HIGH STRAIN DEFORMATION

Modern civilization is based on four foundations:

(1) **Materials,**
(2) **Energy,**
(3) **Technology,** and
(4) **Information.**

Metals and alloys are materials, which have been widely used by mankind for thousands of years, and this is no mere chance:

Metals have many remarkable properties. One their strength at high temperatures is of great scientific and practical importance.

The durability of gas turbine engines, steam pipelines, reactors, aero planes, and aerospace vehicles depends directly on the ability of their parts and units to withstand changes in shape.

On the other hand, a significant mobility of crystal lattice defects and of atoms plays an important role in the behavior of materials under applied stresses at high temperatures and is also of great interest for materials science research and practical applications.

A deep investigation of material structure was impossible in early studies because of the lack of suitable equipment and appropriate techniques.

Even now mechanical tests are a source of indirect information about physical processes that take place in the atomic crystal lattice of metals and alloys.

However, if we want to understand the nature of these processes and to be able to use them in practice we should try to investigate them directly.

The phenomena of high-temperature strain and creep have been studied for many years. Numerous theories have been developed, based on the dependences of the strain rate upon stress and temperature.

The structure of tested metals was also studied. The obtained results are of great value and have been described in books and reviews and important data are also scattered in numerous articles.

Previous investigations improved our knowledge of the problem and stimulated further experimental approaches.

It is essential, however, to emphasize that the physical nature of the high-temperature strain in metals, especially industrial super alloys, is not yet

understood sufficiently. By this we mean the physical background of the deformation on the atomic microscopic scale.

The problem of the high-temperature properties of metallic materials has a number of *experimental*, *theoretical* and *applied aspects*. Naturally, it is necessary to identify the scope of the problem considered in this lecture.

The idea is as follows. The high-temperature diffusion mobility of atoms and the effect of applied forces are the conditions under which special processes occur in the crystal lattice of metallic materials.

Thus, external conditions result in a distinctive structural response of the material. In their turn these specific structural changes lead to a definite macroscopic behavior of the material, especially, to a definite strain rate and to a stress resistance.

Consequently *structure evolution* is the primary stage of response; *mechanical behavior* is the secondary result. The response in the crystal lattice is a cause, while the plastic strain of a metal or an alloy is a consequence.

The structural evolutions therefore a key factor, which determines the mechanical properties of the metallic materials at high temperatures.

In material science is, deformation is a change in the shape or size of an object due to an applied force (the deformation energy in this case is transferred through work) or a change in temperature (the deformation energy in this case is transferred through heat).

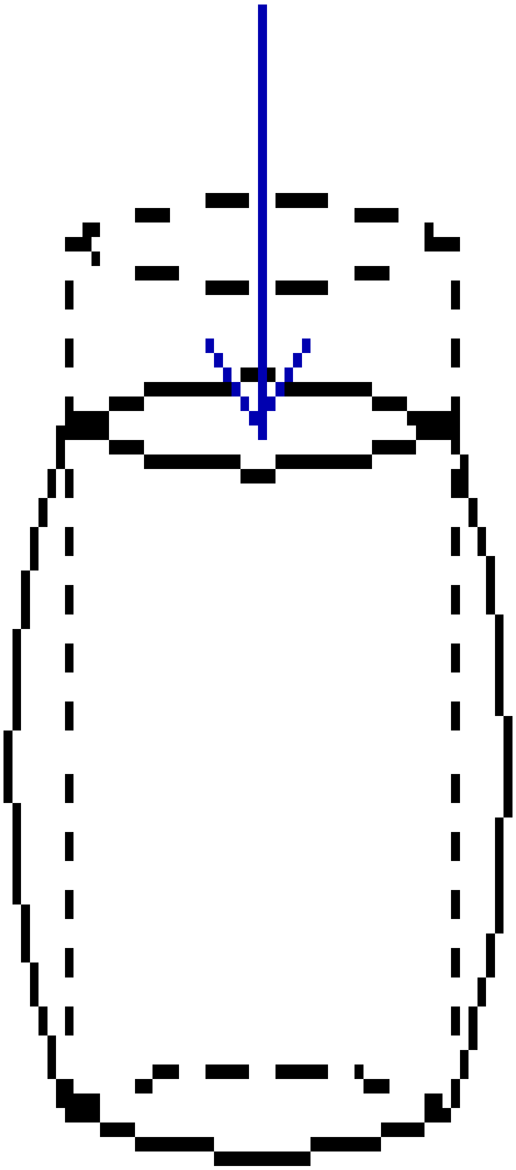
The first case can be a result of tensile (pulling) forces, compressive (pushing) forces, shear, bending or torsion (twisting). In the second case, the most significant factor, which is determined by the temperature, is the mobility of the structural defects such as grain boundaries, point vacancies, line and screw dislocations, stacking faults and twins in both crystalline and non-crystalline solids.

