MECHANICAL PROPERTIES OF CRYSTALLINE MATERIALS

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Keywords: Elastic Deformation, Anelastic Deformation, Viscous Deformation, Crystallography, Schmid Law, Twinning, Polycrystals, Recrystallization, Brittle Fracture, Fatigue, Crack Initiation.

Contents

Summary

Mechanical properties of materials are concerned with deformation as well as fracture of materials under the action of applied forces. Materials tests are used to evaluate the mechanical properties of materials, such as its resistance to failure in terms of the yield strength or fracture toughness. When a uniaxial stress is applied to a specimen, the specimen deforms elastically at first and then plastically, causing permanent deformation. The engineering stress-strain diagram obtained from a tensile test can

provide the 0.2% offset yield strength, ultimate tensile strength, and elongation, which are basic mechanical properties of materials for many engineering designs.

Plastic deformation of materials takes place most commonly by the slip process, involving the movement of dislocations. Slip usually occurs through the action of shear stress on the closely packed planes and in the specified crystallographic directions. The slip plane and slip direction combination constitutes the slip system. Plastic deformation initiates on the slip plane when the resolved shear stress reaches a critical value along the most favorably oriented slip direction. In addition to slip, twinning is another mechanism that helps to account for plastic deformation when slip becomes difficult.

When a material is plastically deformed, it becomes hardened, resulting in an increase in its strength and a decrease in its ductility. This phenomenon is called work-hardening. When the work-hardened material is slowly heated to a certain high temperature, the processes of recovery and recrystallization take place, and the material is softened.

Fracture of materials under simple tensile loading can be classified into ductile, brittle or ductile-brittle types. When a material is subjected to a varied or repeated loading, fatigue failure may take place at a maximum load, which is much less than the static fracture load. Under the action of a constant load at high temperatures, a material may undergo creep, or time-dependent deformation, which may become so severe that creep rupture eventually occurs. A special method called fracture mechanics is used to analyze the propagation of cracks in materials.

Advancing and changing technology continually introduces new challenges, demanding more efficient use of materials and improved materials, which are more resistant to failure. Deformation and fracture are of major economic importance. The costs involved in avoiding fracture and in paying for its consequences in all sectors of the economy are on the order of 4% of the GNP.

1. Introduction

Mechanical properties of materials are concerned with the deformation and fracture of materials under applied loading. Materials are used to manufacture components of machines, vehicles, devices and structures, which are usually subjected to mechanical and/or thermal stresses in service. Designers must guarantee that they are both safe and durable. To assure safety and durability, it is necessary to avoid excess deformation, such as bending, twisting or stretching of the component parts of the engineering items. In addition, cracking in components must be avoided entirely or strictly limited to stable and controllable growth.

The successful utilization of materials requires that they have the ability to resist unacceptable deformation and fracture under applied loading. Knowledge of the mechanical properties of materials provides the basis for avoiding failure caused by deformation or cracking in engineering applications. Once the mechanical behavior of a given material is quantitatively known, the chances of success in a particular engineering design can be evaluated. Therefore, mechanical properties, characterization, processing and design of materials are considered the four principal elements of materials science and engineering, and they are intimately connected to each other.

Because of the space limitations, the subsequent discussion is mainly confined to the mechanical properties of metallic materials, but many aspects also apply to nonmetals, such as ceramics and glasses.

2. Stress-strain Curves

When a piece of metal is subjected to a unaxial tensile force, deformation of the metal occurs. A typical engineering stress-strain curve obtained from a tensile test is shown in Figure 1. By definition, the engineering stress σ is calculated by dividing the applied force on a tensile test specimen by its original cross-sectional area.

