UNIT-2- *MECHANICAL BEHAVIOUR OF MATERIALS*

Linear and non linear elastic properties – Yielding, strain hardening, fracture, Bauchinger's effect –Notch effect testing and flaw detection of materials and components – creep and fatigue -comparative study of metals, ceramics plastics and composites.

Elastic deformation:

When the stress is removed, the material returns to the 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:

$$\sigma = E\,\varepsilon$$

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:

$$\boldsymbol{E} = \mathbf{d}\sigma/\mathbf{d}\varepsilon$$

Shear stresses produce strains according to:

$$\tau = \boldsymbol{G}\,\gamma$$

where *G* is the *shear modulus*. Elastic moduli measure the *stiffness* of the material. They are related to the *second* derivative of the interatomic potential, or the first derivative of the force vs. inter nuclear distance. By examining these curves we can tell which material has a higher modulus. Due to thermal vibrations the elastic modulus decreases with temperature. E is large for ceramics (stronger ionic bond) and small for polymers (weak covalent bond). Since the interatomic distances depend on direction in the crystal, E depends on direction (i.e., it is anisotropic) for single crystals. For *randomly* oriented polycrystals, E is isotropic.

Yield criteria and macroscopic aspects of plastic deformation

Gross plastic deformation of a polycrystalline specimen corresponds to the comparable distortion of the individual grains by means of slip. During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries is constrained, to some degree, in the shape it may assume by its neighboring grains. Before deformation the grains are equiaxed, or have approximately the same dimension in all directions. For this particular deformation, the grains become elongated along the directions. For this particular deformation, the grains become elongated along the direction in which the specimen was extended.

Tensile Properties

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 *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.*

Tensile strength: When stress continues in the plastic regime, the stress-strain passes through a maximum, called the *tensile strength*, and then falls as the material starts to develop a *neck* and it finally breaks at the *fracture point.*

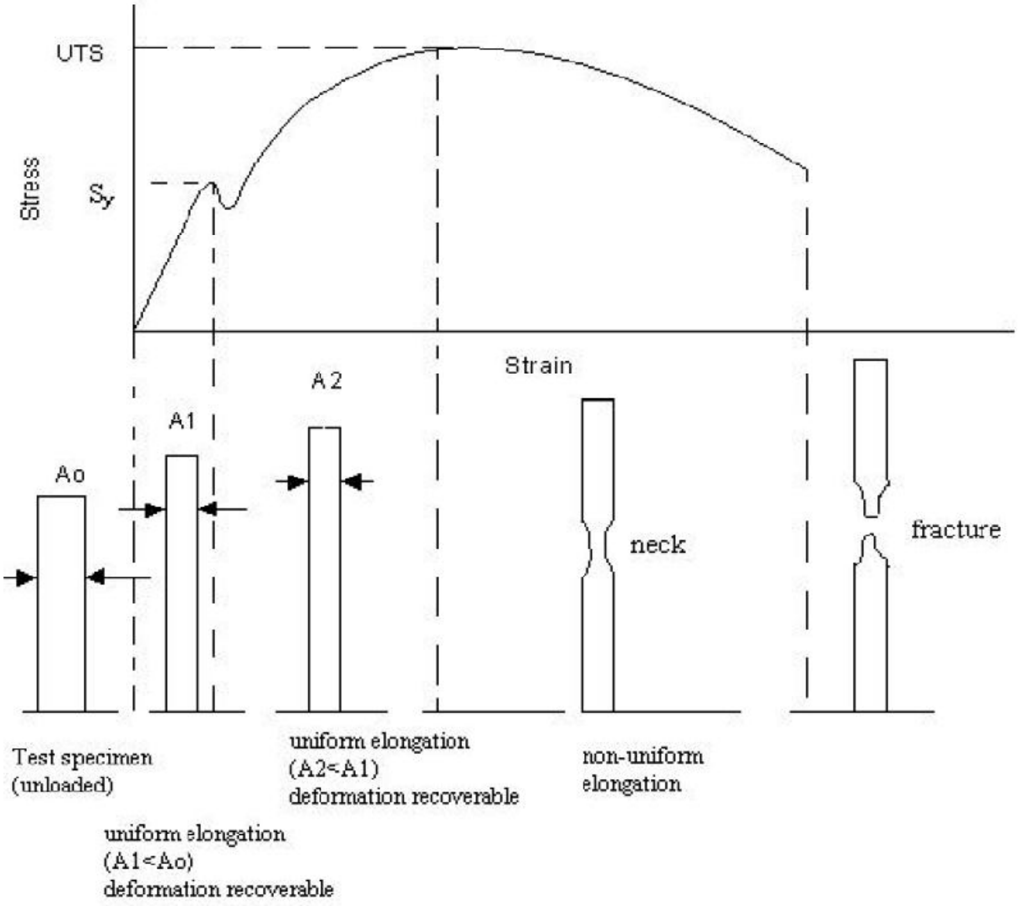
For structural applications, the yield stress is usually a more important property than the tensile strength, since once it is passed, the structure has deformed beyond acceptable limits.

