Chapter 1
Mechanical Properties of Engineering Materials: Relevance in Design and Manufacturing

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Abstract The chapter provides an introduction to mechanical engineering, covering fundamental concepts of mechanical properties of materials and their use in the design and manufacturing. It first explains the notion of mechanical properties of materials and then elaborates on the proper definition of most relevant properties as well as materials testing to obtain these properties. The role of mechanical properties at the design stage in form of the design criterion is explained. The use of material properties to assess equivalent stress and strain in complex loading conditions is revealed. At the manufacturing stage, the notion of additive (material is added to the workpiece), neutral (the volume of the workpiece is preserved), and substantive (the volume of the workpiece is reduced) processes is introduced. The relevant properties of materials in the neutral (forming) and substantive (cutting) processes are considered.

Keywords Engineering materials · Basic mechanical properties
Design and manufacturing · Complex state of stress · Failure criteria

1 Conceptual Introduction

The term "knowledge-based economy" results from a fuller recognition of the role of knowledge and technology in economic growth. Knowledge in technology has always been central to economic development. But only over recent years has its relative importance been recognized, just as that importance is growing. This is because, in today's rapidly changing product marketplace, the critical requirements for product quality, productivity, and reliability have been becoming the most powerful driving force behind any new product design and development.

Products achieve success through a combination of sound technical design and effective manufacturing process to achieve the requirements set by the design. The

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amalgam creates product quality, which is the way material and processes are used to provide functionality, usability, and satisfaction in ownership. This chapter aims to explain (not just formally lists as it commonly done in the reference literature) the basic mechanical properties of part materials in terms of their relevance in the design and manufacturing. Although the material of this chapter is kept at the introductory level following the known Einstein's famous saying: "Make it as simple as possible, but not simpler," the chapter presents unique synergetic approach unifying the design and manufacturing stage in terms of material properties. Moreover, the standard designation and proper definition of the terms related to mechanical properties of engineering materials provided in the chapter aim to provide an essential help to beginners in mechanical engineering.

2 Mechanical Properties of Materials Reported in Reference Sources

2.1 Properties Commonly Reported in Reference Sources

Physical properties (e.g., density, thermal conductivity, specific heat, anisotropy, electrical conductivity, magnetic properties, type of bonds) are usually associated with a particular materials type (steel, wood, plastic, oxide ceramic, etc.), whereas mechanical properties are mostly attributed to a particular grade within the chosen material type (e.g., mild steel 1012, tool steel H13, oak wood).

Mechanical properties of engineering materials are obtained from testing. Standard ASTM E6.14406-1 "Terminology Relating to Methods of Mechanical Testing" covers the principal terms relating to methods of mechanical testing of solids. The general definitions are restricted and interpreted, when necessary, to make them particularly applicable and practicable for use in standards requiring or relating to mechanical tests. These definitions are published to encourage uniformity of terminology in product specifications.

The most common and very useful test of mechanical properties of materials is a tension (a.k.a. tensile) test. It is carried out on a tensile machine (Fig. 1a) according to standard ASTM E8/E8M—16a "Standard Test Methods for Tension Testing of Metallic Materials." This standard describes the test specimens design, test procedure, and evaluation of the test results. Tension tests provide information on the strength and ductility of materials under uniaxial tensile stresses. This information may be useful in comparison with materials, alloy development, quality control, and design under certain circumstances.

Compression tests are carried out on the same machine. Standard ASTM E9 covers the apparatus, specimens, and procedure for axial load compression testing of metallic materials at room temperature.

Shear testing is different from tensile testing in that the forces applied are parallel to the upper and lower faces of the object under test. Materials behave differently in

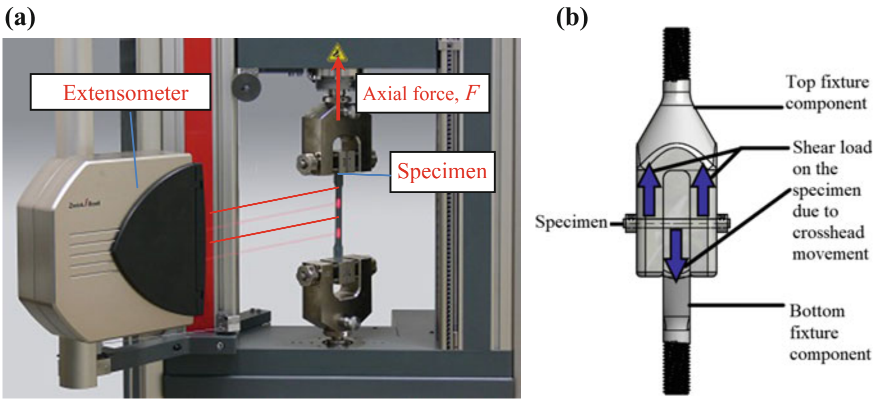


Fig. 1 Basic materials testing: **a** tension and **b** shear

shear than in tension or compression, resulting in different values for strength and stiffness. Usually performed on fasteners, such as bolts, machine screws, and rivets, shear testing applies a lateral shear force to the specimen until failure results. Apart from tension tests, there are a number of various standards on shear testing. One of the most common shear tests is the double shear test of metallic materials. This test can be carried out on the tensile machine using a standard fixture shown in Fig. 1b.

Tensile tests are performed for several reasons [1]. The results of tensile tests are used in selecting materials for engineering applications. Basic tensile properties are normally included in material specifications to be used in the design and manufacturing of products. Tensile properties are often used to predict the behavior of a material under forms of loading other than uniaxial tension (discussed later in this chapter).

The strength of a material often is the primary concern. The strength of interest may be measured in terms of either the stress necessary to cause appreciable plastic deformation or the maximum stress that the material can withstand before fracturing.

These measures of strength are used, with appropriate caution (in the form of safety factors discussed later in this chapter), in engineering design. Also of interest is the material's ductility, which is a measure of how much it can be deformed before it fractures. Rarely is ductility incorporated directly in design; rather, it is a key property in materials manufacturing including forming and cutting as discussed later in this chapter.

In the tension test, a specimen of standard dimension (one of the standard specimens is shown in Fig. 2) is subjected to a continually increasing uniaxial tensile force while simultaneous observations of the elongation of the specimen.

The results of the tension test are stress–strain diagrams. A stress–strain diagram is a diagram in which corresponding values of stress and strain are plotted against each other. Values of stress are usually plotted as ordinates (vertically) and values

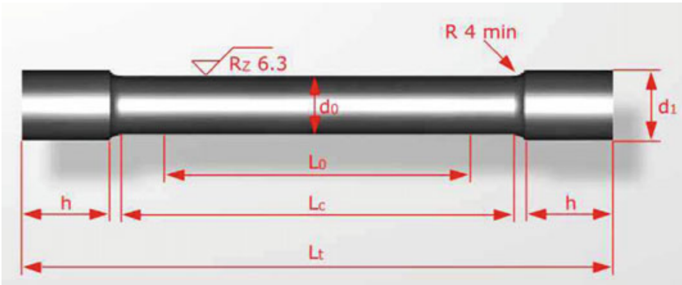


Fig. 2 Geometry of one of the standard specimens: d_0 is the diameter of specimen; d_1 is the diameter of grip (>1.2d_0); L_0 is the gage length (L_0 = 5d_0); L_c is parallel length (L_c = L_0 + d_0) L_t is the total length; *h* is the height of grip

of strain as abscissas (horizontally). Figure 3b shows a typical diagram for a ductile material. Engineering stress, *s*, is defined as

$$s = \frac{F}{A_0} \tag{1}$$

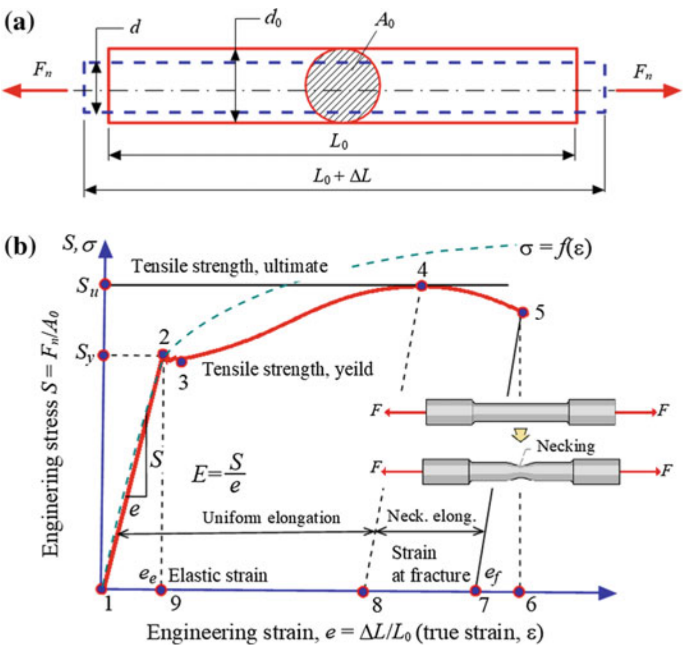


Fig. 3 Standard tension test: **a** deformation in testing and **b** typical stress–strain diagram

where F is the tensile force and A_0 is the initial cross-sectional area of the gage section. Obviously, if the specimen is round then $A_0 = \pi d_0^2/4$.

Engineering strain, or nominal strain, e, is defined as

$$e = \frac{\Delta L}{L_0} \tag{2}$$

where L_0 is the initial gage length and ΔL is the change in gage length ($L - L_0$).

Multiple detailed descriptions of a typical stress–strain diagram is presented in the literature, e.g., in [2]. The most important aspect relevant in mechanical engineering is segments shown by numbered points in Fig. 3b. When a solid material is subjected to small stresses, the bonds between the atoms are stretched. When the stress is removed, the bonds relax and the material returns to its original shape. This reversible deformation is called elastic deformation represented by segment 1–2 in the diagram. For most materials, segment 1–2 is linear. The slope of this linear segment is called *the elastic modulus or Young's modulus.*

$$E = \frac{s}{e} \tag{3}$$

In the elastic range, the ratio, μ, of the magnitude of the lateral contraction strain to the axial strain is called *Poisson's ratio.*

$$\mu = -\frac{e_y}{e_x} \text{ (in an } x\text{-direction test)} \tag{4}$$

At point 2, stresses become high enough to cause planes of atoms slide over one another. This deformation, which is not recovered when the stress is removed, is termed plastic deformation. Note that the term "plastic deformation" does not mean that the deformed material is a plastic (a polymeric material).

Segment 2–3 represents the so-called the transient effects (or yielding instability). For some materials (e.g., low carbon steels and many linear polymers), the stress–strain curves have initial maxima followed by lower stresses as shown in Fig. 3b. After the initial maximum, all the deformation at any instant is occurring within a relatively small region of the specimen with no stress increase. This segment is noticeable only for relatively ductile materials, while for relatively brittle materials a smooth transition of segment 1–2 into segment 3–4 is the case.

Segment 3–4 is called the strain-hardening region. When a metal is stressed beyond its elastic limit, it enters the plastic region (the region in which residual strain remains upon unloading). When the load is increased further (a kind of rearrangement occurs at atom level and the mobility of the dislocation decreases), "dislocation density" increases that in turn makes the metal harder and stronger through the resulting plastic deformation. It means it is more difficult to deform the metal as the strain increases, and hence it is called "strain hardening." This tends to increase the strength of the metal and decrease its ductility. Note that the maximum stress in the diagram is achieved at point 4.

