Lecture 1. Material Properties

1. Background

Manufacturing is the process of converting some material into a part or product. It is the most fundamental activity in any civilization. Everything around you, every item you use, is manufactured. Each object you use is made up of components, each of which utilized very specialized equipment to make it.

Our goal in this course is (a) when we see things around us, we should be able to answer, in most cases, 'how was it made'; (b) we will gain the ability to detect problems with products, and suggest alternate materials/processes that could improve them; (c) we should be able to build a model of a process, and perform analysis that will indicate the optimum conditions for the use of the process under some specified criteria; (d) we should gain some understanding of the economics of manufacturing products.

Example 1. A bottle of Watson's water (~HK$6)

Figure 1. A Plastic water bottle

Four components (bottle, cap, label, water)

- How are each of these manufactured? What does the equipment cost?

Example 2. Stapler (~HK$ 45)

Figure 2. A Stapler

Approximately 15 components;

- How do we select the best material for each component?
- How are each of these manufactured?

Now consider a car – it has approximately 15000 parts; or a Boeing 747-400 plane, with over 6 million parts! Consider your PC; it probably has an Intel Pentium processor, which has millions of tiny electronic components, the feature size, i.e. the separation between the components is around 90 nanometers. How can you manufacture such tiny components?

In order to understand how things are made, we must first understand how they behave. This understanding is crucial in deciding whether they are good for a particular design, and also in deciding the best manufacturing process to use.

2. Materials

There are an endless number of materials that are used in modern manufacturing. Here are some basic kinds:

Ferrous metals (iron-alloys): carbon-, alloy-, stainless-, tool-and-die steels

Non-ferrous metals: aluminum, magnesium, copper, nickel, titanium, superalloys, refractory metals, beryllium, zirconium, low-melting alloys, gold, silver, platinum, …

Plastics: thermoplastics (acrylic, nylon, polyethylene, ABS,…), thermosets (epoxies, Polymides, Phenolics, …), elastomers (rubbers, silicones, polyurethanes, …)

Ceramics, Glasses, Graphite, Diamond, Cubic Boron Nitride, …

Composites: reinforced plastics, metal matrix and ceramic matrix composites

Nanomaterials, shape-memory alloys, superconductors, …

- Can you think of at least one example where each of the above is used?

3. Properties of materials

We shall concern ourselves with three types of issues:

(a) Mechanical properties of materials (strength, toughness, hardness, ductility, elasticity, fatigue and creep).
(b) Physical properties (density, specific heat, melting and boiling point, thermal expansion and conductivity, electrical and magnetic properties)
(c) Chemical properties (Oxidation, corrosion, flammability, toxicity, etc.)

3.1. Mechanical properties

Mechanical properties are useful to estimate how parts will behave when they are subjected to mechanical loads (forces, moments etc.). In particular, we are interested to know when the part will fail (i.e. break, or otherwise change shape/size to go out-of-specification), under different conditions. These include loading under: tension, compression, torsion, bending, repeated cyclic loading, constant loading over long time, impact, etc. We are interested in their hardness, and how these properties change with temperature. We are sometimes interested in their conductivity (thermal, electrical) and magnetic properties. Let’s look at how these properties are defined, and how they are tested.

3.1.1. Basics of Stress Analysis
We briefly study the basics of solid mechanics, which are essential to understand when materials break (this is important in product design, where we usually do not want the material to break; it is important in manufacturing, where most operations, e.g. cutting, are done by essentially ‘breaking’ the material).

Essentially, any load applied to a solid will induce stress throughout the solid. There are two types of stresses: shear and tensile/compressive, as shown in the figure below. Consider that some force(s) are applied to a solid such that it is experiencing stress but is in stable equilibrium. We consider an infinitesimal element inside the solid under such stresses.