Ductility: The ability to deform before braking. It is the opposite of **brittleness**. Ductility can be given either as percent maximum elongation å_{max} or maximum area reduction.

$$\%EL = \text{å}_{max} \text{ x } 100\ \%$$

$$\%AR = (A_0 - A_f)/A_0$$

Stress-Strain curve (Mild Steel)



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.

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 tensile strength. 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.*

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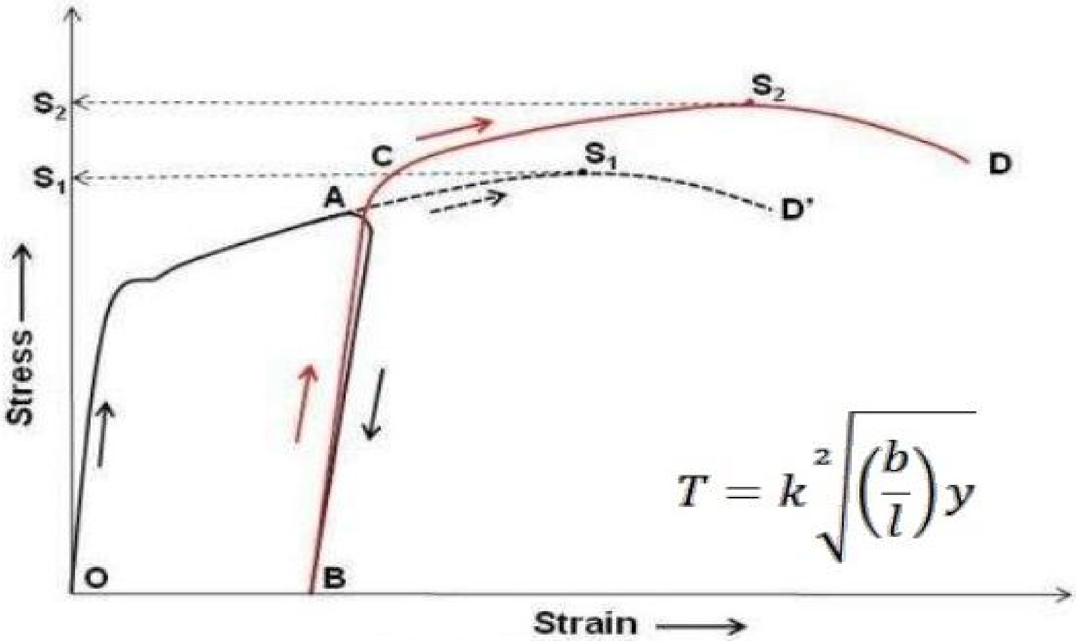
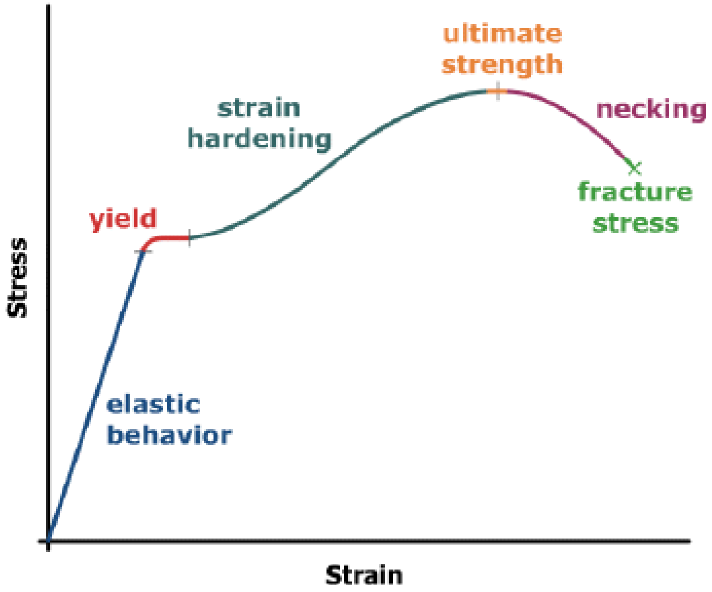
Strain Hardening

Phenomenon where ductile metals become stronger and harder when they are deformed plastically is called strain hardening or work hardening. Increasing temperature lowers the rate of strain hardening. Hence materials are strain hardened at low temperatures, thus also called cold working. During plastic deformation, dislocation density increases. And thus their interaction with each other resulting in increase in yield stress. Strain hardening (work hardening) is the reason for the elastic recovery. The reason for strain hardening is that the dislocation density increases with plastic deformation (cold work) due to multiplication. The average distance between dislocations then decreases and dislocations start blocking the motion of each one





Strain hardening (also called cold working) is an important strengthening process for aerospace alloys that involves plastically deforming the material during manufacturing to greatly increase the number of dislocations. During manufacture the metal is deformed into the final component shape (e.g. flat or curved skin panel, cylindrical landing gear strut) by forming processes such as rolling, forging, and extrusion (which are described in chapter 7). The metal must be plastically deformed to permanently change shape, and this deformation creates dislocations which increase the strength.

