LECTURE 10 Material Testing in Tension and Compression

1 Material Testing in Tension

Mechanical properties of materials are determined by testing the **specimens** of these materials which may have round or rectangular shape (see Figs 1–4).

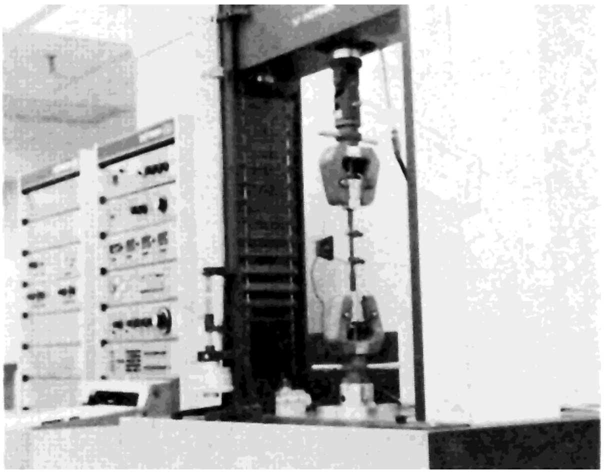

Fig. 1 Instron testing machine

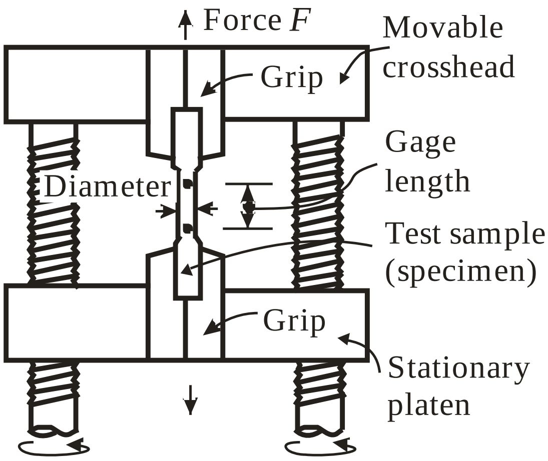

Fig. 2 Scheme of tensile testing machine

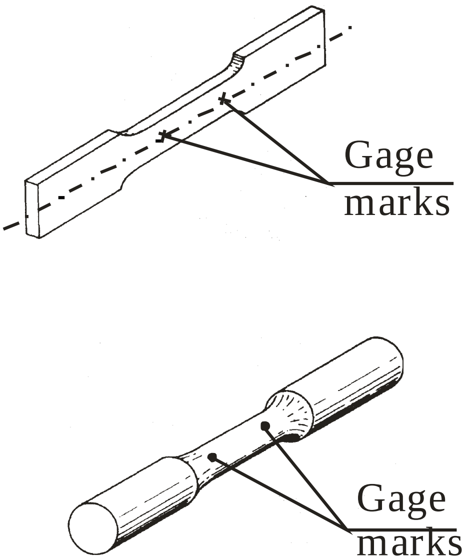

Fig. 3 Types of test specimens

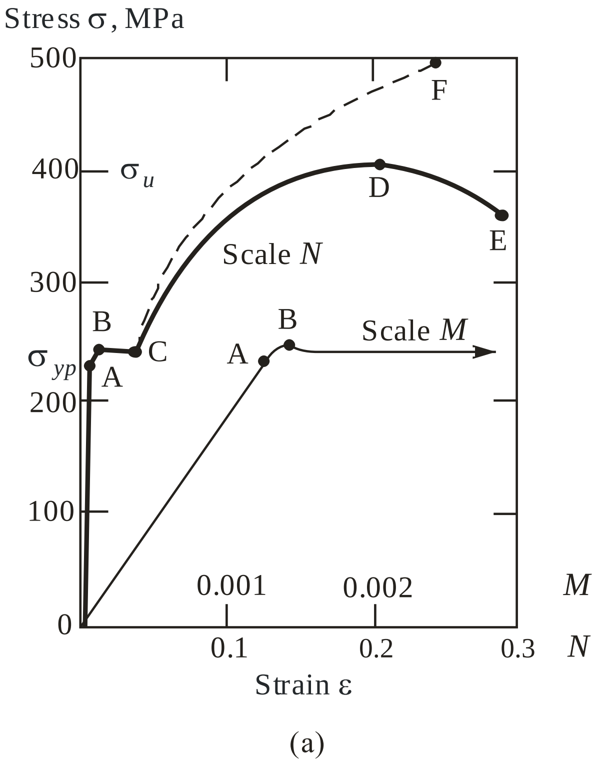

Fig. 4 Stress-strain diagram for ductile steel

The shapes and dimensions of test specimens are specified by a state standards. In Ukrainian industry they are shown in Fig. 5.