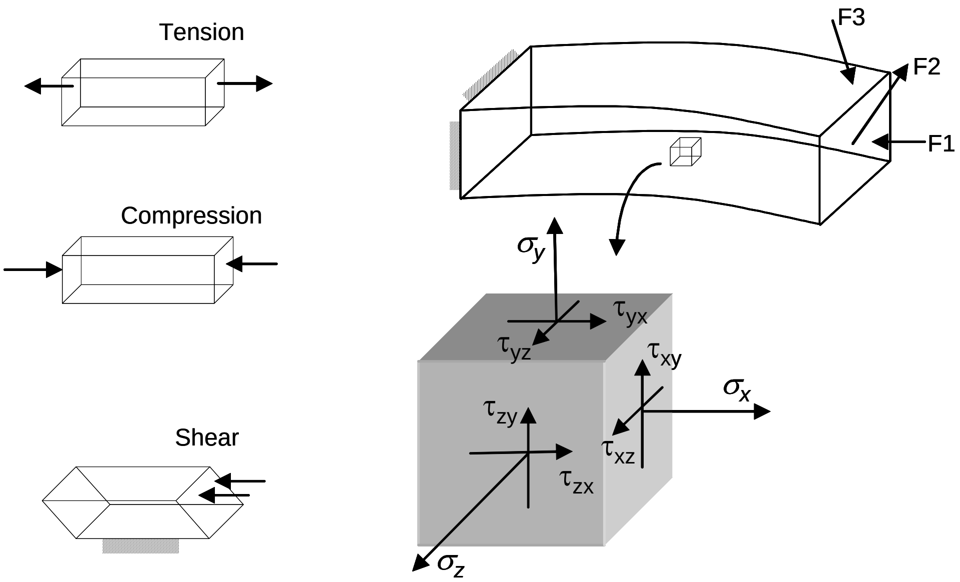


Figure 3. Tensile, compressive and shear stresses; stresses in an infinitesimal element of a beam

The question we need to answer is: under some given set of stresses as shown, will the material fail? To simplify matters, let's look at the 2D situation (XY plane only). To answer our question, we first find the resultant stresses, σ and τ, along some arbitrary direction inclined at angle ϕ to the y-axis (see figure below). Since the element is at equilibrium, the resultant of all forces must balance. Also, by definition, stress = force/area. From this, we get the following relation:

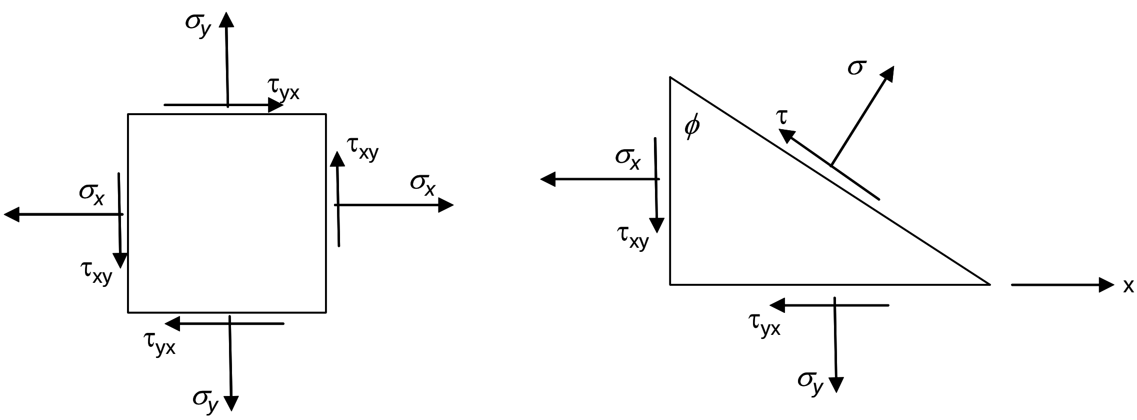


Figure 4. Computing the principal stresses (2D case)

$$\sigma = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\phi + \tau_{xy} \sin 2\phi \tag{1}$$

$$\tau = \frac{\sigma_y - \sigma_x}{2} \sin 2\phi + \tau_{xy} \cos 2\phi \tag{2}$$

Differentiating (1) and equating to zero, we get:

$$\tan 2\phi = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \qquad (3)$$

Equation (3) gives two values of the angle ϕ, one at which the principal stress σ is maximum, and the other at which it is minimum. The corresponding value of σ are called the principal stresses. The angle between the two principal stresses is always 90°. If you calculate the shear stress τ along the direction of the principal stress (called the *principal directions*), you will find that it is zero.

Likewise, differentiating (2) and equating to zero, we can solve for the angles at which we get maximum/minimum shear stresses:

$$\tan 2\phi = \frac{\sigma_x - \sigma_y}{2\tau_{xy}} \qquad (4)$$

And again, if you calculate the tensile/compressive stress corresponding to these angles, you will get:

$$\sigma = \frac{\sigma_x + \sigma_y}{2} \qquad (5)$$

Which indicates that in the direction of the *principal shear stress*, the two normal stresses are equal (but not zero).

Similar relations can be found for the general, 3D case, but are outside the scope of this course. Our interest is limited to note the fact that under some loading conditions, we can compute the stresses in any region of the part (by considering a small element at that location), and then compute the corresponding principal stresses. If the principal stresses (normal or shear) are higher than the strength of the material (we shall soon define strength), then the material will fail.