Bauschinger effect

The Bauschinger effect refers to a property of materials where the material's stress/strain characteristics change as a result of the microscopic stress distribution of the material. For example, an increase in tensile yield strength occurs at the expense of compressive yield strength. The effect is named after German engineer Johann Bauschinger.

While more tensile cold working increases the tensile yield strength, the local initial compressive yield strength after tensile cold working is actually reduced. The greater the tensile cold working, the lower the compressive yield strength.

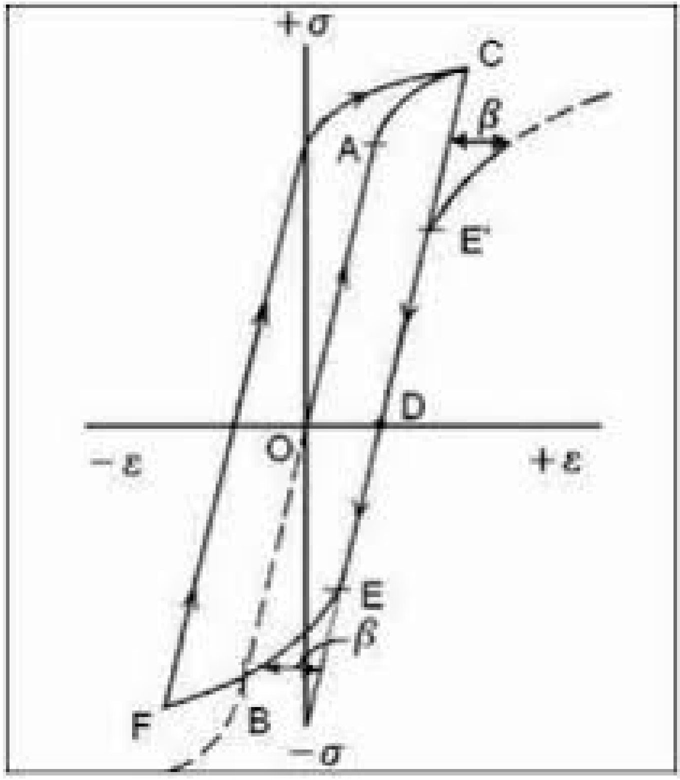
The Bauschinger effect is normally associated with conditions where the yield strength of a metal decreases when the direction of strain is changed. It is a general phenomenon found in most polycrystalline metals. The basic mechanism for the Bauschinger effect is related to the dislocation structure in the cold worked metal. As deformation occurs, the dislocations will accumulate at barriers and produce dislocation pile-ups and tangles. Based on the cold work structure, two types of mechanisms are generally used to explain the Bauschinger effect.

Region OA -This region is Elastic Region in tension. Within this region, if we unload the material it will follow the same path in the reverse direction i. e. From A to O.

Region OB- This region is Elastic Region in compression. Within this region, if we unload the material it will follow the same path in the reverse direction i.e. From B to O.

Region AC- Due to increase in load, tensile stresses overcome the bond strength. Dislocation starts moving towards grain boundary. Material starts yielding due to movement of these dislocations. Accumulation of dislocations near grain boundary creates a back pressure, because same type of dislocations repel each other.

Region CD- Immediate unloading will take curve from C to D. Elastic recovery takes place in this region. Length OD represents the permanent deformation of material.



Region DE- Compression of material takes place from D to E.

Region EB- As in case of tension, back pressure opposes the movement of dislocations i. e. this back pressure resists the tensile load. Same back pressure will now assist the compressive load. Due to combined effect of compression and this back pressure, a curvature is observed from D to Z.

Region EF- Due to further increase in compressive load, material starts yielding in compression. Again a back pressure is created. Now this back pressure will resist the compressive load but will assist the tensile load.

Region FG - Represents removal of compressive load.

Region GA- Again we apply a tensile load.

Failure

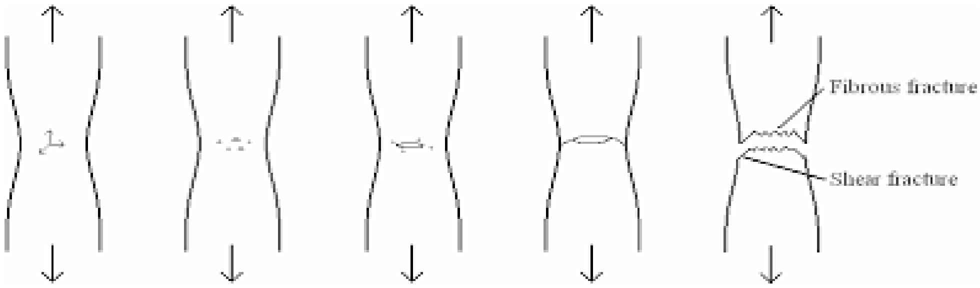
Fundamentals of Fracture

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):