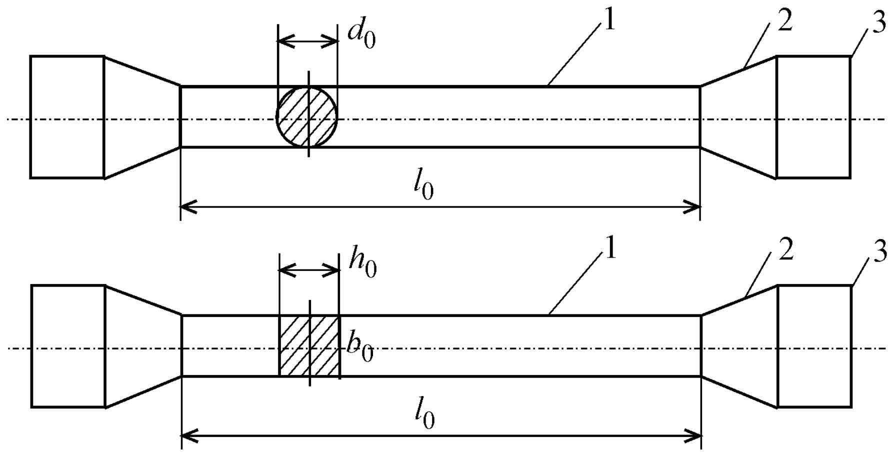

Fig. 5 1 – gauge portion, 2 – thickened portion which is needed for fastening in the grips of a testing machine.

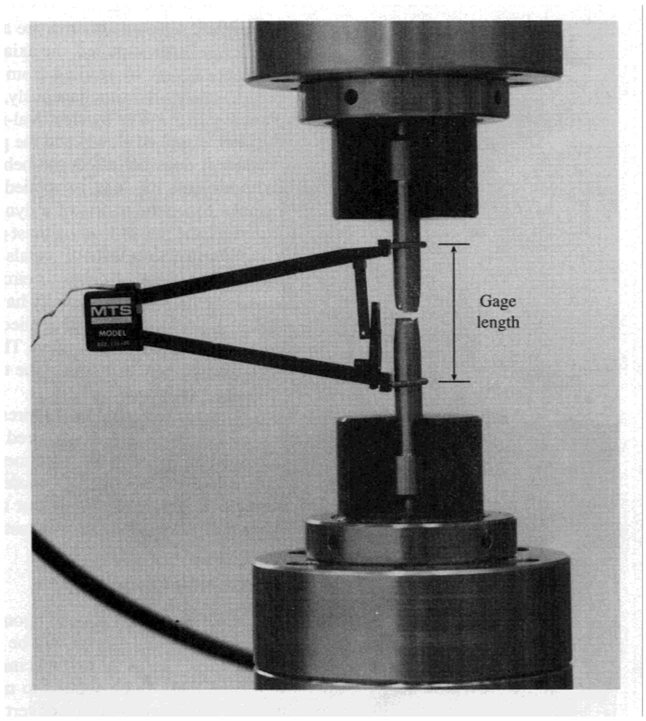

Fig. 6 Typical tensile-test specimen with extensometer attached. The specimen has just fractured in tension.

There exist normal specimens for which $l_0 = 10d_0$ and shortened specimens with $l_0 = 5d_0$. In the case of a rectangular cross section $l_0 = 11.3\sqrt{b_0 h_0}$ or $l_0 = 5.65\sqrt{b_0 h_0}$.

The shape of broken specimen depends on the type of material (ideally plastic, elastoplastic or absolutely brittle (see Figs. 6, 7)). For both, ductile and brittle materials, stress-strain diagram has original elastic portion with linear dependence between stresses and strains (see Fig. 8).

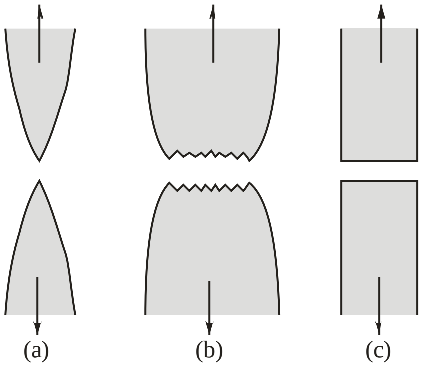

Fig. 7 Types of material failure: a) ideally plastic; b) elastoplastic c) absolutely brittle.