A detailed study of how to compute the stresses in non-uniform shaped parts is outside the scope of this course, but we shall look at some simple cases, which are important.

3.1.2. Failure in Tension, Young's modulus and Tensile strength

Consider a uniform bar of cross section area A_o and length L_o, that is held at both ends and pulled by a force, P. It experiences a tensile stress given by

Engineering stress = $\sigma = P/A_o$ (6)

As a result, its length will increase (very slightly), by an amount $\delta = (L - L_o)$. We say that it has undergone a tensile strain, defined by:

Engineering strain = $e = (L - L_o)/L_o = \delta/L_o$ (7)

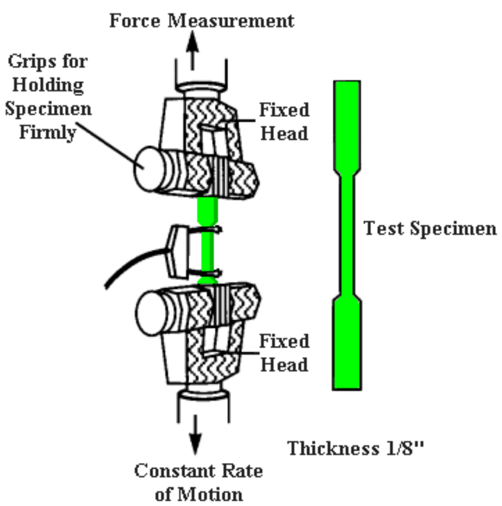
As we increase P, the stain e will increase. If the material is ductile, at some stage it suddenly loses all resistance, at some region, the cross section suddenly becomes very thin, and even if we reduce the loading at this stage, the material will extend rapidly and break (fracture). If we plot the stress versus strain, for most materials, the graph looks something like the following.

Elastic deformation: within the elastic deformation range, if the load is released, the material will return back, like a spring, to its original size.

Linear elastic range: in the initial part of the graph, strain varies linearly with stress.

Plastic region: when the material is stretched beyond the elastic range, the molecular structure rearranges and it undergoes some permanent stretching; the stress at which the deformation first becomes plastic is the *Yield Stress*.

Ultimate Tensile strength (UTS): As we keep increasing the load in the plastic range, at some point, the material suddenly loses strength, and some cross section becomes very narrow and elongates freely (*necking*). The maximum stress that it could withstand is the UTS.



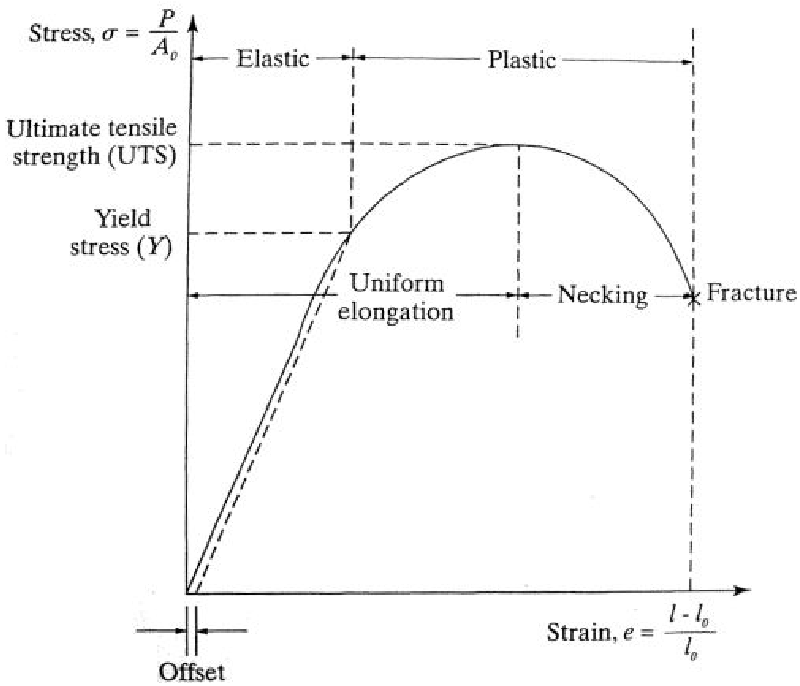


Figure 5. (a) Schematic of a tensile test (b) Stress-Strain curve [source: Kalpakjiam & Schmidt]

In the linear elastic range, we get *Hooke's law*:

$$\sigma = E\,e \quad \text{or,}\ E = \sigma/e \tag{8}$$

where E is a constant called ***Young's modulus*** of the material. E is large => material is *stiff*; if it is small, the material is elastic.

