Mechanical behavior of crystalline materials - Stress Types and Tensile Behaviour

3.1 Introduction

Engineering materials are often found to posses good mechanical properties so then they are suitable for applications. Mechanical properties referred here are tensile strength, ductility, toughness, fatigue strength, hardness etc. Ductility is estimated from uniaxial tensile test. Percentage reduction in area obtained from uniaxial tensile test is taken to be a measure of ductility. In this lecture, we will focus on tensile behavior of materials.

Metallic materials have good ductility. They are easily deformable by application of external forces. Formability, the ease with which metals and alloys can be plastically deformed to a required shape depends on the nature of structure, grain structure and types of metallurgical phases that make a given alloy. For example a hardened steel which has a martensitic structure is impossible to shape.

Forming of materials can be achieved through plastic deformation of the material by applying stress. Therefore, it is important to understand the plastic deformation behavior of materials. Material behavior under three different types of loading, tensile, compressive and torsion loading will be discussed in the following sections.

3.2 Stresses – types:

Suppose a certain force ΔF is acting on an area ΔA. Then the stress acting along an arbitrary direction is given as $\lim_{\Delta A \to 0} \frac{\Delta P}{\Delta A} = \sigma$

This stress can be resolved along a direction perpendicular to the given surface called normal stress, σ.

It is resolved along tangential direction to the given surface, called shear stress, τ.

Normal stress can produce both normal and shear strains in a material. Shear stress produces shear strain. Normal Strain is the change in length divided by original length. Shear strain is the angular change of a right angle edge of the solid.

3.3 Tensile behavior:

3.3.1: The uniaxial tension test

Tension test is a simple test used for finding the strength of materials. A round rod specimen, gripped on ends and is subjected to increasing axial load. The stress applied is measured using load cell. Strain on the specimen is measured using extensometer. A metallic material, when loaded in tension, initially deforms elastically. Elastic deformation refers to material strain which can be recovered fully. In elastic deformation, the nominal stress which is the load applied divided by the initial area of cross section of the rod, increases linearly with strain.

Engineering strain is defined as change in length divided by initial gage length. True strain is defined as change in length divided by instantaneous gage length.

Engineering stress or nominal stress is the load applied divided by initial cross section area of the rod.

In the elastic region, the linear stress – strain relation is given by Hooke's law:

$$\sigma = \boldsymbol{\varepsilon} E$$

The modulus of elasticity, E is a material property, which depends on the nature of bonding in a material. Typical value of E for steels is in the range 190 – 200 GPa, whereas for aluminium, it ranges from 69 to 79 GPa.

Elastic Poisson ratio is defined as ratio of linear [elongation] strain to lateral strain[contraction]. Poisson's ratio for steels ranges from 0.28 to 0.33. Maximum value of Poisson's ratio is 0.

Typical stress-strain curves for ductile materialswith pronounced yielding and without yielding shown below:

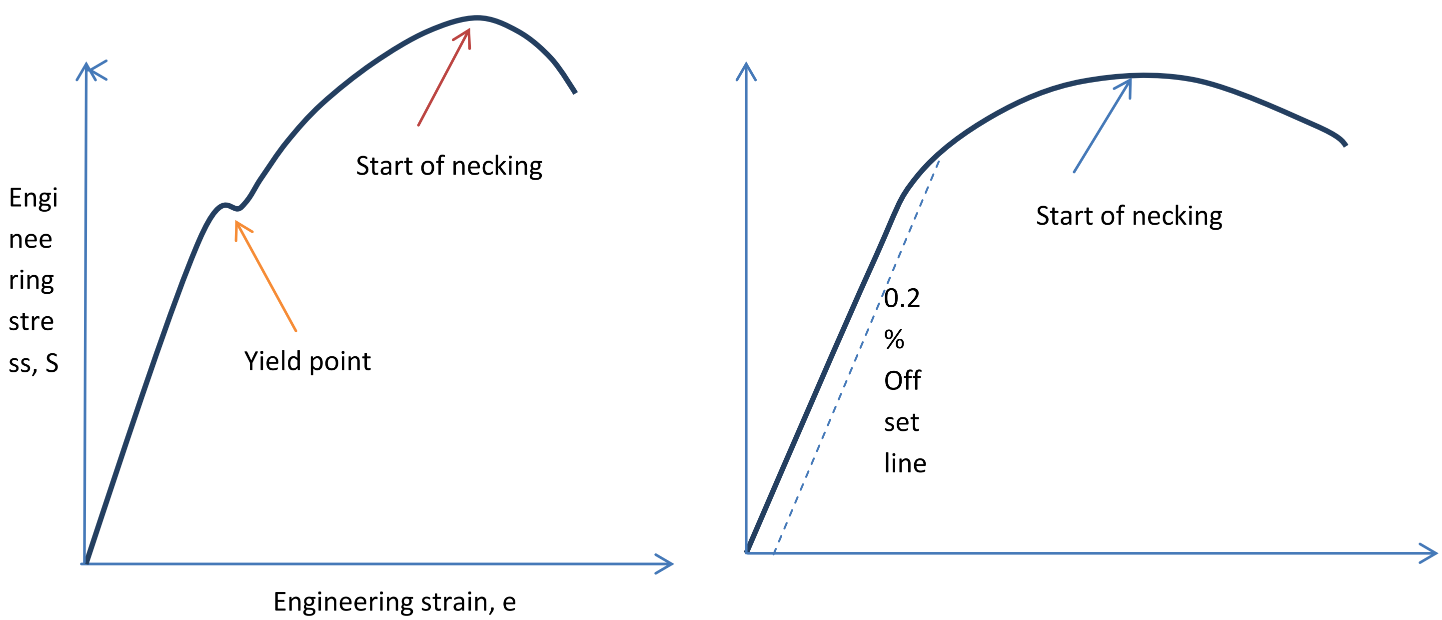


Fig. 3.3.1.1: Engineering and true stress-strain curves for a ductile material

From the tensile curve on can find many properties of the material. Beyond the elastic limit (linear), the material behavior is said to be plastic. The deformation in plastic behavior is permanent. Plastic deformation commences after elastic deformation, which is represented in stress-strain diagram by yielding. Some materials do not show yielding – materials such as copper.