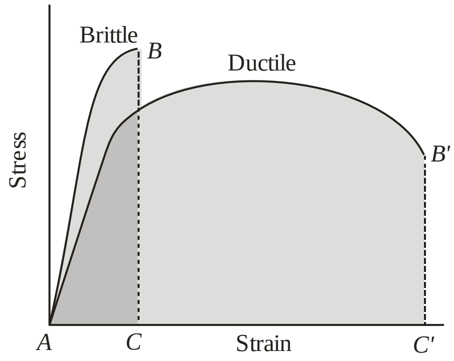

Fig. 8 Difference between stress-strain diagrams for brittle and ductile materials

2 Tension Test Diagram

Consider the main features of a **tension test diagram**. Tension test diagram for soft steel specimen (**ductile material**) in the coordinates F (force), Δl (absolute elongation) is shown in Fig. 9. This can be done in the case of **law-carbon steel**. The curve obtained may be divided into the following four zones.

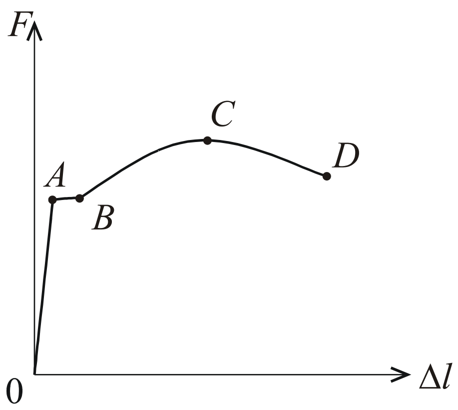

Fig. 9 Force-elongation diagram idealization

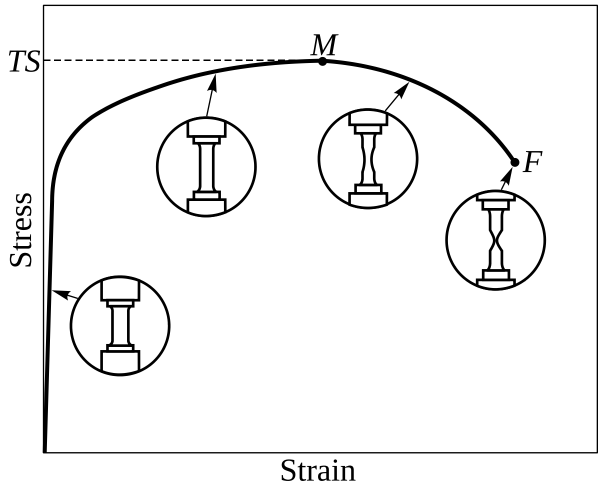

Fig. 10 Necking of the ductile material specimen in tension test

Fig. 11 Cup-and-cone failure of ductile material

Fig. 12 Brittle failure of cast iron

The zone *OA* is termed the **zone of elasticity** (see Fig. 9).

The zone *AB* is called the **yield area** (*AB* – zone of general yielding).

The zone *BC* is called the **zone of strain hardening**. At the stage of strain hardening the location of future rupture begins to show on the specimen (the local reduction of cross-sectional area in Fig. 10).

The portion *CD* of the curve is called the **zone of local yielding**. The point *D* corresponds to **fracture** of the specimen (see Figs 9, 11, 12).

If the test specimen is unloaded before it fractures (point *K* in Fig.13) then during unloading the relation between force *F* and elongation Δl will be represented by the straight line *KL*.

Experiments show that this straight line is parallel to the straight line *OA*. Upon unloading the elongation does not disappear completely. The segment $OM = \Delta l_{el} + \Delta l_{pl}$, where Δl_{pl} is **plastic elongation (plastic strain)**; Δl_{el} is **elastic elongation (elastic strain)**.

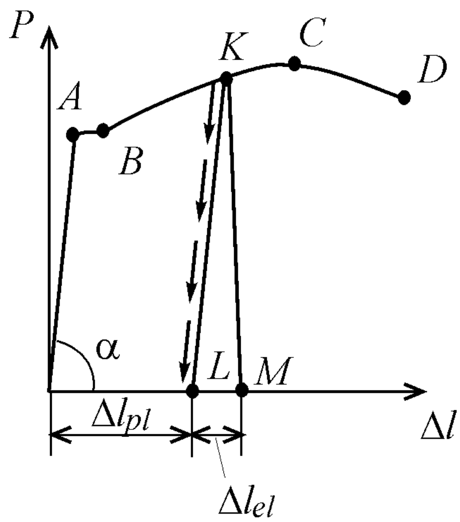

Fig. 13

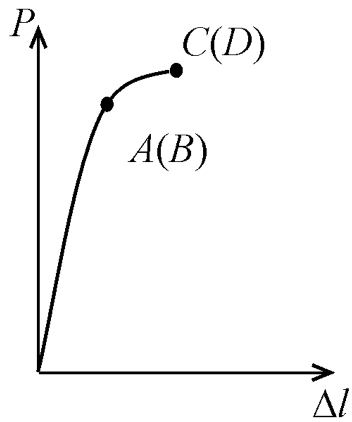

Fig. 14 Typical stress-strain diagram for a brittle material showing the proportional limit (point *A*) and fracture force (point *C*)

Fig. 14 shows a tension test diagram for **brittle material**. The presence of the yield area *AB* is not characterized for this material.