- Crack formation
- Crack propagation

Ductile Fracture

- Stages of ductile fracture
- Initial necking
- Small cavity formation (micro voids)
- Void growth (ellipsoid) by coalescence into a crack
- Fast crack propagation around neck. Shear strain at 45^{o}
- Final shear fracture (cup and cone)

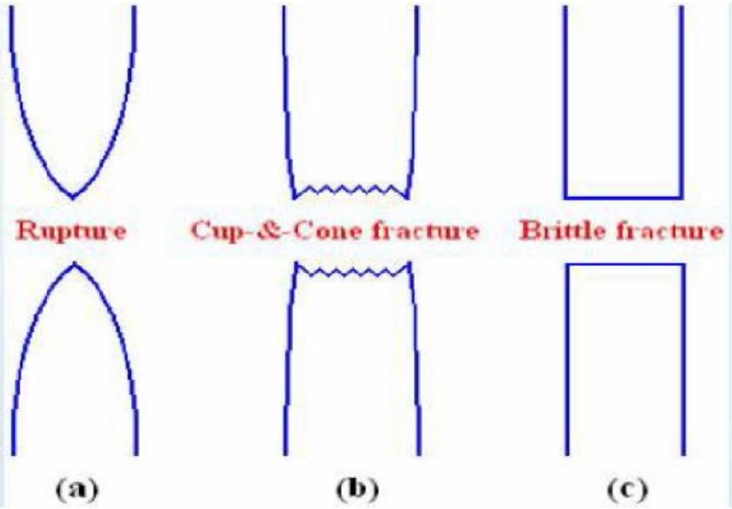


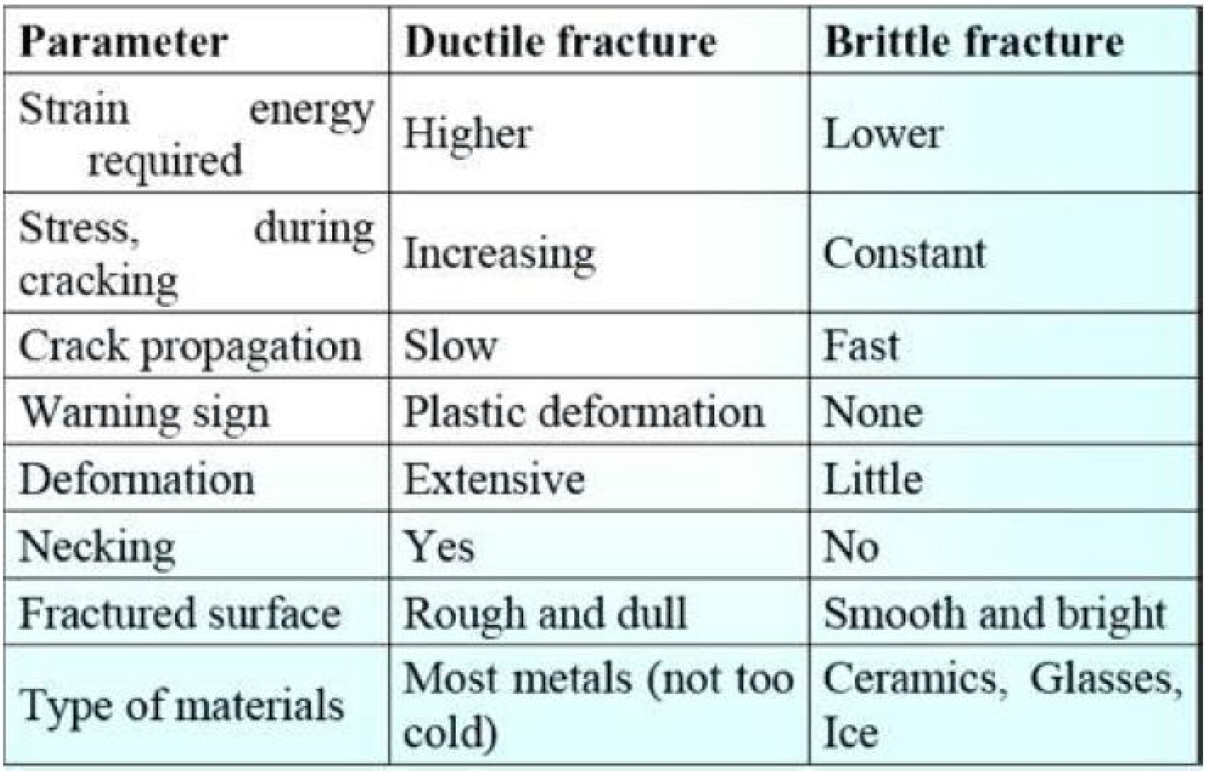
The interior surface is fibrous, irregular, which signify plastic deformation.

