the material c_0 remain unchanged.

Example 1.45

The surface of a 0.1 % C steel is to be strengthened by carburizing. In carburizing, the steel is placed in an atmosphere that provides a maximum of 1.2% C at the surface of the steel at a high temperature. Carbon then diffuses into the surface of the steel. For optimum properties, the steel must contain 0.45% C at a depth of 0.002 m below the surface. How long will carburizing take if the diffusion coefficient is 2×10^{-11} m^2/s?

Answer

From the problem,

$c_s = 1.2\,\%\,\text{C}, \quad c_0 = 0.1\%\,\text{C},$

$c_x = 0.45\,\%\,\text{C}, \quad x = 0.002\ \text{m}.$

From Fick's second law,

$$\frac{c_0 - c_x}{c_s - c_x} = \frac{1.2 - 0.45}{1.2 - 0.1} = 0.68 =$$

$$= \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right) = \operatorname{erf}\left(\frac{0.002}{2\sqrt{(2\times10^{-11})t}}\right).$$

$$0.68 = \operatorname{erf}\left(\frac{224}{\sqrt{t}}\right).$$

From Figure 1.97, we find that

$$\frac{224}{\sqrt{t}} = 0.71,$$

$$t = \left(\frac{224}{0.71}\right)^2 = 99{,}536\ \text{s} = 27.6\ \text{h}.$$

One of the consequences of Fick's second law is that the same concentration profile can be obtained for different conditions, so long as the term *Dt* is constant. This permits us to determine the effect of temperature on the time required for a particular heat treatment to be accomplished.

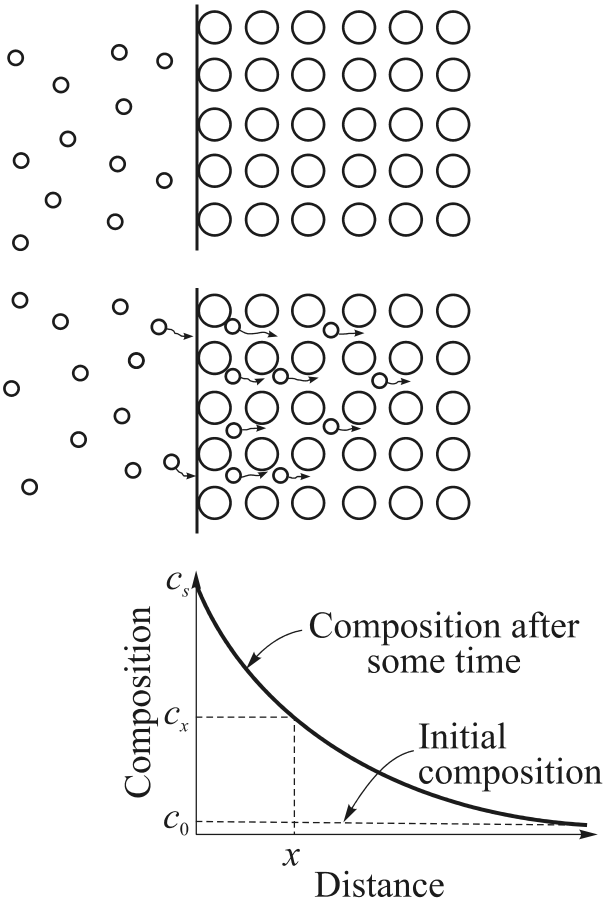


Figure 1.96 Illustration of the concentration gradient

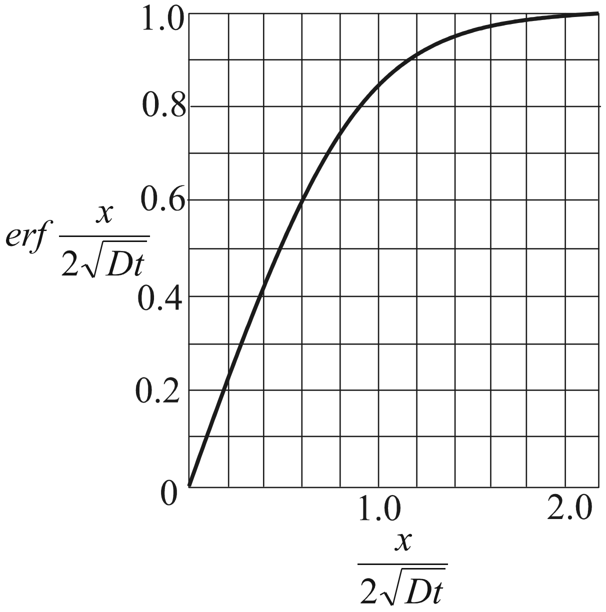


Figure 1.97 The error function

Example 1.46

We find that 10 h are required to cause carbon to diffuse 0.001 m into the surface of a steel gear at 800° C. What time is required to achieve the same carbon depth at 900° C? The activation energy for the diffusion of carbon atoms in FCC iron is 138,180 J/mol.

Answer

The temperatures are 800 + 273 = 1073 K and 900 + 273 = 1173 K. Since we want the carbon profile to remain the same at both temperatures

$$D_{1073}t_{1073} = D_{1173}t_{1173},$$

$$t_{1173} = \frac{D_{1073}t_{1073}}{D_{1173}} = t_{1073}\frac{\exp(-Q/1073R)}{\exp(-Q/1173R)},$$

$$t_{1173} = (10h)\frac{\exp(-138{,}180/(1073)(8.315))}{\exp(-138{,}180/(1173)(8.315))} = 10\exp(-1.315) = (10)(0.268) = 2.68 \text{ h}.$$

1.4.8 Kirkendall's Effect

Equation 1.17 of nonsteady diffusion is true in the case of a constant composition c_0 at the interface; this is the case in a process such as carburizing of steel (Example 1.45), in which carbon is continuously supplied to the steel surface. In many another cases, however, the surface concentration gradually changes during the process. In these cases, *interdiffusion* of atoms occurs (see Figure 1.89), and Equation 1.17 is no longer valid.

Sometimes interdiffusion can cause difficulties. For example, when aluminum is bonded to gold at an elevated temperature, the aluminum atoms will diffuse faster into the gold than gold atoms diffuse into the aluminum. Consequently, more total atoms will eventually be on the original gold side of the interface than on the original aluminum side. This causes the physical location of the original interface to move towards the aluminum side of the diffusion couple. Any foreign particles originally trapped at the interface also move with the interface. This movement of the interface due to unequal diffusion rates is called the *Kirkendall's effect.*

In certain cases, voids form at the interface as a result of the Kirkendall's effect. In tiny integrated circuits, gold wire is welded to aluminum to provide an external lead for the circuit. During operation of the circuit, voids may form by coalescence of vacancies involved in the diffusion process; as the voids grow, the Au-Al connection is weakened and eventually may fail. Because the area around the connection discolors, this premature failure is called *the purple plague.* One technique to prevent this problem is to expose the welded joint to hydrogen. The hydrogen dissolves in the aluminum, fills the vacancies, and prevents self-diffusion of the aluminum atoms. This keeps the aluminum atoms from diffusing into the gold and embrittling the weld.

1.4.9 Diffusion in Ionic Compounds and Polymers

In metals and alloys, atoms can move into any nearby vacancy or interstitial site. But in other materials, atom movement is more restricted.

In ionic materials, such as many ceramics, a diffusing ion only enters a site having the same charge. In order to reach that site, the ion must physically squeeze past adjoining ions, pass by a region of opposite charge, and move a relatively long distance (Figure 1.98). Consequently, the activation energies are high and the rates of diffusion are lower for ionic materials than for metals (see Figure 1.94).

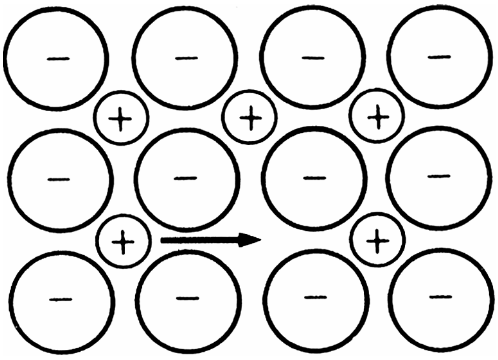


Figure 1.98 Diffusion in ionic compounds. Anions can only enter other anion site

We also find that cations (with a positive charge) often have higher diffusion coefficients than anions (with a negative charge). The cations, because they have given up their valence electrons, typically have a smaller size and thus can diffuse more easily than the larger anions. In sodium chloride, for instance, the activation energy for diffusion of chloride ions is about twice that for diffusion of sodium ions.

Diffusion of the ions also provides a transfer of electrical charge; in fact, the electrical conductivity of ionically bonded ceramic materials is related to temperature by an Arrhenius equation. As the temperature increases, the ions diffuse more rapidly, electrical charge is transferred more quickly, and the electrical conductivity is increased.

In polymers, diffusion of atoms can occur from one location to another *along* a long polymer chain; however, strong covalent bonds must be broken for this to occur.

More often, we are concerned with the diffusion of atoms or small molecules *between* the long polymer chains. For example, polymer films are typically used as packaging to store food. If air diffuses through the film, the food may spoil. If air diffuses through the rubber inner tube of an automobile tire, the tire will deflate. Diffusion of some molecules into a polymer can cause swelling problems. On the other hand, diffusion is required to enable dyes to uniformly penetrate into many of the synthetic polymer fabrics. Selective diffusion through polymer membranes is used to cause *desalinization* of water; while water molecules pass through the polymer membrane, the ions in the salt are trapped.

In each of these examples, the diffusing atoms, ions, or molecules penetrate between the polymer chains rather than moving from one location to another within the chain structure. Diffusion will be more rapid through this structure when the diffusing atom or ion is smaller or when larger voids are present between the chains.

Diffusion through crystalline polymers, for instance, is slower than through amorphous polymers, which have no long-range order and consequently have a lower density.

1.4.10 Importance of a Diffusion in Materials Processing and Properties Changes

Diffusional processes become very important when materials are used or processed at elevated temperatures. In this section, three cases in which diffusion is important will be considered.

Grain Growth A material composed of many grains contains a large number of grain boundaries, which represent a high-energy area because of the inefficient packing of the atoms. A lower overall energy is obtained in the material if the amount of grain boundary area is reduced by grain growth.

Grain growth involves the movement of grain boundaries, permitting some grains to grow at the expense of others. Diffusion of atoms across the grain boundary (Figure 1.99) is required for grain growth to occur. Consequently, the growth of the grain boundaries is related to the activation energy for an atom to jump across the boundary. High temperatures or low activation energies increase the size of the grains. Many heat treatments of metals, which include holding the metal at high temperatures, must be carefully controlled to avoid excessive grain growth.

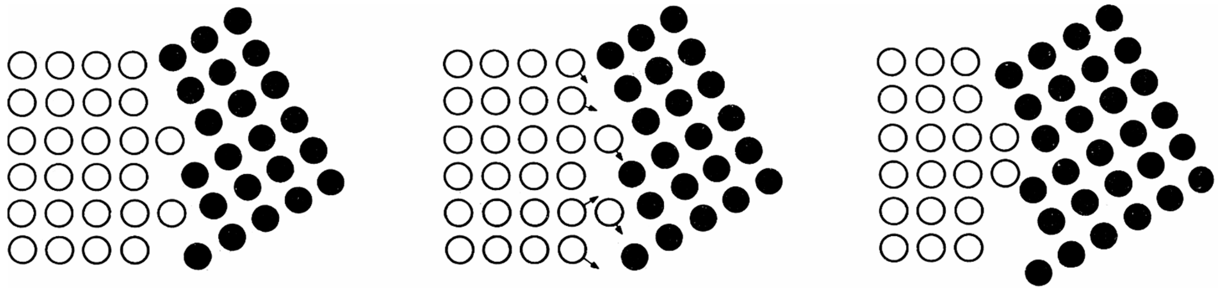


Figure 1.99 Grain growth occurs as atoms diffuse across the grain boundary from one grain to another

We can impede grain growth by introducing obstacles at the grain boundaries that provide a “drag” force which prevents the grains from enlarging. We can introduce these particles in a variety of ways to control grain growth during high-temperature use and processing of many materials.

Diffusion Bonding *Diffusion bonding,* a method used to join materials, occurs in three steps (Figure 1.100). The first step forces the two surfaces together at a high pressure, flattening the surface, fragmenting impurities, and producing a high atom-to-atom contact area. Atomic bonding across the interface establishes a joint. Normally, the pressure is applied at high temperatures at which the material is softer and more ductile.

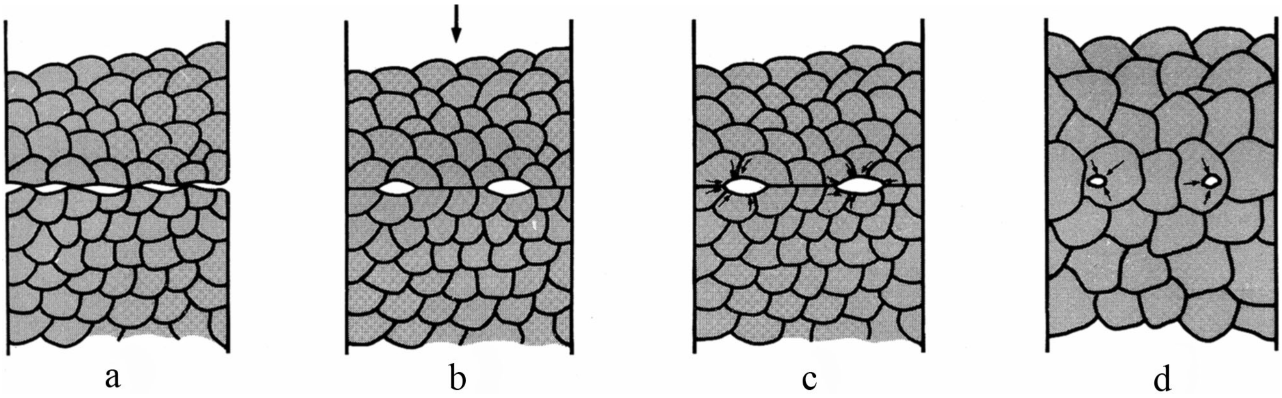


Figure 1.100 The steps in diffusion bonding. (a) Initially the contact area is small, (b) application of pressure deforms the surface, increasing the bonded area, (c) grain boundary diffusion permits voids to shrink, and (d) final elimination of the voids requires volume diffusion

As the surfaces remain pressed together at high temperatures, atoms diffuse along grain boundaries to the remaining voids; the atoms condense and reduce the size of any voids in the interface. Because grain boundary diffusion is rapid, this second step may occur rapidly. Eventually, however, grain growth isolates remaining voids from the grain boundaries. For the third step – final elimination of the voids – volume diffusion, which is comparatively slow, must occur.

The diffusion bonding process is often used with some of the more exotic alloys, such as titanium, for joining dissimilar metals and materials, and even for joining ceramics.

Sintering A number of materials are manufactured into useful shapes by a process that requires consolidation of small particles into a solid mass. *Sintering* is the high-temperature treatment that causes the particles to join together and gradually reduces the volume of pore space between them. Sintering is a frequent step in the manufacture of ceramic components as well as in the production of metallic parts by powder metallurgy. A variety of composite materials are produced using the same techniques.

When a powdered material is compacted into a shape, the powder particles are in contact with one another at numerous sites, with a significant amount of pore space between the particles. In order to reduce the boundary energy, atoms diffuse to the boundaries, permitting the particles to be bonded together and eventually causing the pores to shrink. If sintering is carried out for a long time, the pores may be eliminated and the material becomes dense.

Surfaces that have a small radius of curvature grow rapidly. The points of contact have the smallest radius and thus grow first. Atoms diffuse to these points, while vacancies diffuse away from the interface. The net movement of vacancies permits the particles to move closer together (Figure 1.101), causing the pore size to decrease

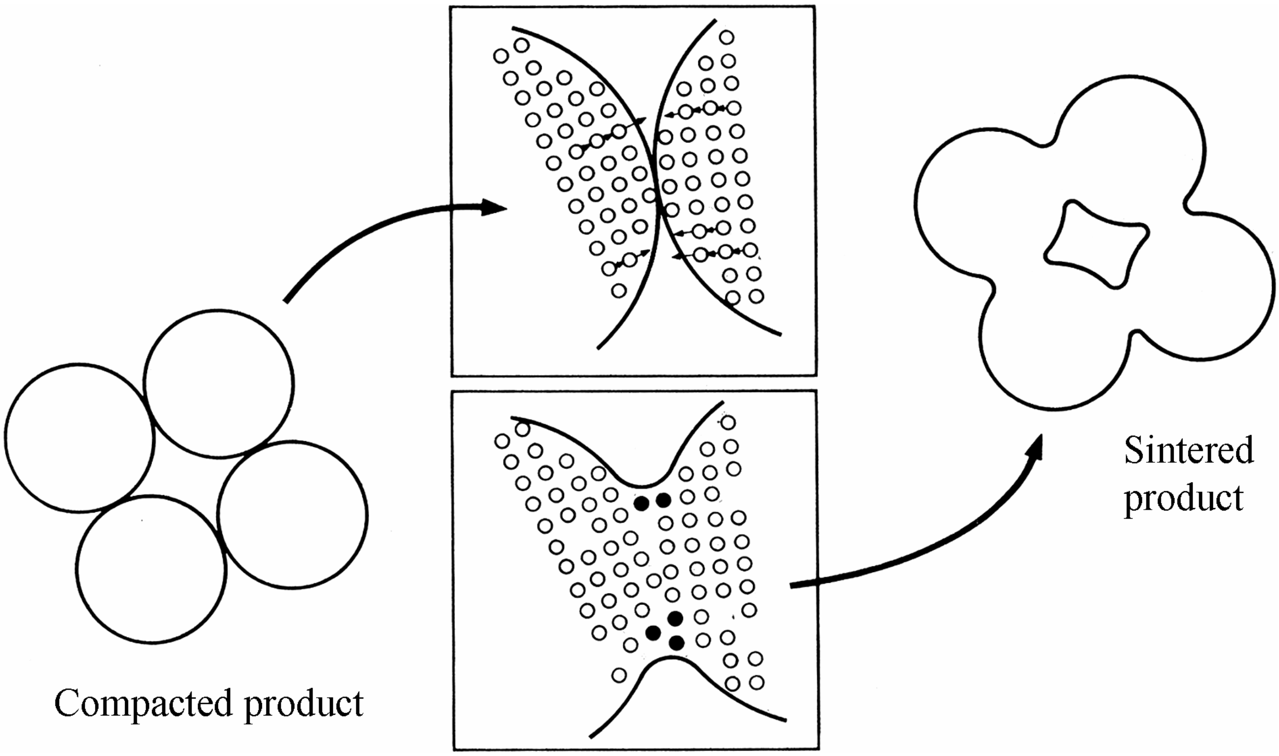


Figure 1.101 Diffusion processes during sintering and powder metallurgy. Atoms diffuse to points of contact, creating bridges, and eventually filling the pores

and the density to increase. The rate of sintering depends on the temperature, the activation energy and diffusion coefficient for diffusion, and the original size of the particles.

As the result of our discussion please remember that atoms move through a solid material by diffusion mechanisms. Atom diffusion is of paramount importance for us, because many of the materials processing techniques, such as sintering, powder metallurgy, and diffusion bonding, require diffusion. Furthermore, many of the heat treatments and strengthening mechanisms used to control structures and properties in materials are diffusion-controlled processes. The stability of the structure and the properties of materials in high temperature use depend on diffusion. Finally, many important materials are produced by deliberately prevented diffusion, thereby forming nonequilibrium structures.

1.5 Materials Failure

Materials failures are not only the result of exceeded external forces application. The sources of these failures include improper design, materials selection, and materials processing and abuse. The engineer must anticipate potential failures and consequently exercise good design, materials and processing selection, quality control, and testing to prevent failures. When failures do occur, the engineer must determine the cause so that failures can be prevented in the future.

We will discuss a few general principles of materials failure. First, we will investigate the fracture mechanism by which failure occurs. Then we will discuss some considerations that may help us prevent failures, in particular nondestructive testing techniques.

1.5.1 Fracture Mechanism in Metal Failures

The failure analysis requires a combination of technical understanding, careful observation, detection work, and common sense. Knowledge of the history of failed component, including applied stress, environment, temperature, intended structure and properties, and unusual changes in any of these factors, helps us to make the identification of the cause of failure much easier.

The understanding of fracture mechanisms is the first step to the cause of failure. We will concentrate on identifying the mechanism by which a metal fails when subjected to a stress as a result of external mechanical loading. We will consider five common fracture mechanisms – *ductile*, *brittle*, *fatigue*, *creep*, and *stress corrosion*.

Ductile Fracture Ductile fracture normally occurs in a *transgranular* manner (through the grains) in metals that have good ductility and toughness. Often a considerable amount of deformation, including necking, is observed in the failed component. The deformation occurs before the final fracture. Ductile fractures are usually due to simple overloads, i.e. applying too high stress to the material.

Ductile fracture in a simple tensile tested specimen begins by the nucleation, growth, and coalescence of microvoids at the center of the test specimen (Figure 1.102). *Microvoids* are formed when a high internal stress causes separation of metal at boundaries or interfaces between the metal and inclusions. As the local stress continues to increase, the *microvoids grow*, *connect*, and *produce larger cavities*. Eventually, the metal-to-metal contact area is too small to support the load and final fracture occurs.

Deformation by slip also contributes to the ductile fracture of a metal. We know that slip occurs when the resolved shear stress reaches the critical resolved shear stress and that the resolved shear stresses are highest at a 45° angle to the applied tensile stress (Schmid's law).

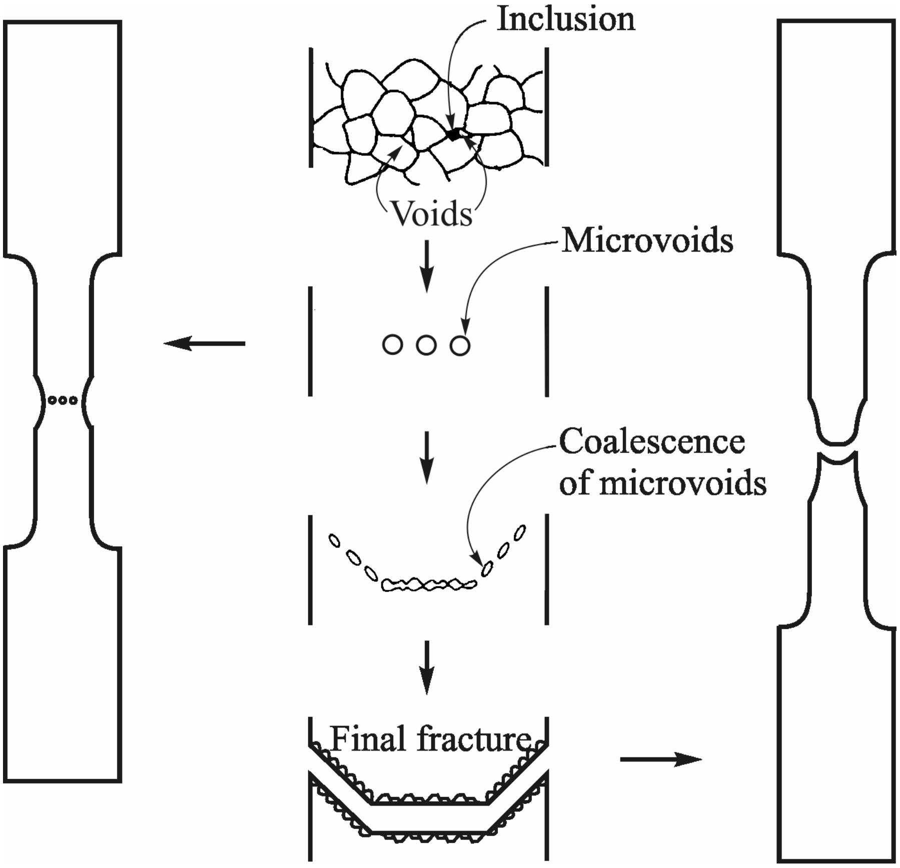


Figure 1.102 Ductile material specimen tension. First of all necking begins and voids form, starting near the center of the specimen by nucleation at grain boundaries or inclusions. As deformation continues, a 45° shear lip may form, producing a final cup and cone fracture

These two aspects of ductile fracture give the failed surface characteristic features that help us to determine whether a metal has failed by ductile fracture. In thick metal sections, we expect to find evidence of necking, with a significant portion of the fracture surface having a flat face where microvoids first nucleated and coalesced, and a small *shear lip* where the fracture surface is at a 45° angle to the applied stress. The shear lip, indicating that slip occurred, causes the fracture a cup and cone appearance (Figure 1.103). Simple macroscopic observation of this fracture may be sufficient to identify the ductile fracture mode.

Examination of the fracture surface at a high magnification, perhaps using a scanning electron microscope, reveals a dimpled surface (Figure 1.104). The dimples are traces of the microvoids produced during fracture. Normally, these microvoids are round, or equiaxed, when

Figure 1.103 The cup and cone fracture observed when a ductile material, in this case an annealed 1018 steel, fractures in a tensile test. The original diameter of the test bar was 12.8 mm

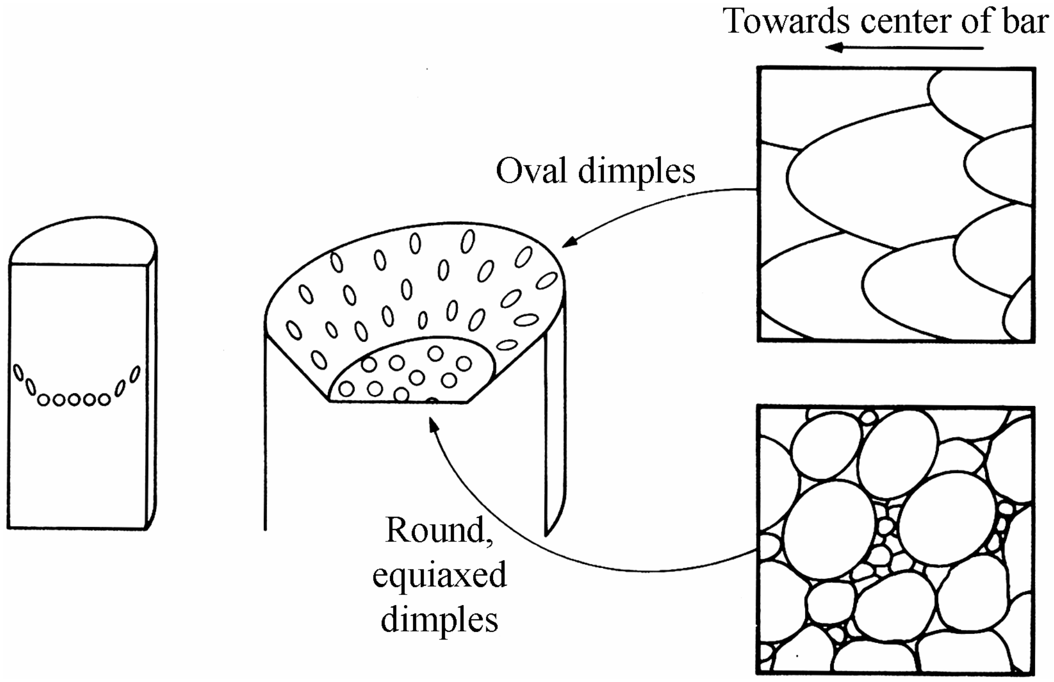


Figure 1.104 Dimples form during ductile fracture. Equiaxed dimples form in the center where microvoids grow. Elongated dimples, pointing towards the origin of failure, form on the shear lip

a normal tensile stress produces the failure (Figure 1.105 (a)). However, on the shear lip, the dimples are oval shaped, or elongated, with the ovals pointing towards the center of the tensile bar where fracture began (Figure 1.105 (b)).

In thin plate, less necking is observed and the entire fracture surface may be a shear face (Figure 1.106). Microscopic examination of the fracture surface shows elongated dimples rather than equiaxed dimples, indicating a greater proportion of 45° slip than in the thicker metals.

Example 1.47

A chain used to stand heavy loads fails. Examination of the failed link indicates considerable deformation and necking prior to failure. List some of the possible reasons for failure.

Answer

This description suggests that the chain failed in a ductile manner by a simple tensile overload. Two factors could be responsible for this failure.

1. The load exceeded the *load carrying capacity* of the chain. Thus, the stress due to the load exceeded the yield strength of the chain, permitting failure. Comparison of the load to the manufacturer's specifications will indicate that the chain was not intended for such a heavy load. This is the fault of the user.

2. The chain was of the wrong composition or was improperly heat treated. Consequently, the yield strength was lower than intended by the manufacturer and

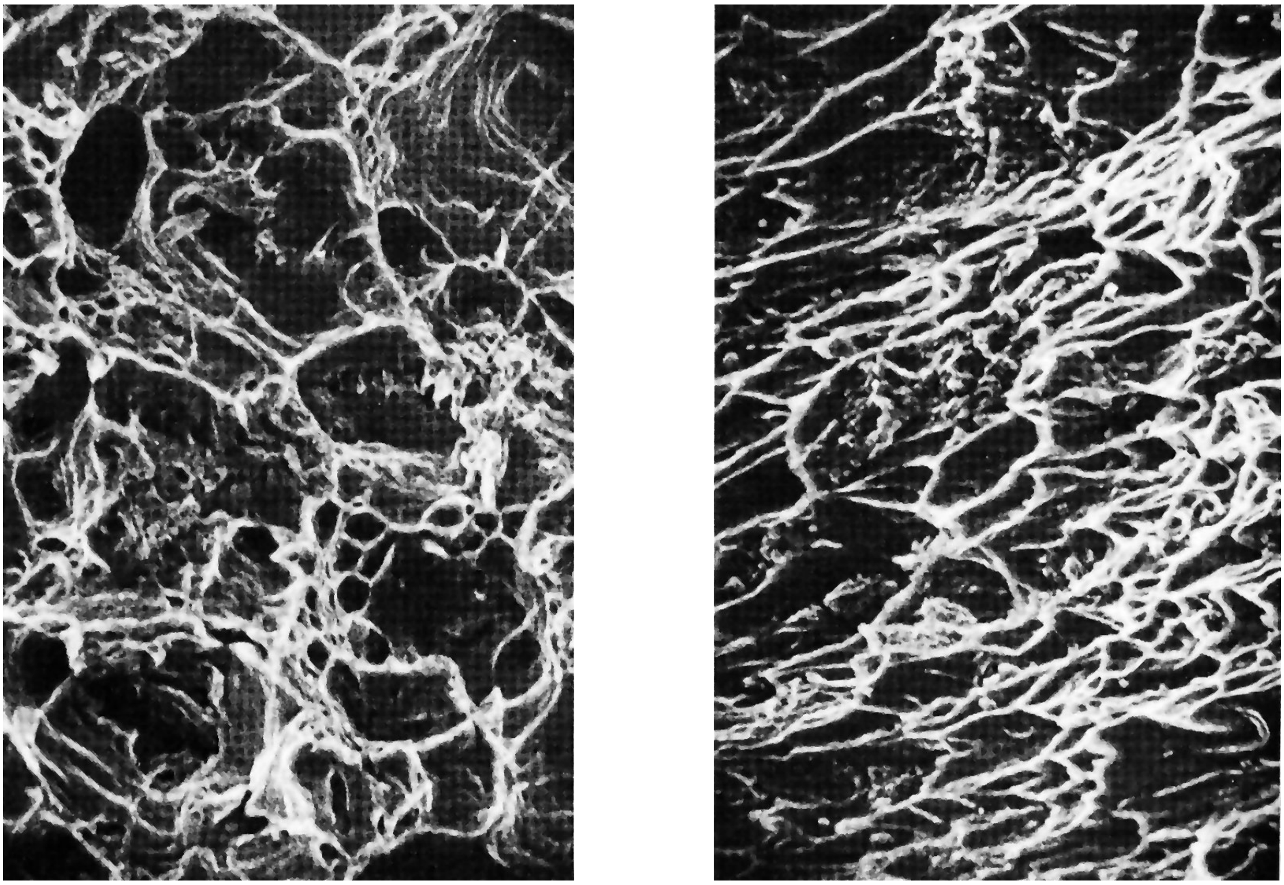

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Figure 1.105 Scanning electron micrographs of an annealed 1018 steel exhibiting ductile fracture in a tensile test. (a) Equiaxed dimples at the flat center of the cup and cone, and (b) elongated dimples at the shear lip (×1250)

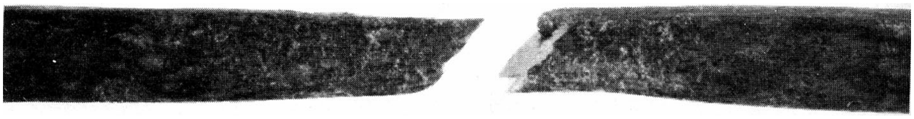

Figure 1.106 Ductile fracture of a thin annealed 1080 steel plate in a tensile test. Necking is observed, but the entire fracture is a shear lip rather then a cup and cone. The specimen is 3.2 mm thick

could not support the load. This is the fault of the manufacturer.

Brittle Fracture Brittle fracture occurs in high-strength metals or metals with poor ductility and toughness. Furthermore, even metals that are normally ductile may fail in a brittle manner at low temperatures, in thick sections, at high strain rates (such as impact), or when flaws play an important role. Brittle fractures are frequently observed when impact rather than overload causes failure.

In brittle fracture, little or no plastic deformation is required. Initiation of the crack normally occurs at small flaws, which cause a *concentration of stress*. The crack may move at a rate approaching the velocity of sound in the metal. Normally, the crack propagates most easily along specific crystallographic planes, often the {100} planes, by cleavage. In some cases, however, the crack may take an *intergranular* (along the grain boundaries) path, particularly when segregation or inclusions weaken the grain boundaries.

Brittle fracture can be identified by observing the features on the failed surface. Normally, the fracture surface is flat and perpendicular to the applied stress in a tensile test (Figure 1.107). If failure occurred by cleavage, each fractured grain is flat, differently oriented, and gives a crystalline appearance to the fracture surface (Figure 1.108).

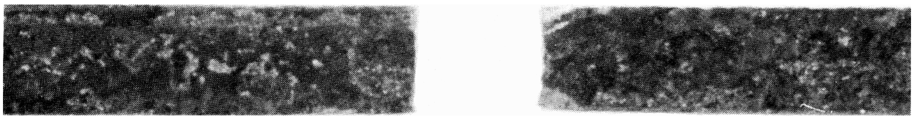

Figure 1.107 Brittle fracture of a quenched 1080 steel tensile bar. Because the microstructure is entirely martensite, a flat, brittle fracture surface is obtained. The sample is 3.2 mm thick

Figure 1.108 Scanning electron micrograph of a brittle fracture surface on a quenched 1080 steel (×5000)

Another common fracture feature is the *chevron pattern* (Figure 1.109), produced by separate crack fronts propagating at different levels in the material. A radiating pattern of surface markings, or ridges, fans away from the origin of the crack (Figure 1.110). The chevron pattern is visible with the naked eye or a magnifying glass and helps us identify both the brittle nature of the failure process as well as the origin of the failure.

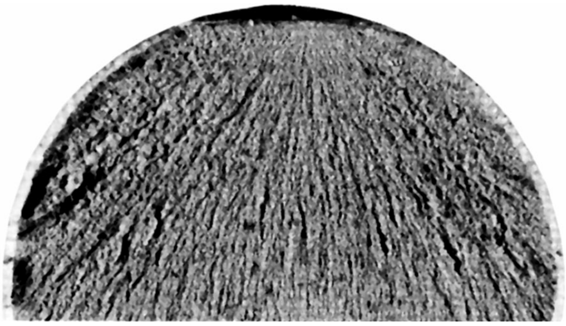

Figure 1.109 The chevron pattern in a 12.7 mm diameter quenched 4340 steel. The steel failed in a brittle manner by an impact blow

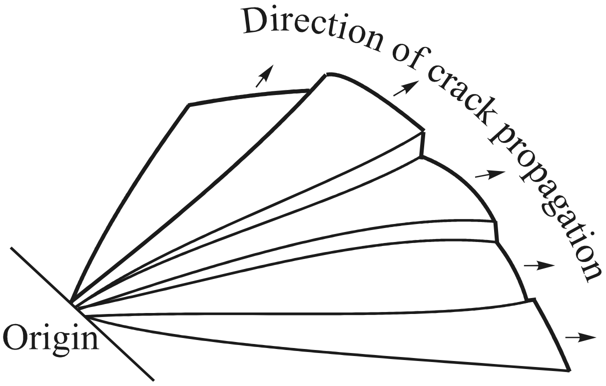

Figure 1.110 The chevron pattern forms as the crack propagates from the origin at different levels. The pattern points back to the origin

Example 1.48

An engineer investigating the cause of an automobile accident finds that the right rear wheel has broken off at the axle. The axle is bent. The fracture surface reveals a chevron pattern pointing towards the surface of the axle. Suggest a possible cause for the fracture.

Answer

The evidence suggests that the axle did not break prior to the accident. The deformed axle means that the wheel was still attached when the load was applied. The chevron pattern indicates that the wheel was subjected to an intense impact blow, which was transmitted to the axle, causing failure. The preliminary evidence suggests that the driver lost control and crashed and the force of the crash caused the axle to break. Further examination of the fracture surface, microstructure, composition, and properties may verify that the axle was properly manufactured.

Fatigue Fracture A metal fails by fatigue when an alternating stress greater than the *endurance limit* is applied. Fracture occurs by a three-step process involving (a) *nucleation of a crack*, (b) *slow*, *cyclic propagation of the crack*, and (c) *catastrophic failure of the metal*. Cracks nucleate at locations of highest stress and lowest local strength. Normally, nucleation sites are at or near the surface, where the stress is at a maximum, and include surface defects such as scratches or pits, sharp corners due to poor design or manufacture, inclusions, grain boundaries, or dislocation concentrations.

Once nucleated, the crack grows towards lower stress regions. Because of the stress concentration at the tip, the crack propagates a little bit further during each cycle until the load-carrying capacity of the remaining metal is approached. The crack then grows spontaneously, usually in a brittle manner.

Fatigue failures are often easy to identify. The fracture surface, particularly near the origin, is typically *smooth*. The surface becomes rougher as the original crack increases in size and finally may be fibrous during final crack propagation.

Microscopic and macroscopic examinations reveal a fracture surface including a *beach mark pattern* and *striations* (Figure 1.111-1.113). *Beach marks* are normally formed when the load is changed during service or when the loading is intermittent, perhaps permitting time for oxidation inside the crack. Striations, which are on a much finer scale, may show the position of the crack tip after each cycle. Observation of beach marks always suggests a fatigue failure; unfortunately, the absence of beach marks does not rule out fatigue failure.

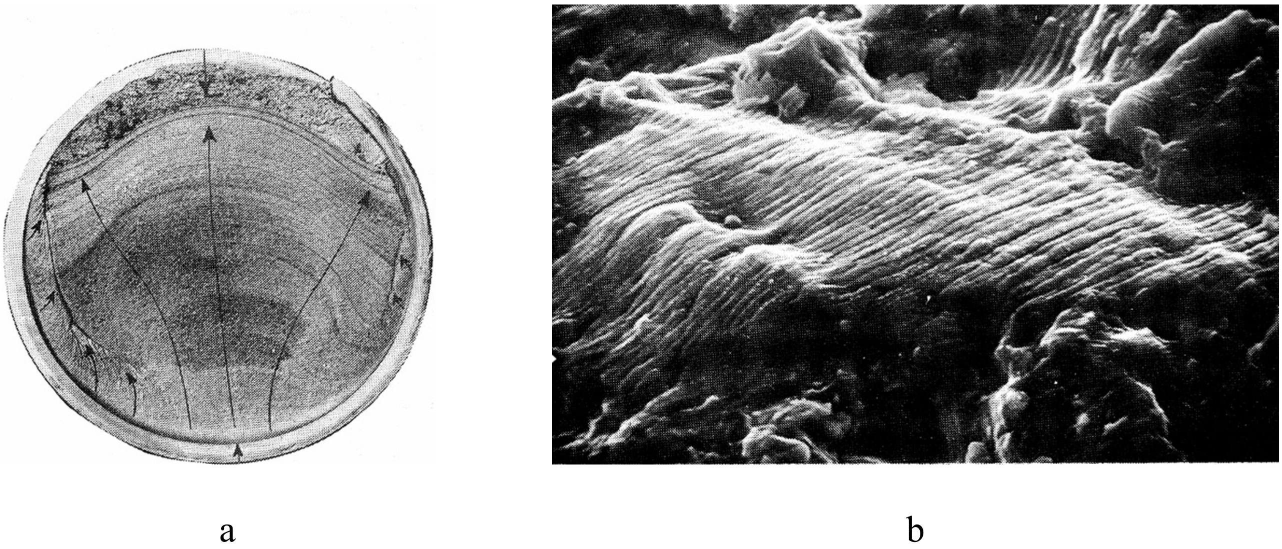
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Figure 1.111 Fatigue fracture surface. (a) At low magnifications, the beach mark pattern indicates fatigue as the fracture mechanism and points to the origin of the failure. (b) At very high magnifications, closely spaced striations formed during fatigue are observed (×1000)

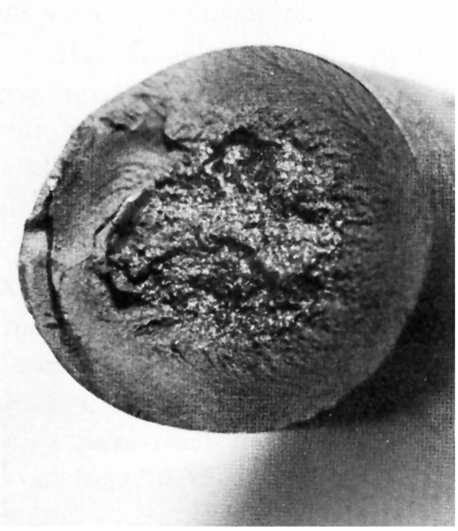


Figure 1.112 Photograph of the fracture surface of an automobile axle

Figure 1.113 Photograph of the fracture surface of a coil spring

Example 1.49

A crankshaft in a diesel engine fails. Examination of the crankshaft reveals no plastic deformation. The fracture surface is smooth. In addition, several other cracks appear at other locations in the crankshaft. What type of failure mechanism would you expect?

Answer

Since the crankshaft is a rotating part, the surface experiences cyclical loading. We should immediately suspect fatigue. The absence of plastic deformation supports our suspicion. Furthermore, the presence of other cracks is consistent with fatigue – the other cracks didn't have time to grow to the size that produced catastrophic failure. Examination of the fracture surface will probably reveal beach marks or fatigue striations.

Creep and Stress Rupture At elevated temperatures, a metal undergoes thermally induced plastic deformation even though the applied stress is below the nominal yield strength. The typical creep curve shows three regions – *primary creep*, as dislocations and other lattice imperfections are rearranged to cause rapid plastic deformation; secondary or *steady-state creep*, when dislocation climb and cross-slip cause a steady, continuous plastic deformation; and *tertiary creep*, when necking, void nucleation and coalescence, or grain boundary sliding cause rapid deformation and failure (Figure 1.114). Creep failures are defined as excessive deformation or distortion of the metal part, even if fracture has not occurred. Stress-rupture failures are defined as the actual fracture of the metal part.

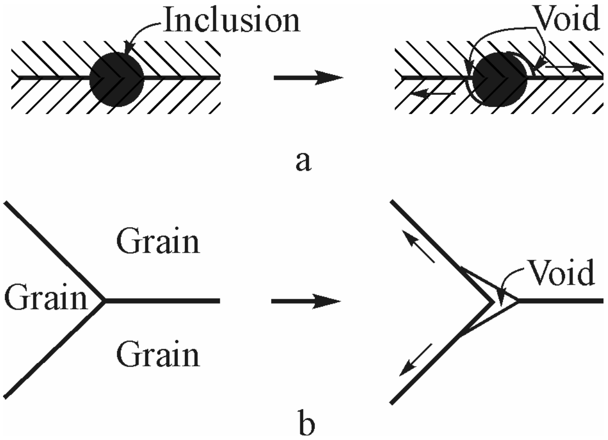


Figure 1.114 Grain boundary sliding during creep causes (a) the creation of voids at an inclusion trapped at the grain boundary and (b) the creation of a void at a triple point where three grains are in contact

Normally, ductile stress-rupture fractures include necking of the metal during tertiary creep and the presence of many cracks that did not have an opportunity to produce final fracture. Furthermore, grains near the fracture surface tend to be elongated. *Ductile stress-rupture failures* are generally *transgranular* and occur at high creep rates, short rupture times, and relatively low exposure temperatures.

Brittle stress-rupture failures usually are *intergranular*, show little necking, and occur more often at slow creep rates and high temperatures. Equiaxed grains are observed near the fracture surface. Brittle failure typically occurs by formation of voids at the intersection of three grain boundaries and precipitation of additional voids along grain boundaries by diffusion processes (Figure 1.115).

Stress-Corrosion Fractures Stress-corrosion fractures occur at stresses well below the yield strength of the metal due to attack by a corrosive medium. Deep, fine corrosion cracks are produced even though the metal as a whole shows little uniform attack. The stresses either can be externally applied or can be stored residual stresses. Stress-corrosion failures are often identified by microstructural examination of the nearby metal. Ordinarily, extensive branching of the cracks along grain boundaries is observed (Figure 1.116). The location at which cracks initiated may be identified by the presence of a corrosion product.

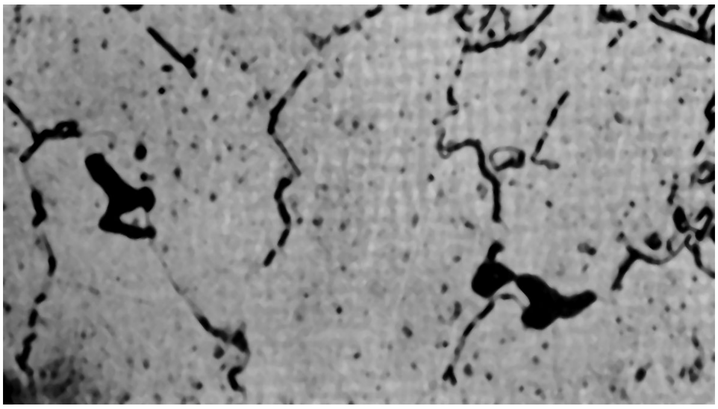


Figure 1.115 Creep cavities formed at grain boundaries in an austenitic stainless steel (×500)

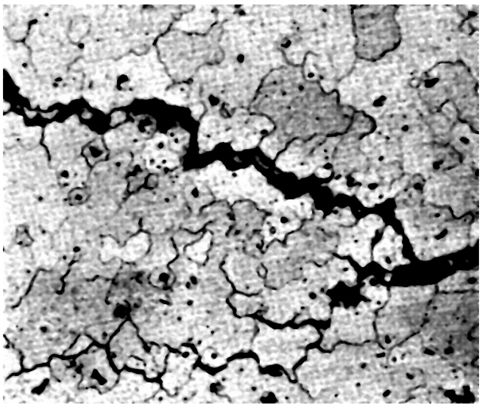


Figure 1.116 Photomicrograph of a metal near a stress-corrosion fracture, showing the many intergranular cracks formed as a result of the corrosion process (×200)

Example 1.50

A titanium pipe used to transport a corrosive material at 400°C is found to fail after several months. How would you determine the cause for the failure?

Answer

Since a period of time at a high temperature was required before failure occurred, we might first suspect a creep or stress-corrosion mechanism for failure. Microscopic examination of the material near the fracture surface would be advisable. If many tiny, branched cracks leading away from the surface are noted, stress-corrosion is a strong possibility. However, if the grains near the fracture surface are elongated, with many voids between the grains, creep is a more likely culprit.

1.5.2 Fracture Mechanism in Nonmetal Materials

In ceramic materials, the ionic or covalent bonds permit little or no slip. Consequently, failure is a result of brittle rather than ductile fracture. Most crystalline ceramics fail by cleavage along widely spaced, close-packed planes. The fracture surface typically is smooth and frequently no characteristic surface features point to the origin of the fracture (Figure 1.117 (a)).

Glasses also fracture in a brittle manner. Frequently, a *conchoidal* fracture surface is observed. This surface contains a very smooth mirror zone near the origin of the fracture, with tear lines comprising the remainder of the surface (Figure 1.117 (b)). The tear lines point back to the mirror zone and the origin of the crack, much like the chevron pattern in metals.

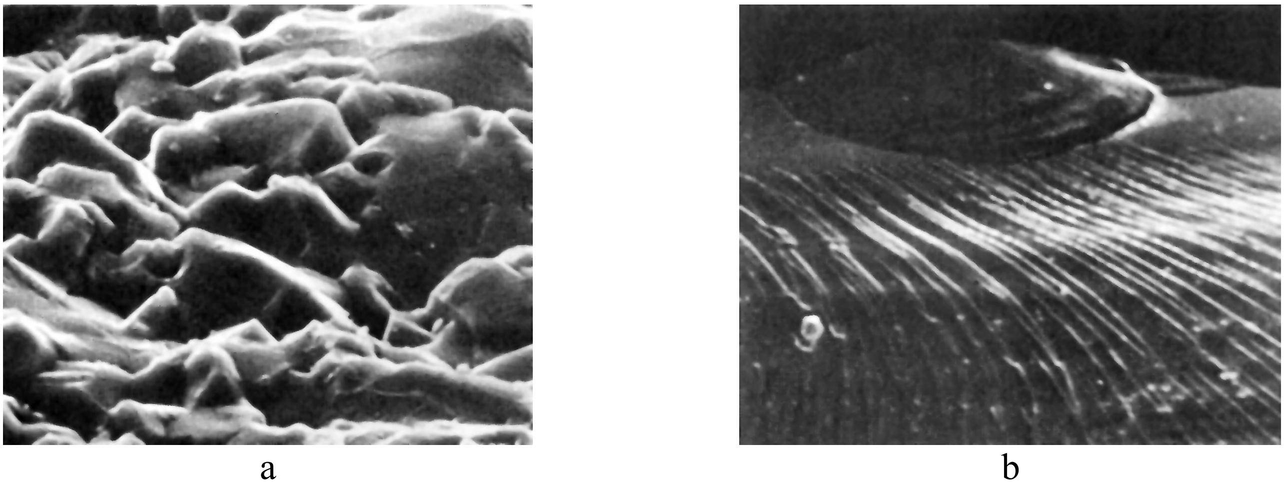


Figure 1.117 Scanning electron micrographs of fracture surfaces in ceramics. (a) The fracture surface of Al_2O_3, showing the cleavage faces (×1250). (b) The fracture surface of glass, showing the mirror zone and tear lines characteristic of conchoidal fracture (×300)

Polymers can fail by either a ductile or a brittle mechanism. Below the *glass transition temperature*, thermoplastic polymers fail in a brittle manner, much like a ceramic glass. Likewise, the hard thermosetting polymers fail by a brittle mechanism. Thermoplastics, however, fail in a ductile manner above the glass transition temperature, giving evidence of extensive deformation and even necking prior to failure. The ductile behavior is a result of sliding of the polymer chains, which is not possible in glassy or thermosetting polymers.

Fracture in fiber-reinforced composite materials is more complex. Typically, these composites contain strong, brittle fibers surrounded by a soft, ductile *matrix*, as, for example, in boron-reinforced aluminum. When a tensile stress is applied along the fibers, the soft aluminum deforms in a ductile manner, with void formation and coalescence eventually producing a dimpled fracture surface. As the aluminum deforms, the load is no longer transmitted effectively to the fibers; the fibers break in a brittle manner until there are too few fibers left intact to support the final load.

Fracture becomes easier if bonding between the fibers is poor. Voids can form between the fibers and the matrix, causing *pull-out.* Voids can also form between layers of the matrix if composite tapes or sheets are not properly bonded, causing *delamination* (Figure 1.118).

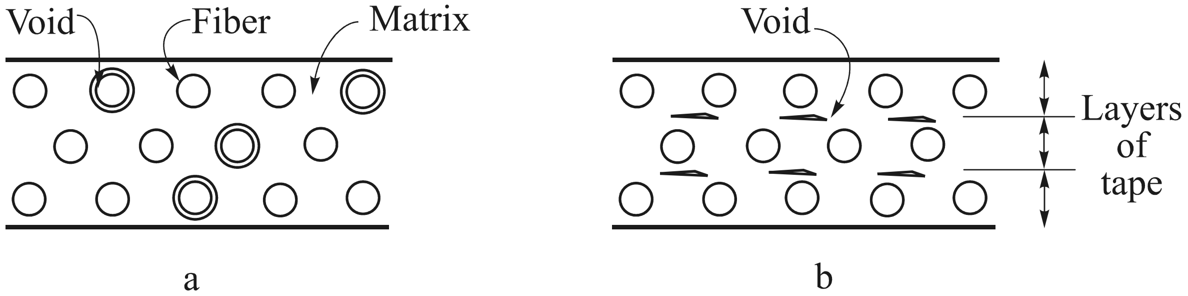


Figure 1.118 Fiber-reinforced composites can fail by several mechanisms. (a) Due to weak bonding between the matrix and fibers, fibers can pull out of the matrix, creating voids. (b) If the individual layers of the matrix are poorly bonded, the matrix may debond, creating voids

Summary

This chapter deals with a survey of the fundamentals of atomic structure. Electron energy states are specified in terms of quantum numbers which give rise to consideration of on electron shells and subshells. The electron configuration of an atom corresponds to the way in which these shells and subshells are filled with electrons. The periodic table of the elements is generated by arrangement of various elements according to valence electron configuration.

Atoms within crystalline solids are positioned in an orderly and repeated pattern, that is in contrast to the random and disorderly atomic distribution in noncrystalline (or amorphous) materials. The great variety of crystal structures were specified in terms of unit cells. The theoretical densities of materials are determined on the basis of unit cell and atomic weight data. Other concepts were also introduced: crystal systems, polymorphism (or allotropy) and anisotropy.

The types of imperfection were considered taking in to account their geometry and size. Point defects are those associated with one or two atomic positions; in metals these include vacancies, self-interstitials and impurity atoms.

Two types of one-dimensional crystalline defects (dislocations): edge and screw were considered in this Chapter. Other imperfections include interfacial defects (external surfaces, grain boundaries (both small- and high-angle), twin boundaries), volume defects (cracks, pores, etc.). The type of imperfection influences on the properties of a material.

Solid-state diffusion is a means of mass transport within solids by stepwise atomic motion. Two mechanisms: vacancy and interstitial were considered. For steady-state diffusion, the flux or rate is proportioned to the negative value of the concentration gradient according to Fick's first law. For nonsteady diffusion Fick's second law is used taking into consideration the Gaussian error function.

Fracture may occur in ductile and brittle modes, both of which deal with the formation and propagation of cracks. For ductile fracture the results of plastic deformation are evident at the fracture surface. In tension, highly ductile metals will essentially neck to a point fracture; cup-and-cone fracture surfaces are characteristic for moderate ductility. In brittle fracture, the fractured surface is relatively flat and perpendicular to the direction of applied tensile load. Chevron and ridgelike patterns, indicating the direction of crack propagation are also possible. Transgranular and intergranular fractures may be found in brittle polycrystalline materials.

Fatigue is a common type of catastrophic failure wherein the applied stress level fluctuates with time. Fatigue strength is a failure stress for a specified number of cycles. Another fatigue property is fatigue life, which, for a specific stress is the number of cycles to failure.

The processes of fatigue crack initiation and propagation were discussed. Two characteristic fatigue surface features are beachmarks and striations.

The creep phenomenon is observed in structural materials. It is the time-dependent plastic deformation of materials subjected to a constant stress and high temperatures. Important design parameters include steady-state creep rate and rapture lifetime.

All these aspects constitute the theoretical base for further deep study of materials engineering.

Chapter 2 The Nature, Types and Properties of Engineering Materials

2.1 Types of Materials

We will classify materials into several classes – *metals*, *ceramics*, *polymers*, *glasses*, *semiconductors*, and *composite materials*. The sphere of applications of each of them is represented in Table 2.1.

Table 2.1 Representative examples, applications, and properties for different classes of materials

Material class	Examples of Applications	Properties
Metals and alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castability, machinability, vibration damping
Alloy steels	Wrenches	Good strengthening by heat treatment
Titanium	Aircraft and space vehicles structures	High strength to weight ratio
Ceramics (main classes, including glasses)		
Single oxides		
– alumina (Al_2O_3)	Electrical insulators, abrasives, refractories for containing molten metal	High electrical insulation High melting temperature
– titania (TiO_2)	Pigment	Corrosion protection, resists oxidation
– silica (SiO_2)	Abrasives, refractories for containing molten metal	Thermal insulation, high melting temperature, relatively inert to molten metal
Mixed oxides		
– kaolinite ($Al_2O_3 \cdot SiO_2 \cdot 2H_2O$)	Clay products	High temperature resistance
– $A1_2O_3$, MgO, SiO_2	Refractories for containing molten metal	Thermal insulation, high melting temperature, relatively inert to molten metal
Carbides		
– tungsten carbide (WC)	Cutting tools	High hardness, high wear resistivity
– titanium carbide (TiC)	Cutting tools, wear-resistant	High hardness, high wear resistivity
– boron carbide (B_4C)	Fibers (whiskers) for composites	High strength
– Silicon carbide (SiC)	Abrasives	High wear resistivity, high hardness

Table 2.1 (continued)

Material class	Examples of Applications	Properties
Sulfides – Molybdenum disulfide (MoS_2)	Lubricant	Low friction
Nitrides – boron nitride (BN) – silicon nitride (Si_3N_4)	Insulator Abrasives	–
Metalloid elements – germanium (Ge) – silicon (Si)	Electronic devices Electronic devices	High semiconductive effect Semiconductive effect
Intermetallic – nickel aluminide ($NiAl_2$)	Wear coating	–
Barium titanate	Transducers for stereo record players	Piezoelectric behavior converting sound to electricity
SiO_2-Na_2O-CaO	Window glass	Good optical properties and thermal insulation
Polymers (important families, including elastomers)		
Ethenic (polyethylene LDPE, HDPE)	Food packaging	Easily formed into thin, flexible, airtight film
Epoxides	Encapsulation of integrated circuits	Good electrical insulation and moisture resistance
Pheholics	Adhesives to join plies in plywood	Strength and moisture resistance
Silicones		
Polyesters		
Acetals	Machine parts (gears)	
Urethanes		
Elastomers		
Cellulosics		
Polycarbonates		
Polyamides		
Semiconductors		
Silicon	Transistors and integrated circuits	Unique electrical behavior
GaAs, ZnSe	Fiber-optic systems	Converts electrical signals to light

Table 2.1 (finished)

Material class	Examples of Applications	Properties
Composites		
Fiber reinforced composites –Carbon fiber reinforced polymer (CFRP) –Glass fiber reinforced polymer (GFRP) –Kevlar fiber reinforced polymer (KFRP) –Borsic fiber reinforced composites	Aircraft components, ships structures, body armours	High strength-to-weight ratio High modulus-to-weight ratio
Particulate composites – Cemented carbides (cermets) (tungsten carbide)	Cutting tools for mashining	High hardness and strength
Laminar composites		
– Aluminum-clad steel – Titanium-clad steel	Corrosion protection of reactor vessels	Low cost and high strength of steel with good corrosion resistance of titanium
– Laminates (aramid aluminum laminate Arall)	Skin for aircraft	Hardness and wear-resistance of surfaces
– Bimetallics	Temperature indicators and controllers	Reversible high expansion characteristics Very different coefficients of thermal expansion

Materials in each of these groups often possess different structures and properties. For example, the differences in electrical conductivity and strength of these groups of materials are shown in Figures 2.1 and 2.2.

2.2 The Nature of Materials

2.2.1 The Nature of Metals

Metals and alloys, which include steel, aluminum, magnesium, zinc, cast iron, titanium, copper, nickel, and many others, have the general characteristics of good electrical and thermal conductivity, relatively high strength, high stiffness, ductility

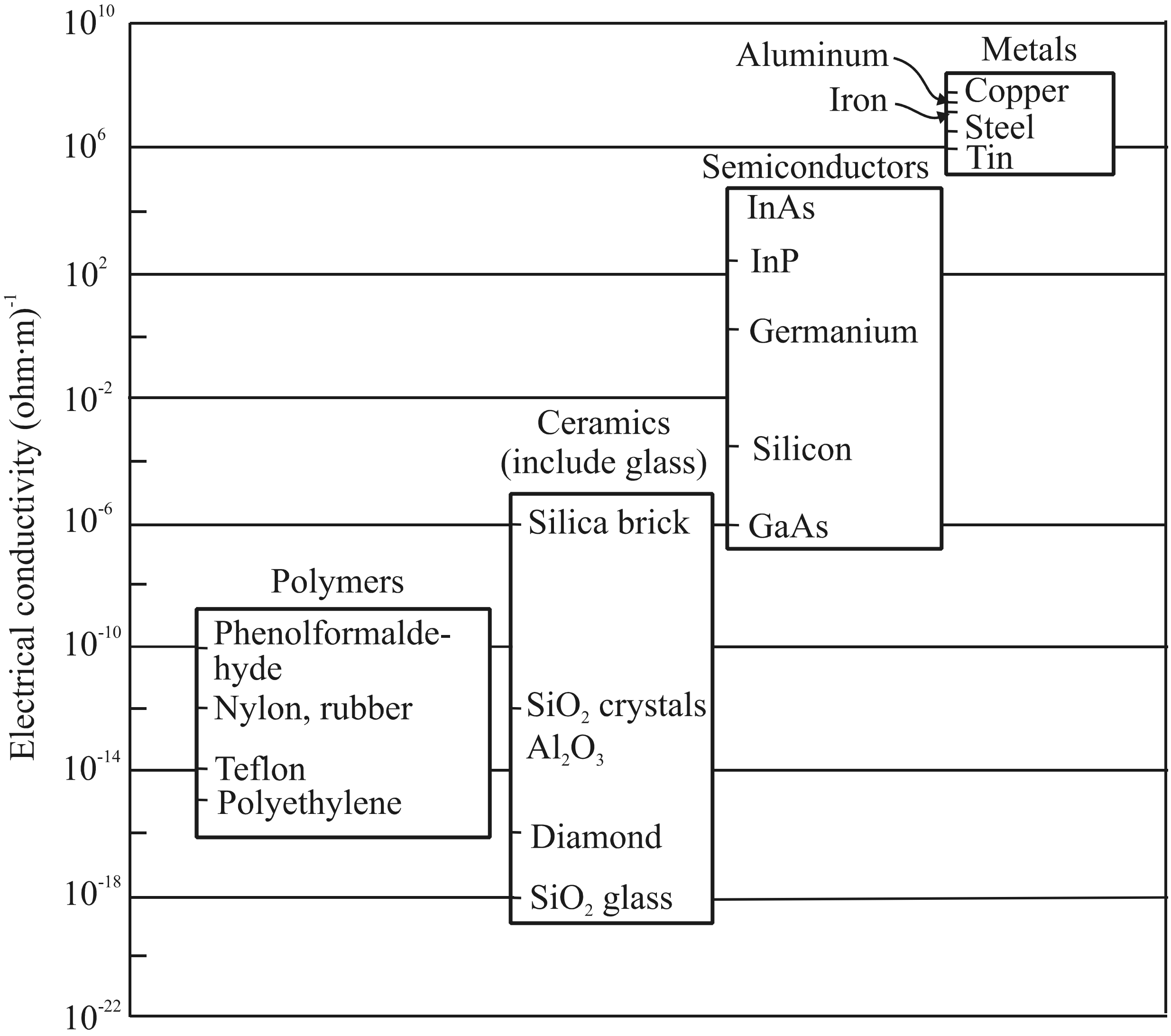


Figure 2.1 Representative electrical conductivities for the various categories of materials. Particularly large differences are observed

or formability, and shock resistance. They are particularly useful for structural or *load-bearing* applications. Although pure metals are occasionally used, combinations of metals called *alloys* are normally designed to provide improvement in a particular desirable property or permit better combinations of properties. The section through a jet engine shown in Figure 2.3 illustrates the use of several metal alloys for a very critical application.

In chemistry, a metal is defined as an element with a valence of 1, 2, or 3. However, a metal can best be defined by the nature of the bonds between the atoms that make up the metal crystals. As you remember, the metallic chemical elements have a low valence and give up their valence electrons to form a “cloud” of electrons surrounding the atoms. These valence electrons are no longer associated with any atom and therefore move freely within the electron “cloud”. They become associated with several atom cores. As the result of mutual electrostatic affraction of atom cores

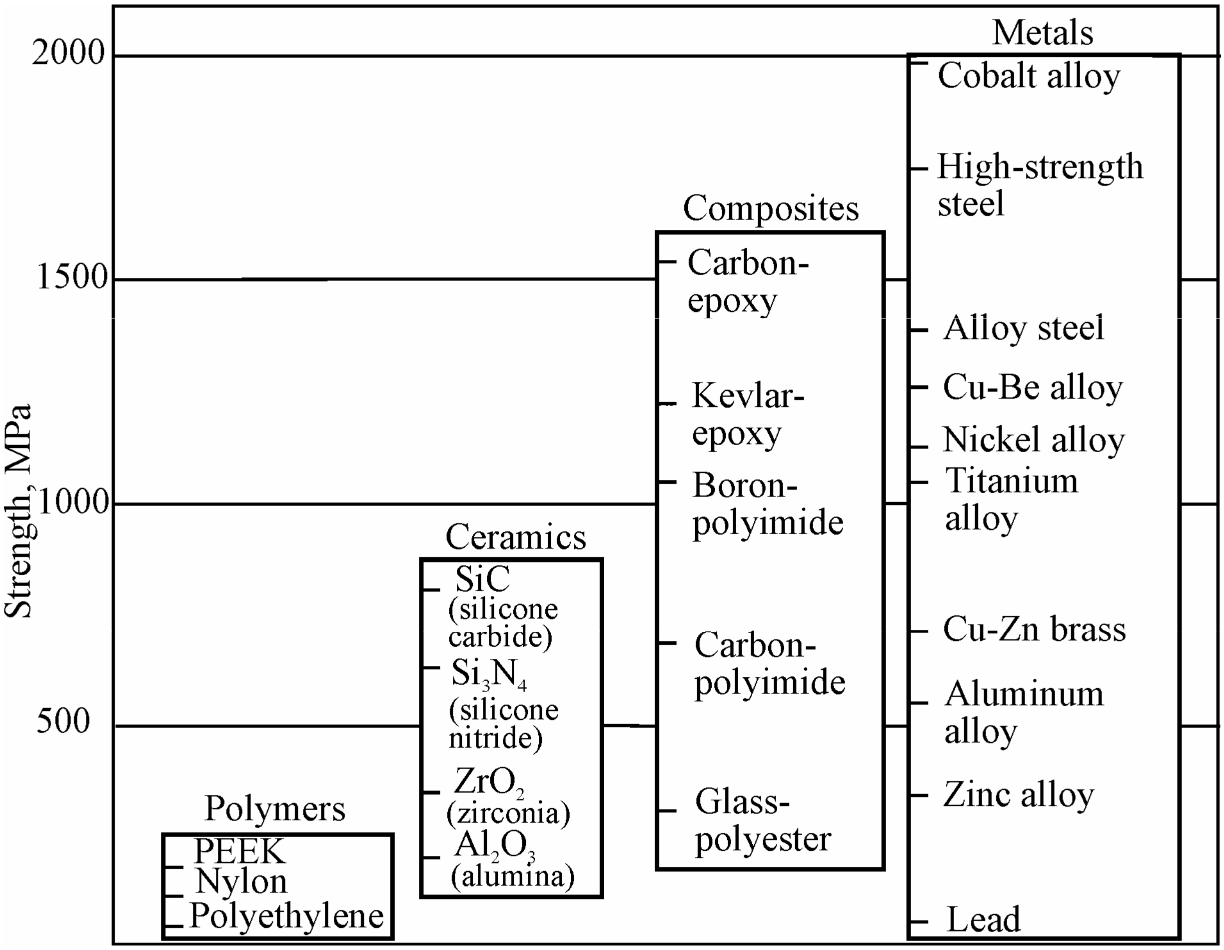


Figure 2.2 Representative strengths of the various categories of materials

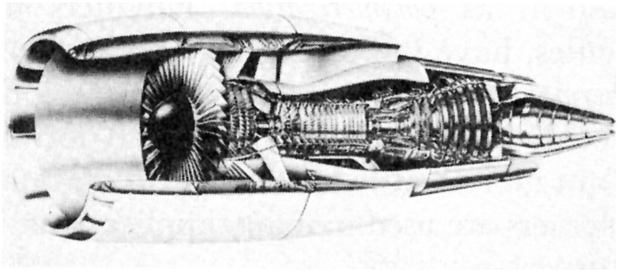


Figure 2.3 A section through a jet engine. The forward compression section operates at low to medium temperatures, and titanium parts are often used. The rear combustion section operates at high temperatures, and nickel-base superalloys are required. The outside shell withstands low temperatures, and aluminum and composites are satisfactory

and electrons the strong metallic bond is produced.

Because the electrons associated with each individual atom are free they can move throughout the volume of the crystal or piece of metal. This is why metals are good conductors of electricity: current flow requires a flow of electrons. Other properties that distinguish metals from other materials are their *malleability* (their ability to deform plastically), their *opacity* (light cannot pass through them), and their *ability to be strengthened*. All general mechanisms of metals strengthening have been considered in Chapter 1.

2.2.2 The Nature of Ceramics

Ceramics, such as brick, glass, tableware, refractories, and abrasives, have low electrical and thermal conductivities and consequently are often used as insulators. Ceramics are strong and hard but also are very brittle. New processing techniques are being developed to allow ceramics to be used in load-bearing applications, such as impellers in turbine engines (Figure 2.4).

Ceramics have excellent resistance to high temperatures and certain corrosive media and have a number of unusual optical and electrical properties that are used in constructing *integrated circuits*, *fiber–optic systems*, and a variety of sensing devices.

In terms of basic chemistry, a nonmetallic element has a valence of 5, 6, or 7. Elements with a valence of 4 are *metalloids* – sometimes they behave as a metal, sometimes as a non-metal. Elements with a valence of 8 are inert. They have a low tendency to combine with other elements, e.g., *inert gases. A ceramic can be defined as a combination of one or more metals with a nonmetallic element.* The thing that really distinguishes a ceramic from other engineering materials, however, is the nature of the bond between atoms. As opposed to the long-range electron matrix bond in metals, ceramic materials usually have very rigid *covalent* or *ionic* bonds between adjacent atoms. As shown in Figure 2.5, the ceramic aluminum oxide Al_2O_3 is formed by the combination of three oxygen atoms and two aluminum atoms in such a manner that by sharing valence electrons each atom has eight electrons in its *outershell*. This sharing of electrons was called *covalent bonding.*

Figure 2.4 A variety of complex ceramic components, including impellers and blades, which allow turbine engines to operate more efficiently at higher temperatures

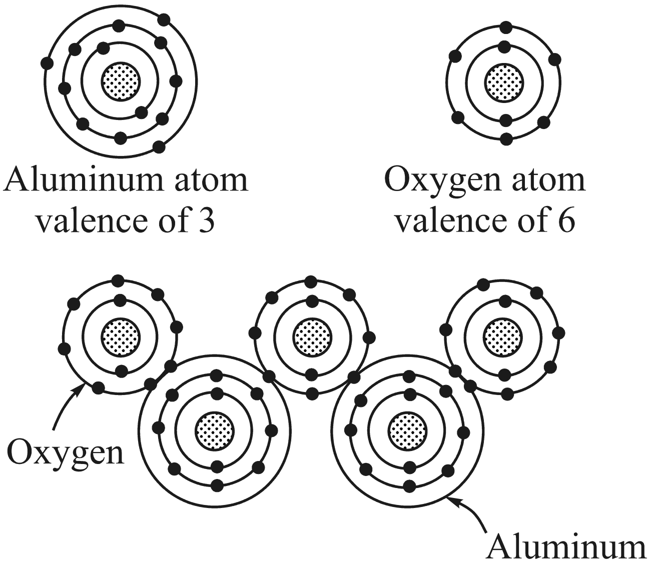


Figure 2.5 Structure of aluminum oxide (Al_2O_3)

In ionic bonding, valence electrons from one atom are transferred to another atom and the atoms involved are then held together by the electrostatic attraction between the two oppositely charged ions.

Both ionic and covalent bonds involve very strong bonds between neighboring atoms. Thus, crystalline ceramics with this type of bond tend to be very brittle. Tensile loading tends to result in crystal cleavage. Deformation by dislocation motion or atomic slippage is difficult. Other property demonstration of these strong bonds are *high hardness*, *chemical inertness*, and *electrical insulation*. Ceramics tend to be electrical insulators because the electrons are "tied up" in bonding and are not free to move throughout the crystal. Ceramics can be strengthened by adding other elements, but the effect is usually not pronounced. They usually cannot be strengthened by cold working or by precipitation hardening. Some ceramics can be strengthened by changes in crystal structure; for example, hexagonal boron nitride is very soft and cubic boron nitride is very hard, but such cases are the exception rather than the rule.

2.2.3 The Nature of Polymers

The engineering materials known as plastics are more correctly called *polymers.* This term comes from the Greek words "poly", which means many, and "meras", which means parts. Polymers are substances composed of long chain-repeating molecules (*mers*). In most cases the element *carbon* forms the backbone of the chain (an organic material).

Polymers have their origin in nature. The building blocks of animal life – animal proteins – are polymers, as are *rosin, shellac, natural rubber*, and a host of other familiar substances. Wood is composed of chains of cellulose molecules bonded together by another natural polymer called *lignin.* Natural polymers have been around from the beginning of life.

The polymeric materials that we use today in machines, packaging, appliances, automobiles, and the like are not made from natural polymers. They are man-made, and they have only come into importance as engineering materials within the last 60 years (Figure 2.6).

The first man-made moldable polymer was *cellulose nitrate*, or celluloid. It was not widely used, but the next generation of polymers, the *phenolics*, found wide application as structural and insulating materials in electrical devices. Light switches are still normally made from phenolic polymers. The era of World War II was characterized by a scarcity of materials, and the evolution of polymers took place at a rapid pace. *Nylon* replaced silk, *vinyls* replaced leathers, and so on. Today there are literally thousands of polymers that are used as engineering materials.

The atoms in the repeating molecule of polymer are strongly bonded (usually covalent), and the bonds between molecules may be due to weaker secondary bonds or similar covalent bonds. The common polymer *polyethylene* is composed of repe-

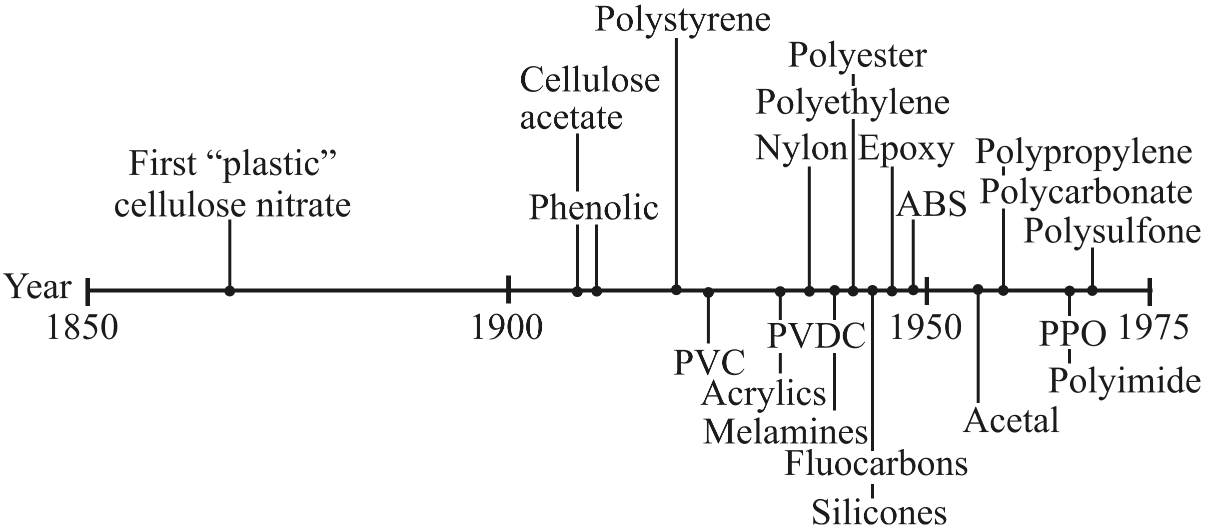


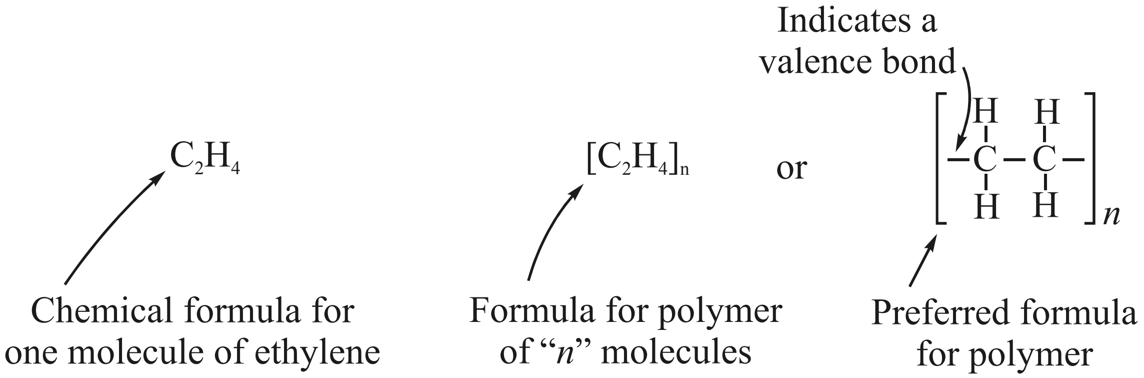
Figure 2.6 Chronological development of important engineering polymers

ating ethylene molecules (C_2H_4). Using the "rule of eight," the carbon atoms have unsaturated valence bands (carbon has a valence of 4 and hydrogen has a valence of 1). If ethylene molecules attach to each side of the one illustrated in Figure 2.7, the valence bands on the carbon atoms in the center molecule will be satisfied. This is why these materials tend to form long chains: carbon-to-carbon bonds satisfy valence requirements. When the chains grow very long and get tangled, they tend to lose their three-dimensional symmetry and they appear amorphous when analyzed by X-ray diffraction techniques. Thus, the degree of crystallinity in a polymer often depends on a chain alignment. Some polymers have a high degree of crystallinity; some do not.

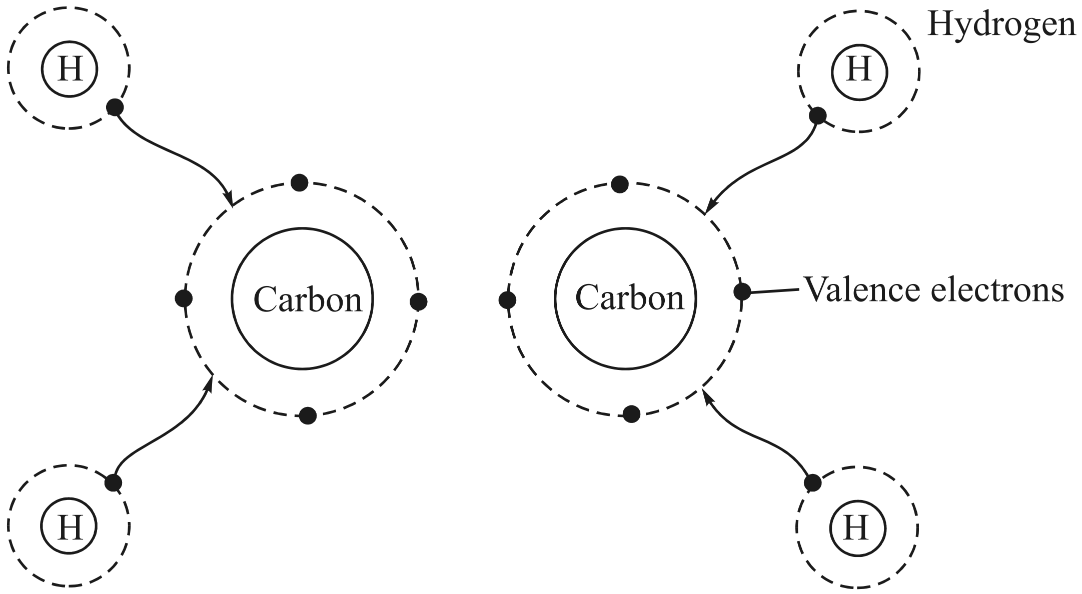
Long-chain polymers are usually weaker than most ceramics and metals because the molecular chains are bonded to each other only with rather weak electrostatic forces called *Van der Waals bond*. When loaded, the long-chain molecules slip with respect to each other. Strengthening is accomplished by techniques that retard chain movement, *fillers, cross-linking* of chains, *chain branching*, and the like.

Polymers are produced by creating large molecules structures from organic molecules in a process known as *polymerization*. Polymers have low electrical and thermal conductivities, have low strengths, and are not suitable for use at high temperatures. *Thermoplastic* polymers, in which the long molecular chains are not rigidly connected, have good ductility and formability; *thermosetting* polymers are stronger but more brittle because the molecular chains are tightly linked (Figure 2.8). Polymers are used in many applications, including electronic devices (Figure 2.9).

The classification system of modern engineering polymers is illustrated in Figure 2.10. It presents an overall picture of the spectrum of engineering polymers. This chart does not contain every engineering polymer. New families may be produ-



A Single Molecule of Polyethylene



Atomic Structure

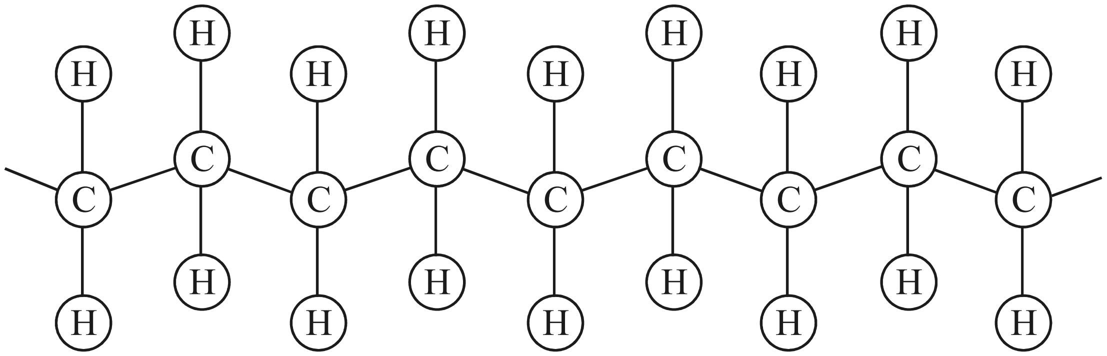


Figure 2.7 Physical Structure of Polyethylene

ced daily by polymer chemists throughout industry, but the polymers listed account for the bulk of those in common usage. Natural polymers, such as lignin, rosin, shellac, and animal protein, are not included since they do not usually enter into design.

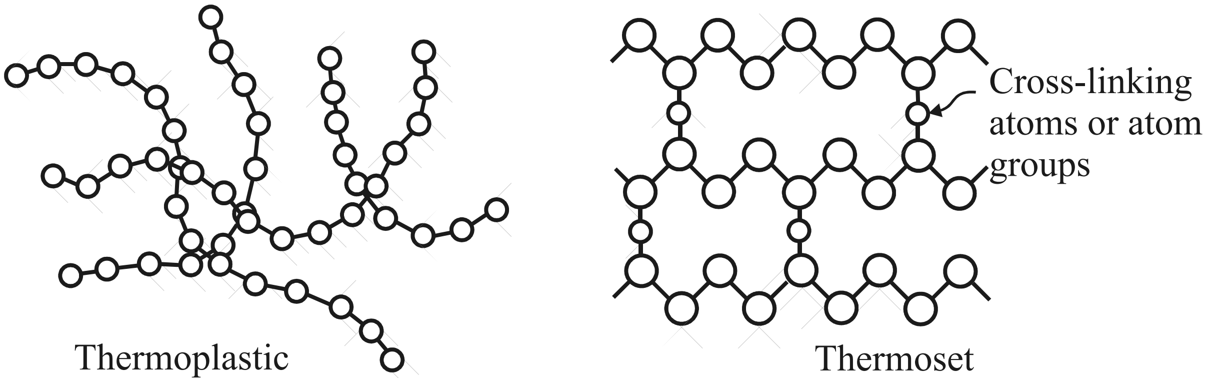


Figure 2.8 Polymerization occurs when small molecules combine to produce larger molecules, or polymers. The polymer molecules can have a chainlike structure (thermoplastics) or can form three-dimensional networks (thermosets)

2.2.4 The Nature of Composites

A *composite* is a combination of two or more materials that has properties that the component materials do not have by themselves. Nature made the first composites in living things. Wood is a composite of cellulose fibers held together with a *glue* or *matrix* of soft *lignin*. *Concrete*, *plywood*, and *fiberglass* are typical examples of composite materials (Figure 2.11). With composites we can produce lightweight, strong, ductile, high temperature-resistant materials that are otherwise unobtainable, or we can produce hard yet shock-resistant cutting tools that would otherwise shatter. Advanced aircraft and aerospace vehicles rely heavily on composites such as carbon-fiber-reinforced polymers (Figure 2.12).

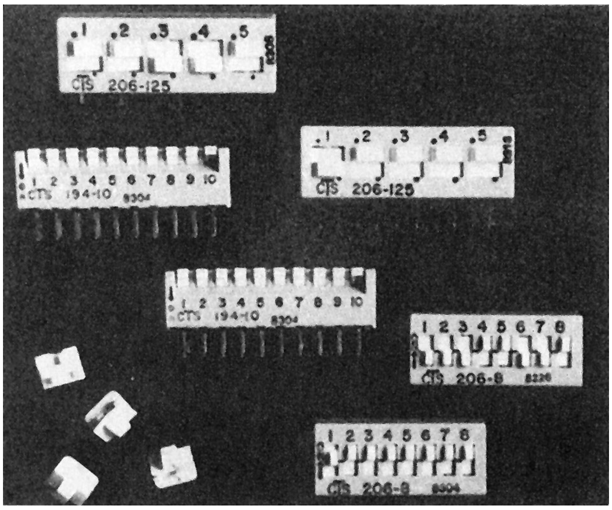


Figure 2.9 Polymers are used in a variety of electronic devices, including these computer dip switches, where moisture resistance and low conductivity are required

Composite can be *metal-metal*, *metal-ceramic*, *metal-polymer*, *ceramic-polymer*, *ceramic-ceramic*, or *polymer-polymer*. Metal-ceramic composites, for example, include cemented carbide cutting tools, silicon carbide fiber-reinforced titanium, and enameled steel.

Composites can be placed into three categories – *particulate*, *fiber*, and *laminar* – based on the shapes of the materials (Figures 2.11, 2.13). *Concrete*, a mixture of *cement* and *gravel*, is a *particulate composite*; fiberglass, containing glass fibers embedded in a polymer, is a *fiber-reinforced composite*; and plywood, having alternating layers of wood veneer, is a *laminar composite*. If the reinforcing particles are

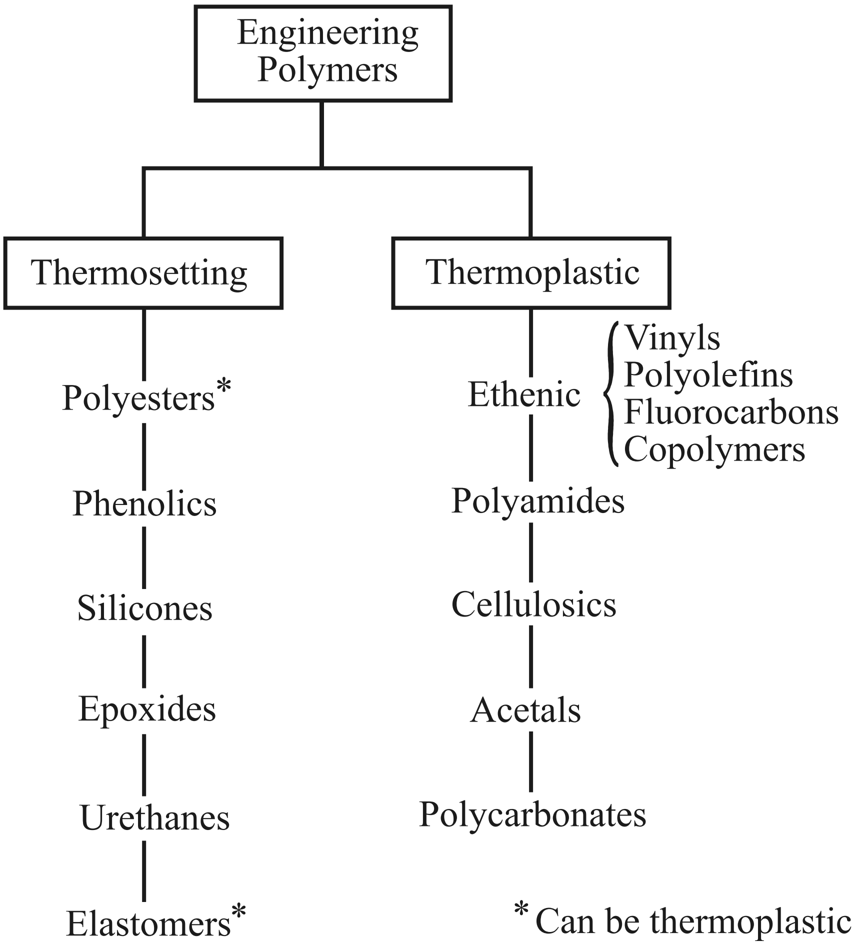


Figure 2.10 Important polymer families

uniformly distributed, particulate composites have isotropic properties; fiber composites may be either isotropic or anisotropic; laminar composites always have anisotropic behavior.

So, in engineering materials, composites are formed by *coatings*, *internal additives*, and by *laminating*. An important metal composite is *clad metals*. Thermostatic controls are made by roll-bonding a high-expansion alloy such as copper to a low-expansion alloy like steel. When the composite is heated, it will deflect to open electrical contacts. Plywood is a similarly common composite.

At the present time the most important composites are combinations of high-strength, but crack-sensitive ceramic-type materials and polymers. The most common example of such a system is fiberglass. Glass fibers are very strong, but if notched they fracture readily. By encapsulating these fibers in a *polyester* resin matrix, they are protected from damage and the polyester transfers applied loads to the glass fibers so that their stiffness and strength can be utilized. More advanced components use fibers of graphite and boron. These fibers are very stiff and strong, yet lightweight. The strengthening effect of the reinforcements in composites depends on the orientation of the reinforcement to the direction of the loads.

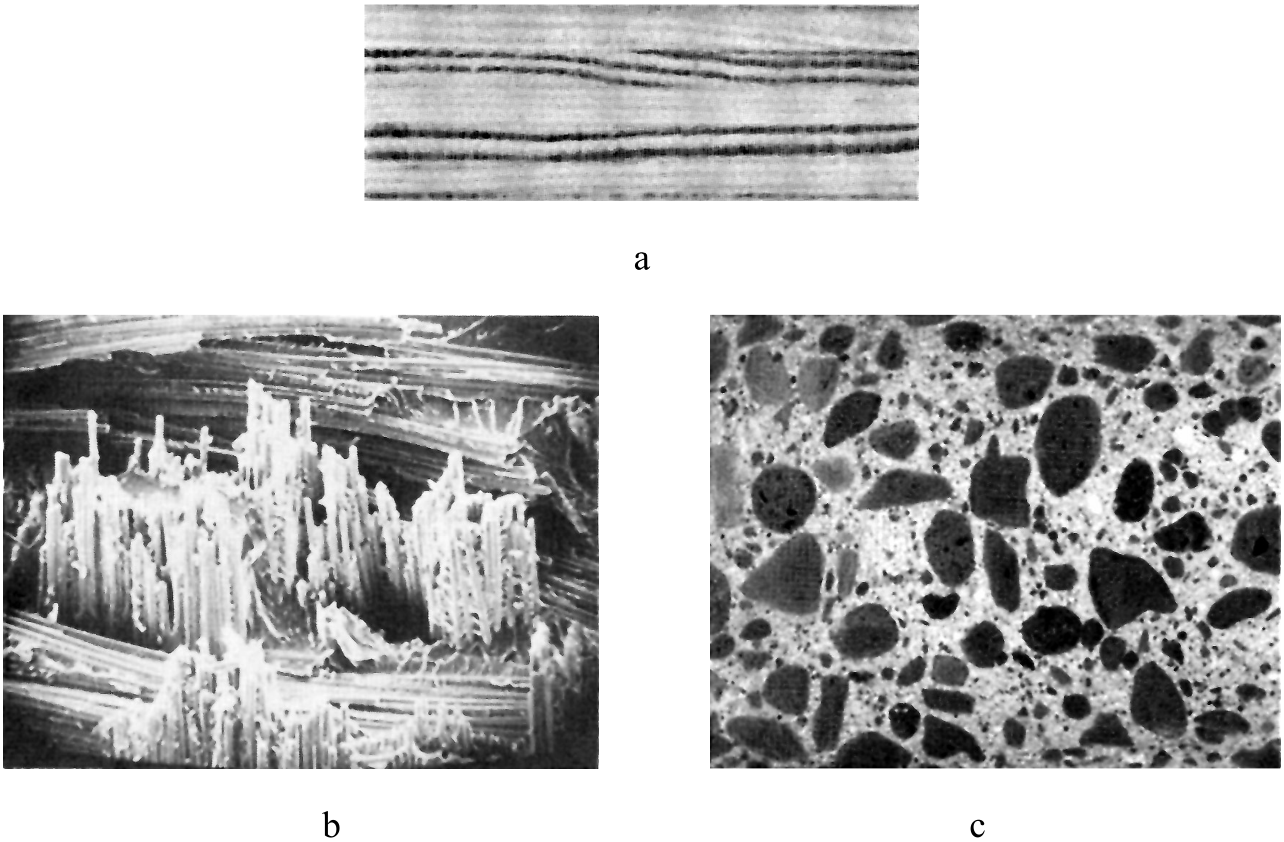


Figure 2.11 Some examples of composite materials, (a) Plywood is a laminar composite composed of layers of wood veneer, (b) Fiberglass is a fiber-reinforced composite containing stiff, strong glass fibers in a softer polymer matrix (x 175). (c) Concrete is a particulate composite containing coarse sand or gravel in a cement matrix (reduced 50%)

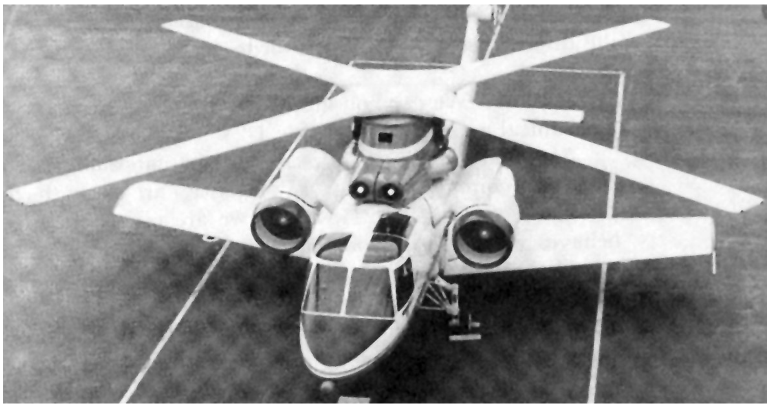


Figure 2.12 The X-wing for advanced helicopters relies on a composite composed of a carbon-fiber-reinforced polymer

Besides polyester, suitable composite matrices are *polyimides*, *epoxies*, and even metals such as aluminum and copper.

Composites as a class of engineering materials provide almost unlimited potential for higher strength, stiffness, and corrosion resistance over the “pure” material systems of metals, ceramics, and polymers. They will probably be the “steels” of the XXI th century.

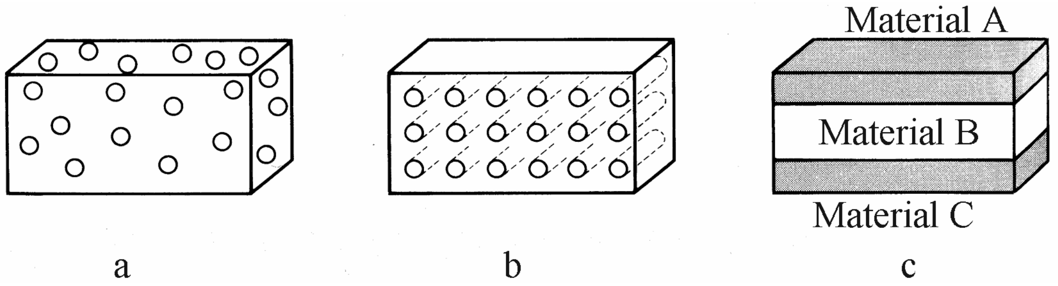


Figure 2.13 Comparison of the three types of composite materials. (a) Particulate composite, (b) fiber-reinforced composite, and (c) laminar composite

2.2.5 Semiconductors

This class of engineering materials is considered separately because *silicon*, *germanium*, and a number of other brittle compounds such as GaAs are essential for electronics, computer, and communication applications. The electrical conductivity of these materials can be controlled so that they can be used in electronic devices such as *transistors, diodes,* and *integrated circuits*. Information is now being transmitted by light through *fiber - optic systems; semiconductors*, which convert electrical signals to light and vice versa, are essential components in these systems.

In this part of the chapter we have tried to show how material systems are interrelated. This knowledge is important in understanding engineering materials, but the overriding goal is to promote the use of a materials concept in design. When a material selection problem arises, all material systems should be equal candidates.

2.3 Properties of Materials. Structure-Property-Processing Relationship

Material selection is based on properties. The designer must decide the properties required of a material for a part under design and then weigh the properties of candidate materials. Before we can discuss the relative merits of various material systems, we must establish the vocabulary of properties. It is the purpose of this part of the chapter to define the properties that are important to selection, to show how they are applied to the major material systems, polymers, metals, and ceramics, and to show in further how these properties are used to select materials. There are literally hundreds of properties that are measured in laboratories for the purpose of comparing materials. We cannot discuss all of these in a single chapter, so we shall concentrate on the more important ones. In some cases, we shall describe measuring techniques (see Chapter 3).

We are always interested in producing a component that has the proper shape and properties, permitting the component to perform its task for its expected *lifetime*. The materials engineer meets this requirement by taking advantage of a complex three-part relationship between the internal structures of the material, the processing of the material, and the final properties of the material (Figure 2.14).

When the materials engineer changes one of these three aspects of the relationship, one or both of the others also change. We must therefore determine how the three aspects interrelate in order to finally produce the required product.

The major properties to be considered in material selection are shown in Figure 2.15.