3 Basic Mechanical Characteristics of Materials

Let us redesign the tension test diagram $F = f(\Delta l)$ in the coordinates σ and ε. To do this we reduce the ordinates by a factor A_0 and the abscissas by a factor l_0, where A_0 and l_0 are respectively the **cross sectional area** and the **gauge length** of the specimen before loading:

$$\sigma_i = \frac{F_i}{A_0}, \tag{1}$$

$$\varepsilon_i = \frac{\Delta l_i}{l_0}. \tag{2}$$

Since these quantities A_0, l_0 are constant, the diagram $\sigma = f(\varepsilon)$ (Figs. 15, 16) has the same shape as the tension test diagram but it characterizes the properties of the materials.

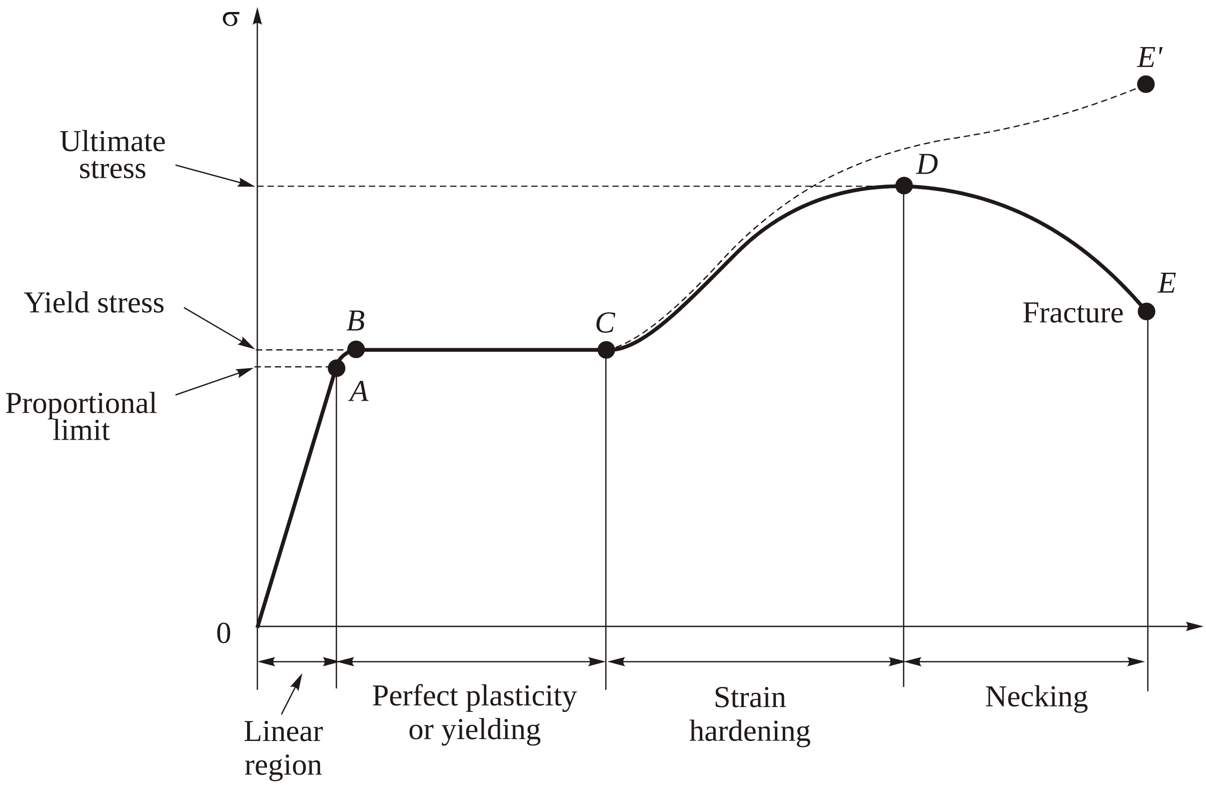

Fig. 15 Stress-strain diagram for a typical structural steel in tension (not to scale)

The maximum stress up to which the material follows Hook's law is called the **proportionality limit** σ_p (see Figs. 15, 16). The expression for σ_p is written as follows:

$$\sigma_p = \frac{F_p}{A_0}, \tag{3}$$

where F_p corresponds to the value of the force up to which the material follows Hooke’s law.