Another interesting effect is noticed when we stretch a material into the plastic range, and then release it. The following figure shows what happens: (a) there is a permanent deformation; (b) the slope of the unload curve is the same as that of the initial load curve – that is, E does not change.

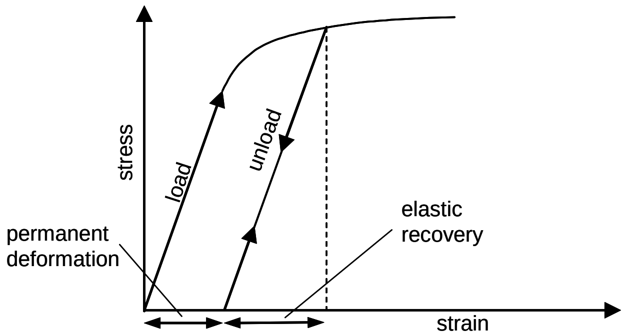


Figure 6. Elastic recovery after plastic deformation

- An important manufacturing process is sheet metal bending. It is used to make the case of PC's and all kinds of electronic products; it is also useful in making IC chip leads. During bending, we'd like to take the metal into the plastic range, but when the bending load is released, the metal "springs-back" a little bit. Why is the information in the above figure useful for design of the bending tools (which determine how much to bend to get the correct angle) ?

3.1.3 Toughness

Toughness is an estimate of how much energy is consumed before the material fractures. Energy consumed = work done = force x distance – which you can easily see, is related to the stress and strain. So:

Toughness = the strain energy = *area under the stress-strain curve*

[Note: to compute toughness, *True stress* and *True strain* are used, which measure the instantaneous stress strain at each point in the σ–ε curve.]

Strength of a material is an estimate of the height of the σ–ε curve, while toughness accounts for both, the height and the width of the curve.

- In cutting process, material is removed by "fracturing" it with a tool; what do you think is the relative energy consumed by the cutting machine tool when cutting steel or copper?

3.1.4. Ductility

Ductility is a measure of how much the material can be stretched before it fractures. A simple measure of ductility is:

$$\text{Ductility} = 100 \times (L_f - L_o)/L_o \tag{9}$$

- Both Aluminum and Copper are good electrical conductors. Which should we use for headphone wires for a walkman?

3.1.5 Hardness

There is no precise definition of hardness. We shall take it to mean “resistance to plastic deformation under load”. Under this definition, it is measured by the permanent deformation on the surface of the material being tested, when subjected to a standard loading. There are several different hardness tests that have been developed over the years. One of the earliest is the Mohs scale, which lists 10 materials (diamond = hardest := 10, and talc = softest := 1). If a material has Mohs hardness = n, then it should be able to put a scratch on all materials below hardness n, and not on any materials above harness n+1. It is usually used by geologist who cannot carry testing machines with them in the field. Most common tests for engineering materials are Brinell, Rockwell and Vickers’ tests. The figure below shows how the test works.