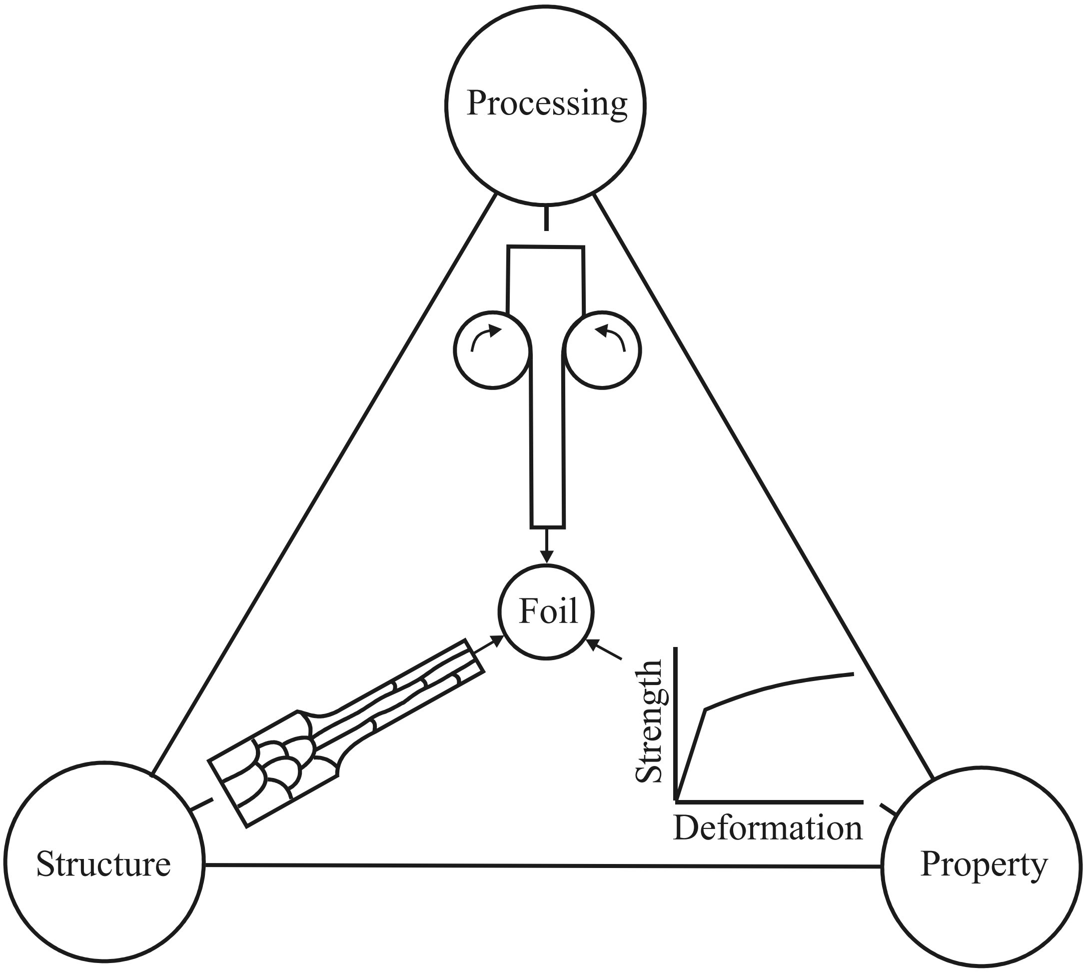


Figure 2.14 The three-part relationship between structure, properties, and processing method. When aluminum is rolled into foil, the rolling process changes the metal's structure and increases its strength

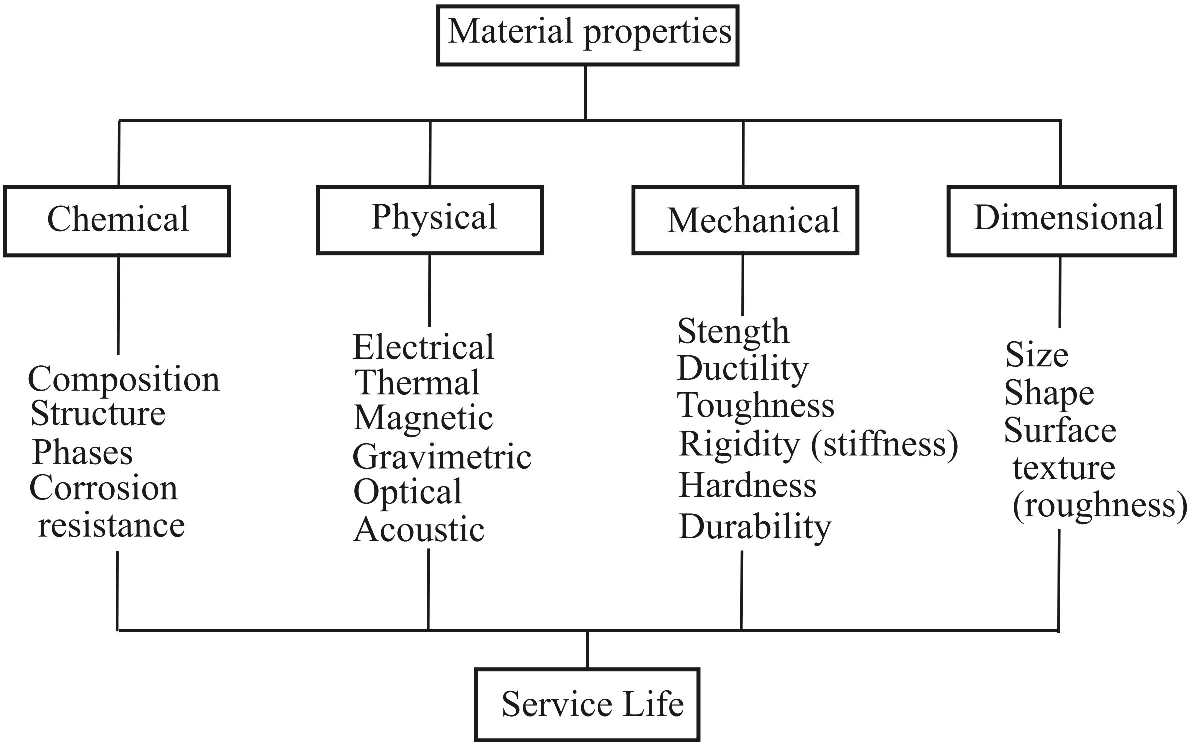


Figure 2.15 The spectrum of material properties

Chemical properties are material characteristics that relate to the structure of a material and its formation from the elements. These properties are usually measured in a chemical laboratory, and they cannot be determined by visual observation. It is usually necessary to change or destroy a material to measure a chemical property.

Physical properties are characteristics of materials that pertain to the interaction of these materials with various forms of energy and with other forms of matter. In essence, they belong to the science of physics. They can usually be measured without destroying or changing the material. *Color* is a physical property; it can be determined by just looking at a substance. *Density* can be determined by weighting and measuring the volume of an object; it is a physical property. The material does not have to be changed or destroyed to measure this property.

Physical properties include *electrical*, *magnetic*, *gravimetric*, *optical*, *thermal*, *acoustic*, depend on both structure and processing of a material. Even tiny changes in composition cause profound changes in the *electrical conductivity* of many semiconducting materials. For example, high firing temperatures may greatly reduce the thermal insulation characteristics of ceramic brick; small amounts of impurities change the color of a glass or polymer.

Mechanical properties are the characteristics of a material that are displayed when a force is applied to the material. They usually relate to the elastic or inelastic behavior of the material, and they often require the destruction of the material for measurement.

The most common mechanical properties are *strength*, *ductility*, and *stiffness* (modulus of elasticity), and *hardness*. However, we are often interested in how a material behaves when it is exposed to a sudden, intense blow (*impact*), continually cycled through an alternating force (*fatigue*), exposed to high temperatures (*creep*), or subjected to abrasive conditions (*wear*). Mechanical properties also determine the ease with which a material can be deformed into a useful shape. A metal part formed by *forging* must withstand the rapid application of a force without breaking and must have a high enough ductility to deform to the proper shape. Often, small structural changes have a profound effect on the mechanical properties of a material.

If we want to select a material for an airplane wing, me must consider some of the key mechanical and another physical properties.

First, let's look at mechanical properties. We obviously want the material to have a high strength to support the forces acting on the wing. We must also recognize that the wing is exposed to a cyclical application of a force as well as vibration – this suggests that fatigue properties are important. In supersonic flight, the wing may become very hot, so resistance to creep is critical.

Important physical properties for wing structure are *density* and *corrosion resistance*. The wing should be as light as possible, so the material should have a low density. If the wing is exposed to a marine atmosphere, *corrosion resistance* also may be important.

If we want to generate electricity for a satellite using a solar cell, the electrical and optical properties are most important in this case. The materials for solar cells, such as silicon, must interact with radiation, or light, to change the electron configuration of the atom. This interaction and change in structure in turn produce the desired electrical current.

Dimensional properties are not listed in property handbooks, and they are not even a legitimate category by most standards. However, the *available size*, *shape*, and *tolerances* of materials are often the most important *selection factors*. Thus we have established a category of properties relating to the shape of a material and its surface characteristics. *Surface roughness* is a *dimensional property*. It is measurable and important for many applications.

In each major category of material properties – chemical, physical, mechanical, and dimensional – there are many specific properties. It is important for the designer to understand the difference between, for example, physical and mechanical properties as well as to be familiar with the important properties in these categories.

In future we shall list a short definition of important properties in each of the major categories and then discuss how some of these properties are measured and used in material selection.

2.4 Property Spectrum

2.4.1 Chemical Properties

COMPOSITION: The elemental or chemical components that make up a material and their relative proportions.

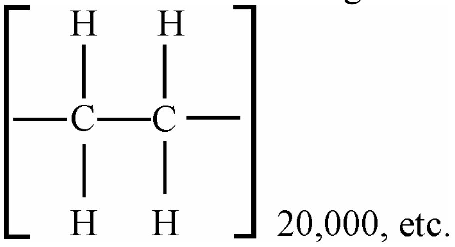
MICROSTRUCTURE: The structure of polished and etched materials as revealed by microscope magnifications greater than ten diameters; structure includes the *phases* present and the *morphology* of the phases.

CRYSTAL STRUCTURE: The ordered, repeating arrangement of atoms or molecules in a material.

STEREOSPECIFICITY: A tendency for polymers to form with an ordered preferential arrangement of monomer molecules.

CORROSION RESISTANCE: The ability of a material to resist *deterioration* by chemical or electrochemical reaction with its environment.

Composition This property can be determined by analytical chemistry. In metals, composition usually means the percentage of the various elements that make up the metal. The composition of a polymer consists of stating the chemical notation of the *monomer* with an indication of the chain length:



$$\left[-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}- \right]_{20{,}000,\text{ etc.}}$$

If the polymer is a *mixture* of polymers, the component *homopolymers* (polymers of a single monomer species) and their percentages should be stated. If the polymer contains a *filler* such as glass, this should also be stated with its proportion. The composition of a ceramic is usually the *stochiometric* (the quantitative relationship of elements in combination) makeup of the compound (e.g., the composition of the ceramic aluminum oxide would be Al_2O_3).

In material selection, composition is a fundamental consideration. The designer should always have some idea of what a material is made of. The composition of materials used in design is an answer.

Microstructure Studies of the *microstructure* of metals is one of the most useful tools of the metallurgist. Microstructure studies indicate grain size, phases present, condition of heat treat, inclusions, and the like. If, for example, the metallurgist wishes to measure the grain size of a steel, he cuts a small piece from the part, mounts it in a potting compound, polishes it to a mirror finish, and then applies a chemical *etching reagent*. Grain boundaries will etch at a different rate than the grains, thus leaving the grains standing out, and they become visible with a reflected light microscope.

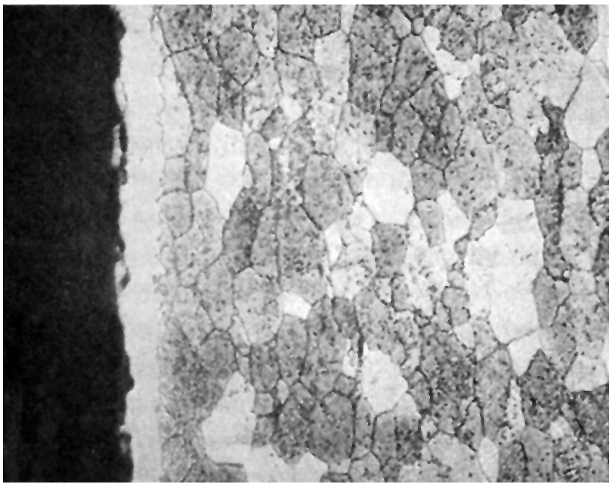


Figure 2.16 Coating penetration (white surface) on carbon steel (400×)

Figure 2.16 is a typical *photomicrograph* of a metal structure, received using *metallurgical microscope*. A similar polish and etch procedure is used to reveal the microstructure of ceramics. Because polymers are resistant to chemical etch, the microstructure of polymers is often revealed by special dying and lighting techniques.

Microstructures are invaluable to the materials engineer in solving problems and in understanding material responses to treatments. To the designer, microstructures may be indirectly involved in selection. For example, if a designer reads about a supercoating that will solve all *wear* problems, he can have it analyzed with metallographic techniques before committing an expensive part to be processed. Microstructure studies are also an important tool in studying why a part failed in service.

Crystal Structure As you know, the structure of a material can be considered on several levels, all of which influence the final behavior of the product (Figure 2.17). At the finest level is the structure of the individual atoms that compose the material (atomic structure). The arrangement of the electrons surrounding the nucleus of the atom significantly affects electrical, magnetic, thermal and optical behavior and may also influence corrosion resistance. Furthermore, the electronic arrangement influences how the atoms are bonded to one another and helps to determine the type of material – metal, ceramic, semiconductor, or polymer.

At the next level, the arrangement of the atoms in space is considered. As you know metals, semiconductors, many ceramics, and some polymers have a very regular atomic arrangement, or crystal structure. The crystal structure influences the mechanical properties of metals. Other ceramic materials and many polymers have no orderly atomic arrangement – these amorphous, or glassy, materials behave very differently from crystalline materials. For instance, glassy polyethylene is *transparent*, whereas crystalline polyethylene is *translucent*. Imperfections in either type of atomic arrangement may be controlled to produce profound changes in properties.

A grain structure is found in most metals, semiconductors, and ceramics and occasionally in polymers. The size and shape of the grains play a key role at this level. In some cases, as with silicon chips for integrated circuits or metals for jet engine parts, we wish to produce a material containing only one grain, or a *single crystal*.

Finally, in most materials, more than one phase is present, with each phase having its unique *atomic arrangement* and properties. Control of the type, size, dis-

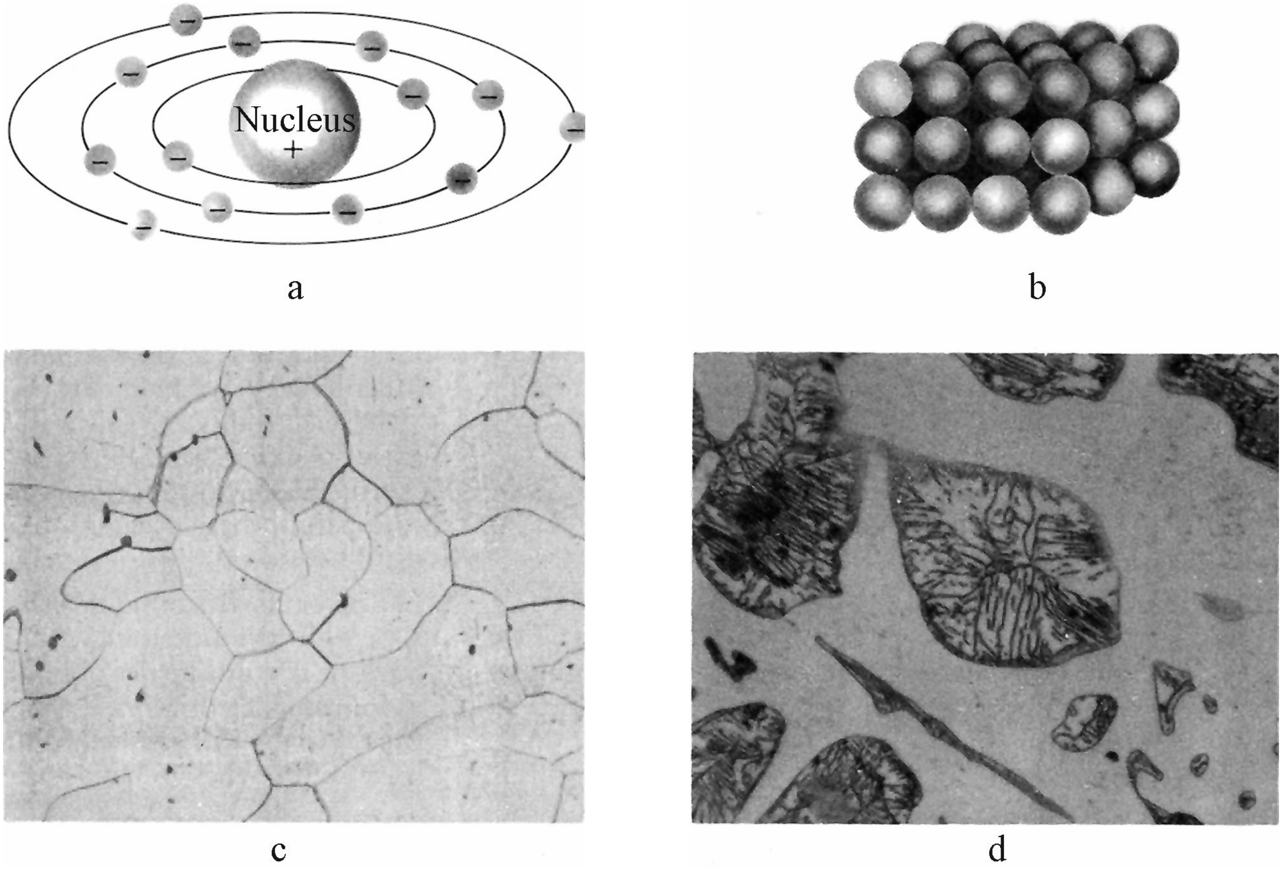


Figure 2.17 Four levels of structure in a material. (a) Atomic structure (aluminum, (b) crystal structure (pure iron), (c) grain structure in iron (×100), (d) multiple-phase structure in white cast iron (×200)

tribution, and amount of these phases within the main body of the material provides an additional way to control properties.

The atomic or molecular structure of metals, polymers, and ceramics is not an easy property to determine. Sophisticated techniques such as *X-ray diffraction* are required. Structure analysis tells the materials user if the structure is, for example, face-centered cubic (FCC) or body-centered cubic (BCC), and it is also used to study structure changes during processing. To be correct, crystal structure only applies to crystalline materials, but many polymers can have structures with enough order that they are considered to be crystalline.

Property of Stereospecificity It refers to the three-dimensional arrangement of elements in polymer molecules. Figure 2.18 shows an isotactic form of *polypropylene*.

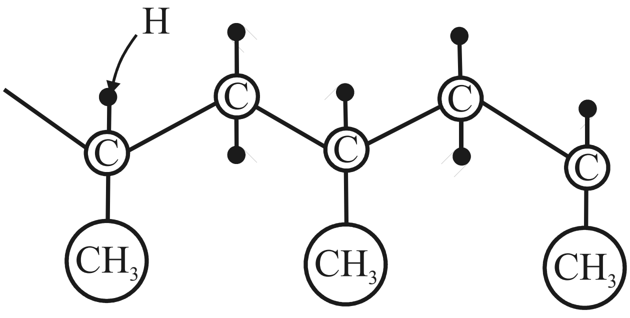


Figure 2.18 Isotactic form of polypropylene

Using techniques developed for studying crystal structure, it has been determined that all the *methyl groups* (CH_3) in this form of polypropylene are located on one side of the *polymer chain*. If these groups were connected at random to the chain, there would be no stereospecificity.

Designers will probably never select a material based on crystal structure, but it is a property of a material that helps the user to understand other more design-related characteristics. In metals, for example, all metals with a body-centered cubic structure get very brittle at *subzero* temperatures. Metals with a face-centered cubic structure do not. In polymers, crystallinity and stereospecificity affect melting characteristics and many mechanical properties. Similarly, many properties of ceramics are affected by the type of crystal structure.

Corrosion Resistance There are many forms of corrosion and many ways of measuring a material's corrosion resistance. At this point it is sufficient to say that this property applies to all materials and is an important selection factor for obvious reasons.

2.4.2 Physical Properties

Among the main physical properties the following are important for engineering use:

- **Gravimetric**
  - Density
  - Porosity
  - Specific gravity
- **Electrical**
  - Conductivity
  - Resistivity
  - Dielectric (for insulation)
  - Ferroelectricity and piezoelectricity
- **Magnetic**
  - Diamagnetic
  - Paramagnetic
  - Ferromagnetic
  - Ferrimagnetic
  - Antiferrimagnetic
- **Optical**
  - Absorption and color
  - Diffraction
  - Reffraction
  - Lasing action
  - Photoconduction

- Transmission

Thermal

- Melting point
- Heat capacity
- Thermal conductivity
- Thermal expansion
- Heat distortion temperature

Main Definitions

MELTING POINT: The point at which a material liquefies on heating or solidifies on cooling. Some materials have a melting range rather than a single melting point.

DENSITY: The mass of a material per unit volume.

SPECIFIC GRAVITY: The ratio of the mass or weight of a solid or liquid to the mass or weight of an equal volume of water.

CURIE POINT: The temperature at which ferromagnetic materials can no longer be magnetized by outside forces.

REFRACTIVE INDEX: The ratio of the velocity of light in a vacuum to its velocity in another material.

THERMAL CONDUCTIVITY: The rate of heat flow per unit time in a homogeneous material under steady-state conditions, per unit area, per unit temperature gradient in a direction perpendicular to area.

THERMAL EXPANSION (linear coefficient of): The rate at which a material elongates when heated. The rate is expressed as a unit increase in length per unit rise in temperature within a specified temperature range.

HEAT DISTORTION TEMPERATURE: The temperature at which a polymer under a specified load shows a specified amount of deflection.

WATER ABSORPTION: The amount of weight gain (%) experienced in a polymer after immersion in water for a specified length of time under controlled environment.

DIELECTRIC STRENGTH: The highest potential difference (voltage) that an insulating material of given thickness can withstand for a specified time without occurrence of electrical breakdown through its bulk.

ELECTRICAL RESISTIVITY: The electrical resistance of a material per unit length and cross section area or per unit length and unit weight.

SPECIFIC HEAT: The ratio of the amount of heat required to raise the temperature of a unit mass of a substance 1 degree (Kelvin) to the heat required to raise the same mass of water 1 K.

Two of the more general types of properties are *thermal* and *electrical*. Thermal properties arise from internal energies that introduce atomic and electronic movements. Also thermal energy can influence mechanical behavior and mechanical properties. Electrical properties have two prime sources: *electron movements* and *charge displacements*.

Thermal properties Three thermal properties will receive principal in this text: (1) *thermal expansion,* (2) *heat capacity,* and (3) *thermal conductivity* (Table 2.2). In general, the reader is aware of these as bulk properties, encountered in physics courses and listed as handbook data. In the last chapter, attention will be given to the origins of these properties and how they are related to the internal structure of materials.

Table 2.2 Principal thermal properties

Property	Symbol	Definition	SI units
Thermodynamic temperature	T	Thermal potential	K
Thermal expansion	α_l	Thermal expansion coefficient (linear)	K^{-1}
Thermal expansion	α_V	Thermal expansion coefficient (volume)	K^{-1}
Heat capacity	c	Mass heat capacity (c_p, c_V)	$\frac{J}{kg \cdot K}$
Thermal conductivity	λ	Thermal conductivity (coefficient of)	$\frac{W}{K \cdot m}$
Heat distortion	T	Heat distortion temperature	K

Electrical properties (Table 2.3) The reader is familiar with the fact that *electrical resistance*, expressed in ohms, is a consequence of geometry as well as of the material itself. In this text, we shall be primarily concerned with the *resistivity* of

Table 2.3 Principal electrical properties

Property	Symbol	Definition	SI units
Conductivity	σ	Proportionality constant between current density and electric field strength	s/m
Resistivity	ρ	Reciprocal of conductivity	$\Omega \cdot m$
Polarization	P	Dipole moment per unit volume	C/m^2
Relative dielectric permittivity	ε_r	Ratio of dielectric permittivity of material to that of free space	dimensionless
Dielectric permittivity	ε_a	Electric charge density per unit field strength $D = \varepsilon_a \cdot E$	F/m

materials. *Resistance* and *resistivity* are related as follows:

$$\rho = (R/l)(A); \tag{2.1}$$

$$\text{resistivity} = (\text{resistance/length}) \cdot (\text{area}) = (\Omega / m) \cdot \left(m^2\right) = \Omega \cdot m.$$

Electrical conductivity is the reciprocal of electrical resistivity and is expressed in mho/m ($\text{mho} = \Omega^{-1}$). Sometimes it is convenient to express conductivity as, the *electrical charge flux* per unit voltage gradient, *V/d:*

$$\sigma = 1/\rho = \text{flux}/(\text{V}/d); \tag{2.2}$$

$$\text{conductivity} = \frac{\text{C}/(\text{m}^2 \cdot \text{s})}{\text{V/m}}.$$

Since

$$\text{C} = \text{A} \cdot \text{s},$$

$$\text{conductivity} = \Omega^{-1} \cdot \text{m}^{-1}.$$

Polarization, an important concept for understanding the structures and properties of certain materials, is commonly defined as the dipole moment per unit volume. A *dipole moment* is developed within a material when the centers of positive and negative charges are not coincident. Assume, for example, that one *coulomb* of negative charge $-Q$, has been introduced on the right end (and a one coulomb positive charge $+Q$, on the left end) of the one-meter dipole ((literally, 2 poles) shown in Figure 2.19 (a)). Within an electric field at right angles to the dipole, a moment, or torque, of $1.00\ \text{C} \cdot \text{m}$ is developed.

The various types of dipole moments present within a material are associated with atoms, ions, or molecules (see Figure 2.19 (b)). Although their individual magnitudes are very small, the numbers of atomic dipoles per unit volume are large and provide a significant polarization.

Figure 2.19 Electrical dipoles (a). Example of a large dipole with a moment of *Qd.* (b) Dipole in an HF molecule. Since all the electrons cluster around the fluorine, leaving the hydrogen as an exposed proton, the centers of positive and negative charges are not coincident, and thus an electrical dipole is created

A third electrical characteristic of significance is the *dielectric constant.* This constant relates to polarization. In the meantime, it is sufficient to indicate that the dielectric permittivity ε_a is the proportionality constant between the electric charge-density, *D*, in C/m^2 and the *field strength* or *voltage gradient, E,* in V/m. This proportionality constant is usually factored into a dielectric constant for a vacuum, ε_0, and the *relative dielectric constant,* ε_r : thus,

$$D = \varepsilon_0 \varepsilon_r E, \tag{2.3}$$

where $\varepsilon_0 = 8.8544 \times 10^{-2}$ F/m (electric constant). The relative dielectric constant ε_r is a useful property for comparing insulators. For example, a capacitor with an insulating spacer of ε_r equal to 10 will hold 10 times the charge of a comparable capacitor with no spacer; i.e.,

$$\varepsilon_r = C/C_0, \tag{2.4}$$

where *C* and C_0 are the capacitances with and without dielectric material present.

Magnetic properties This type of properties is rather important in studying of a systems for electromagnetic energy transformation. The main magnetic properties are summarized in the Table 2.4.

Table 2.4 Principal magnetic properties

Property	Measure of property (definition)	Symbol	SI units
Diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism, antiferrimagnetism,	Magnetic permeability	μ	H/m
	Magnetic susceptibility	χ_m	dimensionless
	Remanent induction	B_r	T
	Saturation induction	B_s	T
	Reluctance	R_m	H^{-1}
	Permeance	Λ	H
	Kurie point	T_C	K
	Neel point	T_N	K

Use of Physical Properties

There are so many physical properties that it is not possible even briefly to describe all of them and how they are measured. Figure 2.15 is an attempt to categorize them, but this list (thermal, electrical, magnetic, gravimetric) is still inadequate. With the advent of nuclear materials in engineering, a whole new group of physical properties has arisen. Physicists measure the *neutron absorption characteristics* and susceptibility to *radiation damage,* for example.

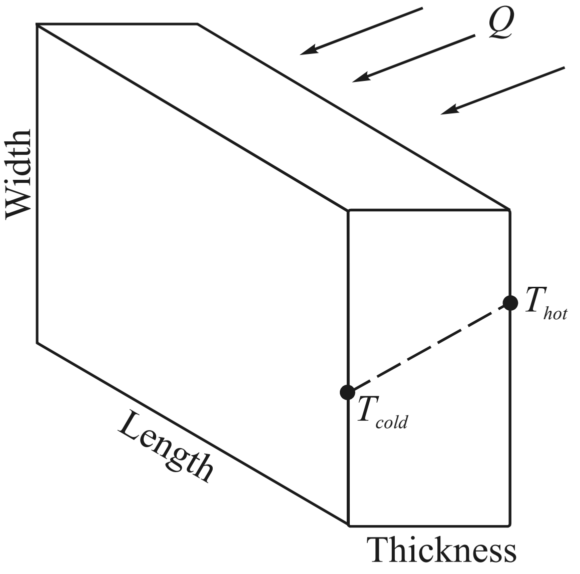


Figure 2.20 Steady-state heat flow through a solid: $Q=k_tA(\Delta T/\Delta x)$; Q – heat flow through a material, (W) per unit time; k_t – thermal conductivity; A – area through which heat will flow (width x length); ΔT-$(T_{hot}$-$T_{cold})$ – temperature differential; x–thickness

The designer must be concerned with thermal properties of materials any time that a part is to be used at some temperature other than the temperature at which it was fabricated, or if it is expected to perform some heat transfer function. Thermal conductivity is important in many machine applications: heat sealing heads, heat exchangers, heat sinks, heating platens, die casting, plastic molding cavities. Figure 2.20 shows the basic equation for steady-state heat flow. This property is simply coefficient λ in this equation. Fortunately, techniques for measuring thermal conductivity are such that λ values for polymers, ceramics, and metals can be compared for selection purposes.

Thermal expansion is important when dissimilar materials will be fastened and heated and when materials are locally heated. As an example, a designer complained to a materials engineer that his aluminum heat seal block was unstable at elevated temperature. He forgot to consider that he had the aluminum bolted to steel, and aluminum expands at twice the rate of steel – thus the cause of the distortion.

One of the most important selection factors for polymers is *maximum use temperature*. Many polymers lose all useful engineering properties at temperatures above 100 °C. The property of *heat distortion temperature* is more quantitative in that it does show what the material will do under a specified stress. Whenever a polymer is used at elevated temperature, a thorough study should be made on its response to the specific environmental conditions of the intended service.

In polymers, *water absorption* can be a very important selection factor if close dimensional tolerances need to be maintained on a part. A large number of engineering polymers swell significantly with increases in ambient relative *humidity*. The *moisture-absorption factor* should always be as low as possible if polymer part dimensions are critical.

The electrical properties of materials are very important when a design calls for a part to be an electrical conductor or insulator. *Electrical resistivity* is analogous to the k_t in the steady-state conduction equation in Figure 2.20. It determines the rate at which current will flow through a given cross section and through a given length. The unit used for metals is Ω·m (ohm·meter) in SI. Resistivity of wires can be measured with an ohmmeter. Metals have resistivities in the range of about 1 to 200 μΩ-cm, while ceramics and other good insulators have values usually greater than 10^{13} μΩ-cm.

Ceramics and polymers are frequently used as electrical insulators. Their relative ability to insulate is measured by such things as *arc resistance*, *dielectric strength*, and *dissipation factor* (*loss coefficient*). The measurement techniques for determining these properties are not discussed in this chapter.

The use of magnetic properties in material selection can be more complicated than using electrical properties. There are at least 20 of these properties listed in handbooks: *permeability*, *retentivity, hysteresis loss, coercivity, intrinsic induction,* and so on. Like some of the electrical properties, effective use of these properties in material selection will require more explanation than can be afforded in this discussion. Of all the magnetic properties of materials, the one that designers will have most occasion to use is simply whether a material will be attracted by a magnetic field. This property is *ferromagnetism* and only three common elements are ferromagnetic: iron, nickel, and cobalt. There are no relative rankings of ferromagnetic properties, and this can be a problem in dealing with some high alloys. Handbook tabulations of physical properties may ignore ferromagnetism. This property is important in solenoid-type devices, in magnetic separating devices, and even in machining. Most surface grinders use magnetic chucks, and fixtures are required for materials that are not ferromagnetic.

All steels except those with austenitic structures (FCC iron) are ferromagnetic, and all other metals except some high nickel and some cobalt alloys are not ferromagnetic. When using these latter alloys, it would be advisable to check alloy data sheets if ferromagnetism is important to the function of a device under design.

Ceramic compounds are magnetic too, because, for example original magnet, lodestone, is Fe_3O_4 and is related to many modern-day ceramic oxide magnets.

Ceramic materials have higher resistivites than metals, therefore, they have low energy losses through joule heating. Saturation magnetization and magnetic permeability are generally lower in ceramic magnets. This is partially due to the dilution effect, which arises from the fact that the oxygen in ceramic magnets gives fewer ferromagnetic atoms per unit volume.

Ceramic magnets are usually *ferrimagnetics.* That is, they possess an antiparallel alignment of ferromagnetic atoms.

In the extreme case of ferrimagnetism, the antiparallel moments are equal, and we use the term *antiferromagnetism*. This is illustrated by MnO in Figure 2.21.

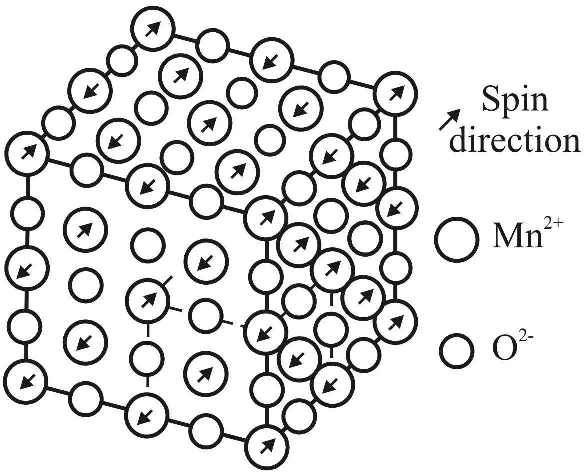


Figure 2.21 Antiferromagnetism (MnO). Although each Mn^{2+} ion has five Bohr magnetons, the net magnetic moment of the unit cell is zero because there are equal numbers of ions with spins aligned in the $[\bar{1}11]$ and $[1\bar{1}\bar{1}]$ directions

Half the Mn^{2+} ions have their spins in each direction, and the O^{2-} ions have no net spin. Although the net magnetic moments is zero, an antiferromagnetic material is unlike a diamagnetic material in that there is a temperature at which this ordered magnetic structure disappears. The magnetic susceptibility of an antiferromagnetic material is large at this temperature.

The last category of physical properties listed in Figure 2.15, *gravimetric*, deals with the weight or mass of materials. The most important properties relating to material selection are *density* and *specific gravity* (specific weight or specific density). It is good practice to compare densities in comparing costs of various materials. A polymer costing $20/kg may not look too expensive when the cost is expressed in dollars/cubic meter. There are more cubic meters in a kilogram of polymer than in a kilogram of steel. Another useful application of density or specific gravity information is to determine *porosity.* Materials such as ceramics and powder metals that are made by *compaction* and *sintering* have varying degrees of porosity. Sometimes property tabulations will show the percent theoretical density or *apparent density.* These types of data will supply information on porosity. In structural parts, porosity is often undesirable. In powdered metal wear parts, porosity is usually desired for retention of lubrication.

The above discussion of physical properties excluded 50 or so properties that could be important for some applications. The optical properties of polymers and ceramics are sometimes important selection factors. Design situations arise where even the velocity of sound in a material is an important selection factor. Unfortunately, there are just too many physical properties to cover them all in detail. The limited number of properties that have been discussed should provide guidance for most selection problems involving the physical properties of materials.

Example 2.1

Copper has a resistivity, ρ, of 1.54×10^{-6} Ω·cm at 0°C, and 2.22×10^{-6} ohm·cm at 100°C. What is the value of *dR/dT* per meter for a wire with diameter $d = 0.5$ mm if one assumes that the resistance, R, varies linearly with temperature?

Answer

$$\frac{1}{l}(\Delta R/\Delta T) = (R_{100^\circ} - R_{0^\circ})/100^\circ C = \frac{4(\rho_{100^\circ} - \rho_{0^\circ})}{(100^\circ \mathrm{C})\pi d^2},$$

$$= \frac{4(0.68\cdot10^{-8})}{100\pi(0.5\cdot10^{-3})^2} = 3.46\cdot10^{-8}\,\frac{\Omega}{\mathrm{K}\cdot\mathrm{m}}.$$

Example 2.2

If an electrical potential $\Delta\varphi$ of 0.10 volt is placed across a 6-meter length of the copper wire described in Example 1.1, how many electrons will enter the wire per second at 0°C? (The charge on each electron is 1.6×10^{-19} °C).

Answer

From Eq. (2.2)

$$\sigma=\frac{1}{\rho}=\frac{flux}{(\Delta\varphi/d)},\text{ where } d=6\text{ m},\ \Delta\varphi=0.10\text{ V},\ \rho=1.54\times10^{-8}\ \Omega\cdot\text{m}.$$

Then flux (current density) is

$$flux=j=\frac{1}{\rho}\cdot\Delta\varphi/d=\frac{0.10}{1.54\cdot10^{-8}\cdot6}=108.23\cdot10^{4}\text{ A/m}^2,$$

and current $I=j\cdot A=j\cdot\pi d^2/4=108.23\cdot10^4\cdot\pi\frac{(0.5\cdot10^{-3})}{4}=0.212\text{ A}$.

Because the charge $\Delta Q=I\cdot\Delta t$, where $\Delta t=1$ s,

$$\Delta Q=0.212\cdot1=0.212\text{ C}^\circ.$$

$$\text{Number of electrons/s }=\frac{0.212}{1.6\cdot10^{-19}}=1.325\cdot10^{18}.$$

Example 2.3

A capacitor designed to use wax-paper spacers (relative dielectric constant, $\varepsilon_{r\ paper}=1.75$) between aluminum-foil electrodes has a capacitance of 0.013 microfarad. A plastic film ($\varepsilon_{r\ plastic}=2.10$) with the same thickness is being considered as a substitute for the paper. If other factors equal, what would be the new capacitance of the capacitor?

Answer

From Eq. (2.4)

$$\varepsilon_r=\frac{C}{C_0};\ \frac{\varepsilon_{r\ plastic}}{\varepsilon_{r\ paper}}=\frac{C_{plastic}/C_0}{C_{paper}/C_0};$$

$$C_{plastic}=\left(\frac{2.10}{1.75}\right)(0.013)=0.0156\text{ microfarad}.$$

2.4.3 Mechanical Properties

By mechanical properties we mean those properties which a material has in response to mechanical forces. Mechanical properties are of foremost importance in selecting materials for structural machine components. Think of any tool, any power transmission device, any wear member, and list the properties needed for serviceability. Chances are your list would include a number of the factors listed in Figure 2.22: *strength, formability, rigidity, toughness,* and *durability.*

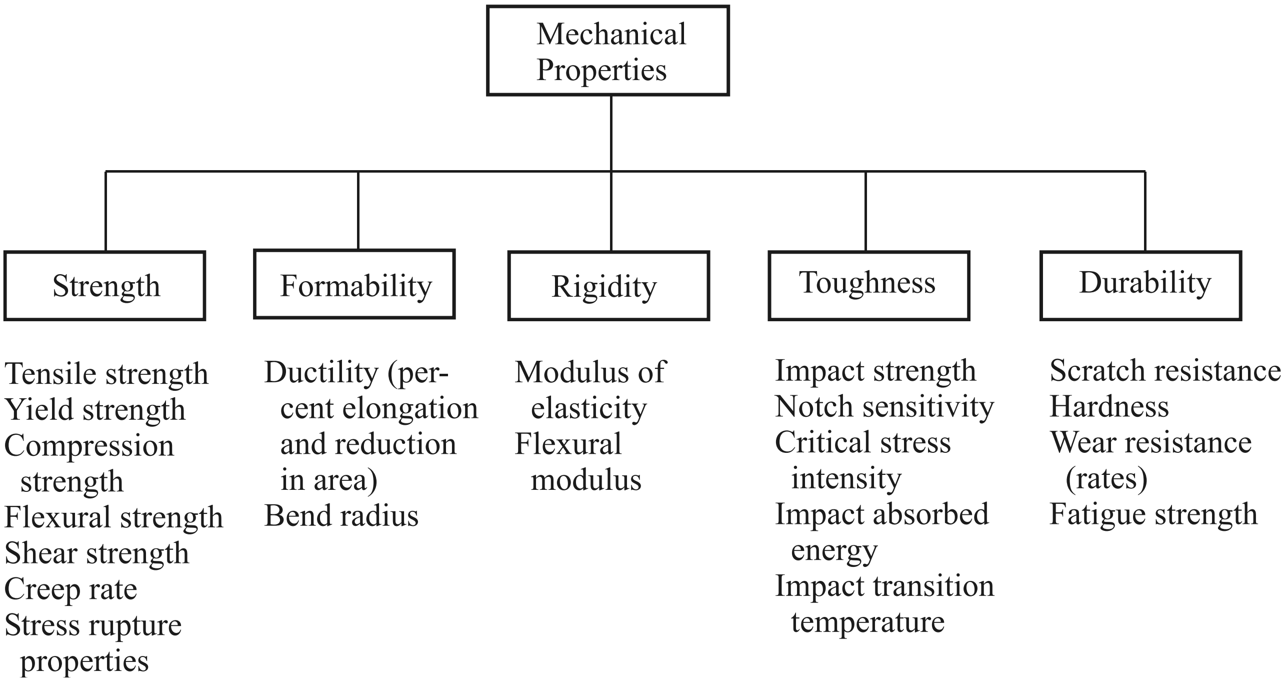


Figure 2.22 Serviceability factors and related mechanical properties

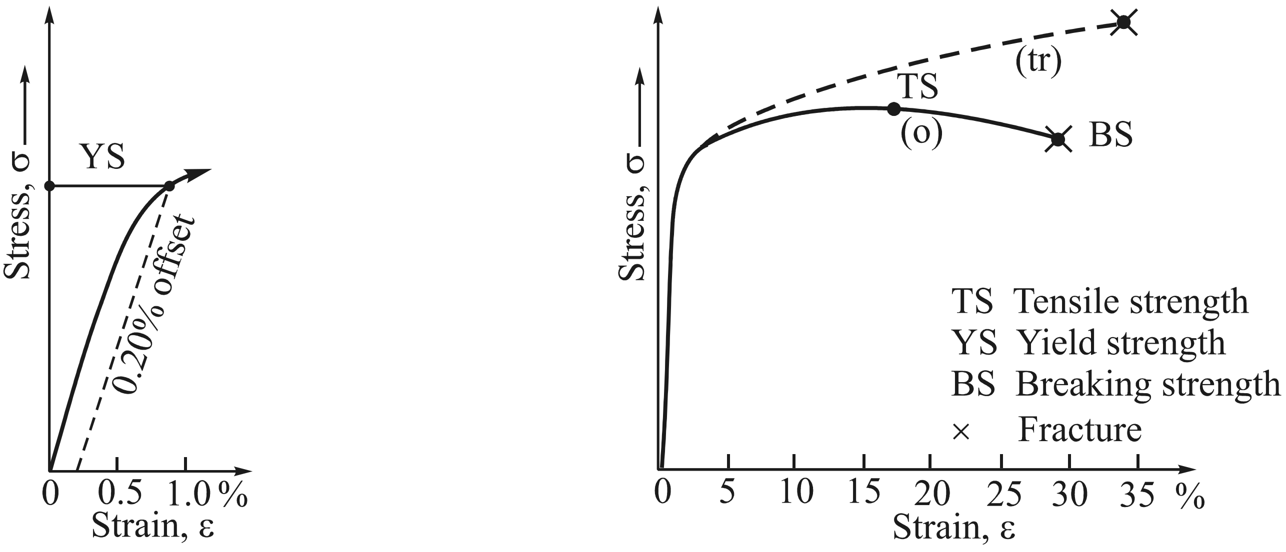
Rigidity, strength, ductility, hardness, and roughness are very important properties to know in order to anticipate the mechanical behavior of various materials. To measure mechanical properties there are many test, but five tests supply the most useful information:

1. Tensile tests;
2. Impact tests;
3. Hardness tests;
4. Creep tests;
5. Fatigue tests.

These tests will be referred in Chapter 3, and materials will be compared on data developed from these tests later.

As the result of tensile tests the main strength characteristics are measured and represented in Figure 2.23. This figure shows a *stress–strain curve (diagram)* which initially is linear and reversible. The *proportionality coefficient* relating the reversible strain to stress is called an *elastic modulus* (*modulus of elasticity*) and will subsequently reveal several characteristics of atomic bonding.

With sufficiently high stresses, ductile materials undergo a nonreversible yielding, or permanent *plastic deformation*. In practice, such plastic deformation produces a *reduction in cross-sectional area*. Thus stress-strain curves can be plotted on the basis of *original* dimensions or on the basis of *instantaneous*, or *true*, dimensions. The former are important for specifying the materials to be used in engineering products; the latter permit calculations of the *actual true stress* and *deformation*, and are important for interpreting what is happening within the materials itself.



a

b

Figure 2.23 Strain versus stress. (a) Enlarged strain axis of (b). Initially strain (deformation) is proportional to stress (force per unit area). This strain is reversible (elastic) when the stress is removed. Stresses beyond the elastic limit, or yield point, introduce a permanent, or plastic, deformation, and finally fracture, ×. (o) stress-strain curve based on original, or design, dimensions. True (tr) stress-strain curve based on minimum cross-sectional, or true, dimensions during deformation

Example 2.4

An aluminum bar has a reduction of area of 62 % and a breaking strength of 28,000 psi based on the original design area, A_0. Calculate (a) the true stress, σ_{tr}, and (b) the true strain, ε_{tr} just prior to fracture.

Answer

a) $\sigma_{tr} = 190\ \text{MPa} = F/A_0, F = 190 \cdot 10^6 A_0$.

Since $A_f = A_0 - 0.62A_0 = 0.38A_0$,

$$\sigma_{tr} = F/A_f = 190 \cdot 10^6 A_0 / 0.38A_0 = 50\ \text{MPa}.$$

b) Since the instantaneous strain $d\varepsilon_{tr}$ is equal to *dl/l,*

$$\varepsilon_{tr} = \int_{l_0}^{l_f} \frac{dl}{l} = \ln\frac{l_f}{l_0}.$$

Assuming constant volume,

$$A_f l_f = A_0 l_0,$$

$$\varepsilon_{tr} = \ln(A_0/A_f) = \ln\left[\frac{A_0}{0.38A_0}\right] = 0.97 = 97\ \%.$$

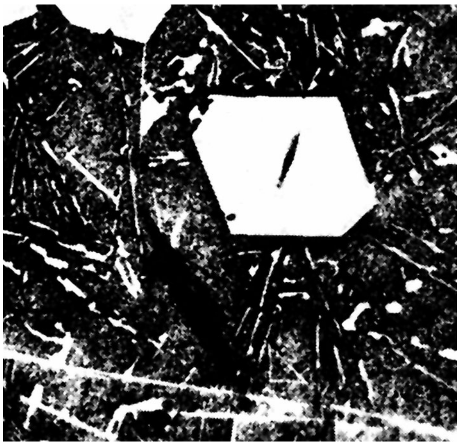


Figure 2.24 Hardness (Al+13% Si) [×125 (linear)]. The indentations made on two different components of a micro-structure reveal that the lighter, high-silicon area is harder than the dark, lower-silicon area. For ductile materials, hardness values may be used as an indication of strength

Hardness, which is the resistance of a material to plastic indentation, is not a simple property because complex stress patterns develop during the testing (Figure 2.24). However, hardness measurements can be made relatively easy and consistently to give an index of strength and structural coherence. Therefore we will make extensive use of these values to develop a qualitative understanding of properties-versus-structure relationships in later chapters.

Toughness is important in fracture and materials failure. Simply stated, toughness is the energy required for fracture. Hence, toughness is the integrated product of the stress and strain per unit volume required to produce fracture. Consequently, the units should be in-lb per in^3. However, the fracture process is complex in that the strains are not uniformly distributed during fracture, particularly in the region of a crack. Accordingly, toughness is represented as the number of inch-pounds (or foot-pounds) of force necessary to break a standard test specimen. Toughness values are of major importance to design engineers and can be related to the internal structure of a material.

Fatigue is a very dangerous mode of materials failure. It is the result of repeated loads applications as the stresses less than yield strength. The *endurance limit* is one of the important parameters of materials *durability*. It is most preferred design criterion.

Creep is the permanent plastic deformation at high and even normal temperatures. High materials qualities in creep are important for long service life.

Definitions of Main Mechanical Properties

TENSILE STRENGTH (ultimate strength): The ratio of the maximum load in a tension test to the original cross-sectional area of the test specimen.

YIELD STRENGTH: The stress in tension at which a material exhibits a specified deviation from proportionality of stress and strain.

COMPRESSIVE STRENGTH: The maximum compressive stress that a material is capable to withstand (based on original area).

COMPRESSIVE YIELD STRENGTH: The stress in compression at which a material exhibits a specified deviation from the proportionality of stress and strain.

MODULUS OF ELASTICITY: The ratio of stress to strain in a material loaded below its yield strength; a measure of rigidity.

POISSON'S RATIO: The absolute value of the ratio of the transverse strain to the corresponding axial strain in a body subjected to uniaxial stress.

FLEXURAL STRENGTH: The maximum stress material can withstand when it is loaded as a simply supported beam and deflected to a certain value of strain.

SHEAR STRENGTH: The stress required to produce failure in the plane of the cross section of a material. The conditions of loading are such that the directions of force and of resistance are parallel and opposite.

PERCENT ELONGATION: In tensile testing, the increase in the gage length measured after the specimen fractures within the gage length.

PERCENT REDUCTION IN AREA: In tensile testing, the difference, expressed as a percentage of original area, between the original cross-sectional area of a tensile test specimen and the minimum cross-sectional area measured after failure.

HARDNESS: The resistance of a material to plastic deformation (usually by indentation).

*IMPACT STRENGTH***:** The amount of energy required to fracture a given volume of material.

ENDURANCE LIMIT: The maximum stress below which a material can theoretically endure an infinite number of stress cycles.

CREEP: Time-dependent permanent strain under stress lower than yield stress.

CREEP STRENGTH: The constant nominal stress that will cause a specified quantity of creep in a given time at constant temperature.

STRESS RUPTURE STRENGTH: The nominal stress at fracture in a tension test at constant load and constant temperature (usually elevated).

2.5 Processing and Properties

Materials processing produces the desired shape of a component from the initial formless material (Table 2.5). Metals can be processed by pouring liquid metal into a mold (*casting*), joining individual pieces of metal (*welding, brazing*, *soldering, adhesive bonding*), forming the solid metal into useful shapes using high pressures (*forging, drawing, extrusion, rolling, bending*) (Figure 2.25), compacting tiny metal powder particles into a solid mass (powder metallurgy), or removing excess material (*machining*). Similarly, ceramic materials can be formed into shapes by related processes such as *casting, forming, extrusion, or compaction*, often while wet, and heat treatment at high temperatures to drive off the fluids and to bond the individual constituents together. Polymers are produced by injection of softened plastic into molds (much like casting), *drawing*, and *forming*. Often a material is heat treated at some temperature below its melting temperature to effect a desired change in structure. The type of processing we use depends on the properties, and thus the structure, of the material.

Table 2.5 Typical materials processing techniques

Metals	
Casting: sand, die cast, permanent mold, investment, continuous casting	Liquid metal is poured or injected into a solid mold to produce a desired shape
Forming: forging, wire drawing, deep drawing, bending, rolling	Solid metal is deformed by high pressure, often while hot, into useful shapes
Joining: gas welding, resistance welding, brazing, arc welding, soldering, friction welding, diffusion bonding	Several pieces of metal are joined together, using liquid metal, deformation, or high pressures and temperatures to provide bonding
Machining: turning, drilling, milling, cutting	Metal is removed by a cutting operation, leaving a finished shape
Powder metallurgy	Metal powders are compacted at high pressures into a useful shape, then heated at high temperatures to permit the particles to join together
Ceramics	
Casting, including slip casting	Liquid or slurries of liquid plus solid ceramics are poured into a desirable shape
Compaction: extrusion, pressing, isostatic forming	Solid or viscous slurries of liquid and solid ceramics are compacted into a useful shape
Sintering	Compacted solids are heated at high temperatures to cause the solids to bond together
Polymers	
Molding: injection molding, transfer molding	Hot or even liquid polymer is forced into a mold; this resembles the casting process
Forming: spinning, extrusion, vacuum forming	Heated polymer is forced through a die opening or around a pattern to produce a shape
Semiconductors	
Crystal growing	A liquid is frozen to produce a single crystal.
Chemical vapor decomposition	A solid is condensed from a gas onto a second substrate material.
Composites	
Casting, including infiltration	A liquid surrounds one of the constituents to produce the completed composite.
Forming	A soft constituent is forced by pressure to deform around a second constituent of the composite

Table 2.5 (finished)

Joining: adhesive bonding, explosive bonding, diffusion bonding	The two constituents are joined together by gluing, deformation, or high-temperature processes
Compaction and sintering	Powdered constituents are pressed into shapes, then heated to cause the powders to join

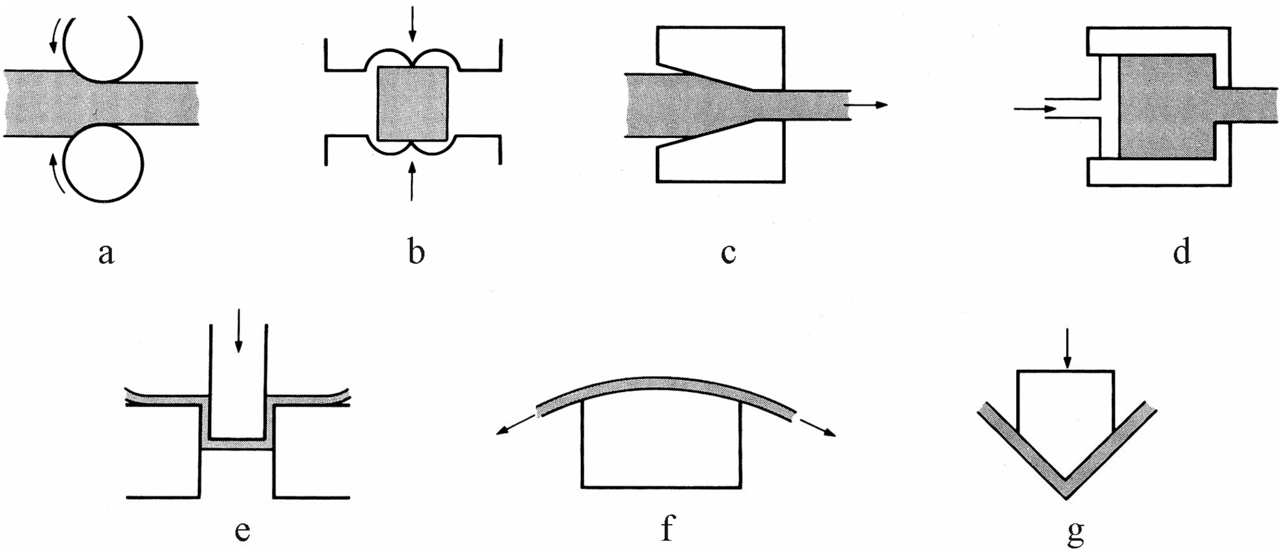


Figure 2.25 Schematic drawings of deformation processing techniques. (a) Rolling, (b) forging, (c) drawing, (d) extrusion, (e) deep drawing, (f) stretch forming, and (g) bending

Often a variety of materials are used during processing to produce a final component. One example of this is the *evaporative pattern casting* process for making aluminum castings illustrated in Figure 2.26. In this manufacturing process, a *polymer pattern* is made by expanding polystyrene beads into a die, forming a shape nearly identical to the intended part. The pattern is then coated with a thin layer of ceramic and backed up by loose sand grains (sand, or silica, is another ceramic). Finally, molten aluminum, a metal, is poured into the mold; the polymer pattern vaporizes as the metal takes its place. Solidification of the molten aluminum produces the final cast shape.

2.6 Environmental Effects on Material Behavior

The structure-property-processing relationship is also influenced by the surroundings to which the material is subjected.

Temperature Changes in temperature dramatically alter the properties of materials (Figure 2.27). The strength of most materials decreases as the temperature increases. Furthermore, sudden catastrophic changes may occur when heating above critical temperatures. Metals that have been strengthened by certain heat treatments or forming techniques may suddenly lose their strength when heated. Very low temperatures may cause a metal to fail in a brittle manner even though the applied loads are low. High temperatures can also change the structure of ceramics or cause polymers to melt or char.

The design of materials with improved resistance to temperature is essential in many technologies, as illustrated by the increase in operating temperatures of aircraft and aerospace vehicles (Figure 2.28).

As faster speeds are obtained, more heating of the vehicle skin occurs due to a friction with the air; in addition, engines operate more efficiently at higher temperatures. In order to obtain higher speeds and better fuel economy, new materials have gradually increased allowable skin and engine temperatures.

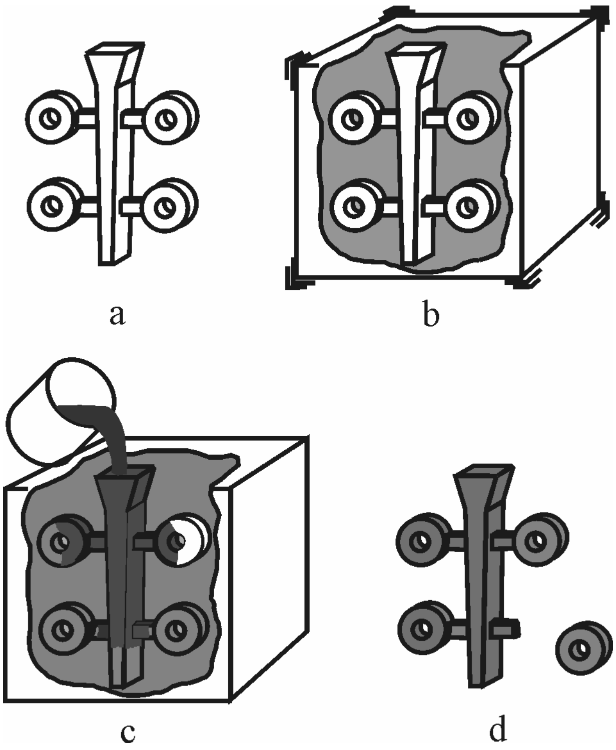


Figure 2.26 The evaporative pattern casting process involves the use of polymers and ceramics to produce a metal part, (a) an expanded polystyrene pattern is coated with ceramic, (b) the coated pattern is surrounded by vibrated sand, (c) molten metal vaporizes and displaces the Styrofoam, and (d) the solidified castings are removed from the tree and cleaned

Corrosion Most metals and polymers react with oxygen or other gases, particularly at elevated temperatures. Metals and ceramics may catastrophically disintegrate (Figure 2.29); polymers may become brittle. Materials are also attacked by a variety of corrosive liquids. A metal may be uniformly or selectively consumed or may develop cracks or pits, leading to premature failure (Figure 2.30). Ceramics can be attacked by other liquid ceramics, and solvents can dissolve polymers. The materials engineer faces the challenge of developing new materials or coatings that will prevent these reactions and permit materials to operate in more extreme *environments*.

If we want to join titanium by a welding process, it is necessary to remember that during welding, the titanium is heated to a high temperature. The high temperature may cause detrimental changes in the structure of the titanium and eliminate some of the strengthening mechanisms by which the properties of this metal were developed. Furthermore, titanium reacts rapidly with oxygen, hydrogen, and other gases at high temperatures. A welding must supply a minimum of heating to protect the metal from the surrounding atmosphere. Special gases, such as argon, or even a vacuum are needed for success.

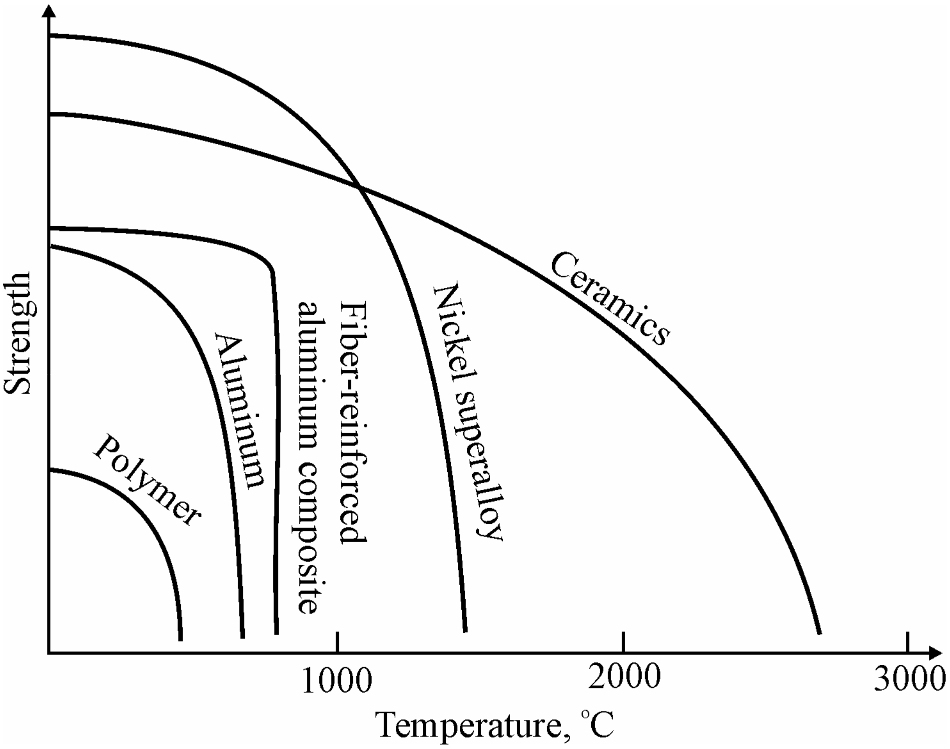


Figure 2.27 Increasing temperature normally reduces the strength of a material. Polymers are suitable only at low temperatures. Some composites, special alloys, and ceramics have excellent properties at high temperatures

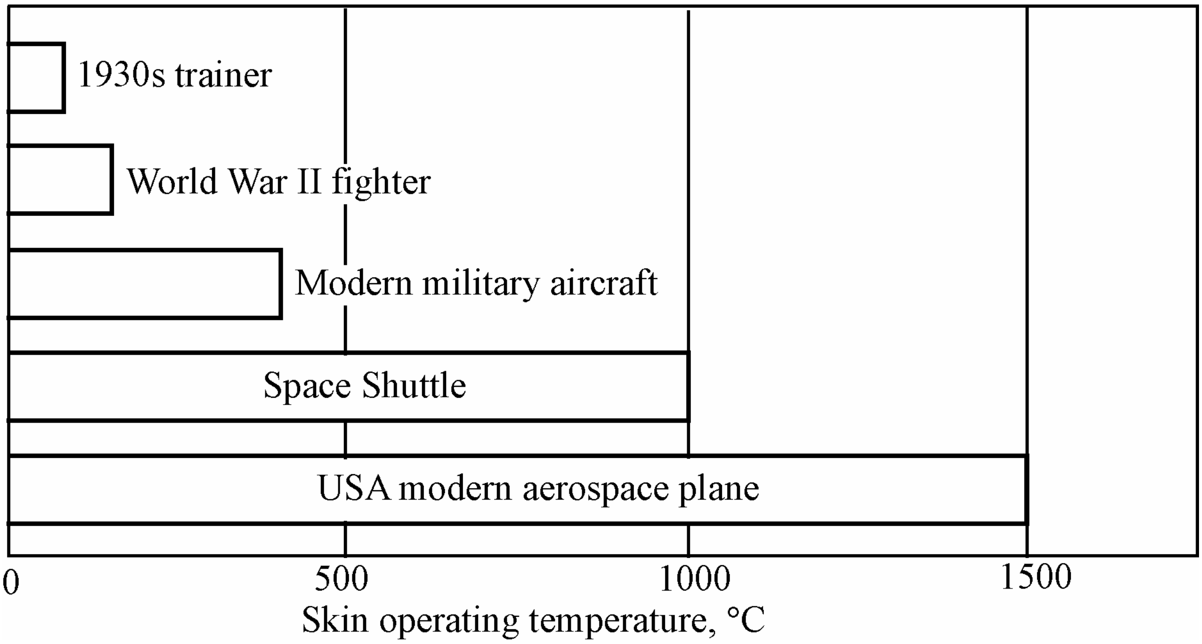


Figure 2.28 Skin operating temperatures for aircraft have increased with the development of improved materials

Figure 2.29 When hydrogen dissolves *in tough pitch copper*, steam is produced at the grain boundaries, thus creating thin voids. The metal is then weak and brittle and fails easily (×50)

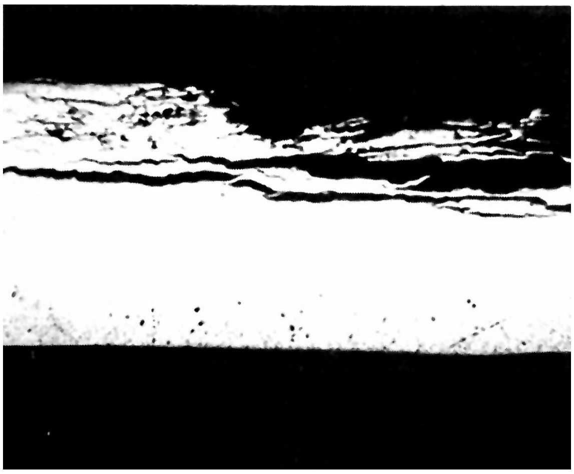


Figure 2.30 Attack of an aluminum fuel tank by bacteria in contaminated jet fuel causes severe corrosion, pitting, and eventual failure (×10)

Radiation High-energy *radiation*, such as neutrons produced in nuclear reactors, can affect the internal structure of all materials, producing a loss of strength, embrittlement, or critical alteration of physical properties. External dimensions may also change, causing swelling or even cracking.

Summary

The procedure of selecting a material, processing the material into a useful shape, and obtaining the needed properties is a complicated process involving knowledge of the structure-property-processing relationship. The remainder of this chapter is intended to introduce the reader to the wide variety of materials available. We must understand the fundamentals of the structure of materials, how the structure affects the behavior of the material, and the role that processing and environment play in shaping the relationship between structure and properties. All these factors must be studied to choose the structural material correctly.

Chapter 3 Mechanical Testing and Properties

Any designer must know the methods of controlling the microstructure and macrostructure of structural materials, because, by controlling the structure we in turn can control the mechanical properties to select the most advanced material for structure.

As has been considered earlier there are six important mechanisms used to control structure and properties – grain size strengthening, solid solution strengthening, strain hardening, dispersion strengthening, age hardening, and phase transformations (see Figure 1.87). All introduce barriers to slip. In the first three methods, we rely on the three types of lattice imperfections. By controlling surface defects such as grain boundaries, we obtain *grain size strengthening.* Controlling point defects such as substitutional atoms gives *solid solution strengthening.* Increasing the number of line defects, or dislocations, provides *strain hardening.*

We obtain strengthening in the other three mechanisms by introducing multiple phases, where each phase has a different composition or crystal structure. The boundaries between the phases can provide strengthening by interfering with the deformation mechanisms. *Dispersion strengthening* is a general term indicating strengthening by multiple phases. *Age hardening* is a special technique that provides an optimum, fine dispersion of phases. *Phase transformations* include more sophisticated treatments, often relying on allotropic transformations.

In technical university courses the strengthening mechanisms are discussed from the point of view of *processing* of the material. That is why *solidification*, *alloying*, *deformation* and *heat treatment* are examined. *Solidification* helps to determine grain size, grain shape, and the fineness and distribution of phases in many multiple-phase alloys. *Alloying* produces solid solution strengthening and provides the basis for dispersion strengthening. *Deformation processing* produces strain hardening and helps to control grain size and shape. *Heat treatment* permits us to perform the dispersion strengthening, age hardening, and phase transformation strengthening techniques.

After looking in Chapter 1 the strengthening mechanisms and the processes used to control these mechanisms, we can briefly examine the mechanical testing of materials and understand the results of these tests, which are the mechanical properties of a material.

We select materials for many components and applications by matching the mechanical properties of the material to the service conditions required of the component. The first step in the selection process requires that we analyze the application to determine the most important characteristics that the material must possess. Should the material be strong, or stiff, or ductile? Will it be subjected to repeated application of a high force, a sudden (impact) force, a high stress at elevated temperature, or abrasive conditions? Once we have determined the required properties, we can select the appropriate material using data listed in handbooks. However, we must know how the properties listed in the hand book are obtained, know what the properties mean, and realize that the properties listed are obtained from idealized tests that may not apply exactly to real-life engineering applications.

In this chapter we will study several tests that are used to measure how a material withstands an applied mechanical force. They are: tensile tests, impact tests, hardness tests, fatigue tests, fracture tests.

These tests will be referred to throughout this text, and materials will be compared on data developed from these tests. It is imperative that the designer understands how these tests are run and how to interpret the test information.

3.1 Tensile Tests

These tests are used to apply statically or slowly a stress to a material and record the material's response to this stress. As you remember the mathematical definition of stress (σ) is the load (F) on a body distributed over the cross-sectional area of the body (A):

$$\sigma = \frac{F}{A}. \tag{3.1}$$

As you know from applied mechanics a tensile stress tends to pull a member apart; a compressive stress tends to crush or collapse a body; a shear stress tends to cleave a structural member; a bending stress tends to deflect a member. Handbooks on material properties invariably list the properties of materials subjected to tensile loading. Data on a material's response to compression and shear are sometimes given, but often are not. The allowable torsional stress that a material can tolerate is measured by shear strength, and the allowable bending stress that a material can tolerate is based on the tensile properties. This is because bending puts the outer fibers of a member in tension.

A material's response to the three major forms of stress – tension, compression, and shear, can be measured on a universal testing machine, more commonly referred to as a *tensile tester*. These machines, one of which is shown in Figure 3.1, can pull axially on a test sample (tensile load) or push on a test sample to measure response to compression loading. Shear tests are run by loading a pin in a special fixture. A test setup is shown in Figure 3.2.

These machines apply a tensile load when one end of the test sample (specimen) is attached to a *movable crosshead* with the other end fixed to a *stationary member*. The crosshead is then driven in such a manner as to pull the sample apart. Compressive loading is achieved by driving the crosshead against short *stubby cylinders* placed on the *stationary* machine *platen*. Attachments are used to hold various shaped specimens, but tensile specimens are usually made in a “dog-bone” shape

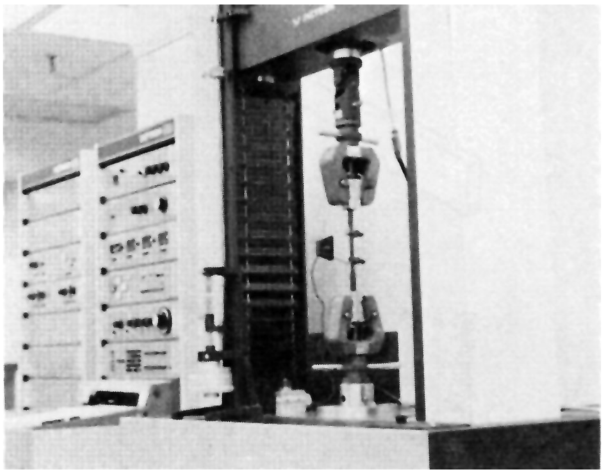


Figure 3.1 Typical universal test machine

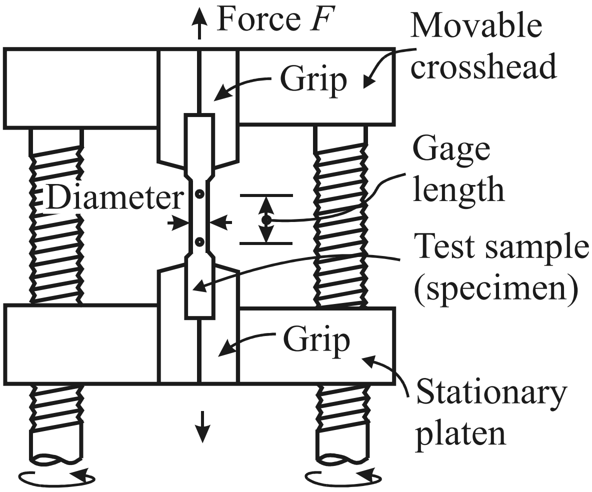


Figure 3.2 A unidirectional force is applied to a specimen in the tensile test by means of the movable crosshead

(Figure 3.3). The "dog-bone" shape ensures that the sample will break in the center and not in the grip area.

A typical specimen has a diameter of 0.505 in. and gage length of 2 in. (in national machinery 10 mm and 100 mm respectively).

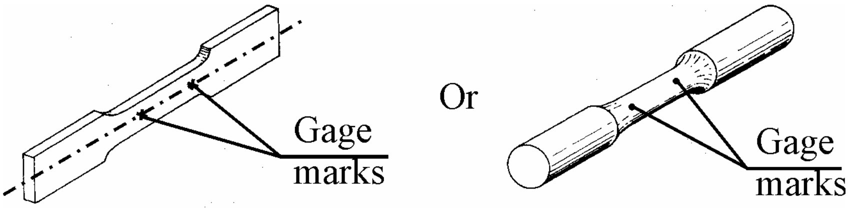


Figure 3.3 Tensile samples (specimens)

3.1.1 Stress–Strain Diagram

The specimen is placed in the testing machine and a force F is applied. A mechanical or electrical device – *strain gage* or *extensometer* is used to measure the amount that the specimen stretches between the *gage marks* when the force is applied until the specimen fails. The stretch, both elastic (recoverable) and plastic (permanent), is converted into *strain* by division of the change in length (extension or elongation) by the *original length*. Using the *original cross-sectional area* of the sample, the load F is converted into *stress*, and an *engineering stress-strain diagram* is obtained (Figure 3.4).

Table 3.1 includes the effect of the load on the gage length of an aluminum alloy test specimen and illustrates the concept of stress and strain.

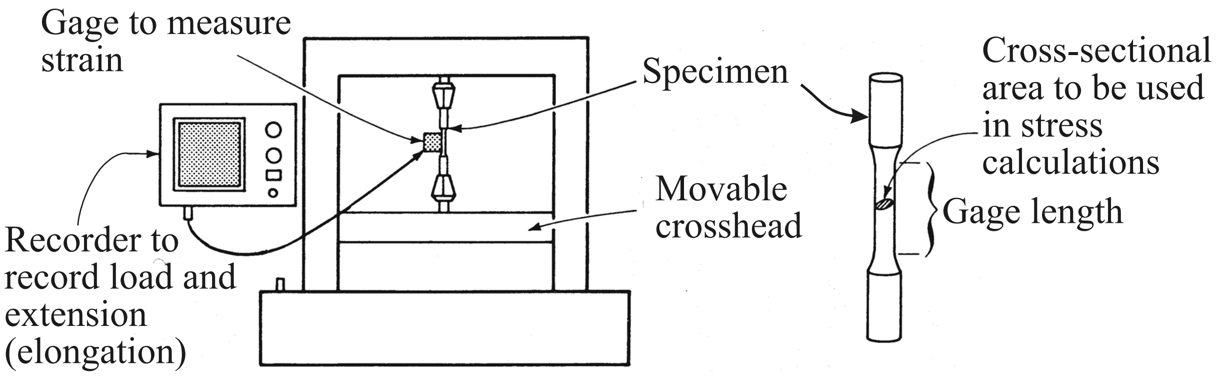


Figure 3.4 Concept of stress and strain

Table 3.1 The results of a tensile test of a 0.505-in. diameter aluminum alloy test specimen

Load, lb	Load, N	Stress, psi	Stress, MPa	Gage Length, in.	Gage Length, $\times 10^{-3}$ m	Strain, m/m
0	0	0	0	2.000	50.80	0
1,000	4,450	5,000	34.5	2.001	50.83	0.0005
3,000	13,350	15,000	103.4	2.003	50.88	0.0015
5,000	22,250	25,000	172.4	2.005	50.93	0.0025
7,000	31,150	35,000	241.3	2.007	50.98	0.0035
7,500	33,375	37,500	258.6	2.030	51.56	0.0500
7,900	35,155	39,500	272.3	2.080	52.83	0.0400
8,000	35,600	40,000	275.8	2.120	53.85	0.0600
8,000 (max.)	35,600 (max.)	40,000	275.8	2.160	54.86	0.0800
7,600 (fracture)	33,820 (fracture)	38,000	262.0	2.205	56.01	0.1025

Figure 3.5 shows the load versus gage length for our test. Displaying the results of the test in this manner describes the behavior of this material when the diameter is 0.505 in. Unfortunately, this figure does not tell us the force required to produce a given amount of stretching if the diameter is larger or smaller.

3.1.2 Engineering Stress and Strain

The results of a single test apply to all sizes and shapes of specimens for a given material if we convert the force to stress and the distance between gage marks to strain. *Engineering stress* and *engineering strain* are defined by the following equations:

$$\text{Engineering stress} = \sigma = \frac{F}{A_0}, \quad (3.2)$$

$$\text{Engineering strain} = \varepsilon = \frac{l - l_0}{l_0} \quad (3.3)$$

where A_0 is the original cross-sectional area of the specimen before the test begins, l_0 is the original distance between the gage marks, and l is the distance between the gage marks after force F is applied. The conversions from load-gage length to stress-strain are also included in Table 3.1. The stress-strain curve (diagram) (Figure 3.6) is usually used to record the results of a tensile test.

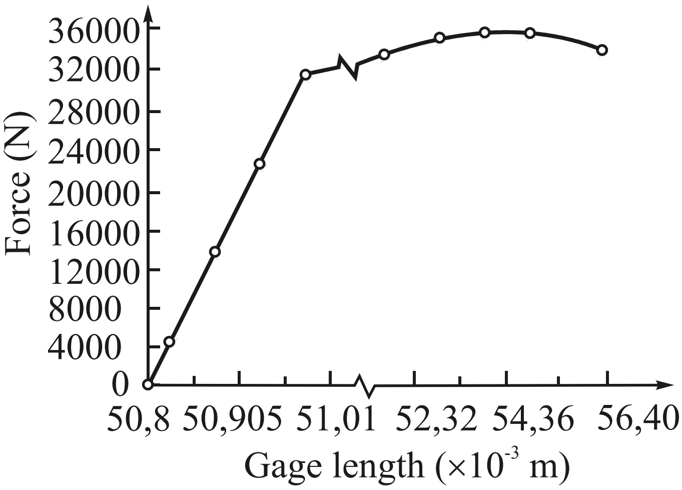


Figure 3.5 Graph of the load–gage length data from Table 3.1 for an aluminum alloy test specimen

Example 3.1

Convert the load-gage length data in Table 3.1 to engineering stress and strain and plot a stress-strain curve (diagram).

For the 1000-lb load (4,450 N)

$$\sigma = \frac{F}{A_0} = \frac{1000}{(\pi/4)\cdot(0.505)^2} = \frac{1000}{0.2} = 5000\,\text{psi} = 34.474\,\text{MPa},$$

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{2.001 - 2.000}{2.000} = 0.0005 \text{ in./in=0.0005 (dimensionless).}$$

The results of similar calculations for each of the remaining loads are given in Table 3.1 and are plotted in Figure 3.6.

It is important to note, that a 0.505-in. diameter is specified for the standard cylindrical test specimen in USA because the original cross-sectional area is 0.20 in^2 (1.29×10^{-5} m^2). We can convert force to stress simply by multiplying by five.

Example 3.2

Compare the force required to produce a stress of 25,000 psi (172,4 MPa) in a 1-in (0.0254 m) diameter bar and in a 2-in (0.051 m) diameter bar:

$$F = \sigma A_0 = (25{,}000)\left(\frac{\pi}{4}\right)(1)^2 = 19{,}635\text{-lb force (87,341 N) – for a 1-in. bar,}$$

$$F = \sigma A_0 = (25{,}000)\left(\frac{\pi}{4}\right)(2)^2 = 78{,}540\text{-lb force (349,363 N) – for a 2-in. bar.}$$

The engineering strain tells us how much each inch of the metal will stretch for a given applied stress. If the metal part is 10in. long, we can multiply the strain

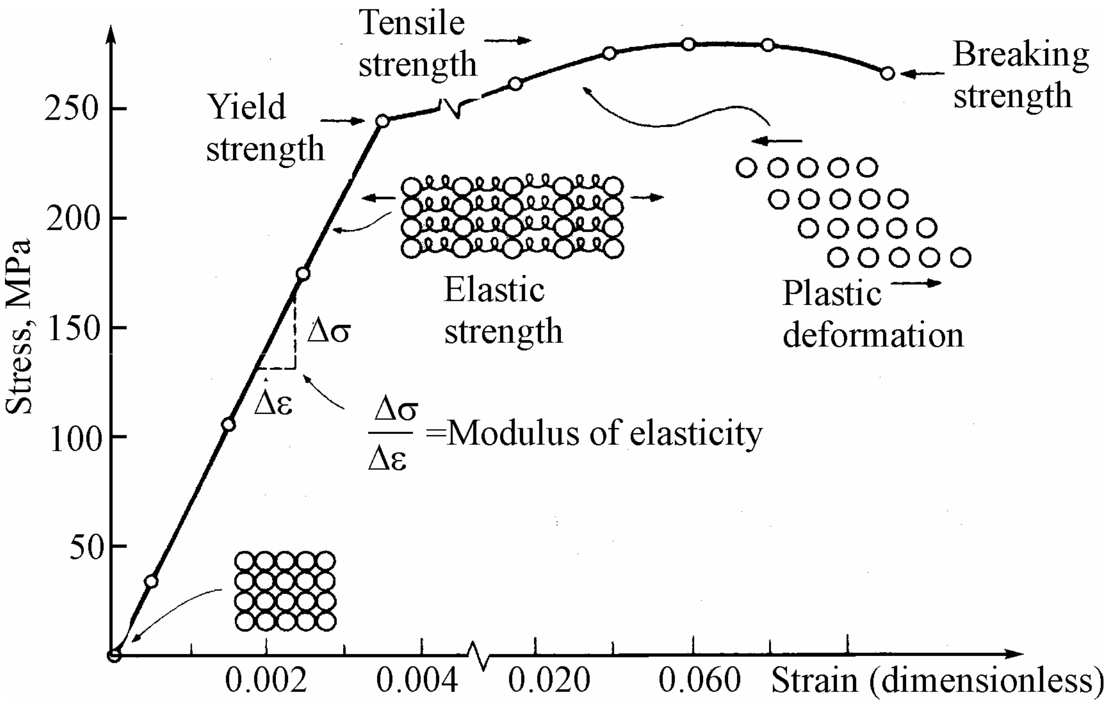


Figure 3.6 The stress–strain curve for an aluminum alloy from Table 3.1

by 10 to determine the total amount that the part will stretch, assuming that the part stretches uniformly.

Elastic versus Plastic Deformation

When a force is first applied to the specimen, the bonds between the atoms are stretched and the specimen elongates. When we remove the force, the bonds return to their original length and the specimen returns to its initial size. Stretching of the metal in this *elastic* portion of the stress-strain curve is recoverable.

Example 3.3

Suppose a 5000-lb force (22,241 N) is applied to a 0.505-in. (0.013 m) diameter bar that is 50 in. (1.27 m) long. The bar is made from the same aluminum alloy we have discussed previously. Determine the length of the bar when the force is applied.

Answer

$$\sigma = \frac{F}{A_0} = \frac{5000}{(\pi/4)(0.505)^2} = 25{,}000 \text{ psi} = 172.37 \text{ MPa}.$$

From Figure 3.6, $\varepsilon = 0.0025$ in./in.

$$\frac{l - l_0}{l_0} = 0.0025;$$

$$\frac{l-50}{50}=0.0025\,;$$
$$l=50+(0.0025)(50)=50.125\ \text{in=1.273 m.}$$

The results of tensile tests are measured using many different *units*. The most common units for stress are *pounds per square inch* (psi) and *megapascals* (MPa). The units for strain include inch/inch, centimeter/centimeter, and meter/meter. The conversion factors for stress are summarized in Table 3.2. Because strain is really dimensionless, no conversion factors are required to change the system of units.

Table 3.2 Units and conversion factors for stress

1 psi = pounds per square inch
1 MPa = megapascal
1 MN/m^2 = 1 MPa = meganewton per square meter
= newton per square millimeter
1 GPa = 1000 MPa = gigapascal
1 ksi = 1000 psi
1 ksi = 6.895 MPa
1 psi = 0.006895 MPa
1 MPa = 0.145 ksi = 145 psi

Example 3.4

Determine the stress in megapascals when a 5000-lb force is applied to a 0.505-in. diameter bar.

Answer

$$\sigma=\frac{F}{A_0}=\frac{5000}{(\pi/4)(0{,}505)^2}=25{,}000\ \text{psi;}$$
$$\sigma=(25{,}000\,\text{psi})(0.006895\,\text{MPa/psi})=172.4\,\text{MPa}\,.$$

3.1.3 Properties Obtained from the Tensile Test

Four very important mechanical properties are determined from the stress-strain diagrams.

1. Yield strength.
2. Tensile strength.
3. Modulus of elasticity.
4. Poisson’s ratio.

3.1.3.1 Yield Strength

If we are designing a structure component that must support a force applied during use, we must be sure that the component does not plastically deform. For this we must know the stress at which *slip* becomes significant, so called *yield strength.* It is the stress that divides the elastic and plastic behavior of the material. At this stress level the material permanently stretched. In most design situations this property is more important than the *tensile strength*, the stress at which the sample pulls apart. Most designers do not want a structure part to permanently deform under service stresses. Thus, design stresses should be significantly lower, than the *yield strength*.

We must select a material that has high yield strength, or we must make the structure component large so that the applied force produces a stress that is bellow the yield strength. On the other hand, if we are manufacturing shapes or components by some deformation process, the applied stress must produce the stress that exceeds the yield strength of the material to develop a permanent change in the shape of the material.

Example 3.5

You are to design a cable that must support an elevator cab that weighs 10,000 1b (44,482 N). The cable is made from the aluminum alloy in Example 2.1. Calculate the minimum diameter of the cable required to support the cab without permanent deformation.

Answer

We must not exceed the yield strength of 35,000 psi (241.32 MPa).

$$A_0 = \frac{F}{\sigma} = \frac{10{,}000}{35{,}000} = 0.286 \text{ in}^2,$$

$$d = \sqrt{\frac{4}{\pi} \cdot A_0} = \sqrt{\frac{4}{\pi} \cdot 0.286} = 0.603 \text{ in=0,015 m}.$$

Example 3.6

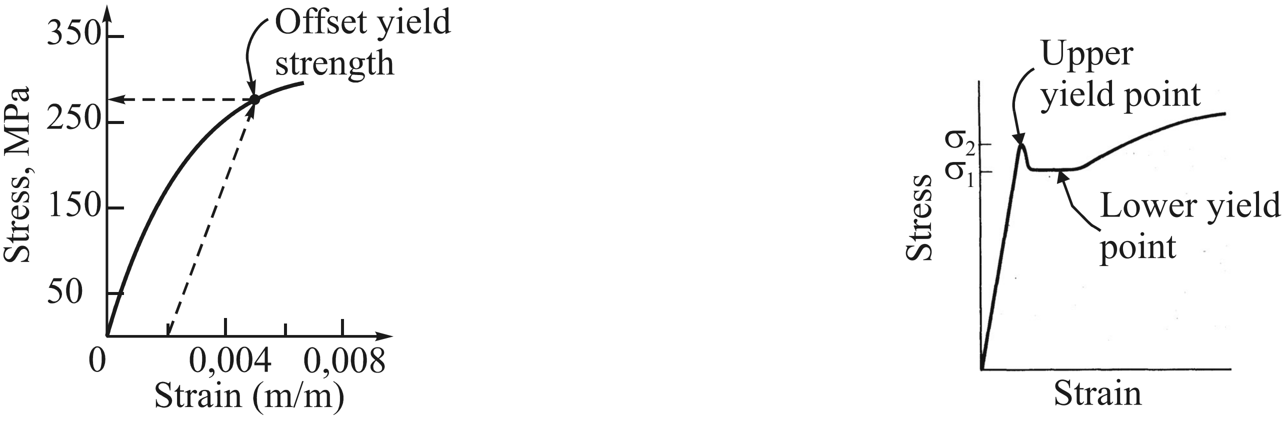
You wish to bend an aluminum bar which is 1/2 in. (0,013 m) × 6 in. (0,152 m) in cross section into a bracket by applying a tensile force. What is the minimum force that must be exerted by your forming equipment?

Answer

We must exceed the yield strength of 35,000 psi (241.3 MPa).

$$F = \sigma \cdot A_0 = (35{,}000)\left(\frac{1}{2}\right)(6) = 105{,}000 \text{ lb force} = 467{,}063 \text{ N}.$$

In some materials, the stress at which the material changes from elastic to plastic behavior is not easily detected and the stress-strain curve often has a different shape from that shown in Figure 3.6. In this case, we may determine an *offset yield* *strength* (Figure 3.7). We decide that a small amount of permanent deformation, such as 0.2% or 0.002 in./in., might be allowable without damaging the performance of our component. We can construct a line parallel to the initial portion of the stress-strain curve but offset by 0.002 in./in. from the origin. The 0.2% offset yield strength is the stress at which our constructed line intersects the stress-strain curve.



a

b

Figure 3.7 (a) Determing the 0.2 % offset yield strength in gray cast iron and (b) upper and lower yield point behavior in a low–carbon steel

Example 3.7

Determine the 0.2% offset yield strength for gray cast iron (Figure 3.7).

Answer

By constructing a line starting at 0.002 in./in. strain, which is parallel to the elastic portion of the stress-strain curve, we find that the 0.2% offset yield strength is 40,000 psi (275.8 MPa).

On the other hand, the stress-strain curve for certain low-carbon steels displays a *double yield point* (Figure 3.7 (b)). The material is expected to plastically deform at stress σ_1. However, small interstitial atoms clustered around the dislocations interfere with slip and raise the yield point to σ_2. Only after we apply the higher stress σ_2 does the dislocation slip. After slip begins at σ_2, the dislocation moves away from the clusters of small atoms and continues to move very rapidly at the lower stress σ_1. We can easily determine the lower (σ_1) yield strength for materials having this type of stress-strain behavior.

3.1.3.2 Tensile Strength

The *tensile strength* is the stress obtained at the highest applied force and thus is the maximum stress on the engineering stress-strain curve. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more

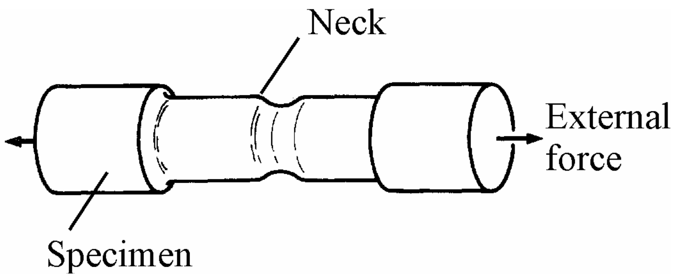


Figure 3.8 Localized deformation of a ductile material during a tensile test produces a necked region

than other areas and a large local decrease in the cross-sectional area occurs (Figure 3.8). This locally deformed region is called a *neck.* Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the *original* area A_0, will decrease. The tensile strength is the stress at which *necking* begins in ductile materials.

Tensile strengths are easy to measure. They are useful in comparing the behaviors of materials, and they permit us to estimate other properties which are more difficult to measure. However, the tensile strength is relatively unimportant for materials selection or materials fabrication – the yield strength determines whether the material will or will not deform.

3.1.3.3 Modulus of Elasticity

The *modulus of elasticity,* or *Young's modulus,* is the slope of the stress-strain curve in the elastic region. This relationship is *Hooke's law* (R. Hook, 1756):

$$E = \frac{\sigma}{\varepsilon} = \text{modulus of elasticity.} \tag{3.4}$$

The modulus of elasticity is closely related to the forces bonding the atoms in the material. A steep slope in the force-distance graph at the equilibrium spacing indicates that high forces are required to separate the atoms and cause the metal to stretch elastically. Thus, the metal has a high modulus of elasticity. Binding forces, and consequently the modulus of elasticity, are higher for high melting point metals (Table 3.3).

The modulus of elasticity is a measure of the *stiffness* or *rigidity* of the material. The units are *pounds per square inch* (psi) or *pascals* (Pa) in SI.

The modulus of elasticity is of crucial importance in material selection. It determines the elastic deflection of a structural member under load. It is also used in many stress and deflection calculations. Polymers have very low stiffness compared to metals, and this must be considered in selection (Figure 3.9).

If we are designing a shaft and bearing, we may need very close tolerances. But if the shaft deforms elastically, those close tolerances may cause excessive *rubbing*, *wear*, or *seizing*. Figure 3.10 shows the elastic behavior of iron and aluminum. If a stress of 30,000 psi (206.8 MPa) is applied to the shaft, the steel deforms elastically 0.001 in./in. while, at the same stress, aluminum deforms 0.003 in./in. Iron has a modulus of elasticity three times greater than that of aluminum.

Table 3.3 Relationship between the modulus of elasticity and the melting temperature of metals

Metal	Melting Temperature, °C	Modulus of elasticity, psi	Modulus of elasticity, MPa
Pb	327	2.0×10^6	13.8×10^3
Mg	650	6.5×10^6	44.9×10^3
Al	660	10.0×10^6	69.0×10^3
Ag	962	10.3×10^6	71.1×10^3
Au	1064	11.3×10^6	78.0×10^3
Cu	1085	18.1×10^6	124.9×10^3
Ni	1453	29.9×10^6	206.3×10^3
Fe	1538	30.0×10^6	207.0×10^3
Mo	2610	43.4×10^6	299.5×10^3
W	3410	59.2×10^6	408.5×10^3

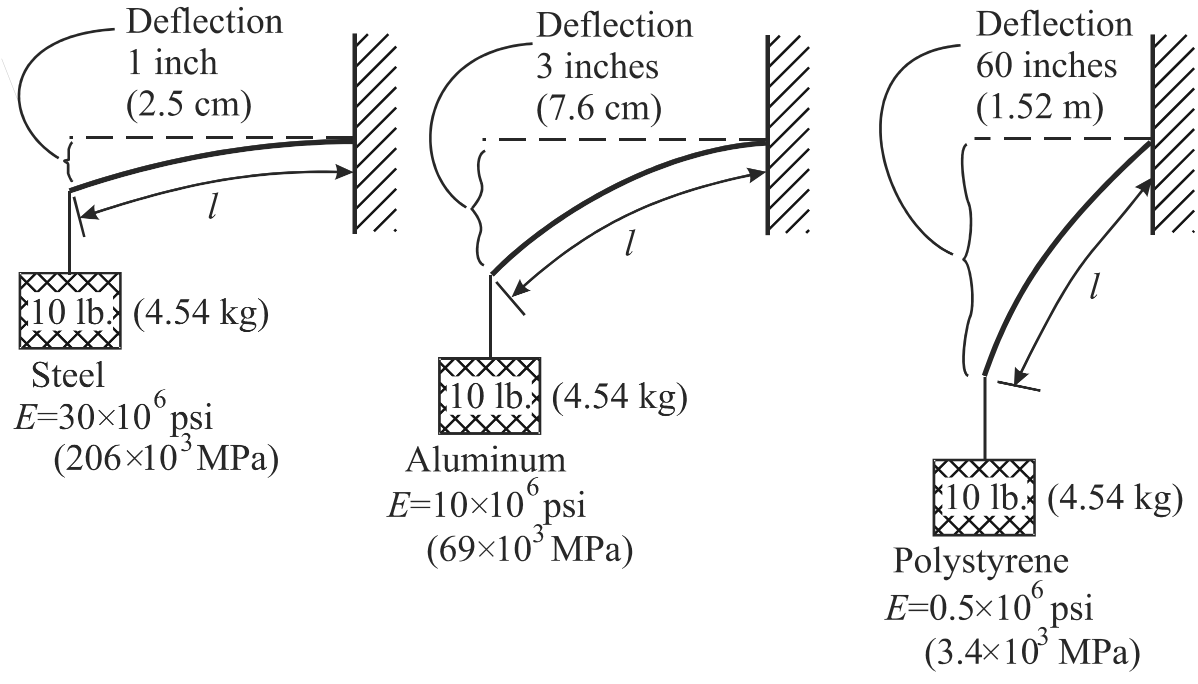


Figure 3.9 Effect of modulus of elasticity on elastic deflection. All beams have the same length and cross section

Example 3.8

From the data in Example 3.1, calculate the modulus of elasticity of the aluminum alloy. Use the modulus to determine the length of a 50-in. (1.27 m) bar to which a stress of 35,000 psi is applied.

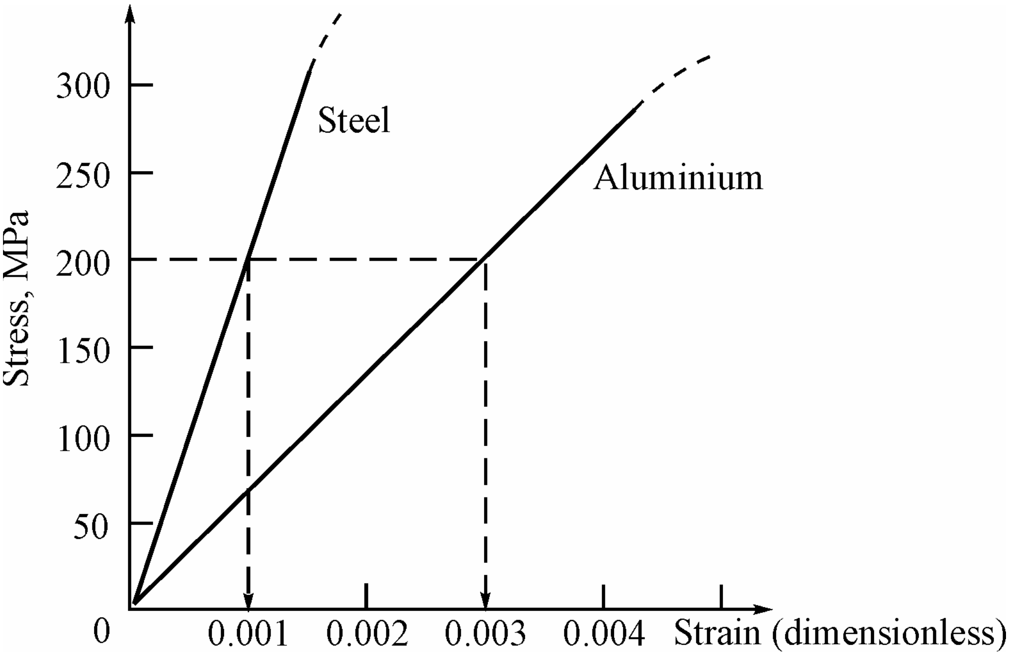


Figure 3.10 Comparison of the elastic behavior of steel and aluminum

Answer

When a stress of 35,000 psi (241.32 MPa) is applied, a strain of 0.0035 is produced. Thus

$$\text{Modulus of elasticity} = E = \frac{\sigma}{\varepsilon} = \frac{35{,}000}{0.0035} = 10 \times 10^6 \text{ psi} = 0.68948 \cdot 10^{11} \text{ Pa.}$$

From Hooke's law

$$\varepsilon = \frac{l - l_0}{l_0} = 0.0035,$$

and total length $l = l_0 + \varepsilon l_0 = 1.27 + (0.0035) \cdot (1.27) = 1.2744$ m.

3.1.3.4 Poisson's Ratio

It relates the *longitudinal* elastic deformation produced by a uniaxial tensile or compressive stress to the *lateral* deformation that must simultaneously occur:

$$\mu = -\frac{\varepsilon_{lateral}}{\varepsilon_{longitudinal}}. \tag{3.5}$$

For ideal materials, we can show that Poisson's ratio is $\mu = 0{,}5$. However, in real materials we find that less lateral strain develops than it would be predicted based on conservation of volume; typically, Poisson's ratios of $\mu = 0{,}3$ are measured for metals and alloys.

There are other important mechanical properties that can be obtained as the result of the tensile test: *percent elongation* (amount of sample stretch in the original gage section) and *percent reduction in area* (amount of necking in the gage section). These two properties are measures of the *ductility* of materials. Percent elongation is obtained by putting the two halves of a fractured tensile specimen back together and measuring the total stretch in the gage length:

$$\text{percent elongation} = \frac{l_f - l_0}{l_0} \cdot 100, \tag{3.6}$$

where l_f is the distance between gage marks after the specimen *breaks*.

A second approach is to measure the percent change in cross-sectional area at the point of fracture *before* and *after* the test. This percent reduction in area describes the amount of thinning that the specimen undergoes during the test:

$$\text{percent reduction in area} = \frac{A_0 - A_f}{A_0} \cdot 100, \tag{3.7}$$

where A_f is the final cross–sectional area at the fracture surface, and A_0 – original area.

Ductility is important to both designers and manufacturers. The designer of a component would prefer a material that displays at least some ductility so that, if the applied stress is too high, the component deforms before it breaks. Fabricators want a ductile material so they can form complicated shapes without breaking the material in the process.

Example 3.9

The aluminum alloy in Example 3.1 has a final gage length after failure of 2.195 in. (0.056 m) and a final diameter of 0.398 in. (0.010 m) at the fractured surface. Calculate the ductility of this alloy.

Answer

a) $$\text{percent elongation} = \frac{l_f - l_0}{l_0} \cdot 100 = \frac{2.195 - 2.000}{2.000} \cdot 100 = 9.75\,\%.$$

b) $$\begin{array}{c}\text{percent}\\ \text{reduction}\\ \text{in area}\end{array} = \frac{A_0 - A_f}{A_0} \cdot 100 = \frac{(\pi/4)(0.505)^2 - (\pi/4)\cdot(0.398)^2}{(\pi/4)\cdot(0.505)^2} \cdot 100 = 37.8\,\%.$$

The final gage length is less than 2.205 in. (0.056 m) (see Table 3.1) since, after fracture, the elastic strain is recovered.

3.1.4 True stress–true strain

The decrease in engineering stress beyond the tensile point occurs because of our definition of engineering stress. We used the original area A_0 in our calculations, which is not precise because the area continually changes (decreases). We define *true stress* and *true strain* by the following equations:

$$\text{True stress} = \sigma_{tr} = \frac{F}{A}, \tag{3.8}$$

$$\text{True strain} = \varepsilon_{tr} = \int \frac{dl}{l_0} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{A_0}{A}\right), \tag{3.9}$$

where A is the *actual area* at which the force F is applied. The expression ln (A_0/A) must be used after necking begins. The true stress-strain curve is compared with the engineering stress-strain curve in Figure 3.11. The true stress continues to increase after necking because, although the load required decreases, the area decreases even more.

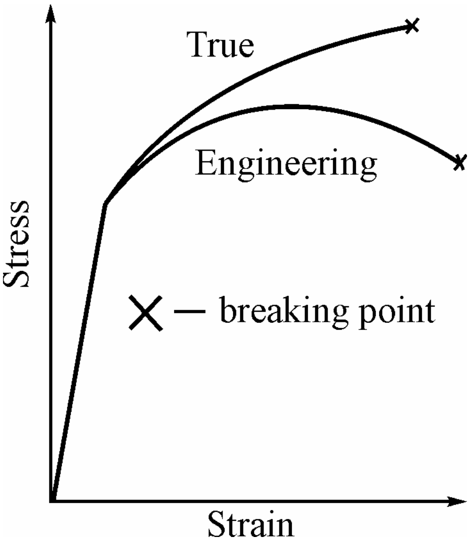


Figure 3.11 The relationship between the true stress-true strain diagram and the engineering stress-strain diagram

We seldom require true stress and true strain. As soon as we exceed the yield strength, the metal begins to deform. Our component has failed because it no longer has the original intended shape. Furthermore, a significant difference develops between the two curves only when necking begins. But when necking begins, our component is grossly deformed and no longer satisfies its intended use.