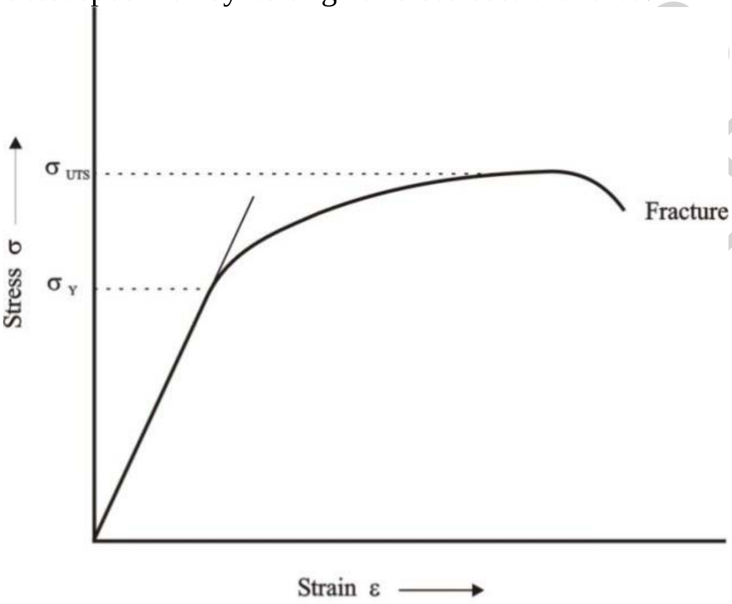

Figure 1. The Typical Tensile Engineering Stress-strain Curve

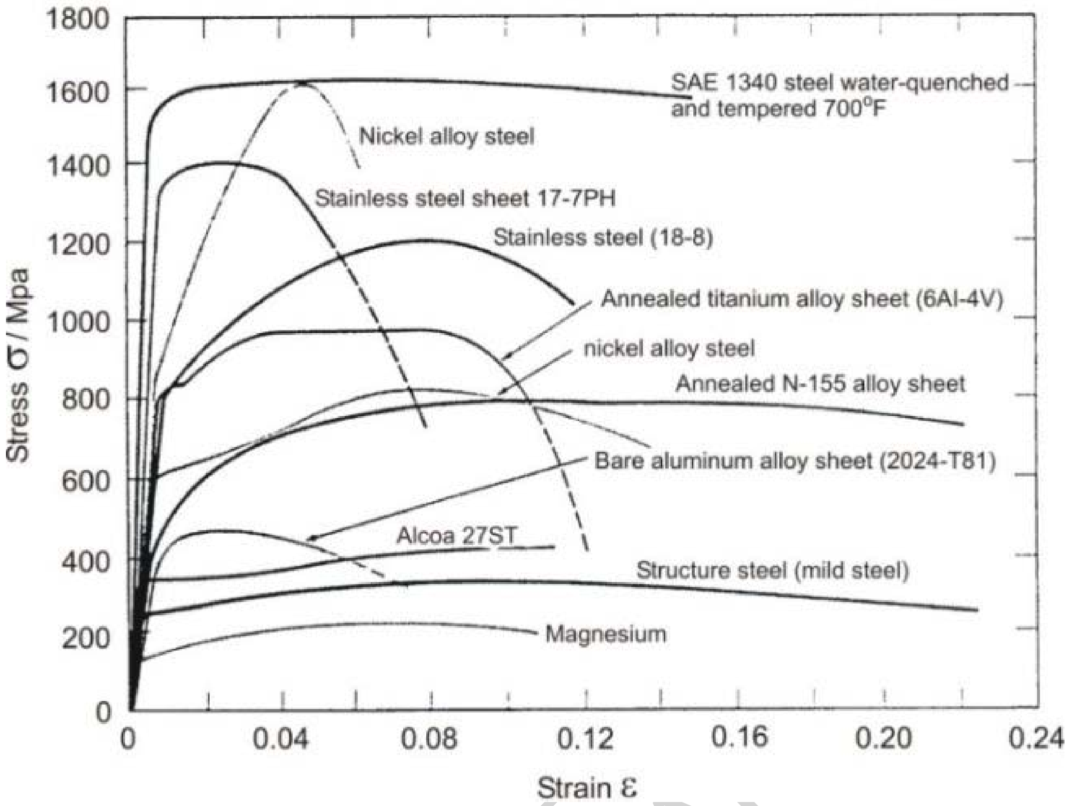

Figure 2. Engineering Stress-strain Curves for Selected Metals and Alloys
(Source: Marin J. (1962). *Mechanical Behavior of Engineering Materials*, p.24,New Jersey:Prentice-Hall.)