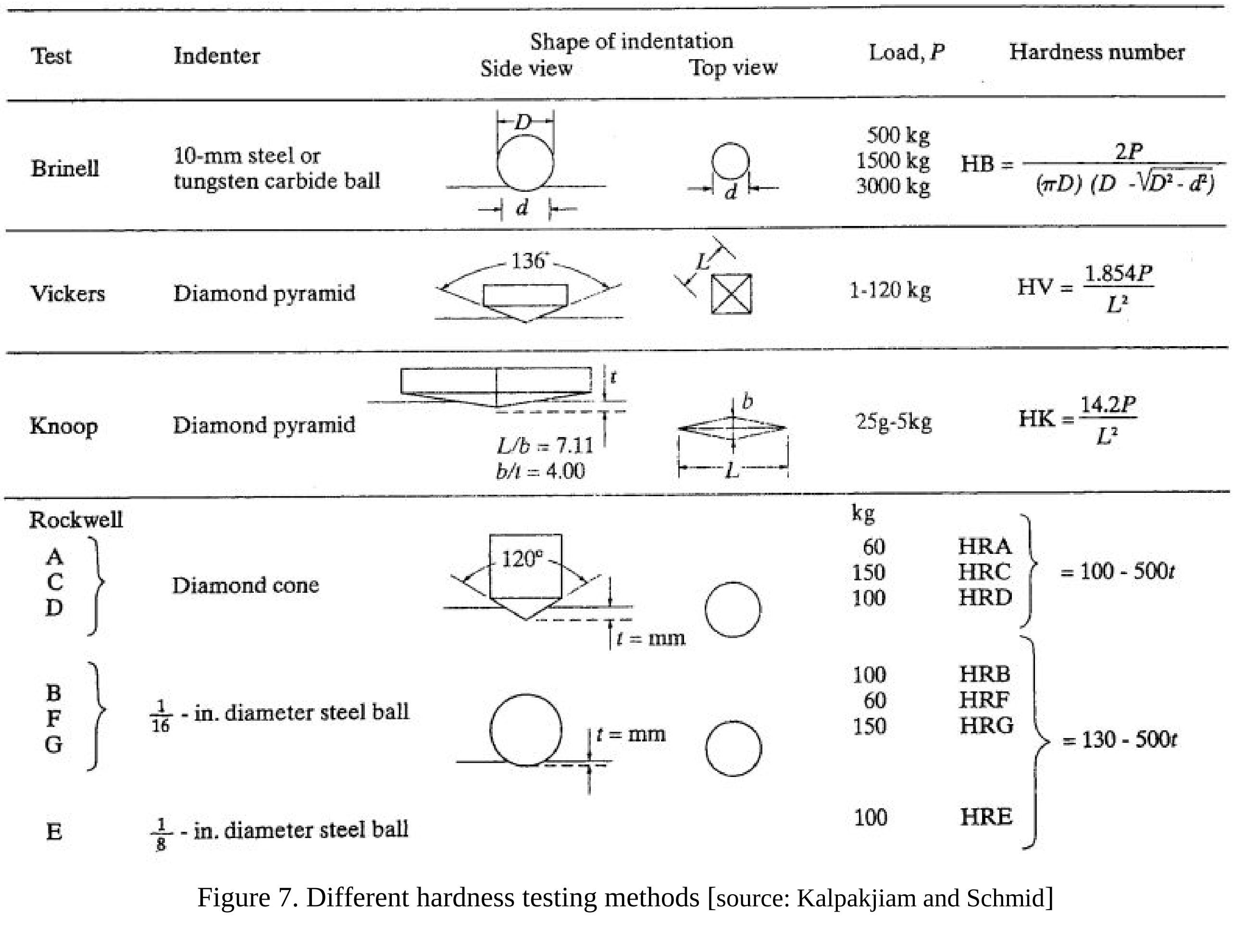


Figure 7. Different hardness testing methods [source: Kalpakjiam and Schmid]

The Brinell hardness (HB) test is the best for achieving the bulk or macro-hardness, particularly for those materials with heterogeneous structures. For harder materials, the Rockwell (HRA or HRC) or Vickers (HV) scales are more commonly used, since for such materials, the ball used in Brinell itself deforms significantly, giving unreliable measurements. If the sample is very small and hard, Knoop hardness may be used (HK). In most cases except Brinell, the surface may have to be made smooth by polishing.

Effect of temperature:

In most cases, hardness varies exponentially with temperature, as: $H = Ae^{-BT}$, where A and B are constants for the given material, T is the temperature in Kelvin, and H is the hardness.

Strength	**Hardness**	**Toughness**	**Stiffness**	**Strength/Density**
glass fiber	Diamond	Steel, Copper	Diamond	Reinforced plastics
graphite fiber	CBN	Wood	Carbides	Titanium
Carbides	Hardened steels	Thermosets	Steel	Steel
Steels	Titanium	Ceramics	Copper	Aluminum
Titanium	Copper	Glass	Aluminum	Magnesium
Copper	Thermosets		Ceramics	Copper
Reinforced thermosets	Magnesium		Wood	
Lead	Lead		Rubber	

Figure 8. Relative mechanical properties in decreasing order for some common materials

3.1.6. Failure in compression

Most materials are much stronger in compression than in tension. If a cylindrical sample is subjected to compression at the two ends, it will usually fail by a process called *buckling*. If the compressive force is totally uniform, then the material can stand very high stress; however, since either the stress, or the material properties are not precisely uniform, and so at some intermediate stage, the sample will bend an infinitesimal amount in the middle; as soon as this happens, the bending moment creates tensile stresses in that region, and the cylinder suffers immediate failure.

- Try to make a disposable wooden chopstick from the cafeteria to buckle.

Failure or plastic deformation in compression (and how to make it happen) are very important for many processes, such as forging, rolling, extrusion, etc.

3.1.7. Torsion

Many cutting processes induce failure by shear, such as cutting of sheet metal (also called *shearing*), cutting paper with a pair of scissors, punching processes that cut holes and slots in sheet metal, etc. Therefore it is useful to study how a material behaves under pure shearing stresses. This is done by the use of a torsion test.