Example 3.10

Compare the engineering stress and strain with the true stress and strain for the aluminum alloy in Example 3.6 at (a) the maximum load and (b) fracture. The diameter at maximum load is 0.497 in. (0.013 m) and at fracture is 0.398 in. (0.010 m).

Answer

(a) At the tensile or maximum load

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{8000}{(\pi/4)(0.505)^2} = 40{,}000 \text{ psi} = 275.8 \text{ MPa}.$$

$$\text{True stress} = \frac{F}{A} = \frac{8000}{(\pi/4)\cdot(0.497)^2} = 41{,}237 \text{ psi} = 284.3 \text{ MPa}.$$

$$\text{Engineering strain} = \frac{l - l_0}{l_0} = \frac{2.120 - 2.000}{2.000} = 0.060.$$

$$\text{True strain} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{2{,}120}{2{,}000}\right) = 0.058.$$

(b) At fracture

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{7600}{(\pi/4)\cdot(0.505)^2} = 38{,}000 \text{ psi}=262 \text{ MPa.}$$

$$\text{True stress} = \frac{F}{A} = \frac{7600}{(\pi/4)\cdot(0.398)^2} = 61{,}090 \text{ psi}=421.2 \text{ MPa.}$$

$$\text{Engineering stress} = \frac{l-l_0}{l_0} = \frac{2.205-2.000}{2.000} = 0.1025 \text{ in./in.}$$

$$\text{True strain} = \ln\left(\frac{A_0}{A}\right) = \ln\left[\frac{(\pi/4)\cdot(0.505)^2}{(\pi/4)\cdot(0.398)^2}\right] = \ln(1.610) = 0.476.$$

The true stress becomes much greater than the engineering stress only after necking begins.

3.1.5 Shear Strength

A common application of metals in engineering design is in shear loading. Bolts, rivets, and drive keys are loaded in such a manner as to cleave the material in half. The shear strength of a material is the stress at which a shear-loaded member will fail. A shear test can be performed in a tensile machine with special grips replacing the tensile specimen (Figure 3.12).

It is not common to use polymers or ceramics as shear-loaded devices in machines, and thus their shear properties are seldom reported in handbooks. The application of the property of shear strength in machine design is obvious. It is this property that must be considered on shear–loaded fasteners and the like. Unfortunately, it is often difficult to find good tabulations in the literature on shear strength. A useful and conservative relationship to use if this is the case is shear strength ≈ 40% of the tensile strength.

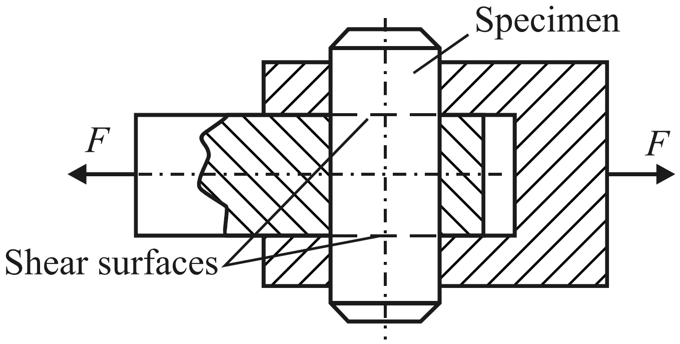


Figure 3.12 Shear test fixture for use in a tensile machine

3.1.6 Temperature Effects in Materials Testing

The tensile properties are significantly affected by temperature (Figure 3.13). The yield strength, tensile strength, and modulus of elasticity decrease at higher temperatures, whereas the ductility, as measured by the amount of strain at failure, commonly increases. A materials fabricator may wish to deform a material at a high temperature (known as *hot working*) to take advantage of the higher ductility and lower required forces.

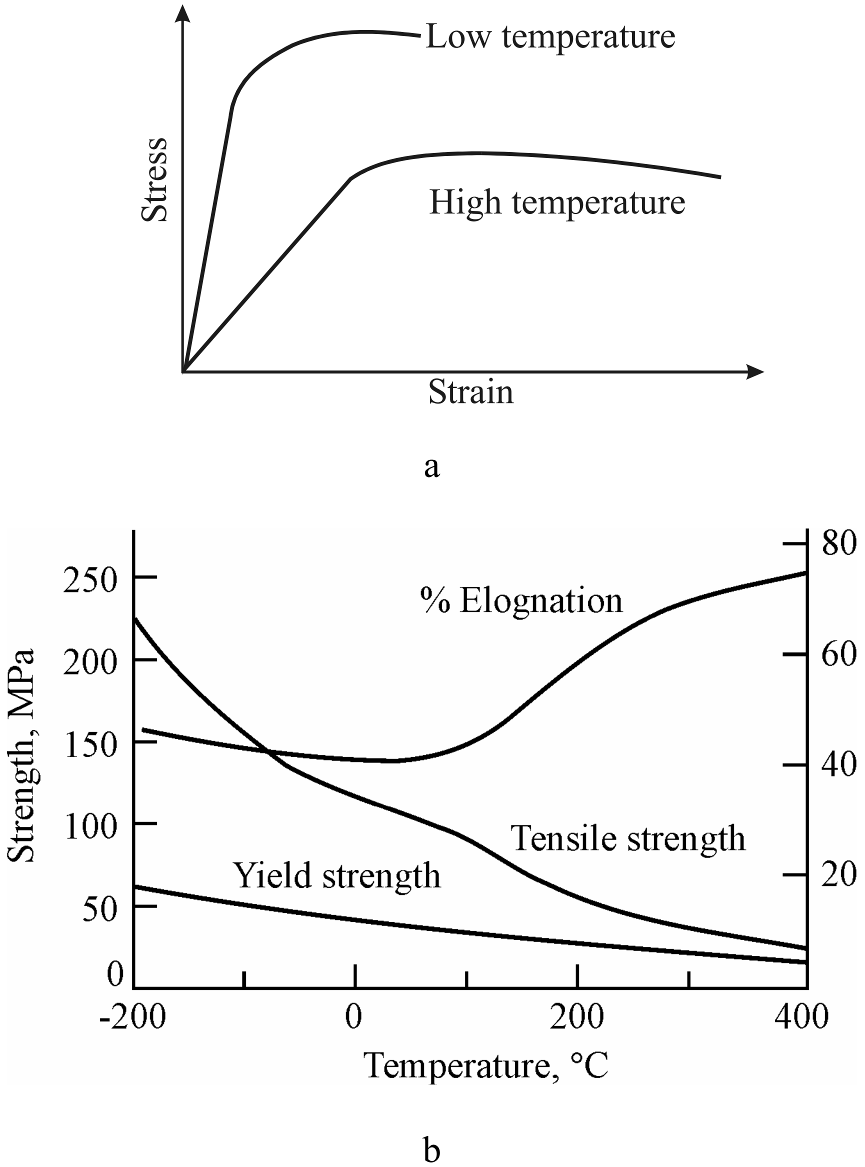


Figure 3.13 The effect of temperature (a) on the stress–strain curve and (b) on the tensile properties of an aluminum alloy

3.1.7 Brittle Behavior

Ductile materials display an engineering stress-strain curve that goes through a maximum at the tensile strength. In more brittle materials, the maximum load or tensile strength occurs at the point of failure. In extremely brittle materials, such as ceramics, the yield strength, tensile strength, and breaking strength are all the same (Figure 3.14).

In many brittle materials, particularly ceramics and certain composite materials, the normal tensile test cannot easily be performed due to the presence of flaws at the surface. Often, placing the brittle material in the grips of the tensile testing machine will cause these flaws to promote cracking, invalidating the test. Preparation of tensile specimens of brittle materials may also be expensive. One approach used to minimize these problems is the *bend test* (Figure 3.15). By applying the load at three points and causing bending, a tensile force acts on the material opposite the middle point. Fracture begins at this location. The *flexural strength* or *modulus of rupture* (MOR), given by equation (3.10), is used to describe the strength of the material:

$$\text{Flexural strength} = \frac{3Fl}{2bh^2} \text{ MPa}, \tag{3.10}$$

where F is the applied load, l is the distance between the two outer points, b is the width of the specimen, and h is the height of the specimen.

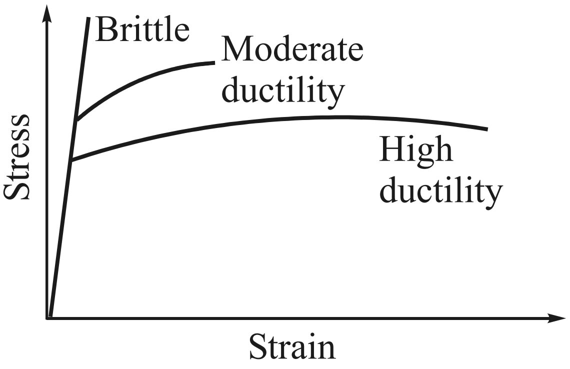


Figure 3.14 The stress-strain behavior for brittle materials compared with that of more ductile materials

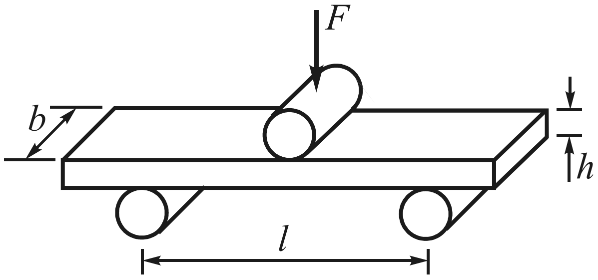


Figure 3.15 The modulus of rupture test often used for measuring the strength of brittle materials

Since cracks and flaws tend to remain closed in compression, brittle materials are often designed so that only compressive stresses are acting on the part. Often, we find that brittle materials fail at much higher compressive stresses than tensile stresses (Table 3.4), although ductile materials such as metals may have tensile and compressive strengths that are nearly equal.

Table 3.4 Comparison of the tensile, compressive, and flexural strengths of selected ceramic and composite materials

Material	Tensile strength, psi	Tensile strength, MPa	Compressive strength, psi	Compressive strength, MPa	Flexural strength, psi	Flexural strength, MPa
Polyester – 50% glass fibers	23,000	159	32,000	221	45,000	310
Polyester – 50% glass fabric	37,000	255	27,000	186	46,000	317
Al_2O_3	30,000	207	375,000	2586	50,000	345
SiC	25,000	172	100,000	689	37,000	255

Example 3.11

The flexural strength of a composite material reinforced with glass fibers is 45,000 psi. The specimen, which is 0.5 in. (0.013 m) wide, 0.375 in. (9.53×10^{-3} m) high, and 8 in. (0.203 m) long, is supported between two rods 5 in. (0.127 m) apart. What force is required to fracture the material?

Answer

In our case the dimensions are: $b = 0.5$ in., $h = 0.375$ in., and $l = 5$ in. From equation (3.10)

$$45{,}000 = \frac{3Fl}{2bh^2} = \frac{(3)(F)(5)}{(2)(0.5)(0.375)^2} = 106.7F\,,$$

$$F = \frac{45{,}000}{106.7} = 422 \text{ lb} = 1877 \text{ N}.$$

3.2 Impact Test

3.2.1 Types of Impact Test

The tensile test is normally performed at a low strain rate, at which the specimen is very slowly loaded and elongated. When a material is subjected to a sudden, intense blow, in which the strain rate is extremely rapid, the material may behave in a much more brittle manner than is observed in the tensile test.

Impact strength is used to measure a material's ability to withstand shock loading. The classic definition of impact strength is the energy required to fracture a given volume of material, so called *impact energy* absorbed by specimen during failure. The units of this property are reported as foot-pounds (ft·lb) in the English system and joules/cubic meter (J/m^3) in the metric system (SI), where $1 \text{ ft} \cdot \text{lb} = 1.356 \text{ J}$.

The ability of a material to withstand an impact blow is often referred to as the *toughness* of the material. It is interesting, that ceramics and brittle metals such as gray cast iron have negligible toughness.

In metals and polymers the impact strength is most commonly measured by a pendulum-type impacting machine. In the test, a heavy pendulum which starts at an elevation h_0 swings through its arc, strikes and breaks the specimen, and reaches a lower final elevation h_f (Figure 3.16). By knowing the initial and final elevations of the pendulum, the *impact energy* as the difference in potential energy can be calculated.

The *Izod test* is often used for nonmetallic materials. The test specimen may be either notched or unnotched; V-notched specimens better measure the resistance of the material to crack propagation (Figure 3.17).

For most metals the specimen as shown in Figure 3.16 has a notch in it to prompt fracture in the desired spot. When the impact data are reported as Charpy V,

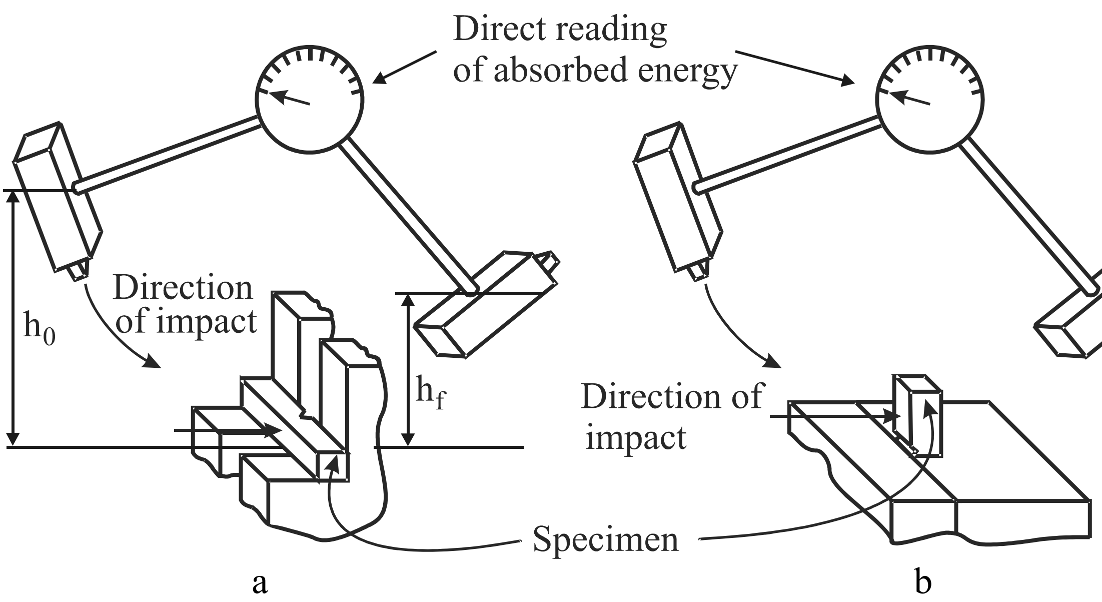


Figure 3.16 The principle of common impact test: Charpy (a), and Izod (b)

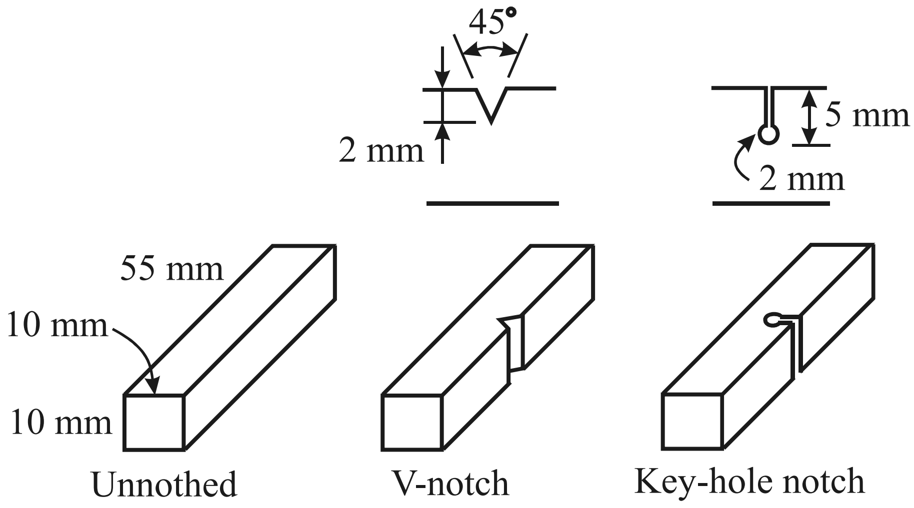


Figure 3.17 The dimensions of typical specimen in Charpy and Izod test

or notched Izod, it will mean that notched specimens were used. In data that do not indicate a notched specimen, chances are the material is really quite brittle. Notched impact data cannot be compared with unnotched.

The *drop–weight* type of test (Figure 3.18) is an important addition to the toughness testing field. Its big advantage is that it uses relatively large specimens (as large as several hundred square centimeters in cross section). The use of large specimens was prompted by research reports that indicated that the data obtained on the small specimens used in standard Charpy and Izod tests do not confirm service characteristics on heavy sections.

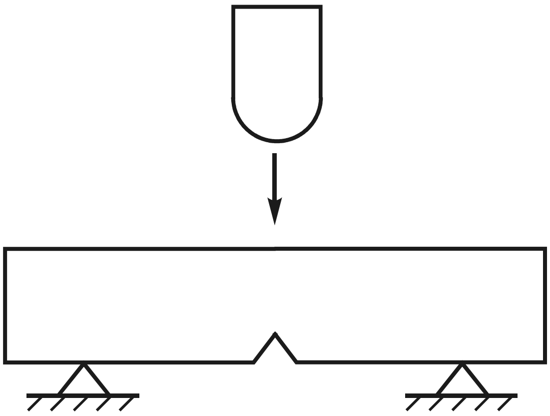


Figure 3.18 The principle of drop weight test

The *drop–weight* type of test (Figure 3.18) is an important addition to the toughness testing field. Its big advantage is that it uses relatively large specimens (as large as several hundred square centimeters in cross section). The use of large specimens was prompted by research reports that indicated that the data obtained on the small specimens used in standard Charpy and Izod tests do not confirm service characteristics on heavy sections. The standard notched and unnotched pendulum test specimens have a cross section only of the order of 0.2 in^2 (0.13 × 10^{-3} m^2). The drop-weight tests have the major disadvantage of being quite expensive, but produce the unique results for design of dynamically loaded structures.

3.2.2 Transition Temperature

Impact strength can be affected by temperature. At high temperatures, a large absorbed energy is required to cause the specimen to fail, whereas at low temperatures even a relatively ductile material may fail with little absorbed energy (Figure 3.19). If at low temperatures the material is brittle, the little deformation at the point of fracture is observed.

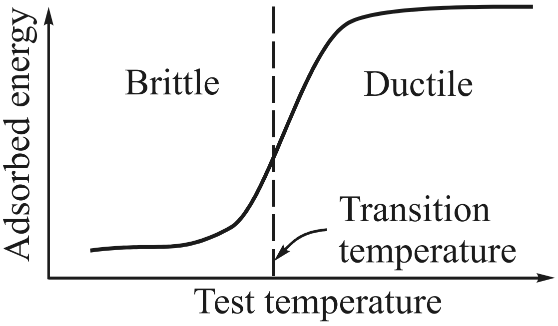


Figure 3.19 Typical results from a series of impact tests

The *transition temperature* is the temperature at which the material changes from ductile to brittle failure.

A material that may be subjected to an impact blow during service must have a transition temperature *below* the temperature of the material's surroundings.

For example, the transition temperature of a steel used for a carpenter's hammer should be below room temperature to prevent *chipping* of the steel.

If low temperatures are a possible service environment for a structure, it would be well to look into the *nil ductility temperature* (NDT). This parameter is a product of Charpy V tests; it is defined as the temperature at which the toughness of the material drops below some predetermined value (usually 15 ft·lb; 21 J). A typical impact strength versus temperature curve showing the NDT is illustrated in Figure 3.20. If the NDT of a steel is less than 32°F (0°C), it should not be used for impact-loaded parts that may operate at a lower temperature.

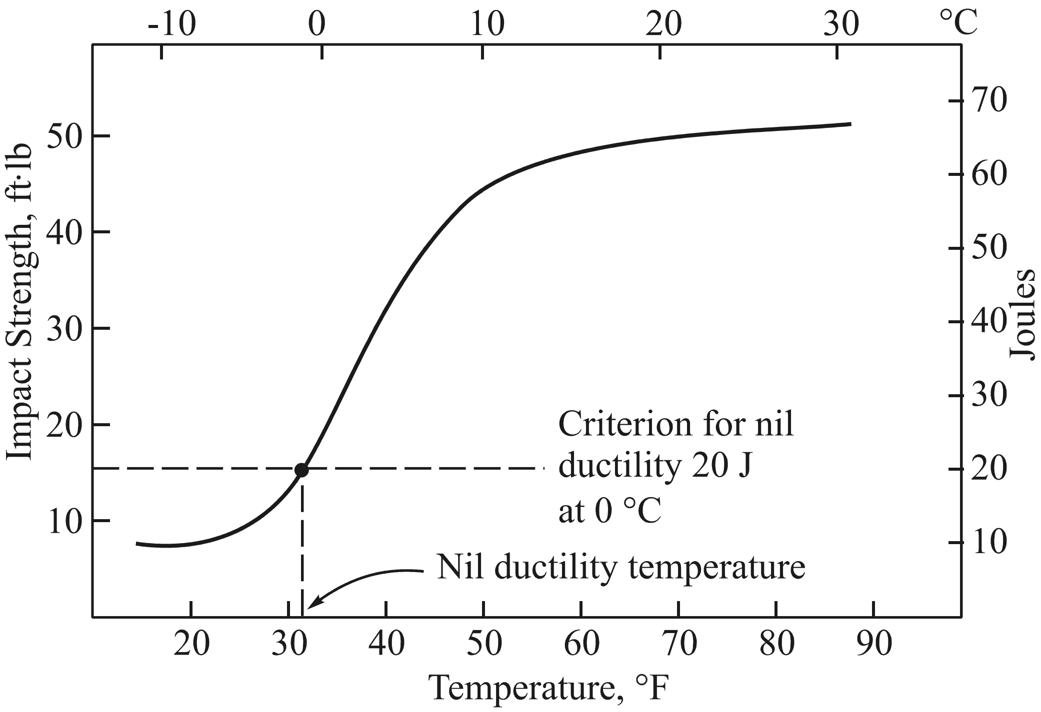


Figure 3.20 Use of impact test data to determine NDT

Not all materials have a distinct transition temperature (Figure 3.21). BCC metals have transition temperatures but most FCC metals do not. FCC metals have high absorbed energies, with the energy decreasing gradually and slowly as the temperature decreases.

3.2.3 Notch Sensitivity

Notches caused by poor machining, fabrication, or design cause stresses to be concentrated, reducing the toughness of the material. The *notch sensitivity* of a material can be evaluated by comparing the absorbed energies of notched versus unnotched specimens. The absorbed energies are much lower in notched specimens if the material is notch sensitive, as in ductile cast iron (Figure 3.22). However, some materials, such as gray cast iron, are not notch sensitive.

3.2.4 Relationship to Stress-Strain Diagram

The energy required to break a material also corresponds to the area contained within the true stress-true strain diagram. Materials that have both high strength and high ductility have a good toughness (Figure 3.23). Ceramics and many composites, on the other hand, have poor toughness because they display virtually no ductility.

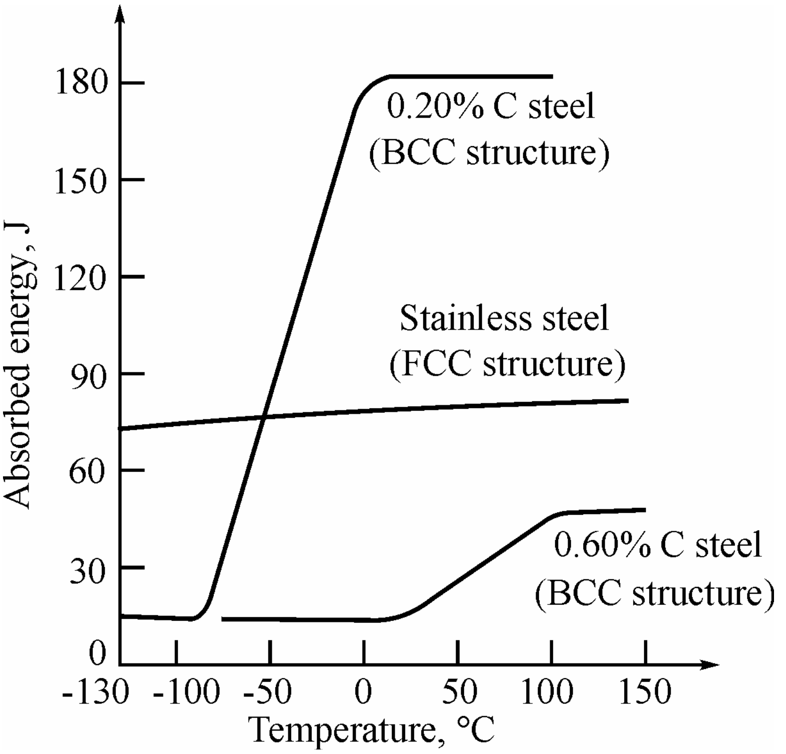


Figure 3.21 The Charpy V-notch properties for two plain-carbon steels (BCC structure) and an FCC stainless steel

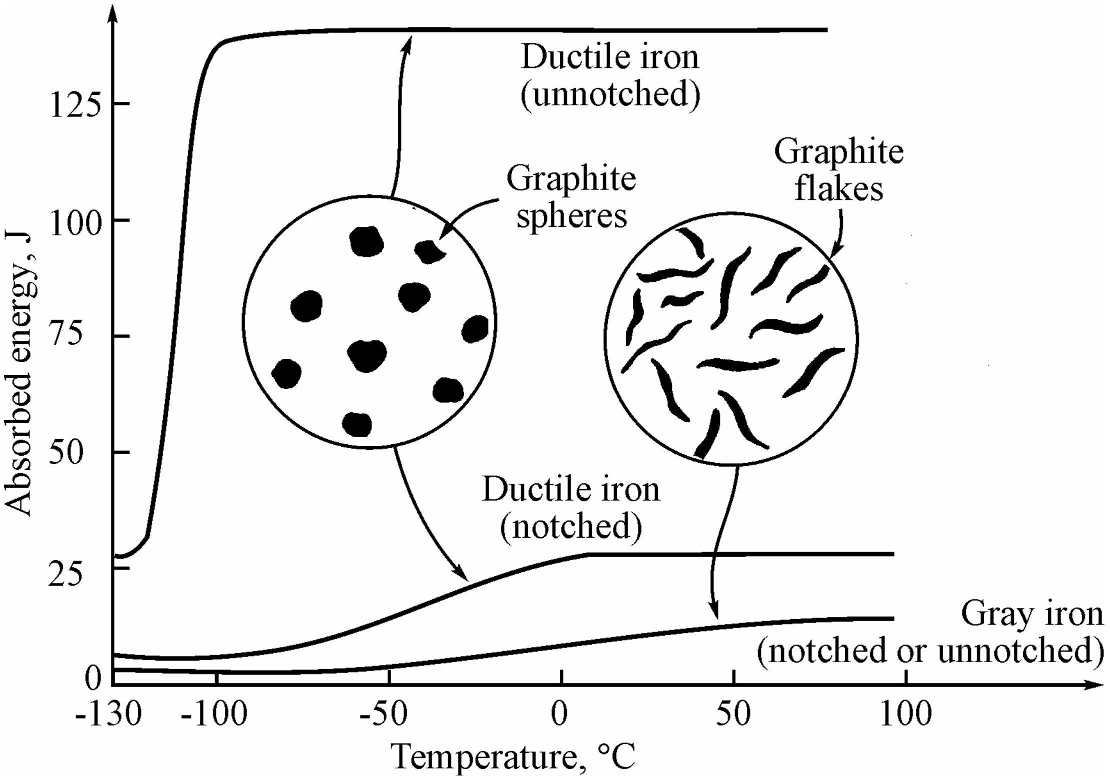


Figure 3.22 The effect of internal and external notches on impact properties. Gray iron structures contain sharp graphite flakes that act as notches and produce low energies. Ductile iron structures contain spherical graphite nodules that do not act as notches. An external notch has a significant effect only on ductile iron

3.2.5 Use of Impact Properties

The absorbed energy and transition temperature are very sensitive to the loading conditions. For example, a higher rate at which energy is applied to the specimen will reduce the absorbed energy and increase the transition temperature. The size of the specimen also affects the results – smaller energies might be required to break thicker materials. Finally, the configuration of the notch may affect the behavior – a surface crack permits lower absorbed energies than does a V-notch. Because we often cannot predict or control all of these conditions, the impact test is best used for comparison and selection of materials rather than as a design criterion.

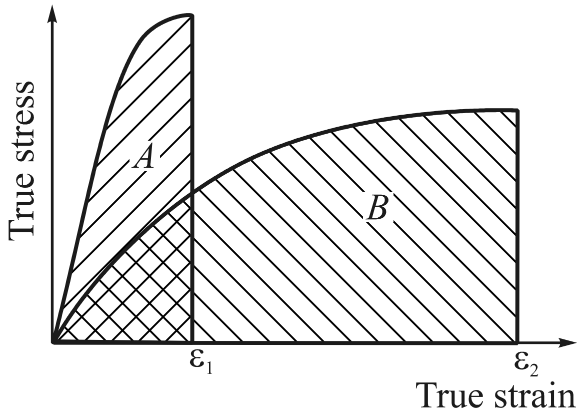


Figure 3.23 The area contained within the true stress-true strain curve is related the impact energy. Although material *B* has a lower yield strength, it absorbs a greater energy than material *A*

3.3 Fatigue Test

3.3.1 Nature of the Fatigue Test

In many applications, a component is subjected to the repeated application of loading which produce a stress below the yield strength of the material. This repeated stress may occur as a result of rotation, bending, or even vibration and random loading. Even though the stress is below the yield strength, the material may fail after a large number of applications of the stress. This mode of failure is known as *fatigue*.

Fatigue strength of material is determined by *endurance limit* and is obtained by repeated loading a specimen at given stress levels until it fails. Any form of loading can be used, and the stress level is usually calculated or measured by strain gauges. For example, a bending fatigue setup is illustrated in Figure 3.24. The specimen is loaded until, for example, the maximum stress in the sample is 40 ksi (275 MPa). At this stress level it may fail in 10 cycles. These data are recorded, and the stress level is reduced to maybe 30 ksi (206 MPa). A specimen may break after 1000 stress cycles at this low stress level. This procedure is repeated until a stress level is determined below which failure does not occur. A test duration of 10 million stress cycles is usually considered *infinite life* (Figure 3.25).

One of two common methods to measure the resistance to fatigue is the *rotating cantilever beam test* (Figure 3.26). One end of a machined, cylindrical specimen is mounted in a motor-driven *chuck*. A weight is suspended from the other end. The specimen initially has tensile force acting on the top surface, while the bottom surface

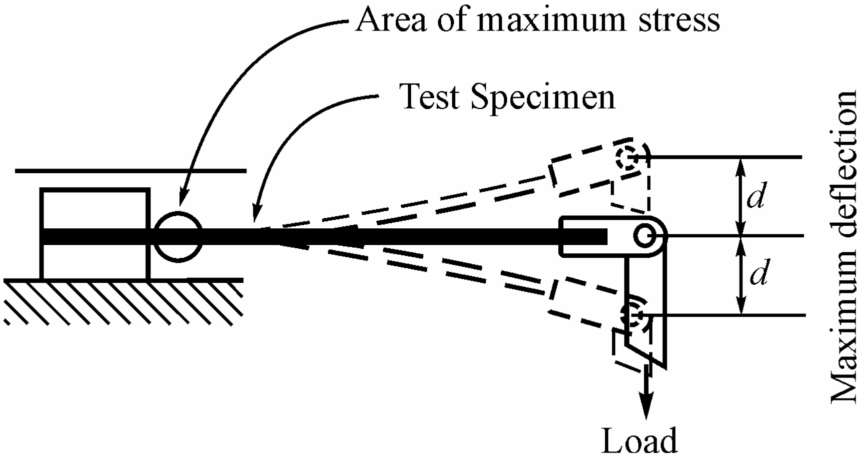


Figure 3.24 Typical test setup for bending fatigue

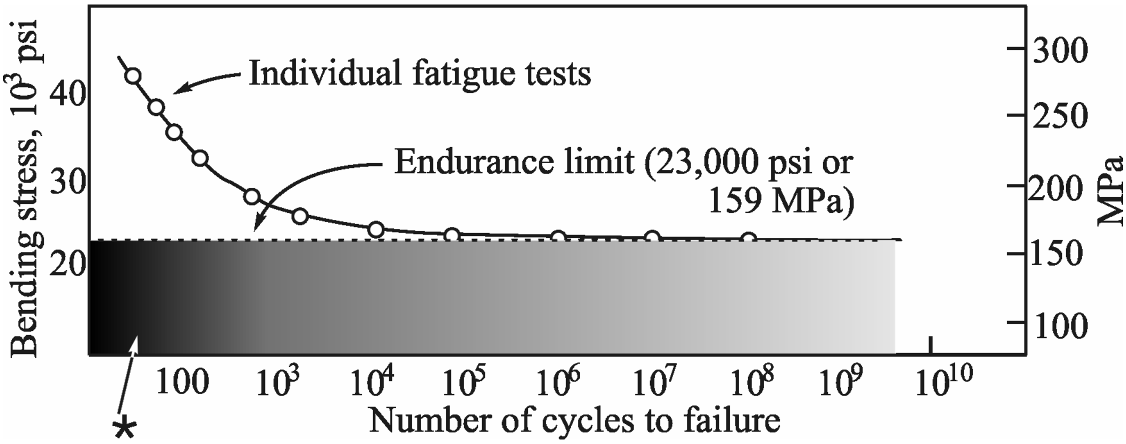


Figure 3.25 Use of an stress–number curve to establish fatigue strength: *– machine components made of this metal will not be subject to fatigue failure if the design stress is in this stress range

is compressed. After the specimen turns 90°, the locations that were originally in tension and compression have no stress acting on them. After a half revolution of 180°, the material that was originally in tension is now in compression. Thus, the stress at any point goes through a complete cycle from zero stress to maximum tensile stress to zero stress to maximum compressive stress. The maximum stress acting on the specimen is given by

$$\sigma = 10.18\frac{l \cdot F}{d^3}, \tag{3.11}$$

where l is the length of the bar, F is the load, and d is the diameter of the specimen. Second common method is the *rotating two – supported beam test* (Figure 3.27).

In this case two movable bearings at the left and right parts of the specimen transfer the action of a tensile force in accordance with the scheme in Figure 3.28.

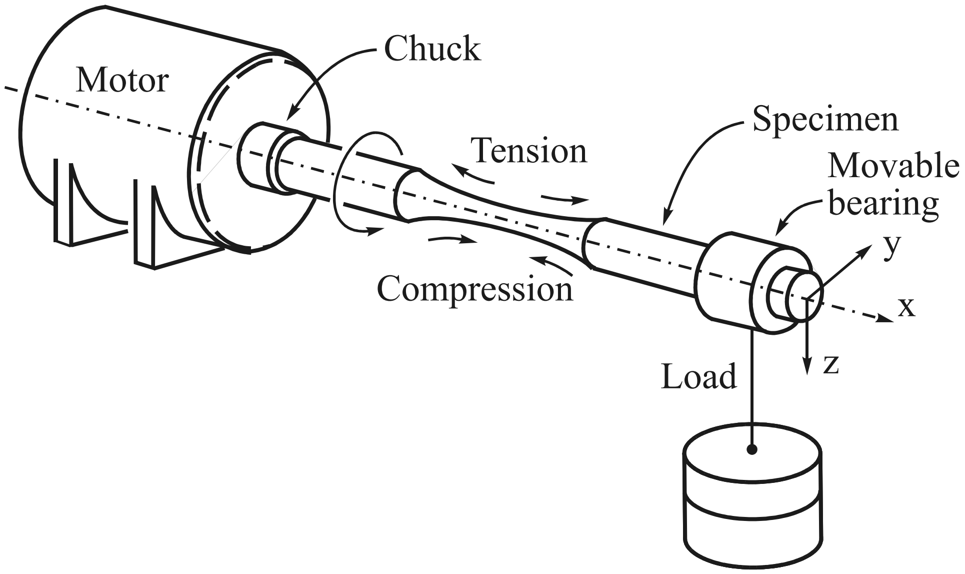


Figure 3.26 The rotating cantilever beam fatigue tester

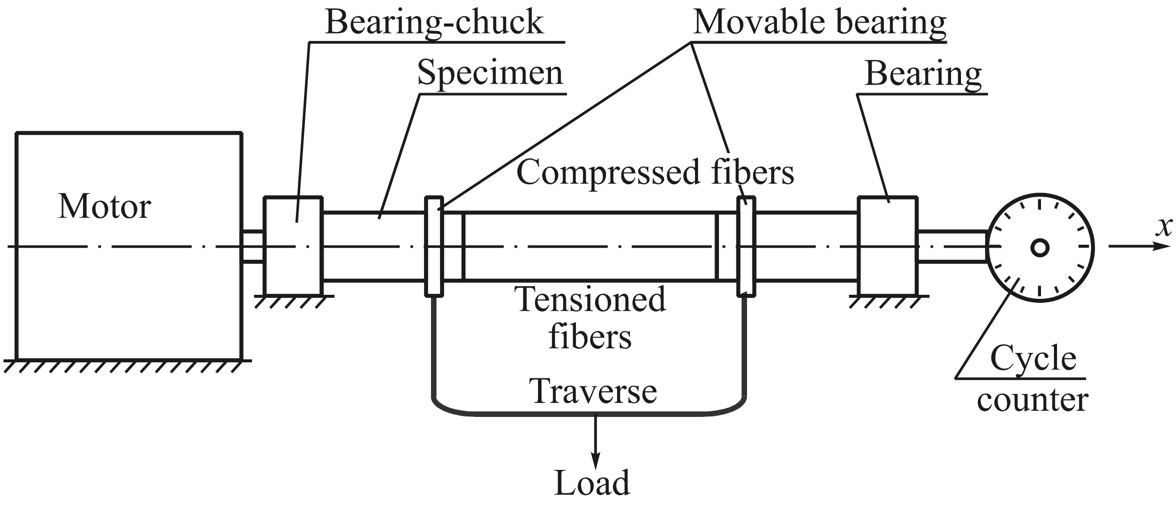


Figure 3.27 The rotating two supported beam tester

The maximum bending moment in an arbitrary cross-section of pure bending part of the specimen (CD) is given by

$$M_{B\max} = \frac{F}{2} \cdot a\,. \tag{3.12}$$

The corresponding maximum normal stress in an external points of the circular section are

$$\sigma_{\max} = \frac{M_{B\max}}{W_{n.a.}} = \frac{32 M_{B\max}}{\pi d^3} \approx \frac{5.1Fa}{d^3}\,. \tag{3.13}$$

During the test after a sufficient number of cycles, the specimen may fail. Generally, a series of specimens (up to 10) are tested at different applied stresses (the

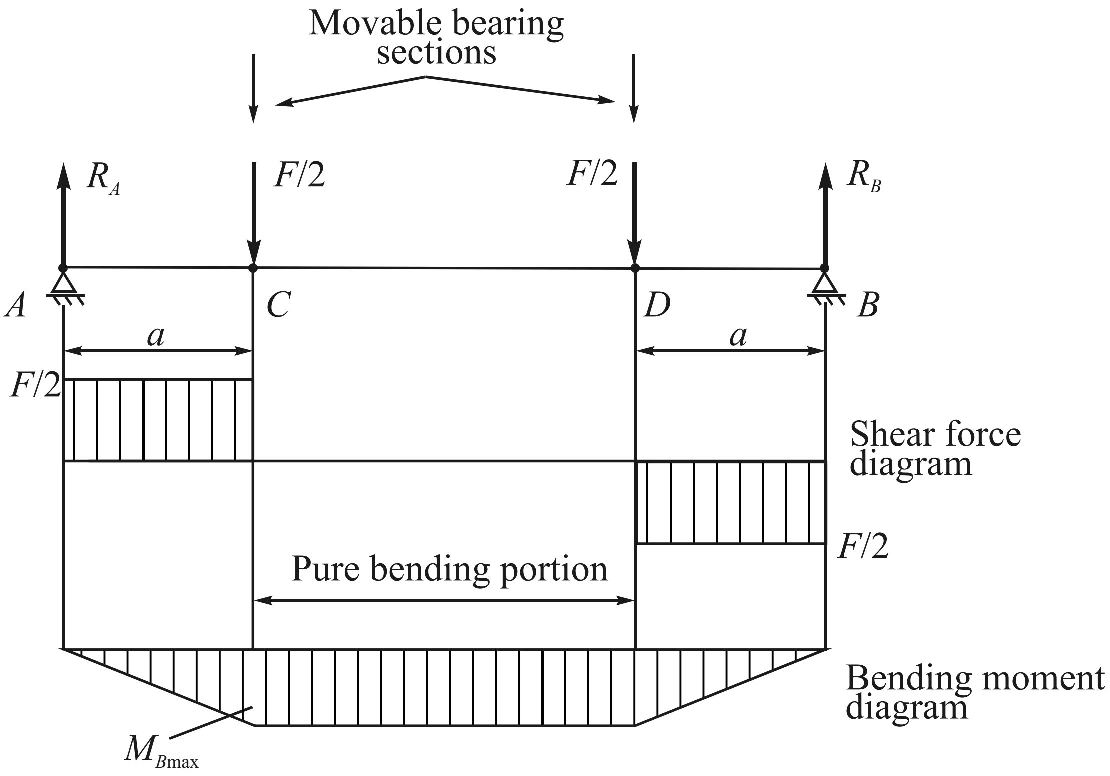


Figure 3.28 The mechanical scheme of the rotating two-supported beam test

first is loaded to $\sigma_{\max_1} = 0{,}86\sigma_y$, $\sigma_{\max_2} < \sigma_{\max_1}$, $\sigma_{\max_3} < \sigma_{\max_2}$ etc.) and the stress is plotted versus of cycles to failure (see Figure 3.25, 3.29).

3.3.2 Results of the Fatigue Test

The fatigue test can tell us how long a part may survive or the maximum allowable loads that can be applied to prevent failure. The end result, the endurance limit of a material, is an extremely important design property.

3.3.2.1 Fatigue Life

The *fatigue life* is the term, which tells how long a part or component survives when a given stress σ is repeatedly applied to the material. If we are designing a tool steel part that must undergo 100,000 cycles during its lifetime, in accordance with Figure 3.29 this part must be designed so that the maximum acting stress must be lower than 620 MPa.

3.3.2.2 Endurance Limit

The *endurance limit* is the stress below which failure by fatigue never occurs. It is our preferred design criterion. To prevent a tool steel part from failing, we must be sure that the applied stress is below 415 MPa (Figure 3.29). This property, rather than allowable static stress, should be used in determining allowable operating stresses in

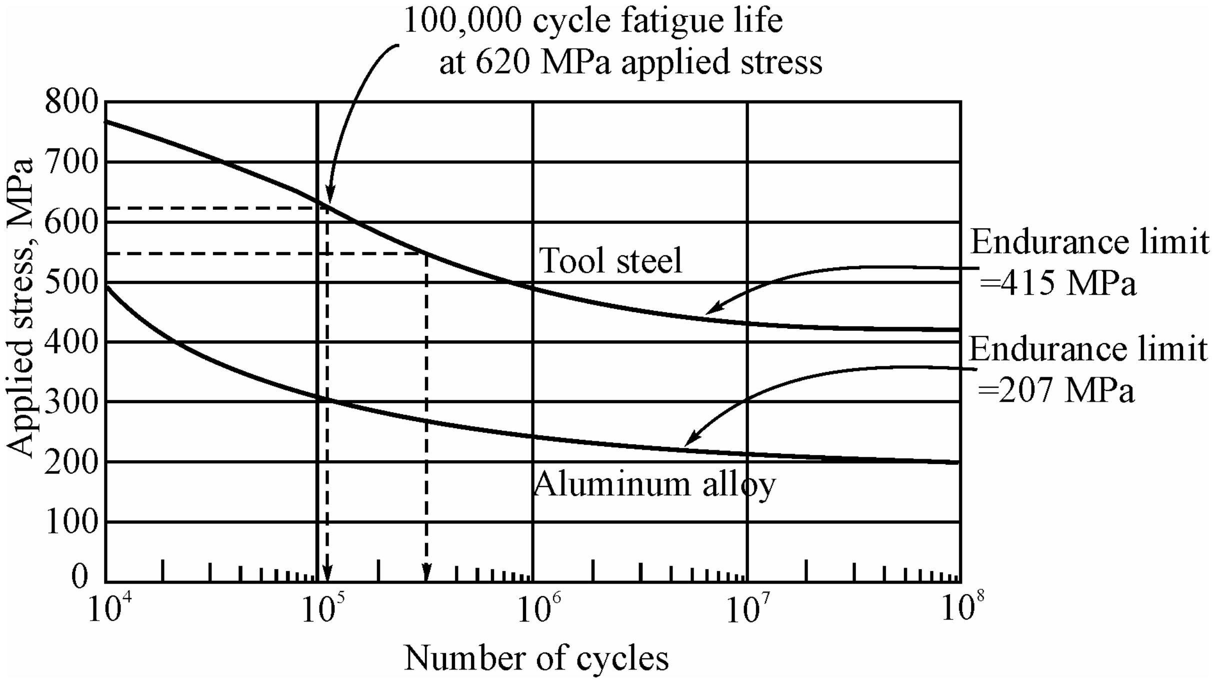


Figure 3.29 The stress-number of cycles to failure curve for a tool steel and an aluminum alloy

components that are subjected to cyclic loading in service. As an example, the American Institute of Steel Construction (AISI) recommends a design (allowable) stress for a 60 ksi tensile strength (A36) steel of 22 ksi (152 MPa) for static loading. In cyclic loading situations, the allowable stress is only about 13 ksi (89 MPa).

3.3.2.3 Fatigue Strength

Some materials, including many aluminum alloys, have no true endurance limit. For these materials, we may specify a minimum fatigue life; then *the fatigue strength* is the stress below which fatigue does not occur within this time period. In many aluminum alloys, the fatigue strength is based on 500 million cycles.

3.3.2.4 Notch Sensitivity in Fatigue

Fatigue cracks initiate at the surface of a loaded material, where the stresses are at a maximum. Any design or manufacturing defect at the surface concentrates stresses and encourages the formation of a fatigue crack. This susceptibility may be measured using a notched fatigue specimen (Figure 3.30). For this reason highly polished surfaces are prepared in order to minimize the likelihood of a fatigue failure.

3.3.2.5 Endurance Ratio

It was admitted that a cyclic loading significantly reduces the allowable stress that a material can withstand. If handbook data are not available on the endurance limit of a material under consideration for use, a percentage of the tensile strength can be used. This percentage varies with different material systems, but for many

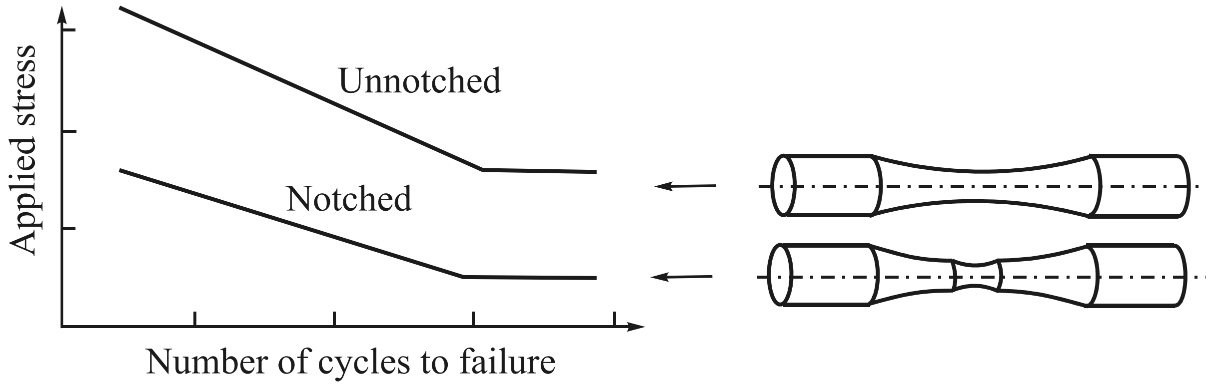


Figure 3.30 The effect of a notch on the fatigue properties of a metal

engineering metals (ferrous, or iron-base, alloys) the endurance limit can be approximated as 50% of the tensile strength of materials (in the absence of stress concentrations). This ratio of endurance limit to tensile strength is the *endurance ratio*:

$$\text{Endurance ratio} = \frac{\text{endurance limit}}{\text{tensile strength}} \approx 0.5\,. \tag{3.14}$$

If the tensile strength at the surface of the material increases, the resistance to fatigue also increases.

3.3.2.6 Temperature Effect in Fatigue

Temperature influences the fatigue resistance. As the temperature of the material increases, the strength decreases and consequently both fatigue life and endurance limit decrease.

Example 3.12

A 650-lb (2893 N) force is applied to a tool steel bar rotating at 3000 cycles/min. The bar is 1 in. (0.0254 m) in diameter and 12 in. (0.305 m) long. Estimate: (a) the time before the bar fails and (b) the diameter of the shaft that would prevent fatigue failure.

Answer

(a) $$\sigma = \frac{10.18 \cdot l \cdot F}{d^3} = \frac{(10.18)(12)(650)}{(1)^3} = 79{,}400\,\text{psi} \cong 550\ \text{MPa}. \tag{3.15}$$

From Figure 3.29, the number of cycles to failure is 300,000. The time to failure is

$$t = \frac{300{,}000}{3000} = 100\,\text{min}\,. \tag{3.16}$$

(b) The endurance limit is 415 MPa.

$$d^3 = \frac{(10.18)(0.305)(2893)}{415 \cdot 10^6} = 21.64 \cdot 10^{-6}\ \text{m}^3, \tag{3.17}$$

$$d = 0.028\,\text{m}\,.$$

3.4 Creep Test

3.4.1 Nature of Creep Test

If we apply a stress to a material at a high temperature, the material may stretch and eventually fail, even though the applied stress is less than the yield strength at that temperature. Long-term plastic deformation at high temperatures is known as *creep*.

This property is used to rate the resistance of a material to plastic deformation under sustained load. For metals, creep strength is often expressed as the stress necessary to produce 0.1% strain in 1000 hrs. In polymers, a percent deformation at a given stress is often used. Creep data must also show the testing temperature.

Typical creep testing is illustrated in Figure 3.31.

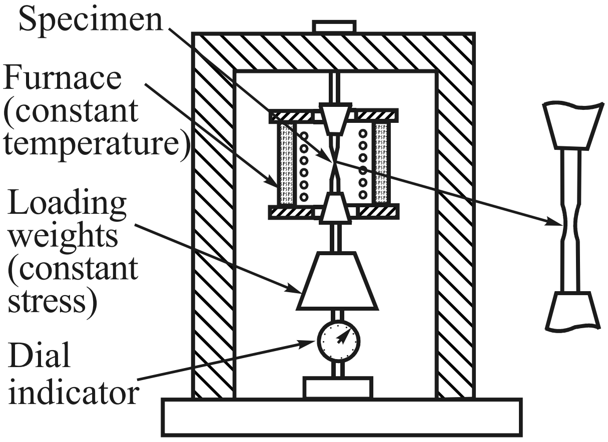


Figure 3.31 Creep tester. A specimen is placed in a furnace at an elevated temperature under a constant applied stress

To determine the creep characteristics of a material, a constant stress is applied to a cylindrical specimen placed in a furnace (Figure 3.31). As soon as the stress is applied, the specimen stretches elastically a small amount ε_0 (Figure 3.32), depending on the applied stress and the modulus of elasticity of the material at the high temperature.

Table 3.5 gives the approximate temperatures at which several metals begin to creep. Creep is not too important with most ferrous metals unless the operating temperature is above 350…400°C.

Creep can be an important selection factor with low melting temperature metals and polymers. It is a principal cause of failure of fixtures and hangers in furnaces. In epoxy–bonded piping systems, the creep strength of the epoxy is often the weak link in the system. Polymeric bearings often develop excessive clearance owing to compressive creep. The solution to these types of problems is to use materials with good creep characteristics.

3.4.2 Dislocation Climb in Creep

As you know the high temperature permits dislocations in the metal to climb. In climb, atoms move either to or from the dislocation line by diffusion, causing the dislocation to move in a direction that is perpendicular, not parallel, to the slip plane (Figure 3.33). The dislocation can now escape from lattice imperfections that block the slip process. The dislocation, after climbing away from the imperfection, continues to slip and causes additional deformation of the specimen even at low applied stresses.

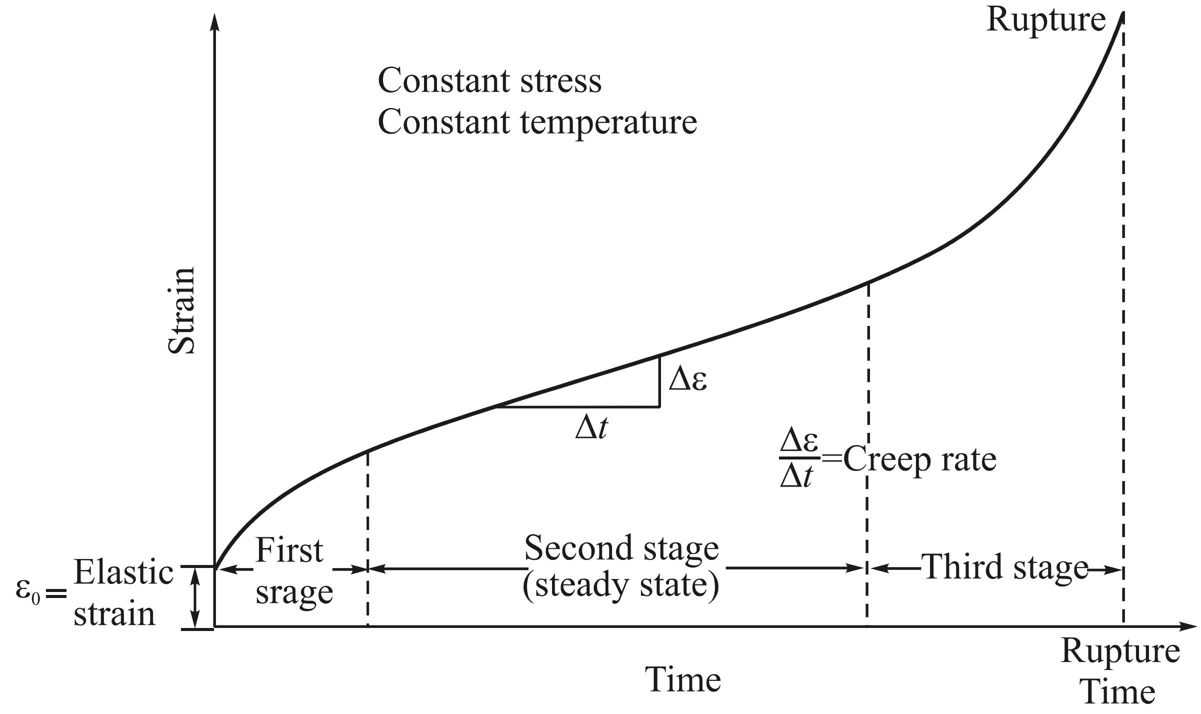


Figure 3.32 A typical creep curve showing the strain produced as a function of time for a constant stress and temperature

Table 3.5 Approximate temperatures at which creep becomes important for selected metals and alloys

Metal	Temperature, °C
Aluminum alloys	200
Titanium alloys	325
Low-alloy steels	375
High-temperature steels	550
Nickel and cobalt superalloys	650
Refractory metals (tungsten, molybdenum)	1000…1550

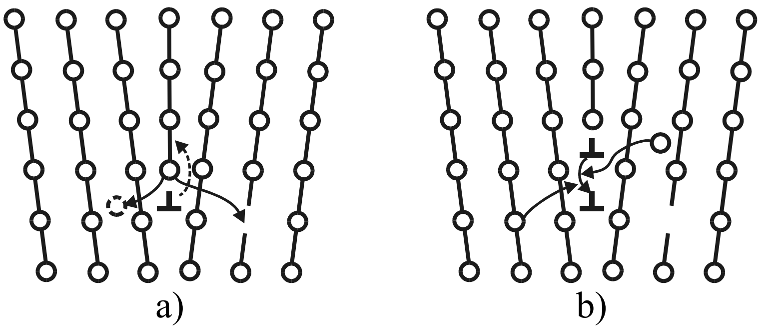


Figure 3.33 Dislocations can climb away from obstacles when atoms leave the dislocation line to create interstitials or to fill vacancies (a) or when atoms are attached to the dislocation line by creating vacancies or eliminating interstitials (b)

3.4.3 Creep Rate and Rupture Time

During the creep test, the strain or elongation is measured as a function of time and plotted to give the creep curve (Figure 3.32). In the first stage of creep, many dislocations climb away from obstacles, slip, and contribute to deformation of the metal. Eventually, the rate at which dislocations climb away from obstacles equals the rate at which dislocations are blocked by other imperfections. This leads to second-stage, or *steady-state*, *creep*. The slope of the steady-state portion of the creep curve is called the *creep rate*:

$$\text{Creep rate} = \frac{\Delta\ \text{strain}}{\Delta\ \text{time}}. \tag{3.18}$$

Eventually, during third-stage creep, necking begins, the stress increases, and the specimen deforms at an accelerated rate until failure occurs. The time required for failure to occur is the *rupture time.* Either a higher stress or a higher temperature reduces the rupture time and increases the creep rate (Figure 3.34).

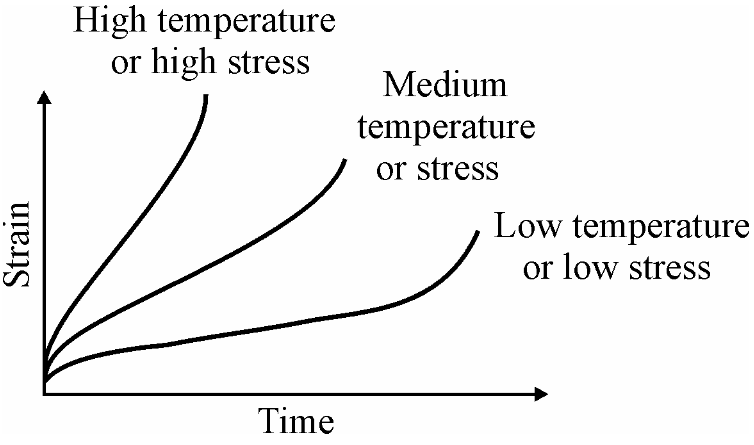


Figure 3.34 The effect of temperature or applied stress on the creep curve

Example 3.13

Use the results of a creep test in Table 3.6 and calculate the creep rate in (m./m.)/h.

Answer

The data in Table 3.6 are plotted in Figure 3.35. From the slope of the steady-state portion of the curve

$$\text{Creep rate} = \frac{\Delta\varepsilon}{\Delta t} = \frac{0.021-0.009}{6000-1000} = \frac{0.012}{5000} = 2.4\times10^{-6}\ \text{(m./m.)/h}. \tag{3.19}$$

Table 3.6 Data from a creep test for Example 3.13

Time, h	0	250	1000	2250	3500	4750	6000	7100	7500	7750
Strain, m./m.	0.003	0.006	0.009	0.012	0.015	0.018	0.021	0.024	0.027	0.030

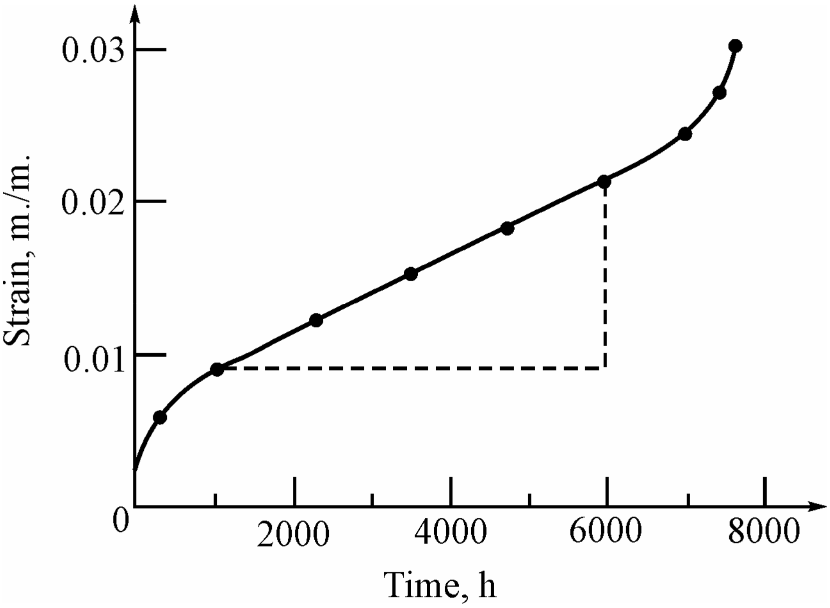


Figure 3.35 Graph of the data in Table 3.6 to produce a creep curve. The slope of the steady-state portion of the graph is the answer to Example 3.13

3.4.4 Use of Creep Data

Four ways are used to present the results from a series of creep tests are shown in Figure 3.36.

1. Stress-rupture curve

The *stress-rupture curve* shown in Figure 3.36 (a) permits us to estimate the expected lifetime of a component for a particular combination of stress and temperature. The property of *stress-rupture* complements creep data. It shows the stress at which a component will fail under sustained load at elevated temperature. Stress rupture tests a usually conducted with dead-weight loading of the specimen, and the strain is not reported. A typical stress-rupture curve is shown in Figure 3.37.

Stress-rupture tests are not usually conducted on polymeric materials, but they are important for metals or ceramics intended for high-temperature service. Reviewing the data in Figure 3.37, it can be seen how stress-rupture data are used. If a part was to be used at 540°C, it would only last 1000 hours if the operating stress was 360 MPa. If the operating stress was lowered to 140 MPa, the expected service life would be in excess of 10,000 hours. At 820°C, a stress level of 140 MPa would result in failure after less than 1000 hours of service. Thus, stress-rupture data can be a useful tool in selecting materials.

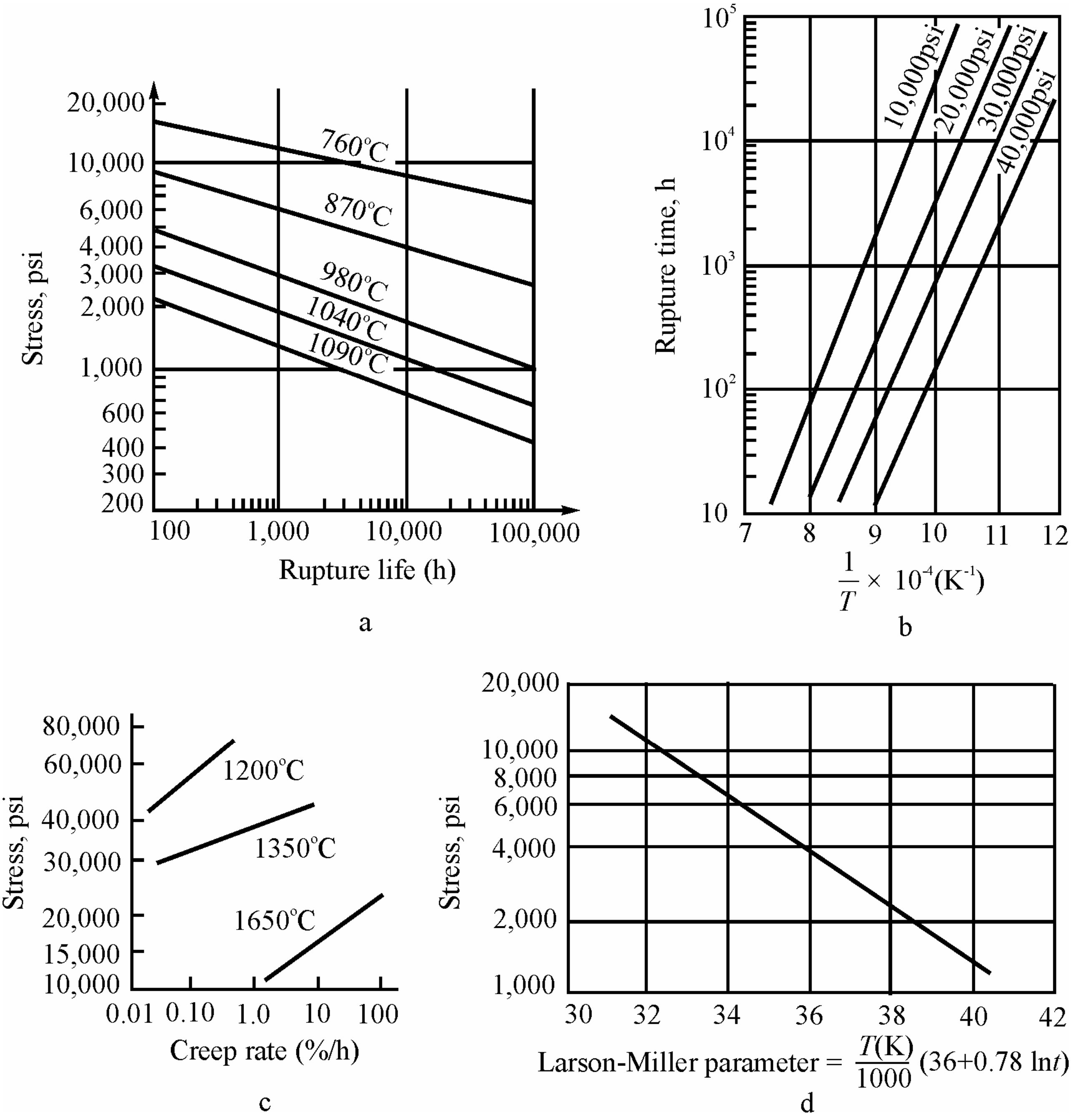


Figure 3.36 Results from a series of creep tests: (a) stress-rupture curves for an iron-chromium-nickel alloy; (b) rupture time versus reciprocal temperature for a nickel heat-resistant alloy; (c) minimum creep rate curves for a tantalum alloy; (d) Larson-Miller parameter for ductile cast iron

2. Rupture time versus temperature

Figure 3.36 (b) depicts the rupture time versus the reciprocal of temperature for a constant stress; this presentation of the data suggests an Arrhenius relationship for the rupture time and would permit an activation energy for the process to be calculated.

3. Stress versus creep rate

Using Figure 3.36 (c) an important selection factor – *creep rate* can be estimated

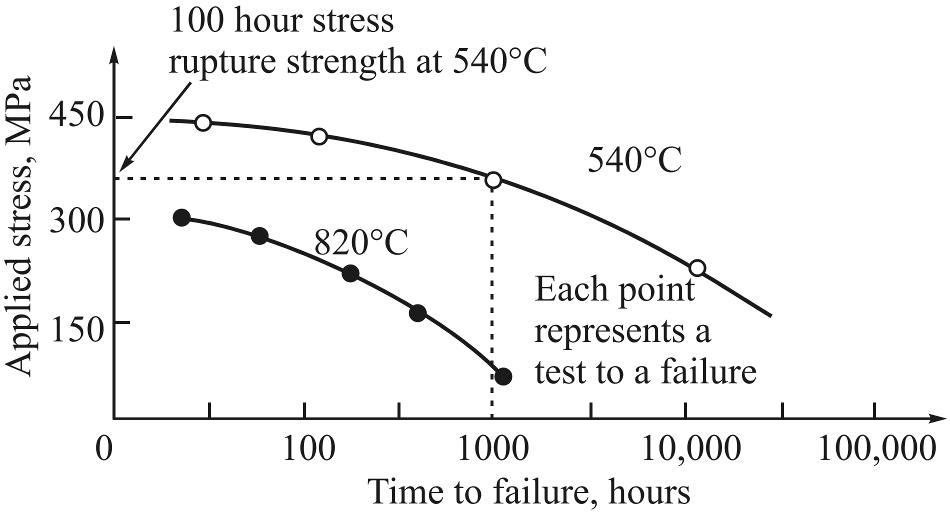


Figure 3.37 Typical stress-rupture data

for a particular combination of an applied stress and temperature.

4. Larson-Miller parameter

The *Larson-Miller parameter,* illustrated in Figure 3.36 (d) is used to consolidate the stress-temperature-rupture time relationship into a single curve.

Example 3.14

Using the Larson-Miller parameter for ductile cast iron, as shown in Figure 3.36 (d), determine the time required before the metal fails at an applied stress of 6000 psi (41,4 MPa) and temperatures of 400°C and 600°C.

Answer

The Larson-Miller parameter for 6000 psi is 34.3.

a) At 400 °C: $34.3 = \frac{(400 + 273\text{K})}{1000}(36 + 0.78\ln t)$,

$$0.78\ln t = (34.4)\left(\frac{1000}{673}\right) - 36 = 14.97,$$

$$t = 2.2 \cdot 10^8\, h = 25{,}000 \text{ years}. \tag{3.20}$$

b) At 600 °C: $34.3 = \frac{(600 + 273\text{K})}{1000}(36 + 0.78\ln t)$,

$$0.78\ln t = (34.4)\left(\frac{1000}{873}\right) - 36 = 3.29,$$

$$t = 67.9h = 2.8 \text{ days}. \tag{3.21}$$

3.5 Hardness Test

3.5.1 Nature of the Hardness Test

Hardness is probably one of the most used selection factors. The hardness of materials is often equated with wear resistance and durability. In steels it serves as a measure of abrasion resistance and strength.

There are many ways of measuring hardness. In the early days of metallurgy, heat–treated steels were tested for hardness by filing an edge. If it did not file, it was hard. The hardness of ceramics and minerals was and still is measured by scratching the surface with different types of minerals. This is called the *Mohs hardness test.* Most present-day hardness tests consist of pushing a penetrator into the material and measuring the effects. Some of the most commonly used penetrators are shown in Figure 3.38. The loading mechanism varies with the various tests, as does the mechanism for measuring the effect of the indentation.

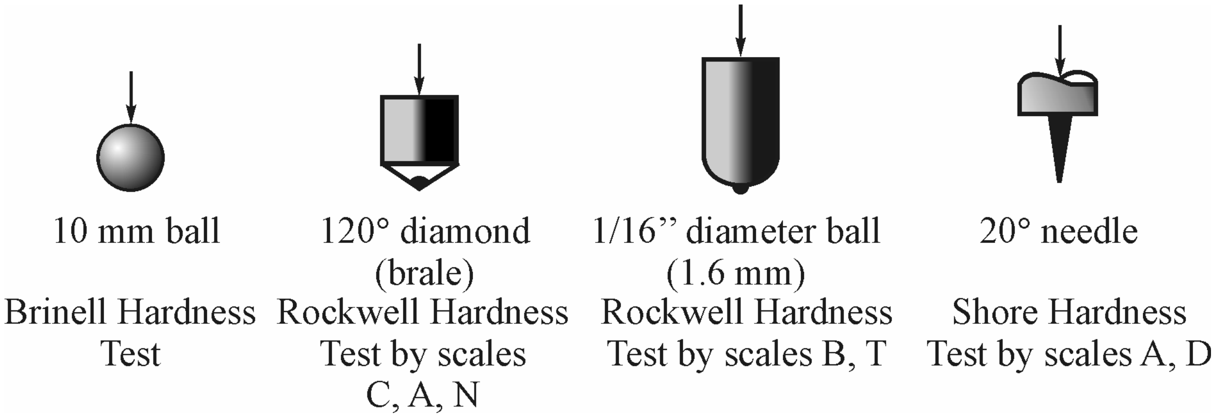


Figure 3.38 Typical penetrators used in hardness tests

The most commonly used are the *Rockwell hardness test* and the *Brinell hardness test*. In the Brinell hardness test a hard steel sphere, usually 10 mm in diameter, is forced into the surface of the material. The diameter of the impression left on the surface is measured using optical measuring device and the Brinell hardness number (HB) is calculated from the following equation:

$$\mathrm{HB} = \frac{F}{(\pi/2)D\left(D - \sqrt{D^2 - D_i^2}\right)}, \tag{3.22}$$

where F is the applied load in kilograms, D is the diameter of the indentor in millimeters, and D_i is the diameter of the impression in millimeters.

The Rockwell hardness test uses either a small diameter steel ball for soft materials or a diamond cone, or Brale, for harder materials. The depth of penetration of the indentor is automatically measured by the testing machine and converted to a Rockwell hardness number.

A more sophisticated tester is the *micro-hardness tester* (the Vickers and Knoop tests). This device has a precise diamond indentor that can be used to measure the hardness of microscopic particles or metal phases. The scale range is such that the hardness of polymers, metals, and ceramics can be measured.

The Vickers and Knoop test form such small indentations that a microscope is required to obtain the measurement (Figure 3.39).

A common hardness test for polymers and elastomers (plastics that behave like rubber) is the *Shore durometer test*. Hardness is measured by pushing a spring–loaded needle into the material (Figure 3.40).

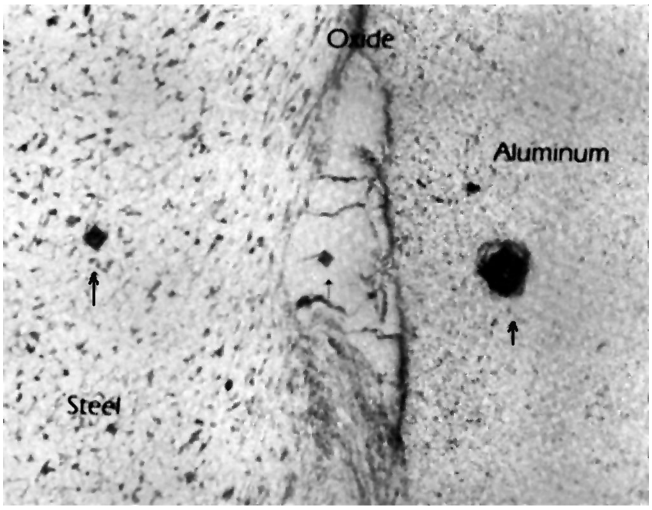


Figure 3.39 Microhardness impressions in an explosive bond joining aluminum to steel. The small size of the impression indicates that the inclusion trapped at the interface is harder than either aluminum or steel (x 200)

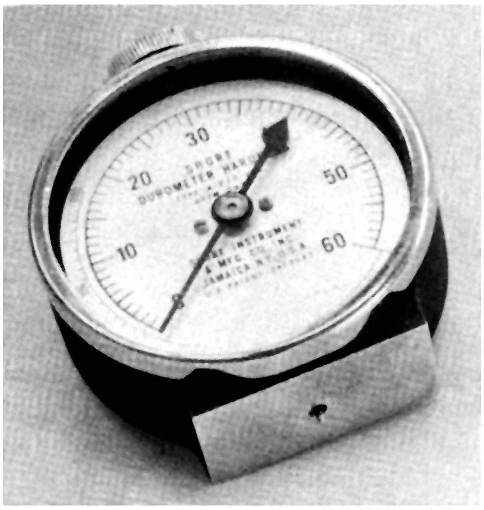


Figure 3.40 Shore durometer hardness tester. Needle on the bottom is the penetrator

3.5.2 Use of the Hardness Test for Material Selection

Hardness numbers are used primarily as a basis for comparison of materials, specifications for manufacturing and heat treatment, quality control, and correlation with other properties and behavior of materials. For example, Brinell hardness is closely related to the tensile strength of steel by the relationship

$$\text{Tensile strength (psi)} = 500\,\text{HB}\,. \tag{3.23}$$

A Brinell hardness number can be obtained without destroying the component, yet provides a close approximation for the tensile strength.

Hardness correlates well with wear resistance. A material used to crush or grind either should be very hard to assure that the material is not eroded or abraded by the hard feed materials. Similarly, gear teeth in a transmission or drive system of a vehicle should be hard so that the teeth do not wear out. Typically we find that polymer materials are exceptionally soft, metals have an intermediate hardness, and ceramics are exceptionally hard.

Example 3.15

A Brinell hardness test is performed on steel using a 10 mm indentor with a load of 3000 kg. A 3.2-mm impression is measured on the surface of the steel. Calculate the *HB,* the tensile strength, and the endurance limit of the steel.

Answers

$$\mathrm{HB} = \frac{3000}{\left(\pi/2\right)(10)\left(10-\sqrt{10^2-3.2^2}\right)} = 363\ \mathrm{kg/mm^2}. \tag{3.24}$$

$$\text{Tensile strength} = 500\ \mathrm{HB} = (500)(363) = 181{,}600\ \mathrm{psi} = 1252\ \mathrm{MPa}.$$

$$\text{Endurance limit} = 0.5\ \text{tensile strengh} = (0.5)(181{,}600) = 90{,}800\ \mathrm{psi} = 626\ \mathrm{MPa}.$$

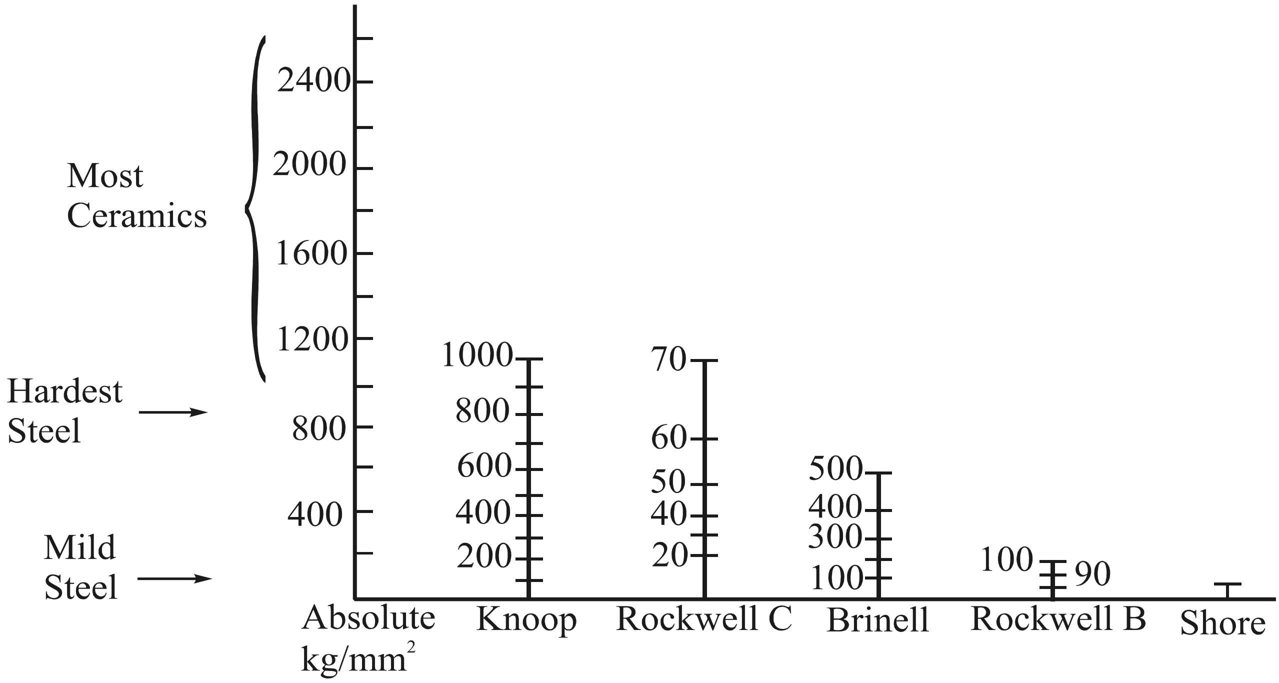
The hardness tests of most importance in material selection are those shown in Figure 3.41. They differ in penetrator, load, and applicability. Unfortunately, hardness numbers measured on one test cannot always be converted to a comparable hardness measured on another scale. An approximate conversion between some scales is shown in Figure 3.41. As a minimum, the designer should become familiar with the Rockwell B, C, and R tests, the Brinell test, and Shore durometer tests. It is the designer's responsibility to specify the desired hardness on engineering drawings where the material can be hardened by heat treatment or fabrication. Of primary concern are hardenable metals and elastomers. The Shore durometer hardness of elastomers can vary over a wide range.

There are various ways of specifying the hardness of metals; a system used by many industries is shown in Figure 3.42. The hardness of ceramics cannot usually be measured by any of the tests listed in Figure 3.41 except the Knoop or Vickers. The scale is shown to stop at 1000 HK, but it continues well above this value. Absolute hardness is measured by a microhardness machine, and the measurement is expressed as a pressure in kilograms/square millimeter (kg/mm^2). These hardness values are obtained by dividing the penetration load by the projected area of the indentation.

3.6 Fracture Characteristics

3.6.1 Introduction to Fracture Mechanics

Fracture mechanics is the discipline that studies the stress-strain state of materials containing cracks or other small flaws. All materials contain some flaws; we wish to know the maximum stress that the material can withstand if it contains flaws of a certain size and geometry.



Hardness Test	Indentor	Load	Application
Knoop or Vickers	Diamond	1 g to 2000 g	Microhardness of soft steels to ceramics
Brinell	Ball	500 & 3000 kg	Soft steels & metals to 40 HRC
Rockwell B	Ball	100 kg	Soft steels & nonferrous metals
Rockwell T	Ball	15, 30 & 45 kg	Thin soft metals
Rockwell N	Diamond	15, 30 & 45 kg	Hard thin sheet metals
Rockwell A	Diamond	50 kg	Cemented carbides
Rockwell R	Ball	10 kg	Polymers
Shore Durometer	Needle	Spring	Elastomers
Rockwell C	Diamond	150 kg	Hardened metals (thick)

Figure 3.41 Comparison of hardness tests

A typical *fracture mechanics test* may be performed by applying a tensile stress to a specimen prepared with a flaw of known size and geometry (Figure 3.43).

If the specimen is thick enough, a “plain strain” condition is produced which gives the worst behavior of the material. The stress required to propagate a crack from the prepared flaw can be measured. The *stress intensity factor K* then can be calculated. In simple tests, the stress intensity factor is

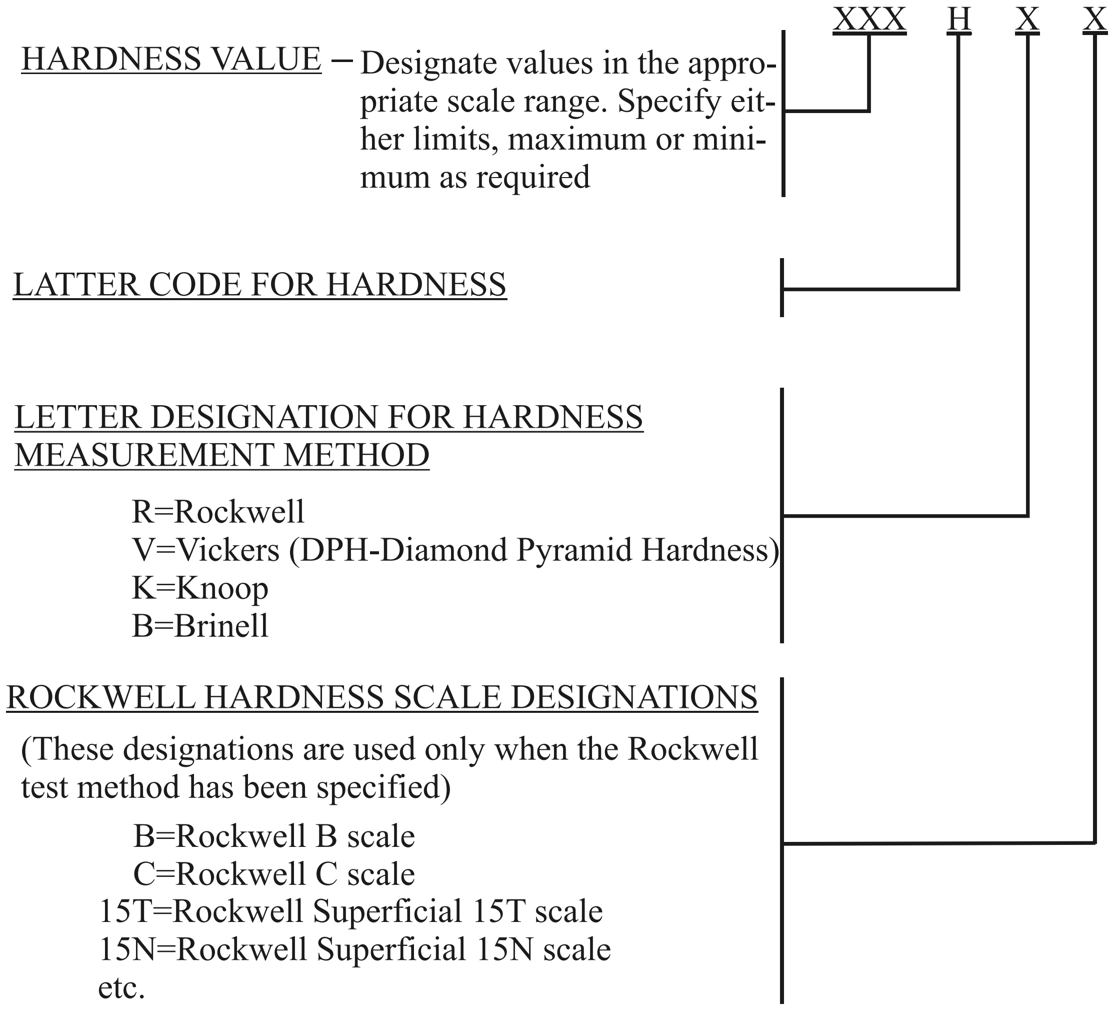
$$K = f\sigma\sqrt{\alpha\pi}\,, \qquad (3.25)$$

where f is a geometry factor for the specimen and flaw, σ is the applied stress, and α

Specify hardness according to the code described in below.

This code is in agreement with the method of designation used by the following standards organizations:

1. American Society for Testing and Materials (ASTM)
2. American National Standards Institute (ANSI)
3. International Standards Organization (ISO)



HARDNESS VALUE – Designate values in the appropriate scale range. Specify either limits, maximum or minimum as required

LATTER CODE FOR HARDNESS

LETTER DESIGNATION FOR HARDNESS MEASUREMENT METHOD

R=Rockwell
V=Vickers (DPH-Diamond Pyramid Hardness)
K=Knoop
B=Brinell

ROCKWELL HARDNESS SCALE DESIGNATIONS

(These designations are used only when the Rockwell test method has been specified)

B=Rockwell B scale
C=Rockwell C scale
15T=Rockwell Superficial 15T scale
15N=Rockwell Superficial 15N scale
etc.

Examples:

1) 50-60HRC means: a hardness value of 50 to 60 using the Rockwell C scale.

2) 85HR15T MAX means: a maximum hardness value of 85 using the Rockwell Superficial 15T scale.

3) $185\text{-}240_{1kgf}$ means: a hardness value of 185-240 using the Vickers hardness tester and a test load of 1 kilogram-force.

4) $500HK_{200gf}$ MIN means: a minimum hardness value of 500 using the Knoop hardness tester and a test load of 200 grams-force.

Figure 3.42 Specification of hardness numbers for metals

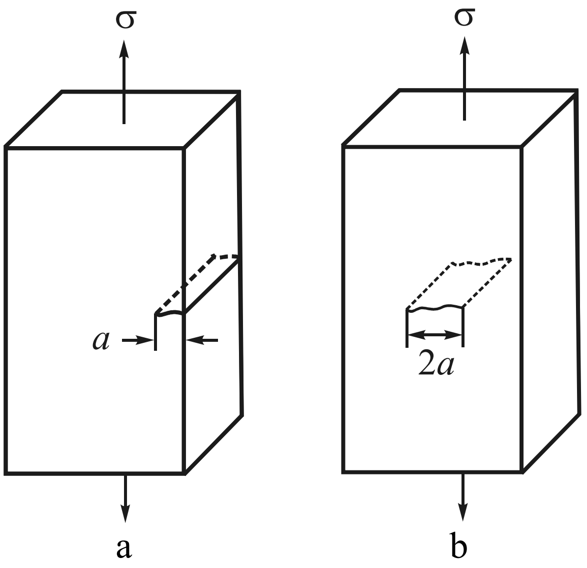


Figure 3.43 Two types of flaws in fracture toughness specimens: (a) - edge; (b) – internal

is the flaw size as defined in Figure 3.43. For thick plate, $f \approx 1$. If K is greater than or equal to a critical value K_{1c}, the flaw grows and the material fails. The *critical fracture toughness* K_{1c} is a property of the material (Table 3.7).

A similar approach can be used to determine the ease with which a flaw grows in torsion, impact, fatigue, or other loading conditions.

The ability of the material to resist the growth of a crack depends on a large variety of factors, including the following.

1. Larger flaws reduce the permitted stress. Special manufacturing techniques have been devised to improve fracture toughness. For example, liquid aluminum is passed through a ceramic filter to remove impurity particles, whereas the AOD process (argon-oxygen decarburization) has been developed to produce steels containing fewer oxide inclusions.

2. Increasing the strength of a given metal tends to reduce fracture toughness, as shown for the titanium alloy in Table 3.7. This is often associated with the lower ductility that the stronger alloys possess.

Table 3.7 The critical fracture toughness for selected materials

Material	Critical Fracture Toughness, psi·in$^{1/2}$	Critical Fracture Toughness, MPa·m$^{1/2}$	Yield Strength, psi	Yield Strength, MPa
Al-Cu alloy	22,000 33,000	24.2 36.3	66,000 47,000	455 324
Ti-6% Al-4% V	50,000 90,000	54.9 98.9	130,000 125,000	896 862
Ni-Cr steel	45,800 80,000	50.3 87.9	238,000 206,000	1641 1420
Al_2O_3	1,600	1.8	30,000	207
Si_3N_4	4,500	4.9	80,000	552
Transformation toughened ZrO_2	10,000	11.0	60,000	414
Si_3N_4-SiC composite	51,000	56.0	120,000	827

3. Thicker materials have a lower stress intensity factor K than thin materials (Figure 3.44 (a)). However, the fracture toughness is less predictable for thin sections, due to the increased section size sensitivity as the thickness of the specimen approaches the size of the flaws.

4. Increasing the temperature normally increases the fracture toughness of BCC and HCP metals. However, the fracture toughness of FCC metals is relatively unaffected by temperature (Figure 3.44 (b)).

5. The ability of a material to deform is critical. In ductile metals, the material near the tip of the flaw can deform, helping to absorb energy and blunt further crack growth. Brittle materials such as glass cannot deform; consequently, the crack propagates with little energy required. Each engineer must know some of the methods used to improve the fracture toughness of brittle materials such as ceramics, thermosetting polymers, and composites.

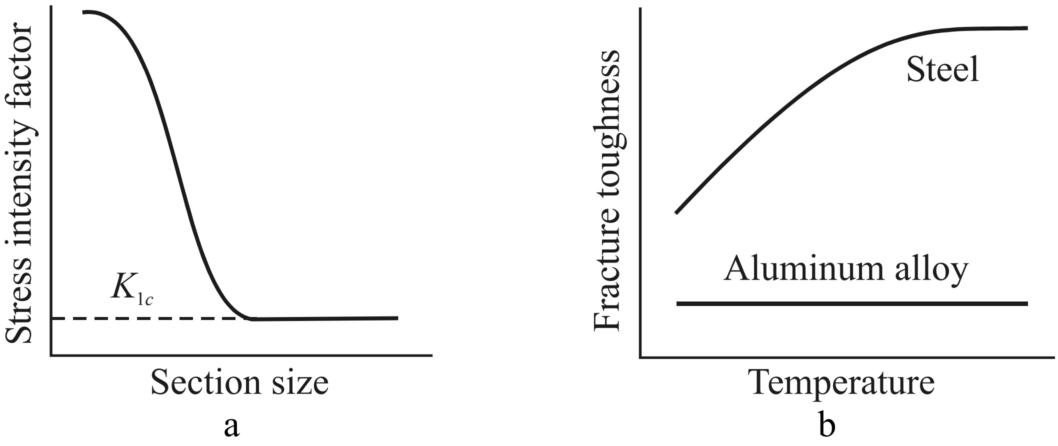


Figure 3.44 The effect of (a) section size, (b) temperature, and crystal structure on the stress intensity factor and fracture toughness of materials

3.6.2 Importance of Fracture Characteristics in Design

Our knowledge in fracture mechanics allows us to design and select materials while taking into account the inevitable presence of flaws. There are three variables to consider – the property of the material (K_{1c}), the stress σ that the material must withstand, and the size of the flaw a.

We must be able to set an upper limit on the size of any flaw that is present by *nondestructive testing*. For example, *ultrasonic testing* or *X-ray radiography* may detect any flaw longer than 0.1 mm. This fixes the largest size a and gives us the worst condition that the material will face. If we know the magnitude of the applied stress, we can select a material that has a fracture toughness K_{1c} large enough to prevent the flaw from growing. Or, if the material has already been specified, we can calculate the maximum permitted stress that can act on the material. Finally, if we know both the applied stress and the fracture toughness of the material, we can determine if our nondestructive testing capability is adequate.

Example 3.16

For a large plate, the geometry factor *f* is one. Suppose a steel-casting alloy has a critical fracture toughness of 80,000 psi·in$^{1/2}$ (87.9 MPa·m$^{1/2}$). The steel will be exposed to a stress of 45,000 psi (310 MPa) during service. Calculate the minimum size of a crack at the surface (edge crack) that will grow. Repeat the calculation for an internal crack.

Answer

$$K = f\sigma\sqrt{a\pi}\ ,$$

$$80{,}000 = (1)(45{,}000)\sqrt{a\pi}\ ,$$

$$\text{or}\quad (87{,}9) = (1)(310)\sqrt{a\pi}\ .$$

$$\text{For a surface (edge) crack}: a = \frac{1}{\pi}\left(\frac{80{,}000}{45{,}000}\right)^2 = 1\text{ in} = 25.4\text{ mm}.$$

$$\text{For an internal crack}: 2a = 2\text{ in} = 50.8\text{ mm}.$$

3.7 Dimensional Properties

3.7.1 Main Definitions

Roughness is a relatively finely spaced surface irregularities, the height, width, and directions of which establish a definite surface pattern.

Waviness is a wavelike variation from a perfect surface; generally much wider in spacing and higher in amplitude than surface roughness.

Lay is the direction of a predominating surface pattern, usually after a machine operation.

Camber is a deviation from edge straightness; usually the maximum deviation of an edge from a straight line of given length.

Out of flat is the deviation of a surface from a flat plane, usually over a macroscopic area.

Surface finish is the microscopic and macroscopic characteristics that describe a surface.

3.7.2 Surface Finish

The surface characteristics of engineering materials often have a significant effect on serviceability and thus cannot be neglected in design. It is the designer's responsibility to specify the nature of the surface on machine components. About 20 mathematical parameters are applied to the characterization of a surface, but the most commonly used parameters are roughness, waviness, and lay (Figure 3.45). Lay is usually macroscopic and can be measured visually or with a simple loupe. Total surface profile, which is the net of the surface roughness and waviness, is usually measured by profilometer devices that electronically measure surface texture with a stylus not unlike a phonograph needle.

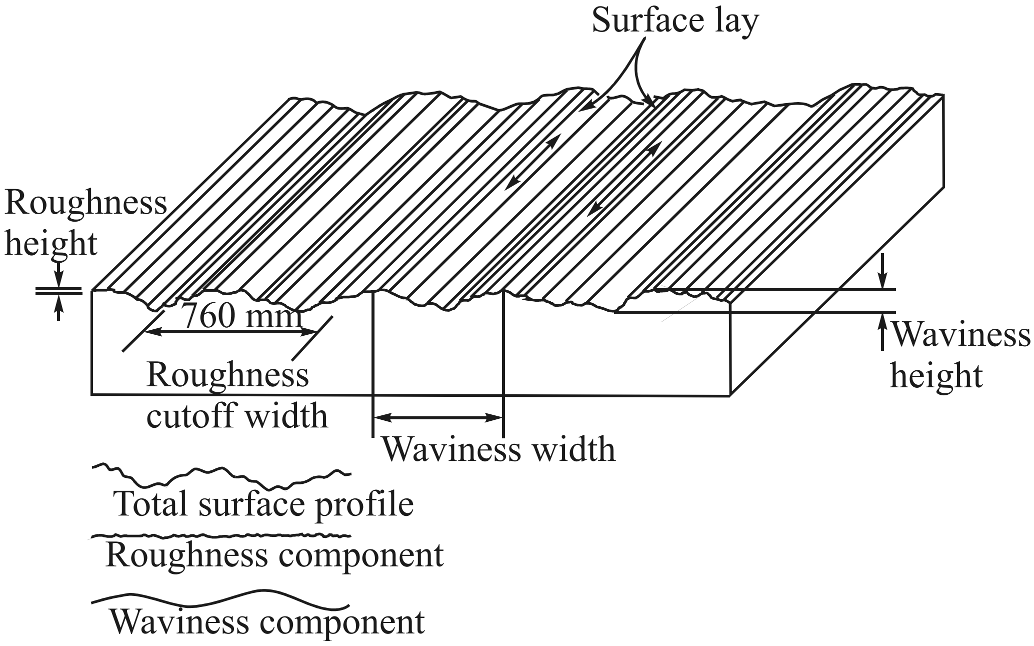


Figure. 3.45 Components of surface microtopography

The simplest profilometers yield only surface roughness data. The more sophisticated devices yield contour maps, single-line surface profiles, and roughness average data (Figure 3.46). Surface roughness is usually expressed as the arithmetic average (AA) of the peak-to-valley height of surface asperities in microinches (μin). The SI units are micrometers (μm). Since a profilometer stylus has a finite radius (usually 0.0001 in or 2.5 μm), it cannot reach the bottom of valleys of surface features; it cannot measure true depth. The AA roughness is approximately 25% of the true peak-to-valley height. Most profilometers average the surface roughness over a set increment of stylus travel. This is called the *cutoff width*. All the surface peaks in this distance are integrated to yield a single roughness reading.

The parameters of waviness are *waviness height* and *waviness width*. Surface lay has no quantitative units, but there are symbols to indicate a desired lay. The American National Standards Institute (ANSI) has devised a system for describing surface texture on engineering drawings (see Figure 3.47).

The surface finish importantly relate to selection and serviceability. There is an optimum range of surface roughness for parts intended for accurate fits, wear applications, release characteristics, and even nonfunctional surfaces. If a rotating shaft is too rough, it could abrade a soft bearing material. Coarse machine marks cause stress concentrations that can lead to fatigue failures. Surfaces with redundant finish characteristics unnecessarily increase fabrication costs.

Figure 3.48 presents some experience guidelines on finishes to call for on selected machine components. Figure 3.49 shows the surface finish ranges possible with various machining techniques. This illustration points out the inadequacy of using surface descriptors such as grind, turn, and drill. A ground surface can be as rough as 120 μin AA (3 μm) or as smooth as 4 μin AA (0.1 μm). Surface finish requirements should always be expressed by using quantitative limits on at least surface roughness. The preferred technique is the use of the ANSI system outlined in Figure 3.47.

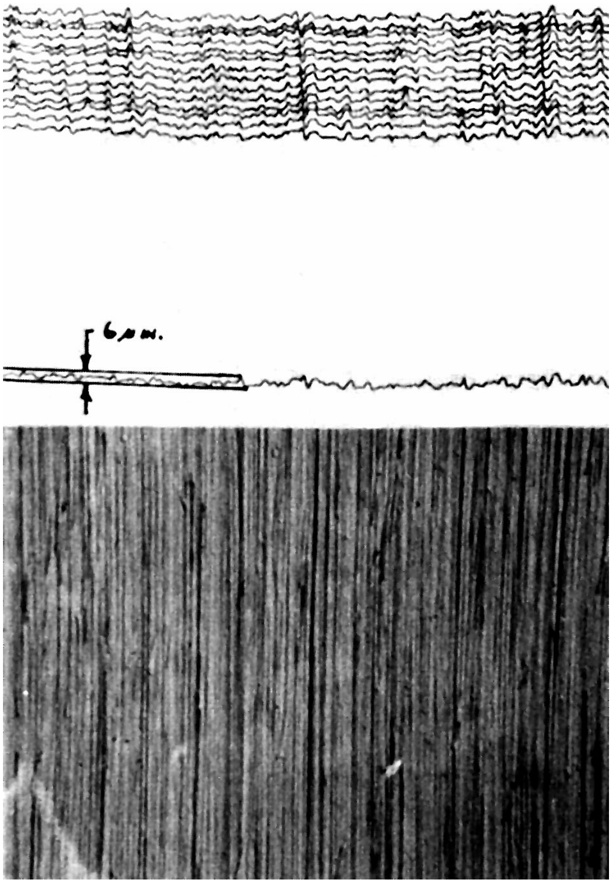


Figure 3.46 Profilometer map of a ground surface (top), single line trace (middle), photomicrograph at 200 × (bottom)

3.7.3 Size and Shape Considerations in Material Selection

A primary material selection factor used by designers is material availability in the size and shape required for the part under design. A mechanical property study may show that type 317 stainless steel is the best material for a support column under design. If the job requires a 3.0 m long, 8 cm by 12 cm channel, and this shape is not available in small quantities from a warehouse, this material cannot be used. Similarly, if a material is required for an accurate machine baseplate, a primary selection factor may be the availability of a material with good flatness tolerances.

Camber, an edge bow in sheet or strip, is important in using sheet and strip materials. If a material is available in the desired thickness and overall size but comes in with excessive camber, it may not be usable for the intended application.