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.

Fracture occurs due to *stress concentration* at flaws, like surface scratches, voids,



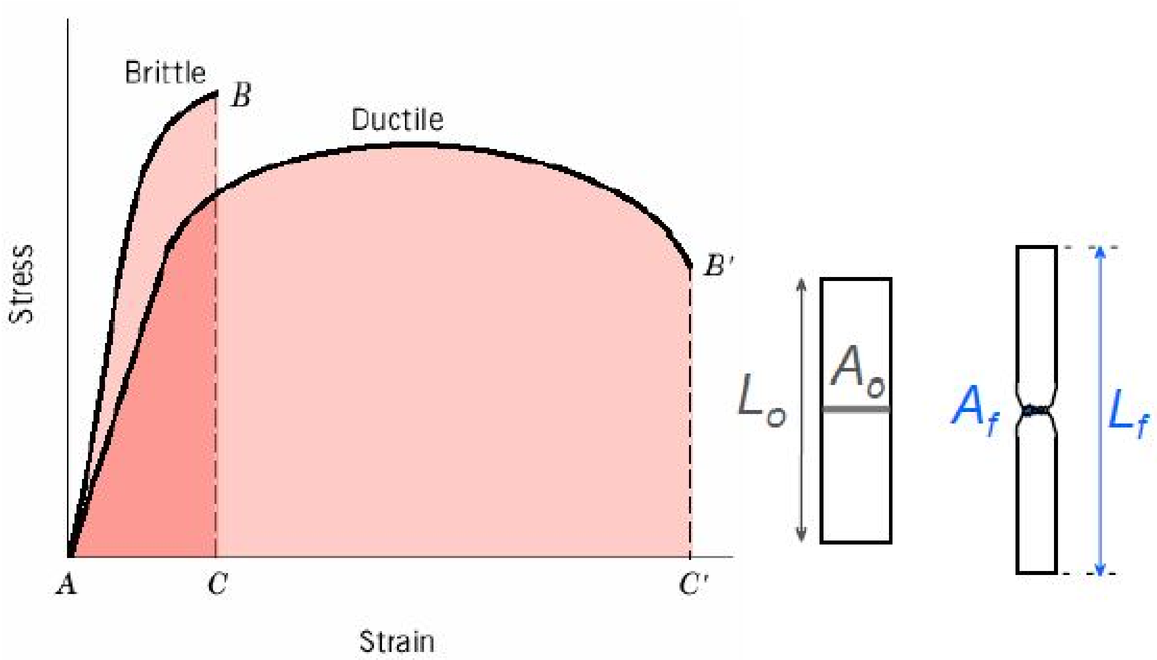


Parameter	Ductile fracture	Brittle fracture
Strain energy required	Higher	Lower
Stress, during cracking	Increasing	Constant
Crack propagation	Slow	Fast
Warning sign	Plastic deformation	None
Deformation	Extensive	Little
Necking	Yes	No
Fractured surface	Rough and dull	Smooth and bright
Type of materials	Most metals (not too cold)	Ceramics, Glasses, Ice

Ductile brittle transition

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

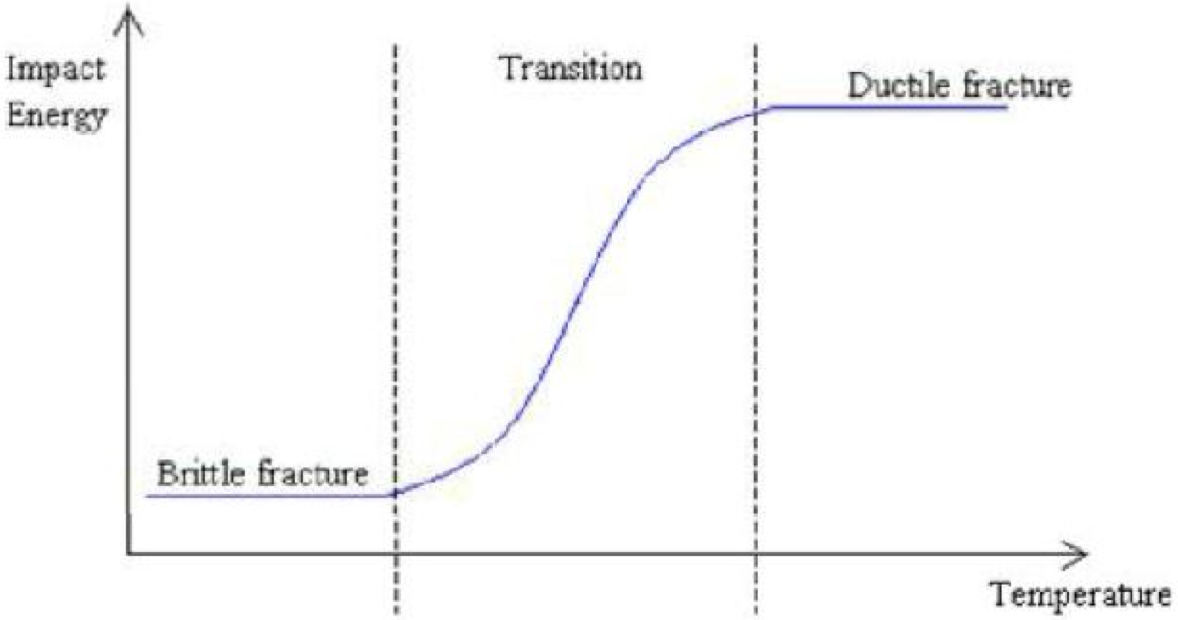
The notched-bar impact test can be used to determine whether or not a material experiences a ductile-to-brittle transition as the temperature is decreased. In such a transition, at higher temperatures the impact energy is relatively large since the fracture is ductile. As the temperature is lowered, the impact energy drops over a narrow temperature range as the fracture becomes more brittle.