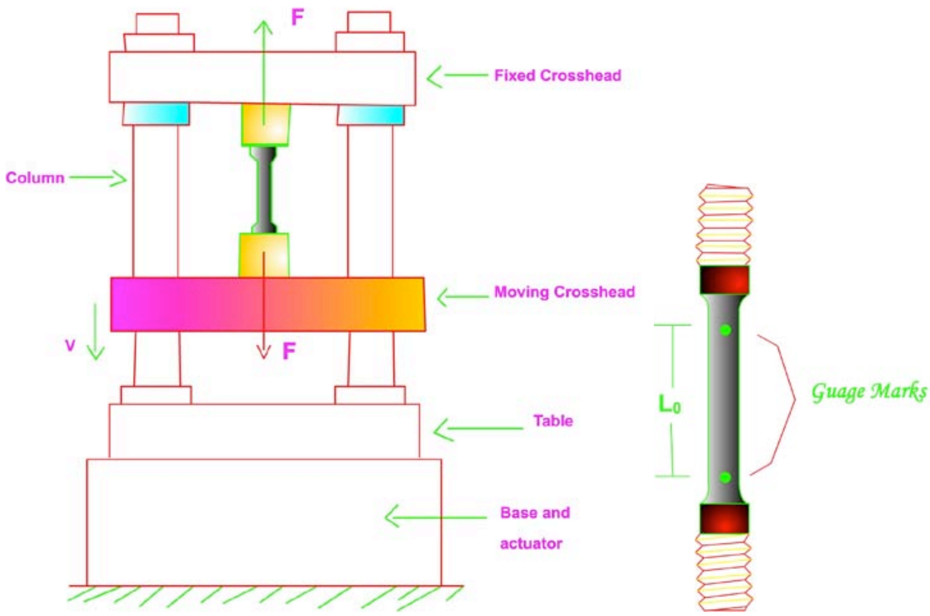


Fig. 3.3.1.2: Tensile test setup and tensile specimen

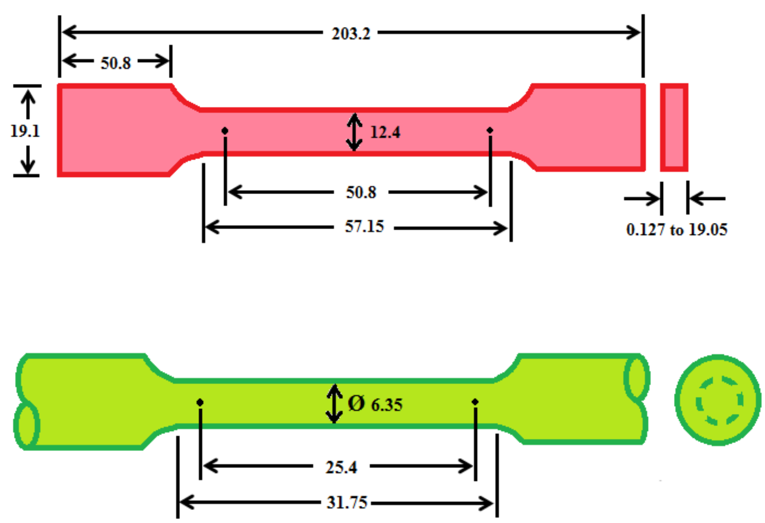


Fig. 3.3.1.3: Standard (ASTM E8) Tensile Specimens of plate and cylindrical types

The stress at yield point is called yield strength. In case of materials which do not show pronounced yielding, the yield point strength is defined by 0.2% proof strength. This is obtained by 0.2% offset on the strain.

Yield point stress is important in case of metal forming operations, because, forming processes require the metal to deform plastically.

The area under the stress-strain curve upto yielding is called Modulus of resilience [MR].

MR = $Y^2/2E$, Y being the yield strength. Springs should have high modulus of resilience, so that they can absorb more energy during elastic deformation and store it.

The plastic portion of the stress-strain curve is non-linear. As the specimen gets loaded beyond yield point, the curve reaches a maximum. The stress corresponding to this maximum point – known as ultimate tensile strength [UTS].

$UTS = F_{max}/A_o$

Until this point there is uniform reduction in area of cross section of the specimen. After the point of maximum engineering stress, with continued loading, the specimen forms a neck – which has low area of cross-section – due to concentration of stress locally. Necking is localized deformation. After necking begins, the deformation is restricted to necked region alone.

With further loading, the engineering stress drops beyond necking point, till the point of fracture. Fracture essentially occurs at the necked region, due to triaxial state of stress in the neck region. Also because the material cross-section in the neck region is very small. The strain at the point of fracture is called total strain.

Some of the useful mechanical properties of the material, which is being subjected to tensile loading, that can be evaluated from the stress-strain behaviour are: a] Yield strength, b] Ultimate strength, c] Percentage elongation and percentage area reduction.

Ductility of a material is defined as percentage elongation or percentage reduction in area of cross-section. The percent elongation is defined as $[l_f-l_o]/l_o$, and the percentage reduction in area = $[A_o-A_f]/A_o$ X 100.

For metals, elongation may range from 10% to 60% and reduction in area may range from 20% to 90%. For some metals tensile properties are listed below:

Table 3.3.1.1: Tensile properties of some alloys

Material	Yield strength, MPa	Tensile strength, MPa	% Elongation
Low carbon steel	175	300	30
Annealed aluminium	28	69	40
Cold worked aluminium	105	125	8
Alloy steels	500	700	20
Austenitic stainless steel	275	650	55

True stress is defined as ratio of load applied to instantaneous cross-section area, $\sigma = P/A$. True strain is defined as change in gage length divided by instantaneous gage length. It is given as:

$$\varepsilon = \int dl/l = \ln(l/l_o) = 2\ln[D_o/D].$$

For small strains, we can take both engineering and trues strains to be equal. However, true strains are more consistent with real phenomena. Advantage of using true strain is apparent from the fact that total true strain is equal to sum of incremental true strains. Moreover, volume strain can be given as sum of the three normal true strains. True strains for equivalent amount of tensile and compressive deformations are equal, only differing in sign.

True stress and engineering stress are related by the expression:

$\sigma = S\,(1+ e)$, where S is engineering stress, e is engineering strain.

Similarly, relation between engineering strain e and true strain ε is given as:

$$\varepsilon = \ln(1+e)$$

True strain is what happens naturally.