Stock tolerances are important if areas of a part are to be used in the as-received condition. Some material shapes are made with a tolerance of plus 1 % of the nominal thickness, minus nothing. If a part requires a minimum thickness of, for example, 1.25 mm, the thickness tolerances should be investigated on candidate ma-

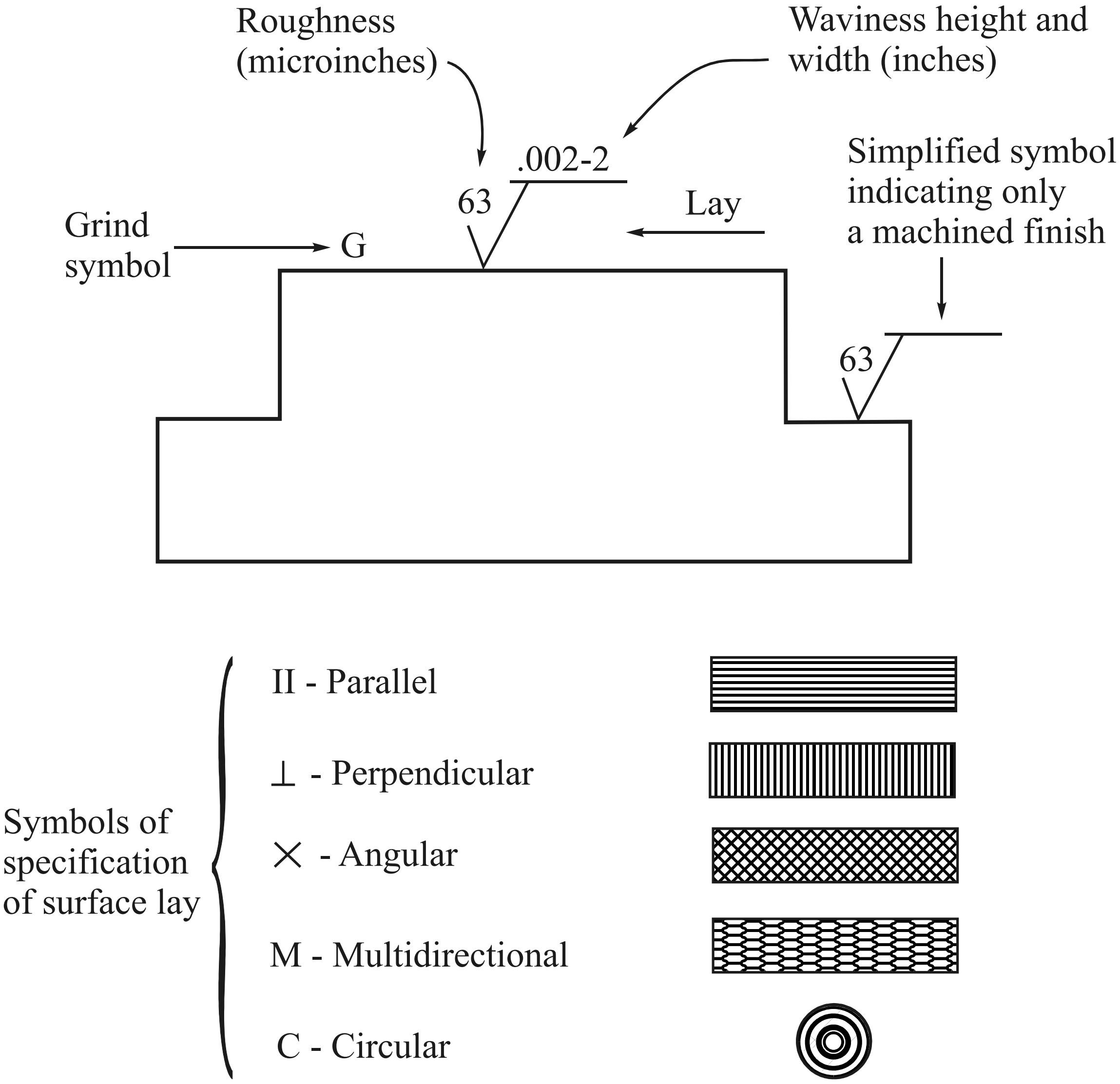


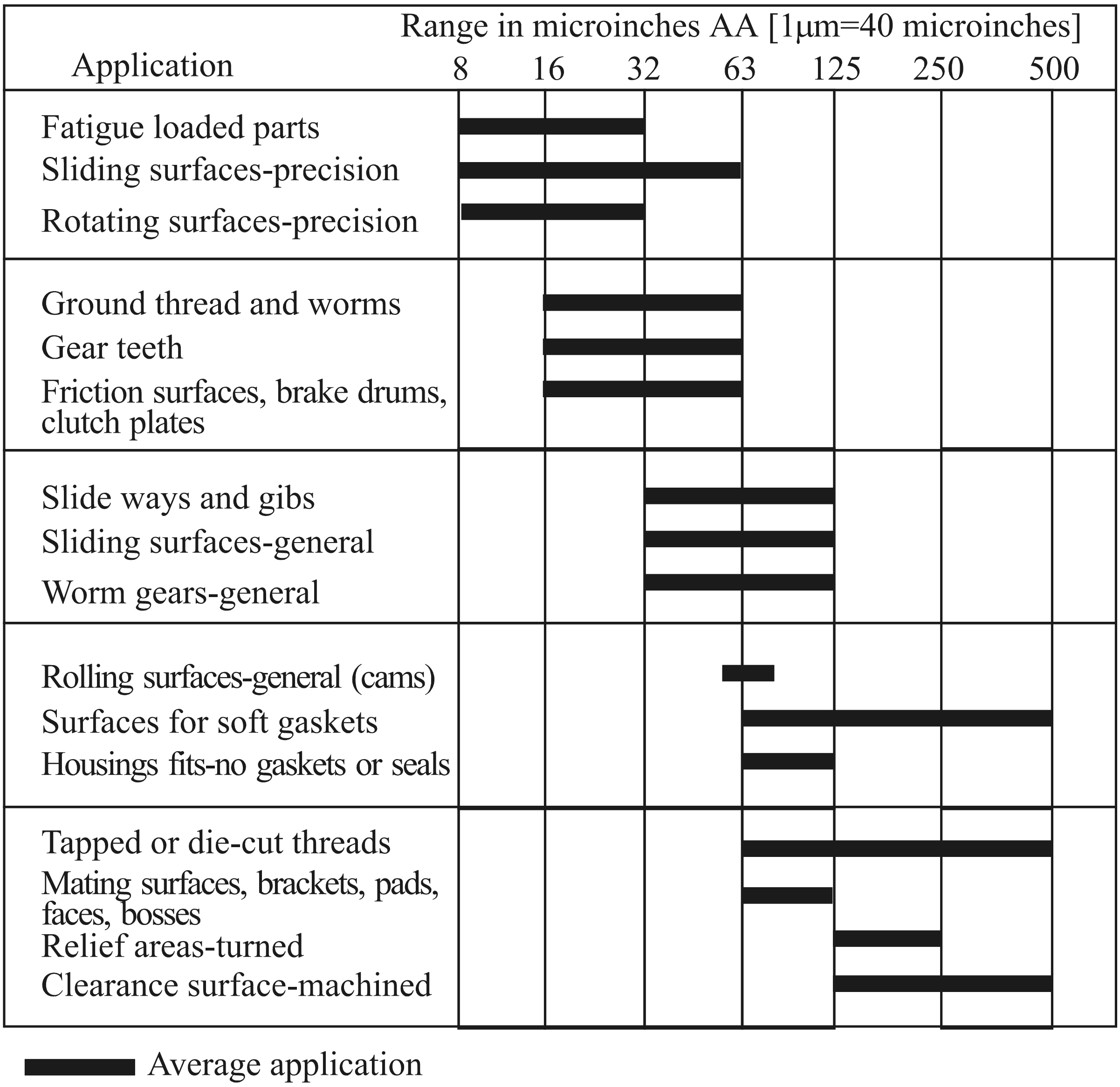
Figure 3.47 Specification of surface texture (American Standard Surface Texture ANSI B46.1-78)

terials for a part under design. If a material with a nominal thickness of 1.25 mm is ordered and it comes in with a thickness of 1.24 mm, it may be useless.

Occasionally, a particular material form will lead to dimensional problems. Hot-rolled steels have a loose “flaky” scale, and the surface finish is usually too poor to use without machining. If the designer did not consider this when the material was specified, it may make the purchased material unusable or it may significantly add to machining costs.

Castings may come from the foundry with gouges left from gate removal; sometimes flash or mold pickup are not removed. The designer can control these factors by drawing notation calling for sandblasted, flash-free castings free of surface defects.

Extruded shapes are usually bowed and twisted when they are made. If long lengths are required, the designer should use materials that are available as straight ened



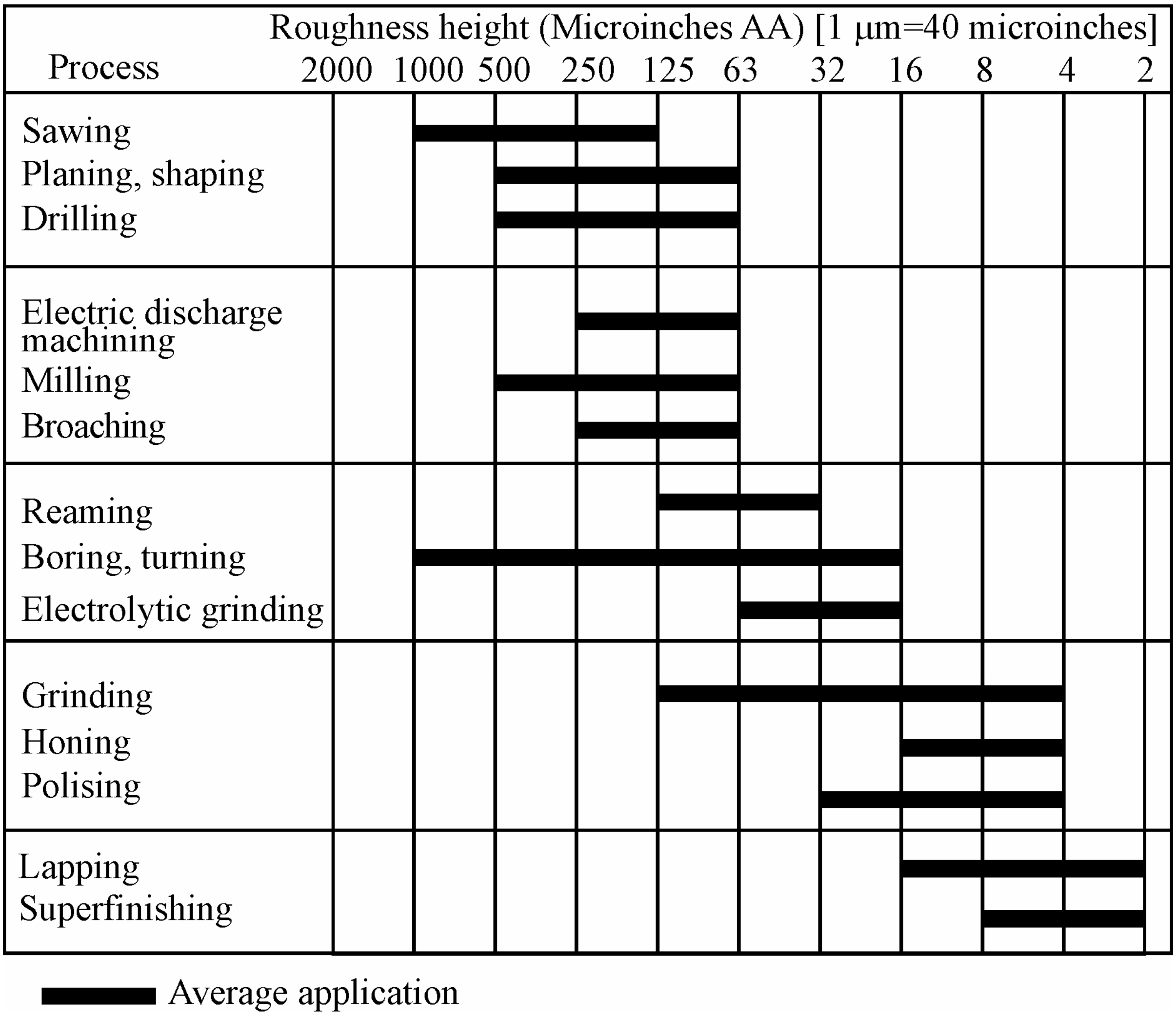
The ranges shown are ordinary considered desirable for the conditions listed.

Figure 3.48 Recommended surface roughness for machine parts

extrusions.

Mentioned above are some of the size and shape considerations that are part of the dimensional properties of materials. How should a designer deal with these factors? A checklist on dimensional property requirements should be mentally reviewed immediately after the part is designed. The checklist should contain the following factors:

1. Surface roughness requirements
2. Flatness requirements
3. Lay



The ranges shown above are typical of the processes listed.

Figure 3.49 Surface roughness produced by various machining techniques

4. Stock tolerances
5. Camber
6. Surface cleanliness
7. Edge tolerances
8. Bow tolerances
9. Surface reflectance
10. Should prefinished material be used?

The designer should establish which of these factors will affect part serviceability. If it is clear that some of these factors are important, then steps should be taken to specify dimensional requirements on engineering drawings and purchasing specifications.

Summary

The mechanical behavior of materials is described by their mechanical properties, which are the results of idealized, simple tests. These tests are designed to present different types of loading conditions. The tensile test describes the resistance of a material to a slowly applied load; the results define the yield strength, ductility, and stiffness of the material. The fatigue test permits us to understand how a material performs when a cyclical stress is applied, the impact test indicates the shock resistance of the material, and the creep test provides information on the load–carrying ability of the material at high temperatures. The hardness test, beside providing a measure of the wear and abrasion resistance of the material, can be correlated to a number of other mechanical properties. Fracture mechanics takes into account the presence of flaws in the material. Finally, dimensional properties are characterized by a number of indices, which permit us to choose recommended parameters for machine parts.

Our discussion of the properties of materials is far from being complete, but the properties described are the ones that refer to most applications of engineering materials in design. If the problem is selection of a material for a unique product design or a very specialized machine application, it may be necessary to consider a number of properties not mentioned here. As an example, there are probably 20 magnetic properties not discussed, as well as many electrical properties of polymers and ceramics. It must be noted that every property that can affect serviceability of a machine component should be given thorough consideration. One final question may arise with regard to material properties. Where do you find this property information? Engineering handbooks and industry–published data books usually present the most valid and unbiased data. Nevertheless extra care should be taken in observing the test conditions under which the data were obtained. It is possible to select a test that makes one material look favorable compared with others. The best method for ensuring validity of data is to use only data developed according to test procedures rigidly outlined by state standards, for example, the American Society for Testing Materials. Each vendor should show the ASTM procedure used with a symbol such as ASTM – ×××. Handbooks do not usually do this, but as mentioned previously they have no reason to enhance data to show one material to be better than another. The complete ASTM procedure for measuring a particular property can be readily obtained from the ASTM or in any engineering library.

Finally, the theme for proper use of material–property information in material selection is to analyze the data and make sure that the same test was used to measure the properties under comparison. This is especially true when considering use of different classes of materials (i.e., polymer versus metal versus ceramic).

Chapter 4 General Principles of Materials Selection

The main idea of this Chapter is to give the designer an understanding of materials systems and the knowledge how to provide the specific engineering materials effective practical use.

We shall summarize our knowledge about materials properties and illustrate how the materials properties and other selection factors are used to make a material selection for given design situations. Our approach to the materials selection is a compilation of the various steps used by the most experienced designers. And, moreover, a modern concept of the connection of the identification of fundamental relationship between materials properties and the selection of materials for engineering design will be proposed.

4.1 Designing and Materials Selection

Each designer in his/her daily work receives an assignment to design a device or machine which usually includes different parts connected together.

How do you start your approaching towards the goal to design a device intended for an expanded service life? Stage 1 – consideration of the problem. This stage implies the development of general ideas in form of sketches, analogue searches in sources, models creation, discussions with a customer, and the like.

If the "consideration" stage is productive, the design concept may take shape at the second stage (Figure 4.1). After sketches are made, sizes are established, drive and actuation systems are envisioned, some questions may appear. Are all the desired functions performed? Is the expected cost within the project limits? Are the desired production rates possible? All these questions are in the mind of a designer.

Step 3 is to make an assembly drawing to find out if the design concept works on paper. If it does not, it may be necessary to return to the beginning. Once an assembly drawing is complete and a motion analysis indicates that parts move as they are supposed to and do not hit each other, it is time to get into hard-core engineering: stress, vibration, acceleration analysis, and the like. It is not even too early to think of such things as wear mode, lubrication, operating environment, and the effect of component failures.

The next step is to establish all the operational requirements of each component in the device. Which parts need to be hard? How much deflection can be tolerated in this shaft? What flatness is needed on the base plate? Is corrosion a problem in the loading mechanism? Can this arm tolerate any wear? What is the bending stress in this shaft? These are the types of factors that must be established.

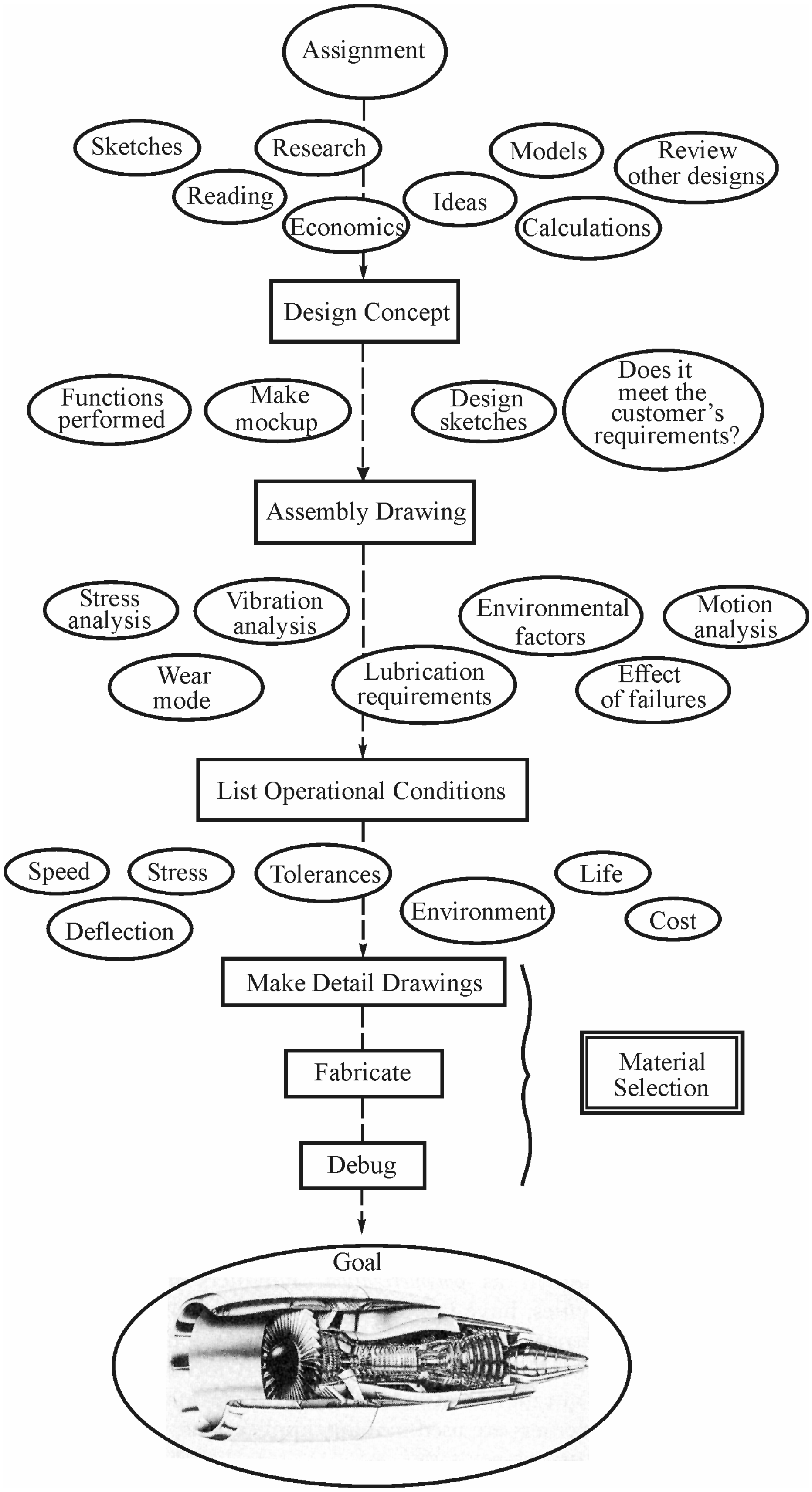


Figure 4.1 Role of material selection in the design process

Once the designer has firmed up in his mind the requirements of each part, it is time to make *detail drawings*. Material selection is a key part of this step in the design process. A set of drawings must be produced that shows the shape, dimensions, material of construction, and applicable treatments or special sequences.

The last steps in the process are to fabricate, debug, and put in service. Materials enter into these steps in fabricability and substitution of new materials for the parts that did not make it through debugging. The major points intended are that the designer should start to think about materials of construction quite early, and more important, effective material selection is predicated on knowing the operational requirements of each and every part. You simply cannot select a material for a part without knowing what that part must do in service.

If an engineering assignment requires purchase of a piece of machinery or subcontracting of a structure or facility, some of the steps in the design process (Figure 4.1) will be different. Instead of assembly and detail drawings, the designer will probably write design specifications. Material selection should be a part of these specifications. When vendor proposals are obtained, they are matched to the established specifications and once again material selection becomes important. The vendor, for example, wants to substitute gray cast iron for the pump housing that you specified to be one of a cast stainless steel. Should you permit it?

Thus, material selection is still a part of the engineering process wherever you design the machine. All of the factors that would go into your own design should also be considered when evaluating someone else's design if it is your responsibility to make the piece of equipment function. If the gray cast iron corrodes through in six months, it is your fault, not the pump manufacturer's. You bought the equipment, and it is the engineer's responsibility to buy something compatible with the intended service environment.

4.2 Selection Factors

There are many different properties of materials. When selecting a material for a given part the most important is to consider those properties that are essential to the function of the part. The modern approach is to put equal importance on *properties*, *availability*, and *economics*. There is no sense in specifying the use of a particular material if it cannot be obtained within the time constraints of a project. Similarly, a material cannot be considered for use if it costs more than the project can bear. Figure 4.2 lists the major selection factors-properties, availability, and economics-along with some pertinent subfactors.

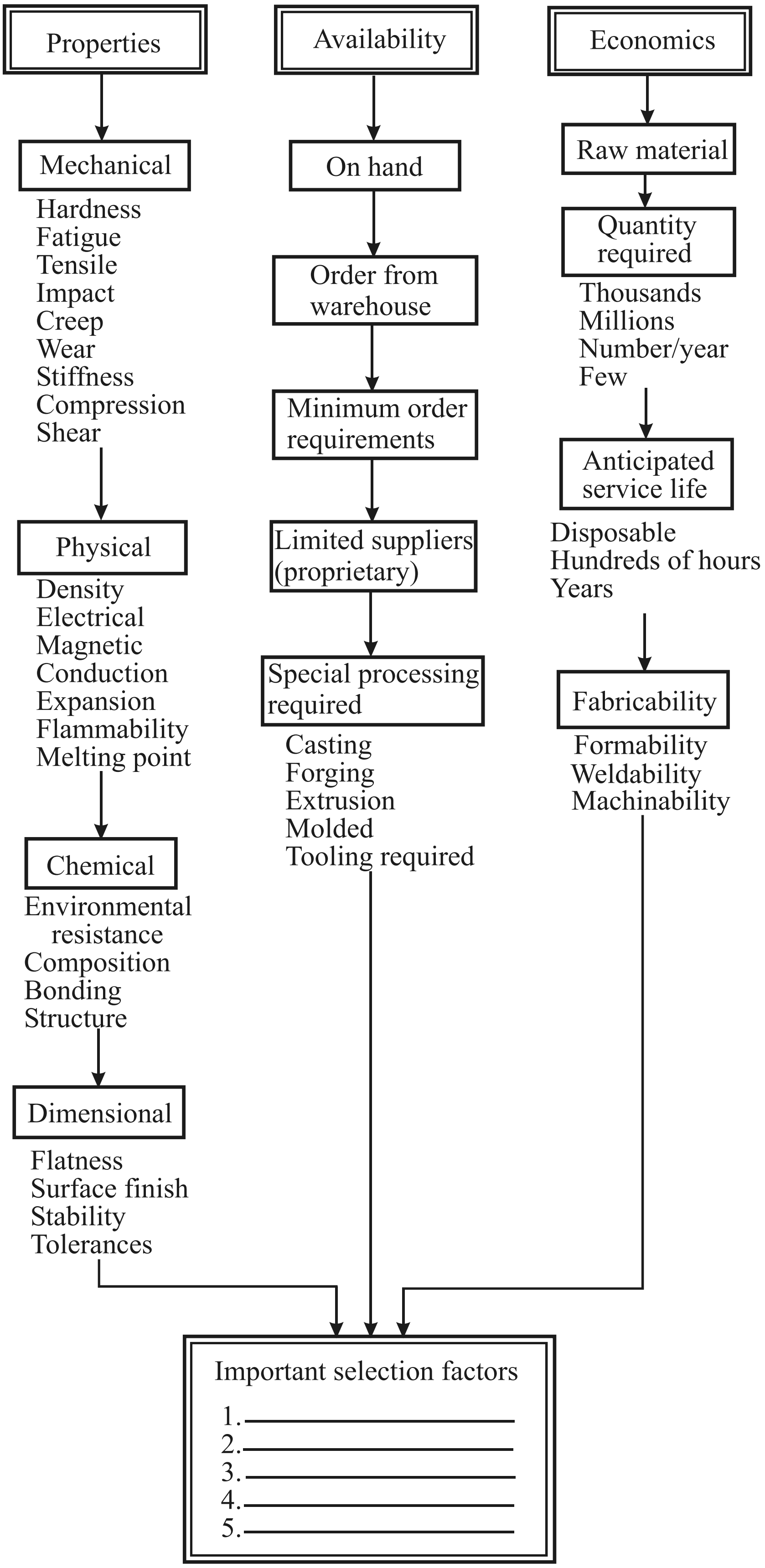


Figure 4.2 Material-selection checklist

4.2.1 Availability

One of the first things that many designers ask when initially considering the use of a particular material is whether the material is on hand. A “no” answer will provoke a second question: can we get it in one week, two weeks, and so on? If this answer is acceptable, the next question is, do we have to order 50,000 lb? Another pertinent question: is the material available from more than one supplier? It is not advisable to use a proprietary material that is available only from one supplier if it is likely that the parts in question will be made again five years hence. The same thing holds true if many parts are required. If you are a captive buyer you are at the mercy of the supplier on cost and delivery.

Sometimes a raw material fabrication technique may limit availability. As an example, it is not uncommon to get delivery times of 60 weeks on special forgings. Even under strict conditions castings may be obtained only in four weeks; in other cases delivery times can be 12 weeks. These are all important selection factors under the category of availability. It is the designer's responsibility to establish a time line for procurement of materials, and if a desired material cannot be obtained within the constraints of this schedule, another material will have to be substituted.

4.2.2 Economics

Assuming that an established availability criterion can be met, the designer should look into the economics of a material. Consciously or unconsciously, every designer uses the cost of materials as a prime selection factor. If a design calls for a soft ductile component, a designer would probably never even consider gold or silver because he has held the belief that these are very expensive metals, too costly to be used in a common machine. However, materials that are sometimes in themselves very expensive are justified because they offer a unique property advantage, or because they are cheaper to use than other lower–cost materials; for example, a design can be simplified and thus made at lower cost.

What are the comparative costs of the materials used in design? Not a single country has a ready supply of all metals, ceramic compounds, or the raw stocks for polymers. The supply of these commodities is dependent on everything from droughts to cold wars. The demand similarly varies with the economic climate, and thus prices fluctuate daily in response to the supply and the demand. It is not possible to put an exact price on a quantity of a material, but the relative costs of some of the materials that we have discussed looked approximately as shown in Figure 4.3.

The most common plastics and metals cost approximately \$0.88/kg. Some of the new exotic polymers can cost as much as \$44/kg, and the precious metals cost as much as \$19,800/kg. These are the extremes in cost, but as was pointed out previously, sometimes the special properties of even very expensive materials can make them the best choice for a particular design. Beryllium costs as much as \$1765/kg in

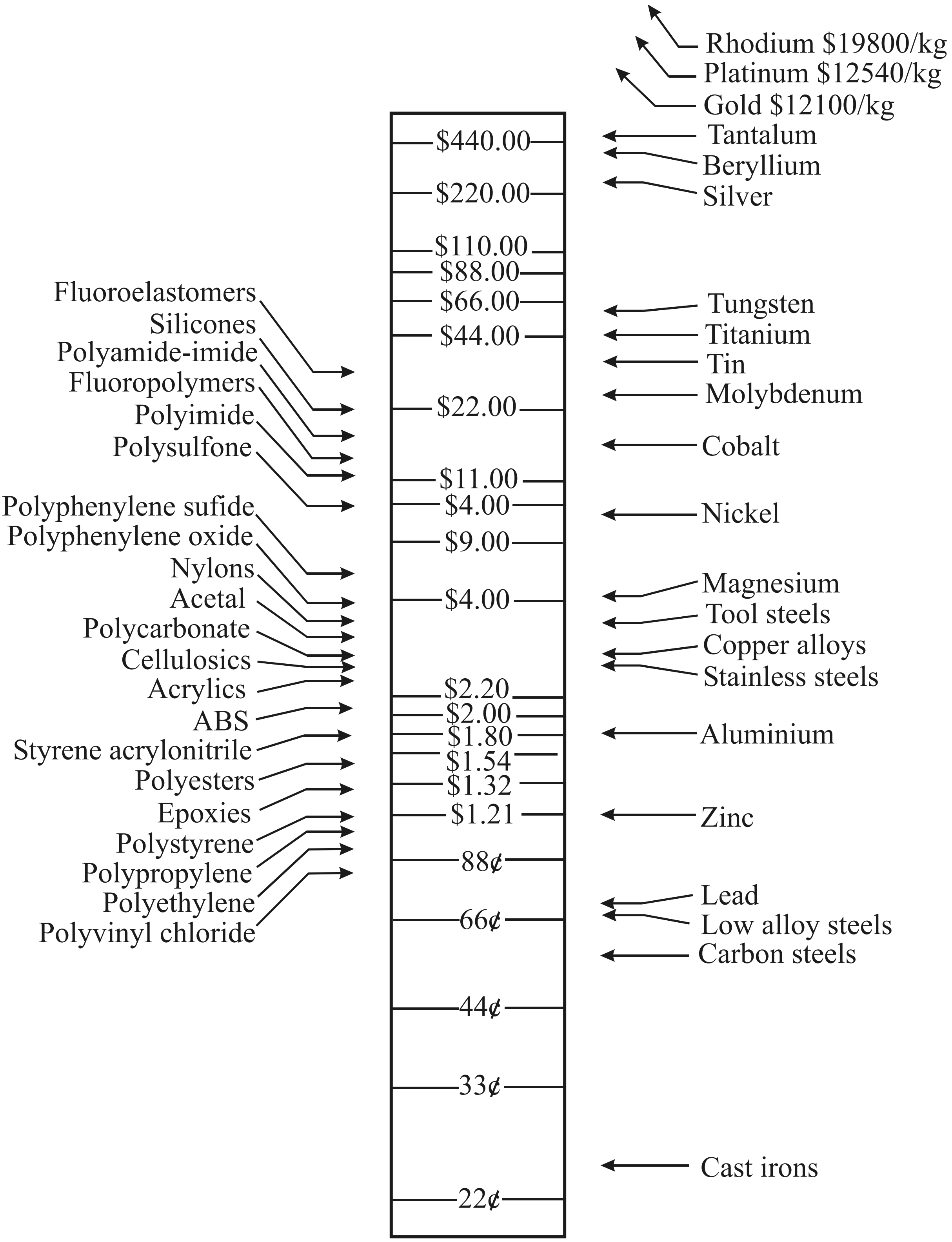


Figure 4.3 Comparative costs of engineering materials per kilogram. Plastics are in molding resin form; metals are in the form of mill products

special sheet form, but it has a stiffness much greater than steel, and it is very light. These properties make it the most economic choice for certain applications. Tantalum at $440/kg is widely used for corrosion applications. A small amount can be used for patching glass–lined vessels handling strong chemicals. It is the cheapest way to repair these expensive vessels.

Nowadays ceramics and composites are widely used in standard shapes, such as plates, bars, and sheets. Ceramics must be molded into a specific shape. Composites can be made as sheets and other shapes for fabrication by conventional machining, but only the simpler composites, such as glass and fabric–reinforced thermosets, are commonly available. The more sophisticated composites, such as carbon– and boron–reinforced epoxies and polyesters, are normally made into the desired shape by lay–up or special techniques.

The cost of boron and carbon filaments for high–strength composites is still in the range of $66 to $220 per kilogram; ceramics can be as cheap as $0.60/lb for aluminum oxide grit to $22/kg for a small molded part of the same material weighing only a few grams. The same thing is true for carbon products. Some small carbon bushings sell for $0.22 each, whereas the same bushing made from another grade of carbon may cost $44. If ceramics or composites are to be considered for a particular job, there is little alternative than to obtain a quotation from a suitable supplier. The good general cost per pound guidelines on these materials doesn’t exist.

Getting back to our cost chart, the cost estimates presented are based on bulk quantities, such as molding pellets in plastics and heats of metals. Any engineering material that is bought in small quantities from a warehouse has many extras added on. As an example, 1030 steel may sell for $0.55/kg if you buy a heat, but that same material in a 2200 kg quantity and vacuum melted costs $13/kg. One of the lowest–cost tool steels, Wl, may cost only $3.3/kg as a hot-rolled round, but as a centerless ground and polished round the cost becomes around $13/kg. Thus, if you are considering small quantities of materials, you must expect many warehouses and handling extras.

If you are designing a part for large–scale production and it appears that a polymeric material, ceramic, or a metal may do the job, one helpful way of comparing material costs is to look at the cost per unit volume. Thirty dollars per kilogram sounds like a lot of money for a plastic, but if that plastic has a specific gravity of 1.5 compared with 7.8 for steel, you get more volume in a pound of plastic than you get in a kilogram of steel; so the $66 becomes much smaller when divided by its volume. Figure 4.4 shows the costs per unit volume of some common engineering materials. It can be seen that the cost ranking changes on a number of materials. Even beryllium looks less expensive. Similarly, many plastics look less expensive. The lowest–cost material of construction is a plastic. Traditionally, cast iron has always been the lowest–cost metal.

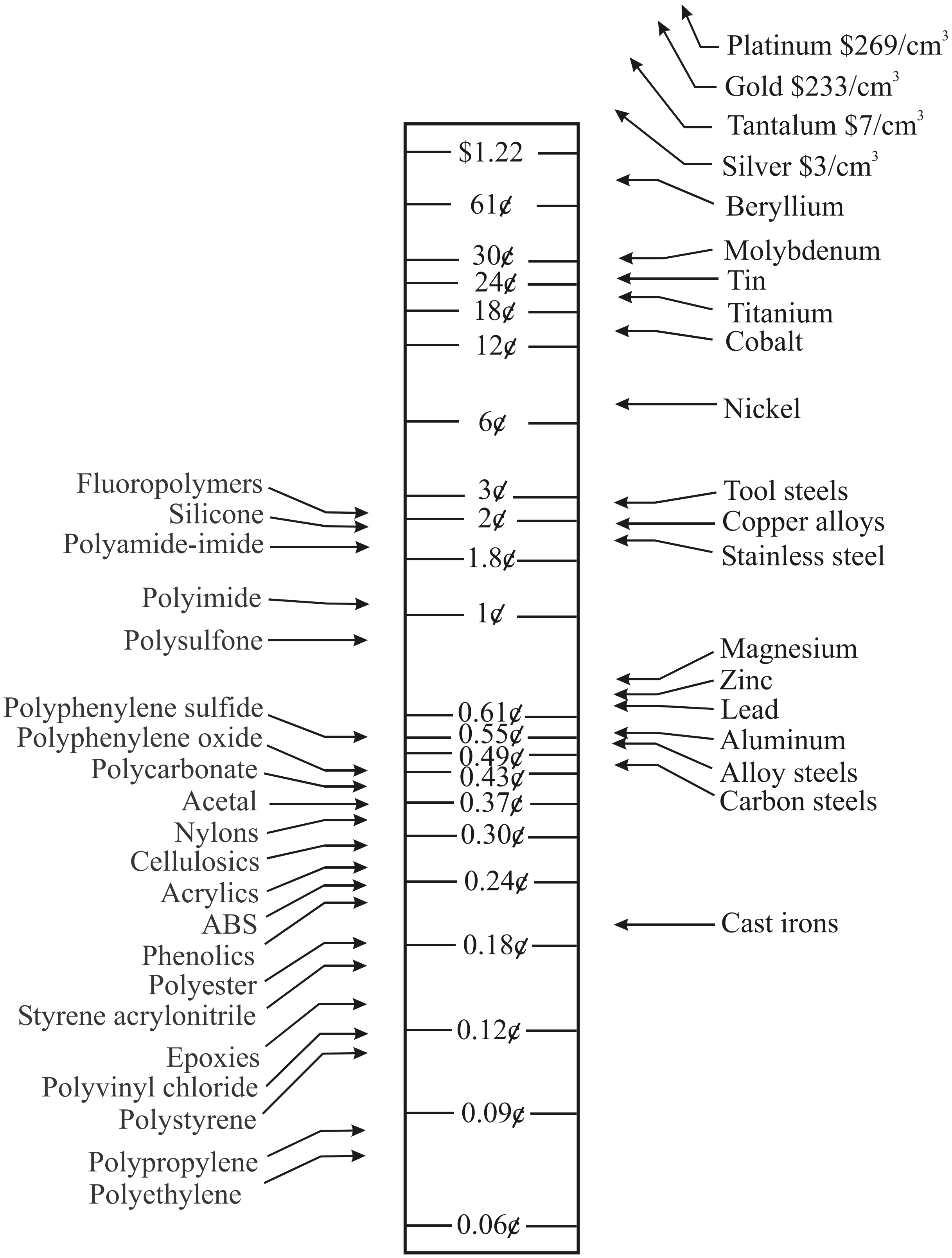


Figure 4.4 Cost of some engineering materials per cubic centimetre

The main point in this discussion of raw material costs is that cost should not be the sole selection factor in making a choice of materials for a particular design. If only a few machine components are to be made, material cost may be almost inconsequential. If a large quantity of material is involved, the answer to the material–cost question should be obtained by a thorough cost study using current material costs.

Other pertinent considerations on the subject of economics are *anticipated service life and fabricability*. If a machine is being designed to last forever, it may be economical to use materials with high raw material costs if these materials have superior strength, wear, or other properties that will contribute to the machine lasting indefinitely. Some examples of designing for indefinite life are equipment associated with the distribution of utilities to a manufacturing operation. Steam turbines put in service in the nineteenth century are still producing power in many old buildings. On the other hand, machines used in the manufacture of dashboards on this year's car need only last a year if a model change is anticipated. Thus the designer must use his judgment on how much extra he wants to pay for long service life in selecting a material.

The final economic factor that we will discuss is *fabricability*, or how easy it is to convert a raw material to a desired shape. If a material has poor machinability, it will cost more to fabricate than a material with good machinability. Some materials such as the cemented carbides cannot be machined at all. They can only be shaped at manufacture or by techniques such as grinding, electrical discharge machining, or electrochemical machining. Most ceramic materials fit into the same category. They cannot even be electrical discharge machined.

Titanium, magnesium, and some other metals in sheet or strip form cannot be formed without special tooling or special hot–forming techniques. These factors make these metals more expensive to use than ductile low–carbon steels or aluminum alloys.

Fabrication costs can also be a factor on polymeric materials. Only a limited number of plastics are available in standard shapes such as rod and plate. If only a few parts are needed of a special plastic, it may be necessary to pay molding costs.

In some cases, even easy–to–machine plastics involve high machining costs because of their tendency to distort during machining. Some of the acetals fall into this category. If accurate dimensions are required, the machining sequence may involve several intermediate stress-relief heat treatments, thus resulting in high machining costs.

Weldability as an economic factor simply means that some materials require special joining techniques that increase costs. Titanium cannot be welded in air. Thus an inert gas welding chamber or special shielding is required. Inertia welding and explosive bonding are the only common techniques used to join aluminum to steels. These processes involve expensive equipment and special techniques. A common example of weldability increasing costs is welding of low–alloy steels, high-strength steels, and tool steels. Special procedures and heat–treating equipment are required. Thus, if a part under design requires welding, the weldability of candidate materials can become a selection factor.

4.2.3 Properties

The properties listed in Figure 4.2 and discussed in Chapters 2 and 3 can be used as a guide in establishing a list of the material properties that will affect the performance of a part under design. Think about your operational conditions; then ask which are the most important mechanical properties. If a device is cyclic loaded, you may want a material with high fatigue strength. If you are designing a support device, compressive strength will be an important property. Shock–loaded devices need good impact strength; shafts must have shear strength adequate to handle the torque transmitted. Stiffness (modulus of elasticity) is important in springs; creep is important in devices used at elevated temperatures for a prolong time. Finally, wear can affect many different types of devices. This latter property should also be qualified as to mode: abrasion, metal-to-metal wear, cavitation, or surface fatigue.

Our list of mechanical properties is not complete, but the point is that a list of applicable mechanical properties should be based on the stresses, motion, and forces applied to the part under design.

The same type of procedure applies to other classes of material properties: physical, chemical and dimensional. The checklist of physical properties may be several pages long. Sometimes an important physical property may be as strange as surface conductivity. Devices handling radio-frequency currents require good surface conductivity. Often it is necessary that parts be ferromagnetic or nonmagnetic. Sometimes plastic parts may require a specific degree of flammability. Coefficient of thermal expansion is an often forgotten physical property, but this property is important whenever dissimilar materials are to be fastened together and heated. There are really no bounds on the number of physical properties that should be considered in material selection; sometimes a relatively obscure property may become important when this class of properties is given thoughtful consideration.

One of the most important chemical properties is environmental resistance. Is corrosion by chemicals important? Will rust interfere with the function of a part? If corrosion is determined to be important, it may be advisable to establish an acceptable corrosion rate. Can a rate of 250 μm/yr be tolerated? Such information is helpful in consulting corrosion data surveys.

Chemical composition may be an important selection factor for reasons other than corrosion resistance. Metal alloys containing cobalt cannot be used in parts of nuclear reactors since radiation can cause the cobalt to form a radioactive isotope with a significant half-life, thus creating a disposal problem if the part ever needs replacement. Sometimes the chemical nature of a surface can be a selection factor.

Copper, zinc, and lead alloys resist adhesive bonding. The same thing is true with many plastics.

The crystal structure of some materials can be important. It was previously mentioned that boron nitride in the hexagonal form is soft and weak; it is hard in the cubic form. Carbon in the cubic form is diamond; it is graphite in the hexagonal form, and amorphous carbon has little use as an engineering material.

The final class of properties to be considered–dimensional ones –applies to all components. The designer must set tolerances and surface–finish requirements. If it is determined that abnormally close tolerances are required, this becomes a selection factor. Some engineering materials are more stable in machining than others. If a plastic is considered, it will be desirable to select a plastic that is not susceptible to a movement by moisture absorption. If a long slender part is under design, it will be necessary to stay away from cold–finished metals. They are notorious for bowing when locally machined. If a part requires a mirror finish, this becomes a material selection factor since some materials can never be made to the low surface roughness required for a mirror finish. Gray cast irons fit into this category. The graphite inclusions preclude the possibility of a mirror finish. The same can be said of fabric–reinforced plastics, porous ceramics, and some coarse-grained cast metals.

4.2.4 Summary

Figure 4.2 may present the impression that material selection involves the consideration of too many factors, but in fact it is not so complicated. We have tried to show that the most important factors are properties, availability, and economics. The relative importance of each of these three factors depends on a particular design situation. If you are designing a part to correct a machine failure, availability of the material used for the part to be replaced may be most important. If you are designing a missile launcher, properties may be most important. Economic factors are most important if your budget is low or if many units are required. Whatever the case is, the designer must establish priorities and then develop a list of the important selection factors that apply to the part or device under design. This list does not have to be formal or even written. Sometimes a mental list is adequate. In any case, the establishment of selection factors is an essential part of the selection process.

4.3 Materials Property Charts

Each property of an engineering material has a characteristic range of values. The range is enormous: of the ten properties considered here–properties such as modulus, toughness, thermal conductivity–all but one ranges through roughly 5 decades, reflecting the diversity in the atomic mechanisms which determine the value of the property.

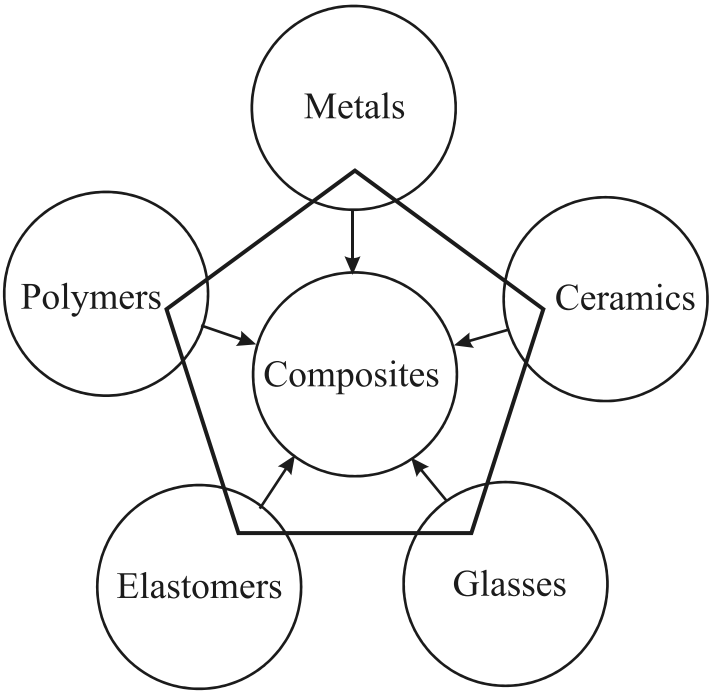


Figure 4.5 The menu of modern engineering materials. Each class has properties, which occupy a particular part (or "field") of the Materials Property Charts

It is conventional to classify the solids themselves into the six broad classes shown in Figure 4.5 – metals, polymers, elastomers, ceramics, glasses and composites.

Within a class the range of properties is narrower, and the underlying mechanisms fewer. But classifications of this sort have their dangers, notably those of narrowing vision and of obscuring relationships.

Using the modern scientific sources let's consider a broad review of engineering materials, examining the relationships between the properties of all six classes.

One way of doing this is by constructing *Material Property Charts.* Figure 4.6 illustrates the idea. One property (the modulus, *E,* in this case) is plotted against another (the density, ρ) on *logarithmic scales*. The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, heaviest metals. It is found that data for a given class of materials (polymers, for example) cluster together on the chart; the *subrange* associated with one material class is, in all cases, much smaller than the *full* range of the property. Data for one class can be enclosed in a property–envelope, as shown in Figure 4.6. The envelope is constructed to enclose all members of the class.

All this is a way of displaying properties in a helpful way. But by choosing the axes and scales appropriately, more can be added. The speed of sound in a solid depends on the modulus, *E,* and the density, ρ; the longitudinal wave speed *v,* for instance, is

$$v=\left[\frac{E}{\rho}\right]^{1/2} \tag{4.1}$$

or, taking logs

$$\log E=\log\rho+2\log v\,. \tag{4.2}$$

For a fixed value of v, this equation plots as a straight line of slope 1 on Figure 4.6. This allows us to add contours of *constant sound velocity* to the chart: they are the family of parallel diagonal lines, linking materials in which sound travels with the same velocity. All the charts allow additional fundamental relationships of this sort to be displayed.

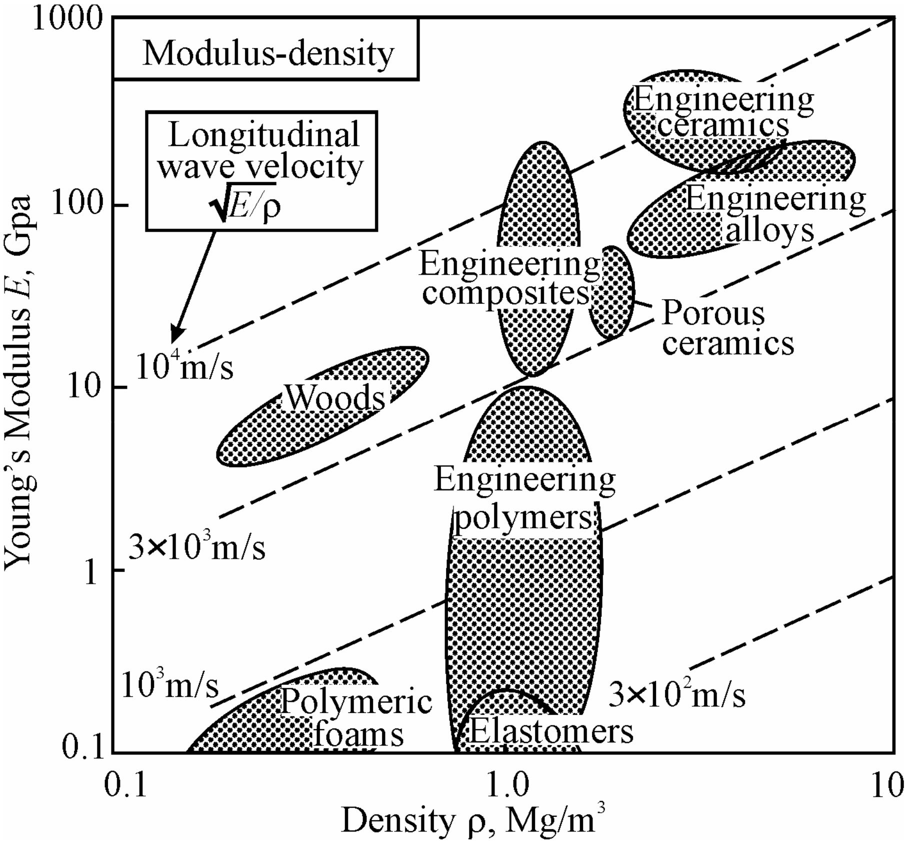


Figure 4.6 The idea of a Materials Property Chart: Young's modulus, E, is plotted against the density, ρ, on log scales. Each class of material occupies a characteristic part of the chart. The log scales allow the longitudinal elastic wave velocity $v = (E/\rho)^{1/2}$ to be plotted as a set of parallel contours

At the more applied end of the spectrum, the charts help in materials selection in engineering design. The performance, in an engineering sense, of load–bearing components is seldom limited by a single property but by one or more combinations of them. The *lightest* tie *rod* which will carry a given tensile load without exceeding a given deflection is that with the *greatest value of* E/ρ. The *lightest column*, which will withstand a given compressive load without buckling, is that with the *greatest value of* $\frac{\sqrt{E}}{\rho}$. The *lightest panel*, which will support a given pressure with minimum deflection, is that with the *greatest value of* $E^{1/3}/\rho$. Figure 4.7 shows how the chart can be used to select materials, which maximize any one of these combinations. The condition

$$\frac{E}{\rho} = C \tag{4.3}$$

or, taking logs

$$\log E = \log \rho + \log C \tag{4.4}$$

is a family of straight lines of slope α_1, one line for each value of the constant C. The condition

$$E^{1/2} / \rho = C \tag{4.5}$$

gives a family with slope α_2, and

$$\frac{E^{1/3}}{\rho} = C \tag{4.6}$$

gives another set with slope α_3. The members of each family are shown on Figure 4.7, labeled "Guidelines for Material Selection". They are found by translating the appropriate guideline sideways.

It is now easy to read off the subset of materials, which are optimal for each loading geometry. If a straight-edge is laid parallel to the $E^{1/2} / \rho = C$ line, all the materials which lie on the line will perform equally well as a light column loaded in compression; those above the line are better (they can withstand greater loads), those below, are worse. If the straight–edge is translated towards the top left corner of the diagram while retaining the same slope, the choice narrows. At any given position of the edge, two materials which lie on it are equally good, and only those which remain above are better. The same procedure, applied to the tie (E / ρ) or plate in bending ($E^{1/3} / \rho$), lead to different equivalences and optimal subsets of materials. There are numerous *criteria for optimal materials selection,* some of which are summarized in Figure 4.8. All of these appear on one or another of the charts described below.

Among the mechanical and thermal properties, there are 10, which are of primary importance, both in characterizing the material, and in engineering design. They are listed in Table 4.1: they include density, modulus, strength, toughness, thermal conductivity, diffusivity and thermal expansion.

The charts display data for these properties for the 9 classes of materials listed in Table 4.2. The class–list is expanded from the original 6 by distinguishing *engineering composites* from *foams* and from *woods* though all, in the most general sense, are composites; and by distinguishing the high–strength *engineering ceramics* (like silicon carbide) from the low strength, *porous ceramics* (like brick). Within each class, data are plotted for a representative set of materials, chosen both to span the full range of behavior for the class, and to include the most common and most widely used members of it. In this way the envelope for a class encloses data not only for the materials listed in Table 4.2, but for virtually all other members of the class as well.

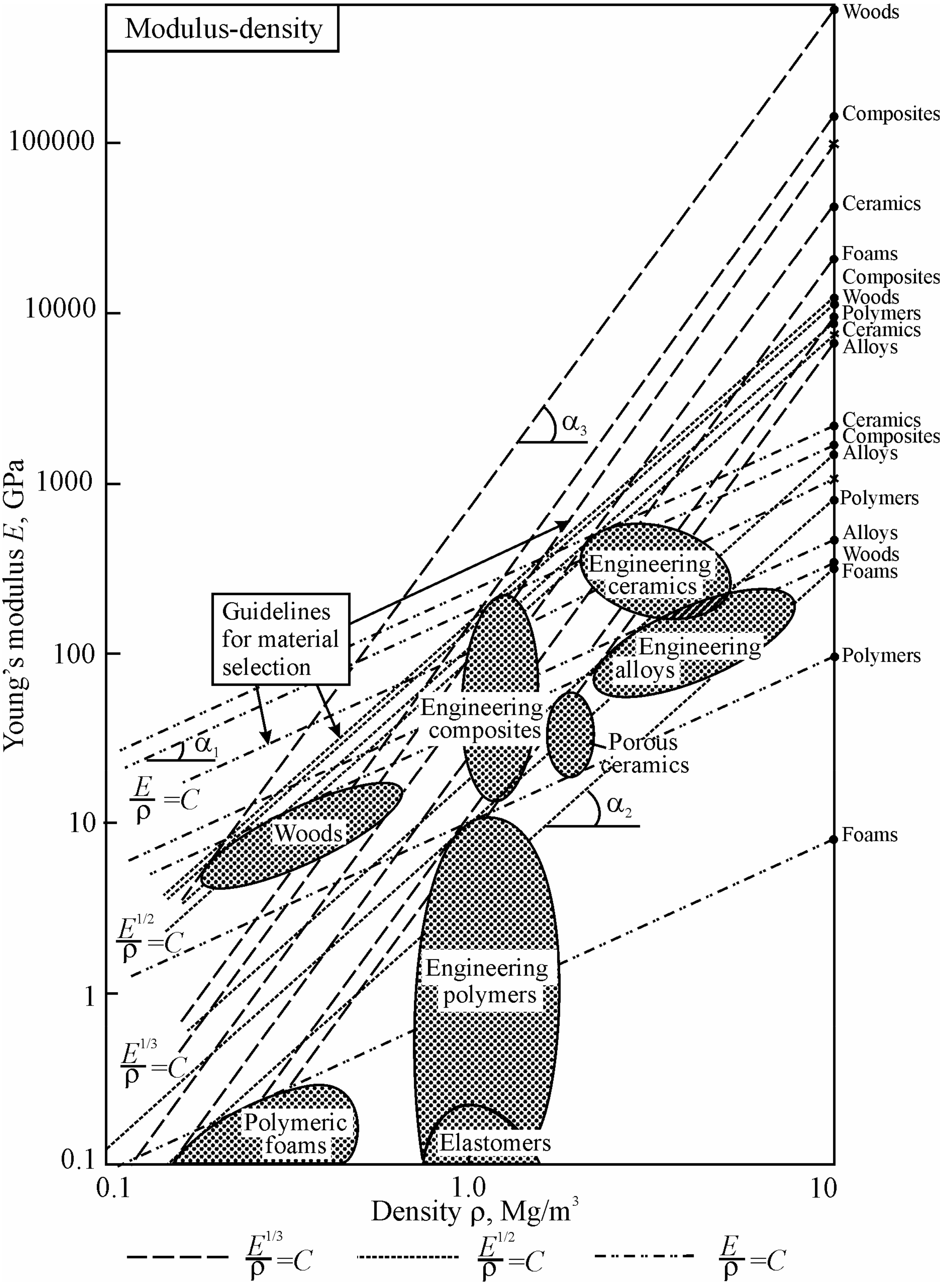


Figure 4.7 The same diagram as Figure 4.6 but showing guidelines for selecting materials for minimum weight design. Because of the log scales the lines are straight even though they describe non–linear relationships between the properties

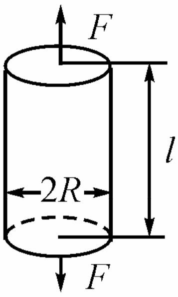
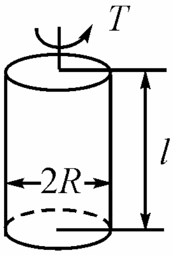
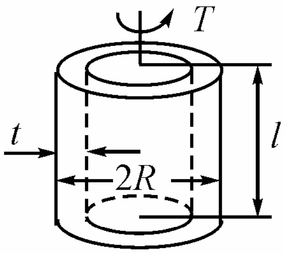
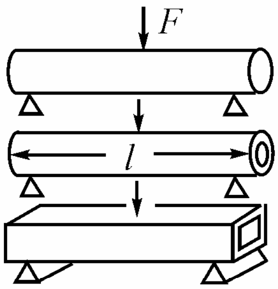
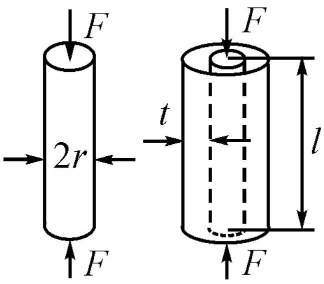
Mode of loading		Minimise weight for given		
		Stiffness	Ductile strength	Brittle strength
Tie F, l specified r free		$\frac{E}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$
Torsion of bar T, l specified r free		$\frac{G}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$
Torsion of tube T, l, r specified t free		$\frac{G}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$
Bending of rods and tubes F, l, specified r or t free		$\frac{E^{1/2}}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}{}^{2/3}}{\rho}$
Buckling of slender column or tube F, l, specified r or t free		$\frac{E^{1/2}}{\rho}$	—	—

Figure 4.8 Some of the property-combinations which determine performance in design (beginning)

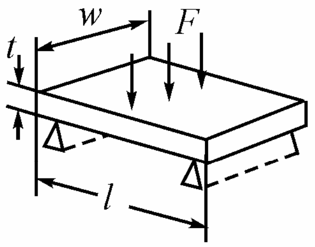
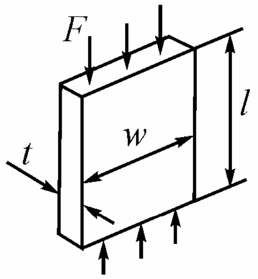
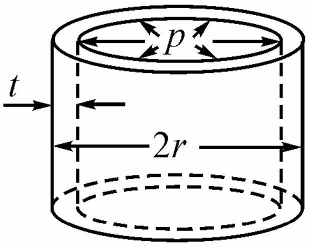
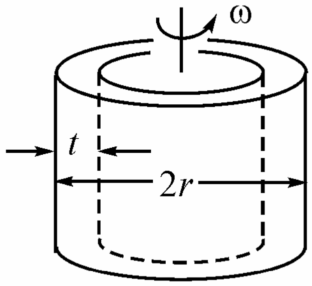
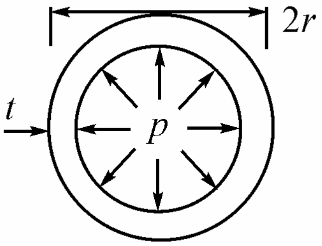
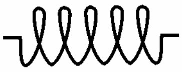
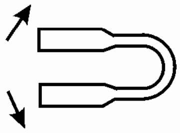
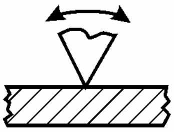
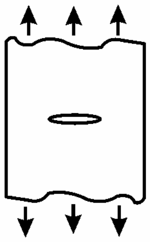
Mode of loading		Minimise weight for given		
		Stiffness	Ductile strength	Brittle strength
Bending of plate F, l, w specified t free		$\frac{E^{1/3}}{\rho}$	$\frac{\sigma_0^{1/2}}{\rho}$	$\frac{K_{1c}^{1/2}}{\rho}$
Buckling of plate F, l, w specified t free		$\frac{E^{1/2}}{\rho}$	—	—
Cylinder with internal pressure p, r, specified		$\frac{E}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$
Rotating cylinder ω, r, specified t free		$\frac{E}{\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$
Sphere with internal pressure p, r, specified t free		$\frac{E}{(1-\mu)\rho}$	$\frac{\sigma_0}{\rho}$	$\frac{K_{1c}}{\rho}$

Figure 4.8 Some of the property-combinations which determine performance in design (continued)

Elastic design

			Chart
Springs 	Spring of min. volume	$\max \sigma_y^2 / E$	4
	Spring of min. weight	$\max \sigma_y^2 / \rho E$	1, 4
Elastic hinges 	Hinge with no axial load	$\max \sigma_y / E$	4
	Hinge with axial load	$\max \sigma_y^2 / E$	4
Knife edges, pivots 	"Point" or "line" contact with min. friction loss	$\max \sigma_y^3 / E^2$ and E	4

Plastic and fracture - safe design

	Load-controlled design	$\max K_{1c}$ and σ_y	6
	Displacement-controlled design	$\max K_{1c}/E$ and σ_y/E	4, 5
	Yield before break	$\max K_{1c}/\sigma_y$	6
	Leak before break	$\max K_{1c}^2/\sigma_y$	6

Thermal design

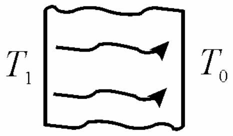
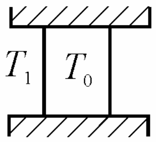
Thermal flux 	Min. heat flux at steady state	$\min \lambda$	8
	Min. temp. rise after time t	$\min \lambda / C_p\rho = a$	8
Thermal stress, shock 	Min. thermal stress	$\min E\alpha$	9
	Max. thermal shock	$\max \sigma_y / E\alpha$	10

Figure 4.8 Some of the property-combinations which determine performance in design (finished)

Table 4.1 Basic subset of material properties

Property	Units
Density, ρ	Mg/m^3
Young's modulus, E	GPa
Strength, σ_y	MPa
Fracture toughness, K_{1c}	$MPa{\cdot}m^{1/2}$
Toughness, G_{1c}	J/m^2
Damping coefficient, η	–
Thermal conductivity, λ	$W/m{\cdot}K$
Thermal diffusivity, a	m^2/s
Volume specific heat, $c_p \cdot \rho$	$J/m^3{\cdot}K$
Thermal expansion coefficient, α	1/K

4.4 The Material–Property Diagrams Review

4.4.1 The Modulus–Density Chart (Chart 1)

Modulus and density are among the most self–evident of material properties. Steel is used for stiff beams; rubber for compliant cushions. The density of lead makes it good for sinkers; that of cork makes it good for floats. Figure 4.9 shows the full range of Young's modulus, E, and density, ρ, for engineering materials.

Data for members of a particular class of material cluster together and can be enclosed by an envelope (heavy line). The same class-envelopes appear on all the diagrams: they correspond to the main headings in Table 4.2. The members of a class were chosen to span the full property–range of that class, so the class- envelopes enclose data not only for the members listed in Table 4.2, but for other unlisted members also.

As you know, the density of a solid depends on three factors: the (mean) atomic weight of its atoms or ions, their (mean) size, and the way they are packed. The size of atoms does not vary much: most have a volume within a factor of two of 2×10^{-29} m^3. Packing fractions do not vary much either–a factor of two, more or less: close–packing gives a packing fraction of 0.74; open networks, typified by the diamond–cubic structure, give about 0.34. The spread of density comes from that of atomic weight, from 1 for hydrogen to 207 for lead. Metals are dense because they are made of heavy atoms, packed more or less closely; polymers have low densities because they are made of light atoms in a linear, 2 or 3–dimensional network. Ceramics, for the most part, have lower densities than metals because they contain light O, N or C atoms. Even the lightest atoms, packed in the most open way, give solids

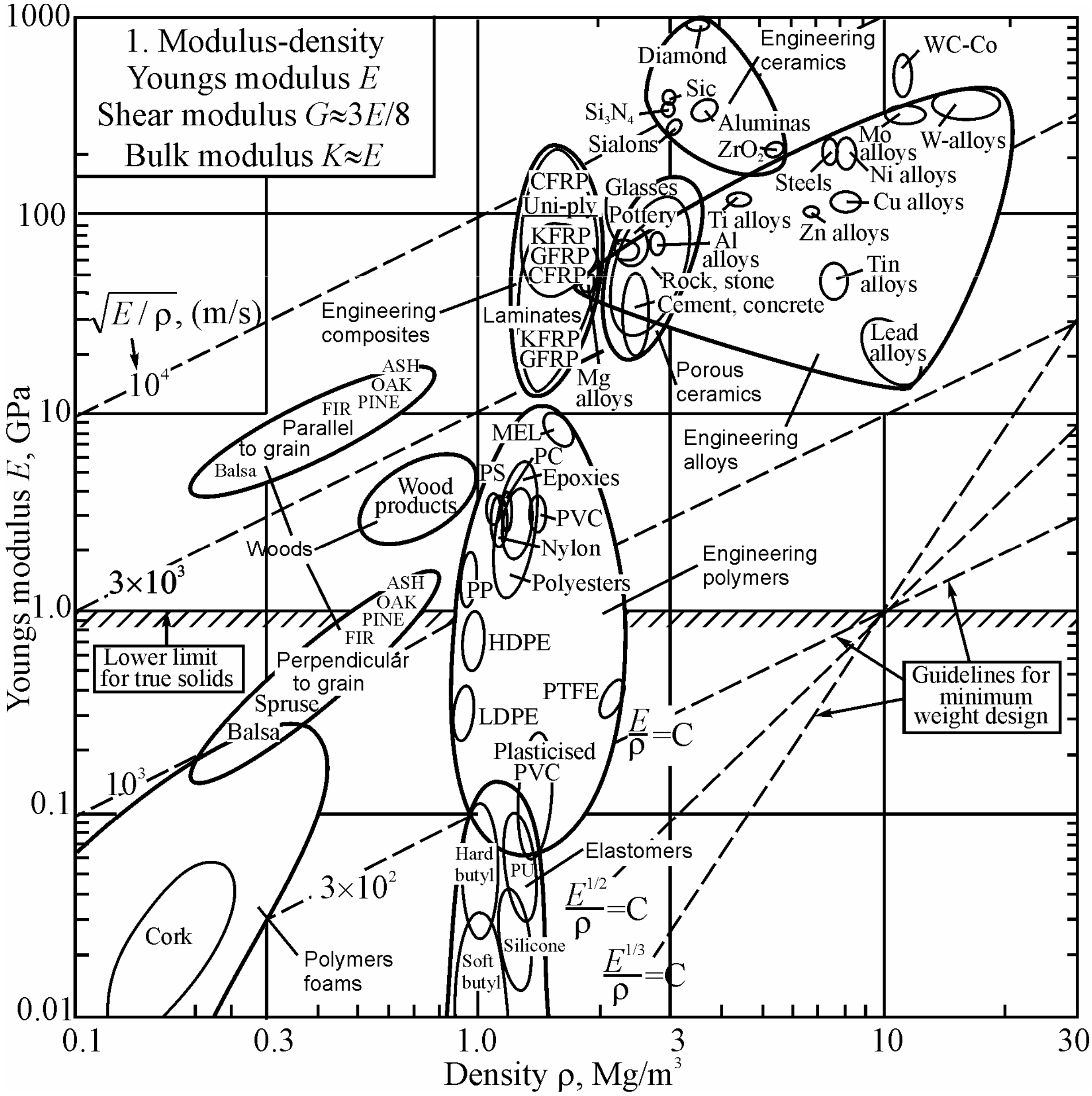


Figure 4.9 Chart 1: Young's modulus, E, plotted against density, ρ. The heavy envelopes enclose data for a given class of material. The diagonal contours show the longitudinal wave velocity. The guide lines of constant E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$ allow selection of materials for minimum weight, deflection–limited, design

with a density of around 1 Mg/m^3. Materials with lower densities than this are foams, containing substantial pore space.

It is evident, that the *moduli* of most materials depend on two factors: bond stiffness, and density of bonds per unit area. A bond is like a spring: it can be characterized by a spring constant, S (units: N/m). Young's modulus, E, is roughly

$$E = \frac{S}{r_0}, \tag{4.6}$$

Table 4.2 Material classes and members of each class

Engineering alloys (metals and alloys of engineering)	Aluminium alloys Lead alloys Magnesium alloys Nickel alloys Steels Tin alloys Titanium alloys Zinc alloys	Al alloys Lead alloys Mg alloys Ni alloys Steels Tin alloys Ti alloys Zn alloys
Engineering polymers (thermoplastics and thermosets of engineering)	Epoxies Melamines Polycarbonate Polyesters Polyethylene, high density Polyethylene, low density Polyformaldehyde Polymethylmethacrylate Polypropylene Polytetrafluorethylene Polyvinylchloride	EP MEL PC PEST HDPE LDPE PF PMMA PP PTFE PVC
Engineering ceramics (fine ceramics capable of load–bearing application)	Alumina Diamond Sialons Silicon carbide Silicon nitride Zirconia	$A1_20_3$ C Sialons SiC Si_3N_4 ZrO_2
Engineering composites (composites of engineering practice. A distinction is drawn between the properties of a ply –"Uniply" – and of a laminate – "Laminates")	Carbon fibre reinforced polymer Glass fibre reinforced polymer Kevlar fibre reinforced polymer	CFRP GFRP KFRP
Porous ceramics (traditional ceramics, cements, rocks and minerals)	Brick Cement Common rocks Concrete Porcelain Pottery	Brick Cement Rocks Concrete Pcln Pot
Glasses (ordinary silicate glass)	Borosilicate glass Soda glass Silica	B–glass Na–glass SiO_2
Woods (separate envelopes describe properties parallel to the fibers and normal to them, and wood products)	Ash Balsa Fir Oak Pine Wood products (ply, etc)	Ash Balsa Fir Oak Pine Wood products

Table 4.2 (finished)

Elastomers (natural and artificial rubbers)	Natural rubber Hard butyl rubber Polyurethanes Silicone rubber Soft butyl rubber	Rubber Hard butyl PU Silicone Soft butyl
Polymer foams (foamed polymers of engineering)	Cork Polyester Polystyrene Polyurethane	Cork PEST PS PU

where r_0 is the atom size (r_0^3 is the (mean) atomic or ionic volume). The wide range of moduli is largely caused by the range of value of S. If you remember, the covalent bond is stiff (S = 20–200 N/m); the metallic and the ionic a little less so (S = 15–100 N/m). Diamond has a very high modulus because the carbon atom is small (giving a high bond density) and its atoms are linked by very strong bonds (S = 200 N/m). Metals have high moduli because close-packing gives a high bond density and the bonds are strong. Polymers contain both strong covalent bonds and weak hydrogen or Van–der–Waals bonds (S = 0.5–2 N/m); it is the weak bonds which stretch when the polymer is deformed, giving low moduli.

But even large atoms ($r_0 = 3 \times 10^{-10}$ m) bonded with weak bonds (S = 0.5 N/m) have a modulus of roughly

$$E = \frac{0.5}{3 \cdot 10^{-10}} \approx 1 \text{ GPa}.$$

This is the *lower limit* for true solids. The Chart shows that many materials have moduli that are lower than this: they are either elastomers, or foams–materials made up of cells with a large fraction of pore space. Elastomers have a low E because the weak secondary bonds have melted (their glass temperature is below room temperature) leaving only the very weak “entropic” restoring force associated with tangled, long-chain molecules; and foams have low moduli because the cell walls bend (allowing large displacements) when the material is loaded.

The Chart shows that the modulus of engineering materials spans 5 decades, from 0.01 GPa (low density foams) to 1000 GPa (diamond); the density spans a factor of 2000, from less than 0,1 to 20 Mg/m^3. At the level of approximation of interest here (that required to reveal the relationship between the properties of materials classes) we may approximate the shear modulus, G, by $3E/8$ and the bulk modulus, K, by E, for all materials except elastomers (for which $G = E/3$ and $K >> E$).

The logarithmic scales allow more information to be displayed. The velocity of elastic waves in a material, and the natural vibration frequencies of a component made of it, are proportional to $(E/\rho)^{1/2}$; the quantity $(E/\rho)^{1/2}$ itself is the velocity of longitudinal waves in a thin rod of the material. Contours of constant $(E/\rho)^{1/2}$ are plotted on the Chart, labeled with the longitudinal wave speed: it varies from less than 50m/s (soft elastomers) to a little more than 10^4m/s (fine ceramics). We note that aluminum and glass, because of their low densities, transmit waves quickly despite of their low moduli. One might have expected the sound velocity in foams to be low because of the low modulus; but the low density almost compensates. That in wood, across the grain, is low; but along the grain, it is high–roughly the same as steel–a fact made use of in the design of musical instruments.

The diagram helps to solve the common problem of material selection for applications in which weight must be minimized. Guidelines corresponding to three common geometries of loading are drawn on the diagram. They are used in the way described to select materials for elastic design at minimum weight.

4.4.2 The Strength–Density Chart (Chart 2)

The modulus of a solid is a well-defined quantity with a sharp value. The strength is not.

The word "strength" needs definition. For metals and polymers it is the *yield strength,* but since the range of materials includes those which have been worked, the range spans initial yield to ultimate strength; for most practical purposes it is the same in tension and compression. For brittle ceramics, it is the *crushing strength in compression,* not that in tension which is about 15 times smaller; the envelopes for brittle materials are shown as broken lines as a reminder of this. For elastomers, strength means the *tear-strength.* For composites, it is the *tensile failure strength* (the compressive strength can be less, because of fiber buckling).

Figure 4.10 shows these strengths, for which we will use the symbol σ_y (despite the different failure mechanisms involved), plotted against density, ρ. The considerable vertical extension of the strength–balloon for an individual material reflects its wide range, caused by degree of alloying, work hardening, grain size, porosity and so forth. As before, members of a class group together and can be enclosed in an envelope (heavy line). Each occupies a characteristic area of the chart, and encompasses not only the materials listed in Table 4.2, but most of the other members of the class also.

The range of strength for engineering materials, like that of the modulus, spans about 5 decades: from less than 0.1 MPa (foams, used in packaging and energy–absorbing systems) to 10^4 MPa (the strength of diamond, exploited in the diamond–anvil press). The single most important concept in understanding this wide range is that of the *lattice resistance* or *Peierls stress:* the intrinsic resistance of the structure to plastic shear, which were discussed earlier. Don't forget, than metals are soft and ceramics are hard because the non–localized metallic bond does little to prevent

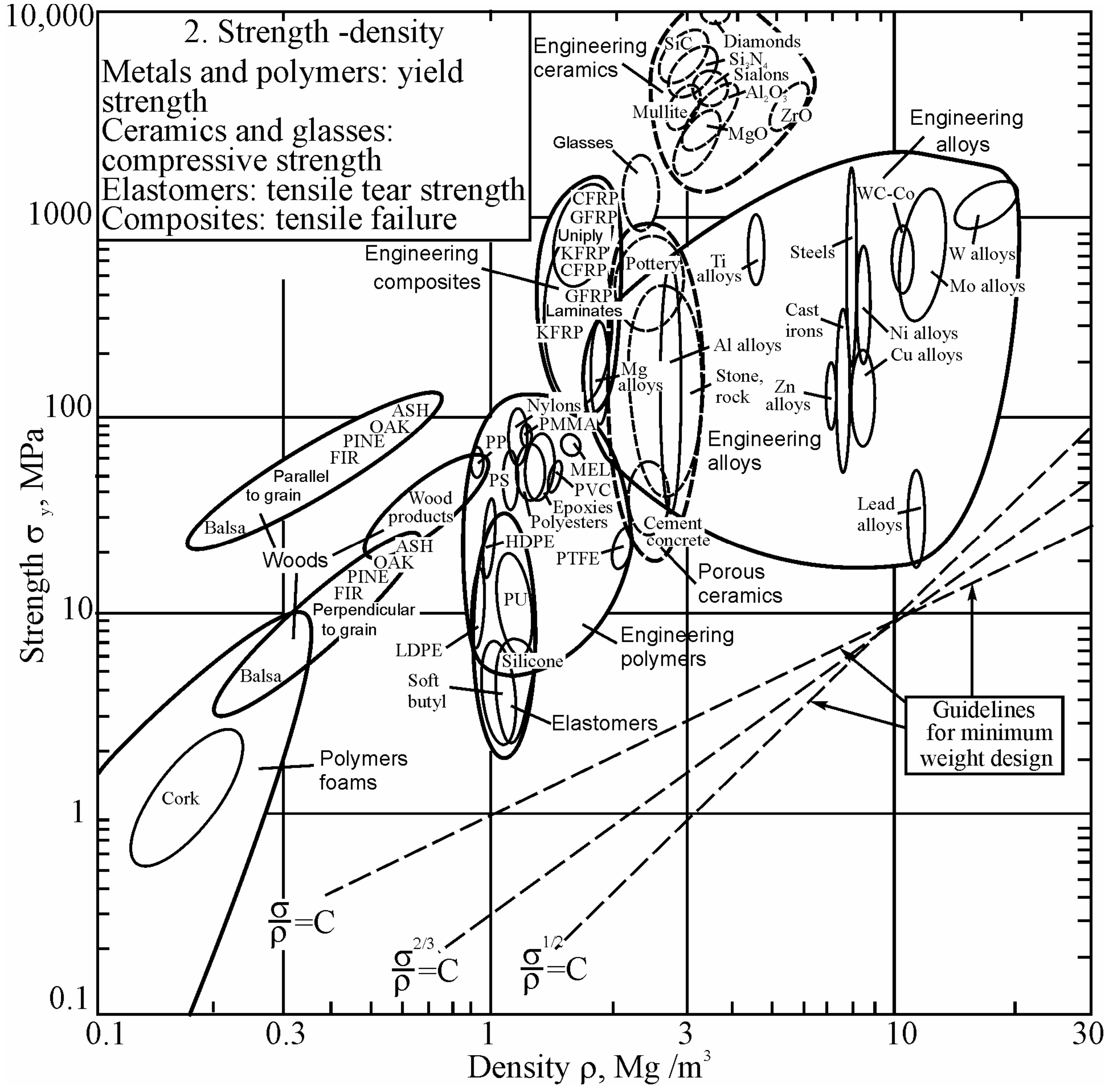


Figure 4.10 Chart 2: Strength, σ_y plotted against density, ρ (yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers and tensile strength for composites). The guide lines of constant σ_y/ρ, $\sigma_y^{2/3}/\rho$ and $\sigma_y^{1/2}/\rho$ are used in minimum weight, yield-limited, design

dislocation motion, whereas the more localized covalent and ionic bonds of the ceramic (which must be broken and reformed when the structure is sheared) lock the dislocations in place. In non–crystalline solids we think instead of the energy associated with the unit step of the flow process: the relative slippage of two segments of a polymer chain, or the shear of a small molecular cluster in a glass network. Their strength has the same origin as that underlying the lattice resistance: if the unit step involves breaking strong bonds (as in an inorganic glass), the material will be strong;

if it only involves the rupture of weak bonds (the Van–der–Waals bonds in polymers for example), it will be weak.

When the lattice resistance is low, the material can be strengthened by introducing obstacles to slip: in metals, by adding alloying elements, particles, grain boundaries and even other dislocations ("work hardening") and in polymers by cross–linking or orientation of chains so that strong covalent as well as weak Van–der–Waals bonds are broken. When the lattice resistance is high, further hardening is superfluous–the problem becomes that of suppressing fracture.

An important use of the chart is in materials selection in plastic design. Figure 4.8 lists the combinations (such as σ_y / ρ, ${\sigma_y}^{2/3} / \rho$ and ${\sigma_y}^{1/2} / \rho$) which enter the equations for minimum–weight design of ties, columns, beams
and plates, and for yield-limited design of moving components in which inertial forces are important. Guidelines with slopes of 1, 2/3 and 1/2, corresponding to these combinations are shown in Figure 4.10. They are used to identify an optimal subset of materials.

4.4.3 The Fracture Toughness–Density Chart (Chart 3)

Increasing the plastic strength of a material is useful only as long as it remains plastic and does not fail by fast fracture. The resistance to the propagation of a crack is measured by *the fracture toughness,* K_{1c}. It is plotted against density in Figure 4.11. The range is large: from 0.01 to over 100 MPa·m$^{1/2}$. At the lower end of this range there are brittle materials which, when loaded, remain elastic until they fracture. For these, linear-elastic fracture mechanics is successfully used, and the fracture toughness itself is a well-defined property. At the upper end lie the super–tough materials, most of which show substantial plasticity before they break. For these the values of K_{1c} are approximate, derived from critical *J*-integral (J_c) and critical crack–opening displacement (δ_c) measurements (by writing $K_{1c} = \left(E \cdot J_c\right)^{1/2}$, for instance). They are helpful in providing a ranking of materials. The Fig. 4.11 shows one reason for the dominance of metals in engineering: they almost all have values of K_{1c} above 20 MPa·m$^{1/2}$, a value often quoted as a minimum for conventional design.

There are a number of fundamental points to be made about the fracture toughness, but they are best demonstrated with Charts 5 and 6, coming later. Here we simply note that minimum-weight design, when the design criterion is that of preventing brittle fracture from a flaw of given size, requires that K_{1c} / ρ, ${K_{1c}}^{2/3} / \rho$ or ${K_{1c}}^{1/2} / \rho$ (depending on loading geometry) be maximized (see Figure 4.8). Guide-lines corresponding to constant values of these parameters are plotted on the diagram. They are used as described in the introduction to Section 4.5.

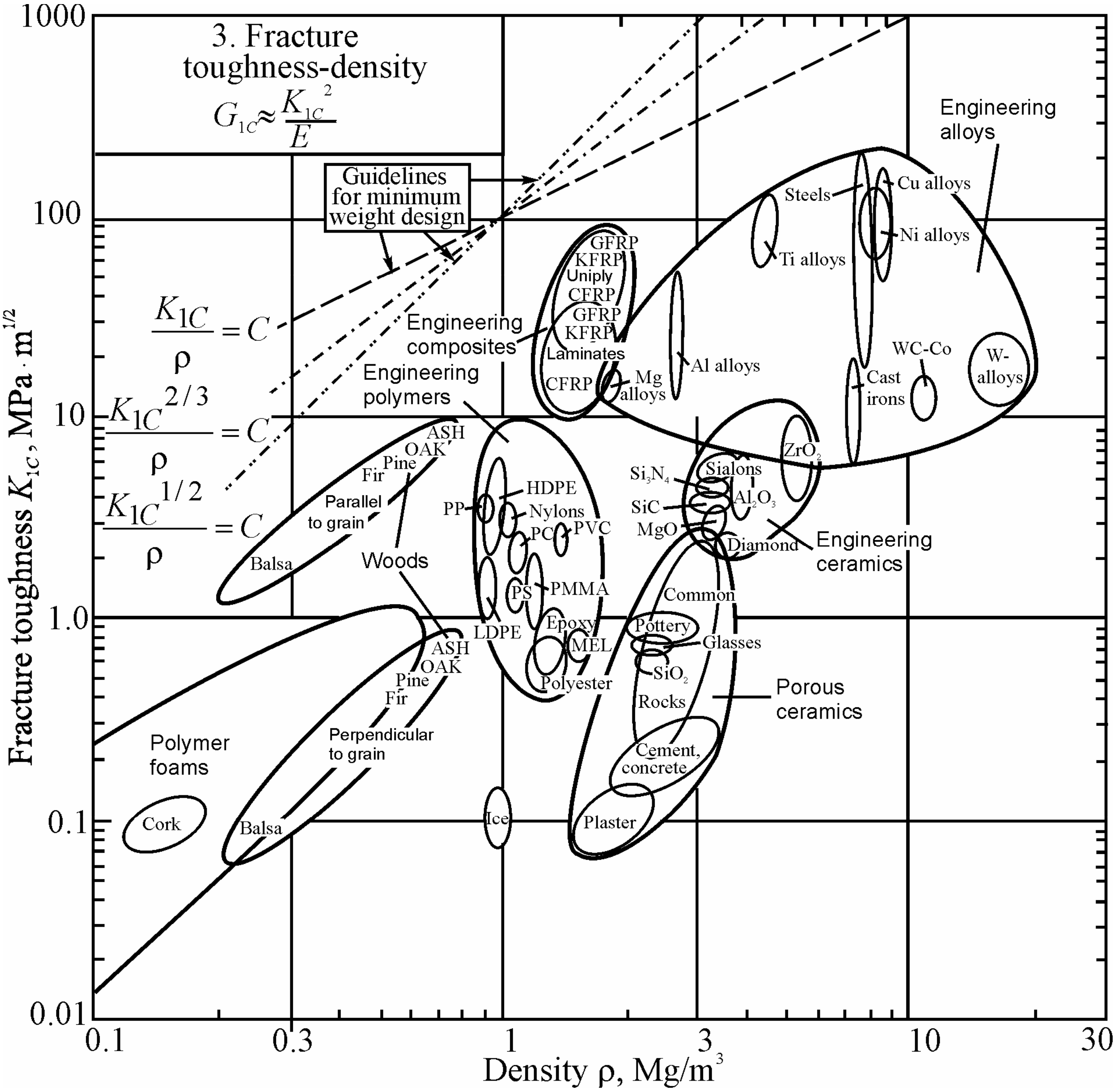


Figure 4.11 Chart 3: Fracture toughness, K_{1c}, plotted against density, ρ. The guide lines of constant K_{1c}/ρ, $K_{1c}^{2/3}/\rho$ and $K_{1c}^{1/2}/\rho$ help in minimum weight, fracture-limited, design

4.4.4 The Modulus–Strength Chart (Chart 4)

High–tensile steel makes good springs. But so does rubber. How is it that two such different materials are both suited for the same task? This and other questions are answered by Figure 4.12, the most useful of all the charts.

It shows Young's modulus, E, plotted against strength, σ_y. The qualifications on “strength” are the same as before: it means yield strength for metals and polymers, compressive crushing strength for ceramics, tear strength for elastomers and

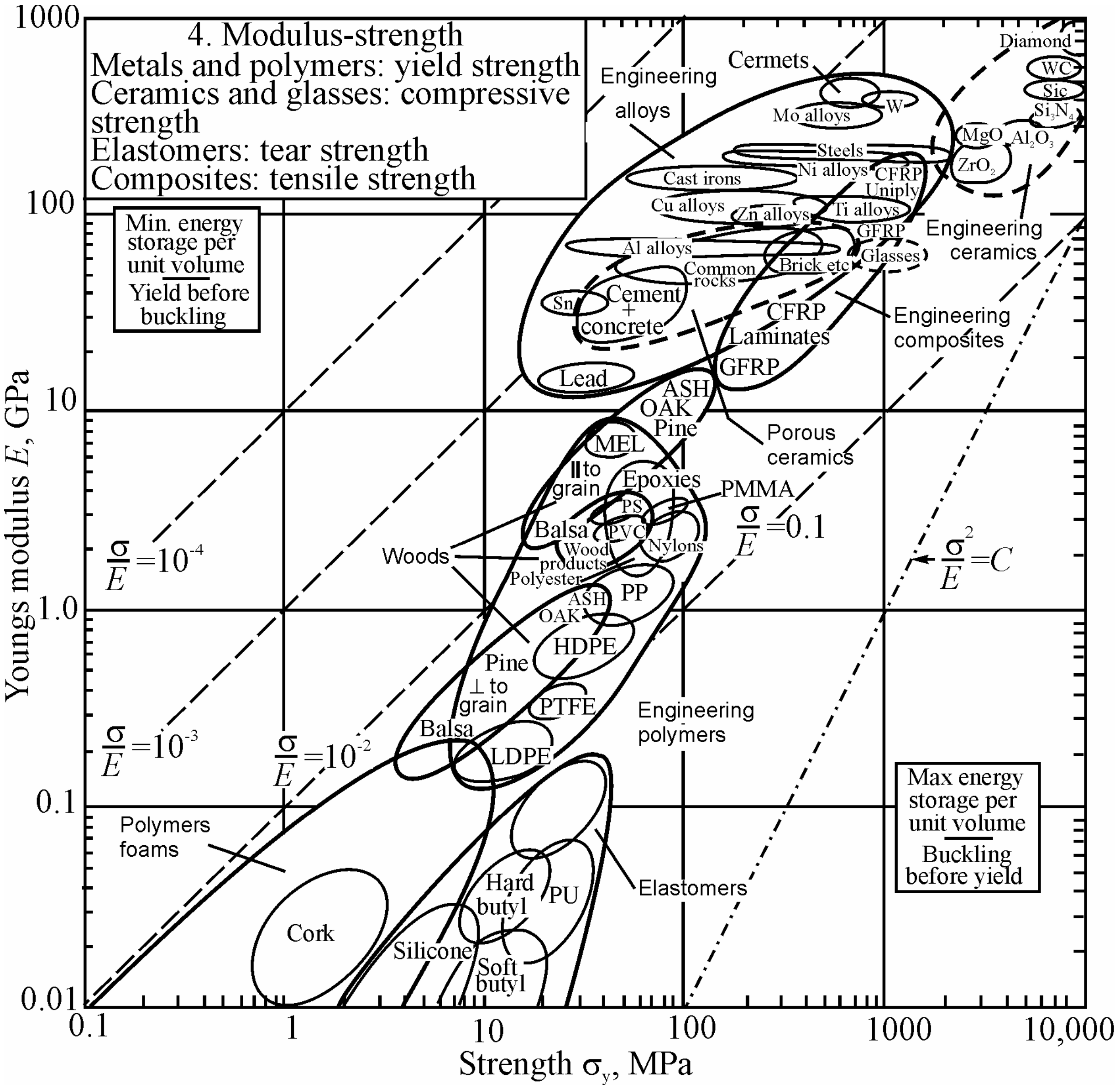


Figure 4.12 Chart 4: Young's modulus, E, plotted against strength σ_y. The guide line of constant σ_y^2/E helps with the selection of materials for springs, pivots and knife–edges; those of constant σ_y/E with choosing materials for elastic hinges

tensile strength for composites and woods; the symbol σ_y is used for them all. The ranges of the variables, too, are the same. Contours of *normalized strength,* σ_y/E, appear as a family of straight parallel lines.

Engineering polymers have normalized strengths between 0.01 and 0.1. In this sense they are remarkably strong: the value for metals are at least a factor of 10 smaller. Even ceramics, in compression, are not as strong, and in tension they are weaker (by a further factor of 15 or so). Composites and woods lie on the 0.01 contour, as good as the best metals. Elastomers, because of their exceptionally low moduli, have values of σ_y / E larger than any other class of material: 0.1 to 10.

As you know the *ideal strength* of a solid is set by the range of interatomic forces. It is small–a bond is broken if it is stretched by more than 10% or so. So the force needed to break a bond is roughly

$$F = \frac{S \cdot r_0}{10} \tag{4.7}$$

where *S* is the bond stiffness (Section 4.5.1). If shear breaks bonds, the strength of a solid should be roughly

$$\sigma_y \approx \frac{F}{r_0^2} = \frac{S}{10r_0} = \frac{E}{10}.$$

The chart shows that, for some polymers, it is. Most solids are weaker, for two reasons.

First, non–localized bonds (those in which the cohesive energy derives from the interaction of one atom with large number of others, not just with its nearest neighbours) are not broken when the structure is sheared. The metallic bond, and the ionic bond for certain directions of shear, are like this; very pure metals, for example, yield at stresses as low as *E*/10,000, and strengthening mechanisms are needed to raise the strength. The covalent bond is localized; and covalent solids do, for this reason, have yield strength which, at low temperatures, are as high as *E*/10 It is hard to measure them (though it can sometimes be done by indentation) because of the second reason for weakness: they generally contain defects–concentrators of stress–from which shear or fracture can propagate, often at stresses well below the "ideal" *E*/10. Elastomers are anomalous (they have strengths of about *E)* because the modulus does not derive from bond–stretching, but from the change in entropy of the tangled molecular chains when the material is deformed.

In the design of columns and beams, the ratio σ_y / E often appears. Structures, which have a high value of σ_y / E will deflect or buckle before they yield; those with low σ_y / E do the opposite. The best materials for an elastic hinge (a thin web or ligament that bends elastically, forming the hinge of a box or container, for example) are those with the maximum value of σ_y / E: the diagram immediately identifies them as elastomers and certain polymers (the polyethylenes, for example).

Finally, return to springs. The best material for a spring is that with the greatest value of σ_y^2 / E (because it stores the most elastic energy per unit volume, $\frac{1}{2}\sigma_y^2 / E$, before it yields). A guideline corresponding to the condition

$$\frac{{\sigma_y}^2}{E} = C \tag{4.9}$$

is plotted on the diagram; it, or any line parallel to it, links materials that are equally good by this criterion. If such a line is drawn through the middle of the elastomers, it just touches spring steel. Ceramics must be rejected because they are weaker, by the factor of 15, in tension, but glass, which can be made defect-free, makes good springs. Slightly further to the right lie CFRP and GFRP. All are good for springs.

4.4.5 The Fracture Toughness-Modulus Chart (Chart 5)

The fracture toughnesses of most polymers are less than those of most ceramics. Yet polymers are widely used in engineering structures; ceramics, because they are "brittle", are treated with much more caution. Figure 4.13 helps resolve this apparent anomaly. It shows the fracture toughness, K_{1c}, plotted against Young's modulus, E. The restrictions described in Section 4.5.3 apply to the values of K_{1c}: when small, they are well defined; when large, they are useful only as a ranking for material selection.

Consider first the question of the *necessary condition for fracture.* It is that sufficient external work be done, or elastic energy released, to supply the true surface energy *(*2γ per unit, area) of the two new surfaces, which are created. We write this as

$$G \geq 2\gamma \tag{4.10}$$

where G is the energy release–rate. Using the standard relation $K \approx (EG)^{1/2}$ between G and stress intensity K, we find

$$K \geq (2E\gamma)^{1/2}. \tag{4.11}$$

Now the surface energies, γ, of solid materials scale as their moduli; to an adequate approximation $\gamma = E \cdot r_0 / 20$, where r_0 is the atom size, giving

$$K \geq E\left[\frac{r_0}{20}\right]^{1/2}. \tag{4.12}$$

We identify the right–hand side of this equation with a lower–limiting value of K_{1c}, when, taking r_0 as $2{\cdot}10^{-10}$ m,

$$\frac{(K_{1c})}{E}\text{min} = \left[\frac{r_0}{20}\right]^{1/2} \approx 3 \cdot 10^{-6}\text{m}^{1/2}.$$

This criterion is plotted on the chart as a shaded, diagonal band near the lower right corner (the width of the band reflects a realistic range of r_0 and of the constant C in $\gamma = E \cdot r_0 / C$*).* It defines a *lower limit* on values of K_{1c}: it cannot be less then this unless some other source of energy (such as a chemical reaction, or the release of

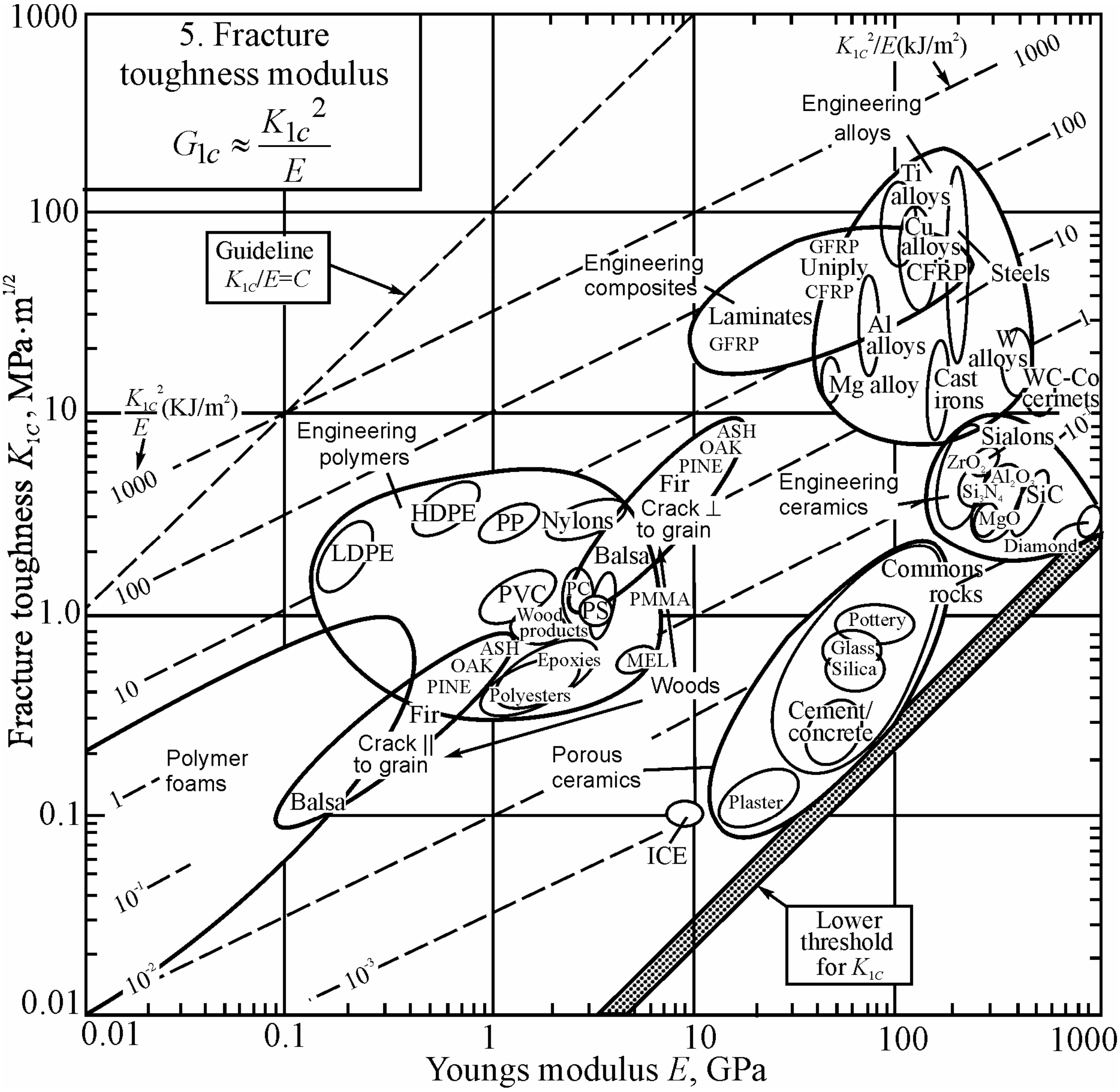


Figure 4.13 Chart 5: Fracture toughness, K_{1c}, plotted against Young's modulus, E. The family of lines is of constant K_{1c}^2/E (roughly, of G_{1c}, the fracture energy). These, and the guideline of constant K_{1c}/E, help in design against fracture. The shaded band shows the "necessary condition" for fracture. Fracture can, in fact, occur below this limit under conditions of corrosion, or cyclic loading

elastic energy stored in the special dislocation structures caused by fatigue loading) is available, when it is given a new symbol such as $(K_{1c})_{scc}$. We note that the most brittle ceramics lie close to the threshold: when they fracture, the energy absorbed is only slightly more than the surface energy. With metals and polymers the energy absorbed by fracture is vastly greater, almost always because of *plasticity* associated with crack propagation. We come to this in a moment, with the next chart.

Plotted on Figure 4.13 are contours of *toughness,* G_{1c}, a measure of the apparent fracture surface–energy ($G_{1c} \approx K_{1c}{}^2 / E$). The true surface energies, γ, of solids lie in the range from 10^{-4} to 10^{-3} kJ/m^2. The diagram shows that the values of the toughness start at 10^{-3} kJ/m^2 and range through almost six decades to 10^3 kJ/m^2. On this scale, ceramics are low (10^{-3}…10^{-1} kJ/m^2), much lower than polymers (10^{-1}…10 kJ/m^2)–and this is a part of the reason that design with polymers is easier than with ceramics. This is not to say that engineering design relies purely on G_{1c}: it is more complicated than that. When the modulus is high, deflections are small. Then designers are concerned about the loads the structure can support. In load–limited design, the fracture toughness, K_{1c}, is what matters: it determines, for a given crack length, the stress the structure can support. Experience shows that a value of K_{1c} above about 20 MPa$^{1/2}$ is necessary for conventional load-limited design methods to be viable. Only metals and composites meet this requirement.

Polymers, woods and foams have low moduli. Design with low-modulus materials focuses on limiting the *displacement,* requiring a high value of K_{1c} / E, (or, equivalently, $(G_{1c} / E)^{1/2}$). Polymers, woods and foams meet these requirements better than metals, as the guide–line of $K_{1c} / E = C$ on the chart shows. The problem with ceramics is that they are poor by either criterion. The solution–since ceramics have other properties too good to ignore–lies in further progress in toughening them, and in new design methods, which allow for their brittleness in tension.