The **elastic limit** σ_e is defined as the maximum stress up to which no permanent deformation occurs (force F_e). The expression for σ_e is:

$$\sigma_e = \frac{F_e}{A_0}. \tag{4}$$

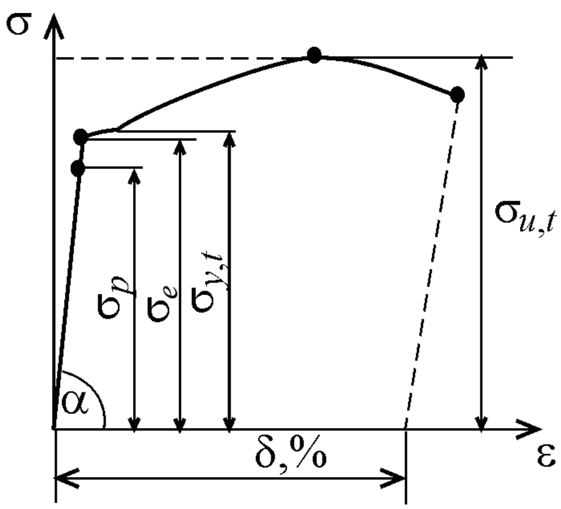

Fig. 16 Mechanical characteristics of ductile material determined by stress-strain diagram analysis.

The limit of elasticity means physically that a specimen returns to its original state upon removal of the load.

The stress σ_y is the **yield strength** at which the tested specimen is deformed without any noticeable increase of the load (see Figs. 15, 16). The expression for $\sigma_{y,t}$ is written as follows:

$$\sigma_{y,t} = \frac{F_y}{A_0}. \tag{5}$$

The force F_y corresponds to point *A* in Fig. 9.

For brittle materials we have got the **conventional yield strength (offset yield strength)** which is called $\sigma_{0,2}$.

The stress σ_u is the **ultimate strength**. The ratio of the maximum force to its original cross-sectional area and is termed the **ultimate tensile strength** (ultimate stress) and denoted by $\sigma_{u,t}$ ($\sigma_{u,c}$ in compression). ***It is important to note that $\sigma_{u,t}$ is not the stress at which the specimen fractures***.

The expression of the ultimate strength $\sigma_{u,t}$ is as follows:

$$\sigma_{u,t} = \frac{F_u}{A_0}. \tag{6}$$

The value of the force F_u corresponds to the point C in Fig. 9.

The **relative elongation on rupture** δ, is the ratio of the increment of specimen length to the initial length:

$$\delta = \frac{\Delta l}{l_0}100\% = \frac{l_r - l_0}{l_0}100\% \tag{7}$$

where l_r is the length of the specimen on rupture, and l_0 is its initial length before the load application.

The **relative contraction** ψ is the ratio of the difference between the initial and final cross-sectional area in the point of rupture to the initial cross-sectional area:

$$\psi = \frac{A_r - A_0}{A_0}100\%. \tag{8}$$

4 True Tension Test Diagram

In the vicinity of the ultimate stress, the reduction in area of the bar becomes clearly visible and a **necking** of the bar occurs (see Figs 6, 7, 11, 17). If the actual cross-sectional area at the narrow part of the neck is used to calculate the stress, the **true stress-strain curve** (the dashed line CE' in Fig. 15 or CD_1-line in Fig. 18) is obtained. Corresponding true stress is determined by the formula

$$\sigma_{true} = \frac{F_{D_1}}{A_r}, \tag{9}$$

where A_r is the cross-sectional area at the **neck** after rupture (see Fig. 18).