Segment 4–5 is the necking region. Necking is defined by standard ASTM E8/E8M—16a as the onset of nonuniform or localized plastic deformation, resulting in a localized reduction of cross-sectional area. In this region, relatively large amounts of strain localize disproportionately in a small region of the material. The resulting prominent decrease in local cross-sectional area provides the basis for the name "neck." Note that because engineering stress [see Eq. (3)] is calculated through the initial diameters of the specimen, d_0 (and hence A_0), the stress in the diagram on segment 4–5 decreases although in reality, when the actual diameter of the neck is considered, it increases.

Two more segments shown in the diagram (Fig. 3b) are of interest. The first is segment 1–9 that represents the maximum elastic strain e_e; segment 1–6 that represents the maximum strain at the instant of fracture; segment 6–7 is elastic recovery of the specimen after fracture. Note that line 5–7 is drawn parallel to line 1–2. Although this segment is of small interest in the design, it is of significant importance in part manufacturing; segment 1–7 is known at strain at fracture, i.e., the plastic strain in the specimen as measured as two parts of the fractured specimen are brought together. From the beginning of loading (point 1) to the beginning of necking (point 4), the specimen undergoes uniform elongating whereas starting from point 4 till point 4 it undergoes necking elongation.

The common tensile properties directly obtained from the stress–strain diagram are:

– *Modulus of Elasticity*, E [see Eq. (3)]. Young's modulus, also known as the elastic modulus, is a measure of the *stiffness* of a solid material. Stiffness is understood as resistance of a material to deformation like elongation, twisting, bending, and deflection.
– *Yield Tensile Strength*, S_y. Yield strength is the stress at which a material exhibits a deviation from the proportionality of stress to strain; i.e., the occurrence permanents plastic strain is the case.
– *Ultimate Tensile Strength*, S_u. Ultimate tensile strength (a.k.a. *UTS*) is the maximum stress developed by the material based on the original cross-sectional area.
– *Elongation at fracture or engineering strain*, e_f. It is normally reported in %, that is $e_f \cdot 100\%$.

Some other important properties and terms used in engineering literature are:

Toughness. There are a number of different approaches to toughness characterization and methods of measurements discussed in the literature [3] or set by standards (e.g., ISO 26843:2015 "Metallic materials. Measurement of fracture toughness at impact loading rates using precracked Charpy-type test pieces"; ASTM E23 "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials"). In the author's opinion, the most engineering-sound approach having clear physical meaning is the energy need to fracture of a unit volume of a material so it is measured in J/m^3. It is characterized by the modulus of toughness which is the total energy absorption capabilities of the material to fracture, and thus is given by the total area under the s–e curve such that

$$U_t = \int_0^{e_f} s\mathrm{d}e \approx \frac{(S_y + S_u)}{2} e_f \tag{5}$$

Energy absorbed per volume of material (toughness) is obtained from numerical integration of data in a measured stress–strain experiment. When all else is equal, this value will be the same for the material from one test to another. Multiple tests of the same material will give a statistically representative report (average and standard uncertainty).

Resilience. It is the strain energy stored by body up to elastic limit. In other words, it is the recoverable/elastic strain energy. It is characterized by the modulus of resilience, which is the amount of energy stored in stressing the material to the elastic limit as given by the area under the elastic portion of the *s*–*e* diagram and can be defined as

$$U_r = \int_0^{e_e} s\mathrm{d}e \approx \frac{S_y e_e}{2} \tag{6}$$

Typical values of U_r and U_t are listed in Table 1 for some common engineering materials.

Hardness. Standard ASTM E6.14406-1 defines hardness as the resistance of a material to deformation, particularly permanent deformation, indentation, or scratching. In reality, it is the resistance of a material to indenter penetration so one should not have any extended interpretation of this characteristic. It is tested for with an indenter hardness machine usually (but not solely) by measuring the size of the indentation after releasing the load.

The most known of the hard materials is diamond. It is so hard; it is usually used as the penetration material (for the Vickers hardness, for example). A typically soft material is aluminum metal or any plastic.

Table 1 Energy properties of materials in tension

Material	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of resilience (kJ/m^3)	Modulus of toughness (kJ/m^3)
SAE 1020 annealed	276	414	186	128,755
SAE 1020 heat treated	427	621	428	91,047
Type 304 stainless	207	586	102	195,199
Ductile cast iron	400	503	462	50,352
Red brass	414	517	828	13,795

Hardness correlates well with scratch-proof ability meaning that harder materials are harder to scratch, i.e., the greater its abrasion resistance. For metallic materials, hardness is uniquely correlated with the ultimate tensile strength of the material as documented in [4]. Therefore, harder materials are also stronger materials and vice versa.

Ductility. This property is defined by standard ASTM E8/E8M—16a as the ability of a material to deform plastically before fracturing. Ductility is usually evaluated by measuring (1) the elongation or reduction of area from a tension test, (2) the depth of cup from a cupping test, (3) the radius or angle of bend from the bend test, or (4) the fatigue ductility from the fatigue ductility test. *Malleability* is the ability to deform plastically under repetitive compressive forces.

Unfortunately, there is no usable theory of ductile behavior. Ductility is measured by dozens of methods, all contradictory, none leading to practical forecasts of a part's behavior. Moreover, the limit is not sharp either. At our present degree of understanding, ductility is a qualitative, subjective property of a material. In general, measurements of ductility are of interest in three ways:

1. To indicate the extent to which a material can be deformed without fracture in metalworking operations such as rolling and extrusion.
2. To indicate to the designer, in a general way, the ability of the metal to flow plastically before fracture. A high ductility indicates that the material is "forgiving" and likely to deform locally without fracture should the designer made a mistake in the stress calculation or the prediction of severe loads.
3. To serve as an indicator of changes in impurity level or processing conditions. Ductility measurements may be specified to assess material quality even though no direct relationship exists between the ductility measurement and performance in service.

A common definition is a material with less than 0.05 (5%) elongation (strain) at fracture is brittle. This includes ceramics, glasses, and some metal alloys. Cast iron would be classified as brittle. For reference, Fig. 4 shows the elongation at fracture of some common engineering materials.

In shear tests (Fig. 1b), the shear force F_s acts tangentially to the top area A as shown in Fig. 5a. The shear stress τ measures the intensity of a reaction to externally applied loading sustained by the material as it maintains equilibrium with this force. This stress is calculated as

$$\tau = \frac{F_s}{A} \tag{7}$$

The material response on the application of force F_s is represented as the shear stress versus shear strain plot shown in Fig. 5b. In full analogy with tension tests, the yield shear strength, τ_y, as the stress at which a material exhibits a deviation from the proportionality of stress to strain, i.e., the occurrence permanents plastic strain is the case, and ultimate shear strength, τ_u, as the maximum stress developed by the material based on the original cross-sectional area are distinguished. Note

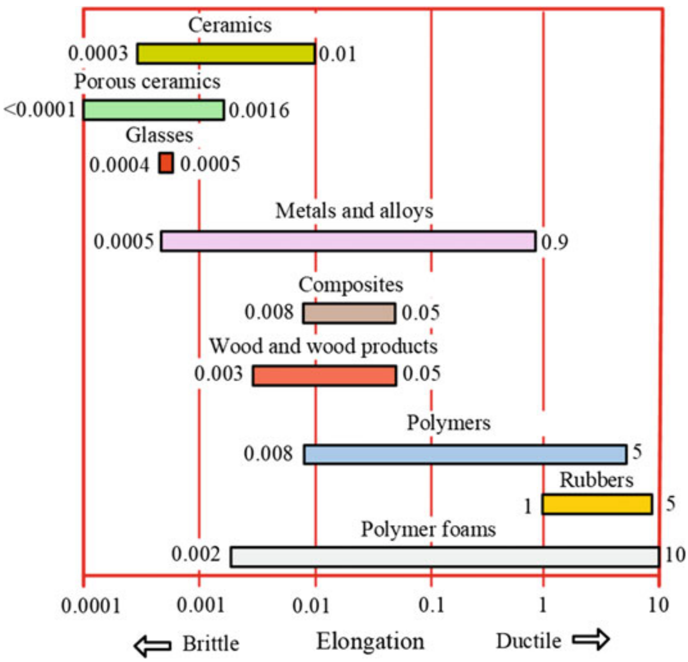


Fig. 4 Elongation at fracture of common engineering materials

that the term "engineering" is used here to explain the occurrence of segment 3–4 in the stress–strain diagram. In testing (schematic of which is shown in Fig. 5c), the ultimate shear strength occurs just before two cracks begin to develop at points *A* and *B*. After the cracks start to run toward each other along the shear plane, the initial shearing area represented by shear plane reduces in full analogy with the necking in tension tests.

In this plot, the engineering shear strain refers to the angular distortion that a material suffers in shear. The shear strain is a dimensionless measure of distortion and is defined in Fig. 5a as

$$\gamma = \tan \phi \tag{8}$$

In Eq. (8), ϕ is the angular change in the right angle measured in radians. Within the elastic region, the shear displacement ΔL is small so ϕ is also small. For small enough angles, the tangent of an angle is equal to the angle itself (when measured in radians) so that the engineering shear strain can be approximated as $\gamma \approx \phi$ (rad). Note that this is not nearly the case in metal forming and cutting when large deformations take place.

In full analogy with the normal stress, Hooke's law is valid for the considered case provided the shear stress varies linearly with shear strain and the shear

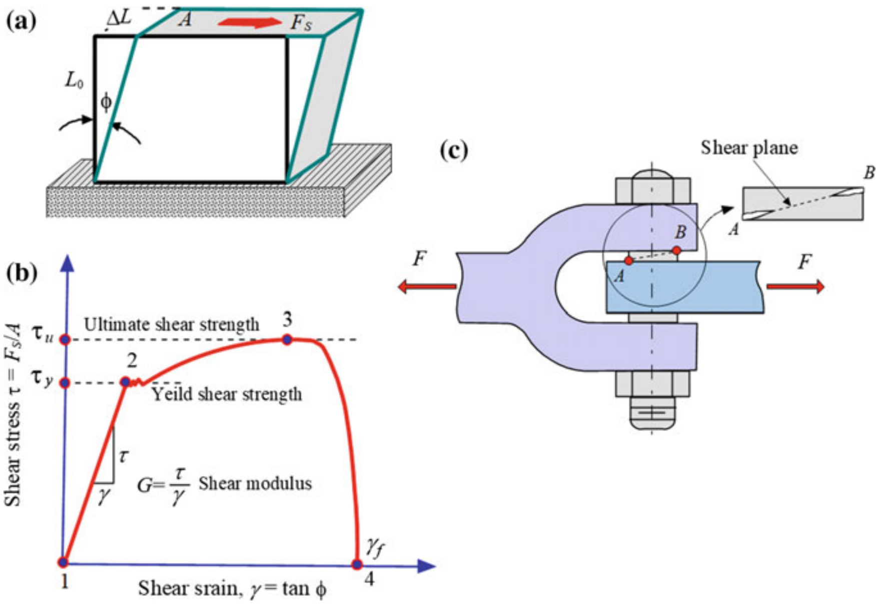


Fig. 5 Standard shear test: **a** deformation in testing, **b** typical stress–strain diagram, **c** test schematics

modulus, G, is the slope of the shear stress–strain (Fig. 5b), and thus it may be determined from the slope of the stress–strain curve or by dividing stress by strain,

$$G = \frac{\tau}{\gamma} \tag{9}$$

Shear properties can also be found from a right circular cylinder loaded in torsion, i.e., in widely performed torsion tests. In solid mechanics, torsion is the twisting of an object due to an applied torque. Torque, like a linear force, will produce both stress and the strain. Torsion causes a twisting stress, called shear stress (τ), and a rotation, called shear strain (γ). A simple model of a torsion test shown in Fig. 6 includes a cylindrical body, which essentially is cantilever beam one end of which is rigidly fixed and torque T is applied to the other (free) end.