4.4.6 The Fracture Toughness–Strength Chart (Chart 6)

The stress concentration at the tip of a crack generates a *process-zone*: a plastic zone in ductile solids, a zone of microcracking in ceramics, a zone of *delamination*, *debonding* and *fiber pull–out* in composites. Within the process zone, work is done against plastic and frictional forces; it is this, which accounts for the difference between the measured *fracture energy* G_{1c} and the true surface energy 2γ. The amount of energy dissipated must scale roughly with the size of the zone d_y, given (by equating the stress field of the crack $r = d_y$ to the strength σ_y of the material) by

$$d_y = \frac{K_{1c}{}^2}{\pi \sigma_y{}^2} \tag{4.13}$$

and with the strength σ_y of the material within it. Figure 4.14–fracture toughness against strength–shows that the size of the zone, d_y (broken lines), varies enormously, from atomic dimensions for very brittle ceramics and glasses to almost 1 meter for the most ductile of metals. At a constant zone size, fracture toughness tends to increase with strength (as expected): it is this that causes the data plotted in Figure 4.14 to be clustered around the diagonal of the chart.

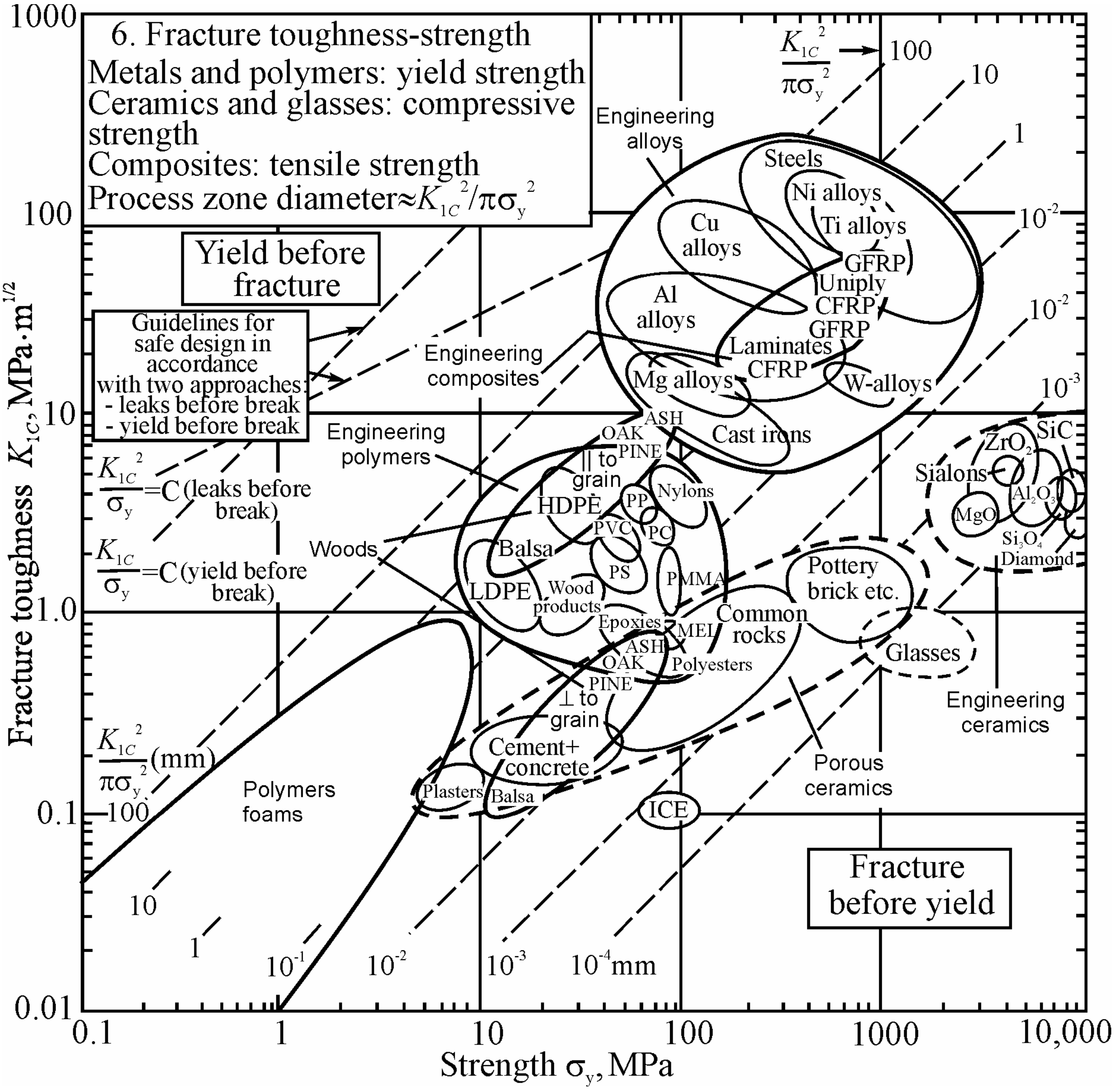


Figure 4.14 Chart 6: Fracture-toughness, K_{1c} plotted against strength, σ_y. The contours show the value of $K_{1c}^2/\pi\cdot\sigma_y^2$–roughly, the diameter of the process–zone at a crack tip (units: mm). The guide lines of constant K_{1c}/σ_y and K_{1c}^2/σ_y are used in yield–before–break and leak–before–break design

The diagram has application in selecting materials for the safe design of load bearing structures. First let's consider some obvious points. Fast fracture occurs when

$$\sigma > C\frac{K_{1c}}{\sqrt{\pi a_c}} \tag{4.14}$$

where $2a_c$ is the length of the longest crack in the structure, and C is a constant near unity (we assume, below, that $C = 1$). The crack, which will just propagate when the stress equals the yield strength, has a length

$$a_c = \frac{K_{1c}{}^2}{\pi \sigma_y{}^2} \tag{4.15}$$

that is, the critical crack length is the same as the process zone size: the contours on the diagram. A valid fracture toughness test (one that gives a reliable value of the plane–strain fracture toughness K_{1c}*.)* requires a specimen with all dimensions larger than 10 times d_y*;* the contours, when multiplied by 10, give a quick idea of this.

There are two criteria for materials selection involving K_{1c} and σ_y. First, safe design at a given *load* requires that the structure will *yield before it breaks* as the result of fast crack propagation. If the minimum detectable crack size is $2a_c$, then this condition can be expressed as

$$\frac{K_{1c}}{\sigma_y} \geq \sqrt{\pi a_c}\,. \tag{4.16}$$

The *safest material* is the one with the greatest value of K_{1c}/σ_y*:* it *will tolerate the longest crack*. But, though safe, it may not be efficient. The section required to carry the load decreases as σ_y increases. We want *high* K_{1c}/σ_y *and high* σ_y. The reader may wish to plot two lines onto Figure, isolating the material which best satisfies both criteria at once: *it is steel*. It is this, which gives steel its pre–eminence as the material for highly stressed structures when weight is not important.

One such structure is the pressure vessel. Here safe design requires that the vessel *leaks before it breaks:* leakage is not catastrophic, fast fracture is. To ensure this, the vessel must tolerate a crack of length, $2a_c$, equal to the wall thickness *t,* and this leads to a different criterion for materials selection. From the last equation, the leak-before-break criterion is

$$\frac{K_{1c}{}^2}{\sigma_y{}^2} \geq \pi t\,. \tag{4.17}$$

But the pressure, *p*, that the vessel can support is limited by yield, so that, for a thin walled cylindrical vessel of radius *R,*

$$\frac{pR}{t} \leq \sigma_y\,. \tag{4.18}$$

Substituting for *t* gives

$$p \leq \frac{1}{\pi \cdot R}\left[\frac{K_{1c}{}^2}{\sigma_y}\right]. \tag{4.19}$$

The greatest pressure is carried by the vessel with the largest value of $K_{1c}{}^2/\sigma_y$. A guideline of $K_{1c}{}^2/\sigma_y$ is shown on the chart. It, and the yield–before–

break line, are used in the way described in Section 1. Again, steel and copper are optimal.

4.4.7 The Loss Coefficient–Modulus Chart (Chart 7)

Bells, traditionally, are made of bronze. They can be (and sometimes are) made of glass; and they could (if you could afford it) be made of silicon carbide. Metals, glasses and ceramics all have low intrinsic damping, or "internal friction", an important material property when structure vibrates. We measure intrinsic damping by the *loss coefficient*, η, which is plotted in Figure 4.15. Other measures include the

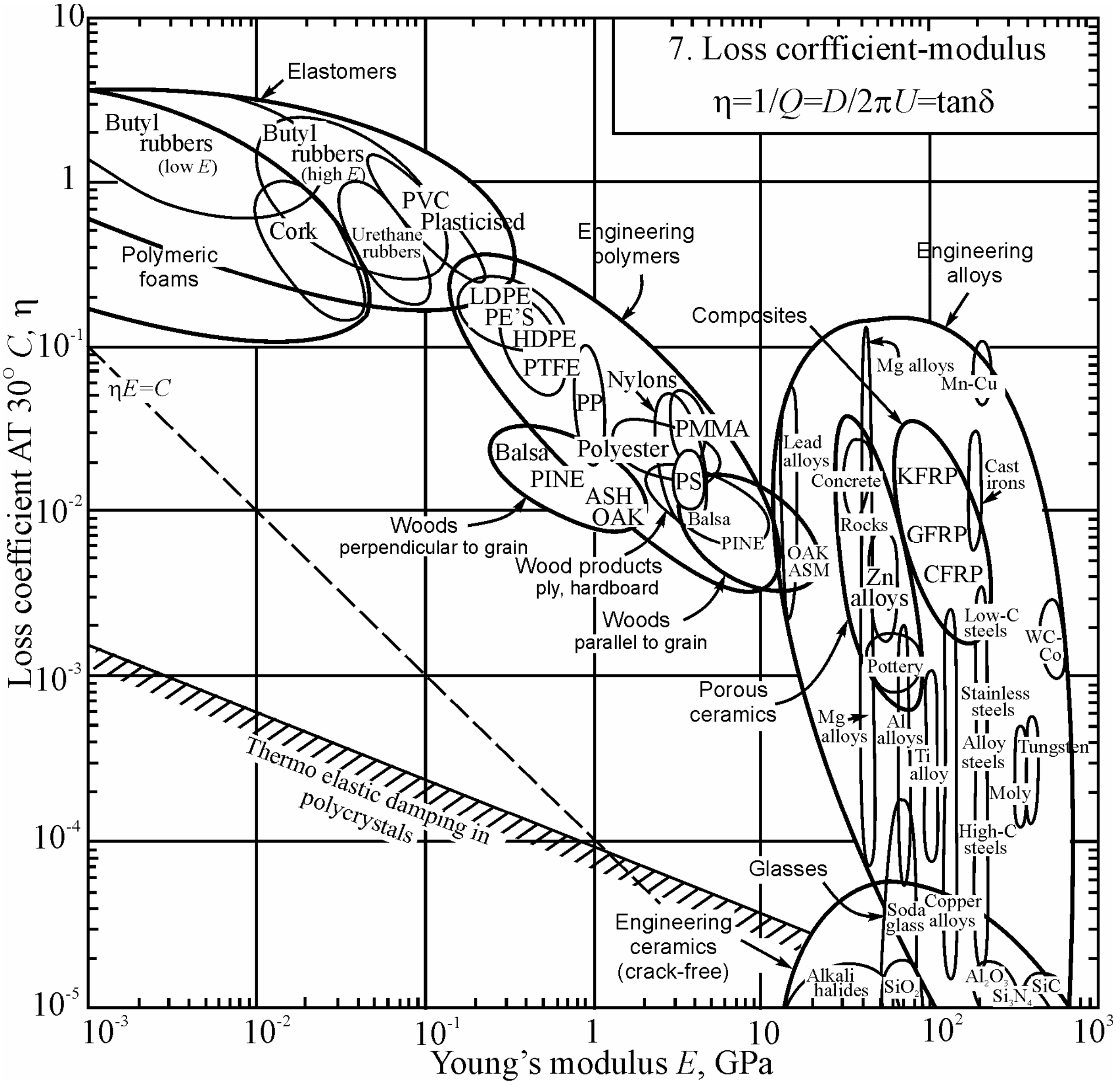


Figure 4.15 Chart 7: The loss coefficient, η, plotted against Young's modulus, E. The guide–line corresponds to the condition $\eta = C/E$.

specific damping capacity D/U (the energy D dissipated per cycle of vibrational energy U), the *log decrement*, Δ (the log of the ratio of successive amplitudes), the *phase lag*, δ, between stress and strain and the *resonance factor*, Q. When the damping is small (η<0,01) these measures are related by

$$\eta = \frac{D}{2\pi U} = \frac{\Delta}{\pi} = \tan\delta = \frac{1}{Q} \tag{4.20}$$

but when the damping is large, the definitions are no longer equivalent. Large η's are best measured by recording a symmetric load cycle and dividing the area of the stress-strain loop by 2π times the peak energy stored.

There are many mechanisms of intrinsic damping and hysteresis. Some (the "damping" mechanisms) are associated with a process that has a specific time constant; then the energy loss is centered about a characteristic frequency. Others (the "hysteresis" mechanisms) are associated with time–independent mechanisms, and absorb energy at all frequencies.

One damping mechanism, common to all materials, is a thermoelastic effect. A suddenly–applied tensile stress causes a true solid to cool slightly as it expands (elastomers are not true solids, and show the opposite effect). As it warms back to its initial temperature it expands further, giving additional strain that lags behind the stress. The anisotropy of moduli means that a polycrystal, even when uniformly loaded, shows a thermoelastic damping because neighboring grains distort–and thus cool–by differing amounts. The damping is proportional to the difference between the adiabatic modulus, E_A and that measured at constant temperature, E_T. A thermodynamic analysis shows that

$$\eta = C\frac{E_A - E_T}{E_T} = \frac{CT\alpha^2 E_T}{\rho C_v} \tag{4.21}$$

where α is the coefficient of linear thermal expansion, c_V is the specific heat, T the temperature and C a constant. This leads to the shaded line on the Chart marked "thermal damping". Single crystals and glasses lie below the line, because, when loaded uniformly, no temperature gradients exist.

The loss coefficient of most materials is far higher than this. In metals a large part of the loss is hysteretic, caused by dislocation movement: it is high in soft metals like lead and aluminium, but heavily alloyed metals like bronze, and high–carbon steels have low loss because the solute pins the dislocations. Exceptionally high loss is found in the Mn-Cu alloys, because of a strain–induced martensite transformation, and in magnesium, perhaps because of reversible twinning. The elongated balloons for metals span the large range accessible by alloying and working. Engineering ceramics have low damping because the enormous lattice resistance (Section 4.5.2) pins dislocations in place at room temperature. Porous ceramics, on the other hand, are filled with cracks, the surfaces of which rub, dissipating energy, when the material is loaded; the high damping of some cast irons has a similar origin. In polymers, chain segments slide against each other when loaded; the relative motion lowers the compliance and dissipates energy. The ease with which they slide depends on the ratio of the temperature (in this case, room temperature) to the glass temperature, T_g, of the polymer. When $T/T_g < 1$, the secondary bonds are "frozen", the modulus is high and the damping is relatively low. When $T/T_g > 1$, the secondary bonds have melted, allowing easy chain slippage: the modulus is low and the damping is high. This accounts for the obvious inverse dependence of η on E for polymers in Figure 4.15; indeed, to a first approximation

$$\eta = \frac{4 \times 10^{-2}}{E} \tag{4.22}$$

with E in *GPa.*

4.4.8 The Thermal Conductivity–Thermal Diffusivity Chart (Chart 8)

As you remember the material property governing the flow of heat through a material at steady state is the thermal *conductivity*, λ (units: J/m·K); that governing transient heat flow is the *thermal diffusivity*, a (units: m^2/s). They are related by

$$a = \frac{\lambda}{\rho c_p}, \tag{4.23}$$

where ρ is the density and c_p the specific heat, measured in J/kg K; the quantity $\rho \cdot c_p$ is the *volumetric specific heat.* Figure 4.16 relates conductivity, diffusivity and volumetric specific heat, at room temperature.

The data span almost 5 decades in λ and α. Solid materials are located along the line

$$\rho c_p \approx 3 \times 10^6 \text{ J/m}^3\cdot\text{K}. \tag{4.24}$$

This can be understood by noting that a solid containing N atoms has $3N$ vibrational modes. Each (in the classical approximation) absorbs thermal energy kT at the absolute temperature T, and the vibrational specific heat is $c_p \approx c_V = 3N \cdot k$ (J/K), where k is Bolzmann's constant. The volume per atom, Ω, for almost all solids lies within a factor of two of 2×10^{-29} m^3, so the volume of N atoms is 2×10^{-29} N. The volume specific heat is then (as the Chart shows)

$$\rho c_V = 3Nk / N\Omega = 3k / \Omega = 3 \times 10^6 \text{ J/(m}^3\cdot\text{K)}. \tag{4.25}$$

For solids, c_p and c_V differ very little. Let's assume them to be equal. As a general rule, then

$$\lambda = 3 \times 10^6 a \tag{4.26}$$

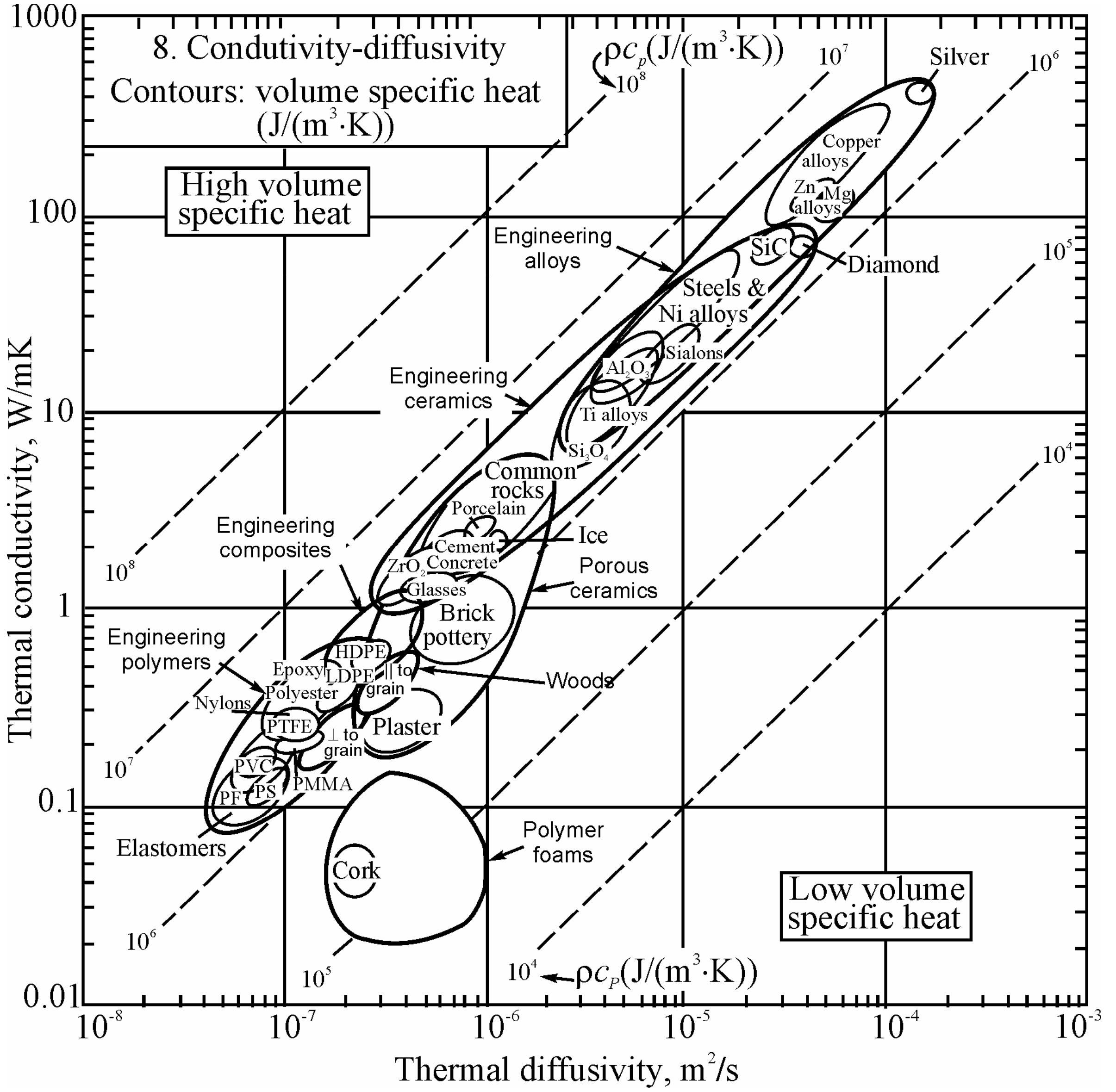


Figure 4.16 Chart 8: Thermal conductivity, λ, plotted against thermal diffusivity, a. the contours show the volume specific heat, $\rho \cdot c_p$. All three properties vary with temperature; the data here are for room temperature

(λ in J/(m·K) and a in m^2/s). Some materials deviate from this rule: they have lower–than–average volumetric specific heat. A few, like diamond, are low because their Debye temperatures lie well above room temperature; then heat absorption is not classical, some modes do not absorb kT and the specific heat is less than $3Nk$. The largest deviations are shown by porous solids: foams, low density firebrick, woods and so on. Their low density means that they contain fewer atoms per unit volume and, averaged over the volume of the structure, $\rho \cdot c_V$ is low. The result is that, although foams have low *conductivities* (and are widely used for insulation) their thermal *diffusivities* are not low: they may not transmit much heat, but they reach a steady state quickly.

The range of λ and of a reflect the mechanisms of heat transfer in each class of solids. Electrons conduct the heat in pure metals such as copper, silver and aluminum (top right of chart). The conductivity is described by

$$\lambda = \frac{1}{3} C_e \bar{c} l \tag{4.27}$$

where c_e is the electron specific heat per unit volume, $\bar{c}$ is the electron velocity (2×10^5 m/s) and l the electron *mean free path*, typically 10^{-7} m in pure metals. In solid solution (steels, nickel–based and titanium alloys) the foreign atoms scatter electrons, reducing the mean free path to atomic dimensions ($\approx 10^{-10}$m), much reducing λ and a.

Electrons do not contribute to conduction in ceramics and polymers. Heat is carried by *phonons*–lattice vibrations of short wavelength. They are scattered by each other (through an inharmonic interaction) and by impurities, lattice defects and surfaces; it is these, which determine the phonon mean free path, l. The conductivity is still given by equation (4.27) which we write as

$$\lambda = \frac{1}{3} \rho c_p \bar{c} l \tag{4.28}$$

but now $\bar{c}$ is the elastic wave speed (around 10^3 m/s— see Chart 1) and $\rho \cdot c_p$ is the volumetric specific heat. If the crystal is particularly perfect, and the temperature is well below the Debye temperature, as in diamond at room temperature, the phonon conductivity is high: it is for this reason that single crystal diamond, silicon carbide, and even alumina have conductivities almost as high as copper. The low conductivity of glass is caused by its irregular amorphous structure: the characteristic length of the molecular linkages (about 10^{-9}m) determines the mean free path. Polymers have low conductivities because the elastic wave speed c is low (Chart 1), and the mean free path in the disordered structure is small.

The best insulators are highly porous materials like firebrick, cork and foams. Their conductivity is limited by that of the gas in their cells, and (in very low density polymer foams) by heat transfer by radiation though the transparent cell walls.

4.4.9 The Thermal Expansion–Modulus Chart (Chart 9)

Almost all solids expand on heating. If you remember the bond between a pair of atoms behaves like a linear– elastic spring when the relative displacement of the atoms is small; but when it is large, the spring is non–linear. Most bonds become stiffer when the atoms are pushed together, and less stiff when they are pulled apart. The thermal vibration of atoms, even at room temperature, involves large displacements; as the temperature is raised, the non–linear spring constant of the bond pushes the atoms apart, increasing their mean spacing. The effect is measured by the linear expansion coefficient

$$\alpha_l = \frac{1}{l}\frac{dl}{dT} \tag{4.29}$$

where l is a linear dimension of the body. A quantitative development of this theory leads to the relation

$$\alpha_l = \frac{\gamma_G \rho c_V}{3E} \tag{4.30}$$

where γ_G is *Gruneisen's constant*; its value ranges between about 0,4 and 4, but for most solids it is near 1. Since $\rho \cdot c_V$ is almost constant (equation 4.25), the equation is proportional to $1/E$. Figure 4.17 confirms this fact. Diamond, with the highest modulus, has one of the lowest coefficients of expansion; elastomers with the lowest moduli expand the most. Some materials with a low coordination number (silica, and some diamond–cubic structured materials) can absorb energy preferentially in transverse modes, leading to a very small (even a negative) value of γ_G and a low expansion coefficient–that is why SiO_2 is exceptional. Others, like Invar, contract as they lose their ferromagnetism when heated through the Curie temperature and, over a narrow range of temperature, show near–zero expansion, useful in precision equipment and in glass–metal seals.

One more useful fact: the moduli of materials scale approximately with their melting point, T_m

$$E \approx \frac{100kT_m}{\Omega} \tag{4.31}$$

where k is Boltzmann's constant and Ω the volume–per–atom in the structure. Substituting this and equation (4.24) for $\rho \cdot c_V$ into equation (4.30) for α_l gives

$$\alpha_l = \frac{\gamma_G}{100T_m}. \tag{4.32}$$

It means that the expansion coefficient varies inversely with the melting point, or (equivalently stated), for all solids the thermal strain, just before they melt, is the same. The result is useful for estimating and checking expansion coefficients.

If the thermal expansion or contraction of a body is prevented, thermal stresses appear; if large enough, they cause yielding, fracture, or elastic buckling. It is necessary to distinguish between a stress caused by external constraint (a rod, rigidly clamped at both ends, for example) and that, which appears without external constraint because of *temperature gradients* in the solids. All scale as the quantity $\alpha_l \cdot E$, shown as a set of diagonal contours on Figure 4.17. More precisely: the stress $\Delta\sigma$ produced by a temperature change of 1°C in a constrained system, or the stress per °C caused by a sudden change of surface temperature in one which is not constrained, is given by

$$C\Delta\sigma = \alpha E \tag{4.33}$$

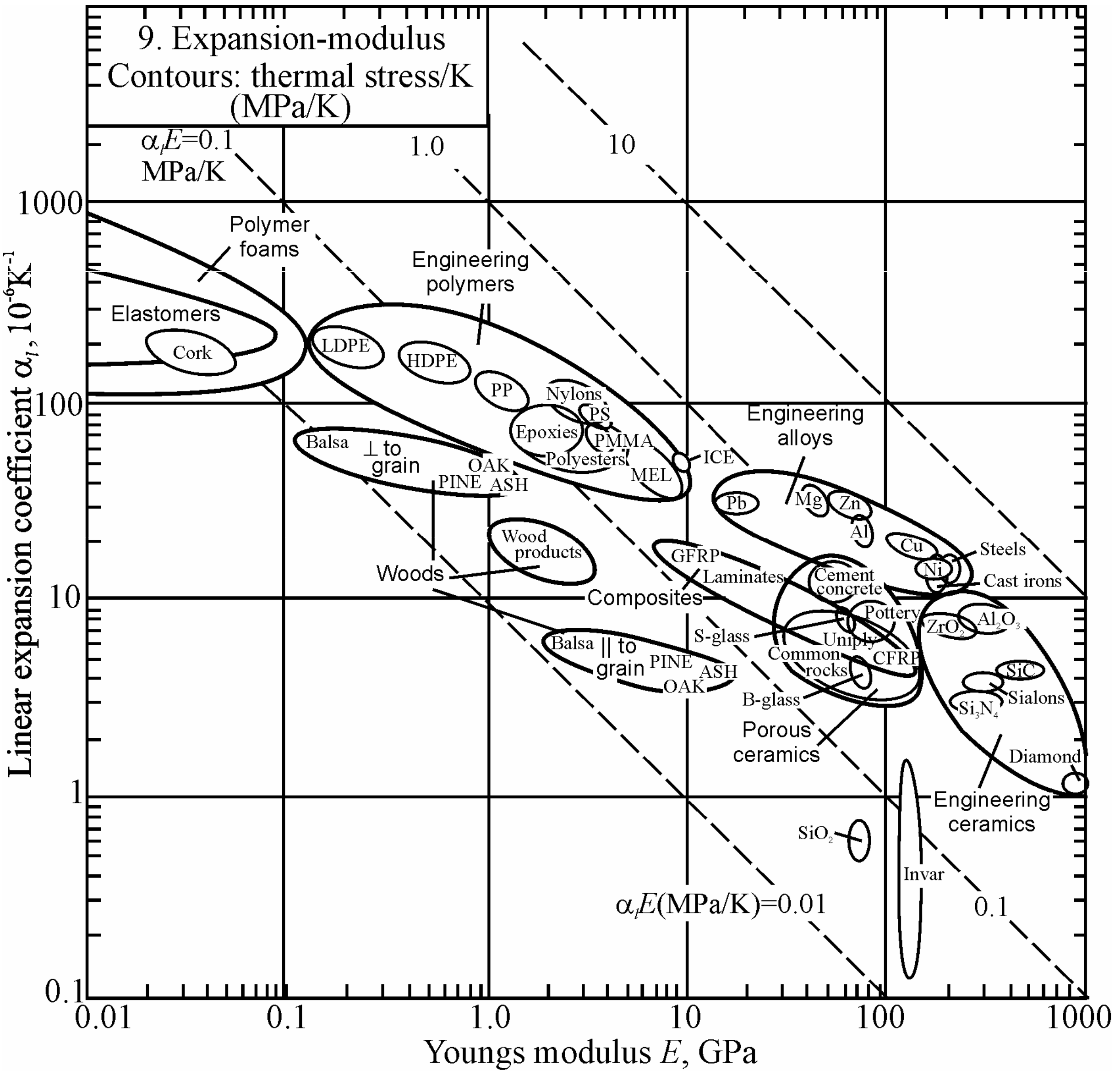


Figure 4.17 Chart 9: The linear expansion coefficient, a, plotted against Young's modulus, *E*. The contours show the thermal stress created by a temperature change of 1°C if the sample is axially constrained. A correction factor *C* is applied for biaxial or triaxial constraint

where C=1 for axial constraint, $(1-\mu)$ for biaxial constraint or normal quenching, and $(1-2\mu)$ for triaxial constraint, where μ is Poisson's ratio. These stresses are large: typically 1 MPa/K; they can cause a material to yield, or crack, or buckle, when it is suddenly heated or cooled. The resistance of materials to such damage is the subject of the next section.

4.4.10 The Normalized Strength–Thermal Expansion Chart (Chart 10)

When a cold ice-cube is dropped into a glass of gin, it cracks audibly. The ice is failing by thermal shock. The ability of a material to withstand such stresses is measured by its *thermal shock resistance*. It depends on its thermal expansion coefficient, α, and its normalized strength, σ_t / E. They are the axes of Figure 4.18, on which contours of constant $\sigma_t / \alpha_l E$ are plotted. The tensile strength, σ_t, requires definition, just as σ_y did. For brittle solids, it is the tensile fracture strength (roughly equal to the modulus of rupture, or MOR). For ductile metals and polymers, it is the

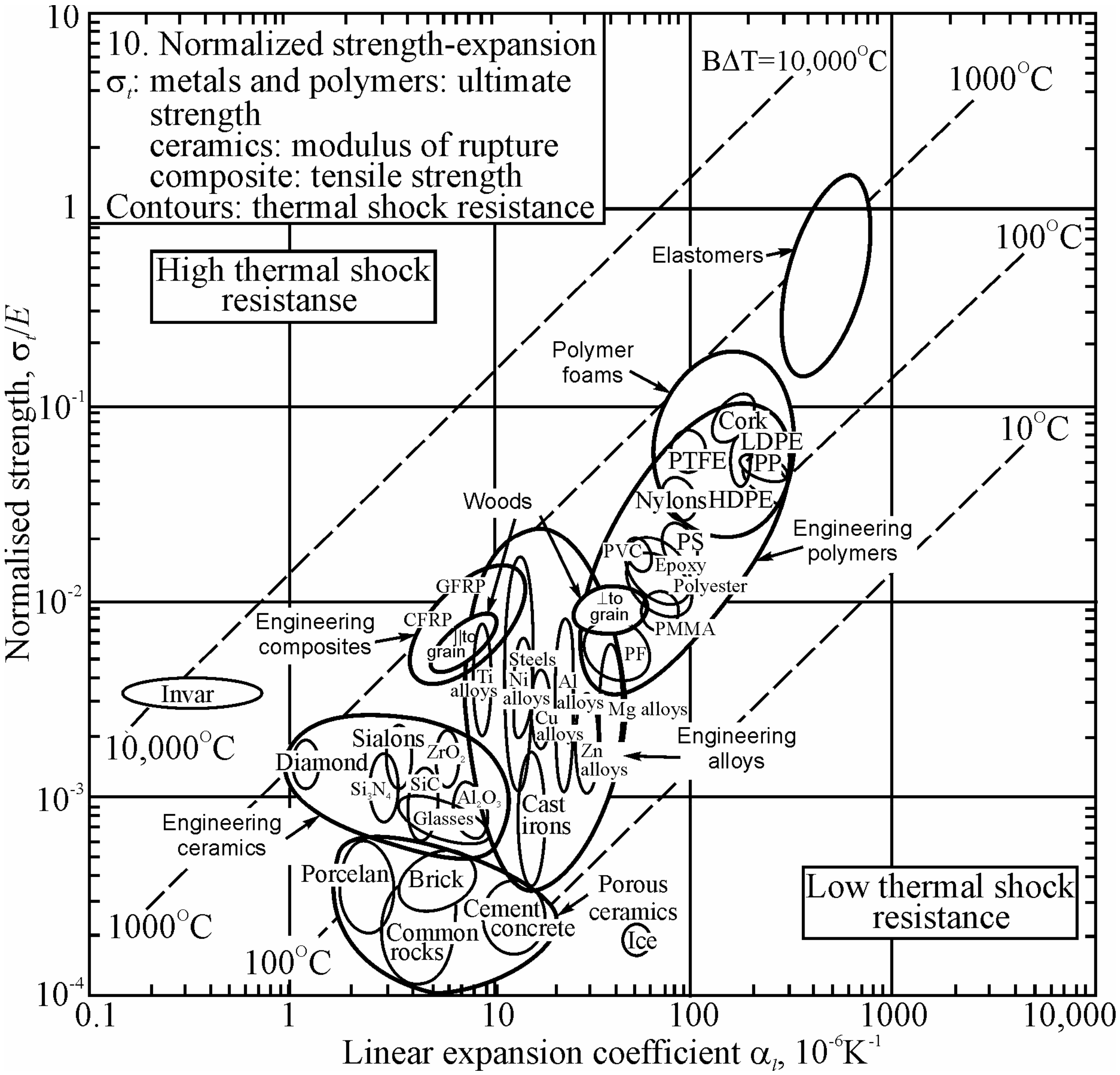


Figure 4.18 Chart 10: The normalized tensile strength, σ_t / E, plotted against linear coefficient of expansion, α_l. The contours show a measure of the thermal shock resistance, ΔT. Corrections must be applied for constraint, and to allow for thermal conduction during quenching

tensile yield strength; and for composites it is the stress, which first causes permanent damage in the form of delamination, matrix cracking of fiber debonding.

To use the chart, we note that a temperature change of ΔT, applied to a constrained body–or a sudden change ΔT of the surface temperature of a body which is unconstrained—induces a stress

$$\sigma = \frac{E\alpha_l \Delta T}{C} \tag{4.34}$$

where C was defined in the last section. If this stress exceeds the local strength σ_t of the material, yielding or cracking appears in the results. Even if it does not cause the component to fail, it weakens it. Then a measure of the thermal shock resistance is given by

$$\frac{\Delta T}{C} = \frac{\sigma_t}{E\alpha_l}. \tag{4.35}$$

When the constraint is internal, the thermal conductivity of the material becomes important. Instant cooling requires an infinite *heat transfer coefficient*, *h*, when the body is quenched. Water quenching gives a high *h*, and then the values of ΔT calculated from equation (4.35) give an approximate ranking of thermal shock resistance. But when heat transfer at the surface is poor and the thermal conductivity of the solid is high (thereby reducing thermal gradients) the thermal stress is less than that given by equation (4.34) by a factor *A*, which, to an adequate approximation, is given by

$$A = \frac{th/\lambda}{1 + th/\lambda} \tag{4.36}$$

where *t* is a typical dimension of the sample in the direction of heat flow; the quantity th/λ is usually called the *Biot modulus*. Table 4.3 gives typical values of *A,* for each class, using a section size of 10 mm. The equation defining the thermal shock resistance, ΔT, now becomes

Table 4.3 Values of the factor A (Section *t* =10 mm)

Conditions	Foams	Polymers	Ceramics	Metals
Air flow, slow (h = 10W/m^2 K)	0.75	0.5	3×10^{-2}	3×10^{-3}
Black body radiation 500 to 0°C (h = 40 W/m^2 K)	0.93	0.6	0.12	1.3×10^{-2}
Air flow, fast (h = 10^2 W/m^2 K)	1	0.75	0.25	3×10^{-2}
Water quench, slow (h = 10^3 W/m^2 K)	1	1	0.75	0.23
Water quench, fast (h = 10^4 W/m^2 K)	1	1	1	0.1-0.9

$$B\Delta T = \frac{\sigma_t}{\alpha E} \tag{4.37}$$

where $B=C/A$. The contours on the diagram are of $B \cdot \Delta T$. Table 4.3 shows that, for rapid quenching, A is unity for all materials except the high conductivity metals: then the thermal shock resistance is simply read from the contours, with appropriate correction for the constraint (the factor C). For slower quenches, ΔT is larger by the factor $1/A$, read from Table.

4.5 Conclusions and Applications

Most research on materials concerns itself, quite properly, with precision and detail. But it is occasionally helpful to stand back and view, as it were, the general lie of the land; to seek a framework into which the parts can be fitted; and when they do not fit, to examine the interesting exceptions. These charts are an attempt to do this for the mechanical and thermal properties of materials. There is nothing new in them except the mode of presentation, which summarizes information in a compact, accessible way. The logarithmic scales are used to include materials as diverse as polymer foams and high performance ceramics–allowing a comparison between the properties of all classes of solid. And by choosing the axes in a sensible way, more information can be displayed: a chart of modulus E against density ρ reveals the longitudinal wave velocity $(E/\rho)^{1/2}$; a plot of fracture toughness K_{1c} against modulus E shows the fracture surface energy G_{1c} : a diagram of thermal conductivity λ against diffusivity, a, also gives the volume specific heat $\rho \cdot c_V$; expansion, α, against normalized strength, σ_t / E gives thermal shock resistance ΔT.

The most striking feature of the charts is the way in which members of a material class cluster together. Despite the wide range of modulus and density associated with metals (as an example), they occupy a field, which is distinct from that of polymers, or that of ceramics, or that of composites. The same is true of strength, toughness, thermal conductivity and the rest: the fields sometimes overlap, but they always have a characteristic place within the whole picture. The position of the fields and their relationship can be understood in simple physical terms: the *nature of the bonding*, the *packing density*, the *lattice resistance* and the *vibrational modes* of the structure (themselves a function of bonding and packing), and so forth. The charts clearly show that the first–order difference between the properties of materials has its origins in the *mass of the atoms*, the *nature of the interatomic forces* and the *geometry of packing*. *Alloying*, *heat treatment* and *mechanical working* all influence microstructure, and through this, properties, giving the elongated balloons shown on many of the charts; but the magnitude of their effect is less, by factors of 10, than that of bonding and structure.

The charts have other applications. One is the checking of data. For example, computers consume data; their output is no better than their input. That creates a need for *data validation;* ways of checking that the value assigned to a material property is reasonable, that it lies within an expected field of values. The charts define the limits of the fields. A value, if it lies within the field, is reasonable; if it lies outside it may not be wrong, but it is exceptional and should, perhaps, be questioned.

Another application concerns the nature of data. The charts are a section through a multi–dimensional property–space. Each material occupies a little space; classes of material occupy a somewhat larger space. If data for a material (a new polymer, for instance) lie outside its characteristic space, then the material is, in some sense, novel. The physical basis of the property deserves investigation and explanation.

There is another facet to this: that of "the new material looking for an application". Established materials have applications; they are known. The first–order approach to identifying applications for a new material is to plot its position on charts and examine its environment: is it lighter, or stiffer, or stronger than its neighbors? Does it have a better value of a design-limiting combination like ${\sigma_y}^2 / E$ than they? Then it may compete in the applications they currently enjoy.

Finally, the charts help in solving problems of materials selection. In the early stages of the design of a component or structure, *all materials should be considered*; failure to do so may mean a missed opportunity for innovation or improvement. The number of materials available to the engineer is enormous (estimates range from 50,000 to 80,000). But any design is limited by certain material properties–by stiffness E or strength σ_y for instance, or by combinations such as $E^{1/2} / \rho$ or ${K_{1c}}^2 / \sigma_y$. These *design–limiting properties* are precisely those used as the axes of the charts, or the "guidelines" plotted on them. By following the procedures of Section 4.5.1, a subset of materials is isolated which best satisfies the primary demands made by the design; secondary constraints then narrow the choice to one or a few possibilities.

Every effort has been made to include in the charts a truly representative range of materials; to find reliable data for them; and to draw the envelopes to enclose all reasonably common members of a class to which they belong.

4.6 An Example of Materials Selection for a Typical Machine Part

We have reviewed the design process and selection factors, and at this point the designer has the drawing of the device he wants to make or to buy, a list of the operational conditions for the device, and a formulated list of the most important selection factors. To cite a simple example, let us assume that the designer wants to make a shaft for a hypothetical device. The drawing for this part is shown in Figure 4.19. The list of operational conditions is as follows:

List of operational conditions on shaft

1. 1.250 diameters must fit with X522 ball bearing.
2. Smallest diameter must carry torque of 130 J and shear stress of 10 ksi (68.9 MPa).
3. Possible shock load of 40 J.
4. Small end must resist damage from frequent removal of keyed gear.
5. No inertial requirements.
6. Surface roughness to be 32 μin max. (0.8 μm 'AA).
7. Diameters must be concentric within 0.001 in (0.025 mm).

Based on these operational conditions and the cost and time constraints of the project, a list of important selection factors is formulated:

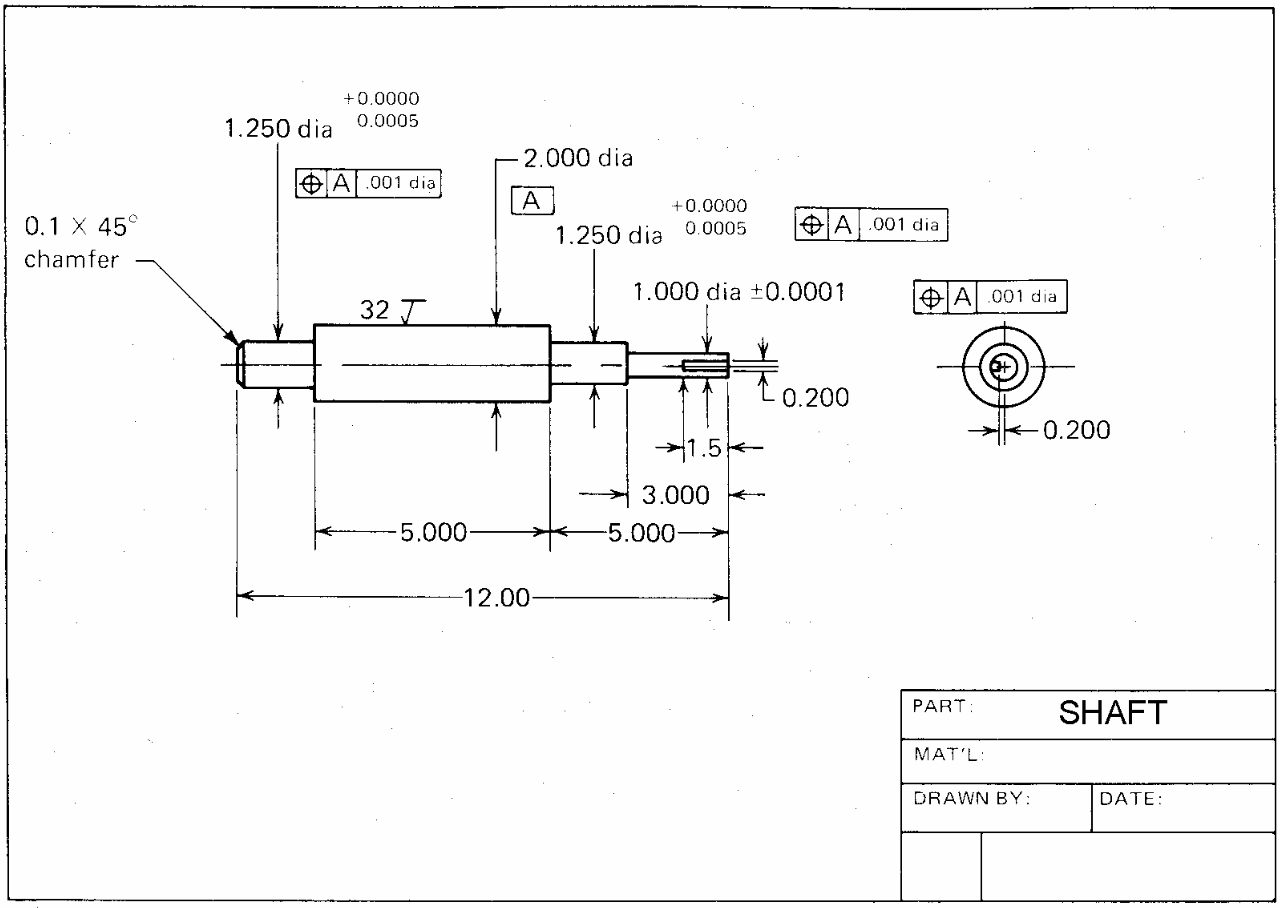


Figure 4.19 Detail drawing for a typical machine part

Important Selection Factors

1. A hardness of at least 30 HRC is needed.
2. Fatigue strength must be at least 30 ksi (207 MPa).
3. Impact strength must be high.
4. Stiffness must be as high as possible.
5. Diameter -A- cannot rust in 50% RH room air.
6. Must be stable and straight within 0.001 in.
7. Part is needed in one week.
8. Three units are required.
9. Maximum material cost: \$5/lb (\$11/ kg).
10. Expected service life: 5 years.

The selection factor list was obtained by using Figure 4.2 as a checklist. The designer simply goes down the list and notes the properties that apply. Additional properties can be added, or a designer may want to establish his own property checklist. Experienced designers may not use a written checklist, but you can be sure that they use for it their memory.

Proceeding on to the next step in the selection process, it is now time to select a material system. Do the important selection factors dictate a plastic, a metal, a ceramic, or even a composite? The answer to this question is obtained by performing a mental scan of the relative properties of various material systems. We have just reviewed relative material costs (Figures 4.3 and 4.4), and in appropriate handbooks there are tabulations of significant properties on all important material systems. Figure 4.20 is a comparison of a few material properties, and the same type of comparison chart can be made for other material properties. Many material handbooks have extensive comparative property tabulations that can be used. By this point, the reader should have developed some awareness of the relative properties of the more common material systems. Assuming that this is the case, the designer now can review his repertoire of engineering materials and select a specific material. The materials that we have recommended as useful for most design situations are shown in Figure 4.21. We list about 70 materials, which may seem like too many, but this list is much briefer than the list of commercial metal alloys, which has some 65,000 entries; the plastics handbooks that list hundreds of basic polymers times an infinite number of modifications to each in the form of fillers, plasticizers, and the like; and the ceramic journals that list thousands of ceramics that are used for various applications. The reader could go down the list of materials and state some facts about each one. It is not a difficult task.

The designer selects a material. The appropriate material specification is then put in the material box on the drawing. This puts the designer in the finish box in the flow chart shown in Figure 4.22. Unfortunately, we are not quite finished yet. More often a material may require some treatment to get the desired properties. It is also

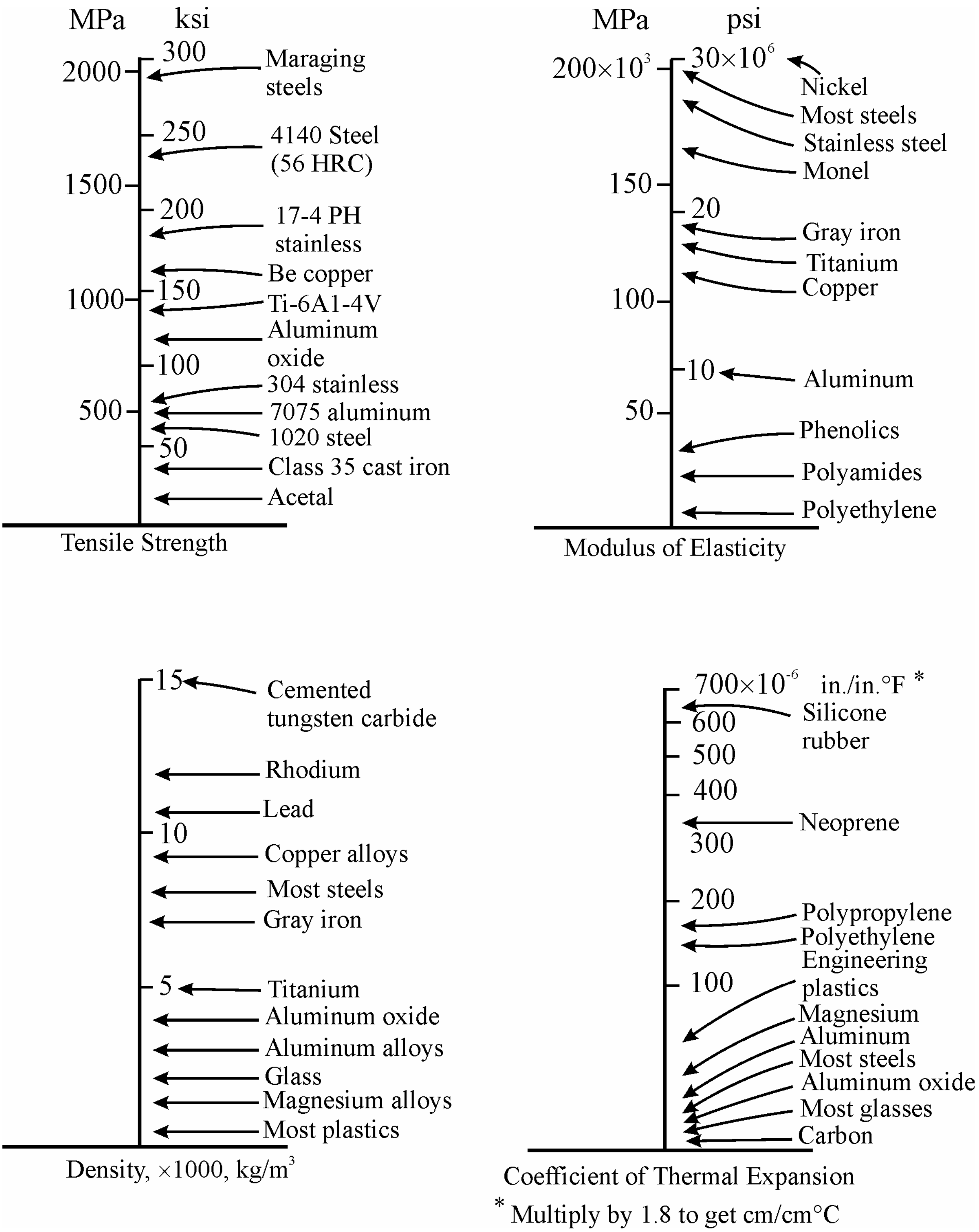


Figure 4.20 Property comparison of various material systems

the designer's responsibility to specify applicable treatments. Figure 4.23 lists some of the material. This can serve as a treatment checklist. At last we can complete an engineering drawing. The accepted name of the selected material is listed along with

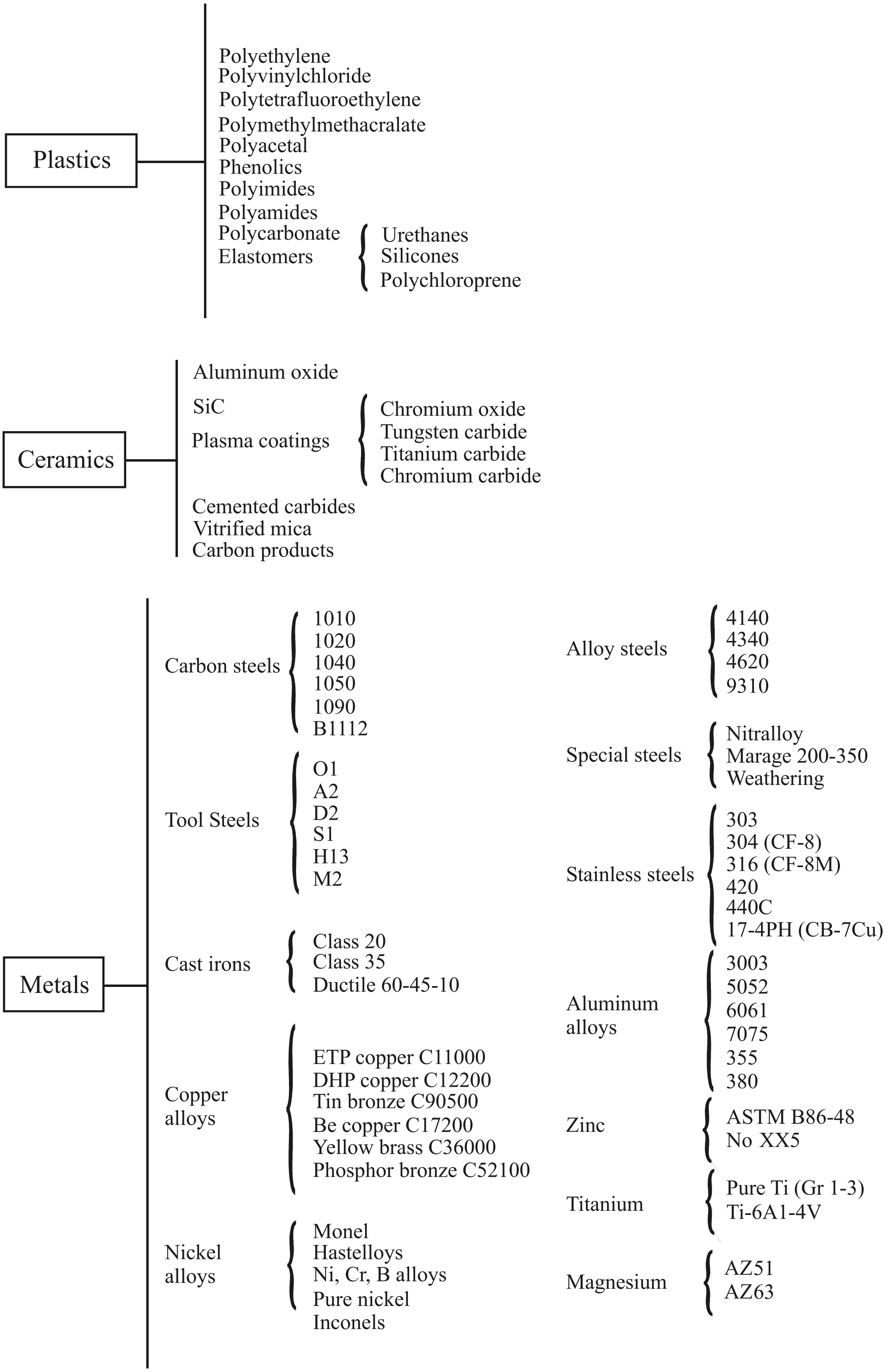


Figure 4.21 Possible designer’s repertoire of engineering materials (metals-USA Standard)

the appropriate designation. Plastics and ceramics often need a trade name for designation. Desired treatments are listed as a footnote. A proper material designation might look like those illustrated in Figure 4.24.

Let us check out this system on the example of the shaft. The list of selection factors shows that high stiffness is required. Immediately, this puts us into the metal or ceramic sections of our materials repertoire. The stiffness parameter, the modulus of elasticity, of plastics is quite low. The requirement of good impact strength eliminates the brittle ceramics and metals. The hardness and stiffness requirements put us into the category of hardenable steels. Which steels meet the remaining cost, availability, and property factors? There are probably five steels that could work (for about the same cost). This will almost always be the case. There are a number of "right" answers, but experience in previous use would direct many designers to select AISI 4140 steel for the material of construction for our shaft. The only selection factor that this material does not meet is resistance to rusting in conditioned air. Thus, we add a material treatment, a 0.001 in (25 μm) cadmium plate on -A- diameter. The other treatment required is harden and temper to 28 to 32 HRC. Now we are done, and the engineering drawing can be completed.

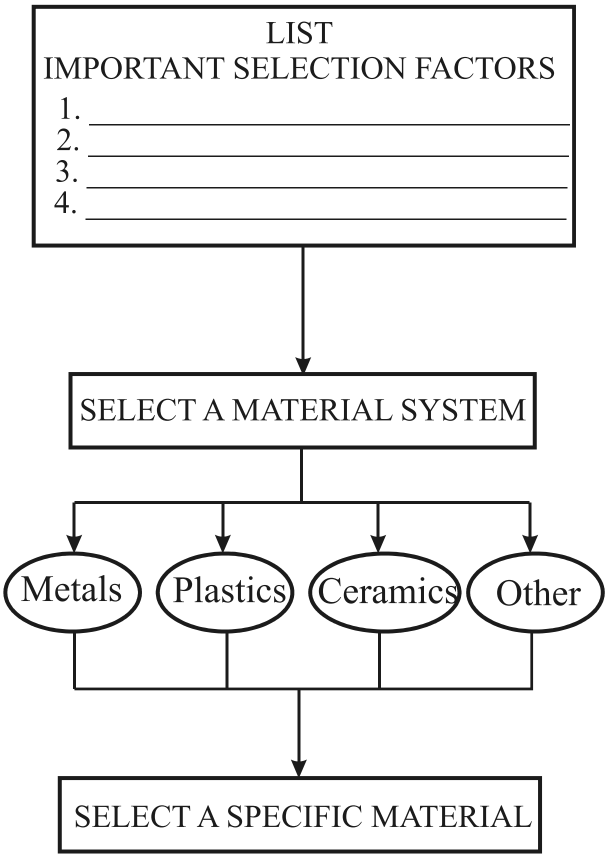


Figure 4.22 Steps involved in material selection

Putting the selection process and a material repertoire into writing makes it seem complicated even to someone who has been using it for many years. This is simply because most designers store their property, availability, and cost information in their heads. With experience, these selection steps become intuitive, and as one's knowledge of materials increases, it is not necessary to scour the literature to look up comparative properties. The whole process becomes almost automatic.

4.7 Materials for Typical Machine Components

In our example of the hypothetical shaft, we outlined a procedure for an in-depth material selection study. Most machines, however, usually contain components that are common to other machines. For example, many machines use shafts of one type or another.

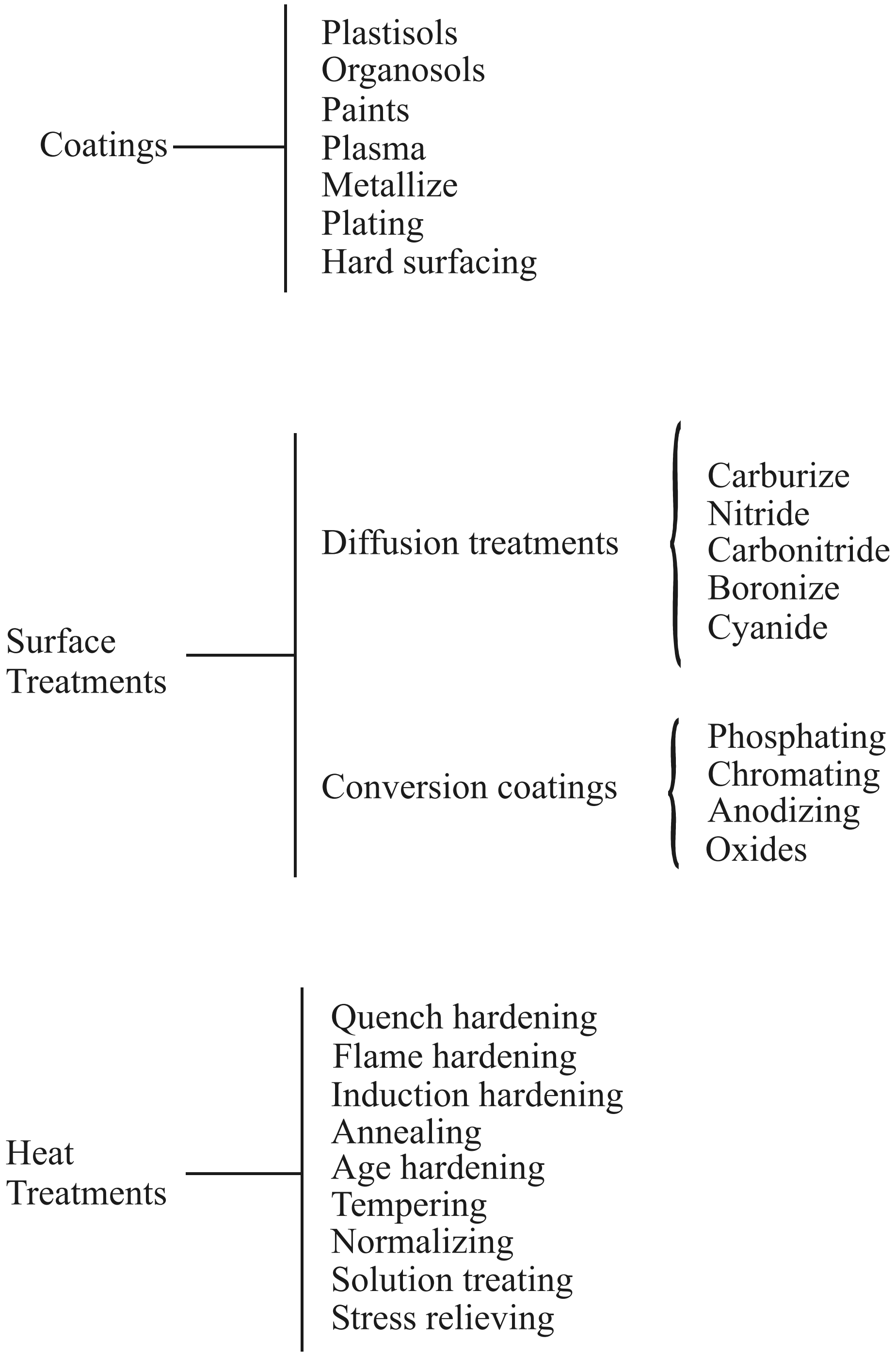
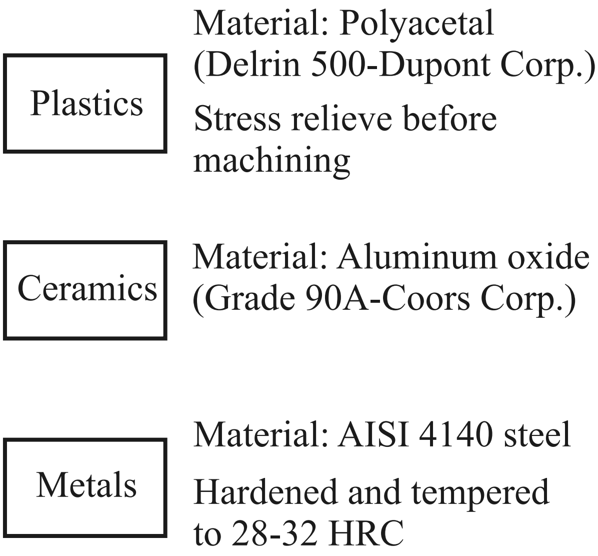


Figure 4.23 Material treatments

The same is true of gears, bushings, fasteners, and other parts. A few materials are frequently used for these types of parts. In Table 4.4 we have tabulated a number of these common machine components, and we have listed several candidate materials that can be used in making these components. It is the purpose of this table to give the designer a starting point in selecting materials for a part under design that may be included in Table.

Several materials are listed for each component, since in all selection problems there is always more than one material that will work satisfactorily. The first candidate material listed. is usually the lowest cost or least wear resistant. The other materials are listed in order of increasing hardness, strength, or wear resistance. The improved serviceability of the latter materials is usually coincident with higher costs in material, fabric ability or both. Thus the designer must still weigh relative merits before making a final selection. As an example, under the subject of springs four materials are listed: phosphor bronze, 1080 steel, and type 301 and 17–7 stainless steel. Phosphor bronze has the lowest strength, but it has excellent fabric ability and does not rust. The 1080 steel, music wire, is used for probably 90% of all wire springs. All wire springs should be made from this material unless there is a reason why it will not work. The 301 stainless steel is used for applications where corrosion resistance is important. The 17–7 wire is used where operating stresses are higher than the 301 can tolerate, and where elevated temperature resistance or corrosion is a selection parameter.



Material: Polyacetal (Delrin 500-Dupont Corp.)
Stress relieve before machining

Material: Aluminum oxide (Grade 90A-Coors Corp.)

Material: AISI 4140 steel
Hardened and tempered to 28-32 HRC

Figure 4.24 Drawing specifications for various engineering materials

Our discussions of various material systems have supplied enough information so that the designer can quantitatively compare the candidate materials and know what heat treatments and processing to use when specifying the material on the drawing. Obviously, it is not possible to compile a list of all the components that are found on machines. Similarly, the materials listed are not the only ones that will work, but the examples reflect a wide range of service experience.

Table 4.4 Materials for machine components

Component or Tool	Candidate Materials
Base plates	Aluminum jig plate, 1020 steel, gray iron
Battering tools	S1,S7 tool steels
Bolts	Acetal, 1020 steel, 1040 steel, 4140 steel
Boring tools	M2, M3-2, T15 tool steels, cemented carbide
Broaches	M2, M3-2 tool steels
Bushings	PTFE filled acetal, cloth–reinforced phenolic, PTFE fabric, leaded tin bronze, P/M bronze, P/M iron, polyimide

Table 4.4 (continued)

Component or Tool	Candidate Materials
Cavities, injection mold	P20, H13, A2 tool steels, 420 stainless steel
Chisels	S1,S7 tool steels
Choppers	A2, D2, M2 tool steels
Chutes	PVC, UMHPE, 1020 steel, 304 stainless steel
Die–casting dies (zinc, aluminum)	H13 tool steel
Dies, blanking	01, A2, D2 tool steels, cemented carbide
Dies, drawing	01, A2, D2 tool steels
Dies, press brake	4140 steel, S7 tool steel
Dies, drawing, wire	D2, M2 tool steels, cemented carbide
Dies, forging, hot	4340 steel, H13, H21 tool steels
Dies, forming	01, A2,D2 tool steels
Dies, threading	M2, M3-2 tool steels
Dowels	W1,A2 tool steels
Drills	M2,M3-2,T15 tool steels
Drill bushings	01, A2 tool steels
Fixtures	Filled epoxy, 6061 T6 aluminum, 01, A2 tool steel
Gages	Acetal, A2 tool steel, cemented carbide
Gears	MoS_2 filled nylon, acetal, cloth-reinforced phenolic, gray iron, ductile iron, 1020 steel, carburized 4615 steel, flame-hardened 1045 steel, 4340 steel
Guards	PVC, acrylic, polycarbonate, expanded metal
Holding blocks (cavity)	P20 tool steel
Hammers	1080 steel, S7 tool steel
Hobs	M2, M2–3, T15 tool steels
Keys, drive	Acetal, yellow brass, 1020 steel, 4140 steel
Knives, steel slitting	A2, D2, M2 tool steels, cemented carbide
Knives, paper	A2, D2, M2–3 tool steels, cemented carbide
Knives, corrosive materials	440 C stainless steel, cemented carbide
Knives, steel shear	S1, S7 tool steel
Knives, square cutter	Flame hardened 1045 steel, D2 tool steel
Lathe tools	M2, M2–3, T15 tool steels, cemented carbides
Machine bases	1020, A–36 steels, gray iron, ductile iron
Pinions	Carburized 4615 steel, A2 tool steel
Pneumatic tools	S1, S7 tool steels
Punches	W1, A2, D2 tool steels
Reamers	M2, T15 tool steels

Table 4.4 (finished)

Component or Tool	Candidate Materials
Rolls, bending	4340 steel
Rolls, conveying	6061 T6 aluminum, 1020 steel, polyurethane coated steel
Rolls, calendaring	Chilled cast iron
Rolls, engraving	D2 tool steel
Screw drivers	S1, S7 tool steels
Seals, face	Graphite versus alumina, polyimide versus 440 C stainless
Seals, shaft	PTFE versus alumina, graphite versus tin bronze, graphite versus alumina
Shafting	1020, 4140, 4340 steels, 15-5 PH stainless steel, nitrided Nitralloy
Springs, flat	Phosphor bronze, beryllium copper, 1080 steel, 6150 steel, 17–7 PH stainless steel
Springs, wire	Phosphor bronze, 1080 steel (music wire), cold-drawn 301 stainless steel, 17–7 PH stainless steel
Worms	Phosphor bronze, aluminum bronze
Wrenches	1050 steel, S1, S7 tool steels

Summary

The material selection process should be started as early as possible in a machine or structure design. The key to proper material selection is to establish a checklist of the properties required for a serviceable design. Does the part have to be hard? Does it require corrosion resistance? Are any special physical properties required? Once the required use properties are established, the designer can draw on his repertoire of available engineering materials to select one or more candidate materials and treatments. At this point it is appropriate to compare candidate materials for availability and economics. The final selection will be a compromise of properties, availability, and economics, but in no case should serviceability be compromised.

APPENDIXIES

Appendix A Symbols, Dimensions, and Units

Table A.1 Base SI Units
Таблица А.1 Основные единицы СИ
Таблиця А.1 Основні одиниці СІ

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	l	length длина довжина	L	m (meter)	м (метр)	м (метр)
2	m	mass масса маса	M	kg (kilogram)	кг (килограмм)	кг (кілограм)
3	t	time время час	T	s (second)	с (секунда)	с (секунда)
4	I	electric current сила электрического тока сила електричного струму	I	A (ampere)	А (ампер)	А (ампер)
5	T	thermodynamic temperature термодинамическая температура термодинамічна температура	θ	K (kelvin)	К (кельвин)	К (кельвін)
6	N	amount of substance количество вещества кількість речовини	N	mol	моль	моль
7	I	luminous intensity сила света сила світла	J	cd (candela)	кд (кандела)	кд (кандела)

Table A.2 SI Supplementary Units
Таблица А.2 Дополнительные единицы СИ
Таблиця А.3 Додаткові одиниці СІ

No.	Sym-bol	Name of Value	Dimen-sions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	α, β, γ	plane angle плоский угол плоский кут	1	rad (radian)	рад (радиан)	рад (радіан)
2	Ω	solid angle телесный угол тілесний кут	1	sr (steradian)	ср (стерадиан)	ср (стерадіан)

Table A.3 SI Special Named Derivative Units
Таблица А.3 Производные единицы СИ, имеющие специальное название
Таблиця А.3 Похідні одиниці СІ, що мають спеціальні назви

No.	Sym-bol	Name of Value	Dimen-sions	SI units			SI base units relationships
		English Russian Ukrainian		English	Russian	Ukrainian	
1	2	3	4	5	6	7	8
1	f	frequency частота частота	T^{-1}	Hz (hertz)	Гц (герц)	Гц (герц)	1 Гц=1 с$^{-1}$
2	F	force, weight сила, вес сила, вага	LMT^{-2}	N (newton)	Н (ньютон)	Н (ньютон)	1 Н = =1 кг·м/с^2
3	p	pressure, mechanical stress давление, механическое напряжение тиск, механічне напруження	$L^{-1}MT^{-2}$	Pa (pascal)	Па (паскаль)	Па (паскаль)	1 Па = =1 Н/м^2
4	E, A, W, Q	work, energy, quantity of heat энергия, работа, количество тепла енергія, робота, кількість тепла	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)	1 Дж= =1 Н·м

Table A.3 (continued)
Таблица А.3 (продолжение)
Таблиця А.3 (продовження)

1	2	3	4	5	6	7	8
5	*P*	power, energy flux мощность, поток энергии потужність, потік енергії	L^2MT^{-3}	W (watt)	Вт (ватт)	Вт (ватт)	1 Вт= =1 Дж/с
6	*Q*	charge, quantity of electricity электрический заряд, количество электричества електричний заряд, кількість електрики	TI	C (coulomb)	Кл (кулон)	Кл (кулон)	1 Кл= =1 А·с
7	φ, *U*, *E*	potential difference, electromotive force (emf), voltage электрический потенциал, разность электрических потенциалов, электрическое напряжение, электродвижущая сила (ЭДС) електричний потенціал, різниця електричних потенціалів, електрична напруга, електрорушійна сила (ЕРС)	$L^2MT^{-3}I^{-1}$	V (volt)	В (вольт)	В (вольт)	1 В= =1 Вт/А

Table A.3 (continued)
Таблица A.3 (продолжение)
Таблиця A.3 (продовження)

1	2	3	4	5	6	7	8
8	C	electric(al) capacitance электрическая емкость електрична ємність	$L^{-2}M^{-1}T^{4}I^{2}$	F (farad)	Ф (фарада)	Ф (фарада)	1 Ф= =1 Кл/В
9	R	electric(al) resistance электрическое сопротивление електричний опір	$L^{2}MT^{-3}I^{-2}$	Ω (ohm)	Ом (ом)	Ом (ом)	1 Ом= =1 В/А
10	G	electric(al) conductivity электрическая проводимость електрична провідність	$L^{-2}M^{-1}T^{3}I^{2}$	S (siemens)	См (сименс)	См (сіменс)	1 См= =1 Ом$^{-1}$
11	Φ	magnetic flux магнитный поток магнітний потік	$L^{2}MT^{-2}I^{-1}$	Wb (weber)	Вб (вебер)	Вб (вебер)	1 Вб= =1 В·с
12	B	induction (magnetic flux density) магнитная индукция (плотность магнитного потока) магнітна індукція (густина магнітного потоку)	$MT^{-2}I^{-1}$	T (tesla)	Тл (тесла)	Тл (тесла)	1 Тл= =1 Вб/м^{2}
13	L, L_m	inductance индуктивность, взаимная индуктивность індуктивність, взаємоіндуктивність	$L^{2}MT^{-2}I^{-2}$	H (henry)	Гн (генри)	Гн (генрі)	1 Гн= =1 Вб/А

Table A.3 (finished)
Таблица А.3 (окончание)
Таблиця А.3 (закінчення)

1	2	3	4	5	6	7	8
14	Φ_v	luminous (light) flux световой поток світловий потік	J	lm (lumen)	лм (люмен)	лм (люмен)	1 лм= =1 кд·ср
15	E_v	illuminance освещенность освітленість	$L^{-2}J$	lx (lux)	лк (люкс)	лк (люкс)	1 лк= =1 лм/м^2
16	A	activity (of a radioactive source) активность (радиоактивного источника) активність (радіоактивного джерела)	T^{-1}	Bq (becquerel)	Бк (беккерель)	Бк (беккерель)	1 Бк= =1 с$^{-1}$
17	K	absorbed radiation doze, kerma поглощенная доза (ионизирующего излучения), удельная переданная энергия, керма поглинена доза (іонізуючого випромінювання), питома передана енергія, керма	L^2T^{-2}	Gy (gray)	Гр (грэй)	Гр (грей)	1 Гр= =1 Дж/кг
18	H	radiation doze (equivalent) эквивалентная доза (ионизирующего излучения) еквівалентна доза (іонізуючого випромінювання)	L^2T^{-2}	Sv (sievert)	Зв (зиверт)	Зв (зіверт)	1 Зв= =1 Дж/кг

Table A.4 SI Derived Units of Space and Time
Таблица А.4 Производные единицы величин, описывающих пространство и время
Таблиця А.4 Похідні одиниці величин, що описують простір і час

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	ω	angular velocity угловая (круговая) частота, угловая скорость кутова (кругова) частота, кутова швидкість	T^{-1}	s^{-1} (rad/s)	с$^{-1}$ (рад/с)	с$^{-1}$ (рад/с)
2	α	angular acceleration угловое ускорение кутове прискорення	T^{-2}	rad/s^{2}	рад/с^{2}	рад/с^{2}
3	v	velocity скорость швидкість	LT^{-1}	m/s	м/с	м/с
4	a	acceleration ускорение прискорення	LT^{-2}	m/s^{2}	м/с^{2}	м/с^{2}
5	g	acceleration due to gravity ускорение свободного падения, гравитационное ускорение прискорення вільного падіння, гравітаційне прискорення	LT^{-2}	m/s^{2}	м/с^{2}	м/с^{2}
6	α, β, γ	plane angle плоский угол плоский кут	1	rad (radian)	рад (радиан)	рад (радіан)
7	Ω	solid angle телесный угол тілесний кут	1	sr (steradian)	ср (стерадиан)	ср (стерадіан)
8	A, S	area площадь площа	L^{2}	m^{2}	м^{2}	м^{2}
9	V	volume объем об’єм	L^{3}	m^{3}	м^{3}	м^{3}

Table A.5 SI Derived Units of Periodic Processes and Phenomena
Таблица А.5 Производные единицы величин, описывающих периодические процессы и явления
Таблиця А.5 Похідні одиниці величин, що описують періодичні процеси та явища

No.	Sym-bol	Name of Value	Dimen-sions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	f	frequency частота частота	T^{-1}	Hz (hertz)	Гц (герц)	Гц (герц)
2	n	rotational frequency частота вращения частота обертання	T^{-1}	r/s	об/с	об/с
3	t	period период період	T	s (second)	с (секунда)	с (секунда)
4	τ	relaxation time время релаксации час релаксації	T	s	с	с
5	ω	angular velocity угловая (круговая) частота, угловая скорость кутова (кругова) частота, кутова швидкість	T^{-1}	s^{-1} (rad/s)	$с^{-1}$ (рад/с)	$с^{-1}$ (рад/с)
6	λ	wavelength длина волны довжина хвилі	L	m, X	м	м
7	δ	damping coefficient коэффициент затухания коефіцієнт згасання	T^{-1}	s^{-1}	$с^{-1}$	$с^{-1}$
8	Λ	damping decrement (logarithm) логарифмический декремент затухания логарифмічний декремент згасання	–	–	–	–

Table A.6 Derived Units of Mechanical Values
Таблица А.6 Производные единицы механических величин
Таблиця А.6 Похідні одиниці механічних величин

No.	Sym-bol	Name of Value English Russian Ukrainian	Dimen-sions	SI units English	 Russian	 Ukrainian
1	2	3	4	5	6	7
1	ρ	density плотность густина	$L^{-3}M$	kg/m^3	кг/м^3	кг/м^3
2	ρ_l	linear density линейная плотность лінійна густина	$L^{-1}M$	kg/m	кг/м	кг/м
3	ρ_A	surface density поверхностная плотность поверхнева густина	$L^{-2}M$	kg/m^2	кг/м^2	кг/м^2
4	γ	specific gravity, specific weight удельный вес питома вага	$L^{-2}MT^{-2}$	N/m^3	Н/м^3	Н/м^3
5	F, F_g	force, weight сила, вес сила, вага	LMT^{-2}	N (newton)	Н (ньютон)	Н (ньютон)
6	p	pressure давление тиск	$L^{-1}MT^{-2}$	Pa (pascal)	Па (паскаль)	Па (паскаль)
7	σ	normal stress нормальное напряжение нормальне напруження	$L^{-1}MT^{-2}$	Pa (pascal)	Па (паскаль)	Па (паскаль)
8	τ	shear stress касательное напряжение дотичне напруження	$L^{-1}MT^{-2}$	Pa (pascal)	Па (паскаль)	Па (паскаль)

Table A.6 (continued)
Таблица А.6 (продолжение)
Таблиця А.6 (продовження)

1	2	3	4	5	6	7
9	ε	strain (относительная) линейная деформация, (относительное) удлинение (відносна) лінійна деформація, (відносне) видовження	–	–	–	–
10	γ	shear strain (относительная) деформация сдвига (відносна) деформація зсуву	–	–	–	–
11	E	modulus of elasticity (Young's modulus) модуль упругости, модуль Юнга модуль пружності, модуль Юнга	$L^{-1}MT^{-2}$	Pa=N/m^2 pascal= =(newton/m^2)	Па (паскаль)	Па (паскаль)
12	G	shear modulus модуль сдвига, модуль Кулона модуль зсуву, модуль Кулона	$L^{-1}MT^{-2}$	Pa=N/m^2 (pascal= =newton/m^2)	Па (паскаль)	Па (паскаль)
13	K	bulk modulus модуль объемного сжатия, модуль объемной упругости, модуль всестороннего сжатия модуль об’ємного стиску, модуль об’ємної пружності, модуль всебічного стиску	$L^{-1}MT^{-2}$	Pa (pascal)	Па (паскаль)	Па (паскаль)
14	η	viscosity coefficient (dynamic) динамический коэффициент вязкости динамічний коефіцієнт в’язкості	$L^{-1}MT^{-1}$	Pa·s	Па·с	Па·с

Table A.6 (finished)
Таблица А.6 (окончание)
Таблиця А.6 (закінчення)

1	2	3	4	5	6	7
15	ν	viscosity coefficient (kinematic) кинематический коэффициент вязкости кінематичний коефіцієнт в’язкості	L^2T^{-1}	m^2/s	$м^2/с$	$м^2/с$
16	σ	coefficient of surface tension коэффициент поверхностного натяжения коефіцієнт поверхневого натягу	MT^{-2}	N/m	Н/м	Н/м
17	A, W	work работа робота	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
18	E	energy энергия енергія	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
19	E_P, U	potential energy потенциальная энергия потенціальна енергія	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
20	E_k, T	kinetic energy кинетическая энергия кінетична енергія	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
21	w	energy per unit volume объемная плотность энергии об’ємна густина енергії	$L^{-1}MT^{-2}$	J/m^3	$Дж/м^3$	$Дж/м^3$
22	P	power мощность потужність	L^2MT^{-3}	W (watt)	Вт (ватт)	Вт (ватт)
23	p	momentum импульс, количество движения імпульс, кількість руху	LMT^{-1}	(kg·m)/s	(кг·м)/с	(кг·м)/с

Table A.7 SI Derived Units of Heat Values
Таблица А.7 Производные единицы тепловых величин
Таблиця А.7 Похідні одиниці теплових величин

No.	Symbol	Name of Value English Russian Ukrainian	Dimensions	SI units		
				English	Russian	Ukrainian
1	2	3	4	5	6	7
1	α_l	thermal-expansion coefficient (linear) температурный коэффициент линейного расширения температурний коефіцієнт лінійного розширення	θ^{-1}	K^{-1}	K^{-1}	K^{-1}
2	α_V	thermal-expansion coefficient (volume) температурный коэффициент объемного расширения температурний коефіцієнт об’ємного розширення	θ^{-1}	K^{-1}	K^{-1}	K^{-1}
3	Q	heat, quantity of heat теплота, количество теплоты теплота, кількість теплоти	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
4	Φ	thermal flux тепловой поток тепловий потік	L^2MT^{-3}	W (watt)	Вт (ватт)	Вт (ватт)
5	λ	thermal conductivity (coefficient of) коэффициент теплопроводности коефіцієнт теплопровідності	$LMT^{-3}\theta^{-1}$	W/(m·K)	Вт/(м·K)	Вт/(м·K)
6	K	heat transfer coefficient коэффициент теплопередачи коефіцієнт теплопередачі	$MT^{-3}\theta^{-1}$	W/(m^2·K)	Вт/(м^2·K)	Вт/(м^2·K)

Table A.7 (continued)
Таблица A.7 (продолжение)
Таблиця A.7 (продовження)

1	2	3	4	5	6	7
7	R_t	thermal resistance термическое сопротивление термічний опір	$L^{-2}M^{-1}T^3\theta$	K/W	К/Вт	К/Вт
8	α	coefficient of thermal diffusivity коэффициент температуропроводности коефіцієнт температуропровідності	L^2T^{-1}	m^2/s	$м^2/с$	$м^2/с$
9	c	mass heat capacity удельная теплоемкость питома теплоємність	$L^2T^{-2}\theta^{-1}$	J/(kg·K)	Дж/(кг·К)	Дж/(кг·К)
10	c_p	heat capacity at constant pressure удельная теплоемкость при постоянном давлении питома теплоємність при постійному тискові	$L^2T^{-2}\theta^{-1}$	J/(kg·K)	Дж/(кг·К)	Дж/(кг·К)
11	c_V	heat capacity at constant volume удельная теплоемкость при постоянном объеме питома теплоємність при постійному об'ємі	$L^2T^{-2}\theta^{-1}$	J/(kg·K)	Дж/(кг·К)	Дж/(кг·К)
12	S	entropy энтропия ентропія	$L^2MT^{-2}\theta^{-1}$	J/K	Дж/К	Дж/К
13	E	energy энергия енергія	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)

Table A.7 (continued)
Таблица А.7 (продолжение)
Таблиця А.7 (продовження)

1	2	3	4	5	6	7
14	U	internal energy, thermodynamic energy внутренняя энергия, термодинамическая энергия внутрішня енергія, термодинамічна енергія	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
15	H	enthalpy (heat content) энтальпия (теплосодержание, тепловая функция Гиббса) ентальпія (тепловміст, теплова функція Гіббса)	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
16	F	Helmgoltz energy, Helmgoltz function энергия Гельмгольца, свободная энергия, изохорно-изотермический потенциал, функция Гельмгольца енергія Гельмгольца вільна енергія, ізохорно-ізотермічний потенціал, функція Гельмгольца	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)
17	G	Gibbs energy энергия Гиббса, свободная энтальпия, изобарно-изотермический потенциал, функция Гиббса енергія Гіббса, вільна ентальпія, ізобарно-ізотермічний потенціал, функція Гіббса	L^2MT^{-2}	J (joule)	Дж (джоуль)	Дж (джоуль)

Table A.7 (finished)
Таблица А.7 (окончание)
Таблиця А.7 (закінчення)

1	2	3	4	5	6	7
18	*e*	specific energy удельная (массовая) энергия питома (масова) енергія	L^2T^{-2}	J/kg (joule/kg)	Дж/кг (джоуль/кг)	Дж/кг (джоуль/кг
19	*u*	specific thermodynamic energy удельная (массовая) термодинамическая энергия питома (масова) термодинамічна енергія	L^2T^{-2}	J/kg (joule/kg)	Дж/кг (джоуль/кг)	Дж/кг (джоуль/кг
20	*h*	specific enthalpy (heat content) удельная (массовая) энтальпия питома (масова) ентальпія	L^2T^{-2}	J/kg (joule/kg)	Дж/кг (джоуль/кг)	Дж/кг (джоуль/кг
21	*f*	specific Helmgoltz energy удельная (массовая) энергия Гельмгольца питома (масова) енергія Гельмгольца	L^2T^{-2}	J/kg (joule/kg)	Дж/кг (джоуль/кг)	Дж/кг (джоуль/кг
22	*g*	specific Gibbs energy удельная (массовая) энергия Гиббса питома (масова) енергія Гіббса	L^2T^{-2}	J/kg (joule/kg)	Дж/кг (джоуль/кг)	Дж/кг (джоуль/кг

Table A.8 SI Derived Units of Electric and Magnetic Values
Таблица А.8 Производные единицы электрических и магнитных величин
Таблиця А.8 Похідні одиниці електричних і магнітних величин

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	Q	charge, quantity of electricity электрический заряд, количество электричества електричний заряд, кількість електрики	TI	C (coulomb)	Кл (кулон)	Кл (кулон)
2	σ	electric charge density (surface) поверхностная плотность электрического заряда поверхнева густина електричного заряду	$L^{-2}TI$	C/m^2	Кл/м^2	Кл/м^2
3	D	electric induction, electric-flux density электрическое смещение (вектор электрической индукции) електричне зміщення (вектор електричної індукції)	$L^{-2}TI$	C/m^2	Кл/м^2	Кл/м^2
4	ρ	electric charge density (volume) (объемная) плотность электрического заряда (об’ємна) густина електричного заряду	$L^{-3}TI$	C/m^3	Кл/м^3	Кл/м^3
5	E	electric field strength напряженность электрического поля напруженість електричного поля	$LMT^{-3}I^{-1}$	V/m	В/м	В/м

Table A.8 (continued)
Таблица А.8 (продолжение)
Таблиця А.8 (продовження)

1	2	3	4	5	6	7
6	V, U	voltage напряжение, разность потенциалов напруженість, різниця потенціалів	$L^2MT^{-3}I^{-1}$	V (volt)	В (вольт)	В (вольт)
7	φ	electric potential электрический потенциал електричний потенціал	$L^2MT^{-3}I^{-1}$	V (volt)	В (вольт)	В (вольт)
8	E	electromotive force электродвижущая сила, ЭДС електрорушійна сила, ЕРС	$L^2MT^{-3}I^{-1}$	V (volt)	В (вольт)	В (вольт)
9	C	electric capacitance электрическая емкость електрична ємність	$L^{-2}M^{-1}T^4I^2$	F (farad)	Ф (фарада)	Ф (фарада)
10	ε_a	dielectric permittivity абсолютная диэлектрическая проницаемость абсолютна діелектрична проникність	$L^{-3}M^{-1}T^4I^2$	F/m	Ф/м	Ф/м
11	ε_r	relative dielectric permittivity относительная диэлектрическая проницаемость відносна діелектрична проникність	–	–	–	–
12	χ_e	dielectric susceptibility относительная диэлектрическая восприимчивость відносна діелектрична проникність	–	–	–	–

Table A.8 (continued)
Таблица А.8 (продолжение)
Таблиця А.8 (продовження)

1	2	3	4	5	6	7
13	P	polarization поляризованность поляризація	$L^{-2}TI$	C/m^2 (coul/m^2)	Кл/м^2 (кулон/м^2)	Кл/м^2 (кулон/м^2)
14	p_e	dipole moment электрический дипольный момент електричний дипольний момент	LTI	C·m (coul·m)	Кл·м (кулон·м)	Кл·м (кулон·м)
15	j	current density плотность (электрического) тока густина (електричного) струму	$L^{-2}I$	A/m^2 (ampere/m^2)	А/м^2 (ампер/м^2)	А/м^2 (ампер/м^2)
16	H	magnetic field strength напряженность магнитного поля напруженість магнітного поля	$L^{-1}I$	A/m (ampere/m)	А/м (ампер/метр)	А/м (ампер/метр)
17	B B_r, B_s	magnetic induction (magnetic flux density), remanent induction, saturation induction магнитная индукция, (плотность магнитного потока), магнітна індукція, (густина магнітного потоку) остаточная магнитная индукция залишкова магнітна індукція магнитная индукция насыщения магнітна індукція насичення	$MT^{-2}I^{-1}$	T=Wb/m^2 (tesla= =weber/m^2)	Тл (тесла)	Тл (тесла)

Table A.8 (continued)
Таблица А.8 (продолжение)
Таблиця А.8 (продовження)

1	2	3	4	5	6	7
18	Φ	magnetic flux магнитный поток магнітний потік	$L^2MT^{-2}I^{-1}$	Wb (weber)	Вб (вебер)	Вб (вебер)
19	μ	magnetic permeability магнитная проницаемость магнітна проникність	$LMT^{-2}I^{-2}$	H/m (henry/m)	Гн/м (генри/метр)	Гн/м (генри/метр)
20	μ_r	relative magnetic permeability относительная магнитная проницаемость відносна магнітна проникність	–	–	–	–
21	χ_μ	magnetic susceptibility абсолютная магнитная восприимчивость абсолютна магнітна проникність	–	–	–	–
22	m	magnetic moment магнитный момент магнітний момент	L^2I	$A \cdot m^2$ (ampere·m^2)	А·м^2 (ампер·м^2)	А·м^2 (ампер·м^2)
23	M	magnetization намагниченность намагніченість	$L^{-1}I$	A/m (ampere/m)	А/м (ампер/метр)	А/м (ампер/метр)
24	J	magnetic polarization магнитная поляризованность магнітна поляризованість	$MT^{-2}I^{-1}$	T	Тл	Тл
25	R	resistance электрическое сопротивление електричний опір	$L^2MT^{-3}I^{-2}$	Ω (ohm)	Ом	Ом
26	G	conductivity электрическая проводимость електрична провідність	$L^{-2}M^{-1}T^3I^2$	S (siemens)	См (сименс)	См (сименс)

Table A.8 (finished)
Таблица A.8 (окончание)
Таблиця A.8 (закінчення)

1	2	3	4	5	6	7
27	ρ	resistivity (electrical) удельное электрическое сопротивление питомий електричний опір	$L^3MT^{-3}I^{-2}$	Ω·m	Ом·м	Ом·м
28	σ	conductivity (electrical) удельная электрическая проводимость питома електрична провідність	$L^{-3}M^{-1}T^3I^2$	S/m (siemens/m)	См/м (сименс/м)	См/м (сименс/м)
29	R_m	reluctance магнитное сопротивление, релуктанс магнітний опір, релуктанс	$L^{-2}M^{-1}T^2I^2$	H^{-1}	Гн$^{-1}$	Гн$^{-1}$
30	Λ	permeance магнитная проводимость, пермеанс магнітна провідність, пермеанс	$L^2MT^{-2}I^{-2}$	H	Гн	Гн
31	Q	Q-factor добротность добротність	–	–	–	–
32	φ	phase angle разность фаз різниця фаз	–	rad	рад	рад
33	δ	loss angle угол потерь кут втрат	–	rad	рад	рад
34	d	loss coefficient коэффициент потерь коефіцієнт втрат	–	–	–	–
35	W	electric(al) energy электрическая энергия електрична енергія	L^2MT^{-2}	J	Дж	Дж

Table A.9 SI Derived Units of Optical Values and Electromagnetic Radiation
Таблица А.9 Производные единицы световых величин оптического излучения
Таблиця А.9 Похідні одиниці світлових величин оптичного випромінювання

No.	Sym-bol	Name of Value	Dimen-sions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	f	frequency частота частота	T^{-1}	Hz (hertz)	Гц (герц)	Гц (герц)
2	ω	angular frequency угловая частота кутова частота	T^{-1}	s^{-1} (rad/s)	$с^{-1}$ (рад/с)	$с^{-1}$ (рад/с)
3	λ	wavelength длина волны довжина хвилі	L	m	м	м
4	C	illumination, candela-second освечивание освітлення	TJ	cd·s	кд·с	кд·с
5	Φ_v	luminous flux световой поток світловий потік	J	lm (lumen)	лм (люмен)	лм (люмен)
6	L_v	luminance яркость яскравість	$L^{-2}J$	cd/m^2	$кд/м^2$	$кд/м^2$
7	M_v	luminous exitance светимость світність	$L^{-2}J$	lm/m^2	$лм/м^2$	$лм/м^2$
8	E_v	illuminance освещенность освітленість	$L^{-2}J$	lx (lux)	лк (люкс)	лк (люкс)
9	D	optical density оптическая плотность оптична густина	–	–	–	–

Table A.9 (finished)
Таблица А.9 (окончание)
Таблиця А.9 (закінчення)

1	2	3	4	5	6	7
10	λ	linear absorption coefficient натуральный показатель поглощения, линейный коэффициент поглощения натуральний показник поглинання, лінійний коефіцієнт поглинання	L^{-1}	m^{-1}	$м^{-1}$	$м^{-1}$
11	n	index of refraction коэффициент преломления коефіцієнт заломлення	–	–	–	–

Table A.10 SI Derived Units of Acoustic Values
Таблица А.10 Производные единицы акустических величин
Таблиця А.10 Похідні одиниці акустичних величин

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	λ	wavelength длина волны довжина хвилі	L	m	м	м
2	ρ	density плотность густина	$L^{-3}M$	kg/m^3	$кг/м^3$	$кг/м^3$
3	c	speed of sound скорость звука швидкість звуку	LT^{-1}	m/s	м/с	м/с
4	δ	damping factor (sound oscillations) коэффициент затухания звуковых колебаний коефіцієнт згасання звукових коливань	T^{-1}	s^{-1}	$с^{-1}$	$с^{-1}$

Table A.11 SI Derived Units of Values of Physical Chemistry and Molecular Physical
Таблица А.11 Производные единицы физической химии и молекулярной физики
Таблиця А.11 Похідні одиниці фізичної хімії та молекулярної фізики

No.	Sym-bol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	A_t	relative atomic mass относительная атомная масса відносна атомна маса	–	–	–	–
2	M_t	relative molecular mass относительная молекулярная масса відносна молекулярна маса	–	–	–	–
3	N	number of molecules of homogeneous system число молекул или других структурных элементов (частиц) однородной системы число молекул або інших структурних елементів (частинок) однорідної системи	–	–	–	–
4	M_N	molar mass молярная масса молярна маса	MN^{-1}	kg/mol	кг/моль	кг/моль
5	V_m	molar volume молярный объем молярний об’єм	L^3N^{-1}	m^3/mol	$м^3$/моль	$м^3$/моль
6	U_m	molar energy молярная внутренняя энергия, молярная термодинамическая энергия молярна внутрішня енергія, молярна термодинамічна енергія	$L^2MT^{-2}N^{-1}$	J/mol	Дж/моль	Дж/моль

Table A.11 (continued)
Таблица A.11 (продолжение)
Таблиця A.11 (продовження)

1	2	3	4	5	6	7
7	Q_m	molar heat молярная теплота молярна теплота	$L^2MT^{-2}N^{-1}$	J/mol	Дж/моль	Дж/моль
8	H_m	enthalpy per mole молярная энтальпия молярна ентальпія	$L^2MT^{-2}N^{-1}$	J/mol	Дж/моль	Дж/моль
9	C_m	molar heat capacity молярная теплоемкость молярна теплоємність	$L^2MT^{-2}N^{-1}\theta^{-1}$	J/(mol·K)	$\frac{\text{Дж}}{\text{моль}\cdot\text{К}}$	$\frac{\text{Дж}}{\text{моль}\cdot\text{К}}$
10	S_m	entropy per mole молярная энтропия молярна ентропія	$L^2MT^{-2}N^{-1}\theta^{-1}$	J/(mol·K)	$\frac{\text{Дж}}{\text{моль}\cdot\text{К}}$	$\frac{\text{Дж}}{\text{моль}\cdot\text{К}}$
11	n	volume concentration of molecules or particles объемная концентрация молекул или частиц об’ємна концентрація молекул або частинок	L^{-3}	m^{-3}	$м^{-3}$	$м^{-3}$
12	m	molecular mass масса молекулы маса молекули	M	kg	кг	кг
13	K^θ	equilibrium constant стандартная постоянная равновесия стандартна стала рівноваги	–	–	–	–
14	p_m	dipole moment of molecule электрический дипольный момент молекулы електричний дипольний момент молекули	LTI	C·m (coul·m)	Кл·м (кулон·м)	Кл·м (кулон·м)

Table A.11 (continued)
Таблица А.11 (продолжение
Таблиця А.11 (продовження)

1	2	3	4	5	6	7
15	α	polarizability электрическая поляризуемость молекулы електрична поляризовність молекули	$M^{-1}T^4I^2$	C·m^2/V (coul× ×m^2/volt)	Кл·м^2/В (кулон× ×м^2/вольт)	Кл·м^2/В (кулон× ×м^2/вольт)
16	λ	mean free path средняя длина свободного пробега середня довжина вільного пробігу	L	m	м	м
17	D	diffusion coefficient, diffusivity factor коэффициент диффузии коефіцієнт дифузії	L^2T^{-1}	m^2/s	м^2/с	м^2/с
18	D_t	thermal diffusivity, thermal diffusivity factor коэффициент термодиффузии коефіцієнт термодифузії	L^2T^{-1}	m^2/s	м^2/с	м^2/с
19	Z	atomic number атомный номер атомний номер	–	–	–	–
20	z	ion charge number число иона, зарядовое число іона, зарядне	–	–	–	–
21	b	mobility of charge carriers подвижность носителей заряда рухливість носіїв заряду	$M^{-1}T^2I$	m^2/(V·s)	м^2/(В·с)	м^2/(В·с)
22	Γ	adsorption адсорбция адсорбція	$L^{-2}N$	mol/m^2	моль/м^2	моль/м^2

Table A.11 (finished)
Таблица А.11 (окончание)
Таблиця А.11 (закінчення)

1	2	3	4	5	6	7
23	*g*	specific adsorption удельная адсорбция питома адсорбція	$M^{-1}N$	mol/kg	моль/кг	моль/кг
24	*G*	surface adsorption activity поверхностная активность адсорбата поверхнева активність адсорбату	L^3T^{-2}	$(N\cdot m^2)/kg$	$(Н\cdot м^2)/кг$	$(Н\cdot м^2)/кг$

Table A.12 SI Derived Units of Atomic and Nuclear Physics, Nuclear Reactions and Ionizing Radiation

Таблица А.12 Производные единицы атомной и ядерной физики, ядерных реакций и ионизирующего излучения

Таблиця А.12 Похідні одиниці атомної та ядерної фізики, ядерних реакцій та іонізуючого випромінювання

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	*Z*	atomic number атомный номер атомний номер	–	–	–	–
2	*N*	neutron number число нейтронов число нейтронів	–	–	–	–
3	*A*	mass number массовое число, число нуклонов масове число, число нуклонів	–	–	–	–

Table A.12 (continued)
Таблица А.12 (продолжение)
Таблиця А.12 (продовження)