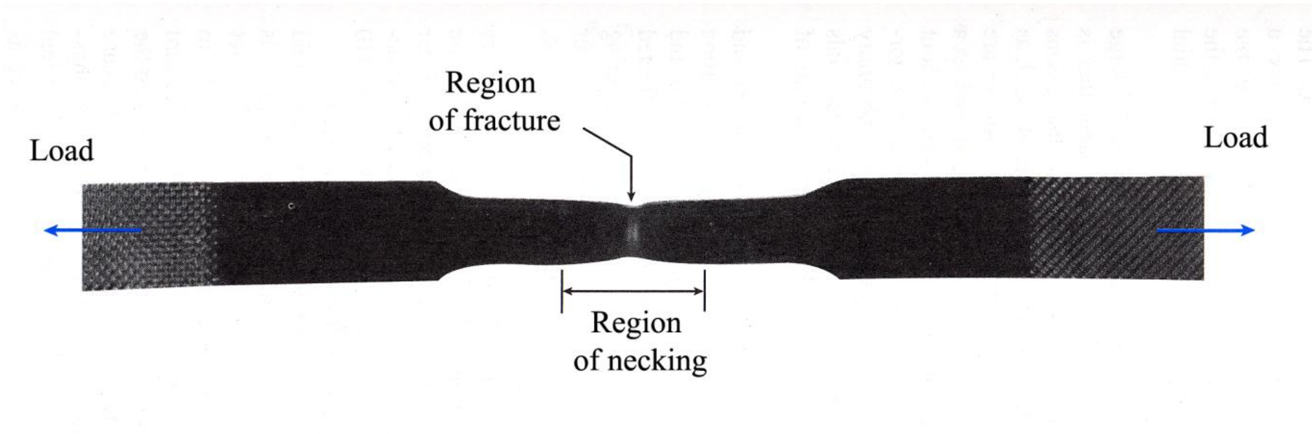

Fig. 17 Necking of a mild-steel bar in tension

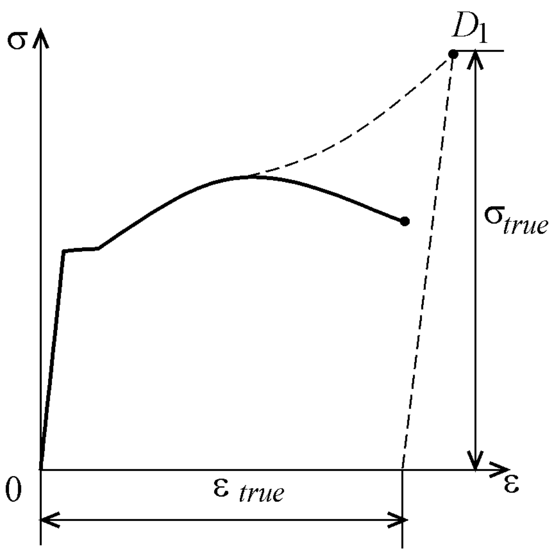

Fig. 18 True stress-strain diagram

The total load the bar can carry does indeed diminish after the ultimate stress is reached (as shown by curve *DE* in Fig. 15), but ***this reduction is due to the decrease in area of the bar and not to a loss in strength of the material itself***. In reality, the material withstands an increase in true stress up to failure (point E' in Fig. 15). Because most structures are expected to function at stresses below the proportional limit, the **conventional stress-strain curve** *OABCDE* (see Fig. 15), which is based upon the original cross-sectional area of the specimen and is easy to determine, provides satisfactory information for use in engineering design.

5 Offset Method

Structural steel is an alloy of iron containing about 0.2% carbon, and therefore it is classified as a low-carbon steel. With increasing carbon contactm, steel becomes less ductile but stronger (higher yield stress and higher ultimate stress). The physical properties of steel are also affected by heat treatment, the presence of other metals, and manufacturing processes such as rolling. Other materials that behave in a ductile manner (under certain conditions) include aluminum, copper, magnesium, lead, molybdenum, nickel brass, bronze, monel metal, nylon, and teflon.

Although they may have considerable ductility, aluminum alloys typically do not have a clearly definable yield point, as shown by the stress-strain diagram of Fig. 19. However, they do have an initial linear region with a recognizable proportional limit. Alloys produced for structural purposes have proportional limits in the range 70 to 410 MPa and ultimate stresses in the range 140 to 550 MPa.