In Fig. 6a, a line AB is drawn on the surface parallel to the beam longitudinal axis. When the torque is applied to the free end of the circular beam (as shown in this figure), line AB becomes helical assuming position AB' in which angle of helix is γ_{tw}. The beam twists by an angle θ_{tw}. This angle is a function of the beam length, L, and stiffness represented by shear modulus G. The twist angle starts at 0 at the fixed end of the beam and increases linearly as a function of z-distance from this end. The change of angle, γ_{tw}, is constant along the length.

A small differential element, dz, is sliced from the beam as shown in Fig. 6b. Because the cross sections bounded this element are separated by an infinitesimal

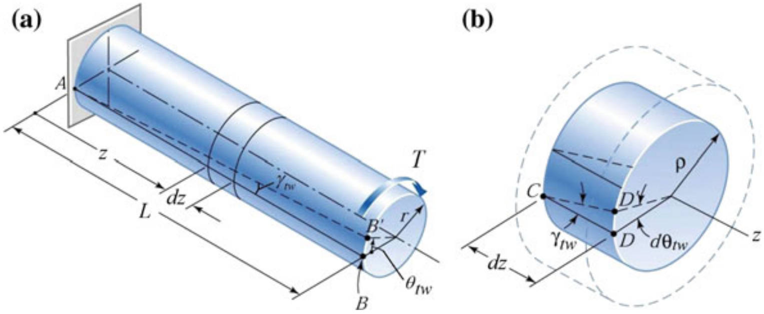


Fig. 6 Model of torsion: **a** A circular beam loaded by torque T and **b** small circular element dz

distance, the difference in their rotations, denoted by the angle $\mathrm{d}\theta_{\mathrm{tw}}$, is also infinitesimal. As the cross sections undergo the relative rotation $\mathrm{d}\theta_{\mathrm{tw}}$, straight line *CD* deforms into the helix *CD′*. By observing the distortion of the sliced element, it should be recognized that the helix angle γ_{tw} is the shear strain of the element.

Two angles γ_{tw} and $\mathrm{d}\theta_{\mathrm{tw}}$ must be compatible at the outside edge (arc length *D*–*D′*). This gives the relationship

$$\text{Arc Length D} - \text{D}' = \rho \mathrm{d}\theta_{\mathrm{tw}} = \gamma_{\mathrm{tw}} \mathrm{d}z \tag{10}$$

from which the shear strain γ_{tw} is

$$\gamma_{\mathrm{tw}} = \rho \frac{\mathrm{d}\theta_{\mathrm{tw}}}{\mathrm{d}z} \tag{11}$$

The quantity $\mathrm{d}\theta_{\mathrm{tw}}/\mathrm{d}x$ is the angle of twist per unit length, where θ_{tw} is expressed in radians. The corresponding shear stress (Fig. 7a) is determined from Hooke's law as

$$\tau = G\gamma_{\mathrm{tw}} = G\rho \frac{\mathrm{d}\theta_{\mathrm{tw}}}{\mathrm{d}z} \tag{12}$$

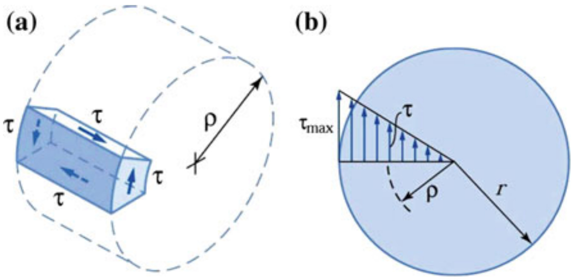


Fig. 7 Shear stress due to torsion (**a**) and shear stress distribution (**b**)

A simple analysis of Eq. (12) reveals that the shear stress varies linearly with the radial distance ρ from the axial of the beam. This variation is shown in Fig. 7b. As can be seen, the maximum shear stress, denoted by τ_{max}, occurs at the surface of the beam. Note that the above derivations assume neither a constant internal torque nor a constant cross section along the length of the beam, i.e., valid for a general case. Two important conclusions follow from this analysis:

- As the maximum shear stress occurs at the surface of a beam/shaft, shaft can be made hollow with minimum compromising of the shaft torsional strength. Using hollow shafts, one can achieve a significant weight reduction—it is widely used in the aerospace industry.
- In the direct torsion test/application, the critical shear stress (yield or ultimate) occurs over the entire cross-sectional area of the specimen/part that leads to failure. In torsion, the critical stress occurs only on the surface that does not lead to failure as the rest of the shaft takes the applied torque.

The shear modulus, G, is related to Young's modulus, E, as

$$G = \frac{E}{2(1+\mu)} \tag{13}$$

As Poisson's ratio, μ (Eq. 4), varies between 0.3 and 0.5 for most materials, the shear modulus is often approximated by $G \sim E/3$.

Two other torsion-related parameters are considered in the technical literature. Torsional rigidity is the ability of an object to resist torsion or in layman's terms "twisting," due to an applied torque *torsional stiffness* or *rotational stiffness* K_T is defined as the ration of the applied torque, T to the angle of twist, θ i.e.,

$$K_T = \frac{T}{\theta} \tag{14}$$

Torsional stiffness can also be expressed in terms of the modulus of rigidity, G (units Pa), torsion constant J (units m^2) known as the polar moment of inertia of the cross section (for a round shaft $J = \pi d^4/32$), and the characteristic length, L (Fig. 6a), as

$$K_T = \frac{JG}{L} \tag{15}$$

The product JG is commonly known as *torsional rigidity*.

2.2 The Concepts of True Stress and Strain

The engineering stress–strain curve does not give a true indication of the deformation characteristics of a metal because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the test. Also, ductile metal which is pulled in tension becomes unstable and necks down during the course of the test.

The initial cross-sectional area of the specimen, A_0, does not change noticeably over the elastic region unless rubber-like materials are considered. However, the cross-sectional area of the specimen is decreasing rapidly after the yield point (point 2 in the diagram shown in Fig. 3b). As a result, the load required continuing deformation falls off as the engineering stress based on original area likewise decreases, and this produces the fall-off in the stress–strain curve beyond the point of maximum load (segment 2–3 in Fig. 3b). In reality, the metal continues to strain-harden all the way up to fracture, so that the stress required to produce further deformation should also increase. The true stress, designated as σ, is based on the actual cross-sectional area of the specimen. If it is used, then the stress–strain curve increases continuously up to fracture as shown by the dashed curve $\sigma = f(\varepsilon)$ in Fig. 3b. Obviously that the true stress, σ, is related to engineering stress/elongation, e, as

$$\sigma = s(1 + e) \tag{16}$$

The concept of the true strain, designated as ε, seems to be more complicated as presented in many literature sources. In reality, it is rather simple and straightforward when properly explained. Strain is normalized deformation so it can be expressed in the differential form for a bar undergoing tension as d(strain) = dL/L or an infinitesimal deformation dL normalized to length L. Therefore, the total axial strain ε (known as the true strain) is found by integrating this expression from the initial length L_0 to the final length $L_F = L_0 + \Delta L$ (see Fig. 3a), i.e.,

$$\varepsilon = \int_{L_0}^{L_F} \frac{dL}{L} = \ln(L)|_{L_0}^{L_F} = \ln\left(\frac{L_F}{L_0}\right) = \ln\left(\frac{L_0 + \Delta L}{L_0}\right) = \ln\left(1 + \frac{\Delta L}{L_0}\right) = \ln(1 + e) \tag{17}$$

How close are the values of e and ε? Figure 8 shows the engineering and true strains for values up to 1. The agreement is quite good for strains of less than 0.1.

Advantages of using the true strain ε compared to engineering strain e are:

1. It is the exact value, not an approximation.
2. Sequential strains can be added: If two strains ε_1 and ε_2 are executed sequentially, the total strain is

$$\varepsilon_1 + \varepsilon_2 = \ln\left(\frac{L_1}{L_0}\right) + \ln\left(\frac{L_2}{L_1}\right) = \ln\left(\frac{L_1}{L_0} \cdot \frac{L_2}{L_1}\right) = \ln\left(\frac{L_2}{L_0}\right) \tag{18}$$

This is not the case with the engineering strain where the total strain is

$$\frac{L_2 - L_0}{L_0} \neq e_1 + e_2 = \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_0} \tag{19}$$

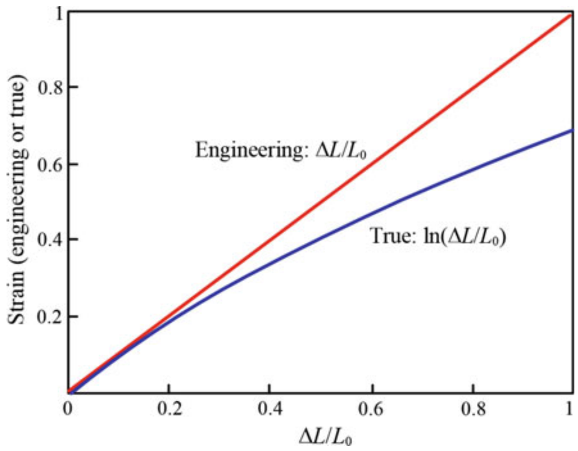


Fig. 8 Engineering and true strains as function of bar deformation

3. It is used to characterize materials that deform by large amounts (considerable fractions of their length up to many times their length). A quick look at the literature shows that true strain has been recently used to characterize materials like polyamide yarn, epoxy, rubber, and cartilage. Moreover, this strain is of prime concern in the analyses and modeling of manufacturing process involved great amounts of plastic deformation of materials.
4. It is geometrically symmetric: That is, if the strain associated with being stretched to n times the original length is ε, then the strain associated with being compressed to $1/n$ the original length is $-\varepsilon$.

3 Materials Properties at the Design Stage

3.1 The Concept of the Critical/Limiting Stress Known as the Design Criterion

At the design stage, the concept designs of the machine and units are developed to meet the intended requirements of machine performance, quality, and reliability. As such, the power inputs and outputs, velocities, limiting weight, operating environment, and many other operating parameters are defined. Once approved, the units are decomposed into parts and a model for each responsible part is constructed to determine the limiting stress considered as the design criterion. Based on the limiting stress, size, and weight limitations as well as the physical properties required for the part's intended performance (e.g., thermal conductivity), the type and grade of the part material are selected by the designer. The problem is in the proper selection of this limiting stress. The practice of the design shows that such a selection is not simple and straightforward.

The first encounter of mechanical engineers with the limiting stress takes place in university/college courses on mechanics of material where stresses and stress distribution in mainly beams loaded by various forces, moments, and torques are calculated and the maximum stress over a certain (often referred to as the critical) section of a beam is found. When the beam is made of a ductile material, this maximum stress is compared to the yield tensile or shear strength (chosen as the design criterion) making sure that this maximum is less or equal to the design criterion. As such, plastic deformation of the beam is considered as its failure mode. If, however, the beam material is brittle, the ultimate strength is selected as the design criterion, and thus, fracture of the beam is considered as its failure mode. The listed mechanical properties of few common materials are provided in the student's textbook that creates impression that these properties are constants for the listed materials, and thus can readily be found when needed.