1	2	3	4	5	6	7
4	$m(X)$	mass of atom масса атома (нуклида X) маса атома (нукліда X)	M	kg	кг	кг
5	E	rest energy энергия покоя частицы (атомного ядра) енергія спокою частинки (атомного ядра)	L^2MT^{-2}	J	Дж	Дж
6	R	radius of nuclear радиус ядра радіус ядра	L	m	м	м
7	l	orbital quantum number орбитальное квантовое число орбітальне квантове число	–	–	–	–
8	s	spin quantum number спиновое квантовое число спінове квантове число	–	–	–	–
9	n	principal quantum number главное квантовое число головне квантове число	–	–	–	–
10	m	magnetic quantum number магнитное квантовое число магнітне квантове число	–	–	–	–

Table A.12 (finished)
Таблица А.12 (окончание)
Таблица А.12 (закінчення)

1	2	3	4	5	6	7
11	*f*	atomic packing factor коэффициент упаковки коефіцієнт пакування	–	–	–	–
12	*H*	equivalent radiation doze эквивалентная доза (ионизирующего излучения) еквівалентна доза (іонізаційного випромінювання)	L^2T^{-2}	Sv	Зв (зиверт)	Зв (зіверт)
13	*K*	kerma керма керма	L^2T^{-2}	Gy	Гр (грей)	Гр (грей)
14	*A*	activity of radionuclide активность (радионуклида) активність (радіонукліда)	T^{-1}	Bq	Бк (беккерель)	Бк (беккерель)
15	*K*	absorbed radiation doze поглощенная доза (ионизирующего излучения), удельная переданная энергия, керма поглинена доза (іонізуючого випромінення), питома передана енергія, керма	L^2T^{-2}	Gy	Гр (грей)	Гр (грей)

Table A.13 SI Derived Units of Solid-state Physics
Таблица А.13 Производные единицы физики твердого тела
Таблиця А.13 Похідні одиниці фізики твердого тіла

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	hkl	Miller indices индексы Миллера індекси Міллера	–	–	–	–
2	d_{hkl}	interplanar spacing межплоскостное расстояние міжплощинна відстань	L	m (meter)	м (метр)	м (метр)
3	σ	short-range order (SRO) parameter параметр близкодействия параметр близькодії	–	–	–	–
4	s	long-range order (LRO) parameter параметр дальнодействия параметр далекодії	–	–	–	–
5	b	Burger’s vector вектор Бюргерса вектор Бюргерса	L	m (meter)	м (метр)	М (метр)
6	D	Debay - Weller factor коэффициент Дебая - Веллера коефіцієнт Дебая - Веллера	–	–	–	–
7	θ_D	Debay temperature температура Дебая температура Дебая	θ	K (kelvin)	К (кельвин)	К (кельвін)
8	Γ	Grunaisen factor параметр Грюнайзена параметр Грюназейна	–	–	–	–

Table A.13 (continued)
Таблица А.13 (продолжение)
Таблиця А.13 (продовження)

1	2	3	4	5	6	7
9	l_{ph}	mean free path of phonon длина свободного пробега фонона довжина вільного пробігу фононів	L	m (meter)	м (метр)	м (метр)
10	l_e	mean free path of electron длина свободного пробега электрона довжина вільного пробігу електронів	L	m (meter)	м (метр)	м (метр)
11	A_H	Hall coefficient коэффициент Холла коефіцієнт Холла	$L^3T^{-1}I^{-1}$	m^3/C	м^3/Кл	м^3/Кл
12	S_{ab}	thermal emf coefficient коэффициент Зеебека для веществ a и b коефіцієнт Зеєбека для речовин a і b	$L^2MT^{-3}I^{-1}\theta^{-1}$	V/K (volt/kelvin)	В/К (вольт/кельвин)	В/К (вольт/ /кельвін)
13	μ	Tompson factor коэффициент Томсона коефіцієнт Томсона	$L^2MT^{-3}I^{-1}\theta^{-1}$	V/K (volt/kelvin)	В/К (вольт/кельвин)	В/К (вольт/ /кельвін)
14	A	Richardson constant постоянная Ричардсона стала Річардсона	$L^{-2}T^{-2}I$	$A/(m^2 \cdot K^2)$	А/(м^2·К^2)	А/(м^2·К^2)
15	E_F	Fermi energy энергия Ферми енергія Фермі	L^2MT^{-2}	J	Дж	Дж
16	E_g	energy gap ширина энергетической щели ширина енергетичної щілини	L^2MT^{-2}	J	Дж	Дж

Table A.13 (continued)
Таблица A.13 (продолжение)
Таблиця A.13 (продовження)

1	2	3	4	5	6	7
17	T_F	Fermi temperature температура Ферми температура Фермі	θ	K	K	К
18	m^*	effective mass эффективная масса ефективна маса	M	kg	кг	кг
19	τ	relaxation time время релаксации час релаксації	T	s	с	с
20	T_C	Curie temperature температура Кюри температура Кюрі	θ	K	K	К
21	T_N	Neele temperature температура Нееля температура Неєля	θ	K	K	К
22	T_C	Transition temperature (superconductivity) температура сверхпроводящего перехода температура надпровідного переходу	θ	K	K	К
23	$N(E)$	density of states (of electrons) плотность состояний (электронов) щільність станів (електронів)	$L^{-5}M^{-1}T^{2}$	J^{-1}/m^{3}	Дж$^{-1}$/м^{3}	Дж$^{-1}$/м^{3}
24	n	electron density плотность электронов щільність електронів	L^{-3}	m^{-3}	м$^{-3}$	м$^{-3}$
25	n_i	density of charge carriers собственная плотность носителей заряда власна щільність носіїв заряду	L^{-3}	m^{-3}	м$^{-3}$	м$^{-3}$

Table A.13 (finished)
Таблица A.13 (окончание)
Таблиця A.13 (закінчення)

1	2	3	4	5	6	7
26	β	compressibility factor коэффициент сжимаемости коефіцієнт стисливості	$LM^{-1}T^{2}$	Pa^{-1}	1/Па	1/Па

Table A.14 Symbols for Specified Values
Таблица A.14 Обозначения специальных величин
Таблиця A.14 Позначення спеціальних величин

No.	Symbol	Name of Value	Dimensions	SI units		
		English Russian Ukrainian		English	Russian	Ukrainian
1	2	3	4	5	6	7
1	a	interatomic distance межатомное расстояние міжатомна відстань	L	m or X	м или X	м
2	a, b, c	unit-cell dimension размер элементарной ячейки розмір елементарної комірки	L	m or X	м или X	м
3	C	composition состав склад	–	weight percent	процент	процент
4	CN	coordination number координационное число координаційне число	–	–	–	–
5	DP	degree of polymerization степень полимеризации ступінь полімерізації	–	mere/mole	мер/моль	мер/моль

Table A.14 (continued)
Таблица A.14 (продолжение)
Таблиця A.14 (продовження)

1	2	3	4	5	6	7
6	U_H	Hall voltage Холловская разность потенциалов Холловська різниця потенціалів	$L^2MT^{-3}I^{-1}$	V (volt)	В/м (вольт/ /метр)	В/м (вольт/ /метр)
7	$F(E)$	Fermi distribution распределение Ферми - Дирака розпозділ Фермі - Дірака	–	–	–	–
8	f	fluidity текучесть текучість	$LM^{-1}T$	$m^2/(s\cdot N)$	$м^2(с\cdot Н)$	$м^2(с\cdot Н)$
9	μ_B	Bohr magneton магнетон Бора магнетон Бора	L^2I	$A\cdot m^2$	$А\cdot м^2$	$А\cdot м^2$
10	A_H, R_H	Hall coefficient коэффициент Холла коефіцієнт Холла	$L^3\ T^{-1}I^{-1}$	m^3/C	$м^3/Кл$	$м^3/Кл$
11	WF	Wiedemann-Franz ratio отношение коэффициентов теплопроводности и электропроводности (закон Видемана - Франца) відношення коефіцієнтів теплопровідності та електропровідності (закон Відемана - Франца)	$L^4M^2T^{-1}I^{-2}\theta^1$	$J\cdot\Omega/(s\cdot K)$	Дж·Ом/ /(с·К)	Дж·Ом/ /(с·К)
12	x, y, z	coordinate directions координатные направления коодинатні напрями	–	–	–	–

Table A.14 (finished)
Таблица A.14 (окончание)
Таблиця A.14 (закінчення)

1	2	3	4	5	6	7
13	Z	valence number валентность валентність	–	–	–	–
14	α	absorption coefficient коэффициент поглощения коефіцієнт поглинання	–	–	–	–
15	β	compressibility factor коэффициент сжимаемости коефіцієнт стисливості	$LM^{-1}T^{2}$	Pa^{-1}	$Па^{-1}$	$Па^{-1}$

Appendix B Fundamental Constants

Name of unit	Sym-bol	Value
English Russian Ukraine		
1	2	3
Universal constants Универсальные постоянные Універсальні сталі		
Speed of light in vacuum Скорость света в вакууме Швидкість світу у вакуумі	c	$299\ 792\ 458\ \mathrm{m{\cdot}s^{-1}}$
Magnetic constant Магнитная постоянная Магнітна стала	μ_0	$4\pi 10^{-7}\ \mathrm{H{\cdot}m^{-1}}=$ $=12.566\ 370\ 614{\cdot}10^{-7}\ \mathrm{H{\cdot}m^{-1}}$
Electric constant Электрическая постоянная Електрична стала	ε_0	$8.854\ 187\ 817{\cdot}10^{-12}\ \mathrm{F{\cdot}m^{-1}}$
Gravitational constant Гравитационная постоянная Гравітаційна стала	G	$6.672\ 59\times10^{-11}{\cdot}\mathrm{m^3{\cdot}kg^{-1}{\cdot}s^{-2}}$
Planck's constant Постоянная Планка Стала Планка	h	$6.626\ 0755{\cdot}10^{-34}\ \mathrm{J{\cdot}s}$
Dirac's constant Постоянная Дирака Стала Дірака	$\hbar$	$1.054\ 572\ 66{\cdot}10^{-34}\ \mathrm{J{\cdot}s}$
Electromagnetic constants Электромагнитные постоянные Електромагнитні сталі		
Charge of electron elementary Элементарный заряд (заряд электрона) Елементарний заряд (заряд електрона)	e	$1.602\ 177\ 33{\cdot}10^{-19}\ \mathrm{C}$
Bohr magneton Магнетон Бора Магнетон Бора	μ_B	$9.274\ 0154{\cdot}10^{-24}\ \mathrm{J{\cdot}T^{-1}}$

1	2	3
Nuclear magneton Ядерный магнетон Ядерний магнетон	μN	5.050 7866·10-27 J·T-1
Atomic constants Атомные постоянные Атомні сталі		
Rydberg constant Постоянная Ридберга Стала Рідберга	R_∞	10 973 731.534 m^{-1}
Bohr radius Боровский радиус Боровський радіус	a_0	0.529 177 249·10^{-10} m
Electron Электрон Електрон		
Mass of electron Масса покоя электрона Маса спокою електрона	m_e	9.109 3897·10^{-31} kg
Electron charge-mass ratio Отношение заряда электрона к его массе Відношення заряду електрона до її маси	$-\frac{e}{m_e}$	–1.75881962·10^{11} C·$кg^{-1}$
Classic electron radius Классический радиус электрона Класичний радіус електрона	re	2.817 940 92·10-15 m
Magnetic moment of electron Магнитный момент электрона Магнітний момент електрона	μe	928.477 01·10-26 J·T-1
Compton wavelength of electron Комптоновская длина волны электрона Комптоновська довжина хвилі електрона	λ_c	2.42631058·10^{-12} m
Proton Протон Протон		
Mass of still proton Масса покоя протона Маса спокою протона	m_p	1.672 6231·10^{-27} kg

1	2	3
Magnetic moment of proton Магнитный момент протона Магнітний момент протона	μ_p	$1.410\ 607\ 61\cdot10^{-26}\ \mathrm{J\cdot T^{-1}}$
Proton charge-mass ratio Отношение заряда протона и его масса Відношення заряду протона та його маси	e/m_p	$9.5788309\cdot10^{-7}\ \mathrm{C\cdot kg^{-1}}$
Neutron Нейтрон Нейтрон		
Mass of still neutron Масса покоя нейтрона Маса спокою нейтрона	m_n	$1.674\ 9286\cdot10^{-27}\ \mathrm{kg}$
Magnetic moment of neutron Магнитный момент нейтрона Магнітний момент нейтрона	μ_n	$0.966\ 237\ 07\cdot10^{-26}\ \mathrm{J\cdot T^{-1}}$
Physical-chemical constants Физико-химические постоянные Фізико-хімічні сталі		
Avogadro's number Постоянная Авогадро Стала Авогадро	N_A	$6.022\ 1367\cdot10^{23}\cdot\mathrm{mol^{-1}}$
Atomic mass unit Атомная единица массы (унифицированная) Атомна одиниця маси (уніфікована)	U_0 а.е.м.	$1.660\ 5402\cdot10^{-27}\ \mathrm{kg}$
Faraday's constant Постоянная Фарадея Стала Фарадея	F	$96\ 485.309\ \mathrm{C\cdot mol^{-1}}$
Gas constant Универсальная (молярная) газовая постоянная Універсальна (молярна) газова стала	R	$8.314\ 510\ \mathrm{J\cdot mol^{-1}\cdot K^{-1}}$
Boltzmann's constant Постоянная Больцмана Стала Больцмана	k	$1.380\ 658\cdot10^{-23}\ \mathrm{J\cdot K^{-1}}$

1	2	3
Volume of ideal gas (0°C and 1 atm) Молярный объем идеального газа при нормальных условиях (T=273.15 K, p=101325 Па) Молярний об’єм ідеального газу при нормальних умовах (T=273.15 K, p=101325 Па)	V_m	$22.414\ 10\cdot10^{-3}\ \mathrm{m^3\cdot mol^{-1}}$
Stefan-Boltzmann’s constant Постоянная Стефана - Больцмана Стала Стефана - Больцмана	σ	$5.670\ 51\cdot10^{-8}\ \mathrm{W\cdot m^{-2}\cdot K^{-4}}$
Ween’s constant Постоянная в законе смещения Вина Стала у законі зміщення Віна	b	$2.897756\cdot10^{-3}\ \mathrm{m\cdot K}$

Appendix C Table of Elements

Element	Symbol	Atomic no.	Electrons in shells							Atomic wt. (C^{12}= =12.000)	Melting point, °C	Boiling point, °C	Density (g)×10^{-3} kg/liter (l)×10^{3} kg/m^3 (s)×10^{3} kg/m^3	Crystal structure of solid	Approx. atomic radius, Å	Valence (most common)	Approx. ionic radius, Å (Coord. No. =6)
			K	L	M	N	O	P	Q								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen	H	1	1							1.008	-259.18	-252.8	(g) 0.0899 (l) 0.070	Hex	0.46	+	Very small
Helium	He	2	2							1.008	-272.2 (26 atm)	-268.9	(g) 0.1785 (l) 0.147	Hcp (?)	1.76	Inert	-
Lithium	Li	3	2	1						6.94	186	1609	(s) 0.534	Bcc	1.519	+	0.78
Beryllium	Be	4	2	2						9.01	1350	1530	(s) 1.85	Hcp	1.12	2+	0.34
Boron	B	5	2	3						10.81	2300	2550	(s) 2.3	Ortho (?)	0.46	3+	~0.25
Carbon	C	6	2	4						12.01	~3500	4200(?)	(s) 2.± (s) 2.25(gr) (s)3.51(d)	Amorphous Hex Cubic	. 0.71 0.77	4+	~0.2
Nitrogen	N	7	2	5						14.007	-209.86	-195.8	(g) 1.2506 (l) 0.808 (s) 1.026	Hex	0.71	3-	0
Oxygen	O	8	2	6						15.9994	-218.4	-183.0	(g) 1.429 (l) 1.14 (s) 1.426	Rhombic (?)	0.60 0.5	2-	1.32
Fluorine	F	9	2	7						19	-223	-188.2	(g) 1.69 (l) 1.108	0	0.6	-	1.33

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Neon	Ne	10	2	8						20.18	-248.67	-245.9	(g) 0.9002 (l) 1.204	Fcc	38139	Inert	-
Sodium	Na	11	2	8	1					22.99	97,5	880	(s) 0.97	Bcc	1.857	+	0.98
Magnesium	Mg	12	2	8	2					24.31	650	1110	(s) 1.74	Hex	1.594	2+	0.78
Aluminum	Al	13	2	8	3					26.98	660.2	2060	(s) 2.699	Fcc	1.431	3+	0.57
Silicon	Si	14	2	8	4					28.09	1480	2300	(s) 2,4	Diamond cubic	1.176	4+	0.41
Phosphorus	P	15	2	8	5					30.97	44,1	280	(s) 1,82	Cubic	-	5+	0.2-0.4
Sulfur	S	16	2	8	6					32.06	119.0	246.2	(s) 2.07 (l) 1.803	Fc ortho	1.06	2- 6+	1.74 0.34
Chlorine	Cl	17	2	8	7					35.45	-101	-34.7	(g) 3.214 (l) 1.557 (s) 1.9	Tetra	0,905	-	1.81
Argon	Ar	18	2	8	8					39,95	-189,4	-185.8	(g) 1.784 (l) 1.40 (s) 1.65	Fcc	1.920	Inert	-
Potassium	K	19	2	8	8	1				39.10	63	770	(s) 0.86	Bcc	2.312	+	1.33
Calcium	Ca	20	2	8	8	2				40.08	850	1440	(s) 1.55	Fcc	1.969	2+	1.06
Scandium	Se	21	2	8	9	2				44.96	1200		(s) 2.5	Fcc	1.605	3+	0.83
Titanium	Ti	22	2	8	10	2				47.90	1820		(s) 4.54	Hcp	1.458	4+	0.64
Vanadium	V	23	2	8	11	2				50.94	1735	3400	(s) 6.0	Bcc	1.316	3+ 5+	0.65 ~0.4
Chromium	Cr	24	2	8	13	1				52.00	1890	2500	(s) 7.19	Bcc	1.249	3+	0.64
Manganese	Mn	25	2	8	13	2				54.94	1245	2150	(s) 7.43	Cubic comp.	1.12	2+	0.91

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Iron	Fe	26	2	8	14	2				55.85	1539	2740	(s) 7.87	Bcc	1.241	2+ 3+	0.83 0.67
Cobalt	Co	27	2	8	15	2				58.93	1495	2900	(s) 8.9	Hcp	1.248	2+	0.82
Nickel	Ni	28	2	8	16	2				58.71	1455	2730	(s) 8.90	Fcc	1.245	2+	0.78
Copper	Cu	29	2	8	18	1				63.54	1083	2600	(s) 8.96	Fcc	1.278	+	0.96
Zinc	Zn	30	2	8	18	2				65.37	419.46	906	(s) 7.133	Hcp	1.332	2+	0.83
Gallium	Ga	31	2	8	18	3				69.72	29.78	2070	(s) 5.91	Fc ortho	1.218	3+	0.62
Germanium	Ge	32	2	8	18	4				72.59	958		(s) 5.36	Diamond cubic	1.224	4+	0.44
Arsenic	As	33	2	8	18	5				74.92	814 (36 atm)	610	(s) 5.73	Rhombic	1.25	3+ 5+	0.69 ~0.4
Selenium	Se	34	2	8	18	6				78.96	220	680	(s) 4.81	Hex	1.16	2-	1.91
Bromine	Br	35	2	8	18	7				79.91	-7.2	19.0	(s) 3.12	Ortho	1.13	-	1.96
Krypton	Kr	36	2	8	18	8				83.80	-157	-152	(g) 3.708 (l) 2.155 (s)	Fcc	2.01	Inert	
Rubidium	Rb	37	2	8	18	8	1			85,47	39	680	(s) 1,53	Bcc	2,44	+	1,49
Strontium	Sr	38	2	8	18	8	2			87.62	770	1380	(s) 2.6	Fcc	2.15	2+	1.27
Yttrium	Y	39	2	8	18	9	2			88.91	1490		(s) 5.51	Hcp	1.79	3+	1.06
Zirconium	Zr	40	2	8	18	10	2			91.22	1750		(s) 6.5	Hcp	1.58	4+	0.87
Niobium (Columbium)	Nb (Cb)	41	2	8	18	12	1			92.91	2415		(s) 8.57	Bcc	1.429	5+	0.69
Molybdenum	Mo	42	2	8	18	13	1			95.94	2625	4800	(s) 10.2	Bcc	1.36	4+	0.68
Technetium	Tc	43	2	8	18	14	1			99	2700		(An artificial element only)				

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Ruthenium	Ru	44	2	8	18	15	1			101.07	2500	4900	(s) 12.2	Hcp	1.352	4+	0.65
Rhodium	Rh	45	2	8	18	16	1			102.91	1966	4500	(s) 12.44	Fcc	1.344	3+	0.68
Palladium	Pd	46	2	8	18	18				106.4	1554	4000	(s) 2.0	Fcc	1.375		
Silver	Ag	47	2	8	18	18	1			107.87	960.5	2210	(s) 10.49	Fcc	1.444	+	1.13
Cadmium	Cd	48	2	8	18	18	2			112.40	320.9	765	(s) 8.65	Hcp	1.489	2+	1.03
Indium	In	49	2	8	18	18	3			114.82	156.4		(s) 7.31	Bc tetra	1.625	3+	0.92
Tin	Sn	50	2	8	18	18	4			118.69	231.9	2270	(s) 7.298	Bc tetra	1.509	4+	0.74
Antimony	Sb	51	2	8	18	18	5			121.75	630.5	1440	(s) 6.62	Rhombic	1.452	5+	0.90
Tellurium	Te	52	2	8	18	18	6			127.6	450	1390	(s) 6.24	Hex	1.43	2-	2.11
Iodine	I	53	2	8	18	18	7			126.9	114	183	(s) 4.93	Ortho	1.35	-	2.20
Xenon	Xe	54	2	8	18	18	8			131.3	-112	-108	(g) 5.851 (l) 3.52 (s) 2.7	Fcc	2.21	Inert	
Cesium	Cs	55	2	8	18	18	8	1		132.9	28	690	(s) 1,9	Bcc	2.62	+	1.65
Barium	Ba	56	2	8	18	18	8	2		137.3	704	1640	(s) 3.5	Bcc	2.17	2+	1.43
Rare earths	La ↓ Lu	57 ↓ 71	2	8	18	18 ↓ 32	8 ↓ 9	2		138.9 ↓ 175.0						3+	1.22 ↓ 0.99
Tantalum	Ta	73	2	8	18	32	11	2		180.95	2996		(s) 16.6	Bcc	1.429	5+	0.68
Tungsten	W	74	2	8	18	32	12	2		183.9	3410	5930	(s) 19.3	Bcc	1.369	4+	0.68
Rhenium	Re	75	2	8	18	32	13	2		186.2	3170	-	(s) 20	Hcp	1.370		
Osmium	Os	76	2	8	18	32	14	2		190.2	2700	5500	(s) 22.5	Hcp	1.367	4+	0.67
Indium	Ir	77	2	8	18	32	17			192.2	2454	5300	(s) 22 5	Fcc	1.357	4+	0.66
Osmium	Os	76	2	8	18	32	14	2		190.2	2700	5500	(s) 22.5	Hcp	1.367	4+	0.67
Indium	Ir	77	2	8	18	32	17			192.2	2454	5300	(s) 22 5	Fcc	1.357	4+	0.66
Platinum	Pt	78	2	8	18	32	17	1		195.1	1773	4410	(s) 21.45	Fcc	1.387		

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Gold	Au	79	2	8	18	32	18	1		197.0	1063	2970	(s) 19.32	Fcc	1.441	+	1.37
Mercury	Hg	80	2	8	18	32	18	2		200.6	-38.87	357	(s) 13.55	Rhombic	1.552	2+	1.12
Thallium	Tl	81	2	8	18	32	18	3		204.4	300	1460	(s) 11.85	Hcp	1.704	3+	1.05
Lead	Pb	82	2	8	18	32	18	4		207.2	327.4	1740	(l) 11.34	Fcc	1.750	2+ 4+	1.32 0.84
Bismuth	Bi	83	2	8	18	32	18	5		209.0	271.3	1420	(s) 9.80	Rhombic	1.556		
Polonium	Po	84	2	8	18	32	18	6		210	600			Monoclinic	1.7		
Astatine	At	85	2	8	18	32	18	7		210							
Radon	Rn	86	2	8	18	32	18	8		222	-71	-61.8				Inert	
Francium	Fa	87	2	8	18	32	18	8	1	223						+	
Radium	Ra	88	2	8	18	32	18	8	2	226	700		(s) 5.0				
Actinium	Ac	89	2	8	18	32	18	9	2	227	1600						
Thorium	Th	90	2	8	18	32	18	10	2	232	1800		(s) 11.5	Fcc	1.800	4+	1.10
Protactinium	Pa	91	2	8	18	32	20	9	2	231	3000						
Uranium	U	92	2	8	18	32	21	9	2	238	1130		(s) 18.7	Ortho	1.38	4+	1.05
Neptunium	Np	93	2	8	18	32	22	9	2	237							
Plutonium	Pu	94	2	8	18	32	23	9	2	239							
Americium	Am	95	2	8	18	32	24	9	2	241							
Curium	Cm	96	2	8	18	32	25	9	2	242							
Berkelium	Bk	97	2	8	18	32	26	9	2	249							
Californium	Cf	98	2	8	18	32	27	9	2	252							
Einsteinium	E	99	2	8	18	32	28	9	2	254							
Fermium	Fm	100	2	8	18	32	29	9	2	253							
Mendelevium	Md	101	2	8	18	32	30	9	2	256							
Nobelium	Nb	102	2	8	18	32	32	8	2	259	827						
Lawrencium	Lr	103	2	8	18	32	32	9	2	262	1627						
Rutherfordium	Rf	104	2	8	18	32	32	10	2	261							

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Dubnium	Db	105	2	8	18	32	32	11	2	262							
Seaborgium	Sg	106	2	8	18	32	32	12	2	266							
Bohrium	Bh	107	2	8	18	32	32	13	2	264							
Hassium	Hs	108	2	8	18	32	32	14	2	269			28.6				
Meitnerium	Mt	109	2	8	18	32	32	15	2	268							
Darmstadtium	Ds	110	2	8	18	32	32	16	2	271							
Unununium	Uuu	111	2	8	18	32	32	17	2	272							
Ununbium	Uub	112	2	8	18	32	32	18	2	285							
-	Uut	113	2	8	18	32	32	19	2								
Ununquadium	Uuq	114	2	8	18	32	32	20	2	289							
Ununpntium	Uup	115	2	8	18	32	32										
Ununhexium	Uuh	116	2	8	18	32	32	18	6								
Ununsptium	Uus	117	2	8	18	32	32	18	7								
Ununoctium	Uu	118	2	8	18	32	32	18	8								

Appendix D Selected Physical Properties of Metals

Metal		Atomic Number	Crystal Structure	Lattice Parameter, Å	Atomic Mass, g/g·mole	Density, g/cm^3	Melting Temperature, °C
1		2	3	4	5	6	7
Aluminum	Al	13	FCC	4.04958	26.981	2.699	660.4
Antimony	Sb	51	hex	*a* = 4.307 *c* = 11.273	121.75	6.697	630.7
Arsenic	As	33	hex	*a* = 3.760 *c* = 10.548	74.9216	5.778	816
Barium	Ba	56	BCC	5.025	137.3	3.5	729
Beryllium	Be	4	hex	*a* = 2.2858 *c* = 3.5842	9.01	1.848	1290
Bismuth	Bi	83	hex	*a* = 4.546 *c* = 11.86	208.98	9.808	271.4
Boron	B	5	rhomb	*a* = 10.12 α = 65.5°	10.81	2.3	2300
Cadmium	Cd	48	HCP	*a* = 2.9793 *c* = 5.6181	112.4	8.642	321.1
Calcium	Ca	20	FCC	5.588	40.08	1.55	839
Cerium	Ce	58	HCP	*a* = 3.681 *c* = 11.857	140.12	6.6893	798
Cesium	Cs	55	BCC	6.13	132.91	1.892	28.6
Chromium	Cr	24	BCC	2.8844	51.996	7.19	1875
Cobalt	Co	27	HCP	*a* = 2.5071 *c* = 4.0686	58.93	8.832	1495
Copper	Cu	29	FCC	3.6151	63.54	8.93	1084.9
Gadolinium	Gd	64	HCP	*a* = 3.6336 *c* = 5.7810	157.25	7.901	1313
Gallium	Ga	31	ortho	*a* = 4.5258 *b* = 4.5186 *c* = 7.6570	69.72	5.904	29.8
Germanium	Ge	32	FCC	5.6575	72.59	5.324	937.4
Gold	Au	79	FCC	4.0786	196.97	19.302	1064.4
Hafnium	Hf	72	HCP	*a* = 3.1883 *c* = 5.0422	178.49	13.31	2227
Indium	In	49	tetra	*a* = 3.2517 *c* = 4.9459	114.82	7.286	156.6
Iridium	Ir	77	FCC	3.84	192.9	22.65	2447
Iron	Fe	26	BCC FCC BCC	2.866 3.589	55.847 (>912°C) (>1394°C)	7.87	1538
Lanthanum	La	57	HCP	a = 3.774 c = 12.17	138.91	6.146	918
Molybdenum	Mo	42	BCC	3.1468	95.94	10.22	2610

1		2	3	4	5	6	7
Nickel	Ni	28	FCC	3.5167	58.71	8.902	1453
Niobium	Nb	41	BCC	3.294	92.91	8.57	2468
Osmium	Os	76	HCP	a = 2.7341 c = 4.3197	190.2	22.57	2700
Palladium	Pd	46	FCC	3.8902	106.4	12.02	1552
Platinum	Pt	78	FCC	3.9231	195.09	21.45	1769
Potassium	K	19	BCC	5.344	39.09	0.855	63.2
Rhenium	Re	75	HCP	a = 2.760 c = 4.458	186.21	21.04	3180
Rhodium	Rh	45	FCC	3.796	102.99	12.41	1963
Rubidium	Rb	37	BCC	5.7	85.467	1.532	38.9
Ruthenium	Ru	44	HCP	a = 2.6987 c = 4.2728	101.07	12.37	2310
Selenium	Se	34	hex	a = 4.3640 c = 4.9594	78.96	4.809	217
Silicon	Si	14	FCC	5.4307	28.08	2.33	1410
Silver	Ag	47	FCC	4.0862	107.868	10.49	961.9
Sodium	Na	11	BCC	4.2906	22.99	0.967	97.8
Strontium	Sr	38	FCC	6.0849	87.62	2.6	768
			BCC	4.84	(>557°C)		
Tantalum	Ta	73	BCC	3.3026	180.95	16.6	2996
Technetium	Tc	43	HCP	a = 2.735 c = 4.388	98.9062	11.5	2200
Tellurium	Te	52	hex	a = 4.4565 c = 5.9268	127.6	6.24	449.5
Thorium	Th	90	FCC	5.086	232	11.72	1755
Tin	Sn	50	FCC	6.4912	118.69	5.765	231.9
Titanium	Ti	22	HCP	a = 2.9503 c = 4.6831	47.9	4.507	1668
			BCC	3.32	(>882°C)		
Tungsten	W	74	BCC	3.1652	183.85	19.254	3410
Uranium	U	92	ortho	a = 2.854 b = 5.869 c = 4.955	238.03	19.05	1133
Vanadium	V	23	BCC	3.0278	50.941	6.1	1900
Yttrium	Y	39	HCP	a = 3.648 c = 5.732	88.91	4.469	1522
Zinc	Zn	30	HCP	a = 2.6648 c = 4.9470	65.38	7.133	420
Zirconium	Zr	40	HCP	a = 3.2312 c = 5.1477	91.22	6.505	1852
			BCC	3.6090	(>862°C)		

Appendix E Properties of Selected Engineering Materials

Table E.1 Density Values for Various Engineering Materials (Room-Temperature Conditions)

Material	g/cm^3	lb$_m$/in.^{3}
1	2	3
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**		
Steel alloy A36	7.85	0.283
Steel alloy 1020	7.85	0.283
Steel alloy 1040	7.85	0.283
Steel alloy 4140	7.85	0.283
Steel alloy 4340	7.85	0.283
Stainless Steels		
Stainless alloy 304	8.00	0.289
Stainless alloy 316	8.00	0.289
Stainless alloy 405	7.80	0.282
Stainless alloy 440A	7.80	0.282
Stainless alloy 17-7PH	7.65	0.276
Cast Irons		
Gray irons		
• Grade G1800	7.30	0.264
• Grade G3000	7.30	0.264
• Grade G4000	7.30	0.264
Ductile irons		
• Grade 60-40-18	7.10	0.256
• Grade 80-55-06	7.10	0.256
• Grade 120-90-02	7.10	0.256
Aluminum Alloys		
Alloy 1100	2.71	0.0978
Alloy 2024	2.77	0.100
Alloy 6061	2.70	0.0975
Alloy 7075	2.80	0.101
Alloy 356.0	2.69	0.0971
Copper Alloys		
C11000 (electrolytic tough pitch)	8.89	0.321
C17200 (beryllium-copper)	8.25	0.298
C26000 (cartridge brass)	8.53	0.308
C36000 (free-cutting brass)	8.50	0.307

Table E.1 (continued)

1	2	3
C71500 (copper-nickel, 30%)	8.94	0.323
C93200 (bearing bronze)	8.93	0.322
Magnesium Alloys		
Alloy AZ31B	1.77	0.0639
Alloy AZ91D	1.81	0.0653
Titanium Alloys		
Commercially pure (ASTM grade 1)	4.51	0.163
Alloy Ti-5Al-2.5Sn	4.48	0.162
Alloy Ti-6Al-4V	4.43	0.160
Precious Metals		
Gold (commercially pure)	19.32	0.697
Platinum (commercially pure)	21.45	0.774
Silver (commercially pure	10.49	0.379
Refractory Metals		
Molybdenum (commercially pure)	10.22	0.369
Tantalum (commercially pure)	16.6	0.599
Tungsten (commercially pure)	19.3	0.697
Miscellaneous Nonferrous Alloys		
Nickel 200	8.89	0.321
Inconel 625	8.44	0.305
Monel 400	8.80	0.318
Haynes alloy 25	9.13	0.330
Invar	8.05	0.291
Super invar	8.10	0.292
Kovar	8.36	0.302
Chemical lead	11.34	0.409
Antimonial lead (6%)	10.88	0.393
Tin (commercially pure)	7.17	0.259
Lead-Tin solder (60Sn-40Pb)	8.52	0.308
Zinc (commercially pure)	7.14	0.258
Zirconium, reactor grade 702	6.51	0.235
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS		
Aluminum oxide		
• 99.9% pure	3.98	0.144
• 96%	3.72	0.134
• 90%	3.60	0.130
Concrete	2.4	0.087

Table E.1 (continued)

1	2	3
Diamond		
• Natural	3.51	0.127
• Synthetic	3.20-3.52	0.116-0.127
Gallium arsenide	5.32	0.192
Glass, borosilicate (Pyrex)	2.23	0.0805
Glass, soda-lime	2.5	0.0903
Glass ceramic (Pyroceram)	2.60	0.0939
Graphite		
• Extruded	1.71	0.0616
• Isostatically molded	1.78	0.0643
Silica, fused	2.2	0.079
Silicon	2.33	0.0841
Silicon carbide		
• Hot pressed	3.3	0.119
• Sintered	3.2	0.116
Silicon nitride		
• Hot pressed	3.3	0.119
• Reaction bonded	2.7	0.0975
• Sintered	3.3	0.119
Zirconia, 3 mol% Y_2O_3, sintere	6.0	0.217
POLYMERS		
Elastomers		
• Butadiene-acrylonitrile (nitrile)	0.98	0.0354
• Styrene-butadiene (SBR)	0.94	0.0339
• Silicone	1.1-1.6	0.040-0.058
Epoxy	1.11-1.40	0.0401-0.0505
Nylon 6,6	1.14	0.0412
Phenolic	1.28	0.0462
Polybutylene terephthalate (PBT)	1.34	0.0484
Polycarbonate (PC)	1.20	0.0433
Polyester (thermoset)	1.04-1.46	0.038-0.053
Polyetheretherketone (PEEK)	1.31	0.0473
Polyethylene		
• Low density (LDPE)	0.925	0.0334
• High density (HDPE)	0.959	0.0346
• Ultrahigh molecular weight (UHMWPE)	0.94	0.0339
Polyethylene terephthalate (PET)	1.35	0.0487
Polymethyl methacrylate (PMMA)	1.19	0.0430

Table E.1 (finished)

1	2	3
Polypropylene (PP)	0.905	0.0327
Polystyrene (PS)	1.05	0.0379
Polytetrafluoroethylene (PTFE	2.17	0.0783
Polyvinyl chloride (PVC)	1.30-1.58	0.047-0.057
FIBER MATERIALS		
Aramid (Kevlar 49)	1.44	0.0520
Carbon (PAN precursor)		
• Standard modulus	1.78	0.0643
• Intermediate modulus	1.78	0.0643
• High modulus	1.81	0.0653
E Glass	2.58	0.0931
COMPOSITE MATERIALS		
Aramid fibers-epoxy matrix ($V_f = 0.60$)	1.4	0.050
High modulus carbon fibers-epoxy matrix ($V_f = 0.60$)	1.7	0.061
E glass fibers-epoxy matrix ($V_f = 0.60$)	2.1	0.075
Wood		
• Douglas fir (12% moisture)	0.46-0.50	0.017-0.018
• Red oak (12% moisture)	0.61-0.67	0.022-0.024

Table E.2 Modulus of Elasticity Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Modulus of Elasticity	
	GPa	10^6 psi
1	2	3
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**		
Steel alloy A36	207	30
Steel alloy 1020	207	30
Steel alloy 1040	207	30
Steel alloy 4140	207	30
Steel alloy 4340	207	30

Table E.2 (continued)

1	2	3
Stainless alloy 304	193	28
Stainless alloy 316	193	28
Stainless alloy 405	200	29
Stainless alloy 440A	200	29
Stainless alloy 17-7PH	204	29.5
Cast Irons		
Gray irons		
• Grade G1800	66-97[a]	9.6-14[a]
• Grade G3000	90-113[a]	13.0-16.4[a]
• Grade G4000	110-138[a]	16-20[a]
Ductile irons		
• Grade 60-40-18	169	24.5
• Grade 80-55-06	168	24.4
• Grade 120-90-02	164	23.8
Aluminum Alloys		
Alloy 1100	69	10
Alloy 2024	72.4	10.5
Alloy 6061	69	10
Alloy 7075	71	10.3
Alloy 356.0	72.4	10.5
Copper Alloys		
C11000 (electrolytic tough pitch)	115	16.7
C17200 (beryllium-copper)	128	18.6
C26000 (cartridge brass)	110	16
C36000 (free-cutting brass)	97	14
C71500 (copper-nickel, 30%)	150	21.8
C93200 (bearing bronze)	100	14.5
Magnesium Alloys		
Alloy AZ31B	45	6.5
Alloy AZ91D	45	6.5
Titanium Alloys		
Commercially pure (ASTM grade 1)	103	14.9
Alloy Ti-5Al-2.5Sn	110	16
Alloy Ti-6Al-4V	114	16.5
Precious Metals		
Gold (commercially pure)	77	11.2
Platinum (commercially pure)	171	24.8
Silver (commercially pure)	74	10.7

Table E.2 (continued)

1	2	3
Refractory Metals		
Molybdenum (commercially pure)	320	46.4
Tantalum (commercially pure)	185	27
Tungsten (commercially pure)	400	58
Miscellaneous Nonferrous Alloys		
Nickel 200	204	29.6
Inconel 625	207	30
Monel 400	180	26
Haynes alloy 25	236	34.2
Invar	141	20.5
Super invar	144	21
Kovar	207	30
Chemical lead	13.5	2
Tin (commercially pure)	44.3	6.4
Lead-Tin solder (60Sn-40Pb)	30	4.4
Zinc (commercially pure)	104.5	15.2
Zirconium, reactor grade 702	99.3	14.4
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS		
Aluminum oxide		
• 99.9% pure	380	55
• 96%	303	44
• 90%	275	40
Concrete	25.4-36.6[a]	3.7-5.3[a]
Diamond		
• Natural	700-1200	102-174
• Synthetic Gallium arsenide, single crystal	800-925	116-134
• In the (100) direction	85	12.3
• In the (110) direction	122	17.7
• In the (111) direction	142	20.6
Glass, borosilicate (Pyrex)	70	10.1
Glass, soda-lime	69	10
Glass ceramic (Pyroceram)	120	17.4
Graphite		
• Extruded	11	1.6
• Isostatically molded	11.7	1.7
Silica, fused	73	10.6

Table E.2 (continued)

1	2	3
Silicon, single crystal		
• In the (100) direction	129	18.7
• In the (110) direction	168	24.4
• In the (111) direction	187	27.1
Silicon carbide		
• Hot pressed	207-483	30-70
• Sintered	207-483	30-70
Silicon nitride		
• Hot pressed	304	44.1
• Reaction bonded	304	44.1
• Sintered	304	44.1
Zirconia, 3 mol% Y_2O_3	205	30
POLYMERS		
Elastomers	0.0034^b	0.00049^b
• Butadiene-acrylonitrile (nitrile)		
• Styrene-butadiene (SBR)	$0.002\text{-}0.010^b$	$0.0003\text{-}0.0015^b$
Epoxy	2.41	0.35
Nylon 6,6	1.59-3.79	0.230-0.550
Phenolic	2.76-4.83	0.40-0.70
Polybutylene terephthalate (PBT)	1.93-3.00	0.280-0.435
Polycarbonate (PC)	2.38	0.345
Polyester (thermoset)	2.06-4.41	0.30-0.64
Polyetheretherketone (PEEK)	1.10	0.16
Polyethylene		
• Low density (LDPE)	0.172-0.282	0.025-0.041
• High density (HDPE)	1.08	0.157
• Ultrahigh molecular weight (UHMWPE)	0.69	0.100
Polyethylene terephthalate (PET)	2.76-4.14	0.40-0.60
Polymethyl methacrylate (PMMA)	2.24-3.24	0.325-0.470
Polypropylene (PP)	1.14-1.55	0.165-0.225
Polystyrene (PS)	2.28-3.28	0.330-0.475
Polytetrafluoroethylene (PTFE)	0.40-0.55	0.058-0.080
Polyvinyl chloride (PVC)	2.41-4.14	0.35-0.60
FIBER MATERIALS		
Aramid (Kevlar 49)	131	19
Carbon (PAN precursor)		
• Standard modulus	230	33.4
• Intermediate modulus	285	41.3

Table E.2 (finished)

1	2	3
• High modulus	400	58
E Glass	72.5	10.5
COMPOSITE MATERIALS		
Aramid fibers-epoxy matrix ($V_f = 0.60$)		
Longitudinal	76	11
Transverse	5.5	0.8
High modulus carbon fibers-epoxy matrix ($V_f = 0.60$)		
Longitudinal	220	32
Transverse	6.9	1.0
E glass fibers-epoxy matrix ($V_f = 0.60$)		
Longitudinal	45	6.5
Transverse	12	1.8
Wood		
• Douglas fir (12% moisture)		
Parallel to grain	10.8-13.6[c]	1.57-1.97[c]
Perpendicular to grain	0.54-0.68[c]	0.078-0.10[c]
• Red oak (12% moisture)		
Parallel to grain	11.0-14.1[c]	1.60-2.04[c]
Perpendicular to grain	0.55-0.71[c]	0.08-0.10[c]

[a] Secant modulus taken at 25% of ultimate strength.
[b] Modulus taken at 100% elongation.
[c] Measured in bending.

Table E.3 Poisson's Ratio Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Poisson's Ratio	Material	Poisson's Ratio
1	2	3	4
METALS AND METAL ALLOY **Plain Carbon and Low Alloy Steels**		**Refractory Metals**	
Steel alloy A36	0.30	Molybdenum (commercially pure)	0.32
Steel alloy 1020	0.30	Tantalum (commercially pure)	0.35
Steel alloy 1040	0.30		
Steel alloy 4140	0.30	Tungsten (commercially pure)	0.28
Steel alloy 4340	0.30		

Table E.3 (continued)

1	2	3	4
Stainless Steels		**Miscellaneous Nonferrous Alloys**	
Stainless alloy 304	0.30	Nickel 200	0.31
Stainless alloy 316	0.30	Inconel 625	0.31
Stainless alloy 405	0.30	Monel 400	0.32
Stainless alloy 440A	0.30	Chemical lead	0.44
Stainless alloy 17-7PH	0.30	Tin (commercially pure)	0.33
Cast Irons		Zinc (commercially pure)	0.25
Gray irons		Zirconium, reactor grade 702	0.35
• Grade G1800	0.26	**GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS**	
• Grade G3000	0.26		
• Grade G4000	0.26	Aluminum oxide	
Ductile irons		• 99.9% pure	0.22
• Grade 60-40-18	0.29	• 96%	0.21
• Grade 80-55-06	0.31	• 90%	0.22
• Grade 120-90-02	0.28	Concrete	0.20
Aluminum Alloys		Diamond	
Alloy 1100	0.33	• Natural	0.10-0.30
Alloy 2024	0.33		
Alloy 6061	0.33	• Synthetic	0.20
Alloy 7075	0.33	Gallium arsenide	
Alloy 356.0	0.33	• (100) orientation	0.30
Copper Alloys		Glass, borosilicate (Pyrex)	0.20
C11000 (electrolytic tough pitch)	0.33	Glass, soda-lime	0.23
		Glass ceramic (Pyroceram)	0.25
C17200 (beryllium-copper)	0.30	Silica, fused	0.17
C26000 (cartridge brass)	0.35	Silicon	
C36000 (free-cutting brass)	0.34	• (100) orientation	0.28
C71500 (copper-nickel, 30%)	0.34	• (111) orientation	0.36
C93200 (bearing bronze)	0.34	Silicon carbide	
Magnesium Alloys		• Hot pressed	0.17
Alloy AZ31B	0.35	• Sintered	0.16
Alloy AZ91D	0.35	Silicon nitride	
Titanium Alloys		• Hot pressed	0.30
Commercially pure (ASTM grade 1)	0.34	• Reaction bonded	0.22
		• Sintered	0.28
Alloy Ti-5Al-2.5Sn	0.34	Zirconia, 3 mol% Y_2O_3	0.31
Alloy Ti-6Al-4V	0.34	**POLYMERS**	

Table E.3 (finished)

1	2	3	4
Precious Metals		Nylon 6,6	0.39
Gold (commercially pure)	0.42	Polycarbonate (PC)	0.36
Platinum (commercially pure)	0.39	Polystyrene (PS)	0.33
Silver (commercially pure)	0.37	Polytetrafluoroethylene (PTFE)	0.46
COMPOSITE MATERIALS		Polyvinyl chloride (PVC)	0.38
Aramid fibers-epoxy matrix ($V_f = 0.6$)	0.34	**FIBER MATERIALS**	
		E Glass	0.22
High modulus carbon fibers-epoxy matrix ($V_f = 0.6$)	0.25	E glass fibers-epoxy matrix ($V_f = 0.6$)	0.19

Table E.4 Elastic and Shear Moduli, and Poisson's Ratio for Main Classes of Materials (Room-Temperature Conditions)

Material	Modulus of Elasticity		Shear Modulus		Poisson's Ratio
	GPa	10^6 psi	GPa	10^6 psi	
1	2	3	4	5	6
Metal Alloys					
Tungsten	407	59	160	23.2	0.28
Steel	207	30	83	12.0	0.30
Nickel	207	30	76	11.0	0.31
Titanium	107	15.5	45	6.5	0.34
Copper	110	16	46	6.7	0.34
Brass	97	14	37	5.4	0.34
Aluminum	69	10	25	3.6	0.33
Magnesium	45	6.5	17	2.5	0.35
Ceramic Materials					
Aluminum oxide (Al2O3)	393	57	—	—	0.22
Silicon carbide (SiC)	345	50	—	—	0.17
Silicon nitride (Si3N4)	304	44	—	—	0.30
Spinel (MgAl2O4)	260	38	—	—	—
Magnesium oxide (MgO)	225	33	—	—	0.18
Zirconiaa	205	30	—	—	0.31
Mullite (3Al2O3-2SiO2)	145	21	—	—	0.24

Table E.4 (finished)

1	2	3	4	5	6
Glass-ceramic (Pyroceram)	120	17	—	—	0.25
Fused silica (SiO2)	73	11	—	—	0.17
Soda-lime glass	69	10	—	—	0.23
Polymers					
Phenol-formaldehyde	2.76-4.83	0.40-0.70	—	—	—
Polyvinyl chloride (PVC)	2.41-4.14	0.35-0.60	—	—	0.38
Polyester (PET)	2.76-4.14	0.40-0.60	—	—	—
Polystyrene (PS)	2.28-3.28	0.33-0.48	—	—	0.33
Polymethyl methacrylate (PMMA)	24-3.24	0.33-0.47	—	—	—
Polycarbonate (PC)	2.38	0.35	—	—	0.36
Nylon 6,6	1.58-3.80	0.23-0.55	—	—	0.39
Polypropylene (PP)	1.14-1.55	0.17-0.23	—	—	—
Polyethylene – high density (HDPE)	1.08	0.16	—	—	—
Polytetrafluoroethylene (PTFE)	0.40-0.55	0.058-0.080	—	—	0.46
Polyethylene – low density (LDPE)	0.17-0.28	0.025-0.041	—	—	—

[a] Partially stabilized with 3 mol% Y_2O_3.

Table E.5 Yield Strength, Tensile Strength, and Ductility (Percent Elongation) Values for Main Classes Engineering Materials (Room-Temperature Conditions)

Material/ Condition	Yield Strength (MPa [ksi])	Tensile Strength (MPa [ksi])	Percent Elongation
1	2	3	4
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**			
Steel alloy A36			
• Hot rolled	220-250 (32-36)	400-500 (58-72.5)	23
Steel alloy 1020			
• Hot rolled	210 (30) (min)	380 (55) (min)	25 (min)
• Cold drawn	350 (51) (min)	420 (61) (min)	15 (min)

Table E.5 (continued)

1	2	3	4
• Annealed (@ 870°C)	295 (42.8)	395 (57.3)	36.5
• Normalized (@ 925°C)	345 (50.3)	440 (64)	38.5
Steel alloy 1040			
• Hot rolled	290 (42) (min)	520 (76) (min)	18 (min)
• Cold drawn	490 (71) (min)	590 (85) (min)	12 (min)
• Annealed (@ 785°C)	355 (51.3)	520 (75.3)	30.2
• Normalized (@ 900°C)	375 (54.3)	590 (85)	28.0
Steel alloy 4140			
• Annealed (@ 815°C)	417 (60.5)	655 (95)	25.7
• Normalized (@ 870°C)	655 (95)	1020 (148)	17.7
• Oil-quenched and tempered (@ 315°C)	1570 (228)	1720 (250)	11.5
Steel alloy 4340			
• Annealed (@ 810°C)	472 (68.5)	745 (108)	22
• Normalized (@ 870°C)	862 (125)	1280 (185.5)	12.2
• Oil-quenched and tempered (@ 315°C)	1620 (235)	1760 (255)	12
Stainless Steels			
Stainless alloy 304			
• Hot finished and annealed	205 (30) (min)	515 (75) (min)	40 (min)
• Cold worked (1/4 hard)	515 (75) (min)	860 (125) (min)	10 (min)
Stainless alloy 316			
• Hot finished and annealed	205 (30) (min)	515 (75) (min)	40 (min)
• Cold drawn and annealed	310 (45) (min)	620 (90) (min)	30 (min)
Stainless alloy 405			
• Annealed	170 (25)	415 (60)	20
Stainless alloy 440A			
• Annealed	415 (60)	725 (105)	20
• Tempered @ 315°C	1650 (240)	1790 (260)	5
Stainless alloy 17-7PH	1210 (175) (min)	1380 (200) (min)	1 (min)
• Cold rolle			
• Precipitation hardened @ 510°C	1310 (190) (min)	1450 (210) (min)	3.5 (min)
Cast Irons			
Gray irons			
• Grade G1800 (as cast)	—	124 (18) (min)	—
• Grade G3000 (as cast)	—	207 (30) (min)	—
• Grade G4000 (as cast)	—	276 (40) (min)	—

Table E.5 (continued)

1	2	3	4
Ductile irons			
• Grade 60-40-18 (annealed)	276 (40) (min)	414 (60) (min)	18 (min)
• Grade 80-55-06 (as cast)	379 (55) (min)	552 (80) (min)	6 (min)
• Grade 120-90-02 (oil quenched and tempered)	621 (90) (min)	827 (120) (min)	2 (min)
Aluminum Alloys			
Alloy 1100			
• Annealed (O temper)	34(5)	90 (13)	40
• Strain hardened (H14 temper)	117 (17)	124 (18)	15
Alloy 2024	75 (11)	185 (27)	20
• Annealed (O temper)			
• Heat treated and aged (T3 temper)	345 (50)	485 (70)	18
• Heat treated and aged (T351 temper)	325 (47)	470 (68)	20
Alloy 6061			
• Annealed (O temper)	55(8)	124 (18)	30
• Heat treated and aged (T6 and T651 tempers)	276 (40)	310 (45)	17
Alloy 7075			
• Annealed (O temper)	103 (15)	228 (33)	17
• Heat treated and aged (T6 temper)	505 (73)	572 (83)	11
Alloy 356.0			
• As cast	124 (18)	164 (24)	6
• Heat treated and aged (T6 temper)	164 (24)	228 (33)	3.5
Copper Alloys			
C11000 (electrolytic tough pitch)			
• Hot rolled	69 (10)	220 (32)	50
• Cold worked (H04 temper)	310 (45)	345 (50)	12
C17200 (beryllium-copper)			
• Solution heat treated	195-380 (28-55)	415-540 (60-78)	35-60
• Solution heat treated, aged @ 330°C	965-1205 (140-175)	1140-1310 (165-190)	4-10
C26000 (cartridge brass)			

Table E.5 (continued)

1	2	3	4
• Annealed	75-150 (11-22)	300-365 (43.5-53.0)	54-68
• Cold worked (H04 temper)	435 (63)	525 (76)	8
C36000 (free-cutting brass)			
• Annealed	125 (18)	340 (49)	53
• Cold worked (H02 temper)	310 (45)	400 (58)	25
C71500 (copper-nickel, 30%)			
• Hot rolled	140 (20)	380 (55)	45
• Cold worked (H80 temper)	545 (79)	580 (84)	3
C93200 (bearing bronze)	125 (18)	240 (35)	20
• Sand cast			
Magnesium Alloys			
Alloy AZ31B			
• Rolled	220 (32)	290 (42)	15
• Extruded	200 (29)	262 (38)	15
Alloy AZ91D			
• As cast	97-150 (14-22)	165-230 (24-33)	3
Titanium Alloys			
Commercially pure (ASTM grade 1)			
• Annealed	170 (25) (min)	240 (35) (min)	30
Alloy Ti-5Al-2.5Sn			
• Annealed	760 (110) (min)	790 (115) (min)	16
Alloy Ti-6Al-4V			
• Annealed	830 (120) (min)	900 (130) (min)	14
• Solution heat treated and aged	1103 (160)	1172 (170)	10
Precious Metals			
Gold (commercially pure)			
• Annealed	nil	130 (19)	45
• Cold worked (60% reduction)	205 (30)	220 (32)	4
Platinum (commercially pure)			
• Annealed	<13.8 (2)	125-165 (18-24)	30-40
• Cold worked (50%)	—	205-240 (30-35)	1-3
Silver (commercially pure)			
• Annealed	—	170 (24.6)	44
• Cold worked (50%)	—	296 (43)	3.5

Table E.5 (continued)

1	2	3	4
Refractory Metals			
Molybdenum (commercially pure)	500 (72.5)	630 (91)	25
Tantalum (commercially pure)	165 (24)	205 (30)	40
Tungsten (commercially pure)	760 (110)	960 (139)	2
Miscellaneous Nonferrous Alloys			
Nickel 200 (annealed)	148 (21.5)	462 (67)	47
Inconel 625 (annealed)	517 (75)	930 (135)	42.5
Monel 400 (annealed)	240 (35)	550 (80)	40
Haynes alloy 25	445 (65)	970 (141)	62
Invar (annealed)	276 (40)	517 (75)	30
Super invar (annealed)	276 (40)	483 (70)	30
Kovar (annealed)	276 (40)	517 (75)	30
Chemical lead	6-8 (0.9-1.2)	16-19 (2.3-2.7)	30-60
Antimonial lead (6%) (chill cast)	—	47.2 (6.8)	24
Tin (commercially pure)	11 (1.6)	—	57
Lead-Tin solder (60Sn-40Pb)	—	52.5 (7.6)	30-60
Zinc (commercially pure)			
• Hot rolled (anisotropic)	—	134-159 (19.4-23.0)	50-65
• Cold rolled (anisotropic)	—	145-186 (21-27)	40-50
Zirconium, reactor grade 702			
• Cold worked and annealed	207 (30) (min)	379 (55) (min)	16 (min)
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS[a]			
Aluminum oxide			
• 99.9% pure	—	282-551 (41-80)	—
• 96%	—	358 (52)	—
• 90%	—	337 (49)	—
Concreteb	—	37.3-41.3 (5.4-6.0)	—
Diamond			
• Natural	—	1050 (152)	—
• Synthetic	—	800-1400 (116-203)	—
Gallium arsenide			
• {100} orientation, polished surface	—	66 (9.6)c	—
• {100} orientation, as-cut surface	—	57 (8.3)c	—
Glass, borosilicate (Pyrex)	—	69 (10)	—

Table E.5 (continued)

1	2	3	4
Glass, soda-lime	—	69 (10)	—
Glass ceramic (Pyroceram)	—	123-370 (18-54)	—
Graphite			
• Extruded (with the grain direction)	—	13.8-34.5 (2.0-5.0)	—
• Isostatically molded	—	31-69 (4.5-10)	—
Silica, fused	—	104 (15)	—
Silicon			
• {100} orientation, as-cut surface	—	130 (18.9)	—
• {100} orientation, laser scribed	—	81.8 (11.9)	—
Silicon carbide			
• Hot pressed	—	230-825 (33-120)	—
• Sintered	—	96-520 (14-75)	—
Silicon nitride			
• Hot pressed	—	700-1000 (100-150)	—
• Reaction bonded	—	250-345 (36-50)	—
• Sintered	—	414-650 (60-94)	—
Zirconia, 3 mol% Y2O3 (sintered)	—	800-1500 (116-218)	—
POLYMERS			
Elastomers			
• Butadiene-acrylonitrile (nitrile)	—	6.9-24.1 (1.0-3.5)	400-600
• Styrene-butadiene (SBR)	—	12.4-20.7 (1.8-3.0)	450-500
• Silicone	—	10.3 (1.5)	100-800
Epoxy	—	27.6-90.0 (4.0-13)	3-6
Nylon 6,6			
• Dry, as molded	55.1-82.8 (8-12)	94.5 (13.7)	15-80
• 50% relative humidity	44.8-58.6 (6.5-8.5)	75.9 (11)	150-300
Phenolic	—	34.5-62.1 (5.0-9.0)	1.5-2.0
Polybutylene terephthalate (PBT)	56.6-60.0 (8.2-8.7)	56.6-60.0 (8.2-8.7)	50-300
Polycarbonate (PC)	62.1 (9)	62.8-72.4 (9.1-10.5)	110-150
Polyester (thermoset)	—	41.4-89.7 (6.0-13.0)	<2.6
Polyetheretherketone (PEEK)	91 (13.2)	70.3-103 (10.2-15.0)	30-150

Table E.5 (continued)

1	2	3	4
Polyethylene			
• Low density (LDPE)	9.0-14.5 (1.3-2.1)	8.3-31.4 (1.2-4.55)	100-650
• High density (HDPE)	26.2-33.1 (3.8-4.8)	22.1-31.0 (3.2-4.5)	10-1200
• Ultrahigh molecular weight (UHMWPE)	21.4-27.6 (3.1-4.0)	38.6-48.3 (5.6-7.0)	350-525
Polyethylene terephthalate (PET)	59.3 (8.6)	48.3-72.4 (7.0-10.5)	30-300
Polymethyl methacrylate (PMMA)	53.8-73.1 (7.8-10.6)	48.3-72.4 (7.0-10.5)	2.0-5.5
Polypropylene (PP)	31.0-37.2 (4.5-5.4)	31.0-41.4 (4.5-6.0)	100-600
Polystyrene (PS)	—	35.9-51.7 (5.2-7.5)	1.2-2.5
Polytetrafluoroethylene (PTFE)	—	20.7-34.5 (3.0-5.0)	200-400
Polyvinyl chloride (PVC)	40.7-44.8 (5.9-6.5)	40.7-51.7 (5.9-7.5)	40-80
FIBER MATERIALS			
Aramid (Kevlar 49)	—	3600-4100 (525-600)	2.8
Carbon (PAN precursor)			
• Standard modulus (longitudinal)	—	3800-4200 (550-610)	2
• Intermediate modulus (longitudinal)	—	4650-6350 (675-920)	1.8
• High modulus (longitudinal)	—	2500-4500 (360-650)	0.6
E Glass	—	3450 (500)	4.3
COMPOSITE MATERIALS			
Aramid fibers-epoxy matrix (aligned, $V_f = 0.6$)			
• Longitudinal direction	—	1380 (200)	1.8
• Transverse direction	—	30 (4.3)	0.5
High modulus carbon fibers-epoxy matrix (aligned, $V_f = 0.6$)			
• Longitudinal direction	—	760 (110)	0.3
• Transverse direction	—	28(4)	0.4

Table E.5 (finished)

1	2	3	4
E glass fibers-epoxy matrix (aligned, $V_f = 0.6$)			
• Longitudinal direction	—	1020 (150)	2.3
• Transverse direction	—	40 (5.8)	0.4
Wood			
• Douglas fir (12% moisture)	—		
Parallel to grain	—	108 (15.6)	—
Perpendicular to grain	—	2.4 (0.35)	—
• Red oak (12% moisture)			
Parallel to grain	—	112 (16.3)	_
Perpendicular to grain	—	7.2 (1.05)	—

[a] The strength of graphite, ceramics, and semiconducting materials is taken as flexural strength.
[b] The strength of concrete is measured in compression.
[c] Flexural strength value at 50% fracture probability.

Table E.6 Mechanical Properties (in Tension) for Main Classes of Materials (Room-Temperature Conditions)

Material	Yield Strength		Tensile Strength		Ductility, %EL [in 50 mm (2in.)][a]
	MPa	ksi	MPa	ksi	
1	2	3	4	5	6
Metal Alloys[b]					
Molybdenum	565	82	655	95	35
Titanium	450	65	520	75	25
Steel (1020)	180	26	380	55	25
Nickel	138	20	480	70	40
Iron	130	19	262	38	45
Brass (70 Cu-30 Zn)	75	11	300	44	68
Copper	69	10	200	29	45
Aluminum	35	5	90	13	40
Ceramic Materials[c]					
Zirconia (ZrO_2)[d]	—	—	800-1500	115-215	—
Silicon nitride (Si_3N_4)	—	—	250-1000	35-145	—
Aluminum oxide (Al2O3)	—	—	275-700	40-100	—
Silicon carbide (SiC)	—	—	100-820	15-120	—

Table E.6 (finished)

1	2	3	4	5	6
Glass-ceramic (Pyroceram)	—	—	247	36	—
Mullite ($3Al_2O_3$-$2SiO_2$)	—	—	185	27	—
Spinel ($MgAl_2O_4$)		—	110-245	16-36	—
Fused silica (SiO_2)		—	110	16	—
Magnesium oxide (MgO)[e]	—	—	105	15	—
Soda-lime glass	—	—	69	10	—
Polymers					
Nylon 6,6	44.8-82.8	6.5-12	75.9-94.5	11.0-13.7	15-300
Polycarbonate (PC)	62.1	9.0	62.8-72.4	9.1-10.5	110-150
Polyester (PET)	59.3	8.6	48.3-72.4	7.0-10.5	30-300
Polymethyl methacrylate (PMMA)	53.8-73.1	7.8-10.6	48.3-72.4	7.0-10.5	2.0-5.5
Polyvinyl chloride (PVC)	40.7-44.8	5.9-6.5	40.7-51.7	5.9-7.5	40-80
Phenol-formaldehyde	—	—	34.5-62.1	5.0-9.0	1.5-2.0
Polystyrene (PS)	—	—	35.9-51.7	5.2-7.5	1.2-2.5
Polypropylene (PP)	31.0-37.2	4.5-5.4	31.0-41.4	4.5-6.0	100-600
Polyethylene – high density (HDPE)	26.2-33.1	3.8-4.8	22.1-31.0	3.2-4.5	10-1200
Polytetrafluoroethylene (PTFE)	—	—	20.7-34.5	3.0-5.0	200-400
Polyethylene – low density (LDPE)	9.0-14.5	1.3-2.1	8.3-31.4	1.2-4.55	100-650

[a] For polymers, percent elongation at break.

[b] Property values are for metal alloys in an annealed state.

[c] The tensile strength of ceramic materials is taken as flexural strength.

[d] Partially stabilized with 3 mol% Y_2O_3.

[e] Sintered and containing approximately 5% porosity.

Table E.7 Plane Strain Fracture Toughness and Strength Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Fracture Toughness		Strength, MPa
	MPa$\sqrt{m}$	ksi$\sqrt{in}$	
1	2	3	4
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**			
Steel alloy 1040	54.0	49.0	260
Steel alloy 4140			

Table E.7 (continued)

1	2	3	4
• Tempered @ 370°C	55-65	50-59	1375-1585
• Tempered @ 482°C	75-93	68.3-84.6	1100-1200
Steel alloy 4340			
• Tempered @ 260°	50.0	45.8	1640
• Tempered @ 425°C	87.4	80.0	1420
Stainless Steels			
Stainless alloy 17-7PH			
• Precipitation hardened @ 510°C	76	69	1310
Aluminum Alloys			
Alloy 2024-T3	44	40	345
Alloy 7075-T651	24	22	495
Magnesium Alloys			
Alloy AZ31B			
• Extruded	28.0	25.5	200
Titanium Alloys			
Alloy Ti-5Al-2.5Sn			
• Air cooled	71.4	65.0	876
Alloy Ti-6Al-4V			
• Equiaxed grains	44-66	40-60	910
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS			
Aluminum oxide			
• 99.9% pure	4.2-5.9	3.8-5.4	282-551
• 96%	3.85-3.95	3.5-3.6	358
Concrete	0.2-1.4	0.18-1.27	—
Diamond			
• Natural	3.4	3.1	1050
• Synthetic	6.0-10.7	5.5-9.7	800-1400
Gallium arsenide			
• In the {100} orientation	0.43	0.39	66
• In the {110} orientation	0.31	0.28	—
• In the {111} orientation	0.45	0.41	—
Glass, borosilicate (Pyrex)	0.77	0.70	69
• Natural	3.4	3.1	1050
• Synthetic	6.0-10.7	5.5-9.7	800-1400
Gallium arsenide			
• In the {100} orientation	0.43	0.39	66
• In the {110} orientation	0.31	0.28	—

Table E.7 (finished)

1	2	3	4
• In the {111} orientation	0.45	0.41	—
• In the {100} orientation	0.43	0.39	66
• In the {110} orientation	0.31	0.28	—
• In the {111} orientation	0.45	0.41	—
Glass, borosilicate (Pyrex)	0.77	0.70	69
Glass, soda-lime	0.75	0.68	69
Glass ceramic (Pyroceram)	1.6-2.1	1.5-1.9	123-370
Silica, fused	0.79	0.72	104
Silicon			
• In the {100} orientation	0.95	0.86	
• In the {110} orientation	0.90	0.82	—
• In the {111} orientation	0.82	0.75	—
Silicon carbide			
• Hot pressed	4.8-6.1	4.4-5.6	230-825
• Sintered	4.8	4.4	96-520
Silicon nitride			
• Hot pressed	4.1-6.0	3.7-5.5	700-1000
• Reaction bonded	3.6	3.3	250-345
• Sintered	5.3	4.8	414-650
Zirconia, 3 mol% Y_2O_3	7.0-12.0	6.4-10.9	800-1500
POLYMERS			
Epoxy	0.6	0.55	—
Nylon 6,6	2.5-3.0	2.3-2.7	44.8-58.6
Polycarbonate (PC)	2.2	2.0	62.1
Polyester (thermoset)	0.6	0.55	—
Polyethylene terephthalate (PET)	5.0	4.6	59.3
Polymethyl methacrylate (PMMA	0.7-1.6	0.6-1.5	53.8-73.1
Polypropylene (PP)	3.0-4.5	2.7-4.1	31.0-37.2
Polystyrene (PS)	0.7-1.1	0.6-1.0	—
Polyvinyl chloride (PVC)	2.0-4.0	1.8-3.6	40.7-44.8

[a] For metal alloys and polymers, strength is taken as yield strength; for ceramic materials, flexural strength is used.

Table E.8 Linear Coefficient of Thermal Expansion Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Coefficient of Thermal Expansion	
	$10^{-6}(^{\circ}C)^{-1}$	$10^{-6}(^{\circ}F)^{-1}$
1	2	3
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**		
Steel alloy A36	11.7	6.5
Steel alloy 102	11.7	6.5
Steel alloy 1040	11.3	6.3
Steel alloy 4140	12.3	6.8
Steel alloy 4340	12.3	6.8
Stainless Steels		
Stainless alloy 304	17.2	9.6
Stainless alloy 316	15.9	8.8
Stainless alloy 405	10.8	6.0
Stainless alloy 440A	10.2	5.7
Stainless alloy 17-7PH	11.0	6.1
Cast Irons		
Gray irons		
• Grade G1800	11.4	6.3
• Grade G3000	11.4	6.3
• Grade G4000	11.4	6.3
Ductile irons		
• Grade 60-40-18	11.2	6.2
• Grade 80-55-06	10.6	5.9
Aluminum Alloys		
Alloy 1100	23.6	13.1
Alloy 2024	22.9	12.7
Alloy 6061	23.6	13.1
Alloy 7075	23.4	13.0
Alloy 356.0	21.5	11.9
Copper Alloys		
C11000 (electrolytic tough pitch)	17.0	9.4
C17200 (beryllium-copper)	16.7	9.3
C26000 (cartridge brass)	19.9	11.1
C36000 (free-cutting brass)	20.5	11.4
C71500 (copper-nickel, 30%)	16.2	9.0
C93200 (bearing bronze)	18.0	10.0

Table E.8 (continued)

1	2	3
Magnesium Alloys		
Alloy AZ31B	26.0	14.4
Alloy AZ91D	26.0	14.4
Titanium Alloys		
Commercially pure (ASTM grade 1)	8.6	4.8
Alloy Ti-5Al-2.5Sn	9.4	5.2
Alloy Ti-6Al-4V	8.6	4.8
Precious Metals		
Gold (commerically pure)	14.2	7.9
Platinum (commercially pure)	9.1	5.1
Silver (commercially pure)	19.7	10.9
Refractory Metals		
Molybdenum (commercially pure)	4.9	2.7
Tantalum (commercially pure)	6.5	3.6
Tungsten (commercially pure)	4.5	2.5
Miscellaneous Nonferrous Alloys		
Nickel 200	13.3	7.4
Inconel 625	12.8	7.1
Monel 400	13.9	7.7
Haynes alloy 25 Invar	12.3 1.6	6.8 0.9
Super invar	0.72	0.40
Kovar	5.1	2.8
Chemical lead	29.3	16.3
Antimonial lead (6%)	27.2	15.1
Tin (commercially pure)	23.8	13.2
Lead-Tin solder (60Sn-40Pb)	24.0	13.3
Zinc (commercially pure)	23.0-32.5	12.7-18.1
Zirconium, reactor grade 702	5.9	3.3
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS		
Aluminum oxide		
• 99.9% pure	7.4	4.1
• 96%	7.4	4.1
• 90%	7.0	3.9
Concrete	10.0-13.6	5.6-7.6
Diamond (natural)	0.11-1.23	0.06-0.68
Gallium arsenide	5.9	3.3
Glass, borosilicate (Pyrex)	3.3	1.8
Glass, soda-lime	9.0	5.0

Table E.8 (continued)

1	2	3
Glass ceramic (Pyroceram)	6.5	3.6
Graphite		
• Extruded	2.0-2.7	1.1-1.5
• Isostatically molded	2.2-6.0	1.2-3.3
Silica, fused	0.4	0.22
Silicon	2.5	1.4
Silicon carbide		
• Hot pressed	4.6	2.6
• Sintered	4.1	2.3
Silicon nitride		
• Hot pressed	2.7	1.5
• Reaction bonded	3.1	1.7
• Sintered	3.1	1.7
Zirconia, 3 mol% Y_2O_3	9.6	5.3
POLYMERS		
Elastomers		
• Butadiene-acrylonitrile (nitrile)	235	130
• Styrene-butadiene (SBR)	220	125
• Silicone	270	150
Epoxy	81-117	45-65
Nylon 6,6	144	80
Phenolic	122	68
Polybutylene terephthalate (PBT)	108-171	60-95
Polycarbonate (PC)	122	68
Polyester (thermoset)	100-180	55-100
Polyetheretherketone (PEEK)	72-85	40-47
Polyethylene		
• Low density (LDPE)	180-400	100-220
• High density (HDPE)	106-198	59-110
• Ultrahigh molecular weight (UHMWPE)	234-360	130-200
Polyethylene terephthalate (PET)	117	65
Polymethyl methacrylate (PMMA)	90-162	50-90
Polypropylene (PP)	146-180	81-100
Polystyrene (PS)	90-150	50-83

Table E.8 (finished)

1	2	3
Polytetrafluoroethylene (PTFE)	126-216	70-120
Polyvinyl chloride (PVC)	90-180	50-100
FIBER MATERIALS		
Aramid (Kevlar 49)		
• Longitudinal direction	-2.0	-1.1
• Transverse direction	60	33
Carbon (PAN precursor)		
• Standard modulus		
Longitudinal direction	-0.6	-0.3
Transverse direction	10.0	5.6
• Intermediate modulus		
Longitudinal direction	-0.6	-0.3
• High modulus		
Longitudinal direction	-0.5	-0.28
Transverse direction	7.0	3.9
E Glass	5.0	2.8
COMPOSITE MATERIALS		
Aramid fibers-epoxy matrix ($V_f = 0.6$)		
• Longitudinal direction	-4.0	-2.2
• Transverse direction	70	40
High modulus carbon fibers-epoxy matrix ($V_f = 0.6$)		
• Longitudinal direction	-0.5	-0.3
• Transverse direction	32	18
E glass fibers-epoxy matrix ($V_f = 0.6$)		
• Longitudinal direction	6.6	3.7
• Transverse direction	30	16.7
Wood		
• Douglas fir (12% moisture)		
Parallel to grain	3.8-5.1	2.2-2.8
Perpendicular to grain	25.4-33.8	14.1-18.8
• Red oak (12% moisture)		
Parallel to grain	4.6-5.9	2.6-3.3
Perpendicular to grain	30.6-39.1	17.0-21.7

Table E.9 Thermal Conductivity Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Thermal Conductivity	
	W/m-K	Btu/ft-h-°F
1	2	3
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**		
Steel alloy A36	51.9	30
Steel alloy 1020	51.9	30
Steel alloy 1040	51.9	30
Stainless Steels		
Stainless alloy 304 (annealed)	16.2	9.4
Stainless alloy 316 (annealed)	16.2	9.4
Stainless alloy 405 (annealed)	27.0	15.6
Stainless alloy 440A (annealed)	24.2	14.0
Stainless alloy 17-7PH (annealed)	16.4	9.5
Cast Irons		
Gray irons		
• Grade G1800	46.0	26.6
• Grade G3000	46.0	26.6
• Grade G4000	46.0	26.6
Ductile irons		
• Grade 60-40-18	36.0	20.8
• Grade 80-55-06	36.0	20.8
• Grade 120-90-02	36.0	20.8
Aluminum Alloys		
Alloy 1100 (annealed)	222	128
Alloy 2024 (annealed)	190	110
Alloy 6061 (annealed)	180	104
Alloy 7075-T6	130	75
Alloy 356.0-T6	151	87
Copper Alloys		
C11000 (electrolytic tough pitch)	388	224
C17200 (beryllium-copper)	105-130	60-75
C26000 (cartridge brass)	120	70
C36000 (free-cutting brass)	115	67
C71500 (copper-nickel, 30%)	29	16.8
C93200 (bearing bronze)	59	34
Magnesium Alloys		
Alloy AZ31B	96[a]	55[a]

Table E.9 (continued)

1	2	3
Alloy AZ91D	72[a]	43[a]
Titanium Alloys		
Commercially pure (ASTM grade 1)	16	9.2
Alloy Ti-5Al-2.5Sn	7.6	4.4
Alloy Ti-6Al-4V	6.7	3.9
Precious Metals		
Gold (commercially pure)	315	182
Platinum (commercially pure)	71[b]	41[b]
Silver (commercially pure)	428	247
Refractory Metals		
Molybdenum (commercially pure)	142	82
Tantalum (commercially pure)	54.4	31.4
Tungsten (commercially pure)	155	89.4
Miscellaneous Nonferrous Alloys		
Nickel 200	70	40.5
Inconel 625	9.8	5.7
Monel 400	21.8	12.6
Haynes alloy 25	9.8	5.7
Invar	10	5.8
Super invar	10	5.8
Kovar	17	9.8
Chemical lead	35	20.2
Antimonial lead (6%)	29	16.8
Tin (commercially pure)	60.7	35.1
Lead-Tin solder (60Sn-40Pb)	50	28.9
Zinc (commercially pure)	108	62
Zirconium, reactor grade 702	22	12.7
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS		
Aluminum oxide		
• 99.9% pure	39	22.5
• 96%	35	20
• 90%	16	9.2
Concrete	1.25-1.75	0.72-1.0
Diamond		
• Natural	1450-4650	840-2700
• Synthetic	3150	1820
Gallium arsenide	45.5	26.3
Glass, borosilicate (Pyrex)	1.4	0.81

Table E.9 (continued)

1	2	3
Glass, soda-lime	1.7	1.0
Glass ceramic (Pyroceram)	3.3	1.9
Graphite		
• Extruded	130-190	75-110
• Isostatically molded	104-130	60-75
Silica, fused	1.4	0.81
Silicon	141	82
Silicon carbide		
• Hot pressed	80	46.2
• Sintered	71	41
Silicon nitride		
• Hot pressed	29	17
• Reaction bonded	10	6
• Sintered	33	19.1
Zirconia, 3 mol% Y_2O_3	2.0-3.3	1.2-1.9
POLYMERS		
Elastomers		
• Butadiene-acrylonitrile (nitrile)	0.25	0.14
• Styrene-butadiene (SBR)	0.25	0.14
• Silicone	0.23	0.13
Epoxy	0.19	0.11
Nylon 6,6	0.24	0.14
Phenolic	0.15	0.087
Polybutylene terephthalate (PBT)	0.18-0.29	0.10-0.17
Polycarbonate (PC)	0.20	0.12
Polyester (thermoset)	0.17	0.10
Polyethylene		
• Low density (LDPE)	0.33	0.19
• High density (HDPE)	0.48	0.28
• Ultrahigh molecular weight (UHMWPE)	0.33	0.19
Polyethylene terephthalate (PET)	0.15	0.087
Polymethyl methacrylate (PMMA)	0.17-0.25	0.10-0.15
Polypropylene (PP)	0.12	0.069
Polystyrene (PS)	0.13	0.075
Polytetrafluoroethylene (PTFE)	0.25	0.14
Polyvinyl chloride (PVC)	0.15-0.21	0.08-0.12
FIBER MATERIALS		
Carbon (PAN precursor), longitudinal		

Table E.9 (finished)

1	2	3
• Standard modulus	11	6.4
• Intermediate modulus	15	8.7
• High modulus	70	40
E Glass	1.3	0.75
COMPOSITE MATERIALS		
Wood		
• Douglas fir (12% moisture)		
Perpendicular to grain	0.14	0.08
• Red oak (12% moisture)	0.18	0.11
Perpendicular to grain		

[a] At 100°C.
[b] At 0°C.

Table E.10 Specific Heat Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Specific Heat	
	J/kg-K	10^{-2}Btu/lb$_m$-°F
1	2	3
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**		
Steel alloy A36	486[a]	11.6[a]
Steel alloy 1020	486[a]	11.6[a]
Steel alloy 1040	486[a]	11.6[a]
Stainless Steels		
Stainless alloy 304	500	12.0
Stainless alloy 316	500	12.0
Stainless alloy 405	460	11.0
Stainless alloy 440A	460	11.0
Stainless alloy 17-7PH	460	11.0
Cast Irons		
Gray irons		
• Grade G1800	544	13
• Grade G3000	544	13
• Grade G4000	544	13
Ductile irons		
• Grade 60-40-18	544	13

Table E.10 (continued)

1	2	3
• Grade 80-55-06	544	13
• Grade 120-90-02	544	13
Aluminum Alloys		
Alloy 1100	904	21.6
Alloy 2024	875	20.9
Alloy 6061	896	21.4
Alloy 7075	960[b]	23.0[b]
Alloy 356.0	963[b]	23.0[b]
Copper Alloys		
C11000 (electrolytic tough pitch)	385	9.2
C17200 (beryllium-copper)	420	10.0
C26000 (cartridge brass)	375	9.0
C36000 (free-cutting brass)	380	9.1
C71500 (copper-nickel, 30%)	380	9.1
C93200 (bearing bronze)	376	9.0
Magnesium Alloys		
Alloy AZ31B	1024	24.5
Alloy AZ91D	1050	25.1
Titanium Alloys		
Commercially pure (ASTM grade 1)	528[c]	12.6[c]
Alloy Ti-5Al-2.5Sn	470[c]	11.2[c]
Alloy Ti-6Al-4V	610[c]	14.6[c]
Precicious Metals		
Gold (commercially pure)	130	3.1
Platinum (commercially pure)	132[d]	32[d]
Silver (commercially pure)	235	5.6
Refractory Metals		
Molybdenum (commercially pure)	276	6.6
Tantalum (commercially pure)	139	3.3
Tungsten (commercially pure)	138	3.3
Miscellaneous Nonferrous Alloys		
Nickel 200	456	10.9
Inconel 625	410	9.8
Monel 400	427	10.2
Haynes alloy 25	377	9.0
Invar	500	12.0
Super invar	500	12.0
Kovar	460	11.0

Table E.10 (continued)

1	2	3
Chemical lead	129	3.1
Antimonial lead (6%)	135	3.2
Tin (commercially pure)	222	5.3
Lead-Tin solder (60Sn-40Pb)	150	3.6
Zinc (commercially pure)	395	9.4
Zirconium, reactor grade 702	285	6.8
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS		
Aluminum oxide		
• 99.9% pure	775	18.5
• 96%	775	18.5
• 90%	775	18.5
Concrete	850-1150	20.3-27.5
Diamond (natural)	520	12.4
Gallium arsenide	350	8.4
Glass, borosilicate (Pyrex)	850	20.3
Glass, soda-lime	840	20.0
Glass ceramic (Pyroceram)	975	23.3
Graphite		
• Extruded	830	19.8
• Isostatically molded	830	19.8
Silica, fused	740	17.7
Silicon	700	16.7
Silicon carbide		
• Hot pressed	670	16.0
• Sintered	590	14.1
Silicon nitride		
• Hot pressed	750	17.9
• Reaction bonded	870	20.7
• Sintered	1100	26.3
Zirconia, 3 mol% Y_2O_3	481	11.5
POLYMERS		
Epoxy	1050	25
Nylon 6,6	1670	40
Phenolic	1590-1760	38-42
Polybutylene terephthalate (PBT)	1170-2300	28-55
Polycarbonate (PC)	840	20
Polyester (thermoset)	710-920	17-22
Polyethylene		

Table E.10 (finished)

1	2	3
• Low density (LDPE)	2300	55
• High density (HDPE)	1850	44.2
Polyethylene terephthalate (PET)	1170	28
Polymethyl methacrylate (PMMA)	1460	35
Polypropylene (PP)	1925	46
Polystyrene (PS)	1170	28
Polytetrafluoroethylene (PTFE)	1050	25
Polyvinyl chloride (PVC)	1050-1460	25-35
FIBER MATERIALS		
Aramid (Kevlar 49)	1300	31
E Glass	810	19.3
COMPOSITE MATERIALS		
Wood		
• Douglas fir (12% moisture)	2900	69.3
• Red oak (12% moisture)	2900	69.3

[a] At temperatures between 50UC and 100°C.
[b] At 100°C.
[c] At 50°C.
[d] At 0°C.

Table E.11 Electrical Resistivity Values for Various Engineering Materials (Room-Temperature Conditions)

Material	Electrical Resistivity, Ω-m
1	2
METALS AND METAL ALLOYS **Plain Carbon and Low Alloy Steels**	
Steel alloy A36[a]	1.60×10^{-7}
Steel alloy 1020 (annealed)[a]	1.60×10^{-7}
Steel alloy 1040 (annealed)[a]	1.60×10^{-7}
Steel alloy 4140 (quenched and tempered)	2.20×10^{-7}
Steel alloy 4340 (quenched and tempered)	2.48×10^{-7}
Stainless Steels	
Stainless alloy 304 (annealed)	7.2×10^{-7}
Stainless alloy 316 (annealed)	7.4×10^{-7}
Stainless alloy 405 (annealed)	6.0×10^{-7}
Stainless alloy 440A (annealed)	6.0×10^{-7}

Table E.11 (continued)

1	2
Stainless alloy 17-7PH (annealed)	8.3×10^{-7}
Cast Irons	
Gray irons	
• Grade G1800	15.0×10^{-7}
• Grade G3000	9.5×10^{-7}
• Grade G4000	8.5×10^{-7}
Ductile irons	
• Grade 60-40-18	5.5×10^{-7}
• Grade 80-55-06	6.2×10^{-7}
• Grade 120-90-02	6.2×10^{-7}
Aluminum Alloys	
Alloy 1100 (annealed)	2.9×10^{-8}
Alloy 2024 (annealed)	3.4×10^{-8}
Alloy 6061 (annealed)	3.7×10^{-8}
Alloy 7075 (T6 treatment)	5.22×10^{-8}
Alloy 356.0 (T6 treatment)	4.42×10^{-8}
Copper Alloys	
C11000 (electrolytic tough pitch, annealed)	1.72×10^{-8}
C172000 (beryllium-copper)	5.7×10^{-8}-1.15×10^{-7}
C26000 (cartridge brass)	6.2×10^{-8}
C36000 (free-cutting brass)	6.6×10^{-8}
C71500 (copper-nickel, 30%)	37.5×10^{-8}
C93200 (bearing bronze)	14.4×10^{-8}
Magnesium Alloys	
Alloy AZ31B	9.2×10^{-8}
Alloy AZ91D	17.0×10^{-8}
Titanium Alloys	
Commercially pure (ASTM grade 1)	4.2×10^{-7}-5.2×10^{-7}
Alloy Ti-5Al-2.5Sn	15.7×10^{-7}
Alloy Ti-6Al-4V	17.1×10^{-7}
Precious Metals	
Gold (commercially pure)	2.35×10^{-8}
Platinum (commercially pure)	10.60×10^{-8}
Silver (commercially pure)	1.47×10^{-8}
Refractory Metals	
Molybdenum (commercially pure)	5.2×10^{-8}

Table E.11 (continued)

1	2
Tantalum (commercially pure)	13.5×10^{-8}
Tungsten (commercially pure)	5.3×10^{-8}
Miscellaneous Nonferrous Alloys	
Nickel 200	0.95×10^{-7}
Inconel 625	12.90×10^{-7}
Monel 400	5.47×10^{-7}
Haynes alloy 25	8.9×10^{-7}
Invar	8.2×10^{-7}
Super invar	8.0×10^{-7}
Kovar	4.9×10^{-7}
Chemical lead	2.06×10^{-7}
Antimonial lead (6%)	2.53×10^{-7}
Tin (commercially pure)	1.11×10^{-7}
Lead-Tin solder (60Sn-40Pb)	1.50×10^{-7}
Zinc (commercially pure)	62.0×10^{-7}
Zirconium, reactor grade 702	3.97×10^{-7}
GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS	
Aluminum oxide	
• 99.9% pure	$>10^{13}$
• 96%	$>10^{12}$
• 90%	$>10^{12}$
Concrete (dry)	10^{9}
Diamond	
• Natural	$10\text{-}10^{14}$
• Synthetic	1.5×10^{-2}
Gallium arsenide (intrinsic)	10^{6}
Glass, borosilicate (Pyrex)	$\sim 10^{13}$
Glass, soda-lime	$10^{10}\text{-}10^{11}$
Glass ceramic (Pyroceram)	2×10^{14}
Graphite	
• Extruded (with grain direction)	$7 \times 10^{-6}\text{-}20 \times 10^{-6}$
• Isostatically molded	$10 \times 10^{-6}\text{-}18 \times 10^{-6}$
Silica, fused	$>10^{18}$
Silicon (intrinsic)	2500
Silicon carbide	
• Hot pressed	$1.0\text{-}10^{9}$
• Sintered	$1.0\text{-}10^{9}$

Table E.11 (continued)

1	2
Silicon nitride	
• Hot isostatic pressed	$>10^{12}$
• Reaction bonded	$>10^{12}$
• Sintered	$>10^{12}$
Zirconia, 3 mol% Y2O3	10^{10}
POLYMERS	
Elastomers	
• Butadiene-acrylonitrile (nitrile)	3.5×10^{8}
• Styrene-butadiene (SBR)	6×10^{11}
• Silicone	10^{13}
Epoxy	10^{10}-10^{13}
Nylon 6,6	10^{12}-10^{13}
Phenolic	10^{9}-10^{10}
Polybutylene terephthalate (PBT)	4×10^{14}
Polycarbonate (PC)	2×10^{14}
Polyester (thermoset)	10^{13}
Polyetheretherketone (PEEK)	6×10^{14}
Polyethylene	
• Low density (LDPE)	10^{15}-5×10^{16}
• High density (HDPE)	10^{15}-5×10^{16}
• Ultrahigh molecular weight (UHMWPE)	$>5 \times 10^{14}$
Polyethylene terephthalate (PET)	10^{12}
Polymethyl methacrylate (PMMA)	$>10^{12}$
Polypropylene (PP)	$>10^{14}$
Polystyrene (PS)	$>10^{14}$
Polytetrafluoroethylene (PTFE)	10^{17}
Polyvinyl chloride (PVC)	$>10^{14}$
FIBER MATERIALS	
Carbon (PAN precursor)	
• Standard modulus	17×10^{-6}
• Intermediate modulus	15×10^{-6}
• High modulus	9.5×10^{-6}
E Glass	4×10^{14}
COMPOSITE MATERIALS	
Wood	
• Douglas fir (oven dry)	
Parallel to grain	10^{14}-10^{16}

Table E.11 (finished)

1	2
Perpendicular to grain	10^{14}-10^{16}
• Red oak (oven dry)	
Parallel to grain	10^{14}-10^{16}
Perpendicular to grain	10^{14}-10^{16}

[a] At 0°C.

Table E.12 Compositions of Metal Alloys for Which Data Are Included in Tables E.1–E.11

Alloy (UNS Designation)	Composition (wt%)
1	2
PLAIN-CARBON AND LOW-ALLOY STEELS	
A 36 (ASTM A 36)	98.0 Fe (min), 0.29 C, 1.0 Mn, 0.28 Si
1020 (G10200)	99.1 Fe (min), 0.20 C, 0.45 Mn
1040 (G10400)	98.6 Fe (min), 0.40 C, 0.75 Mn
4140 (G41400)	96.8 Fe (min), 0.40 C, 0.90 Cr, 0.20 Mo, 0.9 Mn
4340 (G43400)	95.2 Fe (min), 0.40 C, 1.8 Ni, 0.80 Cr, 0.25 Mo, 0.7 Mn
STAINLESS STEELS	
304 (S30400)	66.4 Fe (min), 0.08 C, 19.0 Cr, 9.25 Ni, 2.0 Mn
316 (S31600)	61.9 Fe (min), 0.08 C, 17.0 Cr, 12.0 Ni, 2.5 Mo, 2.0 Mn
405 (S40500)	83.1 Fe (min), 0.08 C, 13.0 Cr, 0.20 Al, 1.0 Mn
440A (S44002)	78.4 Fe (min), 0.70 C, 17.0 Cr, 0.75 Mo. 1.0 Mn
17-7PH (S17700)	70.6 Fe (min), 0.09 C, 17.0 Cr, 7.1 Ni, 1.1 Al, 1.0 Mn
CAST IRONS	
Grade G1800 (F10004)	Fe (bal), 3.4-3.7 C, 2.8-2.3 Si, 0.65 Mn, 0.15 P, 0.15 S
Grade G3000 (F10006)	Fe (bal), 3.1-3.4 C, 2.3-1.9 Si, 0.75 Mn, 0.10 P, 0.15 S
Grade G4000 (F10008)	Fe (bal), 3.0-3.3 C, 2.1-1.8 Si, 0.85 Mn, 0.07 P, 0.15 S
Grade 60-40-18 (F32800)	Fe (bal), 3.4-4.0 C, 2.0-2.8 Si, 0-1.0 Ni, 0.05 Mg
Grade 80-55-06 (F33800)	Fe (bal), 3.3-3.8 C, 2.0-3.0 Si, 0-1.0 Ni, 0.05 Mg
Grade 120-90-02 (F36200)	Fe (bal), 3.4-3.8 C, 2.0-2.8 Si, 0-2.5 Ni, 0-1.0 Mo, 0.05 Mg
ALUMINUM ALLOYS	
1100 (A91100)	99.00 Al (min), 0.20 Cu (max)
2024 (A92024)	90.75 Al (min), 4.4 Cu, 0.6 Mn, 1.5 Mg
6061 (A96061)	95.85 Al (min), 1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr

Table E.12 (finished)

1	2
7075 (A97075)	87.2 Al (min), 5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr
356.0 (A03560)	90.1 Al (min), 7.0 Si, 0.3 Mg
COPPER ALLOYS	
(C11000)	99.90 Cu (min), 0.04 O (max)
(C17200)	96.7 Cu (min), 1.9 Be, 0.20 Co
(C26000)	Zn (bal), 70 Cu, 0.07 Pb, 0.05 Fe (max)
(C36000)	60.0 Cu (min), 35.5 Zn, 3.0 Pb
(C71500)	63.75 Cu (min), 30.0 Ni
(C93200)	81.0 Cu (min), 7.0 Sn, 7.0 Pb, 3.0 Zn
MAGNESIUM ALLOYS	
AZ31B (M11311)	94.4 Mg (min), 3.0 Al, 0.20 Mn (min), 1.0 Zn, 0.1 Si (max)
AZ91D (M11916)	89.0 Mg (min), 9.0 Al, 0.13 Mn (min), 0.7 Zn, 0.1 Si (max)
TITANIUM ALLOYS	
Commercial, grade 1 (R50250)	99.5 Ti (min)
Ti-5Al-2.5Sn (R54520)	90.2 Ti (min), 5.0 Al, 2.5 Sn
Ti-6A1-4V (R56400)	87.7 Ti (min), 6.0 Al, 4.0 V
MISCELLANEOUS ALLOYS	
Nickel 200	99.0 Ni (min)
Inconel 625	58.0 Ni (min), 21.5 Cr, 9.0 Mo, 5.0 Fe, 3.65 Nb + Ta, 1.0 Co
Monel 400	63.0 Ni (min), 31.0 Cu, 2.5 Fe, 0.2 Mn, 0.3 C, 0.5 Si
Haynes alloy 25	49.4 Co (min), 20 Cr, 15 W, 10 Ni, 3 Fe (max), 0.10 C, 1.5 Mn
Invar (K93601)	64 Fe, 36 Ni
Super invar	63 Fe, 32 Ni, 5 Co
Kovar	54 Fe, 29 Ni, 17 Co
Chemical lead (L51120)	99.90 Pb (min)
Antimonial lead, 6% (L53105)	94 Pb, 6 Sb
Tin (commercially pure) (ASTM B339A)	98.85 Pb (min)
Lead-Tin solder (60Sn-40Pb) (ASTM B32 grade 60)	60 Sn, 40 Pb
Zinc (commercially pure) (Z21210)	99.9 Zn (min), 0.10 Pb (max)
Zirconium, reactor grade 702 (R60702)	99.2 Zr + Hf (min), 4.5 Hf (max), 0.2 Fe + Cr

Table E.13 Glass Transition and Melting Temperatures for Common Polymeric Materials

Polymer	Glass Transition Temperature, °C(°F)	Melting Temperature, °C(°F)
Aramid	375 (705)	-640 (-1185)
Polyimide (thermoplastic)	280-330 (535-625)	*a*
Polyamide-imide	277-289 (530-550)	*a*
Polycarbonate	150 (300)	265 (510)
Polyetheretherketone	143 (290)	334 (635)
Polyacrylonitrile	104 (220)	317 (600)
Polystyrene		
• Atactic	100 (212)	*a*
• Isotactic	100 (212)	240 (465)
Polybutylene terephthalate	—	220-267 (428-513)
Polyvinyl chloride	87 (190)	212 (415)
Polyphenylene sulfide	85 (185)	285 (545)
Polyethylene terephthalate	69 (155)	265 (510)
Nylon 6,6	57 (135)	265 (509)
Polymethyl methacrylate		
• Syndiotactic	3(35)	105 (220)
• Isotactic	3(35)	45 (115)
Polypropylene		
• Isotactic	-10 (15)	175 (347)
• Atactic	-18 (0)	175 (347)
Polyvinylidene chloride	-17 (1)	198 (390)
• Atactic	-18 (0)	175 (347)
Polyvinyl fluoride	-20 (-5)	200 (390)
Polyvinylidene fluoride	-35 (-30)	—
Polychloroprene (chloroprene rubber or neoprene)	-50 (-60)	80 (175)
Polyisobutylene	-70 (-95)	128 (260)
cis-Polyisoprene	-73 (-100)	28 (80)
Polybutadiene		
• Syndiotactic	-90 (-130)	154 (310)
• Isotactic	-90 (-130)	120 (250)
High density polyethylene	-90 (-130)	137 (279)
Polytetrafluoroethylene	-97 (-140)	327 (620)
Low density polyethylene	-110 (-165)	115 (240)
Polydimethylsiloxane (silicone rubber)	-123 (-190)	-54 (-65)

[a] These polymers normally exist at least 95% noncrystalline.

Appendix F Unified Numbering System

Unified numbering system (UNS) is a system of designations established in accordance with ASTM E527 and SAE J1086, Recommended Practice for Numbering Metals and Alloys. Its purpose is to provide means of correlating systems in use by such organizations as American Society for Testing Materials (ASTM) and Aluminum Association (AA), as well as individual users and producers over the world.

The UNS designation assignments for certain metals and alloys are established by the relevant trade associations which in the past have administered their own numbering systems; for other metals and alloys, UNS designation assignments are administered by the Society of Automotive Engineers (SAE). Each of these assigners has the responsibility for administering a specific UNS series of designations. Each considers requests for the assignment of new UNS designations, and informs the applicants of the action taken. UNS designation assigners report immediately to the office of the Unified Numbering System for Metals and Alloys the details of each new assignment for inclusion into the system.

The UNS number is not in itself a specification, since it establishes no requirements for form, condition, quality, etc. It is a unified identification of metals and alloys for which controlling limits have been established in specifications published elsewhere.

This designation system establishes 9 series of designations for nonferrous metals and alloys. Each UNS designation consists of a single-letter prefix followed by five digits. In most cases the letter is suggestive of the family of metals identified: for example, **A** – for aluminum, **C** – Copper and Copper Alloys, **Z** – Zinc and Zinc Alloys, etc.

The UNS establishes 9 series of designations for ferrous metals and alloys. Each UNS designation consists of a single-letter prefix followed by five digits. In most cases the letter is suggestive of the family of metals identified: for example, **F** for cast irons, **T** for tool steel, **S** for stainless steels.

Although some of the digits in certain UNS designation groups have special assigned meanings, each series of UNS designations is independent of the others in regard to the significance of digits, thus permitting greater flexibility and avoiding complicated and lengthy UNS designations.

Wherever feasible, and for the convenience of the user, identification "numbers" from existing systems are incorporated into the UNS designations. For example, carbon steel presently identified by the American Iron and Steel Institute as "AISI 1020" is covered by the UNS designation "G10200".

The Unified Numbering System for Metals and Alloys (UNS) provides means of correlating many internationally used metal and alloy numbering systems currently administered by societies, trade associations, and those individual users and producers of metals and alloys. This system avoids the confusion caused by the use of more than one identification number for the same metal or alloy, and the opposite situation of having the same number assigned to two or more different metals or alloys. It provides the uniformity necessary for efficient indexing, record keeping, data storage and retrieval, and cross-referencing.

The listed cross-referenced specifications are representative only and are not necessarily a complete list of specifications applicable to a particular UNS designation.