Torsion is a twisting force, called a *moment*, applied (usually) to a bar. It introduces a shear stress in the material. Consider a solid cylindrical bar at equilibrium and subjected to torsion as shown in figure 9a below. A torque T is applied to it, causing it to twist by an angle of θ over the length L. Initially, the bar remains in the elastic deformation range. Then, due to symmetry, every planar cross-section parallel to the end-faces in the bar gets twisted, but remains planar. So there is a pure shear in the interface between any imaginary cross-section plane. Also, every radial line in the solid is turns around the axis, but remains as a straight line. For such a bar, the shear stress is maximum at the surface and zero at the center along the axis. The stress increases linearly along the radius, and the following relations hold:

Angle of twist: $\theta = TL/GJ$ (10)

Shear stress: $\tau = Tr/J$ (11)

Maximum shear stress = $\tau_{max} = TR/J$ (12)

Shear strain = $\gamma = r\theta/L$ (13)

where

T = torque,

L = cylinder length,

r = distance from axis of the cylinder, and R = radius of the cylinder

J = polar moment of inertia of the cross section of the bar, and is computed as $J = \int r^2 \, dA$

For a solid cylinder, $J = \pi d^4/32$;

For a hollow cylinder with outer diameter D and inner diameter d, $J = \pi(D^4 - d^4)/32$

G is a constant called the modulus of rigidity.

Because the stress and strain vary along the radius, failure begins at the outer surface. It is conventional to measure torsion properties using a thin, hollow cylinder, since for such a part, the shear stress across the cross section is nearly constant. In this case, the above formulas (10), (12) and (13) remain valid by using the correct value of J. The formula for shear stress can be simplified as:

Shear stress for thin wall tube (Figure 9b) = $\tau = T/(2 \pi r^2 t)$ (14)

where t = thickness of the tube = (D-d)/2, and r = mean radius = (D+d)/2.

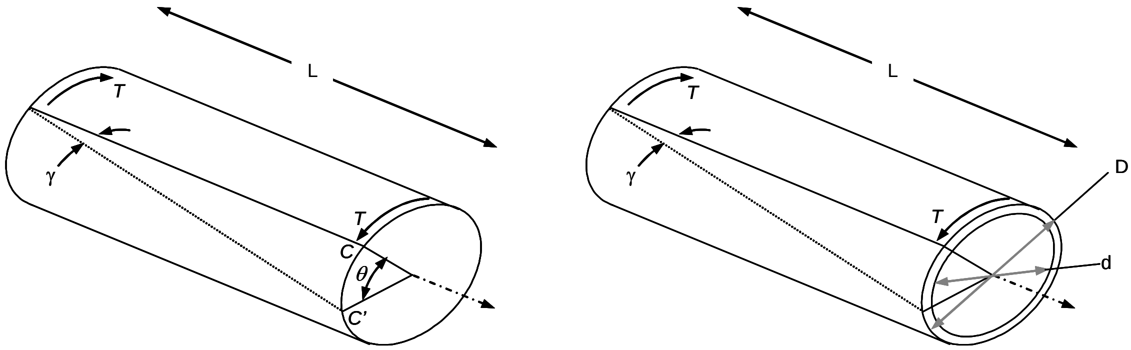


Figure 9 (a). Solid cylinder under torsion (b) Thin walled cylinder under torsion

3.1.8. Fatigue

Fatigue is the fracture/failure of a material that is subjected to repeating cyclical loading, or ***cyclic stresses***. There are two factors: the magnitude of the loading and the number of cycles before the material fails. The behavior is different for different materials, so it is customary to show the fatigue behavior of a given material in terms of an S-N curve; here S denotes the stress amplitude, and N denotes the number of cycles before the material fractures. In each cycle, the stress is raised to maximum value in extension, and reversed to the same value in compression.