Being simple and clear for students, such an approach is an oversimplified version of the real design practice where many other factors are to be considered in obtaining the design criterion in each and every design situation.

3.2 Yield Strength for Ductile Materials

Although the notion of ductility is discussed in Sect. 2 and the 5% elongation criterion to distinguish the "brittle–ductile" boundary is introduced, it is not that "sharp" at the design stage. For elongation under 1%, most people would say "brittle"; over 5%, most people would say "ductile"; at 3% like brass many people would say "a bit brittle". The final call should be made in the consideration of the stress–strain diagram of a material in question. If this diagram (Figs. 3b and 5b) shows the distinguishable shear strength and if the plastic deformation after the initial yielding is of an appreciable amount (elongation/strain) which can lead to undesirable change of the part configuration, then this material is considered as ductile.

Although the yield strength is defined by standard ASTM E8/E8 M—16a as the stress at which a material exhibits a deviation from the proportionality of stress to strain, i.e., the occurrence permanents plastic strain is the case, it is not that certain in the stress–strain diagram. In Sect. 2, it is discussed that segment 2–3 represents the so-called the transient effects (or yielding instability) (see Fig. 3b). To avoid this region, the yield strength S_y is commonly defined by the offset method. According to this method, the yield strength is determined at a certain offset *Om* (Fig. 9) of the original gage length of the specimen. Commonly, the yield strength at 0.2% offset is obtained by drawing through the point of the horizontal axis of abscissa e = 0.2% (or e = 0.002), a line parallel to the initial straight line portion of the stress–strain diagram. The 0.2% of the initial gage length has been chosen by standardization organizations (mainly ASTM) because it is small enough to ensure the accuracy of the yield point but it is sufficiently large to be measured with conventional methods in the laboratory, just with a caliper or micrometer. For brittle materials, such as gray cast iron, the offset is 0.05% of the initial gage length, because the plastic deformation is small. The yield strength obtained using this method is designated as $S_{y0.2}$ and thus actually used in the design calculations.

3.3 Relevance of Material Properties in Complex Loading

The complex loading includes, in the most general case, a three-dimensional state of stress. To understand the stresses involved, let us consider an infinitesimal element in a parallel-sided form with its faces oriented parallel to the three coordinate planes as shown in (a). Each plane will have normal and tangential components of the stress resultants. The tangential or shear stress resultant on each plane can further be represented by two components in the coordinate directions. Although nine components of stress are shown in Fig. 10a, only six of them are independent, namely σ_x, σ_y, σ_z, $\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$, and $\tau_{yz} = \tau_{zy}$. To deal with these components, the so-called equivalent tensile stress or von Mises stress, σ_e, is used

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + \left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)} \tag{20}$$

In two-dimensional application, i.e., when $\sigma_x = \tau_{xz} = \tau_{yx} = 0$, the equivalent stress is calculated as

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2} \tag{21}$$

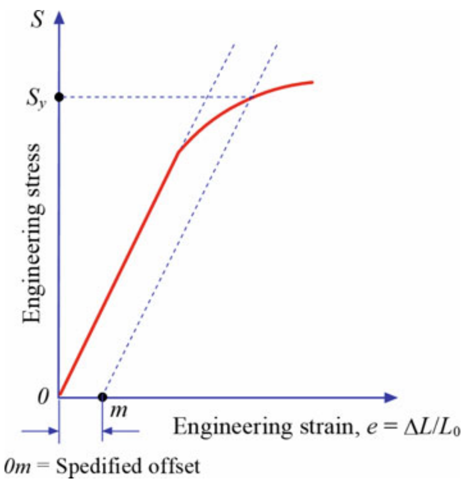


Fig. 9 Determination of yield strength by the offset method

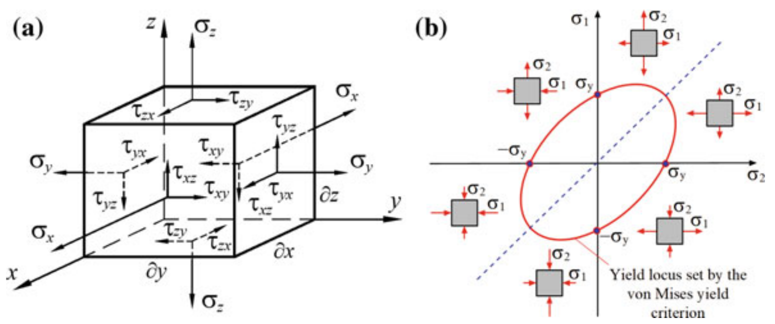


Fig. 10 General state of stress: **a** stress components representation and **b** yield locus set by the von Mises criterion

The von Mises yield criterion [5] (with Hencky's interpretation [6]) states the yielding occurs when the equivalent stress, σ_e, reaches the *yield strength of the material in simple tension*, S_y (σ_y). In other words, using this criterion, one can calculate the design criterion/limiting stress for any general type of loading/state of stress. The corresponding equivalent or von Mises strain is calculated as

$$\varepsilon_e = \frac{\sqrt{2}}{3}\left[\left(\varepsilon_x - \varepsilon_y\right)^2 + \left(\varepsilon_y - \varepsilon_z\right)^2 + \left(\varepsilon_z - \varepsilon_x\right)^2 + 6\left(e_{xy}^2 + e_{yz}^2 + e_{zx}^2\right)\right]^{1/2}. \quad (22)$$

3.4 Safety Factor

Factor of safety (FoS), also known as *safety factor* (SF), is a term describing the structural capacity of a part or system beyond the expected loads or actual loads. Essentially, how much stronger the part or system is than it usually needs to be for an intended load. Safety factors are often calculated using detailed analysis because comprehensive testing is impractical on many engineering projects, such as bridges and buildings, but the structure's ability to carry load must be determined to a reasonable accuracy [7].

Many systems are purposefully built much stronger than needed for normal usage to allow for emergency situations, unexpected loads, misuse, or degradation. Any structure or component can be made to fail if it is subjected to loadings in excess of its strength. Structural integrity is achieved by ensuring that there is an adequate safety margin or reserve factor between strength and loading effects. The margin of safety, or alternatively the safety factor, which is appropriate for a particular application must take into account the following:

– The scatter or uncertainty in the variables which form the input data for load and resistance effects.
– Any uncertainty in the equation used to model failure.

- The consequences of failure.
- The possibility of unknown loadings or mechanisms of failure occurring.
- The possibility of human error causing unforeseen events.

Factors of safety can be incorporated into design calculations in many ways [8]. For most calculation, the following equation is used to obtain the design criterion—the allowable working stress $[s_w]$

$$[s_w] = \frac{S_m}{f_s} \tag{23}$$

where S_m is the strength of the material (the yield strength for ductile materials, $S_{y0.2}$, and ultimate strength, S_u, for brittle materials) and f_s is the factor of safety.

Particular values of the factor of safety and what is actually covered by this factor are regulated by various standards and design recommendation in various industries. Table 2 presents some general recommendations.

3.5 *Materials Properties' Outcome of the Design Stage*

The output of the design is *a drawing* where all materials specification, properties (e.g., hardness), and quality requirements to be achieved in part/unit/machine manufacturing are recorded. In other words, the drawing is the primary document for part/unit/machine quality. In advanced industries, the drawing may have some reference to certain manufacturing procedures and processes to be used to assure the required part quality. For example, a surface roughness callout can have note indicating "ground," brazing joint can have a note to use a certain brazing procedure. The properties of the part set by the drawing are the prime information used in designing manufacturing process for this part/assembly/structure.

Table 2 General recommendation for values of factors of safety

1.3–1.5	For use with highly reliable materials where loading and environmental conditions are not severe, and where weight is an important consideration
1.5–2	For applications using reliable materials where loading and environmental conditions are not severe
2–2.5	For use with ordinary materials where loading and environmental conditions are not severe
2.5–3	For more brittle materials where loading and environmental conditions are not severe
3–4	For applications in which materials properties are not reliable and where loading and environmental conditions are not severe or where reliable materials are to be used under difficult loading and environmental conditions

4 Materials Properties at the Manufacturing Stage

A manufacturing specialist cannot change the material type/grade chosen by the part/unit/machine designer. His or her responsibility is to manufacture parts efficiently while fully complying with quality requirements set by the drawing.

In part production, three general types of manufacturing processes, which can be conditionally classified as additive, "neutral," and subtractive, are used. Additive manufacturing (AM) describes the technologies that build 3D objects by adding layer-upon-layer of material, whether the material is plastic, metal, concrete or one day it will be human tissue. "Neutral" processes (commonly referred to as forming processes) change the shape of the original workpiece (blank), while the volume of the work material remains unchanged. Subtractive processes change the shape of the original workpiece (blank) by removing a part of its original volume. AM processes are relatively new so the standard on material properties is not yet fully developed. Therefore, we will consider only the relevant properties of materials in "neutral" known as forming and subtractive known as cutting processes showing that considerably different properties of the work materials are involved in these processes.

4.1 Forming Processes

Forming is defined by standard DIN 8580 as manufacturing through three-dimensional or plastic modification of a shape while retaining its mass and material cohesion. In other words, forming is the modification of a shape with controlled geometry. Forming processes are categorized as chipless or non-material removal processes. Forming includes a large set of manufacturing operations in which the material is deformed plastically to take the shape of the die geometry. The tools used for such deformation are called die, punch, etc., depending on the type of process. At the most general level [9], these are divided into bulk metal forming and sheet metal forming as shown in Fig. 11.

Bulk deformation processes are generally characterized by significant deformations and massive shape changes, and the surface-area-to-volume of the work is relatively small. The term bulk describes the workparts that have this low area-to-volume ratio. Starting work shapes for these processes include cylindrical billets and rectangular bars. Figure 12 illustrates the following basic operations in bulk deformation:

- Rolling: In this process, the workpiece in the form of slab or plate is compressed between two rotating rolls in the thickness direction, so that the thickness is reduced. The rotating rolls draw the slab into the gap and compress it. The final product is in the form of a sheet.
- Forging: The workpiece is compressed between two dies containing shaped contours. The die shapes are imparted to the final part. Forging is traditionally a hot working process, but many types of forging are performed cold.