Table F.1 Description of Numbers (or Codes) Established for Nonferrous Metals and Alloys

A00001-A99999	**Aluminum and aluminum alloys**
A01001-A63562	Aluminum Foundry Alloys, Ingot or Casting
A82014-A87475	Wrought Aluminum Alloys Clad with Wrought Aluminum Alloys, Non- or Heat Treatable
A91030-A91450	Wrought Aluminum Alloys, Non- Heat Treatable
A93002-A95954	Wrought Aluminum Alloys, Non- Heat Treatable
A98001-A98280	Wrought Aluminum Alloys, Non- Heat Treatable
A92001-A92618	Wrought Aluminum Alloys, Heat Treatable
A96002-A97472	Wrought Aluminum Alloys, Heat Treatable
C00001-C99999	**Copper and copper alloys**
Wrought Alloys	
C10100-C15760	Pure and Low Alloyed Copper (>99%Cu)
C16200-C16500	Cadmium Copper
C17000-C17700	Copper-Beryllium Alloy (Beryllium Bronzes)
C18000-C19900	Copper and High Copper Alloys (>96%Cu)
C20500-C29800	Brasses (Cu-Zn)
C31000-C35600	Leaded Brasses (Cu-Zn-Pb)
C40400-C49080	Tin Brasses (Cu-Zn-Sn-Pb)
C50100-C52900	Phosphor bronzes (Cu-Sn-P)
C53200-C54800	Leaded Phosphor Bronzes
C55180-C56000	Cu-Ag-P and Cu-P Brazing Filler Metal
C60600-C64400	Aluminum Bronzes
C64700-C66100	Silicon Bronzes
C66200-C66420	Copper Alloys
C66700-C67820	Manganese Bronzes
C68000-C69950	Silicon Brasses and Other Copper-Zinc Alloys
C70100-C72950	Copper-Nickel Alloys
C73150-C79900	Nickel Silvers and Leaded Nickel Silvers

Table F.1 (continued)

Cast alloys	
C80100-C81200	Cast Coppers (>99%Cu)
C81300-C82800	Cast Chromium Copper and Beryllium Copper Alloys (>96%Cu)
C83300-C85800	Cast Red, Yellow and Leaded Brasses
C86100-C86800	Cast Manganese Bronzes and Leaded Manganese Bronzes
C87300-C87900	Cast Silicon Brasses and Bronzes
C89320-C89940	Cast Cu-Sn-Bi-(Se, Zn, Ni) Alloys
C90200-C94500	Tin Bronzes and Leaded Tin Bronzes
C94700-C94900	Cast Nickel-Tin Bronzes
C95200-C95810	Cast Aluminum Bronzes
C96200-C96800	Cast Copper-Nickel Alloys
C97300-C97800	Cast Nickel-Silver Alloys
C98200-C98840	Cast Leaded Copper Alloys
C99300-C99750	Cast Copper Alloys
E00001-E99999	**Rare earth and rare earth-like metals and alloys**
E00000-E00999	Actinium
EO1000-E20999	Cerium
E21000-E45999	Mixed rare earths
E46000-E47999	Dysprosium
E48000-E49999	Erbium
E50000-E51999	Europium
E52000-E55999	Gadolinium
E56000-E57999	Holmium
E58000-E67999	Lanthanum
E68000-E68999	Lutetium
E69000-E73999	Neodymium
E74000-E77999	Praseodymium
E78000-E78999	Promethium
E79000-E82999	Samarium
E83000-E84999	Scandium
E85000-E86999	Terbium
E87000-E87999	Thulium
E88000-E89999	Ytterbium
E90000-E99999	Yttrium
L00001-L99999	**Low-melting metals and alloys**
L00001-L00999	Bismuth
L01001-L01999	Cadmium
L02001-L02999	Cesium

Table F.1 (continued)

L01001-L01999	Cadmium
L02001-L02999	Cesium
L03001-L03999	Gallium
L04001-L04999	Indium
L06001-L06999	Lithium
L07001-L07999	Mercury
L08001-L08999	Potassium
L09001-L09999	Rubidium
L10001-L10999	Selenium
L11001-L11999	Sodium
L13001-L13999	Tin
L50001-L59999	Lead
M00001-M99999	**Miscellaneous nonferrous metals and alloys**
M00001-M00999	Antimony
M01001-M01999	Arsenic
M02001-M02999	Barium
M03001-M03999	Calcium
M04001-M04999	Germanium
M05001-M05999	Plutonium
M06001-M06999	Strontium
M07001-M07999	Tellurium
M08001-M08999	Uranium
M10001-M19999	Magnesium
M20001-M29999	Manganese
M30001-M39999	Silicon
P00001-P99999	**Precious metals and alloys**
P00001-P00999	Gold
P01001-P01999	Iridium
P02001-P02999	Osmium
P03001-P03999	Palladium
P04001-P04999	Platinum
P05001-P05999	Rhodium
P06001-P06999	Ruthenium
P07001-P07999	Silver
R00001-R99999	**Reactive and refractory metals and alloys**
R01001-R01999	Boron
R02001.R02999	Hafnium
R03001-R03999	Molybdenum
R04001.R04999	Niobium (Columbium)

Table F.1 (finished)

R05001-R05999	Tantalum
R06001-R06999	Thorium
R07001.R07999	Tungsten
R08001-R08999	Vanadium
R10001.R19999	Beryllium
R20001-R29999	Chromium
R30001.R39999	Cobalt
R40001.R49999	Rhenium
R50001-R59999	Titanium
R60001-R69999	Zirconium
W00001-W99999	**Welding filler metals, classified by weld deposit composition**
W60000-W69999	Copper base alloys
W70000-W79999	Surfacing alloys
W80000-W89999	Nickel base alloys
Z00001-Z99999	**Zinc and zinc alloys**

Table F.2 Description of Numbers (or Codes) Established for Ferrous Metals and Alloys

D00001-D99999	**Steels with specified mechanical properties**
D40450-D40900	Carbon Steels
D50400-D52101	Alloy Steels Casting
F00001-F99999	**Cast irons**
F 10001-F15501	Cast Iron, Gray
F 10090-F10920	Cast Iron Welding Filler Metal
F 20000-F22400	Cast Iron, Malleable
F 22830-F26230	Cast Iron, Pearlitic Malleable
F 30000-F36200	Cast Iron, Ductile (Nodular)
F 41000-F41007	Cast Iron, Gray, Austenitic
F 43000- F43030	Cast Iron, Ductile (Nodular), Austenitic
F45000 F 45009	Cast Iron, White
F47001-F47006	Cast Iron, Corrosion
G00001-G99999	**AISI and SAE carbon and alloy steels (except tool steels)**
G10050-G10950	Carbon Steel
G15130-G15900	Carbon Steel
G11080-G11510	Resulfurized Carbon Steel
G12110-G12150	Rephosphorized and Resulfurized Carbon Steel
G13300-G13450	Mn Alloy Steel

Table F.2 (continued)

G40120-G48200	Mo Alloy Steel, Cr-Mo Alloy Steel, Ni-Cr-Mo Alloy Steel, Ni-Mo Alloy Steel
G81150-G88220	Ni-Cr-Mo Alloy Steel
G50150-G52986	Cr Alloy Steel, Cr-B Alloy Steel
G61180-G61500	Cr-V Alloy Steel
G92540-G98500	Cr-Si Alloy Steel, Si-Mn Alloy Steel, Cr-S-Mn Alloy Steel, Ni-Cr-Mo Alloy Steel, Ni-Cr-Mo-B Alloy Steel
H00001-H99999	**AISI and SAE H-steels**
H10380-H15621	H-Carbon Steel, C-Mn H-Alloy Steel, C-B H Carbon Steel, Mn H-Carbon Steel, B- Mn H -Carbon Steel
H40270-H48200	C-Mo H-Alloy Steel, Cr-Mo H-Alloy Steel Ni-Mo H-Alloy Steel
H50401-H51601	C-Cr-B H-Alloy Steel, C-Cr H-Alloy Steel
H61180-H61500	Cr-V H-Alloy Steel
H81451-H94301	Ni-Cr-Mo H-Alloy Steel
J00001-J99999	**Cast steels (except tool steels)**
J01700-J05003	Carbon Steel Casting
J11442-J84090	Alloy Steel Casting
J91100-J92001	Austenitic Manganese Steel Casting, Alloy Steel Casting
J92110-J93000	Alloy Steel Casting Precipitation Hardening, Alloy Steel Casting, Cast Cr-Ni-Mo Stainless Steel, Cast Cr-Ni Stainless Steel, Cast Cr-Mn-Ni-Si-N Stainless Steel
J93001-J95705	Stainless Steel Casting, Cast Cr-Ni-Mo Stainless Steel, Alloy Steel Casting, Maraging Cast Ferritic-Austenic Stainless Steel, Duplex Alloy Steel Casting, Alloy Steel Casting
K00001-K99999	**Miscellaneous steels and ferrous alloys**
K00040-K08500	Carbon Steel, Carbon Steel with Special Magnetic Properties, Steel Welding Rod, Enameling Steel
K10614-K52440	Alloy Steel, Alloy Steel Electrode and Welding Wire, High-Strength Low-Alloy Steel
K90901-K95000	Alloy Steel, Superstrength; Ferritic Cr-Mo-V Steel; Manganese Steel, Nonmagnetic; Ni-Co Steel Welding Wire; Iron, Electrical Heating Element Alloy; Iron Thermostat Alloy; Martensitic Age-Hardenable Alloy; Maraging Alloy; Fe-Co Soft Magnetic Alloy; Nickel Steel; Invar; Iron, Nickel Sealing Alloy; etc.

Table 2.2 (finished)

S00001-S99999	**Heat and corrosion resistant steels (stainless), valve steels, iron-base "super alloys"**
S13800-S17780	Precipitation Hardenable Cr-Ni-Al-Mo-(Cu, Ti) Stainless Steels
S20100-S39000	Austenitic Cr-Mn-Ni (Si,Mo,Cu,Al) Stainless Steel; Thermal Spray Wire; Austenitic Cr-Mn-Ni Stainless Steel and Welding Filler Metal; Austenitic Cr-Ni Heat Resisting Steel and Welding Filler Metal; Precipitation Hardenable Cr-Ni-(Si, Ti, Mo, Al) Stainless Steel, etc.
S40300-S46800	Martensitic Cr Stainless Steel; Ferritic Cr Stainless Steel with Ti or Ni or Mo; Martensitic Cr-Ni-Mo Stainless Steel; Hardenable Cr Stainless Steel
S50100-S50500	Cr Heat Resisting Steels and Filler Metal
S63005-S64007	Valve Steel
S65006-S65007	Valve Steel
S65150-S67956	Iron Base Super alloy
T00001-T99999	**Tool steels, wrought and cast**
T11301-T12015	High-Speed Tool Steels
T20810-T20843	Hot-Work Tool Steels
T30102-T 30407	Cold Work Tool Steels
T31501-S31507	Oil-Hardening Steels
T41901-T41907	Shock-Resisting Tool Steels
T51602-T51621	Mold Steels
T60601-T60602	C-W Tool Steels
T61202-T61206	Low-Alloy Tool Steels
T72301-T72305	Water Hardening Tool Steels
T74000-T75008	Cr-Steels Solid Welding Wire for Machinable Surfaces and Tool and Die Surfaces
T87510-T87520	Thermal Spray Wire
T90102-T91907	Cast Tool Steels

Appendix G Important Terms

A

ablation (*syn.* entrainment)	абляция, унос [массы]	абляція, винесення [маси]
ablative coating, ablative layer	абляционное покрытие, абляционный слой	абляційне покриття, абляційний шар
abradability	истираемость (свойство материала)	стиранність (властивість матеріалу)
abrasion, abrasive wear, attrition, fretting	абразивное изнашивание, истирание [поверхности материала]	абразивне зношування, стирання [поверхні матеріалу]
absorbat, absorbed material	абсорбат (абсорбируемое вещество)	абсорбат (речовина, що абсорбується)
absorbent, absorbing material	абсорбент, абсорбирующее вещество, абсорбирующий материал, поглощающий материал	абсорбент, абсорбівний матеріал, вбирач, вбиральний матеріал, поглинач, поглинальний матеріал
absorption	абсорбция, впитывание, поглощение	абсорбція, вбирання, поглинання
ABS-resin (*syn.* acrylanitrile butadiene styrene)	акрилонитрилбутадиенстирол (аморфный полимер общего назначения) (представитель группы стиролов)	акрилонітрилбутадієнстирол (аморфний полімер загального призначення) (представник групи стиролів)
acceptor	акцептор	акцептор
acetal (POM)	ацеталь (конструкционный полимер)	ацеталь (конструкційний полімер)
acid	кислота	кислота
acid corrosion, acid attack	кислотная коррозия	кислотна корозія
acid resistance	кислотостойкость, кислотоупорность	кислотостійкість, кислототривкість
acoustic defectoscopy, acoustic - emission test (inspection), acoustic fault detection	акустическая дефектоскопия, метод акустической эмиссии (метод неразрушающего контроля)	акустична дефектоскопія, метод акустичної емісії (метод неруйнівного контролю)
acrylanitrile butadiene styrene (ABS) (*syn.* ABS-resin)	акрилонитрилбутадиенстирол (аморфный полимер общего назначения; представитель группы стиролов)	акрилонітрилбутадієнстирол (аморфний полімер загального призначення; представник групи стиролів)
acrylics	акрилы (группа полимеров)	акрили (група полімерів)
actinide series	актиноиды, актиниды (группа химических элементов)	актиноїди, актиніди (група хімічних елементів)
actinium (chemical element № 89)	актиний (химический элемент № 89)	актиній (хімічний елемент № 89)
activation energy	энергия активации	енергія активації
actual area (cross-sectional)	текущая площадь [поперечного сечения образца]	поточна площина [поперечного перетину зразка]
addition polymer	полимер, полученный в результате реакции полимеризации	полімер, одержаний у результаті реакції полімеризації
addition polymerization (*syn.* chain reaction)	реакция полимеризации	реакція полімеризації
addition, additive, admixture, agent, dope	добавка, агент, присадка	домішки, агент, додаток, присадка
adhesion, adherence	адгезия, прилипание, слипание	адгезія, прилипання, злипання
adiabatic modulus	адиабатический модуль	адіабатичний модуль
adsorbat, adsorbed material	адсорбат, адсорбированное вещество, адсорбированный материал	адсорбат, адсорбована речовина, адсорбований матеріал
adsorbent, adsorbing material	адсорбент, адсорбирующее вещество, адсорбирующий материал	адсорбент, адсорбувальний матеріал
adsorption, adsorptive effect	адсорбция, адсорбционный эффект	адсорбція, адсорбційний ефект
age hardening (type of heat treatment)	упрочнение при старении	зміцнення при старінні
ageing, aging	старение, остаривание	старіння, знестарення
agent, addition	агент, добавка, присадка	агент, домішка, додаток, присадка
agglomeration, agglomerating, agglomeration by sintering, sintering	агломерация	агломерація
aggregate state	агрегатное состояние [вещества]	агрегатний стан [речовини]
air annealing	отжиг на воздухе	відпал у повітрі
air cooling	охлаждение на воздухе	охолодження в повітрі

air-hardening steel	нормализованная сталь	нормалізована сталь
AISI classification	классификация материалов Американского института железа и стали	класифікація матеріалів Американського інституту заліза та сталі
alclad	алклед (дуралюмин, плакированный алюминием)	алклед (дюралюмін, плакований алюмінієм)
aligned (unidirectional) composite	однонаправленный композиционный материал	односпрямований композиційний матеріал
alkali	щелочь	луг
alkali metal	щелочной металл	лужний метал
alkaline corrosion, alkaline attack	щелочная коррозия	лужна корозія
alkaline-earth metal	щелочноземельный металл	лужноземельний метал
alkyds	алкиды (группа полимерных материалов)	алкіди (група полімерних матеріалів)
allotropy	аллотропия	алотропія
alloy	сплав	сплав
alloy addition, alloy additive, alloying addition, alloying additive	легирующая добавка, легирующая присадка	легувальна домішка, легувальна присадка
alloy(ed) steel	легированная сталь	легована сталь
alloying composition, alloying material	лигатура (легирующий материал)	лігатура (легувальний матеріал)
alloying, alloyage	легирование, сплавление, сплавообразование	легування, сплавлення, сплавоутворення
allyls	аллилы (группа полимеров)	аліли (група полімерів)
alumina (*syn.* aluminum oxide Al_2O_3)	окись алюминия, глинозем	окис алюмінію, глинозем
aluminium (aluminum) (chemical element № 13)	алюминий (химический элемент № 13)	алюміній (хімічний елемент № 13)
aluminizing, alitizing, calorizing	алитирование, алюминирование, калоризация	алітування, алюмінування, калоризація
aluminum oxide Al_2O_3 (*syn.* alumina)	окись алюминия, глинозем	окис алюмінію, глинозем
ambient temperature	окружающая температура, температура окружающей среды	навколишня температура, температура навколишнього середовища
americium (chemical element № 95)	америций (химический элемент № 95)	америцій (хімічний елемент № 95)
aminos	амины (группа азотосодержащих полимеров)	аміни (група азотомістких полімерів)
amorphous state	аморфное состояние	аморфний стан
anelastic deformation	неупругая деформация	непружна деформація
anion	анион (отрицательно заряженный ион)	аніон (негативно заряджений іон)
anisotropic behavior	анизотропия свойств [материала]	анізотропія властивостей [матеріалу]
annealing (type of heat treatment)	отжиг	відпал
anode	анод	анод
anodic coating (protection)	анодное покрытие (защита)	анодне покриття (захист)
anodizing (type of coating)	анодирование (вид защитного покрытия)	анодування (вид захисного покриття)
antiferrimagnetism	антиферримагнетизм	антиферимагнетизм
antiferromagnetism	антиферромагнетизм	антиферомагнетизм
antifriction material, bearing material	антифрикционный материал, подшипниковый материал	антифрикційний матеріал, підшипниковий матеріал
antimagnetic point, antiferromagnetic point (*syn.* Neele temperature, Neele point)	Нееля точка, Нееля температура (температура установления антиферромагнитных свойств)	Неєля точка, Неєля температура (температура встановлення антиферомагнітних властивостей)
antimony (chemical element № 51)	сурьма (химический элемент № 51)	сурма (хімічний елемент № 51)
apparent density	кажущаяся плотность (свойство многофазных материалов)	уявна густина (властивість багатофазних матеріалів)
apparent porosity	кажущаяся пористость (свойство многофазных материалов)	уявна пористість (властивість багатофазних матеріалів)
apparent volume	кажущийся объем (свойство многофазных материалов)	уявний об'єм (властивість багатофазних матеріалів)
applied stress	действующее напряжение	діюче напруження

aramide fiber, aramide fibre	арамидное волокно	арамідне волокно
argon (chemical element № 18)	аргон (химический элемент № 18)	аргон (хімічний елемент № 18)
arsenic (chemical element № 33)	мышьяк (химический элемент № 33)	миш'як (хімічний елемент № 33)
artificial aging	искусственное старение	штучне старіння
ash-tree	ясень (сорт дерева)	ясень (сорт деревини)
aspect ratio	удельная длина [волокна] (отношение длины к ширине, характерный размер (параметр, характеризующий геометрические размеры волокна))	питома довжина [волокна] (відношення довжини до ширини, характерний розмір (параметр, що характеризує геометричні розміри волокна))
asperity	шероховатость, неровность [поверхности]	шорсткість, нерівність [поверхні]
astatine (chemical element № 85)	астат (химический элемент № 85)	астат (хімічний елемент № 85)
ASTM grain size number	индекс (шкала) ASTM (Американское общество испытания материалов) для определения размера зерна	індекс (шкала) ASTM (Американське товариство випробування матеріалів) для визначення розмірів зерна
atactic (polymer)	атактический (стереобеспорядочный) полимер	атактичний (стереобезладний) полімер
atom	атом	атом
atom (interatomic) spacing	межатомное расстояние	міжатомна відстань
atom size (radius)	атомный радиус	атомний радіус
atomic (interatomic, chemical) bonding	межатомная (химическая) связь	міжатомний (хімічний) зв'язок
atomic arrangement	атомное строение	атомна будова
atomic mass unit (amu)	атомная единица массы (а.е.м.) (единица измерения атомной массы)	атомна одиниця маси (одиниця виміру атомної маси)
atomic mass, g/g•mole (USA)	атомная масса, г/г·моль (США)	атомна маса, г/г·моль (США)
atomic number	атомный номер	атомний номер
atomic packing factor (APF)	коэффициент упаковки	коефіцієнт пакування
atomic radius	атомный радиус	атомний радіус
atomic structure	атомное строение (структура)	атомна будова
attack (*syn.* corrosion)	коррозия	корозія
attractive force	сила межатомного притяжения	сила міжатомного притягання
austenite	аустенит	аустеніт
austenitization, austenitizing	аустенизация, аустенитизация, получение аустенитной структуры	аустенізація, одержання аустенітної структури
Avogadro number	Авогадро число	Авогадро число
azimutal quautum number	орбитальное квантовое число	орбітальне квантове число

B

bainite	бейнит (игольчатый троостит)	бейніт (голчастий троостит)
balsa	бальза (сорт дерева)	бальза (сорт деревини)
band gap energy, eV	ширина запрещенной энергетической зоны, эВ	ширина забороненої енергетичної зони, еВ
barium (chemical element № 56)	барий (химический элемент № 56)	барій (хімічний елемент № 56)
basal plane	базисная плоскость (специальное название плоскости плотной упаковки в кристаллической решетке)	базисна площина (спеціальна назва площини щільної упаковки в кристалічних гратках)
base metal, original metal, basic metal, matrix metal	основной металл, металл основы, основа сплава, основной металл [в сплаве]	основний матеріал, матеріал основи [у сплаві]
base-centered monoclinic lattice (unit cell)	базоцентрированная моноклинная решетка (элементарная ячейка)	базоцентровані моноклінні гратки (елементарна комірка)
base-centered rhombic (orthorhombic) lattice (unit cell)	базоцентрированная ромбическая решетка (элементарная ячейка)	базоцентровані ромбічні гратки (елементарна комірка)
beach mark pattern	тип (структура) излома (на 1-й стадии усталостного разрушения)	тип (структура) зламу (на 1-й стадії руйнування втомленістю)
bearing material (*syn.* anti-friction material)	подшипниковый материал, антифрикционный материал	підшипниковий матеріал, антифрикційний матеріал
bend test	испытание на изгиб	випробування на згин

bend test fixture	приспособление (установка) для испытания на изгиб (в частности хрупких материалов)	пристрій (установка) для випробування на згин (зокрема крихких матеріалів)
bending fatique test machine	установка для испытаний на усталость при изгибе	установка для випробування на втомленість при згині
bending strength, flexural strength, MOR, modulus of rupture, transverse strength	прочность при изгибе, модуль разрушения, предел прочности при изгибе, поперечная прочность	міцність при згині, модуль руйнування, границя міцності при згині, поперечна міцність
berkelium (chemical element № 97)	берклий (химический элемент № 97)	берклій (хімічний елемент № 97)
beryllium (chemical element № 4)	бериллий (химический элемент № 4)	берилій (хімічний елемент № 4)
bimetal, clad composite metal	биметалл, биметаллический материал	біметал, біметалічний матеріал
binary phase diagram	диаграмма состояния (фазовая диаграмма) двухкомпонентной системы	діаграма стану (фазова діаграма) двокомпонентної системи
binary system	двухкомпонентная (бинарная) система	двокомпонентна (бінарна) система
binder (*syn.* matrix), binding material	связующее (син. матрица), связка, вяжущий материал	зв'язуюче (син. матриця), зв'язка, в'яжучий матеріал
binding energy	энергия связи	енергія зв'язку
biochemical corrosion	биокоррозия, биохимическая коррозия	біокорозія, біохімічна корозія
Biot modulus	Био модуль	Біо модуль
Birbaum hardness	твердость по Бирбауму	твердість за Бірбаумом
bismuth (chemical element № 83)	висмут (химический элемент № 83)	вісмут (хімічний елемент № 83)
blast furnace	доменная печь	доменна піч
block copolymer	блок-сополимер	блок-сополімер
blue brittleness	синеломкость	синьоламкість
body-centered cubic (BCC) lattice (unit cell)	объемоцентрированная кубическая (ОЦК) решетка (элементарная ячейка)	об'ємоцентровані кубічні (ОЦК) гратки (елементарна комірка)
body-centered rhombic (orthorombic) (BCR) lattice (unit cell)	объемоцентрированная ромбическая решетка (элементарная ячейка)	об'ємоцентровані ромбічні гратки (елементарна комірка)
body-centered tetragonal (BCT) lattice (unit cell)	объемоцентрированная тетрагональная решетка (элементарная ячейка)	об'ємоцентровані тетрагональні гратки (елементарна комірка)
Bohr magneton	Бора магнетон	Бора магнетон
bohrium (chemical element № 107)	борий (химический элемент № 107)	борій (хімічний елемент № 107)
boiling	кипение	кипіння
Boltzmann's constant	Больцмана постоянная	Больцмана стала
bond breakage	разрыв связи [напр. в молекуле]	розрив зв'язку [напр. в молекулі]
bond stiffness	жесткость [связи, соединения, напр. клеевого]	жорсткість [зв'язку, з'єднання. напр. клейового]
bond, bonding	соединение, связь (общий термин)	з'єднання, зв'язок (загальний термін)
bonded electrical resistance strain gage	наклеиваемый электрический тензометр сопротивления (тензорезистор)	електричний тензометр опору (тензорезистор), що наклеюється
bonding energy	энергия связи	енергія зв'язку
boron (chemical element № 5)	бор (химический элемент № 5)	бор (хімічний елемент № 5)
boron fiber, boron fibre	борное волокно, волокно бора	борне волокно, волокно бору
boronizing, boronize (type of diffusion treatment)	борирование, насыщение бором поверхности материала	борування, насичення поверхні матеріалу бором
boron-polyimide	боропластик (полиимидная матрица, армированная бороволокном)	боропластик (поліімідна матриця, армована бороволокном)
borsic	борсик (волокна бора, покрытые защитным слоем карбида кремния для жаропрочности)	борсик (волокна бору, покриті захисним шаром карбіду кремнію для жароміцності)
boundary	граница [напр. зерна]	межа [напр. зерна]
boundary friction	граничное трение, трение по границам зерен	граничне тертя, тертя по межах зерен
brale	конический алмазный индентор [для измерения твердости по Роквеллу]	конічний алмазний індентор [для вимірювання твердості за Роквеллом]
branched crack, star crack	разветвленная трещина	розгалужена тріщина
branched polymer	полимер разветвленной структуры	полімер розгалуженої структури

branching	разветвление [полимерной цепи], получение полимера разветвленной структуры	розгалуження [полімерного ланцюга], одержання полімера розгалуженої структури
brand	марка	марка
brass	латунь (сплав меди с цинком)	латунь (сплав міді з цинком)
Bravais lattices (14 types)	Браве решетки (14 возможных вариантов)	решітка (гратки) Браве (14 можливих варіантів)
brazing	пайка твердым припоем, высокотемпературная пайка	паяння твердим припоєм, високотемпературне паяння
brazing temperature	температура пайки [твердым припоем]	температура паяння [твердим припоєм]
breakage (*syn.* breakdown)	разрыв, разрушение (общий термин)	розрив, руйнування (загальний термін)
debonding, breaking of bond	разрыв связи	розрив зв'язку
breaking strength, breaking stress, Pa	напряжение в образце в момент разрушения, Па	напруження в зразку в момент руйнування, Па
Brinell hardness (BH) (*syn.* ball indentation hardness)	твердость по Бринеллю (HB)	твердість за Брінеллем
Brinell hardness number (BHN)	показатель твердости по Бринеллю	показник твердості за Брінеллем
Brinell hardness test	метод испытаний на твердость по Бринеллю	метод випробування твердості за Брінеллем
brittle fracture, brittle failure	хрупкое разрушение	крихке руйнування
brittle material	хрупкий материал	крихкий матеріал
brittle to ductile transition (BDT)	хрупкопластический переход	крихкопластичний перехід
bromine (chemical element № 35)	бром (химический элемент № 35)	бром (хімічний елемент № 35)
bronze	бронза (сплав на основе меди)	бронза (сплав на основі міді)
bulk density (of porous body)	объемная плотность [пористых тел]	об'ємна щільність [пористих тіл]
bulk modulus, modulus of dilation	модуль объемной упругости, модуль всестороннего сжатия, модуль объемного сжатия	модуль об'ємної пружності, модуль всебічного стискання, модуль об'ємного стискання
Burgers vector	Бюргерса вектор	Бюргерса вектор
butylphthalat	бутилфталат (полимерный материал, представитель группы бутилов)	бутилфталат (полімерний матеріал, представник групи бутилів)
butyrale	бутираль (полимерная смола)	бутираль (полімерна смола)

C

cadmium (chemical element № 48)	кадмий (химический элемент № 48)	кадмій (хімічний елемент № 48)
cadmium plating, cadmium coating	кадмирование (тип защитного покрытия)	кадміювання (тип захисного покриття)
caesium (chemical element № 55)	цезий (химический элемент № 55)	цезій (хімічний елемент № 55)
calcination	1) кальцинация, кальцинирование; обжиг [в окислительной среде]; прокаливание 2) декарбонизация	1) кальцинація, кальцинування; випал [в окисному середовищі]; прожарювання; 2) декарбонізація
calcium (chemical element № 20)	кальций (химический элемент № 20)	кальцій (хімічний елемент № 20)
californium (chemical element № 98)	калифорний (химический элемент № 98)	каліфорній (хімічний елемент № 98)
capacity (*syn.* capacitance)	емкость (общий термин)	ємність (загальний термін)
carbon (chemical element № 6)	углерод (химический элемент № 6)	вуглець (хімічний елемент № 6)
carbon black, black	сажа (наполнитель каучуков и резин)	сажа (наповнювач каучуків і гум)
carbon dioxide	диоксид углерода (CO_2), углекислый газ	діоксид вуглецю (CO_2), вуглецевий газ
carbon fiber, carbon fibre	углеродное волокно, волокно углерода	вуглецеве волокно, волокно вуглецю
carbon monoxide	моноксид углерода (CO), угарный газ	моноксид вуглецю (CO), угарний газ
carbon steel, plain steel	углеродистая сталь, нелегированная сталь	сталь вуглецева, сталь нелегована
carbon-carbon composite (CCC), carbon-carbon composite material	углерод-углеродный материал, углерод-углеродный композиционный материал (УУКМ)	вуглецево-вуглецевий матеріал, вуглецево-вуглецевий композиційний матеріал (ВВКМ)

carbone fibre (fiber) reinforced polymer (CFRP)	композиционный материал, армированный углеволокном	композиційний матеріал, армований вуглеволокном
carbon-epoxy composite	композиционный материал, состоящий из эпоксидной матрицы, армированной углеволокном	композиційний матеріал, що складається з епоксидної матриці, армованої вуглеволокном
carbonitriding (*syn.* pyrolizing) (type of diffusion treatment)	нитроцементация, карбонитрирование	нітроцементація, карбонітрування
carbon-polyimide	композиционный материал, состоящий из полиимидной матрицы, армированной углеволокном	композиційний матеріал, що складається з поліімідної матриці, армованої вуглеволокном
carburizing, carburization, cementation	науглероживание, цементация, карбюризация (насыщение поверхности металла углеродом, а также метод получения порошков)	навуглецьовування, цементація, карбюризація (насичення поверхні металу вуглецем, а також метод одержання порошків)
case depth	глубина цементованного слоя, глубина цементации	глибина цементованого шару, глибина цементації
case-hardening	поверхностное упрочнение [напр. закалкой, цементацией]	поверхневе зміцнення [напр. загартовуванням, цементацією]
cast steel	литая сталь (стальное литье)	лита сталь (стальне лиття)
castability	жидкотекучесть	рідкоплинність
casting, casting process	литье (процесс)	лиття (процес)
catalyst	катализатор	каталізатор
cathodic protection	катодная защита	катодний захист
cation	катион (положительно заряженный ион)	катіон (позитивно заряджений іон)
cavitation	кавитация	кавітація
cavity	раковина (неоднородность в материале)	раковина (неоднорідність у матеріалі)
cavity shrinkage	усадочная раковина	усадочна раковина
cell	ячейка [кристаллической структуры]	комірка [кристалічної структури]
cellulosics	целлюлозы (группа полимеров)	целюлози (група полімерів)
cementation,carburizing, carburization (type of treatment)	цементация (химико-термическая обработка)	цементація (хіміко-термічна обробка)
cementite (Fe_3C)	цементит (карбид железа) (Fe_3C)	цементит (карбід заліза) (Fe_3C)
ceramic composite, ceramic composite material, ceramic-matrix composite (CMC)	керамический композиционный материал, композитный материал с керамической матрицей, композиционный материал с керамической матрицей	керамічний композиційний матеріал, композитний матеріал із керамічною матрицею, композиційний матеріал із керамічною матрицею
ceramic fiber, ceramic fibre	керамическое волокно	керамічне волокно
ceramic-ceramic composite	керамо-керамический композит	керамо-керамічний композит
ceramics, ceramic material	керамика, керамический материал	кераміка, керамічний матеріал
cerium (chemical element № 58)	церий (химический элемент № 58)	церій (хімічний елемент № 58)
chain	цепь [молекулярная]	ланцюг [молекулярний]
chain branching	разветвление молекулярных цепей	розгалуження молекулярних ланцюгів
chain reaction	реакция полимеризации	реакція полімеризації
chain scission	разрыв (обрыв) молекулярных цепей	розрив (обрив) молекулярних ланцюгів
chain stiffening	упрочнение молекулярных цепей	зміцнення молекулярних ланцюгів
char	обугливание (вид разрушения полимеров при нагреве)	обвуглювання (вид руйнування полімерів при нагріванні)
Charpy test	ударные испытания по Шарпи (использующие образец на двух опорах)	ударні випробування за Шарпі (використовують зразок на двох опорах)
chemical agent, reagent	реактив, реагент	реактив, реагент
chemical attack (*syn.* chemical corrosion)	химическая коррозия	хімічна корозія
chemical composition, composition	химический состав	хімічний склад
chemical compound	химическое соединение	хімічне з'єднання
chemical corrosion (*syn.* chemical attack)	химическая коррозия	хімічна корозія
chemical deposition	химическое нанесение покрытий, осаждение из растворов (метод нанесения покрытий)	хімічне нанесення покриттів, осадження з розчинів (метод нанесення покриттів)
chemical element, element	химический элемент	хімічний елемент

chemical equilibrium	химическое равновесие	хімічна рівновага
chemical property	химическое свойство	хімічна властивість
chemical reaction, chemical interaction	химическое взаимодействие, химическая реакция	хімічна взаємодія, хімічна реакція
chemical reduction	химическое восстановление	хімічне відновлювання
chemical transformation	химическое превращение	хімічне перетворення
chemical vapour deposition (CVD)	химическое осаждение из парогазовой фазы	хімічне осадження з парогазової фази
chevron pattern	шевронная сетка (структура хрупкого излома при ударном нагружении)	шевронна сітка (структура крихкого зламу при ударному навантаженні)
chill zone	зона мелких кристаллов [в структуре слитка]	зона дрібних кристалів [у структурі злитка]
chilled cast iron	отбеленный чугун, белый чугун	вибілений чавун, білий чавун
chipping	растрескивание материала с образованием осколков [при хрупком разрушении], скалывание	розтріскування матеріалу з утворенням уламків [при крихкому руйнуванні], сколювання
chlorine (chemical element № 17)	хлор (химический элемент № 17)	хлор (хімічний елемент № 17)
chloroprene rubber	хлоропреновый каучук	хлоропреновий каучук
chlorosulfonated polyethylene (CSM)	хлоросульфоновый полиэтилен (представитель группы полиэтиленов)	хлоросульфоновий поліетилен (представник групи поліетиленів)
chromating (type of conversion coating), chromium coating, chromium plating	хромирование	хромування
chromium (chemical element № 24)	хром (химический элемент № 24)	хром (хімічний елемент № 24)
cianiding (type of diffusion treatment)	цианирование	ціанування
cis-polyisoprene	мономер изопрена (основа натурального каучука)	мономер ізопрену (основа натурального каучуку)
clad steel	плакированная сталь	плакована сталь
cladding	плакирование	плакування
clay	глина	глина
cleaning	очистка [поверхности]	очищення [поверхні]
cleavage	скол, разрушение сколом, расщеплением (вид хрупкого разрушения)	руйнування у вигляді сколення, розщеплення (вид крихкого руйнування)
cleavage crack	хрупкая трещина, трещина скола	крихка тріщина, тріщина відколу
cleavage face	поверхность скола, т.е. плоскость хрупкого разрушения	поверхня відколу, тобто площина крихкого руйнування
cleavage failure, cleavage fracture	разрушение отрывом, сколом, разрыв по плоскостям спайности	руйнування відривом, відколом, розрив по площинах спайності
dislocation climb	движение дислокации перпендикулярно ее плоскости скольжения	рух дислокації перпендикулярно її площини ковзання
close-packed direction	плотноупакованное направление (вдоль которого атомы размещены наиболее плотно)	щільноупакований напрямок (уздовж якого атоми розміщені найбільш щільно)
cloth, fabric, textile	ткань	тканина
cluster	кластер, скопление [напр. дислокаций]	кластер, скупчення [напр. дислокацій]
coalescence, junction	коалесценция [напр. зерен]	коалесценція [напр. зерен]
coarse grain structure	крупнозернистая структура	крупнозерниста структура
coarse pearlite	пластинчатый перлит	пластинчастий перліт
coating	1) покрытие 2) нанесение покрытий	1) покриття 2) нанесення покриттів
cladding, plating	нанесение покрытий	нанесення покриттів
cobalt (chemical element № 27)	кобальт (химический элемент № 27)	кобальт (хімічний елемент № 27)
coefficient of friction	коэффициент трения	коефіцієнт тертя
coefficient of refraction, index of refraction	коэффициент преломления [света], показатель преломления [света]	показник заломлення [світла], коефіцієнт заломлення [світла]
coefficient of strain hardening	коэффициент деформационного упрочнения [в уравнении состояния материала]	коефіцієнт деформаційного зміцнення [у рівнянні стану матеріалу]
coefficient of thermal expansion (CTE), thermal expansion coefficient (TEC), 1/K	температурный коэффициент расширения (линейный или объемный), 1/К	температурний коефіцієнт розширення, (лінійний або об'ємний), 1/К

cohesia	когезия	когезія
cold forming	холодное деформирование [металла]	холодне деформування [металу]
cold isostatic pressing (CIP)	холодное изостатическое прессование, ХИП	холодне ізостатичне пресування, ХІП, ізостатичне холодне пресування
cold resistance	хладостойкость	холодостійкість
cold working, cold-work hardening, mechanical hardening, stress reinforcement	1) холодная обработка 2) наклеп, деформационное упрочнение, ударное упрочнение	1) холодна обробка 2) наклеп, деформаційне зміцнення, ударне зміцнення
color	цвет	колір
colorant	краситель [в полимерах]	барвник [у полімерах]
columnar structure	столбчатая структура [слитка]	стовпчаста структура [злитка]
columnar zone	зона столбчатых кристаллов [в структуре слитка]	зона стовпчастих кристалів [у структурі злитка]
combined strain	сложное деформированное состояние (плоское или объемное)	складний деформований стан, складна деформація
combustion, burning	горение, сжигание	горіння, спалювання
compact density, green compact density	плотность прессования	щільність пресування
compacted material, pressed material	прессованный материал	пресований матеріал
compaction	уплотнение (операция при получении керамики)	ущільнення (операція при одержанні кераміки)
component (*syn.* part)	узел, агрегат, деталь	вузол, агрегат, деталь
composite fiber, composite fibre	композиционное волокно, композитное волокно	композиційне волокно, композитне волокно
composite, composite material	композиционный материал, композит, композитный материал	композиційний матеріал, композит, композитний матеріал
compound	соединение (общий термин для обозначения химических соединений, смесей)	сполука (загальний термін для визначення хімічних сполук, сумішей)
compressibility	сжимаемость [среды]	стисливість [середовища]
compression	сжатие	стиск
compressive (compression) strength, Pa	предел прочности при сжатии, прочность при сжатии, Па	границя міцності при стисканні, міцність при стисканні, Па
compressive creep	ползучесть при сжатии	повзучість при стисканні
compressive stress	сжимающее напряжение	стискальне напруження
compressive yield strength, Pa	предел текучести при сжатии, Па	границя текучості при стисканні, Па
concentration	концентрация	концентрація
conchoidal fracture (of glass)	структура излома хрупкого разрушения стекла (раковистый излом)	структура зламу крихкого руйнування скла (раковистий злом)
condensation	конденсация [влаги на поверхности]	конденсація [вологи на поверхні]
condensation point	температура конденсации, точка конденсации	температура конденсації, точка конденсації
condensation polymer	полимерный материал, полученный в результате реакции поликонденсации	полімерний матеріал, одержаний у результаті реакції поліконденсації
condensation polymerization	реакция поликонденсации, полимеризация конденсацией, поликонденсация	реакція поліконденсації, полімеризація конденсацією, поліконденсація
condensed phase	конденсированная фаза	конденсована фаза
conductivity	проводимость	провідність
conductor, electroconducting material	электропроводящий материал, проводник	електропровідний матеріал, провідник
cone fracture	разрушение с конусом (т.е. после предварительной пластической деформации)	руйнування з конусом (тобто після попередньої пластичної деформації)
constant	постоянная	стала
constant-rate-of-traverse tension testing machine (*syn.* CRT tension testing machine)	испытательная машина с постоянной скоростью перемещения подвижной траверсы	машина для випробувань з постійною швидкістю переміщення рухомої траверси
constitutional diagram (*syn.* phase equilibrium diagram)	фазовая диаграмма состояния [многофазного материала]	фазова діаграма стану [багатофазного матеріалу]
contact corrosion	контактная коррозия	контактна корозія
contact fatigue	контактная усталость	контактна втомленість
content	содержание (наличие вещества)	вміст (наявність речовини)
continuity	сплошность [среды]	суцільність [середовища]

continuous cooling transformation (CCT) diagram	диаграмма изотермического охлаждения	діаграма ізотермічного охолодження
contraction crack	усадочная трещина	усадочна тріщина
controlled atmosphere	контролируемая атмосфера	контрольована атмосфера
controlling the grain size	управление размерами зерна (метод изменения свойств металлов и сплавов)	керуваня розмірами зерна (спосіб зміни властивостей металів і сплавів)
convection	конвекция (один из способов теплопереноса)	конвекція (один із способів теплопереносу)
conventional strain	условная (техническая) деформация	умовна (технічна) деформація
conventional stress	условное (техническое) напряжение	умовне (технічне) напруження
cooling	охлаждение	охолодження
cooling curve	кривая охлаждения	крива охолодження
cooling rate	скорость охлаждения	швидкість охолодження
coordination number (*syn.* atom per cell)	координационное число	координаційне число
copolymer	сополимер	сополімер
copolymerization	сополимеризация	сополімеризація
copper (chemical element № 29)	медь (химический элемент № 29)	мідь (хімічний елемент № 29)
copper plating, copper coating	меднение	міднення
corc	пробка (материал)	корок (матеріал)
corrosion (*syn.* attack)	коррозия	корозія
corrosion crack	коррозионная трещина	корозійна тріщина
corrosion cracking	коррозионное растрескивание	корозійне розтріскування
corrosion fatigue	корозионная усталость	корозійна втомленість
corrosion penetration rate (CPR)	скорость коррозии	швидкість корозії
corrosion resistance	сопротивление коррозии	опір корозії
corrosion-fatigue crack	коррозионно-усталостная трещина	тріщина від корозії та втомленості
corrosion-resistant coating, corrosion-resistant layer	коррозионно-стойкое покрытие, антикоррозионное покрытие, антикоррозионный слой	корозійно-стійке покриття, антикорозійне покриття, антикорозійний шар
cost per volume	стоимость единицы объема материала (параметр выбора материала)	вартість одиниці об'єму матеріалу (параметр вибору матеріалу)
coulomb, C	кулон (единица измерения электрического заряда), Кл	кулон (одиниця вимірювання електричного заряду), Кл
Coulombic force	Кулона сила	Кулона сила
covalent bond, covalent bonding	ковалентная связь	ковалентний зв'язок
crack (*syn.* flaw)	трещина в материале [произвольной природы]	тріщина в матеріалі [довільної природи]
crack branching	ветвление трещины	розгалуження тріщин
crack density	плотность трещин (показатель трещиностойкости)	щільність тріщин (показник тріщиностійкості)
crack formation, crack generation	зарождение трещины, образование трещины, трещинообразование	зародження тріщини, утворення тріщини, тріщиноутворення
crack propagation, crack growth	рост трещины, развитие трещины, распространение трещины	збільшення тріщини, поширення тріщин, розвинення тріщини, розвиток тріщини
crack resistance	трещиностойкость	тріщиностійкість
crack tip, tip of crack	вершина трещины	вершина тріщини
cracking	растрескивание [материала при разрушении]	розтріскування [матеріалу при руйнуванні]
creep	ползучесть, крип	повзучість, крип
creep curve	кривая ползучести в координатах деформация–время при σ=const	крива повзучості в координатах деформація–час за σ=const
creep failure	разрушение материала в результате ползучести	руйнування матеріалу в результаті повзучості
creep rate	скорость ползучести	швидкість повзучості
creep strength, Pa	предел ползучести, Па	границя повзучості, Па
creep test	испытание на ползучесть	випробування на повзучість
creep tester (*syn.* creep testing machine)	установка для испытаний на ползучесть	установка для випробувань на повзучість

crevice corrosion	щелевая коррозия	щілинна корозія
crystallization	кристаллизация	кристалізація
critical elongation	предельное, критическое удлинение	граничне, критичне видовження
critical flaw, critical defect	критический дефект (дефект критических размеров)	критичний дефект (дефект критичних розмірів)
critical fracture toughness (*syn.* critical stress intensity factor)	критический коэффициент концентрации напряжений	критичний коефіцієнт концентрації напружень
critical resolved shear stress	критическое напряжение сдвига в идеальном монокристалле (постоянная материала)	критичне напруженння зсуву в ідеальному монокристалі (стала матеріалу)
critical stress	критическое напряжение [потери устойчивости]	критичне напруження [втрати стійкості]
critical stress intensity factor (*syn.* critical fracture toughness)	критический коэффициент концентрации напряжений	критичний коефіцієнт концентрації напружень
critical temperature (*syn.* critical point)	критическая температура, критическая точка	критична температура, критична точка
crosshead	траверса [испытательной машины]	траверса [випробувальної машини]
crosshead speed	скорость перемещения траверсы [испытательной машины]	швидкість переміщення траверси [випробувальної машини]
cross-linking polymer structure	сетчатая структура [полимера]	сітчаста структура [полімера]
cross-section	поперечное сечение [бруса, стержня, вала]	перетин [балки, стержня, вала]
crystal	кристалл	кристал
crystal (crystalline) structure	кристаллическая структура [вещества], кристаллическое строение	кристалічна структура [речовини], кристалічна будова
crystal (crystalline) system	кристаллографическая система (сингония)	кристалографічна система (сингонія)
crystal cell (*syn.* unit cell)	элементарная кристаллическая ячейка	елементарна кристалічна комірка
crystal lattice, lattice	кристаллическая решетка [материала]	кристалічні гратки [матеріалу]
crystal mismatch	несовершенство в кристалле	недосконалість у кристалі
crystallinity (polymers)	кристаллическое состояние [полимеров]	кристалічний стан [полімерів]
crystallisation temperature	температура кристаллизации	температура кристалізації
crystallite	кристаллит (форма существования полимерных цепей)	кристаліт (форма існування полімерних ланцюгів)
crystallographic plane	кристаллографическая плоскость	кристалографічна площина
cubic crystal system	кубическая кристаллографическая система (сингония)	кубічна кристалографічна система (сингонія)
cup and cone fracture	чашка-конус (характерный вид излома образца при пластическом разрушении)	чашка-конус (характерний вид злому зразка при пластичному руйнуванні)
cup test (*syn.* Erichsen test)	испытание на выдавливание, технологическая проба на пластичность по Эриксену	випробування на видавлювання, технологічна проба на пластичність за Еріксеном
curium (chemical element № 96)	кюрий (химический элемент № 96)	кюрій (хімічний елемент № 96)
current density, A/m^2	плотность тока, А/м^2	густина струму, А/м^2
cut off	разрыв волокон (этап в разрушении композитов)	розрив волокон (етап у руйнуванні композитів)
cyanide hardening	науглероживание	навуглецьовування
cycle (of loading)	цикл [нагружения]	цикл [навантаження]
cycle counter	счетчик циклов	лічильник циклів
cyclic deformation	циклическое деформирование	циклічне деформування
cyclic heating	циклический нагрев	циклічне нагрівання, циклічний нагрів
cyclic load, cyclic repeated load	циклическая нагрузка, циклическое нагружение	циклічне навантаження
cyclic sintering	циклическое спекание	циклічне спікання

D

damage	разрушение, повреждение (термин общего значения)	руйнування, пошкодження (термін загального значення)
damping coefficient	коэффициент неупругого рассеяния	коефіцієнт непружного розсіяння
dead-weight loading	длительное нагружение подвешенным грузом [в испытаниях на ползучесть]	тривале навантаження підвішеним тягарем [у випробуваннях на повзучість]
debonding, delamination	расслоение (этап в разрушении композитов)	розшарування (етап в руйнуванні композитів)
decarburization	обезуглероживание, разуглероживание	зневуглецювання, видалення вуглецю
decarburized layer	обезуглероженный слой (детали после термообработки)	зневуглецьований шар (деталі після термообробка)
decomposition, decay	распад [химического соединения]	розпад [хімічної сполуки]
deep hardening	объемное упрочнение (т.е. упрочнение по всему объему материала)	об'ємне зміцнення (тобто зміцнення у всьому об'ємі матеріалу)
defect	дефект [структуры, изделия, пр.]	дефект [структури, виробу та ін.]
defect diffusion	диффузия дефектов	дифузія дефектів
defect hardening	упрочнение дефектами решетки	зміцнення дефектами гратки
defect structure	структура с дефектами	структура з дефектами
defect-free, flawless material	бездефектный материал	бездефектний матеріал
deflagrability	возгораемость	займистість
deformability	деформируемость, способность к деформированию	деформівність, здатність до деформування
deformation	деформация, деформирование (общее понятие)	деформація, деформування (загальне поняття)
deformation processing	деформационная обработка материалов (обработка давлением)	деформаційна обробка матеріалів (обробка тиском)
deformed (strained) state	деформированное состояние [материала]	деформований стан [матеріалу]
degradation	разложение (вид разрушения полимерного материала)	розкладання (вид руйнування полімерного матеріалу)
degradation temperature	температура разложения [полимеров]	температура розкладання [полімерів]
degree of polymerization	степень полимеризации	ступінь полімерізації
degree of sintering (*syn.* sintering level)	степень спекания	ступінь спікання
delamination	расслоение (отслаивание отдельных слоев слоистого материала друг от друга (первый этап в разрушении композитов))	відшарування (від'єднання окремих шарів шаруватого матеріалу один від одного (перший етап у руйнуванні композитів))
dendrite	дендрит (разветвленные древовидные кристаллы)	дендрит (розгалужені деревоподібні кристали)
dendrite fraction	доля дендритов [в структуре металла]	дендритів частка [у структурі металу]
dendritic segregation	дендритная ликвация	дендритна ліквація
dendritic structure	дендритная структура [металла]	дендритна структура [металу]
density	плотность	густина
density ratio (powder metallurgy)	относительная плотность [в порошковой металлургии]	відносна густина [у порошковій металургії]
deoxidation	раскисление, дезоксидация, обескислороживание	розкиснення, дезоксидація, знекиснення
deoxidizer	раскислитель	розкиснювач
depletion	обеднение	збіднення
depletion layer	обедненный слой	збіднений шар
deposition	осаждение	осадження
design stress	расчетное напряжение	розрахункове напруження
desizing	расшлихтовка (снятие аппрета)	розшліхтовування (зняття апрета)
desorption	десорбция	десорбція
destruction	разрушение (общий термин)	руйнування (загальний термін)
destructive test	разрушающее испытание	руйнівне випробування
detection	дефектоскопия	дефектоскопія
deterioration	разложение (вид разрушения полимерного материала)	розкладання (вид руйнування полімерного матеріалу)

devitrification	кристаллизация [стеклоподобного вещества], расстекловывание, девитрификация	кристалізація (склоподібної речовини), розсклування, девітрифікація
diagram of equilibrium (*syn.* phase diagram)	фазовая диаграмма состояния	фазова діаграма стану
diagram, chart, plot	диаграмма, схема, график	діаграма, схема, графік
dial indicator	циферблатный индикатор перемещений (индикатор часового типа)	циферблатний індикатор переміщень (годинникового типу)
diamagnetism	диамагнетизм (магнитное свойство)	діамагнетизм (магнітна властивість)
diamond	алмаз	алмаз
diamond cone (brale)	алмазный конус (наконечник для испытаний на твердость)	алмазний конус (наконечник для випробувань на твердість)
diamond cubic crystal lattice, diamond cubic	решетка (структура) типа алмаза	гратки (структура) типу алмазу
diamond pyramid hardness test (*syn.* Vickers hardness test)	испытание материала на твердость по Виккерсу [вдавливанием алмазной пирамиды]	випробування матеріалу на твердість за Віккерсом (вдавлюванням алмазної піраміди)
die steel	штамповая сталь	штампована сталь
dielectric (breakdown) strength (of an insulator) (*syn.* electric strength, insulating strength)	диэлектрическая прочность, электрическая прочность, напряжение пробоя диэлектриков	діелектрична міцність, електрична міцність, напруга пробивання діелектрика
dielectric constant (*syn.* electric constant, dielectric permittivity)	электрическая постоянная	електрична стала
dielectric displacement, C/m^3	электрическое смещение (индукция), Кл/м^3	електричне зміщення (індукція), Кл/м^3
dielectric material, dielectric, (*syn.* electrical insulating material)	диэлектрический материал, диэлектрик, электроизоляционный материал	діелектричний матеріал, діелектрик, електроізоляційний матеріал
dielectric permittivity, absolute, F/m	диэлектрическая проницаемость среды, абсолютная, Ф/м	діелектична проникність середовища, абсолютна, Ф/м
dielectric susceptibility	диэлектрическая восприимчивость	діелектрична сприйнятливість
diffusion	диффузия	дифузія
diffusion alloying	диффузионное легирование	дифузійне легування
diffusion bonding (*syn.* diffusion welding)	соединения материалов путем диффузии (диффузионная сварка)	з'єднання матеріалів шляхом дифузії (дифузійне зварювання)
diffusion coating	диффузионное нанесение покрытий, диффузионное насыщение	дифузійне нанесення покриттів, дифузійне насичення
diffusion coefficient (*syn.* diffusivity), m^2/s	коэффициент диффузии, м^2/с	коефіцієнт дифузії, м^2/с
diffusion creep	диффузионная ползучесть	дифузійна повзучість
diffusion flux	поток диффузии, диффузионный поток	потік дифузії, дифузійний потік
diluent	разбавитель	розчинник
dimple	лунка, ямка (дефекты поверхности)	лунка, ямка (дефекти поверхні)
dimpled shear rupture	сдвиговое разрушение с образованием ямок	зсувне руйнування з утворенням ямок
dipole moment per unit volume, C·m/m^3	дипольный электрический момент единицы объема$_3$ (син. поляризованность среды), Кл·м/м^3	дипольний електричний момент одиниці об'єму (поляризованість середовища), Кл·м/м^3
directional solidification	направленная кристаллизация	спрямоване твердіння, напрямлене твердіння
disintegration	разрушение (общий термин)	руйнування (загальний термін)
dislocation	дислокация (линейный дефект кристаллической структуры)	дислокація (лінійний дефект кристалічної структури)
dislocation cross-slip	переход дислокаций из одной плоскости скольжения в другую	перехід дислокацій з одної площини ковзання в іншу
dislocation density	плотность дислокаций	густина дислокацій
dislocation loop	дислокационная петля	дислокаційна петля
dislocation multiplication	размножение дислокаций	розмноження дислокацій
dislocation network	сетка дислокаций	сітка дислокацій
dislocation pileup	скопление дислокаций	скупчення дислокацій
dislocation slip	скольжение дислокаций	ковзання дислокацій
dislocation strengthening	дислокационное упрочнение	дислокаційне зміцнення
disorder	беспорядок	безлад
disordered state	неупорядоченное состояние	невпорядкований стан

disperse state	дисперсное состояние, диспергированное состояние	дисперсний стан, диспергований стан
dispersion strengthening	дисперсионное упрочнение (общий термин, описывающий упрочнение многофазных систем, в частности сплавов, дисперсными частицами)	дисперсійне зміцнення (загальний термін, що описує зміцнення багатофазних систем, зокрема сплавів, дисперсними частками)
dispersion-strengthened material	дисперсно-упрочненный материал	дисперсно-зміцнений матеріал
dispersoid, disperse phase	дисперсная фаза, дисперсное включение	дисперсна фаза, дисперсне вкраплення
dissociation	диссоциация, разложение	дисоціація, розкладання
dissolution	растворение, расплавление	розчинення, розплавлення
dog-bone shape	приталенная форма образца для испытаний	приталена форма зразка для випробувань
domain	домен (макрообласть спонтанной намагниченности или поляризованности)	домен (макрообласть спонтанної намагніченості або поляризованості)
domain structure	доменная структура	доменна структура
donor	донор	донор
dope, dopand	агент, добавка	добавка, агент, додаток, присадка
double (upper and lower) yield points (*syn.* double yield stress)	точки верхнего и нижнего предела текучести	точки верхньої та нижньої границі текучості
drop-weight type of test	испытание на ударное растяжение с использованием энергии падающего груза	випробування на ударне розтягування з використанням енергії вантажу, що падає
dual phase steel	двухфазная сталь	двофазна сталь
dubnium (chemical element № 105)	дубний (химический элемент № 105)	дубній (хімічний елемент № 105)
ductile (nodular) cast iron	высокопрочный чугун [с шаровидным графитом]	високоміцний чавун [з кульоподібним графітом]
ductile fracture	пластическое разрушение	пластичне руйнування
ductile-to-brittle transition	порог хладноломкости	межа холодноламкості
ductility	пластичность	пластичність
durability (*syn.* endurance, longevity)	выносливость	витривалість
dye penetrant inspection (*syn.* dye penetrant test, liquid penetrant inspection)	дефектоскопия методом проникающих жидкостей, капиллярная дефектоскопия (метод неразрушающего контроля)	дефектоскопія методом проникаючих рідин, капілярна дефектоскопія (метод неруйнівного контролю)
dynamic ball hardness	твердость по методу отскока	твердість за методом відскоку
dynamic deformation, high-speed deformation, impact deformation	динамическое деформирование, высокоскоростное деформирование, ударное деформирование	динамічне деформування, високошвидкісне деформування, ударне деформування
dynamic test	динамическое испытание	динамічне випробування
dysprosium (chemical element № 66)	диспрозий (химический элемент № 66)	диспрозій (хімічний елемент № 66)

E

eddy current inspection (test, defectoscopy)	метод вихревых токов, вихретоковая дефектоскопия (метод неразрушающего контролю)	метод вихрових струмів, вихрострумова дефектоскопія (метод неруйнівного контролю)
edge dislocation (*syn.* extra plane of atoms)	краевая дислокация (дополнительная полуплоскость атомов)	крайова дислокація (додаткова напівплощина атомів)
einsteinium (chemical element № 99)	эйнштейний (химический элемент № 99)	ейнштейній (хімічний елемент № 99)
elastic (recoverable) deformation (strain)	упругая (обратимая) деформация	пружна (оборотна) деформація
elastic aftereffect, elastic recovery	упругое последействие, упругая разгрузка	пружна післядія, пружне розвантаження
elastic behavior (*syn.* elastic deformation, elasticity)	упругость (свойство материала)	пружність (властивість матеріалу)
elastic limit, elasticity limit, Pa	предел упругости, Па	границя пружності, Па

elastic wave velocity	скорость упругой волны	швидкість пружної хвилі
elasticity modulus (*syn.* Young's modulus), Pa	модуль продольной упругости, модуль (коэффициент) Юнга, Па	модуль поздовжньої пружності, модуль (коефіцієнт) Юнга, Па
elastomers	эластомеры (группа полимерных материалов)	еластоміри (група полімерних матеріалів)
electric charge density (surface), C/m^2	поверхностная плотность электрических зарядов, поляризованность вещества, Кл/м^2	поверхнева густина електричних зарядів, поляризованість речовини, Кл/м^2
electric charge density (volume), C/m^3	обемная плотность электрических зарядов, Кл/м^3	об'ємна густина електричних зарядів, Кл/м^3
electric conductivity, electric conduction, conduction, Sm	электрическая проводимость, электропроводность, См	електрична провідність, електропровідність, См
electric constant (dielectric permittivity for a vacuum), F/m	электрическая постоянная (диэлектрическая проницаемость вакуума), Ф/м	електрична стала (діелектична проникність вакууму), Ф/м
electric current, current, A	сила электрического тока, А	сила електричного струму, А
electric dipole moment, dipole moment, C·m	электрический дипольный момент, Кл·м	електричний дипольний момент, Кл·м
electric field strength (*syn.* voltage gradient), V/m	напряженность электрического поля, В/м	напруженість електричного поля, В/м
electric insulator, insulator	электроизолятор	електроізолятор
electric susceptibility	диэлектрическая восприимчивость [среды]	діелектрична сприйнятливість [середовища]
electric(al) capacitance, F	электрическая емкость, Ф	електрична ємність, Ф
electric(al) conductivity, S	электрическая проводимость, электропроводность, См	електрична провідність, електропровідність, См
electrical insulating material (*syn.* dielectric material, dielectric)	электроизоляционный материал, диэлектрик, диэлектрический материал	електроізоляційний матеріал, діелектрик, діелектричний матеріал
electrical resistance, Ω	электрическое сопротивление, Ом	електричний опір, Ом
electrical resistivity, Ω/m	удельное электрическое сопротивление, Ом/м	питомий електричний опір, Ом/м
electrochemical coating, electrochemical plating	электрохимический метод нанесения покрытий	електрохімічний метод нанесення покриттів
electrochemical corrosion	электрохимическая коррозия	електрохімічна корозія
electrochemical electromotive force (emf) series	ряд электродных потенциалов	ряд електродних потенціалів
electroconducting ceramics	электропроводная керамика, проводящая керамика	електропровідна кераміка, провідна кераміка
electroconducting coating (layer)	электропроводное покрытие, проводящее покрытие, электропроводящее покрытие, электропроводящий слой	електропровідне покриття, провідне покриття, електропровідний шар
electrodiffusion	электродиффузия	електродифузія
electroinsulaling coating, electroinsulaling layer	электроизоляционное покрытие, электроизоляционный слой	електроізоляційне покриття, електроізоляційний шар
electrolyte	электролит	електроліт
electrolytic coating, electroplating	электролитическое нанесение покрытий, гальваническое нанесение покрытий	електролітичне нанесення покриттів, гальванічне нанесення покриттів
electrolytic corrosion	электролитическая коррозия	електролітична корозія
electrolytic coupling	электролитическая совместимость (на предмет предотвращения появления гальванической пары)	електролітична сумісність (щодо запобігання появи гальванічної пари)
electromagnetic field	электромагнитное поле	електромагнітне поле
electromagnetic inspection (test)	электромагнитная дефектоскопия (метод неразрушающего контроля)	електромагнітна дефектоскопія (метод неруйнівного контролю)
electromotive force (EMF), V	электродвижущая сила (ЭДС), В	електрорушійна сила (ЕРС), В
electron	электрон	електрон
electron energy band	энергетическая зона электрона	енергетична зона електрона
electron hole	дырка (электронная)	дірка (електронна)
electron shell	электронная оболочка [атома]	електронна оболонка [атома]
electron state (level)	состояние электрона в атоме (характеризуется четырьмя квантовыми числами)	стан електрона в атомі (характеризується чотирма квантовими числами)
electron structure	электронная структура, электронное строение	електронна структура, електронна будова
electronegativity	электроотрицательность	електронегативність

electroneutrality	электронейтральность	електронейтральність
electronic spin	спин электрона	спін електрона
electroplating	гальваностегия, нанесение покрытия методом электроосаждения, нанесение гальванического покрытия	гальваностегія, нанесення покриття методом електроосадження, нанесення гальванічного покриття
electropositivity	электроположительность	електропозитивність
electrostriction	электрострикция (эффект изменения линейных размеров и объема диэлектриков в переменном электрическом поле)	електрострикція (явище зміни лінійних розмірів та об'ємів діелектриків у змінному електричному полі)
elongation	удлинение (абсолютная величина изменения длины, вызванного внешней силой)	подовження (абсолютна величина зміни довжини, яка викликана зовнішньою силою)
elongation test	испытания по определению относительного удлинения материала в момент разрыва	випробування з визначення відносного видовження матеріалу в момент розриву
electroconducting material, conductor, current-conducting material	электропроводный материал, проводник, проводящий материал	електропровідний матеріал, провідник, провідний матеріал
embeddability	способность к поглощению [абразивных частиц]	здатність до поглинання [абразивних часток]
embrittlement	охрупчивание	окрихчування, окрихчення
embryo	кристаллический зародыш	кристалічний зародок
emission	эмиссия	емісія
emission ability, emissivity	эмиссионная способность	емісійна здатність
emissive coating	эмиссионное покрытие	емісійне покриття
emitting material	эмиссионный материал	емісійний матеріал
endurance (*syn.* durability, longevity)	выносливость	витривалість
endurance limit (*syn*. fatigue limit)	предел выносливости (условный), предел усталости, усталостная прочность, циклическая прочность	границя витривалості (умовна), границя втомленості, міцність від втомленості, циклічна міцність
endurance ratio	отношение предела усталости к пределу прочности	відношення границі втомленості до границі межі міцності
endurance test (*syn.* fatigue test)	испытания на усталость	випробування на втомленість
energy	энергия	енергія
energy band gap	запрещенная (энергетическая) зона	заборонена (енергетична) зона
energy flux, W	поток энергии, Вт	потік енергії, Вт
energy level (*syn.* orbital)	энергетический подуровень (син. орбиталь)	енергетичний рівень (син. орбіталь)
energy release rate	скорость высвобождения энергии [деформации]	швидкість вивільнення енергії [деформації]
energy, work, J	энергия, работа (величина), Дж	енергія, робота (величина), Дж
engineering ceramics	конструкционная керамика	конструкційна кераміка
engineering strain	условная (техническая) деформация	умовна (технічна) деформація
engineering stress, Pa	условное (техническое) напряжение, Па	умовне (технічне) напруження, Па
engineering yield strength, Pa	условный (технический) предел текучести, Па	умовна (технічна) границя текучості, Па
enriched layer	обогащенный слой	збагачений шар
enthalpy (*syn.* heat content), J	энтальпия (син. теплосодержание), Дж	ентальпія (син. тепломісткість), Дж
entrainment (*syn.* ablation)	абляция, унос массы	абляція, винесення маси
entropy, J/K	энтропия, Дж/К	ентропія, Дж/К
environment	окружающая среда	навколишнє середовище
environmental resistance	стойкость к воздействию окружающей среды	стійкість до впливу навколишнього середовища
epitaxial growth	эпитаксиальный рост	епітаксіальний ріст
epitaxy	эпитаксия	епітаксія
epoxides	эпоксиды (группа полимерных материалов)	епоксиди (група полімерних матеріалів)
epoxy resin, epoxy (EP)	эпоксид, эпоксидная смола	епоксид, епоксидна смола
equiaxed dimple	круглая лунка (на поверхности разрушения)	кругла лунка (на поверхні руйнування)

equiaxed zone	зона равноосных кристаллов [в структуре слитка]	зона рівновісних кристалів [у структурі злитка]
equilibrium	равновесие	рівновага
erbium (chemical element № 68)	эрбий (химический элемент № 68)	ербій (хімічний елемент № 68)
Erichsen's cup test machine	установка для испытания на выдавливание по Эриксену	установка для випробування на видавлювання за Еріксеном
erosion	эрозия	ерозія
erosion-resistant coating, erosion-resistant layer	эрозионно стойкое покрытие, эрозионно стойкий слой	ерозійно стійке покриття, ерозійно стійкий шар
erosive wear	эрозионное изнашивание	ерозійне зношування, ерозійне спрацьовування
ester	сложный эфир	складний ефір
etching	химическое травление, травление, протравливание [в методе исследования структуры металлов]	хімічне травлення, травлення, протравлення [у методі дослідження структури металів]
ethenic polymer	полимер на основе этилена	полімер на основі етилену
ether	эфир	ефір
ethylene propylene diene monomer (EPDM)	мономер этиленпропилендиена	мономер етиленпропілендієну
ethylene propylene rubber (EPM) (M - monomer)	этилен пропиленовый каучук	етилен пропіленовий каучук
ethylene-tetrafluoroethylene (PTFE)	тефлон, политетрафторэтилен	тефлон, політетрафторетилен
europium (chemical element № 63)	европий (химический элемент № 63)	європій (хімічний елемент № 63)
eutectic reaction, eutectic	эвтектика	евтектика
eutectoid reaction, eutectoid	эвтектоид	евтектоїд
evaporation ablation, ablation by evaporation	абляция испарением	абляція шляхом випаровування
evaporation, vaporization	испарение	випаровування
example, sample	образец, проба	зразок, проба
excited state	возбужденное состояние [электрона]	збуджений стан [електрона]
exfoliation corrosion	коррозия отслаиванием материала	корозія відшаровуванням матеріалу
expansion	расширение	розширення
extender	наполнитель (компонент пластмасс, лакокрасочных материалов, клея)	наповнювач (компонент пластмас, лакофарбових матеріалів, клею)
extension rate	скорость растяжения (образца материала)	швидкість розтягування (зразка матеріалу)
extensometer	тензометр, экстензометр (устройство для измерения удлинений, деформаций)	тензометр, екстензометр (пристрій для вимірювання видовжень, деформацій)
extra pure (material)	особо чистый [материал]	особливо чистий [матеріал]
extrinsic (impurity) semiconductor	примесный полупроводник, несобственный полупроводник	домішковий напівпровідник, невласний напівпровідник

F

fabricability	технологичность	технологічність
fabric-plastic	текстолит	текстоліт
face-centered cubic (FCC) lattice (unit cell)	гранецентрированная кубическая (ГЦК) решетка, (элементарная ячейка)	гранецентровані кубічні (ГЦК) гратки, (елементарна комірка)
face-centered orthorhombic (rhombic) lattice (unit cell)	гранецентрированная ромбическая решетка (элементарная ячейка)	ромбічні гранецентровані гратки (елементарна комірка)
face-hardened material	поверхностно-упрочненный материал	поверхнево-зміцнений матеріал
factor	коэффициент, показатель	коефіцієнт, показник
failure mode	характер разрушения	характер руйнування
failure, fault, malfunction, trouble	повреждение, разрушение (общий термин), неисправность	пошкодження, руйнування (загальний термін), несправність
failure-proof design	проектирование "на неразрушение" (одна из концепций проектирования)	проектування "на неруйнування" (одна з концепцій проектування)
farad, F	фарада (единица измерения электрической емкости), Ф	фарада (одиниця вимірювання електричної ємності), Ф
fatigue	усталость [материала]	утомленість [матеріалу]

fatigue crack, endurance crack	усталостная трещина	тріщина від утомленості
fatigue fracture, fatigue failure	усталостное разрушение	руйнування від утомленості
fatigue life	число циклов до разрушения, долговечность	число циклів до руйнування, довговічність
fatigue limit (*syn.* endurance limit, fatigue strength), Pa	предел выносливости (условный), предел усталости, усталостная прочность, циклическая прочность, Па	границя витривалості (умовна), границя утомленості, міцність при втомленості, циклічна міцність, Па
fatigue strength (*syn.* fatigue limit), Pa	усталостная прочность, Па	міцність при втомленості, Па
fatigue striation	бороздка усталости [на поверхности усталостного разрушения], бороздчатость [поверхности образца на этапе развития усталостной трещины]	борозна втомленості [на поверхні руйнування від утомленості], борознистість [поверхні зразка на етапі розвитку тріщини від утомленості]
fatigue test (*syn.* endurance test)	испытания на усталость	випробування на втомленість
fault	дефект [кристалла]	дефект [кристала]
fermium (chemical element № 100)	фермий (химический элемент) № 100	фермій (хімічний елемент № 100)
ferrimagnetic material, ferrimagnetic	ферримагнитный материал, ферримагнетик	феримагнітний матеріал, феримагнетик
ferrite (ceramic)	феррит (магнитная керамика, общая формула $MeO\cdot Fe_2O_3$)	ферит (магнітна кераміка, загальна формула $MeO\cdot Fe_2O_3$)
ferroelectricity	сегнетоэлектричество	сегнетоелектрика
ferromagnetic material, ferromagnetic	ферромагнитный материал, ферромагнетик	феромагнітний матеріал, феромагнетик
ferrous alloy	сплав на основе железа (сталь, чугун)	сплав на основі заліза (сталь, чавун)
fiber (амер.), fibre (англ.)	волокно	волокно
fiber pull-out	выдергивание волокон из матрицы (этап в разрушении композитов)	висмикування волокон з матриці (етап у руйнуванні композитів)
fiber reinforcement, fibre reinforcement	армирование волокнами, упрочнение волокнами	армування волокнами, зміцнення волокнами
fiberglass plastic (*syn.* glass fiber reinforced polymer (GFRP))	стеклопластик, композиционный материал, армированный стекловолокнами	склопластик, композиційний матеріал, армований скловолокнами
fiber-reinforced composite, fibre-reinforced composite	волокнистый композиционный материал, армированный волокнами композиционный материал, композиционный материал, упрочненный волокнами	волокнистий композиційний матеріал, армований волокнами композиційний матеріал, композиційний матеріал, зміцнений волокнами
fibres arrangement, fibers stacking sequence, reinforceing scheme, fibers architecture	схема армирования, схема укладки волокон	схема армування, схема укладання волокон
fibrous structure (*syn.* fiber texture, fiber-like structure, fibre-like structure)	волокнистая структура	волокниста структура
Fick's first law	Фика первый закон (установившаяся диффузия)	Фіка перший закон (усталена дифузія)
Fick's second law	Фика второй закон (неустановившаяся диффузия)	Фіка перший закон (неусталена дифузія)
filament	элементарное волокно, нить, пряжа [для армирования]	елементарне волокно, нитка, пряжа [для армування]
filament winding	намотка [армирующей нити]	намотка [армувальної нитки]
filler (filling) material, filler	наполнитель (компонент полимерного материала)	наповнювач (компонент полімерного матеріалу)
fillet	галтель, фаска, скругление	галтель, фаска, округлення
film	пленка	плівка
fine grain structure	мелкозернистая структура	дрібнозерниста структура
fine grinding, fine milling, high grinding	тонкое измельчение, высокий размол, мелкое измельчение, тонкий размол	тонке дрібнення, високий розмел, м'який розмел, тонке мливо, тонке подрібнення, тонкий розмел
fine-grained steel	мелкозернистая сталь	дрібнозерниста сталь
fine-porous material	мелкопористый материал	дрібнопористий матеріал
finishing agent, sizing agent	аппрет	апрет
fireclay	огнеупорная глина	вогнетривка глина
firing	обжиг	випал
fir-tree	пихта, ель	ялиця, ялина

fission reaction	реакция синтеза	реакція синтезу
fissure	трещина, разрыв	тріщина, розрив
fixture,clamp	зажимное приспособление, зажим [в испытательной машине]	затискний пристрій, затискач [у випробувальній машині]
flake(s)	чешуйки, хлопья, флокены [в стали]	лусочки, пластівці, флокени [у сталі]
flaking	отслаивание [в виде чешуек]	відшаровування [у вигляді лусочок]
flaky graphite, flake graphite	чешуйчатый графит	лускатий графіт
flame retardant	антивоспламенитель, противовозгоратель (компонент полимерного материала)	протизапальник, протизаймач (компонент полімерного матеріалу)
flammability, inflammability, pyrophorocity	пирофорность, воспламеняемость, горючесть	пірофорність, займистість, горючість
flaw	трещина, свищ, дефект литья	тріщина, свищ, дефект лиття
flexural strength (*syn.* modulus of rupture (MOR), transverse strength, bending strength), Pa	предел прочности при изгибе, модуль хрупкого разрушения, изгибная прочность, Па	границя міцності при згинанні, модуль крихкого руйнування, згинальна міцність, Па
flow	поток	потік
flow range	область текучести, зона текучести	область текучості, зона текучості
flowability, flowing quality, fluidity	текучесть, жидкотекучесть	текучість, рідкотекучість
fluid, liquid	жидкость (агрегатное состояние)	рідина (агрегатний стан)
fluorescence	флуоресценция, флюоресценция	флуоресценція, флюоресценція
fluorine (chemical element № 9)	фтор (химический элемент № 9)	фтор (хімічний елемент № 9)
fluoroelastomer (FPM)	фторэластомер, фторкаучук	фтореластомір, фторкаучук
fluoroplastic, teflon, polytetrafluorethylene (PTFE)	фторопласт, тефлон, политетрафторэтилен (ПТФЭ)	фторопласт, тефлон, політетрафторетилен (ПТФЕ)
fluoroplastics	фторопласты (группа полимеров)	фторопласти (група полімерів)
flux	1) поток 2) флюс	1) потік 2) флюс
foam plastic (*syn.* porous plastic)	пенопласт	пінопласт
foam rubber (*syn.* porolon)	поролон	поролон
foamed material, foam	пеноматериал, вспененный материал, пенополимер	піноматеріал, спінений матеріал, пінополімер
foil	фольга	фольга
force	сила, усилие	сила, зусилля
forging	штамповка, штампование (вид обработки материалов)	штамповка, штампування (вид обробки матеріалів)
formability	формуемость	формівність
forming	обработка материалов давлением, формование	обробка матеріалів тиском, формування
fracture	разрушение (общий термин)	руйнування (загальний термін)
fracture energy, J/m^2	энергия хрупкого разрушения (удельная), Дж/м^2	енергія крихкого руйнування (питома), Дж/м^2
fracture mechanics	механика разрушения	механіка руйнування
fracture resistance	сопротивление разрушению	опір руйнуванню
fracture test	испытание на трещиностойкость, т.е. испытание по определению показателей трещиностойкости материала	випробування на тріщиностійкість, тобто випробування з визначення тріщиностійкості матеріалу
fracture toughness	вязкость разрушения, трещиностойкость, сопротивление развитию трещины, критический коэффициент концентрации напряжений	в'язкість руйнування, тріщиностійкість, опір розвиненню тріщини, критичний коефіцієнт концентрації напружень
francium (chemical element № 87)	франций (химический элемент № 87)	францій (хімічний елемент № 87)
free electron	свободный электрон	вільний електрон
freezing (cooling) range	температурный интервал [кристаллизации]	температурний інтервал [кристалізації]
freezing point	температура замерзания, точка замерзания	температура замерзання, точка замерзання
Frenkel defect (*syn.* interstitial defect)	Френкеля дефект (межузельный атом)	Френкеля дефект (міжвузловий атом)
frequency, Hz	частота, Гц	частота, Гц

fretting corrosion	фреттинг-коррозия	фретинг-корозія
fretting fatigue	усталость в условиях фреттинга	утомленість в умовах фретінгу
fretting wear	фреттинг-износ	фретінг-знос
friction force	сила трения	сила тертя
friction wear	изнашивание при трении	зношування при терті, спрацьовування при терті
full annealing, dead annealing	полный отжиг	повний відпал
full-scale test, field test	натурное испытание, полевое испытание	натурне випробування, польове випробування
fused material	плавленый материал	плавлений матеріал
fusible material (*syn.* low melting point material)	легкоплавкий материал	легкоплавкий матеріал
fusion reaction	реакция распада	реакція розпаду
fusion zone	зона сплавления	зона сплавлення
fusion, melting	плавка, плавление, сплавление, расплавление, оплавление	плавка, плавлення, сплавлення, розплавлення, оплавлення

G

gadolinium (chemical element № 64)	гадолиний (химический элемент № 64)	гадоліній (хімічний елемент № 64)
gage length, gauge length	база тензометра	база тензометра
gage marks (pl)	метки, ограничивающие длину рабочей части образца	мітки, які обмежують довжину робочої частини зразка
gage reading	показание тензодатчика	показання тензодатчика
galling	фреттинг-коррозия, коррозионное истирание, фрикционная корозия, повреждение, выработка поверхности	фреттинг-корозія, корозійне стирання, фрикційна корозія, пошкодження, виробіток поверхні
gallium (chemical element № 31)	галлий (химический элемент № 31)	галій (хімічний елемент № 31)
galvanic corrosion	гальваническая коррозия	гальванічна корозія
galvanic series	гальванический ряд	гальванічний ряд
galvanizing, galvanization, sherardization, sherardizing	гальванизация, нанесение гальванического покрытия, цинкование, шерардизация	гальванізація, нанесення гальванічного покриття, цинкування, шерардизація
gamma-ray radiography	гамма-рентгеновский метод неразрушающего контроля	гамма-рентгенівський метод неруйнівного контролю
gas absorption	газопоглощение	газопоглинання
gas attack (*syn.* gas corrosion)	газовая коррозия	газова корозія
gas carburizing	науглероживание в газовой среде	навуглецювання в газовому середовищі
gas constant	газовая постоянная, универсальная газовая постоянная	газова стала, універсальна газова стала
gas corrosion (*syn.* gas attack)	газовая коррозия	газова корозія
gas impermeability	газонепроницаемость [материала]	газонепроникність [матеріалу]
gas permeability, permeability to gas	газопроницаемость [материала]	газопроникність [матеріалу]
gas porosity	газонасыщенность [сплава]	газонасиченість [сплаву]
gaseous state	газообразное состояние	газоподібний стан
germanium (chemical element № 32)	германий (химический элемент № 32)	германій (хімічний елемент № 32)
gettering	газопоглощение	газопоглинання
Gibbs energy, J/kg	Гиббса энергия, Дж/кг	Гіббса енергія, Дж/кг
Gibbs phase rule	Гиббса правило фаз	Гіббса правило фаз
glass	стекло (класс неорганических материалов)	скло (клас неорганічних матеріалів)
glass ceramics, glass-ceramic material	ситалл, стеклокерамика, кристаллизованное стекло, стеклокристаллический материал	ситал, склокераміка, кристалізоване скло, склокристалічний матеріал
glass fiber, glass fibre	стекловолокно, стеклянное волокно	скловолокно, скляне волокно

glass fibre reinforced composite (GFRC) (*syn.* glass fibre reinforced polymer (GFRP))	композит на основе стекловолокна, полимер, армированный стекловолокном	композит на основі скловолокна, полімер, армований скловолокном
glass transition temperature	температура стеклования [полимеров]	температура оскляння [полімерів]
glasscloth (*syn.* glass fabric, glass textile)	стеклоткань	склотканина
glass-like state	стеклообразное состояние	склоподібний стан
glass-polyester	композиционный материал, состоящий из полиэфирного связующего, армированного стекловолокном	композиційний матеріал, що складається з поліефірного зв'язуючого, армованого скловолокном
glassy structure (*syn.* amorphous)	аморфная структура	аморфна структура
globular, nodular, spheroidal (graphite)	сфероидальный [графит]	сфероїдальний [графіт]
glue, glue adhesive	клей	клей
glueing	склеивание	склеювання
glyphthal resin	глифталевая смола	гліфталева смола
gold (chemical element № 79)	золото (химический элемент № 79)	золото (хімічний елемент № 79)
gouge	выщербина, выкрашивание лунки (поверхностный концентратор напряжений)	вищербина, викришування лунки (поверхневий концентратор напружень)
grade	класс, марка	клас, марка
grain	зерно (элемент структуры материала)	зерно (елемент структури матеріалу)
grain boundaries strengthening	зернограничное упрочнение	зернограничне зміцнення
grain boundary	межзеренная граница, граница зерна	міжзеренна границя, границя зерна
grain boundary diffusion, intercrystalline diffusion	зернограничная диффузия, диффузия по границам зерен	зернограничнa дифузія, дифузія по границях зерен
grain pattern (*syn.* granular structure, grain structure)	зернистая структура [материала]	зерниста структура [матеріалу]
grain size	размер зерна, величина зерна	розмір зерна, величина зерна
grain size number ASTM	размер зерна по стандарту ASTM (Американское общество испытаний материалов)	розмір зерна за стандартом ASTM (Американське товариство випробувань матеріалів)
grain size strengthening	упрочнение за счет уменьшения размера зерна	зміцнення за рахунок зменшення розміру зерна
grains growth, grains coarsening	рост зерен	ріст зерен
graphite	графит	графіт
graphite fiber, graphite fibre	графитовое волокно	графітове волокно, графітне волокно
graphitization	графитизация (образование (выделение) частиц графита в структуре железных, никелевых и др. сплавов, гл. обр. чугунов)	графітизація (утворення (виділення) часток графіту у структурі залізних, нікелевих та ін. сплавів, головним чином чавунів)
gravimetric property	гравиметрическое свойство (вес, масса и т.д.)	гравіметрична властивість (вага, маса та ін.)
gravimetry, gravimetric analysis	гравиметрия, весовой анализ, гравиметрический анализ	гравіметрія, ваговий аналіз, гравіметричний аналіз
gray cast iron	серый чугун	сірий чавун
green ceramic body	пресованный керамический материал	пресований керамічний матеріал
green density	плотность пресованного керамического материала	густина пресованого керамічного матеріалу
green material (ceramics)	неспеченная керамика	неспечена кераміка
green metal	незакаленный, необработанный металл	незагартований, необроблений метал
green state	материал в термически необработанном состоянии	матеріал у термічно необробленому стані
Griffith crack theory	Гриффитса теория возникновения и распространения трещин	Гріффітса теорія виникнення та розповсюдження тріщин
grind, grinding	1) шлифование, шлифовка. 2) размалывание, измельчение (грубое)	1) шліфування, шліфовка; 2) розмелювання, подрібнення (грубе)
gripping head	головка [образца] для захвата в испытательной машине	головка [зразка] для затискання у випробувальній машині
grips	захваты для установки образца в испытательной машине	затискачі для встановлення зразка у випробувальній машині
groove	канавка (вид концентратора напряжений)	канавка (вид концентратора напружень)
Gruneissen's constant	Грунейзена постоянная	Грунейзена стала

H

hafnium (chemical element № 72)	гафний (химический элемент № 72)	гафній (хімічний елемент № 72)
Hall - Petch equation	Петча - Холла уравнение (устанавливает связь между размером зерна и пределом текучести материала)	Петча - Холла рівняння (встановлює зв'язок між розміром зерна та границею текучості матеріалу)
hammer	молот	молот
hammer-and-anvil method	метод "молота и наковальни"	метод "молота і ковадла"
hand lay-up	ручная выкладка [композита]	ручне викладання [композиту]
hard electrolyte, ionoconductive ceramics	твердый электролит, ионнопроводящая керамика	твердий електроліт, іоннопровідна кераміка
hard magnetic material, hard magnet	магнитотвердый материал	магнітотвердий матеріал
hard solder, brazing solder, strong solder	высокотемпературный припой, твердый припой, тугоплавкий припой	високотемпературний припій, твердий припій, тугоплавкий припій
hardbutyl rubber	резина из тяжелого бутила	резина з важкого бутилу
hardenability curve	кривая закаливаемости	крива загартовуваності
hardenability, hardening capacity (penetration)	закаливаемость, прокаливаемость	здатність до гартування, прогартовуваність
hardenable steel	закаливаемая (прокаливаемая) сталь	сталь, здатна до загартовування
hardening	упрочнение (в результате термической, механической химической и пр. обработки)	зміцнення (у результаті термічної, механічної, хімічної та ін. обробки)
hardening crack	закалочная трещина	гартівна тріщина
hardness	твердость	твердість
hardness number	показатель твердости	показник твердості
hardness test	испытание на твердость	випробування на твердість
hardness tester	твердомер	твердомір
hassium (chemical element № 108)	хассий (химический элемент № 108)	хасій (хімічний елемент № 108)
heat capacity at constant pressure, J/(kg·K)	удельная теплоемкость при постоянном давлении, Дж/(кг·К)	питома теплоємність при постійному тиску, Дж/(кг·К)
heat capacity at constant volume, J/(kg·K)	удельная теплоемкость при постоянном объеме, Дж/(кг·К)	питома теплоємність при постійному об'ємі, Дж/(кг·К)
heat capacity, molar, J/(mol·K)	молярная теплоемкость, Дж/(моль·К)	молярна теплоємність, Дж/(моль·К)
heat conductive material, thermal conductive material, heat-conducting material	теплопроводный материал, теплопроводящий материал	теплопровідний матеріал
heat content (*syn.* enthalpy), J	теплосодержание, тепловая функция Гиббса (син. энтальпия), Дж	тепловміст, теплова функція Гіббса (син. ентальпія), Дж
heat distortion temperature (*syn.* heat deflection temperature)	температура теплового разрушения [полимеров]	температура теплового руйнування [полімерів]
heat flow, heat flux	тепловой поток	тепловий потік
heat protecting coating, heat protecting layer	теплозащитное покрытие, теплозащитный слой	теплозахисне покриття, теплозахисний шар
heat protecting material	теплозащитный материал	теплозахисний матеріал
heat resistance	жаростойкость	жаростійкість
heat resistant material	теплостойкий материал	теплостійкий матеріал
heat transfer coefficient, W/(m^2·K)	коэффициент теплопередачи, Вт/($м^2$·К)	коефіцієнт теплопередачі, Вт/($м^2$·К)
heat treatment	термообработка, термическая обработка	термообробка, термічна обробка
heat, J	теплота, Дж	теплота, Дж
heat-affected zone	зона термического влияния	зона термічного впливу
heat-insulating material	теплоизоляционный материал	теплоізоляційний матеріал
heat-resistant coating, heat resisting coating	жаростойкое покрытие	жаростійке покриття
helium (chemical element № 2)	гелий (химический элемент № 2)	гелій (хімічний елемент № 2)
henry, H	генри (единица измерения индуктивности), Гн	генрі (одиниця вимірювання індуктивності), Гн

Herbert hardness, pendulum hardness, Herbert number	твердость по методу маятника, твердость по Герберту	твердість за методом маятника, твердість за Гербертом
hertz, Hz	герц (единица измерения частоты), Гц	герц (одиниця вимірювання частоти), Гц
heterodiffusion, interdiffusion	гетеродиффузия, взаимная диффузия, взаимодиффузия	гетеродифузія, взаємна дифузія, взаємодифузія
heterogeneity, inhomogeneity	неоднородность [внутренней структуры материала]	неоднорідність [внутрішньої структури матеріалу]
heterogeneous material	гетерогенный материал, неоднородный материал	гетерогенний матеріал, неоднорідний матеріал
hexagonal close-packed (HCP) lattice (unit cell)	гексогональная плотноупакованная решетка (элементарная ячейка)	гексагональні щільноупаковані гратки (елементарна комірка)
hexagonal crystal system	гексагональная кристаллографическая система (сингония)	гексагональна кристалографічна система (сингонія)
high density polyethylene (HDP)	полиэтилен высокого давления [плотности]	поліетилен високого тиску [густини]
high polymer	высокомолекулярное соединение	високомолекулярна сполука
high-alloy steel	высоколегированная сталь	високолегована сталь
high-alloyed cast iron	высоколегированный чугун	високолегований чавун
high-angle grain boundary	высокоугловая граница зерен	висококутова границя зерен
high-carbon steel	высокоуглеродистая сталь	високовуглецева сталь
high-frequency dielectric, HF dielectric	высокочастотный диэлектрик	високочастотний діелектрик
high-modulus fiber, high-modulus fibre	высокомодульное волокно	високомодульне волокно
high-porosity material	высокопористый материал	високопористий матеріал
high-speed quenching, quenching from liquid state	быстрая закалка, закалка из жидкого состояния	швидке гартування, гартування з рідкого стану
high-temperature (high) tempering	высокотемпературный (высокий) отпуск	високотемпературний (високий) відпуск
high-temperature strength	жаропрочность	жароміцність
high-temperature superconductive (HTS) ceramics	высокотемпературная сверхпроводящая керамика	високотемпературна надпровідна кераміка
high-temperature superconductivity (HTS)	высокотемпературная сверхпроводимость	високотемпературна надпровідність
high-temperature thermomechanical treatment (HTTT)	высокотемпературная термомеханическая обработка (ВТМО)	високотемпературна термомеханічна обробка (ВТМО)
hole (electron)	электронная дырка	електронна дірка
holmium (chemical element № 67)	гольмий (химический элемент № 67)	гольмій (хімічний елемент № 67)
holographic nondestructive testing (HNDT)	голографический метод неразрушающего контроля	голографічний метод неруйнівного контролю
homogeneity	однородность [по составу, структуре]	однорідність [за складом, структурою]
homogeneous nucleation	гомогенное зарождение (образование зародышей)	зародження гомогенне (утворення зародків)
homogenization heat treatment	гомогенизация (вид термической обработки)	гомогенізація (вид термічної обробки)
homogenizing annealing	гомогенизационный отжиг	гомогенізаційний відпал
homopolymer	гомополимер	гомополімер
honeycomb material, honeycomb	сотовый заполнитель (ячеистый материал)	сотовий заповнювач (комірчастий матеріал)
Hooke's law	Гука закон	Гука закон
hot forging	горячая штамповка	гаряче штампування
hot isostatic pressing (HIP)	горячее прессование	гаряче пресування
hot working	горячая обработка [материала]	гаряча обробка [матеріалу]
hot-shortness (*syn.* hot-brittness)	горячеломкость, красноломкость	гарячеламкість, червоноламкість
hot-shortness temperature, hot-brittleness temperature	температура горячеломкости	температура гарячеламкості
H-steel	1) прокаливаемая сталь, сталь с регламентированной прокаливаемостью (амер.) 2) широкополочная двутавровая сталь	1) прогартовувана сталь, сталь з регламентованою здатністю до прогартовування (амер.) 2) широкополична двотаврова сталь
humidity	влажность, влагосодержание [в воздухе]	вологість, вологовміст [у повітрі]

hydrogen (chemical element № 1)	водород (химический элемент № 1)	водень (хімічний елемент № 1)
hydrogen bond	водородная связь	водневий зв'язок
hydrogen brittleness	водородная хрупкость	воднева крихкість
hydrogen corrosion, hydrogen attack	водородная коррозия	воднева корозія
hydrogen embrittlement	водородное охрупчивание	водневе окрихчування
hygroscopicity	гигроскопичность	гігроскопічність
hypereutectic alloy	заэвтектический сплав	заевтектичний сплав
hypereutectoid reaction, hypereutectoid	заэвтектоидная реакция, заэвтектоид	заевтектоїдная реакція, заевтектоїд
hypoeutectic solulion	доэвтектический раствор	доевтектичний розчин
hypoeutectoid alloy	доэвтектоидный сплав	доевтектоїдний сплав
hysteresis loop	петля гистерезиса	петля гістерезиса

I

ignition	возгорание, воспламенение	займання
immunization (*syn.* passivation)	пассивация (вид химико-термической обработки)	пасивація (вид хіміко-термічної обробки)
impact energy (*syn.* notch toughness, impact toughness), J/m^2	ударная вязкость, Дж/м^2 (свойство материала)	ударна в'язкість, Дж/м^2 (властивість матеріалу)
impact machine, impact test machine)	установка для испытаний на удар, копер	установка для випробувань на удар, копер
impact test	испытания на ударные нагрузки	випробування на ударні навантаження
imperfection	дефект, включение и др. несовершенства структуры	дефект, вкраплення та ін. недосконалості структури
impingement attack, impingement	ударная коррозия	ударна корозія
implantation (*syn.* penetration)	внедрение, проникновение	проникнення
impregnated material	пропитанный материал	імпрегнований матеріал, просочений матеріал
impregnating material	материал для пропитки	матеріал для просочення
impregnation	пропитка, импрегнирование маслом	просочення, імпрегнування маслом
impression	отпечаток на поверхности материала, получаемый при вдавливании в него индентора в испытаниях на твердость	відбиток на поверхні матеріалу, одержаний при вдавлюванні в нього індентора в випробуваннях на твердість
impurity (*syn.* contaminant, inclusion)	примесь (напр. примесный атом), включение и др. неоднородности	домішка (напр. домішковий атом), включення, вкраплення та ін. неоднорідності
impurity atom	атом внедрения, примесный атом	домішковий атом
impurity band, extrinsic zone	примесная зона	домішкова зона
impurity diffusion	диффузия примесей	дифузія домішок
indentation method	метод индентора (один из методов измерения твердости)	метод індентора (один з методів вимірювання твердості)
indentation, impress	вдавливание, отпечаток от индентора	вдавлювання, відбиток від індентора
indentor	индентор (наконечник твердомера)	індентор (кінцівка твердоміра)
index of refraction (*syn.* coefficient of refraction)	показатель преломления [света], коэффициент преломления [света]	показник заломлення [світла], коефіцієнт заломлення [світла]
indium (chemical element № 49)	индий (химический элемент № 49)	індий (хімічний елемент № 49)
induction hardening (type of heat treatment)	упрочнение индукционными токами (тип термообработки)	зміцнення індукційними струмами (тип термообробки)
inelastic material	неупругий материал	непружний матеріал
inert gas	инертный газ	інертний газ
infiltration	пропитка, импрегнирование металлом [в порошковой металлургии]	просочення, імпрегнування металом [у порошковій металургії]
infinite life	база усталостных испытаний (обычно 10^7–10^8 циклов)	база випробувань на втомленість (зазвичай 10^7–10^8 циклів)
ingot	слиток	зливок, злиток

inhibitor, inhibiting addition, inhibiting admixture, inhibiting agent	замедлитель [химической реакции], ингибитор, ингибирующая добавка, ингибирующая присадка, ингибирующий агент	сповільнювач [хімічної реакції], інгібітор, інгібірувальна добавка, інгібірувальна присадка, інгібірувальний агент
initial crack	исходная трещина, начальная трещина	вихідна тріщина, початкова тріщина
inoculation	модифицирование [сплавов]	модифікування [сплавів]
inorganic material, inorganics	неорганический материал	неорганічний матеріал
insoluble (material)	нерастворимый [материал]	нерозчинний [матеріал]
inspection	дефектоскопия, метод неразрушающего контроля	дефектоскопія, метод неруйнівного контролю
interatomic bonding	межатомная связь	міжатомний зв'язок
interatomic spacing (*syn.* interatomic distance)	межатомное расстояние (параметр кристаллической решетки)	міжатомна відстань (параметр кристалічної гратки)
intercrystalline corrosion	межкристаллитная коррозия, интеркристаллитная коррозия	міжкристалітна корозія, інтеркристалітна корозія
intercrystalline fracture, intercrystalline failure, intercrystalline cracking, intergranular fracture	межзеренное разрушение, интеркристаллитное разрушение, межкристаллитное растрескивание, межкристаллитное разрушение	міжзеренне руйнування, інтеркристалітне руйнування, міжкристалітне розтріскування, міжкристалітне руйнування
intercrystalline phase	межзеренная фаза, зернограничная фаза	міжзеренна фаза, зернограничнa фаза
interdiffusion	взаимная диффузия	взаємна дифузія
interface	межфазная граница, граница раздела фаз	міжфазова границя, границя розділу фаз
intergranular corrosion	межзеренная коррозия, межкристаллитная корозия (вид электрохимической коррозии)	міжзеренна корозія, міжкристалітна корозія (вид електрохімічної корозії)
intergranular crack	междузеренная трещина	міжзеренна тріщина
intermetallic compound, intermetallic	интерметаллид, интерметаллическое соединение	інтерметалід, інтерметалева сполука
internal energy	внутренняя энергия	внутрішня енергія
internal structure	внутренняя структура [материала]	внутрішня структура [матеріалу]
interpenetrating polymer networks	полимер сетчатой структуры, состоящий из разных макромолекул, сшитых между собой	полімер сітчастої структури, що складається з різних макромолекул, зшитих між собою
interplanar spacing	межплоскостное расстояние	міжплощинна відстань
interstitial alloy	сплав внедрения	сплав проникнення
interstitial atom	атом внедрения, междоузельный атом	атом проникнення, міжвузловий атом
interstitial defect, Frenkel defect	межузельный атом, Френкеля дефект	міжвузловий атом, Френкеля дефект
interstitial diffusion	диффузия по междоузлиям [в кристаллах]	дифузія у міжвузловинах [у кристалах]
interstitial site (in unit cell)	междоузлие [в элементарной ячейке]	міжвузловина [в елементарній комірці]
interstitial solid solution	твердый раствор внедрения	твердий розчин проникнення
interstitialcy diffusion	диффузия через междоузлия	дифузія у міжвузловинах
intracrystalline corrosion	внутрикристаллитная коррозия	внутрішньокристалітна корозія
intrinsic defect	изначальный дефект, присущий дефект	первісний дефект, притаманний дефект, властивий дефект
intrinsic semiconductor	беспримесный полупроводник, собственный полупроводник	бездомішковий напівпровідник, власний напівпровідник
iodine (chemical element № 53)	йод (химический элемент № 53)	йод (хімічний елемент № 53)
ion	ион	іон
ionic bond, electrovalent binding, electrovalent bond, heteropolar binding, heteropolar bond, ionic binding	ионная связь, гетерополярная связь	іонний зв'язок, гетерополярний зв'язок
ionic coating	ионное нанесение покрытий	іонне нанесення покриттів
ionic conduction	ионная электропроводность, ионная проводимость	іонна електропровідність, іонна провідність
ionic polarization	ионная поляризация	іонна поляризація
ionization energy	энергия ионизации	енергія іонізації
ionization potential, V	ионизационный потенциал (потенциал ионизации), В	іонізаційний потенціал (потенціал іонізації), В

ionoconductive ceramics (*syn.* hard electrolyte)	ионопроводящая керамика, твердый электролит	іоннопровідна кераміка, твердий електроліт
iridium (chemical element № 77)	иридий (химический элемент № 77)	іридій (хімічний елемент № 77)
iron (chemical element № 26)	железо (химический элемент № 26)	залізо (хімічний елемент № 26)
iron ore	железная руда	залізна руда
iron plating, iron coating	железнение	залізнення
irregularity	неупорядоченность, несовершенство; нарушение [порядка, симметрии]	невпорядкованість, недосконалість; порушення [порядку, симетрії]
irreversible reaction	необратимая реакция	необоротна реакція
isomer	изомер	ізомер
isomorphism	изоморфизм	ізоморфізм
isomorphous phase diagram	диаграмма состояния сплава с неограниченной растворимостью компонентов в твердом состоянии (напр. медь-никель)	діаграма стану сплаву з необмеженою розчинністю компонентів в твердому стані (напр. мідь-нікель)
isopleth	изоплета	ізоплета
isotactic polymer, isotactic	изотактический полимер	ізотактичний полімер
isothermal annealing	изотермический отжиг	ізотермічний відпал
isothermal process	изотермический процесс	ізотермічний процес
isothermal transformation	изотермическое превращение	ізотермічне перетворення
isothermal transformation (T-T-T) diagram (*syn.* isothermal transformation curve)	диаграмма изотермического превращения аустенита	діаграма ізотермічного перетворення аустеніту
isotope	изотоп	ізотоп
isotropy, isotropism	изотропия [свойств материала]	ізотропія [властивостей матеріалу]
Izod impact test	ударные испытания по Изоду	ударні випробування за Ізодом