The engineering strain ε is defined as the ratio of the change in length of the specimen in the direction of the force divided by the original length of specimen considered. At the beginning of the test, the strain ε is directly proportional to the stress σ and the specimen returns to its original length on removal of the stress. The material is said to have undergone elastic deformation. With further loading beyond the yield stress σ_y, however, the response is no longer linear. The applied stress σ produces plastic deformation, so that the specimen cannot fully recover its original dimensions after removal of the applied load. The stress continues to increase with elongation due to work-hardening until ultimate tensile stress or the tensile strength σ_{UTS} is reached. At this point a neck begins to develop somewhere along the length of the specimen and further plastic deformation is localized within the neck. After necking has begun, the nominal or engineering stress decreases until the material fractures. Some typical stress-strain curves for different metals and alloys are shown in Figure 2. For all materials, the stress-strain relationship depends on the chemical composition, the heat-treatment and the method of manufacture. In ductile materials, such as aluminum, copper, and annealed mild steel, which exhibit large strains before failure, the engineering stress at fracture is lower than the tensile strength although the actual or true stress in the neck will be higher. In brittle materials, such as cast iron, high strength steel, tungsten carbide, and high strength aluminum alloys, necking does not occur.

3. Elastic Deformation

The elastic deformation can be described by an equation as follows:

$$\sigma = E\varepsilon \tag{1}$$

where E is a constant called Young’s modulus. The equation is known as Hooke’s law. This linear relationship between stress and strain when a material is deforming elastically in tension is also found under other conditions of stressing. Thus, for the simple shear stress situation, there is

$$\tau = G\gamma \tag{2}$$

where τ and γ are the shear stress and strain respectively and G is the shear modulus. While if a hydrostatic pressure P_H is applied to a specimen so that the volume V changes elastically by an amount ΔV, a bulk modulus, K, may be defined as

$$P_H = K\Delta V / V \tag{3}$$

Elastic deformation is instantaneous, that is, if we suddenly increase the stress from σ_1 to σ_2 the strain immediately changes from ε_1 to ε_2. Elastic deformation is also completely reversible and if the stress is reduced to its former value of σ_1 the strain falls back to ε_1. In fact, if the specimen is unloaded ($\sigma = 0$) the specimen immediately reverts to its initial size and shape.

4. Anelastic Deformation

Unlike elastic deformation, which is instantaneous on the application of a stress, anelastic deformation is time dependent. When a force is suddenly applied to a solid, which exhibits anelastic behavior, there is no instantaneous displacement; but it gradually approaches an asymptotic value. Conversely, when the force is suddenly removed, the solid suffers no instantaneous recovery, but the displacement gradually disappears. This behavior is illustrated in Figure 3. It is evident that such solids manifest an elastic aftereffect and internal friction.

Anelastic deformation is the result of time dependent processes, such as the movement of point defects in response to the stress and the straightening out of kinked or coiled molecular chains, occurring within the materials. Although anelastic deformation occurs in all materials, the strain associated with it may not be significant. For example, in metals, the anelastic strain is small and its contribution to the total strain is negligible compared with that from elastic and plastic deformation.

5. Viscous Deformation

A liquid flows irreversibly and continuously when a stress is applied. This is referred to as viscous flow and it also occurs in some solids, especially at elevated temperatures. For example, it is common in glasses and polymers. In contrast, viscous flow in metals is rare and is only found under specific conditions of high temperatures and low stresses.