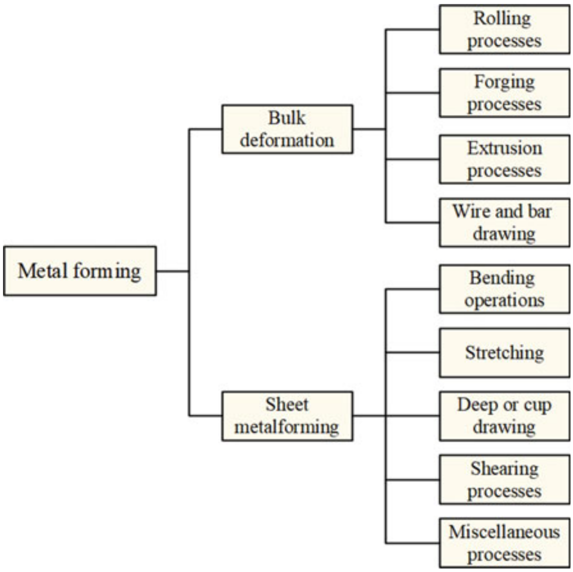


Fig. 11 General classification of metal-forming processes

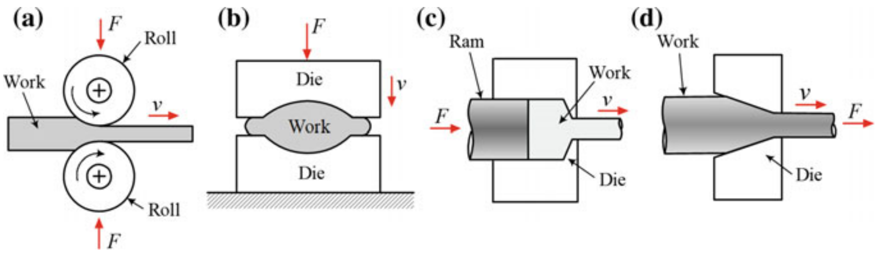


Fig. 12 Basic bulk deformation processes: **a** rolling, **b** forging, **c** extrusion, and **d** drawing. Relative motion in the operations is indicated by *v*; forces are indicated by *F*

- Extrusion: This is a compression process in which the work metal is forced to flow through a die opening, thereby taking the shape of the opening as its own cross section.
- Drawing (often referred to as wire or rod drawing): In this forming process, the diameter of a round wire or bar is reduced by pulling it through a die opening.

Sheet metal forming involves operations performed on metal sheets, strips, and coils. The surface-area-to-volume ratio of the starting metal is relatively high; thus, this ratio is a useful means to distinguish bulk deformation from sheet metal processes. Pressworking is the term often applied to sheet metal operations because the machines used to perform these operations are presses. A part produced in a sheet metal operation is often called a stamping.

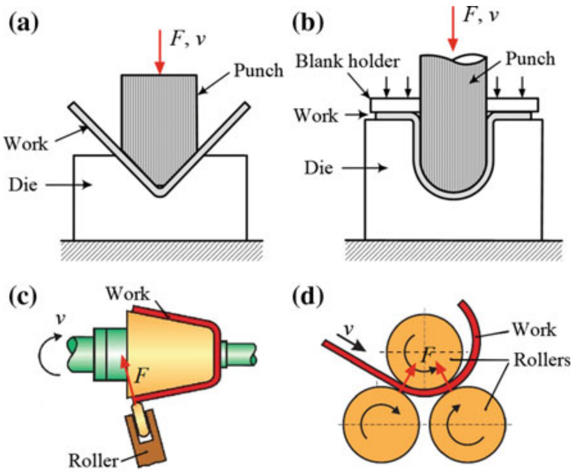


Fig. 13 Basic sheet metalworking operations: **a** bending, **b** drawing, **c** shear spinning, and **d** roll bending

Sheet metal operations are always performed as cold working processes and are usually accomplished using a set of tools called a punch and die. The punch is the positive portion, and the die is the negative portion of the tool set. The basic sheet metal operations are sketched in Fig. 13a, b which are defined as follows:

- Bending: In this, the sheet material is strained by punch to give a bend shape (angle shape) usually in a straight axis.
- Drawing: In sheet metalworking, drawing refers to the forming of a flat metal sheet into a hollow or concave shape, such as a cup, by stretching the metal. A blank holder is used to hold down the blank, while the punch pushes into the sheet metal. To distinguish this operation from bar and wire drawing, the terms cup drawing or deep drawing are often used.

The miscellaneous processes within the sheet metalworking classification include a variety of related shaping processes that do not use punch and die tooling. Examples of these processes are stretch forming, roll bending, spinning, and bending of tube stock. Schematic representations of shear spinning and roll bending are shown in Fig. 13c, d.

4.1.1 Material Properties Involved

When one designs a forming process, the following important parameters are considered:

- Work material characterization, and thus formability.
- Process parameters: plastic deformation characterization, strain and strain rate.
- Microstructural alternations of the work material.
- Forces and energies involved.
- Friction in metal forming.

In the section to follow, only work material characterization is considered.

4.1.2 Stress–Strain Diagram

In forming, the most relevant material properties are represented by the so-called flow curve shown in Fig. 14, which is actually the stress–strain diagram in the true stress-true strain coordinate, i.e., obtained from the standard stress–strain diagram discussed in Sect. 2. Note that the elastic region is not accounted for as the elastic strain is insignificant for many metals. In forming of other materials with significant elastic region, the curve does not start from zero but rather from the point of maximum elastic strain before material yields.

The flow curve for many metals in the region of plastic deformation can be expressed by the simple power curve relation

$$\sigma = K\varepsilon^n \tag{24}$$

where n is the strain-hardening exponent and K is the strength coefficient. These parameters are determined as follows. A log–log plot of the flow curve will result in a straight line. The linear slope of this line is n, and K is the true stress at $\varepsilon = 1.0$ as shown in Fig. 15. The strain-hardening exponent may have values from $n = 0$ (perfectly plastic solid) to $n = 1$ (perfectly elastic solid). For most metals, n has values between 0.10 and 0.50; see Table 3.

Only a part of the entire flow curve 1–2 (Fig. 14) is feasible to use in forming to avoid fracture and fracture-associated defects of the finished parts. That is, why a certain safety margin (segment 3–5 in Fig. 14) is always assigned so the actual flow curve is represented by segment 1–4 in Fig. 14. The area under this actual flow curve (area bounded by segments 1–4–5–1) defines the energy needed for deformation. This energy is used to calculate the process power and forces involved.

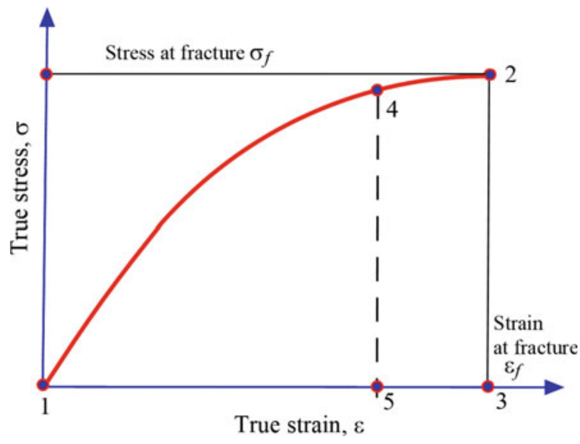


Fig. 14 Flow curve

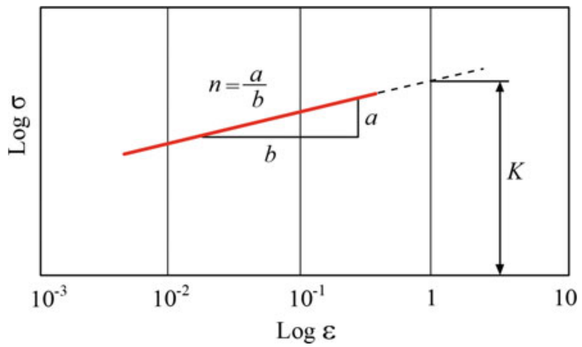


Fig. 15 Log–log plot of true stress-true strain curve to determine strain-hardening exponent *n* and the strength coefficient *K*

4.1.3 Accounting for the Process Temperatures, Strain Rates, and the State of Stress

In forming, high temperatures and potentially high strain rates occur particularly in complicated die designs and high-productivity hot (with preheated blanks) forming operations. It is known that the flow stress decreases with temperature while the strain at fracture increases. The opposite is true when the strain rate increases [10]. Figure 16 shows that the influence of temperature and strain rake is highly non-linear. Moreover, different temperature and strain rate may occur in various regions of the blank (workpiece, billet, etc.) that complicates the forming process design in terms of defects (cracks, wrinkles) prevention.

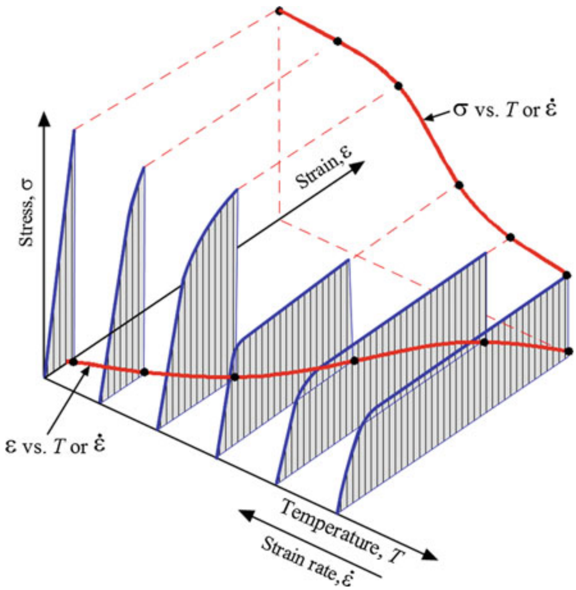
Another materials' aspect of forming operations design is the accounting for the complex state of stress. It was discussed in Sect. 3.3 that when a complex state of stress is the case then the equivalent (von Mises) stress is calculated and the von Mises yield criteria are used to define the beginning of material yielding, i.e., the appearance of irreversible plastic deformation. In mechanical engineering, this criterion is often considered as failure criteria as a part of a mechanism or machine normally cannot function properly if its shape changes due to plastic deformation.

In deforming manufacturing process where severe plastic deformation takes place, the von Mises stress and yield criterion are also fully applicable, thus used in many FEM commercial software packages for designing forming operations. The so-called rule of isotropic hardening is discussed here as it is allocable for most of

Table 3 Values for *n* and *K* for metals at room temperature [1]

Materials	Conditions	*n*	*K* (MPa)
0.05% carbon steel	Annealed	0.26	530
SAE 4340 steel	Annealed	0.15	641
0.6% carbon steel	Quenched and tempered at 540 °C	0.10	1572
0.6% carbon steel	Quenched and tempered at 705 °C	0.19	1227
Copper	Annealed	0.54	320
70/30 brass	Annealed	0.49	896

Fig. 16 Showing the influence and the temperature and strain rate on the flow stresses and strain at fracture of a common metallic material used in forming



materials used in forming. Therefore, the equivalent stress and strain are used as materials' properties in the design of forming processes

Figure 17 illustrates this rule within two common plane stress states: (a) tension–torsion and (b) principal biaxial stress. The two shown figures connect the rule to simple shear and uniaxial hardening curves *OPQ*, as yield loci expand to contain flow stresses between *P* and *Q*. The single most attractive feature of isotropic hardening over alternative hardening rules is its mathematical simplicity, while the use of this rule can predict plastic strain paths acceptably.

