**Mechanical Properties of Metals**

* 1. **Stress—Strain Behavior**

**Elastic deformation**. When the stress is removed, the material returns to the original dimension it had before the load was applied. Valid for small strains (except the case of rubbers). Deformation is *reversible, non permanent*

**Plastic deformation**. When the stress is removed, the material does not return to its previous dimension but there is a *permanent*, irreversible deformation.

In tensile tests, if the deformation is *elastic*, the stress-strain relationship is called Hooke's law:

**s = *E* e**

That is, *E* is the slope of the stress-strain curve. E is *Young's modulus* or *modulus of elasticity*. In some cases, the relationship is not linear so that E can be defined alternatively as the local slope:

***E =* ds/de**

Shear stresses produce strains according to:

**t = *G* g**

Where *G* is the *shear modulus*.

* 1. **Anelasticity**

Here the behavior is elastic but not the stress-strain curve is not immediately reversible. It takes a while for the strain to return to zero. The effect is normally small for metals but can be significant for polymers.

* 1. **Elastic Properties of Materials**

Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the *Poisson's ratio* n*.*

**n = elateral/eaxial**

The elastic modulus, shear modulus and Poisson's ratio are related by *E* = 2*G*(1+n)

* 1. **Tensile Properties**

**Elasticity:** The ability of a material to return to its original form after a load has been applied and removed. Good examples include rubber, mild steel and some plastics such as nylon.

**Plasticity:** The materials which deform permanently when small forces are applied show plasticity. Plasticine and clay are good examples**.**

**Yield point**. If the stress is too large, the strain deviates from being proportional to the stress. The point at which this happens is the *yield point* because there the material yields, deforming permanently (plastically)*.*

**Yield stress**. Hooke's law is not valid beyond the yield point. The stress at the yield point is called *yield stress*, and is an important measure of the mechanical properties of materials. In practice, the yield stress is chosen as that causing a permanent strain of 0.002 (strain offset, Fig. 6.9.)

*The yield stress measures the resistance to plastic deformation*.

The reason for plastic deformation, in normal materials, is not that the atomic bond is stretched beyond repair, but the motion of dislocations, which involves breaking and reforming bonds.

*Plastic deformation is caused by the motion of dislocations.*

**Strength**: The general ability of a material to withstand an applied force is called its strength.

**Tensile strength:** The ability to withstand *pulling* or stretching forces (tension). When stress continues in the plastic regime, the stress-strain passes through a maximum, called the *tensile strength* (sTS) , and then falls as the material starts to develop a *neck* and it finally breaks at the *fracture point* (Fig. 6.10).

Note that it is called strength, not stress, but the units are the same, MPa.

*For structural applications, the yield stress is usually a more important property than the tensile strength, since once it is passed, the structure has deformed beyond acceptable limits.*

**Compressive strength:** The ability to withstand*pushing* or squeezing forces (compression).

**Ductility**. It is the ability to be drawn out into a thin wire or threads. It is a measure of how easily a material can be *worked*. Good examples are gold, copper, titanium, wrought iron, low carbon steels and brass.

The ability to deform before braking, it is the opposite of **brittleness**. Ductility can be given either as percent maximum elongation emax or maximum area reduction.

**%EL = emax x 100 %**

**%AR = (*A*0 - *A*f)/*A*0**

These are measured after fracture (repositioning the two pieces back together).

**Brittleness:** A material that has a tendency to break easily or suddenly without any extension first. Good examples are Cast iron, concrete, high carbon steels, ceramics, and some polymers such as urea formaldehyde (UF).

**Resilience.** Capacity to absorb energy *elastically.* The energy per unit volume is the *area under the strain-stress curve in the elastic region.*

**Toughness.** Ability to absorb energy up to fracture. The energy per unit volume is the *total area under the strain-stress curve*. It is measured by an impact test (Ch. 8).

**Malleability:** The ability to plastically deform and shape a material by forging, rolling or by any other method of applying pressure. Being easy to beat into a thin sheet is the literal meaning. Good examples are lead, gold and copper.