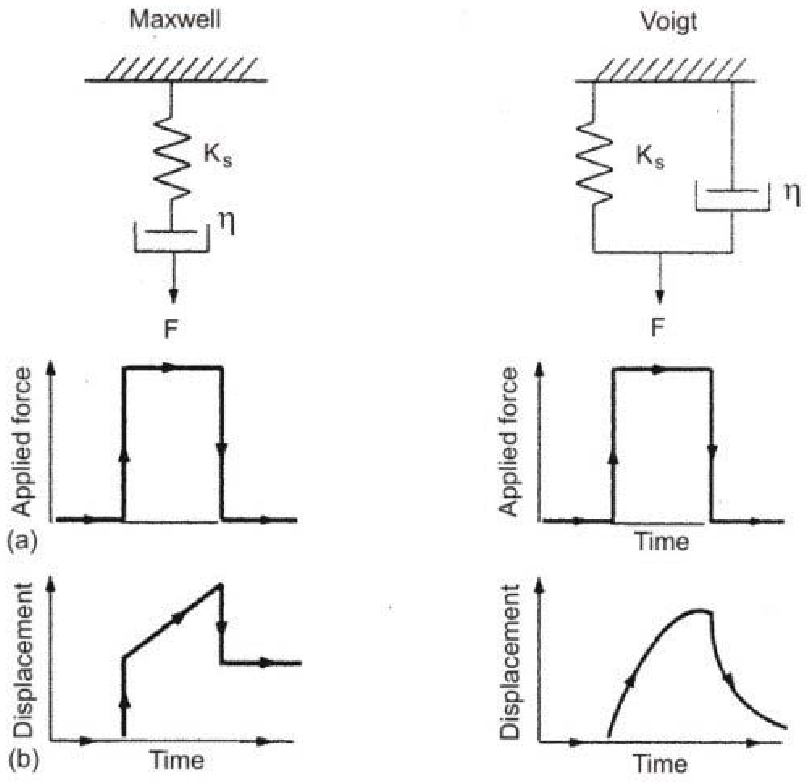

Figure 3. Anelastic Deformation
(a) Applied load is initially zero, raised to a constant level for a fixed time, and then unloaded; (b) Resultant time-dependent displacement

When a material flows viscously, the resulting shear strain γ is a function of both the shear stress τ and time t. Ideal viscous behavior is described by Newton's Law of viscous flow:

$$\tau = \eta \frac{d\gamma}{dt} \tag{4}$$

where η is the viscosity. For ideal or Newtonian behavior η is independent of the rate of shear. A glass above the glass transition temperature becomes viscous liquid and behaves as a Newtonian materials.

Viscous flow in solids normally involves the thermally activated movement of atoms or molecules within the materials. The rate of a thermally activated process such as this is controlled by the Boltzmann exponential factor. Consequently, over limited ranges of temperatures the viscosity varies with temperature according to

$$\frac{1}{\eta} = A exp(-Q/kT) \tag{5}$$

When A is a constant, Q is the activation energy for viscous flow, T is the absolute temperature, and k is Boltzmann's constant.

6. Geometry and Crystallography of Plastic Deformation

6.1. Resolved Shear Stress and Schmid Law

The anisotropic deformation of single crystals is characterized in terms of the resolved shear stress τ acting on a specific slip plane along a specific slip direction. Figure 4 shows a cylindrical specimen of a single crystal of cross-sectional area A, which is subjected to a uniaxial tensile or compressive load P. Let the slip plane normal and the slip direction be oriented at an angle ϕ and θ, respectively, with respect to the loading axis.