To account for process temperatures, strain rate, and complex state of stress, in the practice of modern CAD of forming processes, a more sophisticated [compared to the flow approximation represented by Eq. (24)] representation of the flow curve known as the Johnson and Cook model [11] is used. Its full form is

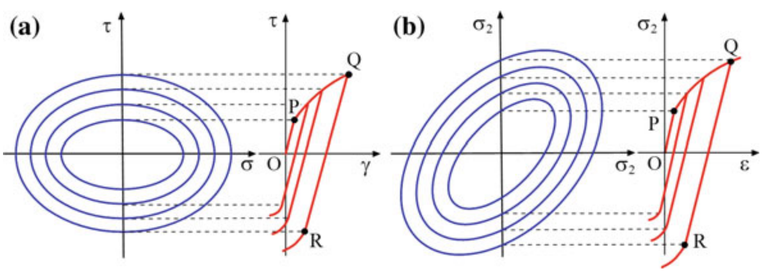


Fig. 17 Rule of isotropic hardening under plane stress: **a** tension–torsion and **b** principal biaxial stress

$$\sigma_e = \left(A + B\varepsilon_{\text{eq}}^n\right)\left(1 + C\,\ln\left(\frac{\dot{\varepsilon}_{\text{eq}}}{\dot{\varepsilon}_{\text{eq}}^0}\right)\right)\left[1 - \left(\frac{T - T_0}{T_F - T_0}\right)^m\right] \quad (25)$$

where $\varepsilon_{\text{eq}}^n$ is the equivalent plastic strain [see Eq. (22)], $\dot{\varepsilon}_{\text{eq}}$ is the equivalent plastic strain rate, $\dot{\varepsilon}_{\text{eq}}^0$ is the reference equivalent plastic strain rate (normally $\dot{\varepsilon}_{\text{eq}}^0 = 1s^{-1}$), T is the temperature, T_0 is the room temperature, T_{F} is the melting temperature, and *A, B, C*, *n,* and *m* are constants, which depend on the material. These constants are determined through material tests.

In the Johnson and Cook model, the equivalent stress and strains are used to account for any 3D state of stress. The first term of this equation accounts for work material strain hardening, the second term accounts for the process and local strain rates, and the third term accounts for the process and local temperatures.

Deformation in sheet forming is limited by necking, tearing, fracture, or wrinkling that define forming limits (i.e., allowable strains). As a result, only a part of the flow curve 1–2 (shown as 1–4 in Fig. 14) is actually utilized in forming. The science and art of sheet forming is to achieve the required final shape without producing strains that approach any of these limits. Forming limit diagram (FLD) first introduced by Keeler and Backofen [12] and Goodwin [13] has been developed for decades and is widely used in deep-drawing industry as a useful tool for predicting strain limits of sheet forming operations.

A schematic of FLD is illustrated in Fig. 18a. The flow limit curve (FLC) in this diagram can be split into two branches known as the "left branch" and "right branch." The "right branch" of FLC is valid for positive major and minor strains, whereas the "left branch" of FLC is applicable for positive major and negative minor strains. FLC is solely applicable for proportional strain path. Therefore, to construct FLC, different ratios of major and minor strains are chosen in proportional strain paths.

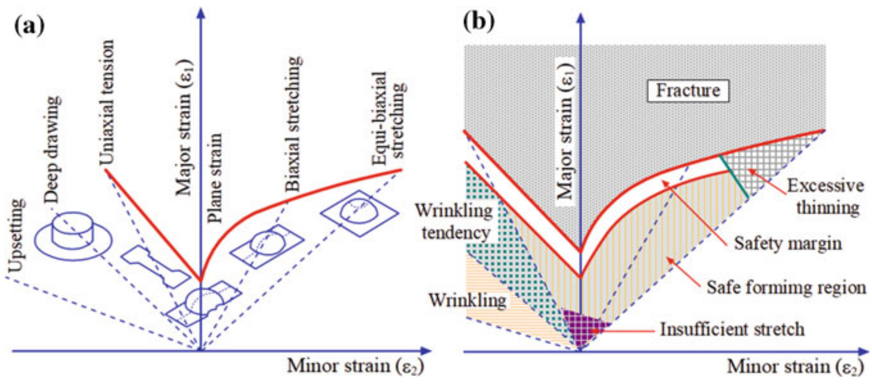


Fig. 18 Forming limit diagram: **a** principle of construction and **b** schematic representation of save the forming regions

While forming, strains in the workpiece should be located below FLC everywhere in order to avoid forming defects. By offsetting FLC (generally 10%), a safety margin is normally introduced. The risk of necking/failure is determined by how close is the maximum strain in the process to that set by the boundary set by FLC. Rejection of the formed part is based not only on occurrence of necking but also involves other defects such as excessive thinning, wrinkling, or insufficient stretch. Therefore, apart from necking, all other failure conditions are normally also evaluated by studying the strain levels involved in the process. Such considerations result in further modifications of FLD as shown in Fig. 18b.

As mentioned above, forming operations are successfully modeled using FEM in manufacturing practice. It is to say that such a modeling is widely used in the designing forming operations and forming tools. Standard ASTM E2218—14 “Standard Test Method for Determining Forming Limit Curves” are used to construct FLDs, which now are included in modeling FEM packages. In the process of design of forming operations and forming tools, strains at various regions of the part being formed are calculated and plotted on the corresponding FLD. The design/optimization of a given forming operations is carried out until all the strains are found below FLC accounting for the above-mentioned safety margins.

4.1.4 Summary of Relevant Materials Properties in Forming Operations

What unites forming processes listed in Fig. 11 in terms of materials properties involved is all of them are accomplished by plastic deformation in order to change the shape of the workpiece/blank into the final desirable shape of the part. This implies the following:

- The stress needed for plastic deformation of the work material must be well above the yield strength of the work material. This sets manufacturing materials-related calculating apart from those used in the design.
- Plasticity (commonly referred to as ductility) as the amount of plastic deformation of the work material before undesirable phenomena occur, for example, cracks, wrinkling, is the prime mechanical characteristic of the work material in forming operations. The greater the plasticity/ductility of the work material, the better its formability. To increase ductility, special measures are often used, for example preheating of the workpiece/blank.
- Fracture is the “principal enemy” in forming processes. As a result, only a part of the flow curve 1–2 (shown as 1–4 in Fig. 14) and many other precautions are used to stay away from the fracture regions.

As the relevant materials properties in forming operations are clearly understood, simulations of the forming process are successfully carried out using commercial FEM packages obtaining vital information on the optimal tool/process design. As a result, tool development and production time have been reduced by about 50% due to the use of simulations in recent years and a further 30% reduction over the next few years appears realistic. The simulation of forming tool has already reached the stage where its result can be fed directly into the press tool digital planning and validation process. Thus today, starting from the design model and through practically all process steps as far as the actual design of the press tool, the production of component can be fully simulated before a first prototype is built [14].

4.2 Cutting Processes

The notion "*cutting*" is not defined by any standard that creates a lot of confusion. To clarify the issue, the author would like to state the following. First, cutting is *physical separation* of a material into two or more parts (a subtractive process). Second, by definition, *fracture is physical separation* of a body into two or more parts. Therefore, *cutting is fracture*. Third, cutting in the manufacturing sense is physical separation of a material into two or more parts carried out by a cutting tool (blade) in a controllable manner. Therefore, in terms of materials properties, those related to fracture should be considered/analyzed in the design of cutting operations including process parameters, tools.

Figure 19 shows a generalized classification of cutting processes/operations. Besides some special cases (e.g., cutting by a knife or splitting by a hatchet), all manufacturing cutting operations are divided into two principal groups, namely shearing operations/processes and metal cutting operations/processes. Both processes aim to physically separate a blank/workpiece into two or more parts so materials should be brought to fracture in both processes. The only difference is how this fracture is achieved; i.e., how much energy (per unit volume of the work material) is spent and how good are the fractured surfaces.

4.2.1 Relevant Material Properties in Shearing Processes

Figure 20 shows some examples of common shearing operations. In punching, the sheared slug is discarded, while in blanking, this slug is the part and the rest is scrap. Die cutting includes perforating or punching a number of holes in a sheet; parting or shearing the sheet into two or more pieces; notching or removing pieces of various shapes from the edges; lancing or leaving the tab without removing any material.

All shearing operations include the deformation and then separation of a material substance in which parallel surfaces are made to slide past one another. In shearing, one layer of a material is made to move on the adjacent layer in a linear direction due to action of two parallel forces F_{sh} located at distance a_{cl} known as the clearance distance as shown in Fig. 21a. A plane over which the sliding occurs is known as the shear plane. A typical example of shearing is cutting with a pair of scissors (Fig. 21b). Scissors are cutting instruments consisting of a pair of metal blades connected in such a way that the blades meet and cut materials placed

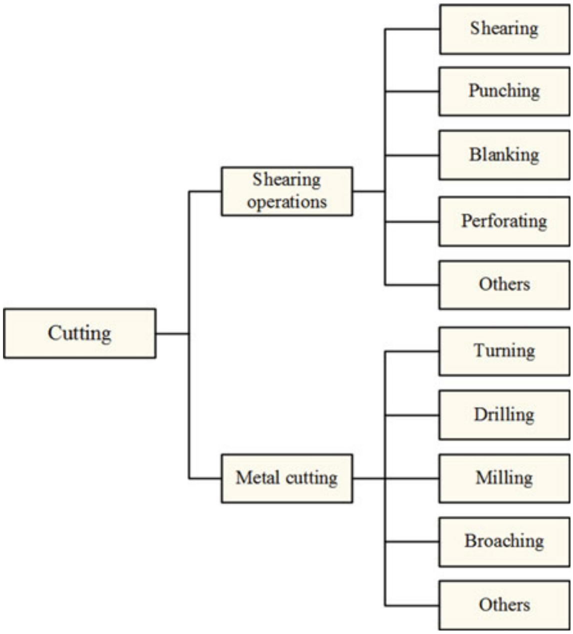


Fig. 19 General classification of cutting processes/operations

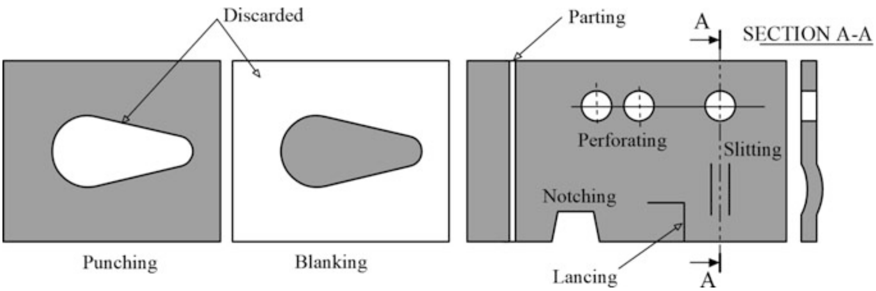


Fig. 20 Examples of common shearing operations

between them when the handles are brought together. Shearing machines (sheet metal shears) are yet another example.

A shearing or scissor-like action is used to cut metal into sheets or strips. Shearing machines and shearing machinery are multipurpose devices used in the cutting of alloys and other sheet metals. Shearing machines are used in steel furniture industries, refrigeration, doorframe manufacturers, automobile industries, and control panel manufacturers. There are many types of shearing machines. Examples include hydraulic, conventional, mechanical, cut-to-length line, and plastic devices.

In these operations, the sheet is cut by subjecting it to shear stress typically between a punch and a die as shown in Fig. 22. Shearing usually starts with the formation of the shear planes and then cracks on both the top and bottom edges of

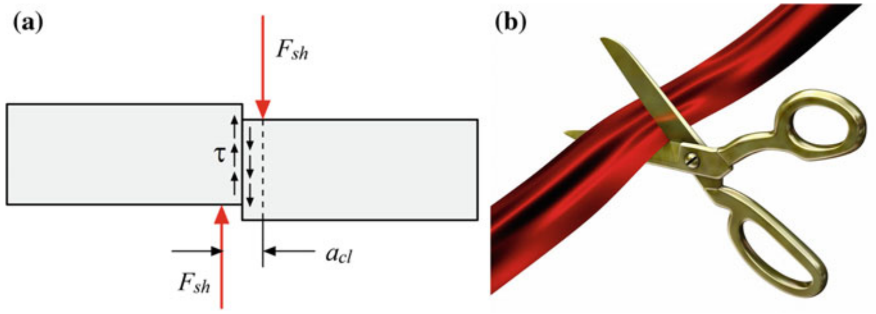


Fig. 21 Principle of shearing operations: **a** force and deformation model and **b** typical example

the workpiece (*A* and *B*, and *C* and *D* in Fig. 22). These cracks eventually meet each other and separation occurs. The rough fracture surfaces are due to these cracks.