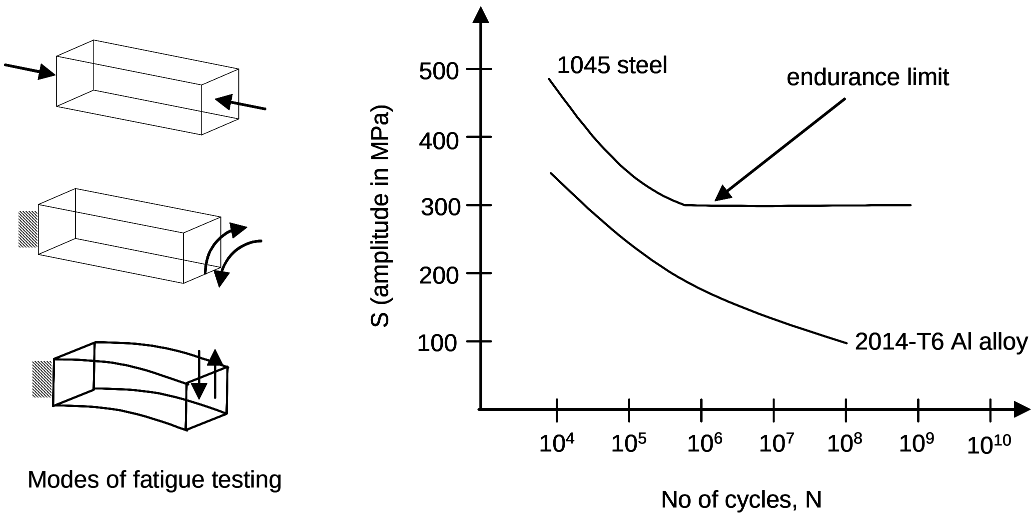


Figure 10. Modes of fatigue testing, and typical SN curve for compressive loading case

- Try to break a paper clip by using a cyclic loading; notice the appearance and propagation of cracks

3.1.9. Creep

If a material is kept under a constant load over a long period of time, it undergoes permanent deformation. This phenomenon is seen in many metals and several non-metals. For most materials, creep rate increases with increase in temperature. The phenomenon does not have much direct implication in manufacturing, but has significant use in design of parts that, for example, carry a load permanently during their use.

3.1.10. Failure under impact

Impact is measured by the energy transfer (i.e., in units of work) when a body with inertia collides with a part over a very short time. Examples are the striking of a hammer to break stones, or the shaping of metallic shapes using the *drop forging* process. Impact strength is measured in terms of the energy transfer from a pendulum strike to break a fixed size sample that has a notch (see figure below). Usually, materials with high impact toughness are those with high ductility and high strength – namely, materials with high toughness.

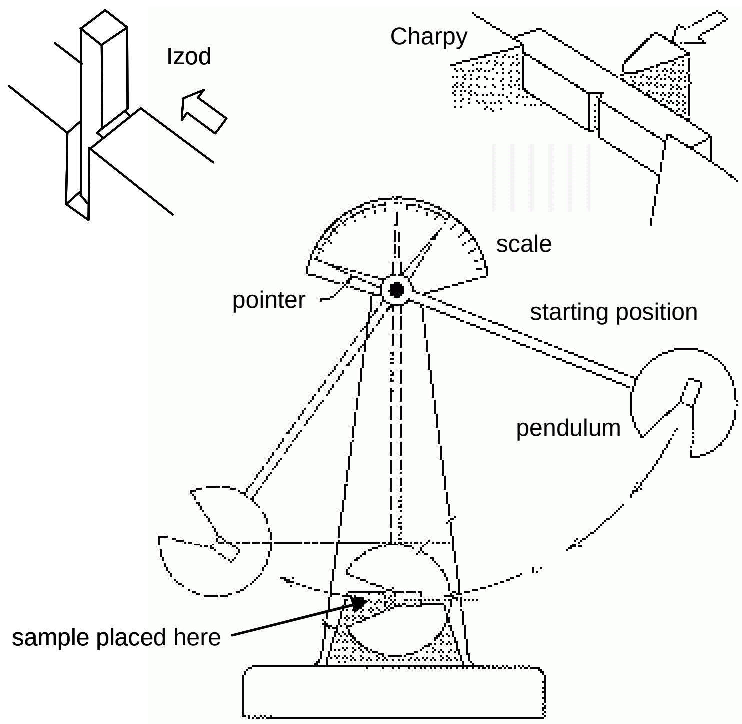


Figure 11. The setup for Charpy and Izod tests for Impact strength

3.1.11 Some related phenomena

There are a few manufacturing process related terms that you should have some knowledge about. They are briefly listed here.

Strain hardening (also called work hardening)

In most metals, the atoms are arranged in a lattice forming a crystalline structure. A piece of metal has a large number of crystal-grains. When the metal undergoes plastic strain, basically the grains are slipping along the boundaries as the part changes its shape. Often, as the crystals slip, they also get locked with each other more tightly, and therefore the strength of the material actually increases. This is called strain hardening.

Thus, if a sheet of metal is rolled (we shall study the rolling process later), it becomes stronger. Forging also increases strength. Therefore some parts that are required to be strong during usage are made using such a forming process instead of, say, casting or machining.