* 1. **True Stress and Strain**

When one applies a constant tensile force the material will break after reaching the tensile strength. The material starts necking (the transverse area decreases) but the stress cannot increase beyond sTS. The ratio of the force to the initial area, what we normally do, is called the engineering stress. If the ratio is to the actual area (that changes with stress) one obtains the *true stress.*

* 1. **Elastic Recovery During Plastic Deformation**

If a material is taken beyond the yield point (it is deformed plastically) and the stress is then released, the material ends up with a permanent strain. If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point *that is higher than the original yield point* (strain hardening, Ch. 7.10). The amount of elastic strain that it will take before reaching the yield point is called *elastic strain recovery* (Fig. 6. 16).

* 1. **Compressive, Shear, and Tensional Deformation**

Compressive and shear stresses give similar behavior to tensile stresses, but in the case of compressive stresses there is no maximum in the s-e curve, since no necking occurs.

* 1. **Hardness**

**Hardness** is the resistance to plastic deformation (e.g., a local dent or scratch). Thus, it is a measure of *plastic* deformation, as is the tensile strength, so they are well correlated. Historically, it was measured on an empirically scale, determined by the ability of a material to scratch another, diamond being the hardest and talc the softer. Now we use standard tests, where a ball or point is pressed into a material and the size of the dent is measured. There are a few different hardness tests: Rockwell, Brinell, Vickers, etc. They are popular because they are easy and non-destructive (except for the small dent).

**Stiffness:** The ability to*resist bending.*

* 1. **Variability of Material Properties**

Tests do not produce exactly the same result because of variations in the test equipment, procedures, operator bias, specimen fabrication, etc. But, even if all those parameters are controlled within strict limits, a variation remains in the materials, due to uncontrolled variations during fabrication, non homogenous composition and structure, etc. The measured mechanical properties will show scatter, which is often distributed in a Gaussian curve (bell-shaped), that is characterized by the mean value and the standard deviation (width).

* 1. **Design/Safety Factors**

To take into account variability of properties, designers use, instead of an average value of, say, the tensile strength, the probability that the yield strength is above the minimum value tolerable. This leads to the use of a *safety factor* *N* > 1 (typ. 1.2 - 4). Thus, a working value for the tensile strength would be sW = sTS / *N*.

Chapter 8. Failure

1. **Introduction**

Failure of materials may have huge costs. Causes included improper materials selection or processing, the improper design of components, and improper use.

1. **Fundamentals of Fracture**

Fracture is a form of failure where the material separates in pieces due to stress, at temperatures below the melting point. The fracture is termed ductile or brittle depending on whether the elongation is large or small.

Steps in fracture (response to stress):

* track formation
* track propagation

***Ductile vs. brittle fracture***

|  |  |  |
| --- | --- | --- |
|   | **Ductile** | **Brittle** |
| **deformation** | extensive | little |
| **track propagation** | slow, needs stress | fast |
| **type of materials** | most metals (not too cold) | ceramics, ice, cold metals |
| **warning** | permanent elongation | none |
| **strain energy** | higher | lower |
| **fractured surface** | rough | smoother |
| **necking** | yes | no |

* **Ductile Fracture**

Stages of ductile fracture

* Initial necking
* small cavity formation (microvoids)
* void growth (elipsoid) by coalescence into a crack
* fast crack propagation around neck. Shear strain at 45o
* final shear fracture (cup and cone)

The interior surface is fibrous, irregular, which signify plastic deformation.

**Brittle Fracture**

There is no appreciable deformation, and crack propagation is very fast. In most brittle materials, crack propagation (by bond breaking) is along specific crystallographic planes (***cleavage*** planes). This type of fracture is transgranular (through grains) producing grainy texture (or faceted texture) when cleavage direction changes from grain to grain. In some materials, fracture is intergranular.

**Principles of Fracture Mechanics**

Fracture occurs due to *stress concentration* at flaws, like surface scratches, voids, etc. If *a* is the length of the void and rthe radius of curvature, the enhanced stress near the flaw is:

**sm » 2 s0 (*a*/*r*)1/2**

where s0 is the applied macroscopic stress. Note that *a* is 1/2 the length of the flaw, not the full length for an internal flaw, but the full length for a surface flaw. The stress concentration factor is:

***K***t = sm/s0 » 2 (*a*/*r*)1/2

Because of this enhancement, flaws with small radius of curvature are called *stress raisers*.