The transition can also be observed from the fracture surfaces, which appear fibrous or dull for totally ductile fracture, and granular and shiny for totally brittle fracture. Over the ductile-to brittle transition features of both types will exist.

While for pure materials the transition may occur very suddenly at a particular temperature, for many materials the transition occurs over a range of temperatures. This causes difficulties when trying to define a single transition temperature and no specific criterion has been established.

The ductile-brittle transition is exhibited in bcc metals, such as low carbon steel, which become brittle at low temperature or at very high strain rates. Fcc metals, however, generally remain ductile at low temperatures.



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.*

Crack Initiation and Propagation

Stages is fatigue failure:

I. crack initiation at high stress points (stress raisers)
II. propagation (incremental in each cycle)

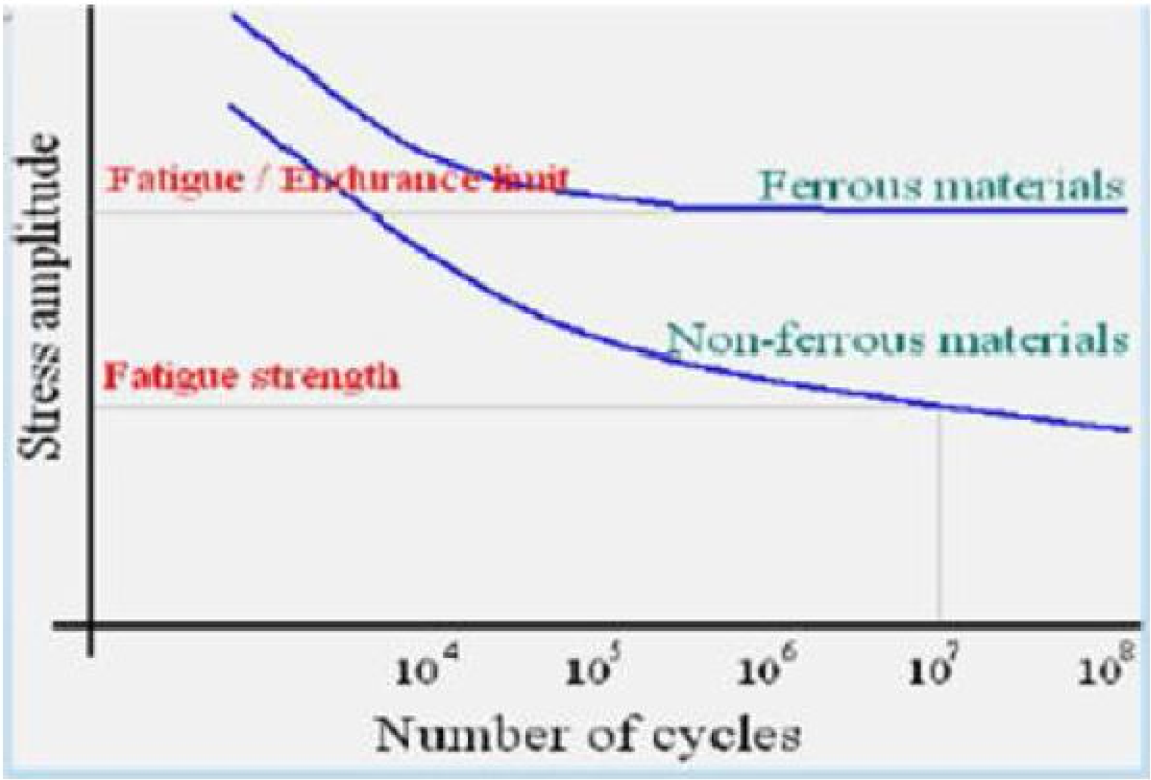
III. final failure by fracture

Stage I - propagation

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

Stage II - propagation

Crack propagates by repetitive plastic blunting and sharpening of the crack tip.