The movement or displacement of such mobile defects is thermally activated, and thus limited by the rate of atomic diffusion. Deformation is often described as strain. As deformation occurs, internal inter-molecular forces arise that oppose the applied force.

If the applied force is not too large these forces may be sufficient to completely resist the applied force, allowing the object to assume a new equilibrium state and to return to its original state when the load is removed. A larger applied force may lead to a permanent deformation of the object or even to its structural failure.

In the figure it can be seen that the compressive loading (indicated by the arrow) has caused deformation in the cylinder so that the original shape (dashed lines) has changed (deformed) into one with bulging sides. The sides bulge because the material, although strong enough to not crack or otherwise fail, is not strong enough to support the load without change, thus the material is forced out laterally. Internal forces (in this case at right angles to the deformation) resist the applied load.

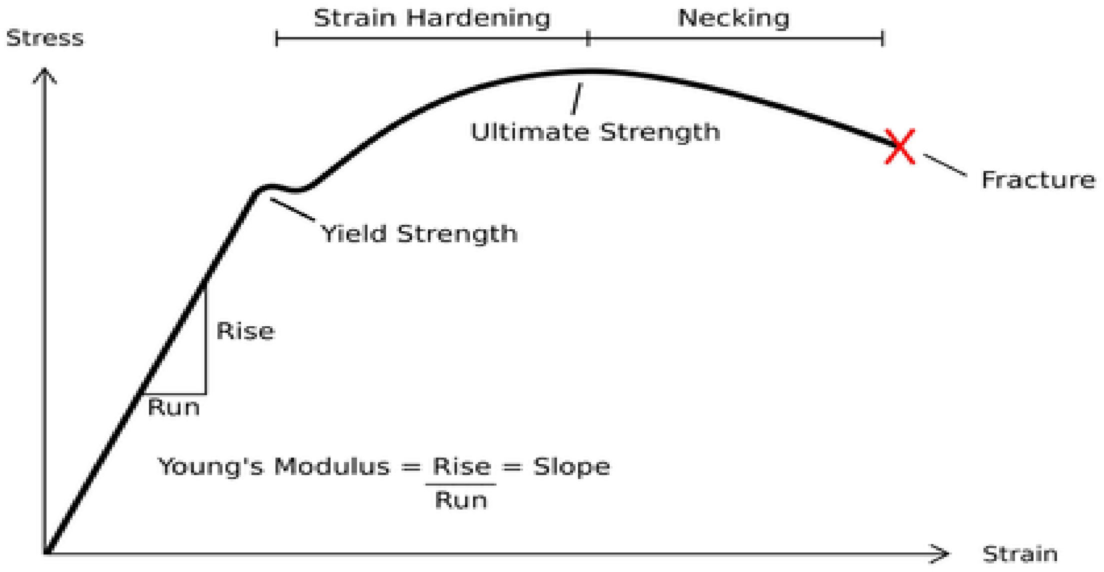
The concept of a rigid body can be applied if the deformation is negligible.



Compressive stress results in deformation which shortens the object but also expands it outwards.

Types of deformation:

Depending on the type of material, size and geometry of the object, and the forces applied, various types of deformation may result. The image to the below shows the engineering stress vs. strain diagram for a typical ductile material such as steel. Different deformation modes may occur under different conditions, as can be depicted using a deformation mechanism map.



Typical stress vs. strain diagram with the various stages of deformation.

Elastic deformation:

This type of deformation is reversible. Once the forces are no longer applied, the object returns to its original shape. Elastomers and shape memory metals such as Nitinol exhibit large elastic deformation ranges, as doe's rubber. Soft thermoplastics and conventional metals have moderate elastic deformation ranges, while ceramics, crystals, and hard thermosetting plastics undergo almost no elastic deformation. Linear elastic deformation is governed by Hooke's law, which states: $\sigma = E\varepsilon$

Where σ is the applied stress, E is a material constant called Young's modulus, and ε is the resulting strain. This relationship only applies in the elastic range and indicates that the slope of the stress vs. strain curve can be used to find Young's modulus. Engineers often use this calculation in tensile tests. The elastic range ends when the material reaches its yield strength. At this point plastic deformation begins.