**Impact Fracture Testing**

Normalized tests, like the Charpy and Izod tests measure the *impact energy* required to fracture a notched specimen with a hammer mounted on a pendulum. The energy is measured by the change in potential energy (height) of the pendulum. This energy is called ***notch toughness.***

**Ductile to brittle transition** occurs in materials when the temperature is dropped below a *transition temperature.* Alloying usually increases the ductile-brittle transition temperature (Fig. 8.19.) For ceramics, this type of transition occurs at much higher temperatures than for metals.

***Fatigue***

Fatigue is the catastrophic failure due to dynamic (fluctuating) stresses. It can happen in bridges, airplanes, machine components, etc. The characteristics are:

* long period of cyclic strain
* the most usual (90%) of metallic failures (happens also in ceramics and polymers)
* is brittle-like even in ductile metals, with little plastic deformation
* it occurs in stages involving the initiation and propagation of cracks.

**Cyclic Stresses**

These are characterized by *maximum, minimum* and *mean stress, the stress amplitude*, and the *stress ratio* (Fig. 8.20).

**The *S—N* Curve**

*S—N* curves (stress-number of cycles to failure) are obtained using apparatus like the one shown in Fig. 8.21. Different types of *S—N* curves are shown in Fig. 8.22.

**Fatigue limit** (endurance limit) occurs for *some* materials (like some ferrous and Ti allows). In this case, the *S—N* curve becomes horizontal at large *N* . This means that there is a maximum stress amplitude (the fatigue limit) below which the material never fails, no matter how large the number of cycles is.

For other materials (e.g., non-ferrous) the *S—N* curve continues to fall with *N*.

Failure by fatigue shows substantial *variability* (Fig. 8.23)*.*

Failure at low loads is in the elastic strain regime, requires a large number of cycles (typ. 104 to 105). At high loads (plastic regime), one has low-cycle fatigue (*N* < 104 - 105 cycles).

**Crack Initiation and Propagation**

Stages is fatigue failure:

I. crack initiation at high stress points (stress raisers)

II. propagation (incremental in each cycle)

III. final failure by fracture

*N*final = *N*initiation + *N*propagation

Stage I - propagation

* slow
* along crystallographic planes of high shear stress
* flat and featureless fatigue surface

Stage II - propagation

crack propagates by repetive plastic blunting and sharpening of the crack tip. (Fig. 8.25.)

* + . Crack Propagation Rate (not covered)

**Factors That Affect Fatigue Life**

* Mean stress (lower fatigue life with increasing smean).
* Surface defects (scratches, sharp transitions and edges). Solution:
* polish to remove machining flaws
* add *residual compressive stress* (e.g., by shot peening.)
* case harden, by carburizing, nitriding (exposing to appropriate gas at high temperature)

**Environmental Effects**

* Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained. Solution:
* eliminate restraint by design
* use materials with low thermal expansion coefficients.
* Corrosion fatigue. Chemical reactions induced pits which act as stress raisers. Corrosion also enhances crack propagation. Solutions:
* decrease corrosiveness of medium, if possible.
* add protective surface coating.
* add residual compressive stresses.

***Creep***

Creep is the time-varying plastic deformation of a material stressed at high temperatures. Examples: turbine blades, steam generators. Keys are the time dependence of the strain and the high temperature.

**Generalized Creep Behavior**

At a constant stress, the strain increases initially fast with time (primary or transient deformation), then increases more slowly in the secondary region at a steady rate (creep rate). Finally the strain increases fast and leads to failure in the tertiary region. Characteristics:

* *Creep rate*: *d*e/*dt*
* *Time to failure.*

**Stress and Temperature Effects**

Creep becomes more pronounced at higher temperatures (Fig. 8.37). There is essentially no creep at temperatures below 40% of the melting point.

Creep increases at higher applied stresses.

The behavior can be characterized by the following expression, where *K, n* and *Q*c are constants for a given material:

*d*e/*dt* = *K s*n exp(-*Q*c/*RT*)

* Data Extrapolation Methods (not covered.)

**Alloys for High-Temperature Use**

These are needed for turbines in jet engines, hypersonic airplanes, nuclear reactors, etc. The important factors are a high melting temperature, a high elastic modulus and large grain size (the latter is opposite to what is desirable in low-temperature materials).

Some creep resistant materials are stainless steels, refractory metal alloys (containing elements of high melting point, like Nb, Mo, W, Ta), and superalloys (based on Co, Ni, Fe.)