In students' textbooks (e.g., [15]), the punching force is calculated as the product of the shear strength, τ_u, of the work material (see Fig. 5) obtained in the direct shear test (see Fig. 1) and the shearing area, A_{sh}, that is,

$$F_{pn} = A_{sh}S_{sh} = L_{pn}T_w S_{sh} \tag{26}$$

where L_{pn} is the length or perimeter of cut. If the punch is round, then $L_{pn} = \pi d_{pn}$ where d_{pn} is the punch diameter and T_w is the thickness of sheet being sheared.

Although the same formula for calculating the punching force appears in engineering reference books (e.g., [8]), it is pointed out that this force needs to be increased by 20–40%. No valid reasons for such an increase are provided. The problem is that being seemingly simple and straightforward, Eq. (26) is incorrect as it stems from misunderstanding of the essence of the shear stress–strain diagram shown in Fig. 5b. The area under the shear stress–strain curve defines the energy needed for shearing of a unit volume of the work material. Knowing this energy, one can easily calculate the power needed in punching, and then dividing this power over the punching speed (*v* in Fig. 22), one can obtain the punching force.

As the product $L_{pn}T_w$ is significant, a great force in punching is needed. Even for punching relatively small holes (10 mm), a 50 ton punching press is used whereas 200 ton presses are common for many applications.

4.2.2 Relevant Material Properties in Metal Cutting Processes

Machining is one of the oldest yet still most common manufacturing operations with a wide range of techniques such as turning, milling, drilling, grinding. Regardless of this great variety, the essence of metal cutting can be explained using a simple model shown in Fig. 23. The cutting tool is actually a cutting wedge having the rake (the rake angle γ) and the flank (the clearance angle α) faces that

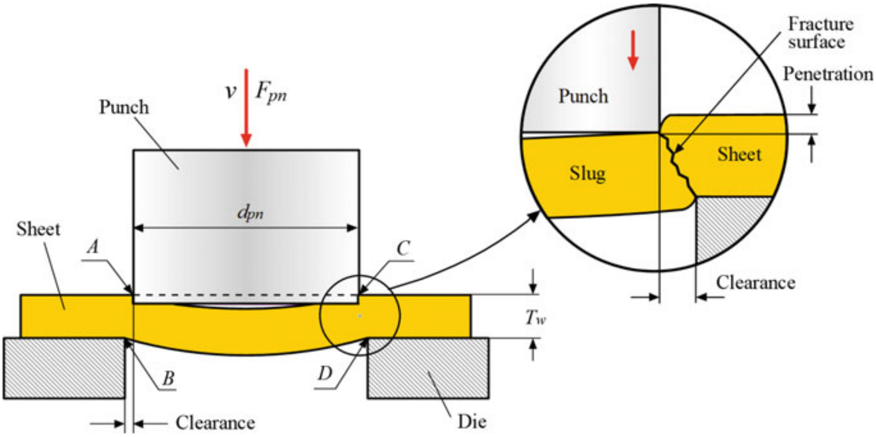


Fig. 22 Schematic illustration of shearing with punch and die

meet to form the cutting edge. As pointed out by Taylor [16], while a metal cutting tool looks like a wedge, its function is far different from that of the wedge. The flank face is never (at least theoretically) allowed to touch the workpiece. Therefore, the presence of the clearance angle α distinguishes a metal cutting tool from other cutting tools with cutting edges. As such, it does not matter what work material is actually cut—metal wood, plastic—the process is still referred to as metal cutting.

When the tool is in contact with the workpiece, the application of the force N leads to the formation of a deformation zone ahead of the cutting edge (point A). The tool moves forward with a cutting speed v. The workpiece first deforms elastically and then plastically. As a result of the plastic deformation, a "bump" forms in close contact with the rake face. Thus, the plastic deformation of the layer

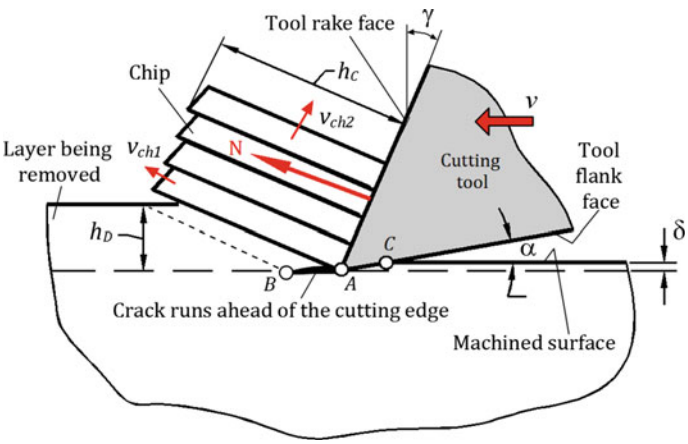


Fig. 23 Model of metal cutting

to be removed and formation of the bump in front of the cutting tool is actually beginning of the metal cutting process as the state of stress ahead of the tool becomes complex including a combination of bending (as the bumps act as a lever due to which the bending stress in the deformation zone is formed), compressive (compression of the layer being removed by the rake face), and shear (due to the friction over the tool–chip interface) stresses. When the combined stress just in front of the cutting edge (point *A*) reaches a limit (for a given work material), a small crack *AB* forms ahead of the cutting edge so that a chip fragment of the layer being removed disengages from the rest of the workpiece and starts to slide over a sliding surface formed in the direction of the maximum combined stress with velocity v_{ch1} and simultaneously over the tool rake face with velocity v_{ch2}. The chip fragment continues to slide until the force acting on this fragment from the tool is reduced, when a new portion of the work material enters into the contact with the tool rake face. This new portion attracts part of the cutting force, and thus the stress along the sliding surface diminishes, becoming less than the limiting stress and arresting the sliding. A new fragment of the chip starts to form.

The uniqueness of the metal cutting process (among other cutting operations, e.g., shearing operations and methods, e.g., cutting by a knife, scissors, splitting by a hatchet [17]) in terms of materials properties involved is in the following:

- The cutting process is a cyclic process. Each cycle includes elastic, then plastic deformation and finishes with fracture; i.e., the whole stress–stress diagram (as shown in Figs. 3b and 14) up to fracture is followed.
- In machining of brittle materials, a well visible crack forms in each cycle, whereas in machining of ductile materials, a series of micro-cracks hampered and then healed by a great hydrostatic pressure [18] within each chip element occurs in each cycle. As plastic deformation and fracture take place only within a small chip fragment, the power per unit volume of the cut material is much low in metal cutting compared to other cutting operations and methods.
- The plastic deformation imposed by the tool is concentrated in the chip and measured by the ratio of the chip thickness, h_C, to the uncut chip thickness, h_D [19]. In contrary to other cutting operations, the machine surface is not subjected to significant plastic deformation. Only a few percent the total plastic deformation that is imposed into the machined surface (coldworked layer on this surface) by the tool–workpiece interface *AC* (Fig. 23) due to the spring back δ of this surface. The essence of this spring back is not unfortunately clear to many. In the author's opinion, it is rather simple as it follows from the stress–strain diagram shown in Fig. 3b. The amount of spring back is actually represented by segment 6–7 so it appears to be the elastic recovery of the work material. Reading this diagram intelligently, one can calculate the value of spring back. Moreover, he or she can conclude that two major materials properties, namely its ultimate strength and elastic module, fully define this spring back as it follows from Fig. 3b.
- This allows achieving the closest tolerance and low surface roughness of the machined surface (approximately two orders high compared to other cutting

operations). That is why metal cutting operations are most widely used in industry to manufacture finished parts made of variety of different work materials.

The energy needed for fracture of the unit volume of the work material is the area under the true stress–strain curve considered up to fracture known as the damage curve [20] shown in Fig. 24. This curve is obtained from the flow curve shown in Fig. 14 by gining attention to, and thus adding the work material degradation and fracture regions. As can be seen, the real damage curve which describes behavior of the work material in fracture has well-defined, and thus measurable, area.

The elastic–plastic undamaged path *abc* is the same as in the flow curve (Fig. 14) followed by the departure of the experimental yield surface from the virtual undamaged yield surface at point *c*. Point *c* can be considered as the hypothetic damage initiation site where the material hardening modulus becomes progressively sensitive to the amount of damage leading to the declination of the material loading capacity. Due to increased damage, the material reaches its ultimate stress capacity at *d* where the hardening modulus becomes zero. This usually occurs in ductile metals when the material loading capacity decreases by 30–70% of its full capacity due to the accumulated damage [21]. The observed fracture initiation site is denoted by point *e,* and finally, the fracture is indicated by point *f*.

The damage curve is approximated as follows: Its segment *ac* is described by Eq. (25), whereas the scalar damage parameter (*D*) [20] is used to describe the material flow past damage initiation (segment *cf*)

$$\sigma_{e-cf} = (1 - D)\sigma_e \tag{27}$$

where σ_e is the hypothetic undamaged stress as predicted by Eq. (25).

The partition of the total energy spent in cutting is represented through the power balance as

$$P_{\mathrm{c}} = P_{\mathrm{pd}} + P_{\mathrm{fR}} + P_{\mathrm{fF}} \tag{28}$$

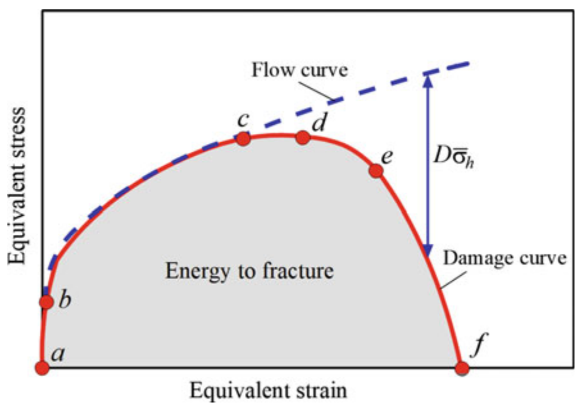


Fig. 24 Damage curve

where P_c is the cutting power, i.e., the power required by the cutting system for its existence. It is calculated using the total energy supplied to this system, E_{cs}; P_{pd} is the power spent on the plastic deformation of the layer being removed, calculated through the energy of plastic deformation of the work material to fracture, E_f; P_{fR} is the power spent at the tool–chip interface; P_{fR} is the power spent at the tool–workpiece interface.

The analysis of the energy/power partition in metal cutting represented by Eq. (28) revealed that the power spent on plastic deformation of the work material in its transformation into the chip during machining P_{pd} constitutes up to 75% of the total energy supplied to the cutting system [22]. The greater the ductility of the work material, the higher is P_{pd}. As plastic deformation of the chip serves no useful purpose after machining, up to 75% of the energy supplied to the cutting system is simply wasted. Moreover, only less than 2% of this energy is actually stored in the chip whereas remaning 98% converts into the thermal energy flowing as heat in the chip, tool and workpiece. This causes high temperatures in the machining zone, that, in turn, reduces tool life and restricts the allowable cutting speed, and thus productivity of machining.