Note that not all elastic materials undergo linear elastic deformation; some, such as concrete, gray cast iron, and many polymers, respond nonlinearly. For these materials Hooke's law is inapplicable.

Plastic deformation:

This type of deformation is irreversible. However, an object in the plastic deformation range will first have undergone elastic deformation, which is reversible, so the object will return part way to its original shape. Soft *thermoplastics* have a rather large plastic deformation range as do ductile metals such as *copper*, *silver*, and *gold*. *Steel* does, too, but not *cast iron*.

Hard thermosetting plastics, rubber, crystals, and ceramics have minimal plastic deformation ranges. One material with a large plastic deformation range is wet *chewing gum*, which can be stretched dozens of times its original length.

Under tensile stress plastic deformation is characterized by a *strain hardening* region *and* a *necking* region *and finally*, fracture (also called rupture).

During strain hardening the material becomes stronger through the movement of *atomic dislocations*. The necking phase is indicated by a reduction in cross-sectional area of the specimen. Necking begins after the ultimate strength is reached. During necking, *the material can no longer withstand the maximum stress* and *the strain in the specimen rapidly increases*. Plastic deformation ends with the fracture of the material.

Metal fatigue:

Another *deformation* mechanism is *metal fatigue*, which occurs primarily in *ductile* metals. It was originally thought that a material *deformed* only within the elastic range returned completely to its original state once the forces were removed. However, faults are introduced at the molecular level with each deformation.

After many *deformations*, cracks will begin to appear, followed soon after by a fracture, with no apparent *plastic deformation* in between. Depending on the material, shape, and how close to the elastic limit it is *deformed,* failure may require thousands, millions, billions, or trillions of *deformations.*

Metal fatigue has been a major cause of aircraft failure, such as the De Havilland Comet, especially before the process was well understood. There are two ways to determine when a part is in danger of metal fatigue; either predicts when failure will occur due to the material/force/shape/iteration combination, and replace the vulnerable materials before this occurs, or perform inspections to detect the microscopic cracks and perform replacement once they occur.

Selection of materials not likely to suffer from metal fatigue during the life of the product is the best solution, but not always possible. Avoiding shapes with sharp corners limits metal fatigue by reducing stress concentrations, but does not eliminate it.

Fracture:

This type of deformation is also irreversible. A break occurs after the material has reached the end of the elastic, and then plastic, deformation ranges. At this point forces accumulate until they are sufficient to cause a fracture. All materials will eventually fracture, if sufficient forces are applied.