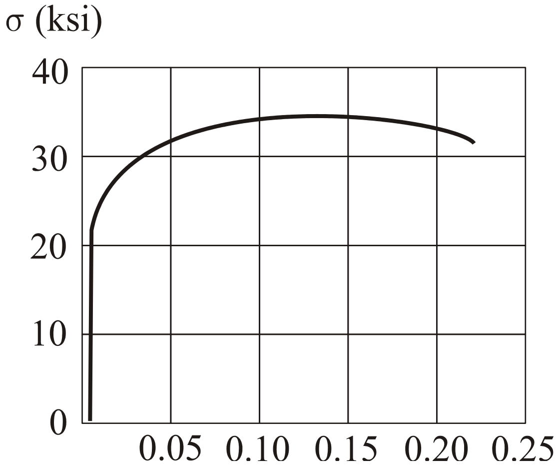

Fig. 19 Typical stress-strain diagram for an aluminum alloy

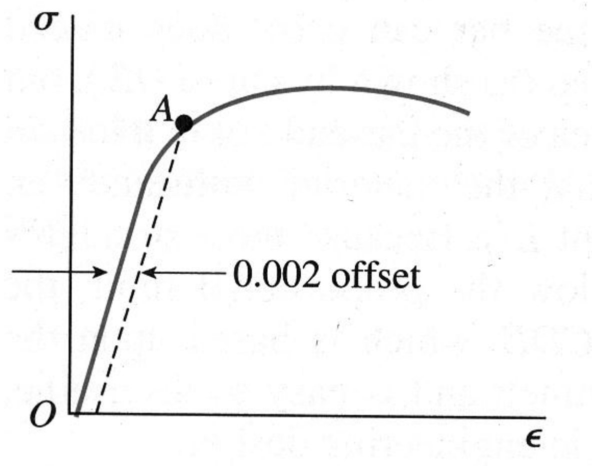

Fig. 20 Arbitrary yield stress determined by the offset method

When a material such as aluminum does not have an obvious yield point and yet undergoes large strains after the proportional limit is exceeded, an **arbitrary yield stress** may be determined by the **offset method**. A straight line is drawn on the stress-strain diagram parallel to the initial linear part of the curve (Fig. 20), but offset by some standard strain, such as 0.002 (or 0.2%). The intersection of the offset line and the stress-strain curve (point *A* in Fig. 20) defines the yield stress. Because this stress is determined by an arbitrary rule and is not an inherent physical property of the material, it should be distinguished from a true yield stress by referring to it as the **offset yield stress**. For a material such as aluminum, the offset yield stress is slightly above the proportional limit. In the case of structural steel, with its abrupt transition from the linear region to the region of plastic stretching, the offset stress is essentially the same as both the yield stress and the proportional limit.

6 Material Testing in Compression

In **compression test**, short cylindrical (square) specimens are used. Their height is not more than twice the diameter of the cross section:

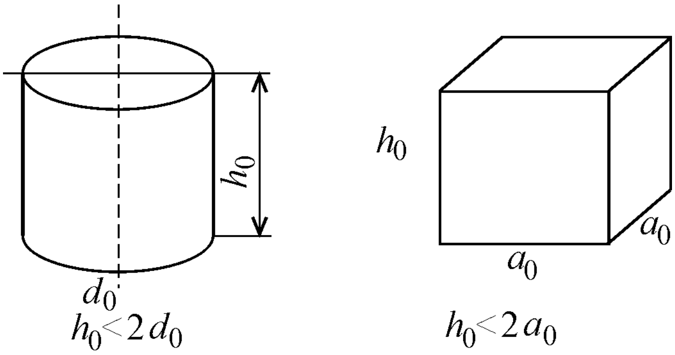

Fig. 21

The compression test diagram for low-carbon steel has a shape such as represented in Fig. 22.

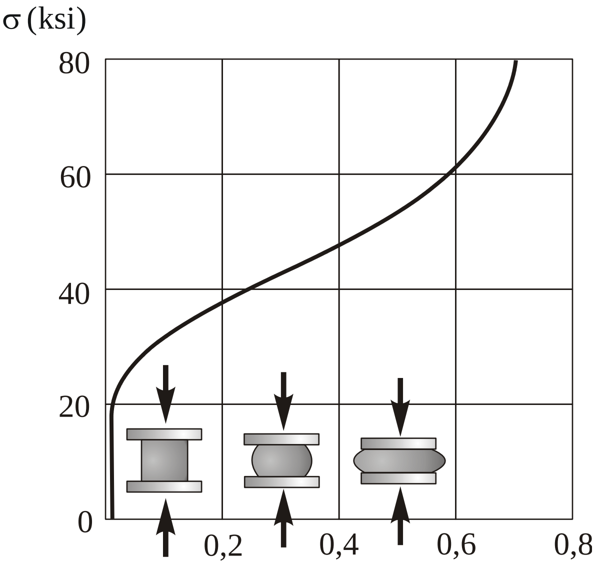

Fig. 22 Stress-strain diagram for cooper in compression

Stress-strain curves for materials in compression differ from those in tension. Ductile metals such as steel, aluminum, and cooper have proportional limits in compression very close to those in tension, and the initial regions of their compressive and tensile stress-strain diagrams are about the same. However, after yielding begins, the behavior is quite different, In a tension test, the specimen is stretched, necking may occur, and fracture ultimately takes place. When the material is compressed, it bulges outward on the sides and becomes barrel-shaped, because friction between the specimen and the end plates prevents lateral expansion. With increasing load, the specimen is flattened out and offers greatly increased resistance to further shortening, which means that the stress-strain curve becomes very steep). This characteristics are illustrated in Fig. 22, which shows a compressive stress-strain diagram for cooper. Since the actual cross-sectional area of a specimen tested in compression is larger than the initial area, the true stress in a compression test is smaller than the nominal stress.

Brittle materials loaded in compression typically have an initial linear region followed by a region in which the shortening increases at a slightly higher rate than does the load. The stress-strain curves for compression for compression and tension often have similar shapes, but the ultimate stresses in compression are much higher than those in tension. Also, unlike ductile materials, which flatten out when compressed, brittle materials actually brake at the maximum load.

A comparison of the ultimate tensile strength $\sigma_{u,t}$ and the ultimate compressive strength $\sigma_{u,c}$ of brittle materials shows that these materials possess, as a rule, higher strength indices in compression than in tension. The magnitude of the ratio

$$K = \sigma_{u,t} / \sigma_{u,c} = 0.2 \div 0.4 \text{ for cast iron.}$$

But for low-carbon steel $K = \dfrac{\sigma_{y,t}}{\sigma_{y,c}} \cong 1$.