Residual stresses

Often, after a material has been processed (e.g. by casting or forming process), it has internal stresses even after the external forces have been removed. In casting, these stresses may occur due to different cooling rate, and the associated thermal contraction. In forming, such as bending, they are due to non-uniform deformation. Such residual stresses are usually not desirable – they can cause the part to warp over time (the internal stresses effectively cause creep). One way to release the internal stresses is a process called ***annealing***: the metal is heated to a temperature below its melting point, and then allowed to cool slowly. This process allows the residual stresses to change the crystal structure in such a way that the stresses are released.

3.2. Physical properties of materials

Some important physical properties include: Density, Melting point, Specific heat, Thermal conductivity, Coefficient of thermal expansion, Electrical conductivity, Magnetic properties, and Corrosion resistance. It is extremely important to be familiar with these during product design, since choice of material affects all aspects of a product from cost, function during its expected life, aesthetics, size, shape, manufacturability etc. From the perspective of this course, physical properties of the material affect the choice of manufacturing process we can use economically. For example, a very common manufacturing process to make complex and delicate shapes is Electro-Discharge Machining (EDM) – which can only be used on materials that are electrical conductors; hence we cannot use EDM on most ceramics or composites. Similarly, ceramics are often refractory (don't melt even at very high temperature), so they require different joining processes than metals, which can usually be welded.

Here, we shall just define each property, and give some examples of their significance in manufacturing processes.

3.2.1. Density

Density = ρ = mass/volume

Applications:

- Why is steel a good material for the *wrecking ball* used to demolish old buildings?

- Many machines used in automatic manufacturing have fast-moving components, e.g. assembly head for surface-mounted electronics components, or printing heads for textiles. Would you select steel, aluminum-alloy, or titanium to construct the head? Why ?

3.2.2. Melting point

This is the temperature at which the material changes phase from solid to liquid.

Applications:

- Hot forging requires heating the metal to just below its melting point before beating it into the required shape (many movies show scenes of blacksmiths making swords from steel)

- In injection molding, plastic is melted and injected into the mould cavity. How much higher than the melting point should it be melted?

- Components made of steel can be joined by a process called brazing, which uses a copper alloy to weld the components together. This operation will not damage the steel parts since the copper alloy melts at much lower temperature than steel.

3.2.3. Specific heat

The amount of heat energy that will raise the temperature of a unit mass of the material by 1°C.

Application:

- In machining and forming processes, a lot of heat is generated due to deformation and friction between the tool and workpiece. If the specific heat of the work piece is low, then its temperature will rise very rapidly, resulting in poor surface finish. So extra or more efficient coolants may be required. Likewise, if the specific heat of the tool material is low, the tool will heat up rapidly, leading to lower tool life.

3.2.4. Thermal conductivity

The thermal conductivity of a material is the quantity of heat that passes in unit time through unit area of a plate, when its opposite faces are subject to unit temperature gradient (e.g. one degree temperature difference across a thickness of one unit).

Thermal conductivity = Heat flow rate / (Area × Temperature gradient)

Applications:

- Titanium is used in many designs where light, hard and strong metal components are required, e.g. in aircraft components. However, it is not easy to machine (e.g. using milling machines) in part due to its poor thermal conductivity – the high temperature gradients causes very high temperature near the point of cutting, which rapidly heats the tool cutting edge and destroys the tool.

3.2.5. Thermal expansion

The linear coefficient of thermal expansion is defined as the proportional change in a material's length when its temperature changes by 1°C:

coefficient of linear thermal expansion = $\alpha = \Delta L/(L\ \Delta T)$

Applications:

- In machine tools where different components are made of different components, the assembly may jam, or become too loose and vibrate, when the temperature changes. Their design must account and compensate for the different rates of thermal expansion for the materials.

3.2.6. Electrical conductivity

Electrical conductivity is the reciprocal of the specific resistance. Most metals are good conductors, while many plastics, ceramics, rubbers etc. are very poor conductors.

Applications:

- Some processes, such as EDM, Electro Chemical Machining, Electroplating etc require that the workpiece is an electrical conductor. They cannot be used on non-conductors.

3.2.7. Magnetic properties

Ferro-magnetic materials have high magnetic permeability, and therefore can be magnetized by induction.

Application:

- Several grinding machines use magnetic chucks since the machining force in grinding is quite low. The machine tool bed contains an electromagnet, and the steel workpiece is held in position by magnetic force during the grinding operation.

- Automobile wrecking workshops use lifts that have a large electro-magnet on a crane. The magnet is used to grab the car magnetically, and the crane picks it up and locates it on the crushing machine (you may have seen a similar operation in some movies).