For many years of machining history, the cycle time due to actual machining was "a drop in the bucket" compared to the total time part spent in the machine as part loading–unloading, part proper positioning in the chuck (e.g., with an indicator), tool change, part measuring, inspection within the machine, etc. Even a 100% reduction of the actual machining time or increasing tool life by 50% did not contribute noticeably to machining productivity and efficiency.

This "gloomy picture" has been rapidly changing since the beginning of the twenty-first century as global competition forced many manufacturing companies, first of all car manufacturers, to increase efficiency and quality of machining operations. To address these issues, leading tool and machine manufacturers have developed a number of new products as new tool materials and coatings, new cutting inserts and tool designs, new tool holders, powerful precision machines, part fixtures, advanced controllers that provide a wide spectrum of information on cutting processes, and so on. These increase the efficiency of machining operations in industry by increasing working speeds, feed rates, tool life, and reliability. These changes can be called the "silent" machining revolution as they happened in rather short period of time. Implementation of the listed developments led to a stunning result: For the first time in the manufacturing history, the machining operating time became a bottleneck in the part machining cycle time.

To address this challenge of a new era, a closer look at the materials properties involved in cutting should be taken. As the energy of plastic deformation of the material to fracture is greatest by far and thus affects the productivity and efficiency of machining operations, this energy should be analyzed so that some means to reduce this energy can be developed.

The energy of plastic deformation of the material to fracture is calculated as the area under the damage curve [18] as

$$E_f = \int_0^{\varepsilon_f} \sigma_e \mathrm{d}\varepsilon \tag{29}$$

Therefore, a question is if this area and thus energy can be reduced or it is an inherent property of the work material.

It was pointed out earlier that metal cutting involved a three-dimensional state of stress in the deformation zone ahead of the cutting tool. It is known that the material ductile fracture (i.e., the strain at fracture) is affected by the path under which this deformation was developed [23]. The process of fracture is strictly path dependent, and the fracture strain in one process may differ from another. Bai and Wierzbicki [24] showed that the stress triaxiality state parameter (η), which reflects the effect of the mean stress (σ_{m}), can be used to characterize the state of stress. This dimensionless parameter is calculated as

$$\eta = \frac{\sigma_m}{\sigma_e} \tag{30}$$

and is considered as an important factor in formulating ductile fracture models in the literature [25, 26].

In practical assessments of the influence of the state of stress and in materials fracture tests, another parameter of the stress state, known as the normalized third deviatoric invariant, ξ, that affects a material's ductility and thus affects its fracture strain [27] is used. Parameters ξ and η are correlated as

$$\xi = \frac{27}{2}\eta\left(\eta^2 - \frac{1}{3}\right) \tag{31}$$

The tensile and compression axial symmetry loading states $\xi = 1$ and $\xi = -1$ can be achieved experimentally by using the classical notched or smooth round bar specimen.

According to the authors' opinion, reducing strain to fracture by controlling the state of stress in the deformation zone in machining through cutting tool design and selection of machining regime is the most efficient measure of the metal cutting process optimization because this does not involve additional costs. To explore this option, one must be able to determine the stress-state dependence of the work material, incorporate this dependence in material constitutive models, and then correlate the parameters of the tool geometry and machining regime with this state in order to find their combination for the tool and process optimization.

The last question to be answered is how much the state of stress influences the strain at fracture, and thus the energy of plastic deformation to fracture. To visualize this influence, the fracture locus, which is a curve representing the dependence of the strain at fracture on the state of stress, should be constructed using experimental data [20]. Figure 25 shows fracture locus for steel AISI 1045. As can be seen, varying the stress triaxiality from −0.25 to 0.6, the plastic strain at damage initiation

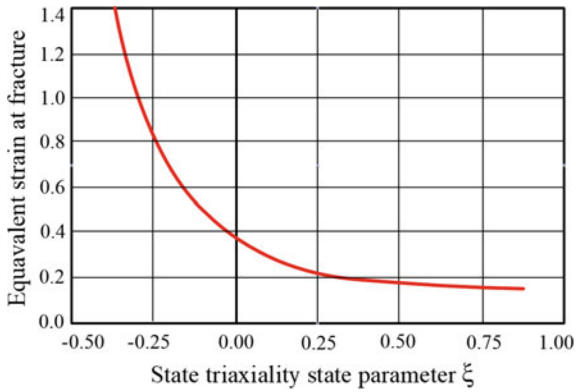


Fig. 25 Fracture locus for steel AISI 1045 obtained using the developed double-notched specimen

decreased from 0.81 to 0.17. In other words, the area under the damage curve for a given work material (Fig. 24), which represents the work of plastic deformation in cutting, can be altered to a wide extent by varying stress triaxiality.

4.2.3 Summary of Relevant Materials Properties in Cutting Operations

What unites forming processes listed in Fig. 19 in terms of materials properties involved is all of them are accomplished by fracture in order to bring the workpiece into the final desirable shape part through cutting chip/slag. This implies the following:

- The stress needed for fracture of the work material must be achieved. This sets manufacturing materials-related calculating apart from those used in the design.
- Contrary to forming processes/operations (see Fig. 11), plasticity (commonly referred to as ductility) as the amount of plastic deformation of the work material before fracture occurs should be brought to its minimum as it causes: (a) deformed edges of the part after fracture (i.e., poor quality), (b) increased cutting force and temperature that increase tool wear and thus lower tool life. The smaller the plasticity/ductility of the work material, the better its machinability.
- The objective of any cutting process, and thus its criterion of optimization, is achieving fracture with minimum possible energy defined by the area under the shear stress–strain diagram (Fig. 5b) or under the damage curve (Fig. 14). While not much can be done to reduce this energy in shearing operations besides optimizing the clearance between punch and die [17], in metal cutting, on the contrary, this energy can be varied in wide range and thus successfully minimized by altering the state of stress in the deformation zone [23].

To obtain the full advantage of the state of stress in meat cutting, one should realize that this state depends on practically all geometrical and design parameters of the cutting tool (mainly the rake, clearance, cutting edge, and inclination angles), tool material (adhesion properties) parameters of the machining regime (the cutting speed, feed, depth of cut), and so on. A cyclic nature of the cutting process complicates the whole picture even further. Therefore, to design/optimize machining operation the influence of the listed parameters on the state of stress should be accounted for properly. Unfortunately, the available software packages for metal cutting simulations do not meet these requirements even to the first approximation. As a result, they are not really of the same help as the commercial FEM packages used in forming operations (see Sect. 4.1.4) although metal cutting process is often thought of as a metal deforming process [28].

Questions

1. What is the most common and very useful test to obtain mechanical properties of materials? Why is it so?
   The most common and very useful test of mechanical properties of materials is a tension test. Tensile tests are performed for several reasons. The results of tensile tests are used in selecting materials for engineering applications. Basic tensile properties are normally included in material specifications to be used in the design and manufacturing of products. Tensile properties are often used to predict the behavior of a material under forms of loading other than uniaxial tension.
2. What is the major outcome of a tension test?
   The major outcome of the tension test is a stress–strain diagram. A stress–strain diagram is a diagram in which corresponding values of stress and strain are plotted against each other. Values of stress are usually plotted as ordinates (vertically) and values of strain as abscissas (horizontally).
3. What is the design criterion?
   It is the allowable working stress obtained by dividing the strength of this material (the yield strength for ductile materials and ultimate strength for brittle materials) by the factor of safety.
4. What is a forming process in the manufacturing sense?
   A forming process is a chipless or non-material removal process through three-dimensional or plastic modification of a shape while retaining its mass and material cohesion.
5. What are two types of forming processes?
   At the most general level, forming processes are divided into bulk metal forming and sheet metal forming.
6. What is formability of a material?
   Formability of a material is defined by its plasticity (ductility) considered as the amount of plastic deformation of the work material before undesirable phenomena occur, for example cracks, wrinkling.
7. What is cutting in the manufacturing sense?
   Cutting in the manufacturing sense is physical separation of a material on two or more parts carried out by a cutting tool (blade) in a controllable manner.

8. What is the most relevant property of the work material in shearing processes?
The area under the shear stress–strain curve defines the energy needed for shearing of a unit volume of the work material. Knowing this energy, one can easily calculate the power needed in punching, and then dividing this power over the punching speed one can obtain the punching force.
9. What is the prime work material property in metal cutting?
The energy of plastic deformation of the material to fracture is calculated as the area under the damage curve. This energy defines all other process outcomes as the cutting force, cutting temperature, tool life, quality of the machined surface, etc.
10. What is the technical objective of the cutting process optimization?
The objective of any cutting process, and thus its criterion of optimization, is achieving fracture with minimum possible energy defined by the area under the damage curve. This energy can be varied in wide range and thus successfully minimized by altering the state of stress in the deformation zone.

Glossary

A stress–strain diagram A diagram in which corresponding values of stress and strain are plotted against each other. Values of stress are usually plotted as ordinates (vertically) and values of strain as abscissas (horizontally).

Cutting Physical separation of a material into two or more parts.

Ductility Ability of a material to deform plastically before fracturing.

Damage curve Curve is obtained from the flow curve by adding the work material degradation and fracture regions.

Factor of safety (FoS) also known as safety factor (SF) A term describing the structural capacity of a part or system beyond the expected loads or actual loads.

Flow curve A curve in the true stress-true strain coordinate describing the material behavior up to fracture.

Forming processes Manufacturing processes done through three-dimensional or plastic modification of a shape while retaining its mass and material cohesion

Fracture locus An experimentally obtained curve representing the dependence of the strain at fracture on the state of stress.

Hardness The resistance of a material to indenter penetration. Measured in MPa or GPa.

Metal cutting (machining) Purposeful fracture of a thin layer on the workpiece by a wedge-shaped cutting tool occurring under a combined stress in the deformation zone in cyclic manner.

Modulus of elasticity The slope of elastic segment of a stress–strain diagram. It is a measure of the stiffness of a solid material. Measured in GPa.

Poisson's ratio The ratio of the magnitude of the lateral contraction strain to the axial strain. Dimensionless.

Resilience The strain energy stored by body up to elastic limit. Measured in J/m^3.

Shear modulus The slope of the elastic segment of a shear stress–strain diagram. Measured in GPa.

Shearing operations Cutting operations the deformation and then separation of a material substance in which parallel surfaces are made to slide past one another.

Stress triaxiality state parameter The ratio of the mean and equivalent stress. Used to characterize the state of stress.

True stress and true strain Stress and strain determined based on the actual cross-sectional area of the specimen.

Toughness The energy need to fracture of a unit volume of a material. Measured in J/m^3.

von Mises stress criterion States that yielding of a material occurs when the equivalent stress reaches the yield strength of the material in simple tension.

Ultimate shear strength The shear maximum stress developed by the material before fracture based on the original cross-sectional area. Measured in MPa.

Ultimate tensile strength (UTS) The maximum normal stress developed by the material before fracture based on the original cross-sectional area. Measured in MPa.

Yield shear strength The shear stress at which a material exhibits a deviation from the proportionality of stress to strain. Measured in MPa.

Yield tensile strength The normal stress at which a material exhibits a deviation from the proportionality of stress to strain, i.e., the occurrence permanents plastic strain is the case. Measured in MPa

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