7 Limiting Stress. Allowable Stress

It is customary to take either the yield strength $\sigma_{y,t}$ (for the ductile material) or the ultimate tensile strength $\sigma_{u,t}$ (for the brittle material) as the limiting stress $\sigma_{\lim}$.

The quantity
$$[\sigma] = \frac{\sigma_{lim}}{n}. \tag{10}$$

is called the **allowable stress**:

(a) for the ductile material
$$[\sigma] = \frac{\sigma_{y,t}}{n}; \tag{11}$$

(b) for the brittle material $$[\sigma]=\frac{\sigma_{u,t}}{n},\qquad (12)$$

where n is a number greater, than unit. It is called the **factor of safety**.

Mechanical characteristics for main classes of engineering materials are shown in Table 1.

Table 1 Yield Strength, Tensile Strength, and Ductility (Percent Elongation) Values for Main Classes of 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)
• 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 rolled			
• 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)	—
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)			
• 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
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)	—

Concrete[b]	—	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)	—
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
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
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.

8 Strain Hardening

If the material remains within the elastic rauge, it can be loaded, unloaded, and loaded again without significantly changing the behavior (Fig. 23, left). However when loaded into the plastic range, the internal structure of the material is altered and its properties change. It was observed earlier that a permanent strain exists in the specimen after unloading from the plastic region (Fig. 23, right). Now suppose that material is reloaded after such an unloading (Fig. 24). The new loading begins at point *C* on the diagram and continues upward to point *B*, the point at which unloading began during the first loading cycle. The material then follows the original stress-strain diagram toward point *F*. Thus, for the second loading, we can imagine that we have a new stress-strain curve with its origin at point *C*. During the second loading, the material behaves in a linearly elastic manner from *C* to *B* with the slope on line *CB*, being the same as the slope of the tangent to the original loading curve at the origin *O*. The proportional limit is now at point *B*, which is at a higher stress than the original elastic limit (point *E*). Thus, by stretching a material such as steel or aluminum into the inelastic or plastic range, the properties of the material are changed – the linearly elastic region in increased, the proportional limit is raised, and the elastic limit is raised. However, the ductility is reduced because in the "new material" the amount of yielding beyond the elastic limit (from *B* to *F*) is less than in the original material (from *E* to *F*). This effect is called **strain hardening**.

Note, that the study of material behavior under various environmental and loading conditions is an important branch of applied mechanics

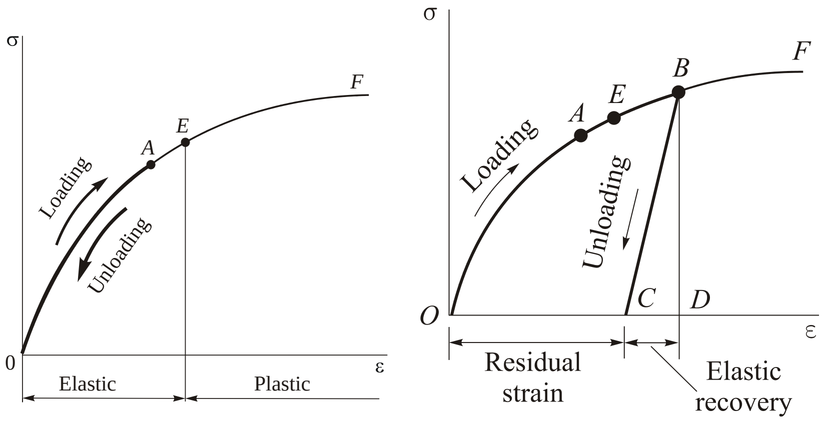

Fig. 23 Stress-strain diagrams illustrating: (a) elastic behavior, and (b) partially elastic behavior

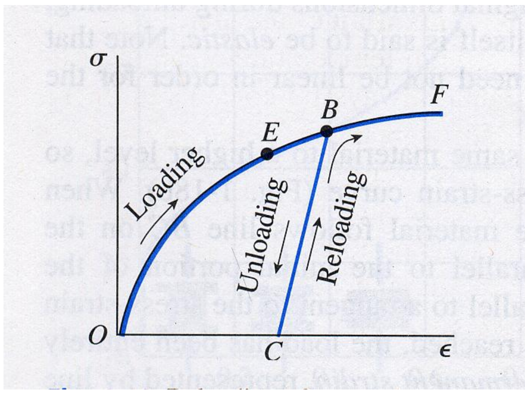

Fig. 24 Reloading of a material and raising of the elastic and proportional limits