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**.**

The Creep Curve

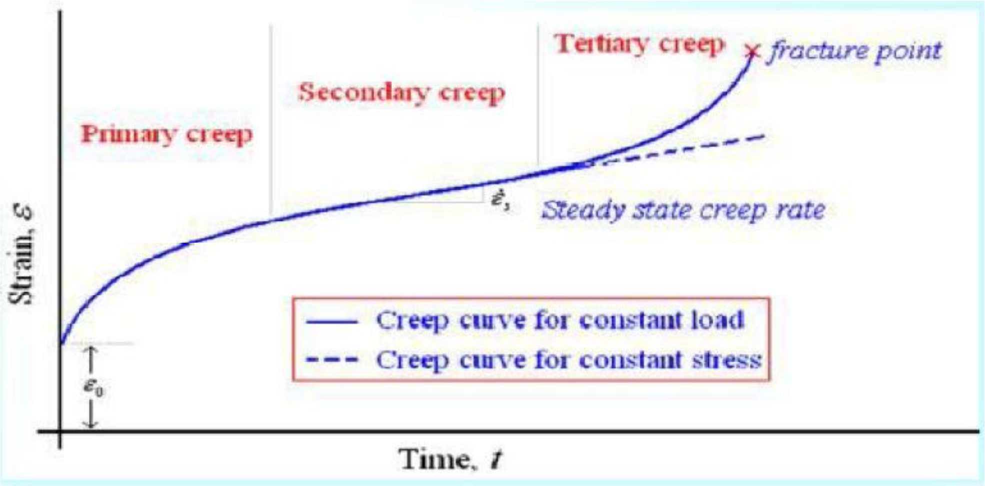
Creep in metals is defined as time dependent plastic deformation at constant stress (or load) and temperature. The form of a typical creep curve of strain versus time is in Figure. The slope of this curve is the **creep rate** $d\varepsilon$ /dt**.** The curve may show the instantaneous elastic and plastic strain that occurs as the load is applied, followed by the plastic strain which occurs over time. Three stages to the creep curve may be identified:

Primary creep: in which the creep resistance increases with strain leading to a decreasing creep strain rate.

Secondary (Steady State) creep: in which there is a balance between work hardening and recovery processes, leading to a minimum constant creep rate.

Tertiary creep: in which there is an accelerating creep rate due to the accumulating damage, which leads to creep rupture, and which may only be seen at high temperatures and stresses and in constant load machines.

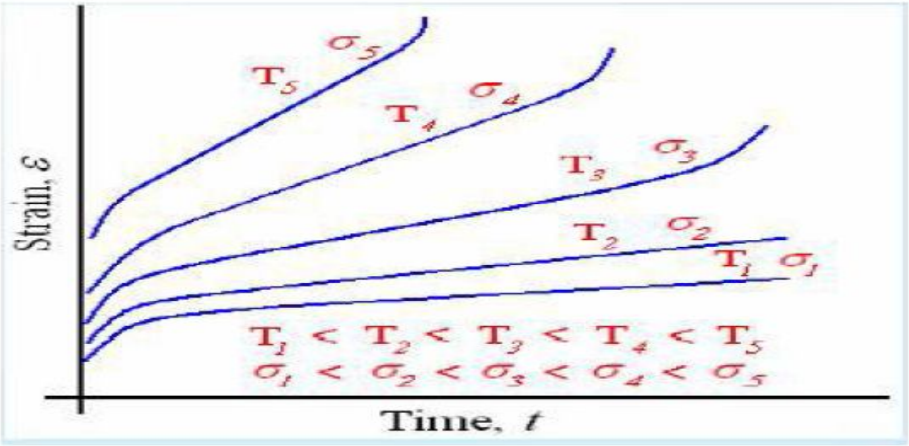
The minimum secondary creep rate is of most interest to design engineers, since failure avoidance is required and in this region some predictability is possible. In the USA two Standards are commonly used: (i) The stress to produce a creep rate of 0.0001% per hour (1% in 10,000 hours). (ii) The stress to produce a creep rate of 0.00001% per hour (1% in 100,000 hours or approximately 11.5 years). The first requirement would be typical of that for gas turbine blades, while the second for steam turbines. Constant load machines simulate real engineering situations more accurately, but as the specimen extends its cross section area reduces, leading to a rising stress. Machines designed to reduce the load to compensate for the reduced area and maintain constant stress may produce an extended steady state region.



Stress and Temperature Effects

Both temperature and the level of the applied stress influence the creep characteristics. The results of creep rupture tests are most commonly presented as the logarithm of stress versus the logarithm of rupture lifetime. Creep becomes more pronounced at higher temperatures. 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:

$$d\varepsilon / dt = K \sigma_n \exp(-Q_c / RT)$$



Impact Fracture:

Impact fractures can best be described as a flute or strip of material that was cleanly sheared from a projectile point. The most common type of impact fracture starts at the tip of a point and runs down one blade edge possibly reaching the shoulder of a point. Some points were reworked into a useable point after having been damaged by an impact fracture. 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.***

Non-Destructive testing (NDT)

NDT is the method of detection and measurement of properties or condition of materials, structures, machines without damaging or destroying their operational capabilities. Examples of

NDT are: **magnetic dust method, penetrating liquid method, ultrasonic test and radiography**. All NDTs are used to detect various types of flaws on the surface of material or internal inclusions of impurities and these techniques are also very useful during preventive maintenance and repair. There are few techniques which do not require any special apparatus and are quite simple to handle and only a moderate skill being required. Some of the applications of

NDTs are detecting: (i) surface cracks (ii) material composition (iii) internal inclusions (iv) internal voids and discontinuities and (v) condition of internal stresses.