The load P can be resolved along the slip direction to give a shear force P$\cos\theta$, acting in the slip direction. The resolved shear stress τ on the slip plane and in the slip direction is the shear force P$\cos\theta$ divided by the area of the slip plane A/$\cos\phi$, so that

$$\tau = \frac{\mathrm{P}}{\mathrm{A}}\cos\phi\cos\mathrm{A} = \sigma\cos\phi\cos\theta \qquad (6)$$

The condition for the onset of plastic deformation is given by the so-called Schmid law, which states that a crystalline solid flows plastically when the resolved shear stress τ acting along the slip direction in the slip plane reaches a critical value τ_c:

$$\sigma\cos\phi\cos\theta = M\sigma = \tau_c \qquad (7)$$

$M = \cos\phi\cos\theta$ is known as the Schmid factor, which has a maximum value of 0.5 corresponding to the orientation $\phi = \theta = 45°$.

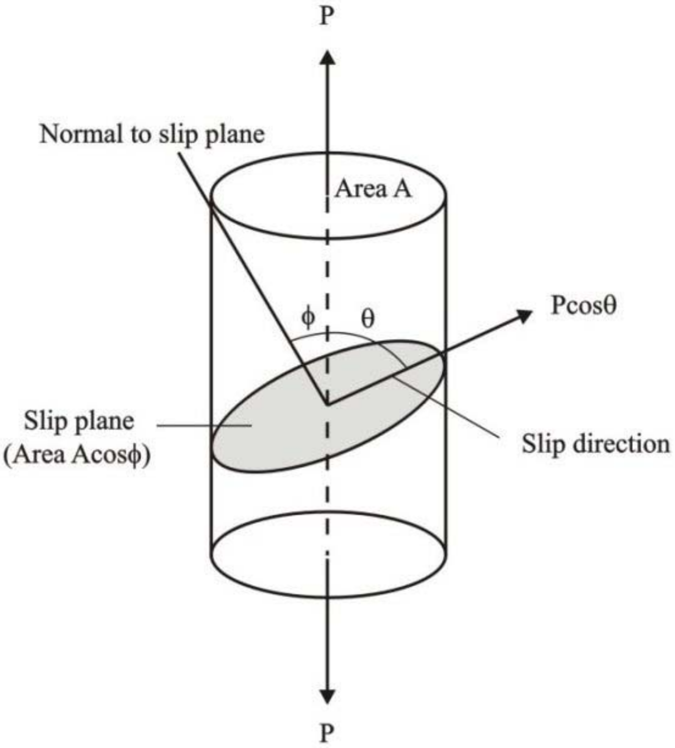

Figure 4: Determination of the Resolved Shear Stress on the Slip Plane and in the Slip Direction for a Single Crystal
(Source: Anderson J. C., Leaver K. D., Rawlings R. D., and Alexander I. M. (1990). *Materials Science*, p.193, London: Chapman & Hall)

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Biographical Sketch

Zhongguang Wang was born in 1936 in the Zhejiang Province, China, and received his early education in the Hunan Province, China. He later attended Tsinghua University in Beijing, China and received his B.Sc. degree in metallic materials in 1959. Subsequently, he jointed the Institute of Metal Research, Chinese Academy of Sciences, Shenyang, China, and has been responsible for research on fatigue mechanisms of metallic materials since then. He became a full professor in 1986 and was the first director of the State Key Laboratory for Fatigue and Fracture of Materials from 1988 to 1997. He is the author or co-author of over 200 technical publications in the field of fatigue of materials. He is also the co-editor of four conference volumes for Fatigue'99.

His eminence in research was recognized by a number of awards, including one national third and one national fourth class prizes for nature sciences and five second class prizes for nature sciences, awarded by the Chinese Academy of Sciences. He was appointed member of several international organizations, including the International Committee of the Strength of Materials and the International Committee of Fatigue. As a co-chairman, he organized the 7th International Conference on Fatigue (Fatigue'99), to be held in Beijing in 1999. He also holds several positions in academic societies in China. He is the member of the Board of Material Research Society of China (C-MRS) and the chairman of the Chinese Society of Fatigue. He is now the associate editor of the international journals *Acta Materialia* and *Scripta Materialia*. He is also the member of the editorial advisory board of *International Journal of Fatigue*.