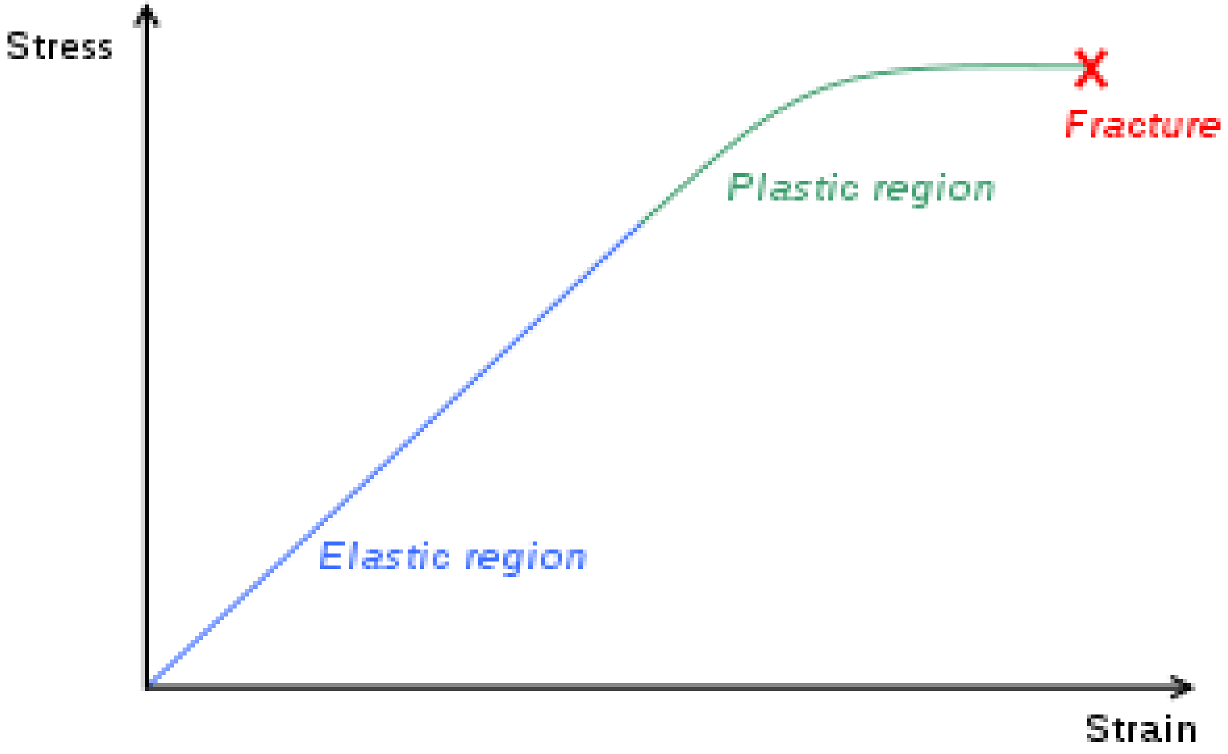


Diagram of a stress-strain curve, showing the relationship between stress (force applied) and strain (deformation) of a ductile metal.

DEFORMATION AIM:-

The ultimate goal of engineer deformation is to produce metal components with required geometrical shape and structurally optimized for a given application.

Deformation processing exploits the ability of metal to flow plastically without altering the other properties.

The required forces are often very high. Cast ingots, slabs, blooms and billets are reduced in size and converted into plates, sheets, rods and others.

These forms experience further deformation to produce the desired products formed by processes such as forging, extrusion and other sheet metal forming.

The deformation may be bulk flow in three dimensions, simple shearing, simple bending, or any combination of these and other processes.

The stresses could either be tensile or compressive or shear or combination of them. In this connection the metal chemistry and cleanliness are important factors for deformation processing.

Deformation processing can be carried out either under hot or cold condition. In the following general features of *hot* and *cold* working are described. Details can be obtained in any text book on deformation processing.

Hot working:

It is plastic deformation of metals above their recrystallization temperatures. Hot working of steel requires to heat steel near 1000°C for plastic deformation. Hot working of steel involves the deformation of fcc austenite.

- **Hot working does not produce strain hardening. Hence no increase in either yield strength or hardness occurs. In addition yield strength decreases as temperature increases and the ductility improves.**
- **Hot working can be used to drastically alter the shape of metals without fear of fracture and excessively high forces.**
- **Elevated temperatures promote diffusion that can remove chemical in homogeneties; pores can be welded or reduced in size during deformation.**
- **The dendritic grain structure, small gas cavities and shrinkage porosity formed during solidification in large sections can be modified by hot working to produce a fine, randomly oriented, spherical-shaped grain structure which results in a net increase in strength, ductility and toughness.**
- **Hot working results in reorientation of inclusions or impurity particles in the metal with the result that an impurity originally oriented so as to aid crack movement through the metal can be reoriented into a "crack arrestor" configuration.**

The various hot working processes are rolling, extrusion, forging, hot drawing .....Etc.

Cold working:

Cold working is plastic deformation of metals below the recrystallization temperature and is generally performed at room temperature. *Some advantages* are:

- No heating is required.
- Better surface finish and superior dimensional control are achieved.
- Strength, fatigue, and wear properties are improved.
- Directional properties can be imparted.

Disadvantages:

- Heavier forces are required.
- Strain hardening occurs (may require intermediate annealing treatment to relieve internal stresses).
- Residual stresses may be produced.

Annealing:

Plastic deformation of polycrystalline material in cold working produces microstructural and property changes that include :

(a) Change in grain shape,
(b) Strain hardening,
(c) Increase in dislocation density.

Appropriate heat treatment such as annealing reverts back to the pre-cold worked states. The purpose of annealing may involve one or more of the following aims:

* to soften the material and to improve machinability.
* to relieve internal stresses induced by rolling,forging etc.
* to remove coarseness of grains.

The annealing consists of :-

° heating the material to a certain temperature.
° soaking at this temperature.
° cooling at a predetermined rate.

Such restoration results from recovery, recrystallization, which may be followed by grain growth.

During recovery some of the stored internal strain energy is relieved by virtue of dislocation motion due to atomic diffusion.

Even after recovery is complete, the grains are still in a relatively high strain energy state. Recrystallization is the formation of a new set of strain-free and equixed grains (having approximately equal dimensions in all directions). Strength and hardness decrease, but ductility increases.

After recrystallization is complete, the strain-free grains will continue to grow, if the metal is left at the elevated temperature.