Ultrasonic Test

High frequency ultrasonic (sound) waves are applied to the test piece by a Piezoelectric crystal. If the test piece is free from cracks, or flawless, then it reflects ultrasonic waves without distortion. If there are any flaws in the specimen, the time taken by the ultrasonic waves will be less as the reflection of these waves will be from flaw points and not from the bottom of the specimen. Cathode ray oscilloscope (CRO) is used to receive the sound signals, whose time base circuit is connected to it. Knowing the time interval between the transmission of the sound pulse and the reception of the echo signal, we can calculate the depth of the crack. This test is a very fast method of inspection and often used to test aerospace components and automobiles. This test is generally used to detect internal cracks like shrinkage cavities, hot tears, zones of corrosion and non-metallic inclusions.

Liquid-Penetration test

This test is employed for detection of small defects which are very small to detect with the naked eye. This test is used to detect surface cracks or flaws in non-ferrous metals. This test employs a visible colour contrast dye penetrant technique for the detection of open surface flaws in metallic and non-metallic objects. The penetrants are applied by spraying over the surface of material to be inspected. The excess penetrant is then washed or cleaned. Absorbent powder is then applied to absorb the penetrants in the cracks, voids which reveals the flaws. This test reveals flaws such as shrinkage cracks, porosity, fatigue cracks, grinding cracks, forging cracks, seams, heat treatment cracks and leaks etc., on castings, weldings, machined parts, cutting tools, pipes and tubes. If the fluorescent penetrant is used, the developed surface must be examined under ultra violet light to see the presence of defects. This technique is used for non-porous and nonabsorbent materials. Care may be taken to clean the surface so that it is free from dust, scale, etc. to have better results. Penetrants are highly toxic and flammable and hence proper precautions should be taken both during use and of storage of penetrants.

Microstructural Exam

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25× magnification. The microstructure of a material can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behavior, wear resistance, and so on, which in turn govern the application of these materials in industrial practice.

a) Sectioning and cutting

The areas of interest forming the metallography specimens need to be sectioned for ease of handling. Depending on the type of material, the sectioning operation can be done by using abrasive cutter (for metal and metallic composite), diamond wafer cutter (ceramics, electronics and minerals) or thin sectioning with a microtome (plastics). In order not to damage the specimen, proper cutting requires the correct selection of abrasive cutting wheel, proper cutting speed & cutting load and the use of coolant.

b) Mounting

The mounting operation accomplishes three important functions:

1. To protects the specimen edge and maintain the integrity of materials surface features.
2. Fill voids in porous materials.
3. Improves handling of irregular shaped samples.

Samples for microstructure evaluation are typically encapsulated in a plastic mount for handling during sample preparation. Large sample or samples for macrostructure evaluation can be prepared without mounting.

The metallography specimen mounting is done by encapsulating the specimen into:

1. A compression/hot mounting compound (thermosets – e.g. phenolics, epoxies or thermoplastics – e.g. acrylics)
2. A castable resin/cold mounting (e.g. acrylics resins, epoxy resins and polyester resins)

c) Grinding

Grinding is required to ensure the surface is flat & parallel and to reduce the damage created during sectioning. Grinding is accomplished by decreasing the abrasive grit size sequentially to obtain the required fine surface finish prior to polishing. It is important to note that the final appearance of the prepared surface is dependent on the machine parameters such as grinding/polishing pressure, relative velocity distribution and the direction of grinding/polishing.

d) Polishing

For microstructure examination a mirror/reflective finish is needed whereas a finely ground finish is adequate for macrostructure evaluation. Polishing can be divided into two main steps:

1. Rough polishing

The purpose is to remove the damage produced during grinding. Proper polishing will maintain the specimen flatness and retain all inclusions or secondary phases by eliminating the previous damage and maintaining the specimen integrity.

2. Fine polishing

The purpose is to remove only surface damage.

e) Etching

Etchans are specially formulated for the specific material and evaluation objectives. Etching alters the micro structural features based on composition; stress or crystal structure and it will develop the surface topology, which can be visible in the microscope. Typically, chemical etching involve immersing the polished surface in the prepared chemical solution for a specified time (usually seconds) followed by rinsing the etched specimen under running tap water and drying.

f) Microscopic Analysis

For microscopic analysis, a reflective surface is required. The analysis can be done by using a metallurgy microscope.