J

Jominy test	Джомини испытание [сталей на прокаливаемость]	Джоміні випробування [сталей на прогартовуваність]
joule, J	джоуль (единица измерения работы, энергии, количества тепла), Дж	джоуль (одиниця вимірювання роботи, енергії, кількості тепла), Дж

K

kelvin, k	кельвин (единица измерения термодинамической температуры), К	кельвін (одиниця вимірювання термодинамічної температури), К
kevlar	кевлар (композит на основе органических волокон)	кевлар (композит на основі органічних волокон)
kevlar fibre reinforced polymer (kFRP)	полимер, армированный кевларом	полімер, армований кевларом
kilogram, kg	килограмм (единица измерения массы), кг	кілограм (одиниця вимірювання ваги), кг
Kirkendall effect	Киркендала эффект	Кіркендала ефект
knitted material	плетеный материал	плетений матеріал
knitted structure	сетчатая структура	сітчаста структура
Knoop hardness test	испытания на твердость по Кнупу	випробування на твердість за Кнупом
Knoop hardness, Knoop hardness number (KHN)	твердость по Кнупу	твердість за Кнупом
krypton (chemical element № 36)	криптон (химический элемент № 36)	криптон (хімічний елемент № 36)

L

laminar composite	слоистый композиционный материал	шаруватий композиційний матеріал
laminated coating	слоистое покрытие	шарувате покриття
laminated martensite	пластинчатый мартенсит	пластинчастий мартенсит
laminated structure, lamellar structure	пластинчатая структура	пластинчаста структура

lanthanide series, lanthanides	лантаноиды, лантаниды	лантаноїди, лантаніди
lanthanum (chemical element № 57)	лантан (химический элемент № 57)	лантан (хімічний елемент № 57)
Larson – Miller parameter	Ларсона – Миллера параметр	Ларсона – Міллера параметр
latent heat of crystallization	скрытая теплота кристаллизации	прихована теплота кристалізації
lattice defect, lattice imperfection	дефект решетки	дефект гратки
lattice directions	направления в кристаллической решетке	напрямки в кристалічній гратці
lattice energy	энергия решетки	енергія гратки
lattice parameters	параметры решетки, периоды решетки, постоянные решетки	параметри гратки, періоди гратки, сталі гратки
lattice plane	плоскость в кристаллической решетке	площина в кристалічній гратці
lattice point	узел кристалической решетки	вузол кристалічної гратки
lattice spacing	период решетки	період гратки
lawrencium (chemical element № 103)	лоуренсий (химический элемент № 103)	лоуренсій (хімічний елемент № 103)
lay	направление шероховатости поверхности, образованное обрабатывающим инструментом (не имеет количественной меры, но указывается в спецификациях как желательное)	напрям шорсткості поверхні, створений оброблювальним інструментом (не має кількісної міри, але його вказують в специфікаціях як бажаний)
layer	слой	шар
layered material, lamellar material, multilayer material	слоистый материал, слоистый композиционный материал	шаруватий матеріал, шаруватий композиційний матеріал
lead (chemical element № 82)	свинец (химический элемент № 82)	свинець (хімічний елемент № 82)
leak(age) before break (fracture)	утечка до трещины – принцип выбора материала при рационального проектирования сосудов под давлением	витік до тріщини – принцип вибору матеріалу при раціональному проектуванні посудин під тиском
ledeburite	ледебурит	ледебурит
lever law (*syn.* lever rule)	правило отрезков	правило відрізків
lifetime, service life	срок службы	термін служби
light (low-density) metal	легкий металл	легкий метал
light flux	световой поток	світловий потік
lignin	лигнин (составное вещество стенок древесных клеток)	лігнін (складова стінок клітин деревини)
limit	предел	межа, границя
limited solubility	ограниченная растворимость	обмежена розчинність
limiting (critical) state	предельное (критическое) состояние [материала конструкции]	граничний (критичний) стан [матеріалу конструкції]
linear defect (*syn.* dislocation)	линейное несовершенство, линейный дефект структуры, дислокация	лінійна недосконалість, лінійний дефект структури, дислокація
linear density	линейная плотность	лінійна густина
linear elastic material	линейно-упругий материал	лінійно-пружний матеріал
linear expansion	линейное расширение	лінійне розширення
linear molecule	ленточная или цепочечная молекула	стрічкова або ланцюгова молекула
linear polymer	линейный полимер	лінійний полімер
liquation (*syn.*segregation)	сегрегация, ликвация (неоднородность сплава по химическому составу)	сегрегація, ліквація (неоднорідність сплаву за хімічним складом)
liquid	жидкость	рідина
liquid crystal	жидкий кристалл	рідкий кристал
liquid crystal polymer (LCP) (*syn.* liquid-crystalline polymer)	жидкокристалический полимер	рідкрокристалічний полімер
liquid penetrant inspection (test)	метод проникающих жидкостей, капиллярная дефектоскопия (метод неразрушающего контроля)	метод проникних рідин, капілярна дефектоскопія (метод неруйнівного контролю)
liquid phase	жидкая фаза	рідка фаза
liquid-crystalline polymers	кристаллические полимеры (химические связи в таких полимерах придают им большую прочность, жесткость и теплостойкость)	кристалічні полімери (хімічні сполуки в таких полімерах надають їм великої міцності, жорсткості та теплостійкості)

liquidus line, liquidus curve, liquidus temperature, liquidus	ликвидус линия, поверхность ликвидуса (линия на диаграмме состояния сплава, выше которой сплав существует только в жидком состоянии)	лінія ліквідусу, поверхня ліквідусу (лінія на діаграмі стану сплаву, вище якої сплав існує тільки в рідкому стані)
lithium (chemical element № 3)	литий (химический элемент № 3)	літій (хімічний елемент № 3)
load bearing	несущая способность	носійна здатність
load bearing structure	несущая конструкция	носійна конструкція
load duration	продолжительность приложения нагрузки [в испытаниях]	тривалість прикладання навантаження [у випробуваннях]
load-indicating dial	шкала нагрузок [испытательной машины]	шкала навантажень [випробувальної машини]
loading fixture	силонагружающее устройство в испытательной машине	пристрій силонавантажувальний у випробувальній машині
loading rate (of specimen in testing)	скорость нагружения [образца при испытании]	швидкість навантажування, швидкість навантаження [зразка при випробуванні]
long-range order	дальний порядок	дальній порядок
long-term strength, long-time strength, Pa	предел длительной прочности, длительная прочность, Па	границя тривалої міцності, тривала міцність, Па
Lorentz constant	Лоренца постоянная	Лоренца стала
low alloy steel	низколегированная сталь	низьколегована сталь
low angle boundary (of grain)	малоугловая граница [зерна]	малокутова границя [зерна]
low density polyethylene (lDP)	полиэтилен низкого давления (плотности)	поліетилен низького тиску (густини)
low melting point (*syn.* fusible) material	легкоплавкий материал	легкоплавкий матеріал
low-carbon steel	малоуглеродистая сталь, низкоуглеродистая сталь	маловуглецева сталь, низьковуглецева сталь
low-cycle fatigue	малоцикловая усталость	малоциклова втомленість
lower yield point (LYP), lower yield limit, Pa	нижний предел текучести, Па	нижня границя текучості, Па
low-temperature tempering, first-stage tempering	низкотемпературный, низкий отпуск	низькотемпературний, низький відпуск
lubricant	смазка, смазочный материал	мастило, мастильний матеріал
Luders deformation	Людерса деформация	Людерса деформація
lumen, lm	люмен (единица измерения светового потока), лм	люмен (одиниця вимірювання світлового потоку), лм
luminescence	люминесценция	люмінесценція
luminiscent defectoscopy (*syn.* fluoroscopic flaw detection)	люминесцентная дефектоскопия	люмінесцентна дефектоскопія
lustreless fracture	матовый излом (мелкозернистая поверхность)	матовий злам (дрібнозерниста поверхня)
lutetium (chemical element № 71)	лютеций (химический элемент № 71)	лютецій (хімічний елемент № 71)
lux, lx	люкс (единица измерения освещенности), лк	люкс (одиниця вимірювання освітленості), лк

M

machinability	обрабатываемость (свойство материала)	оброблюваність (властивість матеріалу)
machining	обработка [станочная]	обробка [верстатна]
macropore	макропора	макропора
macrorelief	макрорельеф	макрорельєф
macrosection	макрошлиф	макрошліф
macrostructure	макроструктура	макроструктура
magnesium (chemical element № 12)	магний (химический элемент № 12)	магній (хімічний елемент № 12)
magnetic constant (*syn.* magnetic permeability of free space)	магнитная постоянная (магнитная проницаемость вакуума)	магнітна стала (магнітна проникність вакууму)
magnetic crack detection (test) (*syn.* magnetic particle inspection (test))	магнитопорошковая дефектоскопия (метод неразрушающего контроля)	магнітопорошкова дефектоскопія (метод неруйнівного контролю)

magnetic field	магнитное поле	магнітне поле
magnetic field strength, A/m	напряженность магнитного поля, А/м	напруженість магнітного поля, А/м
magnetic flux density (*syn.* magnetic induction), T=Wb/m^2	плотность магнитного потока, магнитная индукция, Тл=Вб/$м^2$	густина магнітного потоку, магнітна індукція, Тл=Вб/$м^2$
magnetic flux, Wb	магнитный поток, Вб	магнітний потік, Вб
magnetic induction (*syn.* magnetic flux density), T=Wb/m^2	магнитная индукция, плотность магнитного потока, Тл=Вб/$м^2$	магнітна індукція, густина магнітного потоку, Тл=Вб/$м^2$
magnetic material, magnet	магнитный материал	магнітний матеріал
magnetic moment, A·m^2	магнитный момент, А·$м^2$	магнітний момент, А·$м^2$
magnetic particle inspection (test) (*syn.* magnetic crack detection (test))	магнитопорошковая дефектоскопия (метод неразрушающего контроля)	магнітопорошкова дефектоскопія (метод неруйнівного контролю)
magnetic permeability of free space (*syn.* magnetic constant)	магнитная постоянная (магнитная проницаемость вакуума)	магнітна стала (магнітна проникність вакууму)
magnetic permeability, H/m	магнитная проницаемость [среды], Гн/м	магнітна проникність [середовища], Гн/м
magnetic quantum number	магнитное квантовое число	магнітне квантове число
magnetic saturation	магнитное насыщение	магнітне насичення
magnetic susceptibility	магнитная восприимчивость [среды]	магнітна сприйнятливість [середовища]
magnetic transition temperature (*syn.* Curie temperature)	температура магнитного превращения (син. Кюри температура)	температура магнітного перетворення (син. Кюрі температура)
magnetization, A/m	намагниченность, А/м	намагніченість, А/м
magnetodielectric material, ferrite	магнитодиэлектрик, магнитодиэлектрический материал, феррит	магнітодіелектрик, магнітодіелектричний матеріал, ферит
magnetostriction	магнитострикция	магнітострикція
magnification	увеличение [микроскопа]	збільшення [мікроскопа]
malleability, forgeability	ковкость, способность деформироваться в холодном состоянии	ковкість, здатність деформуватися в холодному стані
malleable cast iron	ковкий чугун [с хлопьевидным графитом]	ковкий чавун [з графітом у вигляді пластівців]
manganese (chemical element № 25)	марганец (химический элемент № 25)	марганець (хімічний елемент № 25)
Martens hardness, Martens number, scratch hardness, scratch number	твердость по Мартенсу, твердость по царапанию	твердість за Мартенсом, твердість по дряпанню
Martens tilting mirror gage, Martens strain gage	Мартенса зеркальный тензометр	Мартенса дзеркальний тензометр
martensite	мартенсит	мартенсит
martensitic steel	мартенситная сталь	мартенситна сталь
martensitic transformation	мартенситное превращение	мартенситне перетворення
mass absorption coefficient, 1/кг	коеффициент поглощения, массовый, 1/кг	коефіцієнт поглинання, масовий, 1/кг
mass heat capacity, J/(kg·K)	удельная теплоемкость, Дж/(кг·K)	питома теплоємність, Дж/(кг·K)
mass, kg	масса, кг	маса, кг
mat	хаотически армированный композиционный материал	хаотично армований композиційний матеріал
material	материал	матеріал
material purity	чистота материала	чистота матеріалу
material selection	выбор материала	вибір матеріалу
matrix, matrix phase (*syn.* binder)	матрица (син. связующее) [в композиционном материале]	матриця (син. пов'язівник) [у композиційному матеріалі]
matter, substance	вещество	речовина
machinability	способность материала поддаваться механической обработке	здатність матеріалу до механічної обробки
mean free path	средняя длина свободного пробега [напр. электрона]	середня довжина вільного пробігу [напр. електрона]
measuring microscope	измерительный микроскоп	вимірювальний мікроскоп
mechanical mixture	механическая смесь	механічна суміш
mechanical properties	механические свойства (прочностные и деформационные характеристики материала)	механічні властивості (міцнісні та деформаційні характеристики матеріалу)

mechanical test	механическое испытание	механічне випробування
mechanical test machine, mechanical tester	установка для механических испытаний, машина для механических испытаний	установка для механічних випробувань, машина для механічних випробувань
medium	среда	середовище
medium-angle grain boundary	среднеугловая граница зерна	середньокутова границя зерна
medium-density polyethylene	полиэтилен средней плотности	поліетилен середньої густини
megapascal, MPa	мегапаскаль, единица измерения напряжений в системе СИ, 1 МПа=10^6 Па	мегапаскаль, одиниця вимірювання напружень у системі СІ, 1 МПа=10^6 Па
meitnerium (chemical element № 109)	мейтнерий (химический элемент № 109)	мейтнерій (хімічний елемент № 109)
melamine formaldehyde	меламиноформальдегид (меламин) (представитель группы формальдегидных смол)	меламіноформальдегід (меламін) (представник групи формальдегідних смол)
melt	расплав	розплав
melting	плавление	плавлення
melting heat	теплота плавления	теплота плавлення
melting temperature, melting point	температура плавления, точка плавления	температура плавлення, точка плавлення
mendelevuim (chemical element № 101)	менделеевий (химический элемент № 101)	менделєєвій (хімічний елемент № 101)
mer	мер, элементарная молекула полимера (мономер)	мер, елементарна молекула полімера (мономер)
mercury (chemical element № 80)	ртуть (химический элемент № 80)	ртуть (хімічний елемент № 80)
metal	металл	метал
metal binder	металлическая связка, металлическое связующее	металева зв'язна речовина
metal fiber, metal fibre	металлическое волокно	металеве волокно
metal filler	металлический наполнитель [в композиционном материале]	металевий наповнювач [у композиційному матеріалі]
metal matrix composite	металл-металлический композиционный материал	метал-металічний композиційний матеріал
metal powder	порошок металла, металлический порошок	порошок металу, металевий порошок
metal working	металлообработка	металообробка
metal-base laminate, metal-plastic composite	металлопласт, металлопластмасса	металопласт, металопластмаса
metal – dielectric – semiconductor structure, MDS-structure	структура металл – диэлектрик – полупроводник, МДП-структура	структура метал – діелектрик – напівпровідник, МДН-структура
metal-film gage	фольговый тензодатчик	фольговий тензодатчик
metal-graphite composite	металлографит	металографіт
metallic bond, metallic binding	металлическая связь	металічний зв'язок
metalloid	металлоид	металоїд
metal-matrix composite (MMC), metal-matrix composite material	металломатричный композиционный материал (композиционный материал с металлической матрицей, металлический композиционный материал)	металоматричний композиційний матеріал (композиційний матеріал з металевою матрицею, металевий композиційний матеріал)
metal-oxide-semiconductor structure, MOS-structure	структура металл – оксид – полупроводник, МОП-структура	структура метал – оксид – напівпровідник, МОН-структура
metasilicate	метасиликат	метасилікат
metastable state, metastable	метастабильное состояние	метастабільний стан
meter, metre (USA), м	метр (единица измерения длины), м	метр (одиниця вимірювання довжини), м
Meyer hardness (HM)	твердость по Мейеру	твердість за Мейєром
mica	слюда	слюда
microconstituent	микрокомпонент, микроструктурная составляющая	мікрокомпонент, мікроструктурна складова
microhardness	микротвердость	мікротвердість
micrometer, μm	микрометр, микрон, 10^{-6} м	мікрометр, мікрон, 10^{-6} м
microsection, metallographic section	микрошлиф, металлографический шлиф	мікрошліф, металографічний шліф

microstructure	микроструктура, металлографическая структура	мікроструктура, металографічна структура
microvoid	микротрещина, микропустота, микропора, раковина	мікротріщина, мікропустота, мікропора, раковина
microvoid coalescence	слияние микротрещин	злиття мікротріщин
middle-carbon steel	среднеуглеродистая сталь	середньовуглецева сталь
mild steel	мягкая сталь, сварочная сталь	м'яка сталь, сталь для зварювання
mill	мельница	млин
Miller indices	Миллера индексы	Міллера індекси
milling	размалывание, измельчение [мелкодисперсное]	розмелювання, подрібнення (дрібнодисперсне)
mineral fiber, mineral fibre	минеральное волокно	мінеральне волокно
mineral substance	минеральное вещество	мінеральна речовина
mixed (intermediate) bonding	промежуточная (смешанная) связь	проміжний (змішаний) зв'язок
mixing	смешивание, перемешивание [различных веществ]	змішування, перемішування [різних речовин]
mixture	смесь [различных веществ]	суміш [різних речовин]
mobility (electron or hole)	подвижность (электронная или дырочная)	рухливість (електронна або діркова)
modifier	модификатор	модифікатор
modulus	модуль, показатель	модуль, показник
modulus of elasticity, Young's modulus, Pa	модуль продольной упругости, Юнга модуль, Па	модуль поздовжньої пружності, Юнга модуль, Па
modulus of rupture (MOR), (*syn.* flexural strength, bending strength), Pa	модуль хрупкого разрушения, изгибная прочность, Па	модуль крихкого руйнування, згинальна міцність, Па
Mohs hardness number, Mohs scratch hardness	твердость по Моосу, твердость по минералогической шкале	твердість за Моосом, твердість за мінералогічною шкалою
Mohs hardness test (*syn.* scratching)	Мооса испытание на твердость [нанесением царапин на поверхность материала]	Мооса випробування на твердість [нанесенням подряпин на поверхню матеріалу]
moire strain analysis	исследование деформаций методом муара	дослідження деформацій методом муара
moisture absorption	влагопоглощение, водопоглощение	вологовбирання, водопоглинання, вологопоглинання
moisture resistance	влагостойкость, сопротивление влагопоглощению, водостойкость	вологостійкість, водостійкість
moisture-absorption factor	коэффициент влагопоглощения	коефіцієнт вологовбирання
molding (plastics)	формование, литье [пластмасс]	формування, лиття [пластмас]
mole	моль	моль
molecular cluster	молекулярный кластер, скопление	молекулярний кластер, скупчення
molecular structure (polymer)	молекулярная структура [полимера]	молекулярна структура [полімеру]
molecule	молекула	молекула
molten metal	расплавленный металл	розплавлений метал
molybdenum (chemical element № 42)	молибден (химический элемент № 42)	молібден (хімічний елемент № 42)
monoclinic crystal system	моноклинная кристаллографическая система, сингония	моноклінна кристалографічна система, сингонія
monocrystalline material	монокристаллический материал	монокристалічний матеріал
monomer	мономер	мономер
monotectic	монотектика	монотектика
movable crosshead	подвижная траверса (подвижный элемент испытательной машины)	рухома траверса (рухомий елемент випрбувальної машини)
multicomponent alloy	многокомпонентный сплав	багатокомпонентний сплав
multicycle fatigue	многоцикловая усталость	багатоциклова втомленість
multiple-phase structure	многофазная структура	багатофазна, багатофазова структура
multiplication of dislocations	размножение дислокаций	розмноження дислокацій

N

natural aging	естественное старение	природне старіння
natural resin	природная, натуральная смола	природна, натуральна смола
neck	шейка на образце (образуется в сечении, где локализуется пластическая деформация)	шийка на зразку (утворюється в перерізі, де локалізована пластична деформація)
necked tensile sheet specimen	листовой образец со суженной рабочей частью (для испытания на растяжение)	листовий зразок зі звуженою робочою частиною (для випробування на розтяг)
necking (*syn.* neck-down), neck formation	шейкообразование (местное утонение образца материала при растяжении)	шийкоутворення, утворення шийки (місцеве стоншення зразка матеріалу при розтягуванні)
necking point	точка на диаграмме растяжения, соответствующая образованию шейки и началу зоны локальной текучести	точка на діаграмі розтягування, яка відповідає утворенню шийки й початку зони місцевої текучості
Neele temperature, Neele point (*syn.* antimagnetic point)	Нееля температура, Нееля точка	Неєля температура, Неєля точка
neodymium (chemical element № 60)	неодим (химический элемент № 60)	неодим (хімічний елемент № 60)
neon (chemical element № 10)	неон (химический элемент№ 10)	неон (хімічний елемент № 10)
neoprene	неопрен (группа каучуков)	неопрен (група каучуків)
neptunium (chemical element № 93)	нептуний (химический элемент № 93)	нептуній (хімічний елемент № 93)
net	сетка [напр. дислокаций]	сітка [напр. дислокацій]
network polymer	сетчатый, разветвленный полимер	сітчастий, розгалужений полімер
neutral medium	нейтральная среда, инертная среда	нейтральне середовище, інертне середовище
neutron	нейтрон	нейтрон
newton, n	ньютон (единица измерения силы), Н	ньютон (одиниця вимірювання сили), Н
nickel (chemical element № 28)	никель (химический элемент № 28)	нікель (хімічний елемент № 28)
nil ductility temperature (NDT) (USA standard)	порог хладноломкости (температура охрупчивания) (стандарт США)	межа холодноламкості (температура окрихчування) (стандарт США)
niobium (chemical element № 41)	ниобий (химический элемент № 41)	ніобій (хімічний елемент № 41)
nitrogen (chemical element № 7)	азот (химический элемент № 7)	азот (хімічний елемент № 7)
no order	отсутствие порядка [в расположении атомов]	відсутність порядку [у розміщенні атомів]
nobelium (chemical element № 102)	нобелий (химический элемент № 102)	нобелій (хімічний елемент № 102)
nodular	шаровидный, сфероидальный, узловатый (о структуре включений материала, напр. графита)	кулястий, сфероїдальний, вузловатий (про структуру включень матеріалу, напр. графіту)
nodular iron (*syn.* ductile iron)	чугун с шаровидным графитом, высокопрочный ковкий чугун	чавун з кулястим графітом, високоміцний ковкий чавун
noncrystalline state, noncrystalline (*syn.* amorphous material, amorphous, glassy, vitreous)	аморфное состояние	аморфний стан
nondestructive testing (NDT) (*syn.* nondestructive inspection (NDI))	неразрушающее испытание, неразрушающий контроль	неруйнівне випробування, неруйнівний контроль
nonequilibrum process	неравновесный процесс	нерівноважний процес
nonferrous alloy	цветной сплав	кольоровий сплав
non-magnetic steel	немагнитная сталь	немагнітна сталь
nonmetal	неметалл, металлоид	неметал, металоїд
non-porous material, ore-free material	беспористый материал	безпористий матеріал
nonpropagating crack	нераспространяющаяся трещина	непоширювана тріщина
non-saturated solution	ненасыщенный раствор	ненасичений розчин
non-steady process	нестационарный процесс	нестаціонарний процес
nonsteady-state diffusion	нестационарная диффузия	нестаціонарна дифузія

nonstoichiometric intermetallic compound	нестехиометрический интерметаллид (интерметаллическое соединение с отклонением от стехиометрического состава)	нестехіометричний інтерметалід (інтерметалічна сполука з відхиленням від стехіометричного складу)
non-wettable (material)	несмачиваемый (материал)	незмочуваний (матеріал)
normal strain	линейная деформация	лінійна деформація
normal strain sensitivity	продольная чувствительность [тензодатчика]	повздовжня чутливість [тензодатчика]
normal stress	нормальное напряжение	нормальне напруження
normalizing, normalization (type of heat treatment)	нормализация (вид термообработки)	нормалізація (вид термообробки)
notch sensitivity	чувствительность к надрезу [материала]	чутливість до надрізу [матеріалу]
notched specimen	образец с надрезом [для ударных испытаний]	зразок із надрізом [для ударних випробувань]
notched tensile strength	прочность на разрыв образца с надрезом	міцність на розрив зразка з надрізом
notched test	испытание образцов с надрезом	випробування зразків із надрізом
n-type semiconductor	полупроводник n-типа [с електронной проводимостью]	напівпровідник n-типу [з електронною провідністю]
nucleation	зародышеобразование, создание центров кристаллизации	зародкоутворення, утворення центрів кристалізації
nucleus	атомное ядро	атомне ядро
nylons	найлоны (класс полимеров)	найлони (клас полімерів)

O

oak	дуб	дуб
occlusion	окклюзия (поглощение газов микроскопическими полостями в металлах, минералах)	оклюзія (поглинання газів мікроскопічними порожнинами в металах, мінералах)
offset yield strength (*syn.* offset yield limit, engineering yield strength), Pa	условный предел текучести, Па	умовна границя текучості, Па
ohm, Ω	ом (единица измерения электрического сопротивления), Ом	ом (одиниця вимірювання електричного опору), Ом
oil hardening, oil quenching, quenching in oil	закалка в масло	гартування з охолодженням у мастилі, гартування в мастило
olivines (*syn.* orthosilicates)	ортосиликаты	ортосилікати
opacity	непрозрачность, коэффициент непрозрачности (свойство материала)	непрозорість, коефіцієнт непрозорості (властивість матеріалу)
opaque (material)	непрозрачный, непросвечивающийся [материал]	непрозорий, непросвічуваний [матеріал]
operating temperature, working temperature	рабочая температура	робоча температура
optical defectoscopy, optical flaw detection	оптическая дефектоскопия (метод неразрушающего контроля)	оптична дефектоскопія (метод неруйнівного контролю)
orbitale (*syn.* energy level)	орбиталь (энергетический подуровень электрона)	орбіталь (енергетичний підрівень електрона)
ordered reinforcement, regular reinforcement	упорядоченное армирование	упорядковане армування
orderly fiber-reinforced composite, orderly fibre-reinforced composite	композиционный материал с упорядоченным армированием	композиційний матеріал з упорядкованим армуванням
ore	руда	руда
ore-free material (*syn.* non-porous material)	плотный материал, беспористый материал	щільний матеріал, безпористий матеріал, матеріал з великою густістю
organic binder	органическая связка, органическое связующее	органічна зв'язка
organic glass (*syn.* polymethyl metacrylate)	органическое стекло, полиметилметакрилат	органічне скло, поліметилметакрилат
organic material, organic	органический материал	органічний матеріал
oriented crystallization	направленная кристаллизация	направлена кристалізація, спрямована кристалізація
original cross-sectional area	первоначальная, исходная площадь поперечного сечения [образца]	початкова, вихідна площа перерізу [зразка]

orthorhombic crystal system (unit cell)	ромбическая кристаллографическая, система, сингония	ромбічна кристалографічна система, сингонія
orthosilicates (*syn.* olivines)	ортосиликаты	ортосилікати
orthotropic fiber-reinforced composite, ortholropic fibre-reinforced composite	композиционный материал с ортотропным армированием	композиційний матеріал з ортотропним армуванням
osmium (chemical element № 76)	осмий (химический элемент № 76)	осмій (хімічний елемент № 76)
overlaying, surfacing	наплавка (нанесение покрытий наплавкой)	наплавлення (нанесення покриттів наплавленням)
oversaturation, supersaturation	пересыщение	пересичення
oxidability	окисляемость	окиснюваність
oxidation	1) окисление 2) оксидирование	1) окислення 2) оксидація, оксидування
oxidation reaction	реакция окисления	реакція окислення
oxidation resistance	сопротивление окислению	опір окисленню
oxygen (chemical element № 8)	кислород (химический элемент № 8)	кисень (хімічний елемент № 8)
oxygen corrosion, oxygene attack	кислородная коррозия	киснева корозія

P

packed density (*syn.* tap density)	объемная плотность [сыпучих или пористых материалов]	об'ємна густина [сипучих або пористих матеріалів]
packing	упаковка (процесс)	упаковка, пакування (процес)
packing density	плотность упаковки [атомов]	густина пакування, густина упаковки
packing factor	коэффициент упаковки [атомов в решетке]	коефіцієнт пакування [атомів у гратці]
paint	краска	фарба
palladium (chemical element № 46)	палладий (химический элемент № 46)	паладій (хімічний елемент № 46)
paper based gage	тензодатчик на бумажной подложке	тензодатчик на паперовій підкладці
paramagnetic material, paramagnetic	парамагнетик, парамагнитный материал	парамагнетик, парамагнітний матеріал
participated material, loose material	сыпучий материал	сипкий матеріал, сипучий матеріал
particle-reinforced composite	дисперсно-упрочненный композиционный материал	дисперсно-зміцнений композиційний матеріал
particulate composite, particulate-reinforced composite, filled composite, filled material	композиционный материал с порошковым наполнителем, материал с наполнителем, армированный частицами композиционный материал, композиционный материал с дисперсной фазой, композиционный материал с наполнителем, наполненный композиционный материал	композиційний матеріал з порошковим наповнювачем, матеріал з наповнювачем, армований частинками композиційний матеріал, композиційний матеріал з дисперсною фазою, композиційний матеріал з наповнювачем, наповнений композиційний матеріал
passivation, passivating	пассивация, пассивирование (вид химико-термической обработки)	пасивація, пасивування (вид хіміко-термічної обробки)
pattern	муаровая картина, сетка, узор, рельеф [поверхности разрушения]	муарова картина, сітка, візерунок, рельєф [поверхні руйнування]
pearlitic steel	перлитная сталь, эвтектоидная сталь	перлітна сталь, евтектоїдна сталь
pearlitic transformation	перлитное превращение	перлітне перетворення
peeling	отслаивание [от поверхности]	відшаровування [від поверхні]
Peierls stress	Пайерлса напряжение	Пайерлса напруження
pendulum-type impacting machine	машина для испытаний на ударную вязкость маятникового типа	машина для випробувань на ударну в'язкість маятникового типу
pendulum-type tension-testing machine	машина для испытания на растяжение, снабженная маятниковым силоизмерителем	машина для випробувань на розтяг, оснащена маятниковим силовимірювачем
penetrant	проникающая жидкость [в методе неразрушающего контроля]	проникна рідина [в методі неруйнівного контролю]
penetration (*syn.* implantation)	проникновение, внедрение	проникнення
penetrator (*syn.* indentor)	индентор, вдавливаемый в материал с целью определения твердости последнего	індентор, що вдавлюється в матеріал з метою визначення твердості останнього

percent (%) elongation	относительное удлинение [в момент разрыва образца]	відносне видовження [у момент розриву зразка]
percent (%) reduction in area	относительное сужение [в момент разрыва образца]	відносне звуження [у момент розриву зразка]
periodic table of elements	периодическая таблица (система) элементов [Менделеева]	періодична таблиця (система) елементів [Менделєєва]
peritectic reaction, peritectic	перитектическая реакция, перитектика	перитектична реакція, перитектика
peritectoid reaction, peritectoid	перитектоидная реакция, перитектоид	перитектоїдна реакція, перитектоїд
pearlite, perlite	перлит	перліт
permeability	проницаемость (газо- или магнито-)	проникність (газо- або магніто-)
permeable material	проницаемый материал	проникний матеріал
perspex	плексиглас – то же, что и метилметакрилат (одно из торговых названий)	плексиглас – те ж, що і метилметакрилат (одна з торгових назв)
phase	фаза	фаза
phase boundary	межфазная граница, граница раздела фаз	міжфазна границя, границя відокремлення фаз, межа відокремлення фаз
phase composition	фазовый состав	фазовий склад
phase diagram (*syn.* state diagram, phase equilibrium diagram, stable diagram)	фазовая диаграмма состояния, диаграмма равновесия	фазова діаграма стану, діаграма рівноваги
phase equilibrium	фазовое равновесие	фазова рівновага
phase equilibrium diagram (*syn.* phase diagram, state diagram)	диаграмма состояния, диаграмма равновесия, фазовая диаграмма	діаграма стану, діаграма рівноваги, фазова діаграма
phase transformation	фазовое превращение, фазовый переход	фазове перетворення, фазовий перехід
phase transformation heat, phase transition heat	теплота фазового превращения, теплота фазового перехода	теплота фазового перетворення, теплота фазового переходу
phase transformation strengthening	упрочнение в результате фазовых превращений	зміцнення фазовими перетвореннями
phase transition temperature	температура фазового перехода, точка фазового перехода	температура фазового переходу, точка фазового переходу
phenolformaldehyde	фенолформальдегид (представитель группы формальдегидных смол)	фенолформальдегід (представник групи формальдегідних смол)
phenolics	фенолы (группа полимеров)	феноли (група полімерів)
phonon	фонон	фонон
phosphor bronze, deoxidized bronze (use for flat and wire springs, for worms)	фосфористая бронза	фосфориста бронза
phosphorescence	фосфоресценция	фосфоресценція
phosphorus (chemical element № 15)	фосфор (химический элемент № 15)	фосфор (хімічний елемент № 15)
photoceramics	фотокерамы (группа ситаллов)	фотокерами (група ситалів)
photoconduction	фотопроводимость (процесс)	фотопровідність (процес)
photoconductivity	фотопроводимость (свойство материала)	фотопровідність (властивість матеріалу)
photoelasticity	фотоупругость	фотопружність
photoelasticity method	метод фотоупругости	метод фотопружності
photoemission	фотоэлектронная эмиссия	фотоелектронна емісія
photomicrograph	микрофотография, микрофотографический снимок	мікрофотографія, мікрофотографічний знімок
photon	фотон	фотон
photoresistive effect	фоторезистивный эффект	фоторезистивний ефект
physical vapour deposition (PVD), vacuum spraying	физическое осаждение из паровой фазы, вакуумное напыление	фізичне осадження з парової фази, вакуумне напилення
pickling (*syn.* etching)	декапирование, травление (очистка поверхности)	декапірування, травлення (очищення поверхні)
piezoelectric effect, piezoelectricity	пьезоэлектрический эффект	п'єзоелектричний ефект
piezoelectric material, piezoelectric	пьезоэлектрический материал, пьезоэлектрик	п'єзоелектричний матеріал, п'єзоелектрик
piezoelectric modulus	пьезомодуль, пьезоэлектрический модуль	п'єзомодуль, п'єзоелектричний модуль
piezomagnetic effect, magnetoelastic effect	пьезомагнетизм, магнитоупругий эффект	п'єзомагнетизм, магнітопружний ефект

pig iron	передельный чугун, чушковый чугун	переробний чавун, чушковий чавун
pigment, colour, colouring agent	пигмент, краситель	пігмент, барвник
pine	сосна	сосна
pipe shrinkage, pipe	усадочная раковина [в отливке, слитке]	усадочна раковина [у виливку, злитку]
pitting, pitting-corrosion	питтинг, точечная коррозия, изъязвление, образование поверхностных раковин, выкрашивание [с образованием ямок]	пітинг, точкова корозія, виразка, утворення поверхневих раковин, викришування [з утворенням ямок]
plain carbon steel (*syn.* plain steel, carbon steel)	углеродистая сталь, нелегированная сталь	вуглецева сталь, нелегована сталь
planar density	плотность упаковки [атомов в плоскости]	щільність пакування [атомів у площині]
Planck's constant	Планка постоянная	Планка стала
plane defect	плоский дефект [упаковки]	плоский дефект [пакування]
plane strain state, plane strain	плоское деформированное состояние, плоская деформация	плоский деформований стан, плоска деформація
plane stress	плоское напряженное состояние	плоский напружений стан
plastic	пластик (сокр. назв. полимерного материала)	пластик (скор. назва полімерного матеріалу)
plastic (non-reversible) strain (deformation)	пластическая деформация, остаточная деформация, необратимая деформация	пластична деформація, залишкова деформація, необоротна деформація
plastic alloy	пластичный сплав	пластичний сплав
plastic behavior (*syn.* plastic deformation)	пластическая деформация, деформация за пределами упругости	пластична деформація, деформація за межею пружності
plastic deformation (*syn.* plastic behavior)	пластическая деформация, деформация за пределами упругости	пластична деформація, деформація за межею пружності
plastic material (*syn.* inelastic material)	неупругий материал	непружний матеріал
plasticity, ductility	пластичность [твердого тела]	пластичність [твердого тіла]
plasticization	пластификация, пластифицирование	пластифікація
plasticizer	пластификатор, пластифицирующая добавка, пластифицирующая присадка	пластифікатор, пластифікаційна добавка, пластифікаційна присадка
plating (type of coating)	гальваническое покрытие, гальванизация	гальванічне покриття, гальванізація
platinum (chemical element № 78)	платина (химический элемент № 78)	платина (хімічний елемент № 78)
platinum coating, platinum plating, platinization	платинирование	платинування
plutonium (chemical element № 94)	плутоний (химический элемент № 94)	плутоній (хімічний елемент № 94)
ply steel	плакированная сталь	плакована сталь
plywood	фанера	фанера
p-n junction	p-n переход, электронно-дырочный переход	p-n перехід, електронно-дірковий перехід
point	точка [температуры, давления, напряжения и т.д.]	точка [температури, тиску, напруження та ін.]
point defect (of structure)	точечный дефект [структуры]	точковий дефект [структури]
Poisson's ratio	Пуассона коэффициент	Пуассона коефіцієнт
polarization	поляризация (процесс в диэлектриках)	поляризація (процес у діелектриках)
polarization (electronic)	поляризация, электронная	поляризація, електронна
polarization, C/m^2	поляризованность, Кл/м^2	поляризованість , Кл/м^2
polish, polishing	полирование, полировка	полірування, поліровка
polonium (chemical element № 84)	полоний (химический элемент № 84)	полоній (хімічний елемент № 84)
polyacetal	полиацеталь (представитель группы ацеталей) (конструкционный полимер)	поліацеталь (представник групи ацеталей) (конструкційний полімер)
polyacrylic rubber	полиакриловый каучук	поліакриловий каучук
polyamide	полиамид (представитель группы полиамидов; конструкционный полимер)	поліамід (представник групи поліамідів; конструкційний полімер)
polyamide-imide (PAI)	полиамидимид (конструкционный полимер; представитель группы полиамидов)	поліамідімід (конструкційний полімер; представник групи поліамідів)
polybutadiene	полибутадиен (представитель группы бутадиенов)	полібутадієн (представник групи бутадієнів)

polybutylene	полибутилен (представитель группы полимеров - бутилов)	полібутилен (представник групи полімерів - бутилів)
polybutylene terephthalate (PBT)	полибутилентерефталат (представитель группы бутиленов)	полібутилентерефталат (представник групи бутиленів)
polycarbonate (PC)	поликарбонат (представитель группы карбонатов; конструкционный полимер)	полікарбонат (конструкційний полімер; представник групи карбонатів)
polychloroprene (PCRP)	хлоропрен (представитель группы полимеров)	хлоропрен (представник групи полімерів)
polycrystalline structure, polycrystalline	поликристаллическая структура	полікристалічна структура
polyester - 50% glass fibers	композит на основе полиэфирной смолы, армированной стекловолокном (50%)	композит на основі поліефірної смоли, армованої скловолокном (50%)
polyester - 50% glassfabric	композит на основе полиэфирной смолы, армированной стеклотканью (50%)	композит на основі поліефірної смоли, армованої склотканиною (50%)
polyesters	полиэфиры (группа полимеров)	поліефіри (група полімерів)
polyether ether ketones (PEEK)	полиэфир эфиркетон (представитель группы [сложных эфиров])	поліефір ефіркетон (представник групи полімерів [складних ефірів])
polyethylene (PE) (HD, LD, UHMW)	полиэтилен (ПЭ) – продукт полимеризации этилена [высокой плотности, низкой плотности, сверхвысокой молекулярной массы]	поліетилен (ПЕ) – продукт полімеризації етилену [високої густини, низької густини, надвисокої молекулярної маси]
polyethylene terephthalate (PET)	полиэтилен терефталат (представитель группы полиэфиров)	поліетилен терефталат (представник групи поліефірів)
polygonization	полигонизация	полігонізація
polyimide (PI)	полиимид (конструкционный полимер; представитель группы полиимидов)	поліімід (конструкційний полімер; представник групи поліімідів)
polyisobutylene	полиизобутилен	поліізобутилен
polyisoprene	полиизопрен (представитель группы углеводородов)	поліізопрен (представник групи вуглеводнів)
polymerization	полимеризация	полімеризація
polymer-matrix composite (PMC)	композиционный материал с полимерной матрицей	композиційний матеріал з полімерною матрицею
polymers	полимеры (класс материалов)	полімери (клас матеріалів)
polymethyl pentene	полиметилпентан (группа полимеров)	поліметилпентан (група полімерів)
polymethylmetacrylate (PMMA) (*syn.* organic glass)	полиметилметакрилат, плексиглас, полимерный материал общего назначения, органическое стекло	поліметилметакрилат, плексиглас, полімерний матеріал загального призначення, органічне скло
polymorphic (polymorphous) transformation	полиморфное превращение	поліморфне перетворення
polymorphism	полиморфизм	поліморфізм
polyphase system	многофазная система, полифазная система	багатофазна система, поліфазна система
polyphenol	полифенол (представитель группы полимеров-фенолов)	поліфенол (представник групи полімерів-фенолів)
polyphenylene oxide (PPO)	полифенилоксид (представитель группы ароматических углеводородов – термопластичный материал, близкий по свойствам к нейлону)	поліфенілоксид (представник групи ароматичних вуглеводнів – термопластичний матеріал, близький за властивостями до нейлону)
polyphenylene sulfide (PPS)	полисульфон (конструкционный полимер – ароматический полиэфир со звеньями оксида серы)	полісульфон (конструкційний полімер – ароматичний поліефір з ланцюгами оксиду сірки)
polypropylene (PP)	полипропилен (полимер общего назначения)	поліпропілен (полімер загального призначення)
polystyrene (PS)	полистирол (полимер общего назначения)	полістирол (полімер загального призначення)
polysulfone	полисульфон (термопластичный материал)	полісульфон (термопластичний матеріал)
polytetrafluoroethylene (PTFE) (*syn.* fluoroplastic, teflon)	политетрафторэтилен (ПТФЭ, тефлон, фторопласт-4), представитель группы полимеров-полиэтиленов	політетрафторетилен (ПТФЕ, тефлон, фторопласт-4), представник групи полімерів-поліетиленів
polytrifluorochloroethylene (PTFCE)	политрифторхлорэтилен (представитель группы полиэтиленов)	політрифторхлоретилен (представник групи поліетиленів)
polyurethanes (PUR)	полиуретаны (группа полимеров)	поліуретани (група полімерів)
polyvinyl (PV)	поливинил (представитель группы поливинилов; конструкционный полимер)	полівініл (представник групи полівінілів; конструкційний полімер)
polyvinyl acetate (PVAc)	поливинил ацетат	полівініл ацетат

polyvinyl chloride (PVC plastic)	поливинилхлорид (представитель группы поливинилов; конструкционный полимер)	полівінілхлорид (представник групи полівінілів; конструкційний полімер)
polyvinyl fluoride (PVF)	поливинилфторид (представитель группы поливинилов; конструкционный полимер)	полівінілфторид (представник групи полівінілів; конструкційний полімер)
polyvinylidene chloride (PVDC)	поливинилэденхлорид (представитель группы полимеров - поливинихлоридов)	полівініледенхлорид (представник групи полімерів-полівінілхлоридів)
polyvinylidene fluoride (PVDF)	поливинилэденфторид (синтетический полимер-пьезоэлектрик)	полівиниледенфторид (синтетичний полімер-п'єзоелектрик)
pop marks, (pl)	метки, наносимые на базовой длине обраца для испытаний	позначки, які наносять на базовій довжині зразка для випробувань
porcelain, china, china white	фарфор	порцеляна
pore	пора (пустота в сплошном материале)	пора (пустота в суцільному матеріалі)
pores coalescence	коалесценция пор, рост пор	коалесценція пор, збільшення пор, зростання пор
porolon (*syn.* foam rubber)	поролон	поролон
porosity	пористость	пористість
porous plastic (*syn.* foam plastic)	поропласт (подгруппа пенопластов)	поропласт (підгрупа пінопластів)
postyield gage	тензодатчик для измерения больших пластических деформаций (до 15%)	тензодатчик для вимірювання великих пластичних деформацій (до 15%)
potassium (chemical element № 19)	калий (химический элемент № 19)	калій (хімічний елемент № 19)
pound force, lbf	фунт-сила (единица измерения силы, равная 4,448 Н)	фунт-сила (одиниця вимірювання сили, що дорівнює 4,448 Н)
pound per square inch, psi	фунт на квадратный дюйм (единица измерения напряжений, равная 6895 Па)	фунт на квадратний дюйм (одиниця вимірювання напружень, що дорівнює 6895 Па)
pound, lb	фунт (единица измерения массы, равная 0,454 кг)	фунт (одиниця вимірювання маси, що дорівнює 0,454 кг)
pouring (*syn.* teeming)	разлив стали (процесс)	розлив сталі (процес)
powder	порошок, пудра	порошок, пудра
powder metallurgy (PM)	порошковая металлургия	порошкова металургія
power, W	мощность, Вт	потужність, Вт
praseodymium (chemical element № 59)	празеодим (химический элемент № 59)	празеодім (хімічний елемент № 59)
precipitate (*syn.* sediment)	включение, выделение, новая фаза [в процессе фазового превращения]	вкраплення, виділення, нова фаза [у процесі фазового перетворення]
precipitation	осаждение, выделение новой фазы	осадження, виділення нової фази
precipitation hardening	дисперсионное упрочнение, дисперсионное твердение	дисперсійне зміцнення, дисперсійне твердіння
precipitation-hardening alloy (material), ageing alloy (material)	дисперсионно-твердеющий сплав (материал), стареющий сплав (материал)	дисперсійно-тверднучий сплав (матеріал), сплав (матеріал), що старіє
precursor	прекурсор, полуфабрикат для получения углеродных волокон	прекурсор, полуфабрикат для одержання вуглецевих волокон
prepreg	препрег (предварительно пропитанный связующим армирующий материал, но полностью не заполимеризованный)	препрег (попередньо просочений зв’язуючим армуючий матеріал, але повністю не заполімеризований)
pressing, compacting, compaction (ceramics)	компактирование, прессование [керамики]	компактування, пресування [кераміки]
primary bonds	первичные связи	первинні зв'язки
primary microconstituent, primary phase	первичная фаза	первинна фаза
principal quantum number	главное квантовое число	головне квантове число
processing	обработка, переработка	обробка, переробка
promethium (chemical element № 61)	прометий (химический элемент № 61)	прометій (хімічний елемент № 61)
proof test	контрольное, проверочное испытание	контрольне, перевірне випробування
propagating crack, running crack	распространяющаяся трещина	тріщина, що поширюється
property	свойство, характеристика, качество [конструкционного материала]	властивість, характеристика, якість [конструкційного матеріалу]
proportional limit, Pa	предел пропорциональности, Па	границя пропорційності, Па
protactinium (chemical element № 91)	протактиний (химический элемент № 91)	протактиній (хімічний елемент № 91)

protective coating, protective layer	защитное покрытие, защитный слой	захисне покриття, захисний шар
proton	протон	протон
p-type semiconductor	полупроводник p-типа [с дырочной проводимостью]	напівпровідник p-типу [з дірковою провідністю]
pulforming	пултрузия с последующим формованием	пултрузія з наступним формуванням
pull-out	отделение (вытягивание) волокна от матрицы [при разрушении композита], выдергивание крепежного элемента из соединения	витягання волокна [в композиційному матеріалі], витягування волокна
pultrusion	пултрузия (протяжка пропитанного связующим волокнистого наполнителя через фильеру с последующим отверждением в термокамере)	пултрузія (протягування волокневого наповнювача, просоченого зв'язуючим, крізь фільєру з наступним затвердненням у термокамері)
pure metal	чистый, беспримесный металл	чистий, бездомішковий метал
pyroceramics	пирокерамы (группа ситаллов)	пірокерами (група ситалів)
pyrolizing	науглероживание (насыщение волокон углеродом)	навуглецьовування (насичення волокон вуглецем)
pyrosilicates	пиросиликаты (солеобразные химические соединения, содержащие оксид кремния и обладающие высокой температурной стойкостью)	піросилікати (солеподібні хімічні сполуки, які містять оксид кремнію та мають високу температурну стійкість)

Q

quantum shell	электронная оболочка [атома]	електронна оболонка [атома]
quartz glass, silica glass, vitreous silica glass	кварцевое стекло	кварцове скло
quench crack, quenching crack	закалочная трещина	гартівна тріщина
quench hardening	повышение твердости в результате закалки	підвищення твердості внаслідок загартовування
quench, quenching	закалка (действие), закаливание (быстрое охлаждение), упрочнение (вид термообработки)	загартування (дія), загартовування (швидке охолодження), зміцнення (вид термообробки)

R

radian, rad	радиан (единица измерения плоских углов), рад	радіан (одиниця вимірювання плоских кутів), рад
radiation (*syn.* emission)	лучеиспускание, излучение	випромінювання
radiation damage	радиационное повреждение (вид разрушения)	радіаційне пошкодження (вид руйнування)
radiography (*syn.* X-ray radiography)	рентгенография (метод неразрушающего контроля)	рентгенографія (метод неруйнівного контролю)
radium (chemical element № 88)	радий (химический элемент № 88)	радій (хімічний елемент № 88)
radon (chemical element № 86)	радон (химический элемент № 86)	радон (хімічний елемент № 86)
random copolymer	сополимер со случайным расположением мономеров вдоль основной цепи	сополімер з випадковим розміщенням мономерів уздовж основного ланцюга
random fiber-reinforced composite, random fibre-reinforced composite	композиционный материал с хаотичным армированием, композитный материал с хаотичным армированием	композиційний матеріал з хаотичним армуванням, композитний матеріал з хаотичним армуванням
random reinforcement	хаотическое армирование	хаотичне армування
range of plasticity, plastic range	область пластичности (область пластического деформирования)	область пластичності (область пластичного деформування)
rare-earth metal	редкоземельный элемент (РЗЭ), редкоземельный металл (РЗМ)	рідкісноземельний елемент (РЗЕ), рідкісноземельний метал (РЗМ)
rate of deformation	скорость деформирования	швидкість деформування
ratio	отношение	відношення
raw material	сырой, нетермообработанный материал, сырье	сирий, нетермооброблений матеріал, сировина
rebounding hammer	установка для определения твердости по отскоку	установка для визначення твердості за величиною відскоку

recalescence	рекалесценция	рекалесценція
recovery	отдых, возврат [кристаллов]	відпочинок [кристалів] (спочинок [кристалів], спочин [кристалів])
recrystallization	рекристаллизация (образование и рост одних кристаллических зерен за счет соседних зерен той же фазы), вторичная кристаллизация, перекристаллизация	рекристалізація (утворення та ріст одних кристалічних зерен за рахунок сусідніх зерен тієї ж фази), вторинна кристалізація, перекристалізація, повторна кристалізація
recrystallization annealing	рекристаллизационный отжиг	рекристалізаційний відпал
recrystallization lowest temperature, recrystallization threshold	температурный порог рекристаллизации	температурна межа рекристалізації
recrystallization temperature	температура рекристаллизации	температура рекристалізації
red hardness	красностойкость (свойство инструментальной стали)	червоностійкість (властивість інструментальної сталі)
reduction	химическое восстановление, раскисление	хімічне відновлення, розкиснення
reduction-oxidation, redox	восстановительно-окислительный процесс	відновлювально-окисний процес
refining	рафинирование, очистка [по химическому составу]	рафінування, очищення [за хімічним складом]
reflection coefficient, reflectivity	коэффициент отражения, отражательная способность	коефіцієнт відбиття, відбивна здатність
refraction	лучепреломление, рефракция	променезаломлення, рефракція
refraction coefficient (*syn.* index of refraction, refractive index)	коэффициент преломления [среды]	коефіцієнт заломлення [середовища]
refractory metal, high melting point metal, refractory	1) тугоплавкий металл 2) огнеупор, огнеупорный материал	1) тугоплавкий метал 2) вогнетрив, вогнетривкий матеріал
Rehbinder effect, effect of strength reduction through adsorption	Ребиндера эффект (снижение прочности за счет адсорбции)	Ребіндера ефект (зниження міцності за рахунок адсорбції)
reinforcement, reinforcing	армирование	армування
reinforcing fiber, reinforcing fibre	армирующее волокно	армувальне волокно
relaxation time	время релаксации	час релаксації
relief	1) рельеф [поверхности или излома]; 2) снятие, снижение (напр. напряжений)	1) рельєф [поверхні або зламу]; 2) зняття, зниження (напр. напружень)
relief annealing, stress relief annealing	отжиг для снятия напряжений	відпал для зняття напружень
reluctance, magnetic resistance, H^{-1}	релуктанс, магнитное сопротивление $Гн^{-1}$	релуктанс, магнітний опір, $Гн^{-1}$
remainder, residue	остаток [в химических реакциях]	решта, залишок [у хімічних реакціях]
remanent (residual) magnetization, A/m	остаточная намагниченность, А/м	залишкова намагніченість, А/м
remanent (residual) polarization, C/m^2	остаточная поляризованность, $Кл/м^2$	залишкова поляризованість, $Кл/м^2$
remanent induction, remanence, T	остаточная магнитная индукция, остаточная намагниченность, Тл	залишкова магнітна індукція, залишкова намагніченість, Тл
remelting	переплавка, переплав	переплавка, переплав
repeat distance (*syn.* interatomic spacing)	расстояние между атомами в данном направлении	відстань між атомами у даному напрямку
repulsive force	сила межатомного отталкивания	сила міжатомного відштовхування
residual (irreversible) strain	остаточная (необратимая) деформация	залишкова (необоротна) деформація
residual stresses	остаточные напряжения	залишкові напруження
resin	смола	смола
resin binder	смоляная связка, смоляное связующее	смоляна зв'язка, смоляне зв'язне
resistance	сопротивление (электрическое, магнитное)	опір (електричний, магнітний)
resolved shear stress	теоретическое сопротивление сдвигу [в монокристалле]	теоретичний опір зсуву [у монокристалі]
resonant machine	машина для испытания на усталость в резонансном режиме	машина дли випробування на міцність при втомленості в резонансному режимі
rhenium (chemical element № 75)	рений (химический элемент № 75)	реній (хімічний елемент № 75)
rhodium (chemical element № 45)	родий (химический элемент № 45)	родій (хімічний елемент № 45)

rhombic (orthorhombic) crystal system	ромбическая кристаллографическая система, сингония	ромбічна кристалографічна система сингонія
rhombohedral crystal system	тригональная (ромбоэдрическая) кристаллографическая система (сингония)	тригональна (ромбоедрична) кристалографічна система (сингонія)
rigidity	жесткость	жорсткість
ripple, ripple markings	1) волнистость (дефект прокатки) 2) чешуйчатость [сварного шва]	1) хвилястість (дефект прокатки) 2) лускатість [зварного шва]
Rockwell hardness test	Роквелла метод испытаний на твердость	Роквелла метод випробувань на твердість
Rockwell hardness, Rockwell hardness number, conical indentation hardness	твердость по Роквеллу (HR)	твердість за Роквеллом (HR)
rod, bar	стержень, пруток	стрижень, пруток
room temperature, indoor temperature	комнатная температура	кімнатна температура
rosette	розетка, многорешетчатый тензодатчик	розетка, багаторешітчастий тензодатчик
rotating cantilever beam tester (machine)	машина для усталостных испытаний консольного типа	машина для випробування на міцність при втомленості консольного типу
rotating two-supported beam tester (machine)	машина для усталостных испытаний с образцом, исследуемым в условиях чистого изгиба	машина дли випробування на міцність при втомленості зі зразком, що досліджується в умовах чистого згину
roughness	шероховатость [поверхности]	шорсткість [поверхні]
roving	ровинг (жгут, пучок нитей)	ровінг (джгут, пучок ниток)
rubber (*syn.* caoutchouc)	натуральный каучук, резина	натуральний каучук, резина
rubidium (chemical element № 37)	рубидий (химический элемент № 37)	рубідій (хімічний елемент № 37)
rupture	разрыв, излом, разрушение [в частн. при ползучести]	розрив, злам, руйнування [зокрема, при повзучості]
rupture time	время разрушения при ползучести	час руйнування при повзучості
ruthenium (chemical element № 44)	рутений (химический элемент № 44)	рутеній (хімічний елемент № 44)
rutherfordium (*syn.* kurchatovium) (chemical element № 104)	резерфордий (химический элемент № 104)	резерфордій (хімічний елемент № 104)

S

safe stress (*syn.* allowable stress)	допускаемое напряжение	допустиме напруження
samarium (chemical element № 62)	самарий (химический элемент № 62)	самарій (хімічний елемент № 62)
sample (*syn.* specimen)	образец [для испытаний]	зразок [для випробувань]
sandwich structure, sandwich	многослойная, трехслойная (слоистая) структура	багатошарова, тришарова (шарувата) структура
saturated solution	насыщенный раствор	насичений розчин
saturation	насыщение	насичення
saturation induction, T	магнитная индукция насыщения, Тл	магнітна індукція насичення, Тл
scale	1) масштаб, шкала 2) окалина	1) масштаб, шкала 2) окалина
scale resistance	окалиностойкость	окалиностійкість
scale-resistant coating	окалиностойкое покрытие	окалиностійке покриття
scandium (chemical element № 21)	скандий (химический элемент № 21)	скандій (хімічний елемент № 21)
scattering ability	рассеивающая способность	розсіювальна здатність
schedule	график, документ	графік, документ
Schottky defect	Шоттки дефект (дефект кристаллической решетки)	Шотткі дефект (дефект кристалічної гратки)
scission	разрыв (обрыв) молекулярных цепей	розрив (обрив) молекулярних ланцюгів
scratch	царапина	подряпина
scratch resistance	сопротивление образованию задиров	опір утворенню задирів
scratching (*syn.* Mohs hardness test)	Мооса испытание на твердость [нанесением царапин на поверхность материала]	Мооса випробування на твердість [нанесенням подряпин на поверхню матеріалу]
screw dislocation, Burgers dislocation	винтовая дислокация, Бюргерса дислокация	гвинтова дислокація, Бюргерса дислокація

seaborgium (chemical element № 106)	сиборгий (химический элемент № 106)	сиборгій (хімічний елемент № 106)
secondary bond	вторичная связь [напр. Ван-дер-Ваальса]	вторинний зв'язок [напр. Ван-дер-Ваальса]
sediment	осадок	осад
sedimentation, settling	оседание, седиментация	осідання, седиментація
Seebeck effect	Зеебека ефект	Зеєбека ефект
seepage	абсорбция, впитывание, поглощение	абсорбція, вбирання, поглинання
seizure	схватывание, заедание	схоплювання, заїдання
seizure ability	схватываемость	здатність до схоплювання
selection process	процесс выбора (подбора) конструкционного материала	процес вибору (підбору) конструкційного матеріалу
selective corrosion	избирательная коррозия	вибірна корозія
selenium (chemical element № 34)	селен (химический элемент № 34)	селен (хімічний елемент № 34)
self-adjusting grip	самоустанавливающийся захват [испытательной машины]	самовстановлювальний затискач [випробувальної машини]
self-diffusion	самодиффузия	самодифузія
self-extinguishing (plastic)	самопогашающийся [пластик]	здатний до самогасіння [пластик]
self-ignition	самовоспламенение, самовозгорание	самозаймання, самозапалення
self-interstitial atom, self-interstitial	межузельный атом	міжвузловий атом
semiconductor, semiconducting material, semiconductive material	полупроводник, полупроводниковый материал, полупроводящий материал	напівпровідник, напівпровідниковий матеріал, напівпровідний матеріал
sensitivity	чувствительность	чутливість
service life (*syn.* durability, longevity, useful life)	долговечность, ресурс, срок службы, стойкость [инструмента]	довговічність, довгочасність, ресурс, термін служби, стійкість [інструмента]
service conditions	условия эксплуатации	умови експлуатації
service properties	эксплуатационные свойства	експлуатаційні властивості
serviceability	эксплуатационная пригодность, ремонтная технологичность, ремонтопригодность	експлуатаційна придатність, ремонтна технологічність, ремонтопридатність
shallow crack	плоская трещина	плоска тріщина
shape, form	форма, геометрическая конфигурация	форма, геометрична конфігурація
shear	срез, сдвиг (вид деформации)	зріз, зсув (вид деформації)
shear (*syn.* torsional) stress	касательное (сдвиговое) напряжение	дотичне (зсувне) напруження
shear lip	губа среза (участок вязкого разрушения в изломе образца)	губа зрізу (ділянка в'язкого руйнування в зламі зразка)
shear modulus	модуль сдвига	модуль зсуву
shear strain	сдвиговая деформация	деформація зсуву
shear strength, Pa	предел прочности при срезе, предел прочности при сдвиге, прочность при сдвиге, прочность при срезе, Па	границя міцності при зрізі, границя міцності при зсуві, міцність на зсув, міцність на зріз, Па
shear test	испытание на сдвиг, испытание на срез	випробування на зсув, випробування на зріз
shellac	природная, натуральная смола	природна, натуральна смола
shock (*syn.* impact)	удар	удар
shock resistance	сопротивление удару	опір ударові
shock wave	ударная волна, взрывная волна	ударна хвиля, вибухова хвиля
Shore durometer test	испытания на твердость по Шору	випробування на твердість за Шором
Shore hardness, Shore hardness number, dynamic ball indentation hardness	твердость по Шору, склерометрическая твердость	твердість за Шором, склерометрична твердість
short-range order	ближний порядок [в расположении атомов]	ближній порядок [у розміщенні атомів]
shrinkage cavity	усадочная раковина	усадочна раковина
shrinkage, shrinkage factor, shrinkage ratio	усадка, коэффициент усадки	усадка, коефіцієнт усадки
sialos	сиалиты	сіаліти
silica brick	силикатный кирпич	силікатна цегла
silica gel	силикагель	силікагель

silica, silicium dioxide, silicium oxide (SiO_2)	двуокись (диоксид) кремния, кремнезем (SiO_2)	двоокис (діоксид) кремнію, кремнезем (SiO_2)
silicate	силикат	силікат
silicate glass, soda-lime glass	силикатное стекло	силікатне скло
silicide	силицид	силіцид
silicon (chemical element № 14)	кремний (химический элемент № 14)	кремній (хімічний елемент № 14)
silicones	силиконы (группа полимеров)	силікони (група полімерів)
silver (chemical element № 47)	серебро (химический элемент № 47)	срібло (хімічний елемент № 47)
simple cubic crystal lattice, cubic crystal lattice (unit cell)	простая кубическая решетка (элементарная ячейка)	прості кубічні гратки (елементарна комірка)
simple monoclinic lattice (unit cell)	простая моноклинная решетка (элементарная ячейка)	прості моноклинні гратки (елементарна комірка)
simple rhombic (orthorhombic) lattice (unit cell)	простая ромбическая решетка (элементарная ячейка)	прості ромбічні гратки (елементарна комірка)
simple tetragonal lattice (unit cell)	простая тетрагональная решетка (элементарная ячейка)	прості тетрагональні гратки (елементарна комірка)
single crystal (*syn.* monocrystal)	монокристалл	монокристал
single-phase material	однофазный материал	однофазний матеріал
sinterability	спекаемость (свойство материала)	спікливість, здатність до спікання (властивість матеріалу)
sintered aluminium alloy	спеченный алюминиевый сплав (САС)	спечений алюмінієвий сплав (САС)
sintered aluminium powder (SAP)	спеченная алюминиевая пудра (САП)	спечена алюмінієва пудра (САП)
sintering (*syn.* firing) (ceramics)	спекание (технологическая операция в методе получения керамики), обжиг	спікання (технологічна операція в методі одержання кераміки), випал
size	размер, величина (безразмерная характеристика)	розмір, величина (безрозмірна характеристика)
sizing	аппретирование	апретування
slip line	линия сдвига, линия скольжения	лінія зсуву, лінія ковзання, смуга зсуву, смуга ковзання
slip plane	плоскость скольжения	площина ковзання
slip step	элементарный (единичный) сдвиг	елементарний (одиничний) зсув
slip system	система скольжения (совокупность направлений и плоскостей скольжения)	система ковзання (сукупність напрямів і площин ковзання)
small angle grain boundary	малоугловая граница зерна	малокутова границя зерна
smelt	плавка, сплавление [материалов]	плавка, сплавлення [матеріалів]
soda lime silicate (*syn.* soda lime glass)	силикатное стекло	силікатне скло
sodium (chemical element № 11)	натрий (химический элемент № 11)	натрій (хімічний елемент № 11)
soft magnetic material, soft magnet	магнитно-мягкий материал	магнітно-м'який матеріал
softening	размягчение	розм'якшення
softening point (glass)	температура размягчения [стекла]	температура розм'якшення [скла]
sol gel processing	золь-гель процесс (метод получения керамики из органических растворов)	золь-гель процес (метод одержання кераміки з органічних розчинів)
sol, colloidal solution	золь, коллоидный раствор	золь, колоїдний розчин
soldering	пайка; пайка мягким (легкоплавким) припоем	паяння легкоплавким припоєм
solid	твердое тело	тверде тіло
solid solution	твердый раствор	твердий розчин
solid solution strengthening	твердорастворное упрочнение [материала]	твердорозчинне зміцнення [матеріалу]
solid state	твердое состояние	твердий стан
solidification	затвердевание, твердение (неок.)	тверднення, твердіння (незак.)
solidification shrinkage	усадка при затвердевании [расплавленного металла]	усадка при твердненні [розплавленого металу]
solidifying temperature, solidifying point, solidification temperature, solidification point	температура затвердевания, точка затвердевания	температура тверднення, точка тверднення

solidus, solidus curve	солидус (линия или поверхность конца кристаллизации на фазовой диаграмме)	солідус (лінія або поверхня кінця кристалізації на фазовій діаграмі)
solubility	растворимость	розчинність
solubility limit	предел растворимости	границя розчинності
solute	растворенное вещество	розчинена речовина
solution	раствор	розчин
solvent	растворитель	розчинник
sorbate	сорбат	сорбат
sorbent	сорбент	сорбент
sorbite	сорбит	сорбіт
sorption	сорбция	сорбція
sound absorption coefficient, acoustic absorptivity	коэффициент звукопоглощения	коефіцієнт звукопоглинання, коефіцієнт звуковбирання
space charge, C	объемный заряд, пространственный заряд, Кл	об'ємний заряд, просторовий заряд, Кл
spalling	1) отслаивание [в виде мелких частиц] 2) растрескивание, выкрашивание [с поверхности]	1) відшаровування [у вигляді дрібних часток] 2) розтріскування, викришування [з поверхні]
specific gravity (*syn.* specific weight)	1) удельный вес 2) вес единицы объема материала по отношению к весу такого же объема воды	1) питома вага 2) вага одиниці об'єму матеріалу у відношенні до ваги такого ж об'єму води
specific heat (*syn.* mass heat capacity), J/(kg·K)	удельная теплоемкость, Дж/(кг·K)	питома теплоємність, Дж/(кг·K)
specific heat at constant pressure (*syn.* heat capacity at constant pressure), J/(kg·K)	удельная теплоемкость при постоянном давлении, Дж/(кг·K)	питома теплоємність при постійному тиску, Дж/(кг·K)
specific heat at constant volume (*syn.* heat capacity at constant volume), J/(kg·K)	удельная теплоемкость при постоянном объеме, Дж/(кг·K)	питома теплоємність при постійному об'ємі, Дж/(кг·K)
specific humidity	удельная влажность	питома вологість
specific modulus (*syn.* specific stiffness)	удельная жесткость	питома жорсткість
specific strength	удельная прочность	питома міцність
specific weight (*syn.* specific gravity)	удельный вес	питома вага
specimen (*syn.* test sample)	образец материала для механических испытаний	зразок матеріалу для механічних випробувань
spectroscopy, spectroscopic analysis, spectrum analysis	спектроскопия, спектральный анализ	спектроскопія, спектральний аналіз
spheroidal graphite (SG) iron	чугун с шаровидным графитом, ковкий чугун	чавун з кульоподібним графітом, ковкий чавун
spin quantum number	спиновое квантовое число	спінове квантове число
sponge	губка, пористый материал, поропласт, металл губчатой структуры	губка, пористий матеріал, поропласт, метал губчастої структури
sponginess	рыхлость	пухкість
spongy iron, iron sponge	губчатое железо, железная губка	губчасте залізо, губчате залізо, залізна губка
spraying	1) разбрызгивание, распыление [жидкостей] 2) нанесение покрытий напылением	1) розбризкування, розпилення [рідин] 2) нанесення покриттів шляхом напилення
stabilizer, stabilizing addition, stabilizing additive (alloys)	стабилизирующая добавка, стабилизирующая присадка, карбидообразующий легированный элемент [в сплавах]	стабілізуюча добавка, стабілізуюча присадка, карбідоутворюючий легований елемент [у сплавах]
stabilizer, stabilizing addition, stabilizing additive (polymers)	стабилизирующая добавка, стабилизирующая присадка, антикоагулятор, противокоагулирующее средство [в полимерах]	стабілізаційна добавка, стабілізаційна присадка, стабілізаційний додаток [у полімерах]
stacking fault, stacking defect	дефект упаковки (нарушение последовательности кристаллографических плоскостей)	дефект упаковки, дефект пакування (порушення послідовності кристалографічних площин)
stacking sequence	1) порядок расположения кристаллографических плоскостей (характеристика материала) 2) схема армирования композиционного материала	1) порядок розміщення кристалографічних площин (характеристика матеріалу) 2) схема армування композиційного матеріалу
stainless steel	нержавеющая сталь	нержавіюча сталь
staple	рубленое (штапельное) волокно	рублене (штапельне) волокно
state	состояние, положение [системы]	стан, положення [системи]

static deformation	статическое деформирование, статическая деформация	статичне деформування, статична деформація
static test, statical test	статическое испытание	статичне випробування
stationary platen (member)	неподвижная опора испытательной машины [на которой установлен неподвижный захват для фиксации образца для испытаний]	нерухома опора випробувальної машини [на якій встановлений нерухомий затискач для фіксації зразка для випробувань]
steady state	установившееся состояние [системы]	сталий стан [системи]
steady-state diffusion	стационарная, установившаяся диффузия	стаціонарна, усталена дифузія
steady-state wear	установившееся изнашивание	усталене зношування, усталене спрацьовування
steel	сталь	сталь
steel fiber, steel fibre	стальное волокно	сталеве волокно
steel mill products (*syn.* cast steel shapes)	продукты сталелитейного производства	продукти сталеливарного виробництва
steel specification (*syn.* steel grading)	маркировка сталей	маркування сталей
steel-making process, steel making (*syn.* steel production)	производство стали	виробництво сталі
steem corrosion, steem attack	пароводяная коррозия	пароводяна корозія
Stefan - Boltzmann constant	Стефана - Больцмана постоянная	Стефана - Больцмана стала
stereoisomerism (polymers)	стереоизомерия [полимеров]	стереоізомерія [полімерів]
stereospecificity	стереорегулярность (свойство структуры полимеров)	стереорегулярність (властивість структури полімерів)
stiffener	загуститель	загусник
stiffness (*syn.* rigidity)	жесткость (свойство материала)	жорсткість (властивість матеріалу)
stoichiometric composition, stoichiometry	стехиометрический состав, стехиометрия	стехіометричний склад, стехіометрія
stoichiometric intermetallic compound	стехиометрическое интерметаллическое соединение (т.е. без нарушения стехиометрического состава)	стехіометрична інтерметалічна сполука (тобто без порушення стехіометричного складу)
strain	деформация, относительное удлинение (общее понятие)	деформація, відносне видовження (загальний термін)
strain aging	деформационное старение	деформаційне старіння
strain energy, J	энергия деформации, работа деформации, Дж	енергія деформації, робота деформації, Дж
strain gage (*syn.* extensometer)	датчик деформации, тензодатчик	датчик деформації, тензодатчик
strain hardening (*syn.* work hardening)	деформационное упрочнение	деформаційне зміцнення
strain rate, 1/s	скорость деформации, измеряется в 1/с	швидкість деформації, вимірюється в 1/с
strain, engineering	деформация, условная	деформація, умовна
strain, true	деформация, истинная	деформація, істинна
strain-hardening coefficient	коэффициент деформационного упрочнения	коефіцієнт деформаційного зміцнення
strength	прочность	міцність
strengthening, hardening, reinforcement	упрочнение [материала]	зміцнення [матеріалу]
stress	механическое напряжение	механічне напруження
stress concentration	концентрация напряжений	концентрація напружень
stress concentration factor	коэффициент концентрации напряжений	коефіцієнт концентрації напружень
stress concentrator (*syn.* stress raiser)	концентратор напряжений	концентратор напружень
stress corrosion	коррозия под действием напряжений	корозія під дією напружень
stress corrosion cracking (SCC)	коррозионное растрескивание, растрескивание в результате коррозии	корозійне розтріскування, розтріскування внаслідок корозії
stress corrosion cracking (SCC) threshold	порог коррозионной стойкости	межа коррозійної стійкості
stress free tensile specimen	образец для испытания на растяжение, в котором сняты остаточные напряжения	зразок для випробування на розтяг, в якому зняті залишкові напруження
stress intensity factor	коэффициент интенсивности напряжений	коефіцієнт інтенсивності напружень

stress raiser (*syn.* stress concentrator)	концентратор напряжений	концентратор напружень
stress relaxation	релаксация напряжений (уменьшение напряжений со временем)	релаксація напружень (зменшення напружень за часом)
stress, engineering	напряжение, условное	напруження, умовне
stress, true	напряжение, истинное	напруження, істинне
stress-corrosion fracture	коррозионно-механическое разрушение (разрушение, вызванное действием механических напряжений в условиях коррозии)	корозійно-механічне руйнування (руйнування, що спричинене дією механічних напружень в умовах корозії)
stressed state	напряженное состояние	напружений стан
stress-number curve (diagram)	диаграмма напряжение – число циклов до разрушения (Веллера кривая)	діаграма напруження – число циклів до руйнування (Вьоллера крива)
stress-rupture curve (diagram)	диаграмма связи напряжений ползучести и времени разрушения	діаграма зв'язку напружень повзучості та часу руйнування
stress-rupture fracture	разрушение материала вследствие ползучести [как правило при длительной эксплуатации при повышенной температуре]	руйнування матеріалу через повзучість [як правило, при довгочасній експлуатації при підвищеній температурі]
stress-rupture strength (*syn.* creep strength), Pa	предел ползучести, прочность при ползучести, Па	границя повзучості, міцність при повзучості, Па
stress-strain curve (diagram)	условная диаграмма растяжения, кривая зависимости напряжений от деформаций	умовна діаграма розтягу, крива залежності напружень від деформацій
stretching	удлинение (абсолютная величина изменения длины), вызванное внешней растягивающей силой	видовження (абсолютна величина зміни довжини), спричинене розтяжною силою
striation	бороздка (напр. усталости)	борозна (напр. утомленості)
strontium (chemical element № 38)	стронций (химический элемент № 38)	стронцій (хімічний елемент № 38)
structural alloy, engineering alloy	конструкционный сплав	конструкційний сплав
structural cast iron	конструкционный чугун	конструкційний чавун
structural ceramics	конструкционная керамика	конструкційна кераміка
structural component, structure component (*syn.* constituent) (of an alloy)	структурная составляющая [сплава]	структурна складова [сплаву]
structural composite	конструкционный композиционный материал	конструкційний композиційний матеріал
structural steel	конструкционная сталь	конструкційна сталь
structural transformation	структурное превращение	структурне перетворення
structure	структура, строение [материала]	структура, будова [матеріалу]
structure defect	дефект структуры	дефект структури
structure-dependent properties, structure-sensitive properties	структурно-чувствительные свойства [материала]	структурно-чутливі властивості [матеріалу]
styrene	стирол (представитель группы полимеров - стиролов)	стирол (представники групи полімерів - стиролів)
styrene acrylonitrile	акрилонитрилстирол (полимерный материал) (сополимер полистирола, обладающий повышенной ударной вязкостью, термостойкостью и стойкостью к действию окружающей среды)	акрилонітрилстирол (полімерний матеріал) (сополімер полістиролу, що має підвищену ударну в'язкість, термостійкість і стійкість до дії навколишнього середовища)
styrene butadiene rubber (SBR)	бутадиенстирольный каучук	бутадієнстирольний каучук
styrene polyester	стирольный полиэфир	стирольний поліефір
subcritical temperature	докритическая температура	докритична температура
sublimation	1) сублимация 2) возгонка	1) сублімація 2) перегін
sublimation ablation, ablation by sublimation	абляция сублимацией	абляція шляхом сублімації
sublimation temperature	1) температура сублимации 2) температура возгонки	1) температура сублімації 2) температура перегону
subshell	энергетический подуровень [электронной оболочки атома]	енергетичний підрівень [електронної оболонки атома]
substitution alloy	сплав замещения	сплав заміщення
substitution(al) solid solution	твердый раствор замещения	твердий розчин заміщення
substitutional atom (defect)	атом замещения, точечный дефект	атом заміщення, точковий дефект

substraction solid solution	твердый раствор вычитания	твердий розчин віднімання
substructure	субструктура	субструктура
sulfur, sulphur (chemical element № 16)	сера (химический элемент № 16)	сірка (хімічний елемент № 16)
superalloy	суперсплав, сверхсплав	суперсплав, надсплав
superconducting coating, superconducting layer	сверхпроводящее покрытие, сверхпроводящий слой	надпровідне покриття, надпровідний шар
superconductivity	сверхпроводимость	надпровідність
superconductivity critical temperature	критическая температура сверхпроводимости, температура исчезновения сверхпроводимости	критична температура надпровідності, температура зникнення надпровідності
superconductivity transition temperature	температура (точка) перехода в сверхпроводящее состояние	температура (точка) переходу в надпровідний стан
supercooling	переохлаждение [материала]	переохолодження [матеріалу]
superfinish, superfinishing	суперфиниширование	суперфінішування
super-hard material, ultra-hard material	сверхтвердый материал (СТМ)	надтвердий матеріал (НТМ)
superplastic material	сверхпластичный материал	надпластичний матеріал
superplasticity	сверхпластичность	надпластичність
supersaturated solid solution	пересыщенный твердый раствор	перенасичений твердий розчин
surface finish (*syn.* surface roughness)	чистота поверхности	чистота поверхні
surface free energy, J	поверхностная свободная энергия, Дж	поверхнева вільна енергія, Дж
surface lay	направление шероховатости поверхности [образованное обрабатывающим инструментом]	напрям шорсткості поверхні [утворений обробним інструментом]
surface layer	поверхностный слой	поверхневий шар
surface relief	рельеф поверхности	рельєф поверхні
surface roughness (*syn.* surface finish)	чистота поверхности	чистота поверхні
surface strain hardening	поверхностный наклеп	поверхневий наклеп
surface-active substance	поверхностно-активное вещество (ПАВ)	поверхнево-активна речовина (ПАР)
surfacing	1) плакирование 2) наплавка поверхности	1) плакування 2) наплавка поверхні
susceptibility	восприимчивость	сприйнятливість
suspension	суспензия, взвесь	суспензія
sweating coating	потеющее покрытие	покриття, що пітніє
swelling	набухание материала	набрякання матеріалу
syndiotactic	синдиотактический полимер	синдіотактичний полімер
syngony	сингония	сингонія
system of units	система единиц	система одиниць

T

tacticity	тактическое строение полимера	тактична будова полімера
tangential stress	тангенциальное напряжение, касательное напряжение	тангенціальне напруження, дотичне напруження
tantalum (chemical element № 73)	тантал (химический элемент № 73)	тантал (хімічний елемент № 73)
tape	лента	стрічка
tapered specimen (*syn.* dog-bone shape specimen)	образец для испытания на растяжение (имеет суживающийся участок для локализации шейки)	зразок для випробування на розтяг (має ділянку завуження для локалізації шийки)
tear-strength	сопротивление раздиранию [у композитов]	опір роздиранню [у композитів]
technetium (chemical element № 43)	технеций (химический элемент № 43)	технецій (хімічний елемент № 43)
technical data	технические характеристики	технічні характеристики
teeming (*syn.* pouring)	разливка стали (процесс)	розливання сталі (процес)
teflon (*syn.* polytetrafluoroethylene)	тефлон, политетрафторэтилен	тефлон, політетрафторетилен
tellurium (chemical element № 52)	теллур (химический элемент № 52)	телур (хімічний елемент № 52)

temper, tempering	1) отпуск, отпускать 2) твердость [стали] после отпуска 3) улучшение структуры металла термообработкой 4) содержание углерода (о стали) 5) добавка, легирующие металлы 6) смесь, состав, раствор 7) марка стального листа 8) дрессировать [стальные листы]	1) відпуск, відпускати 2) твердість [сталі] після відпуску 3) поліпшення структури металу термообробкою 4) вміст вуглецю (про сталь) 5) добавка, легуючі метали 6) суміш, склад, розчин 7) марка сталевого листа 8) дресирувати [сталеві листи]
temperature	температура	температура
tenacity	вязкость, клейкость, тягучесть, способность к сцеплению, связность [полимеров]	в'язкість, клейкість, тягучість, здатність до зчеплення, зв'язність [полімерів]
tensile load	растягивающая сила (в частности, создаваемая силонагружающим устройством испытательной машины (гидравлическим, рычажным или др.))	розтягальна сила (зокрема, створювана силонавантажуючим пристроєм випробувальної машини (гідравлічним, ричажним та ін.))
tensile strength (*syn.* ultimate strength), Pa	предел прочности при растяжении, прочность при растяжении, Па	границя міцності при розтягуванні, міцність при розтягуванні, Па
tensile test (*syn.* tension test)	испытание на растяжение	випробування на розтягування
tensile tester (*syn.* tensile testing machine)	машина для испытаний на растяжение (разрывная машина)	машина для випробувань на розтягання (розривна машина)
tensile testing machine (*syn.* tensile tester)	машина для испытаний на растяжение (разрывная машина)	машина для випробувань на розтягання (розривна машина)
tension-compression fatigue testing machine	установка для испытания на усталость при растяжении-сжатии	установка для випробування на втомленість при розтяганні-стисканні
terbium (chemical element № 65)	тербий (химический элемент № 65)	тербій (хімічний елемент № 65)
ternary phase diagram	фазовая диаграмма состояния трехкомпонентной системы	фазова діаграма стану трикомпонентної системи
terpolymer	тример (тройной сополимер)	тример (потрійний сополімер)
tesla, T	тесла (единица измерения магнитной индукции), Тл	тесла (одиниця вимірювання магнітної індукції), Тл
test (*syn.* testing)	испытания материала [с целью экспериментального установления количественной меры его того или иного свойства]	випробування матеріалу [з метою експериментального встановлення кількісної міри його тієї чи іншої властивості]
test sample (*syn.* specimen)	образец материала для механических испытаний	зразок матеріалу для механічних випробувань
tester	1) испытательная машина 2) измеритель	1) випробувальна машина 2) вимірювач
tetragonal crystal system	тетрагональная кристаллографическая система (сингония)	тетрагональна кристалографічна система (сингонія)
tetragonal lattice (unit cell)	тетрагональная решетка (элементарная ячейка)	тетрагональні гратки (елементарна комірка)
textolite	текстолит	текстоліт
texture	текстура	текстура
thallium (chemical element № 81)	таллий (химический элемент № 81)	талій (хімічний елемент № 81)
thermal conductive alloy, heat conductive alloy	теплопроводящий сплав	теплопровідний сплав
thermal conductive coating, heat conductive coating, heat conductive layer, thermal conductive layer	теплопроводящее покрытие, теплопроводящий слой	теплопровідне покриття, теплопровідний шар
thermal crack, heat crack	термотрещина	термотріщина
thermal cycling	термоциклирование	термоциклування
thermal energy (BTU-in english system or joules in SI)	тепловая энергия (в британских единицах теплоты или в джоулях в системе СИ)	теплова енергія (у британських одиницях теплоти або в джоулях у системі СІ)
thermal equilibrium, heat equilibrium	тепловое равновесие, термическое равновесие	теплова рівновага, термічна рівновага
thermal expansion	термическое расширение, тепловое расширение	термічне розширення, теплове розширення
thermal expansion coefficient (volume), K^{-1}	температурный коэффициент объемного расширения, $К^{-1}$	температурний коефіцієнт об'ємного розширення, $К^{-1}$
thermal fatigue	термоусталость, термическая усталость	термовтомленість, термічна втомленість
thermal insulation	теплоизоляция	теплоізоляція
thermal shock resistance	термостойкость, стойкость к термоудару	термостійкість, стійкість проти термоудару

thermal shock resistant coating	термостойкое покрытие	термостійке покриття
thermal shock, heat shock	термоудар, тепловой удар, термический удар	термоудар, тепловий удар, термічний удар
thermal stress, temperature stress	термическое напряжение, температурное напряжение, тепловое напряжение	термічне напруження, температурне напруження, теплове напруження
thermochemical treatment, chemical heat treatment	химико-термическая обработка (ХТО)	хіміко-термічна обробка (ХТО)
thermocouple, thermal converter, thermal element, thermoelement, thermojunction	термопара, термопреобразователь, термоэлектрический элемент, термоэлемент	термопара, термоперетворювач, термоелектричний елемент, термоелемент
thermodiffusion	термодиффузия	термодифузія
thermodynamic potential	термодинамический потенциал	термодинамічний потенціал
thermoelectromotive force, thermo-emf, V	термоэлектродвижущая сила, термо-ЭДС, В	термоелектрорушійна сила, термо-ЕРС, В
thermomechanical treatment	термомеханическая обработка (ТМО)	термомеханічна обробка (ТМО)
thermoplastic polymer, thermoplastic	термопластичный полимер, термопласт	термопластичний полімер, термопласт
thermosetting polymer, thermoset	термореактивный полимер, реактопласт	термореактивний полімер, реактопласт
thickness	толщина	товщина
thinner	разбавитель	розріджувач
thixotropy	тиксотропность (свойство жидкостей, лаков и красок)	тиксотропність (властивість рідин, лаків та красок)
thorium (chemical element № 90)	торий (химический элемент № 90)	торій (хімічний елемент № 90)
thulium (chemical element № 69)	тулий (химический элемент № 69)	тулій (хімічний елемент № 69)
tie line (*syn.* conoda)	конода (отрезок, параллельный оси концентрации, соединяющий линии ликвидус и солидус на фазовой диаграмме состояния)	конода (відрізок, паралельний осі концентрації, що з'єднує лінії ліквідус і солідус на фазовій діаграмі стану)
time-temperature-transformation diagram (TTT diagram), isothermal austenite transformation diagram	диаграмма изотермического превращения аустенита	діаграма ізотермічного перетворення аустеніту
tin (chemical element № 50)	олово (химический элемент № 50)	олово (хімічний елемент № 50)
tin plating, tin coating, tinning	лужение	лудіння, лудження
tip (of a crack)	вершина [трещины]	вершина [тріщини]
titanium (chemical element № 22)	титан (химический элемент № 22)	титан (хімічний елемент № 22)
tolerance	допуск	допуск
tool ceramics	инструментальная керамика	інструментальна кераміка
tool steel	инструментальная сталь	інструментальна сталь
torsion test	испытание на кручение	випробування на крутіння
torsional strength, twisting strength, Pa	предел прочности при кручении, прочность при кручении, Па	границя міцності при крученні, міцність при крученні, Па
total solidification time	время полного затвердевания [расплава]	час повного затверднення [розплаву]
toughness	вязкость [твердого тела]	в'язкість [твердого тіла]
tow	жгут из волокон	джгут з волокон
toxicity	токсичность [вещества]	токсичність [речовини]
transcrystalline corrosion	транскристаллитная коррозия	транскристалітна корозія
transcrystalline fracture, transgranular fracture	внутризеренное разрушение, внутрикристаллитное разрушение, транскристаллитное разрушение	внутрішньозеренне руйнування, внутрішньокристалітне руйнування, транскристалітне руйнування
transformation	превращение	перетворення
transformation point, transition point	точка перехода, точка превращения	точка переходу, точка перетворення
transformation temperature	температура превращения	температура перетворення
transistor	транзистор	транзистор
transition	переход из одного состояния в другое	перехід з одного стану в інший
transition element (metal)	переходной элемент (металл)	перехідний елемент (метал)
transition temperature	температура перехода	температура переходу

translucence	светопропускание, просвечивание (полу)прозрачность	світлопропускання, просвічування (напів)прозорість
transparency, transparence	прозрачность, оптическая прозрачность	прозорість, оптична прозорість
trapping	захват, улавливание [атомов, электронов]	захват, уловлювання [атомів, електронів]
treatment	обработка (придание требуемых свойств)	обробка (надання потрібних властивостей)
tribotechnical cast iron	триботехнический (антифрикционный) чугун	триботехнічний (антифрикційний) чавун
tribotechnical coating, tribotechnocal layer	триботехническое покрытие, триботехнический слой	триботехнічне покриття, триботехнічний шар
triclinic crystal system	триклинная кристаллографическая система (сингония)	триклинна кристалографічна система (сингонія)
triclinic lattice (unit cell)	триклинная решетка (элементарная ячейка)	триклинні гратки (елементарна комірка)
trifunctional mer	трифункциональность [мономера]	трифункціональність [мономера]
triple point	точка равновесного существования трех фаз	потрійна точка
troostite	троостит	троостит
true density	истинная плотность	справжня густина
true heat capacity	истинная теплоемкость	справжня теплоємність, дійсна теплоємність
true porosity	истинная пористость (доля закрытых пор в материале)	справжня пористість (доля закритих пор у матеріалі)
true strain	истинная деформация	справжня деформація
true stress	истинное напряжение [в процессе растяжения образца]	справжнє напруження [в процесі розтягування зразка]
true stress-strain diagram (curve)	истинная диаграмма растяжения	справжня діаграма розтягнення
tungsten (*syn.* wolfram) (chemical element № 74)	вольфрам (химический элемент № 74)	вольфрам (хімічний елемент № 74)
twin	двойник	двійник
twin boundary	двойниковая граница	двійникова межа
twinning	двойникование, образование двойников	двійникування, утворення двійників

U

u-gage	ненаклеиваемый, компенсационный тензодатчик	ненаклеюваний, компенсаційний тензодатчик
ultimate solubility	предельная растворимость	гранична розчинність
ultimate strain	предельная деформация	гранична деформація
ultimate stress, limiting stress	предельное напряжение	граничне напруження
ultimate tensile strength, Pa	предел прочности при растяжении, Па	границя міцності при розтяганні, Па
ultrasonic defectoscopy, ultrasonic inspection, ultrasonic testing	ультразвуковая дефектоскопия, УЗ дефектоскопия (метод неразрушающего контроля)	ультразвукова дефектоскопія, УЗ дефектоскопія (метод неруйнівного контролю)
unalloyed metal	нелегированный металл	нелегований метал
unary phase diagram	фазовая диаграмма состояния однокомпонентного материала	фазова діаграма стану однокомпонентного матеріалу
undercooling	переохлаждение	переохолодження [матеріалу]
undersintering	недопекание, неполное спекание	недопікання, неповне спікання
undersurface layer	подповерхностный слой, приповерхностный слой	підповерхневий шар, приповерхневий шар
unequiaxial grain	неравноосное зерно	нерівновісне зерно
unidirectional fiber-reinforced composite, unidirectional fibre-reinforced composite	композиционный материал с однонаправленным армированием	композиційний матеріал з односпрямованим армуванням
unidirectional reinforcement	однонаправленное армирование, армирование однонаправленными волокнами	однонапрямлене армування, армування однонапрямленими волокнами
unified numbering system (UNS) (USA)	универсальная система обозначения металлов и сплавов (США)	універсальна система позначення металів і сплавів (США)
unit cell (*syn.* crystall cell)	элементарная ячейка [кристаллической решетки]	елементарна комірка [кристалічних граток]

unlimited solubility	неограниченная расторимость	необмежена розчинність
unstable state	неустойчивое состояние	нестійкий стан
unsteady state	неустановившееся состояние	неусталений стан
ununbium (chemical element № 112)	унунбий (экартуть) (химический элемент № 112)	унунбій (екартуть) (хімічний елемент № 112)
ununhexium (chemical element № 116)	экаполоний (химический элемент № 116)	екаполоній (хімічний елемент № 116)
ununnilium (chemical element № 110)	унуннилий, дармштадтий (химический элемент № 110)	унуннілій, дармштадтій (хімічний елемент № 110)
ununoctium (chemical element № 118)	экаэманация (химический элемент № 118)	екаеманація (хімічний елемент № 118)
ununpentium (chemical element № 115)	экависмут (химический элемент № 115)	екавісмут (хімічний елемент № 115)
ununquadium (chemical element № 114)	унунквадий (экасвинец) (химический элемент № 114)	унунквадій (екасвинець) (хімічний елемент № 114)
ununseptium (chemical element № 117)	экаастат (химический элемент № 117)	екаастат (хімічний елемент № 117)
ununtrium (chemical element № 113)	унунтрий (экаталлий) (химический элемент № 113)	унунтрій (екаталій) (хімічний елемент № 113)
unununium (chemical element № 111)	унунуний (экназолото) (химический элемент № 111)	унунуній (еказолото) (хімічний елемент № 111)
uranium (chemical element № 92)	уран (химический элемент № 92)	уран (хімічний елемент № 92)
urea resin	карбамидная смола	карбамідна смола

V

vacancy	вакансия (точечный дефект в кристаллической решетке)	вакансія (точковий дефект у кристалічній гратці)
vacancy (substitutional) diffusion	диффузия по вакансионному механизму	дифузія за вакансійним механізмом
vacuum atomization	вакуумное распыление, распыление в вакуум	вакуумне розпилення, вакуумне розпилювання, вакуумне розпорошення, розпилення у вакуумі, розпилювання у вакуумі, розпорошення у вакуумі
vacuum degassing (VD)	вакуумная дегазация	вакуумна дегазація
vacuum infiltration	вакуумная пропитка	вакуумне просочення
vacuum refining	вакуумная очистка	вакуумне очищення
vacuum sintering	вакуумное спекание (спекание в вакууме)	вакуумне спікання, спікання у вакуумі
valence band (амер.), valency band (англ.)	валентная зона	валентна зона
valence electron	валентный электрон	валентний електрон
valency (англ.), valence (амер.)	валентность	валентність
Van der Waals bond (force)	Ван дер Ваальса связь (сила)	Ван дер Ваальсовий зв'язок (сила)
vanadium (chemical element № 23)	ванадий (химический элемент № 23)	ванадій (хімічний елемент № 23)
vapor (vapour)	пар, пары	пара, пари
vapor deposition	осаждение из газовой фазы	осадження з газової фази
vaporization	испарение	випаровування
vaporization temperature	температура испарения	температура випаровування
vaporous state	парообразное состояние	пароподібний стан
vapour-phase precipitation	конденсация из парогазовой фазы, осаждение из парогазовой фазы (метод получения порошков)	конденсація з парогазової фази, осадження з парогазової фази (метод одержання порошків), газофазний метод одержання порошків
Vickers hardness (HV), Vickers hardness number, diamond pyramid hardness, diamond pyramid number	твердость по Виккерсу (HV)	твердість за Віккерсом (HV)
Vickers hardness test (*syn.* diamond pyramid hardness test)	испытание материала на твердость по Виккерсу [вдавливанием алмазной пирамиды]	випробування матеріалу на твердість за Віккерсом [вдавлюванням алмазної піраміди]
vinyl	винил (полимер общего назначения, представитель группы винилов)	вініл (полімер загального призначення, представник групи вінілів)

vinylidene fluoride	винилиден фторид (полимер общего назначения, представитель группы винилов)	вініліден фторид (полімер загального призначення, представник групи вінілів)
viscoelasticity	вязкоупругость	в'язкопружність
vitreous silica	кварцевое стекло	кварцеве скло
vitrification	витрификация, стеклование	вітрифікація, склування
void, cavity, caverne	раковина, полость, пустота (дефект материала)	раковина, порожнина, пустота (дефект матеріалу)
volatility, volatileness	летучесть (свойство вещества)	леткість (властивість речовини)
volume	объем	об'єм
volume defect, 3D defect	объемный дефект, трехмерный дефект [кристалличной решетки]	об'ємний дефект, тривимірний дефект [кристалічної гратки]
volume diffusion	объемная диффузия	об`ємна дифузія
volume fraction of fibers, fiber volume fraction	объемная плотность волокон (отношение объема волокон к объему всего композита)	об'ємна густина волокон (відношення об'єму волокон до об'єму всього композиту)
vulcanization	вулканизация (процесс превращения каучука в резину)	вулканізація (процес перетворення каучуку в резину)

W

water absorption	водопоглощение (свойство материала)	водопоглинання (властивість матеріалу)
water hardening, water quenching	закалка в воде	гартування з охолодженням у воді, гартування у воді
water permeability	водопроницаемость	водопроникність
water-hardening steel	сталь, закаленная в воде	сталь, загартована у воді
watt, W	Ватт (единица измерения мощности), Вт	Ватт (одиниця вимірювання потужності), Вт
waveness	волнистость [поверхности материала]	хвилястість [поверхні матеріалу]
waviness height	высота профиля волны [волнистой поверхности материала]	висота профілю хвилі [хвилястої поверхні матеріалу]
waviness width	ширина профиля волны [волнистой поверхности материала]	ширина профілю хвилі [хвилястої поверхні матеріалу]
wear	механический износ	механічне зношування, спрацьовування
wear debris	продукты изнашивания, продукты износа	продукти зношування, продукти зносу, продукти спрацьовування
wear factor	коэффициент износа	коефіцієнт зношування
wear life	долговечность с учетом износа	довговічність з урахуванням спрацювання
wear resistance	износостойкость	зносостійкість
weathering steel	сталь, стойкая к атмосферной коррозии	сталь, стійка до атмосферної корозії
weber, Wb	Вебер (единица измерения магнитного потока), Вб	Вебер (одиниця виміру магнітного потоку), Вб
weight	вес	вага
weldability	свариваемость (свойство материала)	здатність до зварювання (властивість матеріалу)
welding	сварка (процесс)	зварювання (процес)
wet density	плотность материала с учетом содержащейся в нем влаги	щільність матеріалу з урахуванням вологи, що міститься у ньому
wet grinding, wet milling	мокрое измельчение, мокрый размол	мокре дрібнення, мокре подрібнення, мокрий розмел
wettability	смачиваемость (свойство материала)	змочуваність, здатність до змочування (властивість матеріалу)
whisker-reinforced composite	армированный усами композиционный материал, армированный усами композит	армований вусами композиційний матеріал, армований вусами композиційний матеріал
whiskers, monocrystalline fibres	усы, вискеры (монокристаллические волокна, нитевидные кристаллы)	вуса, віскери (монокристалічні волокна, ниткоподібні кристали)
white cast iron	белый чугун	білий чавун
white ceramics	белая керамика	біла кераміка
width	ширина	ширина
wood	дерево	дерево
work hardening	нагартовка, наклеп	нагартовування, наклеп

workability	обрабатываемость, пригодность к обработке	оброблюваність, здатність до обробки
working	обработка (общий термин)	обробка (загальний термін)
working point (glass)	температура формовки [стекла]	температура формовки [скла]
wrought alloy	деформируемый (ковочный) сплав	деформівний (кувальний) сплав

X

xenon (chemical element № 54)	ксенон (химический элемент № 54)	ксенон (хімічний елемент № 54)
x-rays	рентгеновские лучи	рентгенівські промені

Y

yarn	жгут, пучок нитей	джгут, пучок ниток
yield before break (fracture)	текучесть до трещины (принцип выбора материала при рациональном проектировании конструкций под давлением газа, учитывающий особую опасность последствий хрупкого разрушения)	текучість до тріщини (принцип вибору матеріалу при раціональному проектуванні конструкцій під тиском газу, що враховує особливу небезпечність наслідків крихкого руйнування)
yield strain	деформация предела текучести	деформація границі текучости
yield strength, yield point, yield stress, Pa	предел текучести, напряжение предела текучести, Па	границя текучості, напруження границі текучости, Па
yielding	текучесть (переход в пластическое состояние)	текучість (перехід до пластичного стану)
Young's modulus (*syn.* elasticity modulus), Pa	модуль (коэффициент) Юнга, модуль продольной упругости, Па	модуль (коефіцієнт) Юнга, модуль поздовжньої пружності, Па
ytterbium (chemical element № 70)	иттербий (химический элемент № 70)	ітербій (хімічний елемент № 70)
yttrium (chemical element № 39)	итрий (химический элемент № 39)	ітрій (хімічний елемент № 39)

Z

zinc (chemical element № 30)	цинк (химический элемент № 30)	цинк (хімічний елемент № 30)
zirconium (chemical element № 40)	цирконий (химический элемент № 40)	цирконій (хімічний елемент № 40)
zone refining	зонная очистка [сплава]	зонне очищення [сплаву]

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ФІЗИЧНІ ПРИНЦИПИ ВИБОРУ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

Редактори: Т.А. Ястремська, С.П. Гевло

Комп’ютерна верстка: Р.П. Шевчук

Зв. план, 2004
Підписано до друку 28.12.2004
Формат 60×84 1/16. Папір офс. № 2. Офс. друк.
Ум. друк. арк. 22,4. Обл.-вид. арк. 25,19. Наклад 200 прим.
Замовлення 583. Ціна вільна

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