Flow stress:Metal forming operations involve plastic deformation of materials. The stress required to sustain a given amount of plastic deformation (plastic strain) is called flow stress. Flow stress is an important parameter in forming. It depends on type of material, temperature of working, conditions of friction at workpiece – tool interface, tool and work piece geometry etc.

3.3.2 True stress – true strain curve:

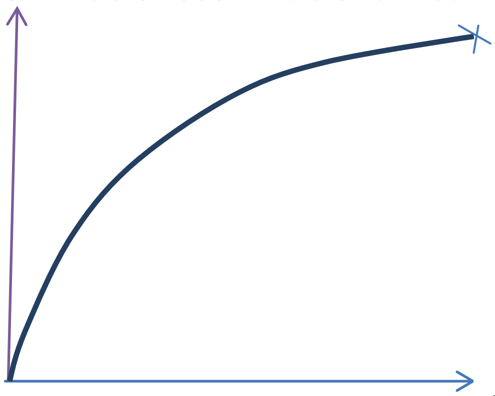


Fig. 3.3.2.1: True stress- true strain curve

True stress-strain curve does not indicate any yield point. It also does not show the elastic region.

The total area under the true stress-strain curve is known as toughness.

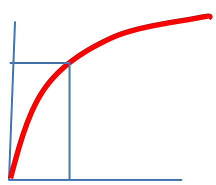
Toughness = $\int_0^{\varepsilon} \sigma d\varepsilon$, where ε is the fracture strain.

The true stress – true strain relation in the plastic portion is given by the power law expression:

$$\sigma = k\varepsilon^n$$

where k is strength coefficient, n is called strain hardening exponent.

Stress required,σ in plastic range to maintain plastic deformation at a certain strain, ε is called **flow stress**.



When the true stress is plotted against true strain on log-log plane, the power law relation, becomes a straight line. Slope of the line is n. n is called strain hardening exponent.

K, the strength coefficient is the value of stress σ, under ε=1.

During plastic deformation, as the ultimate strength is reached, the localized deformation called necking begins. This is called point of instability, as the specimen is no longer able to support the load. It can be shown that at the point of instability, n = ε_u, where ε_u is strain at ultimate point. At the neck, triaxial state of stress is known to exist, due to larger area reduction. Axial stress varies across the specimen in the neck region

Necking begins when the true strain is equal to the strain hardening exponent.

That is $n = \varepsilon$

Higher the value of n, higher the strain the material can withstand before necking.

During instability, the material becomes stronger due to strain hardening. However, the localized reduction in area makes the specimen less capable of bearing the load. The rate of decrease in area is more than rate of increase in strength due to strain hardening, thereby leading to instability. This is called geometric softening.

Instability due to necking may pose problems during forming of sheet metals.

3.3.3: Different types of stress-strain curves:

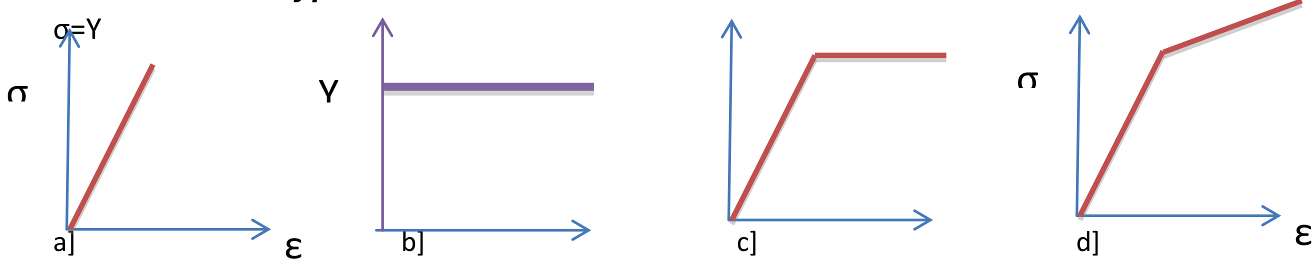


Fig. 3.3.3.1: Stress-strain behavior of different types of materials

Perfectly elastic: Figure – a, Brittle materials such as glass, ceramics, cast irons etc show only perfectly elastic behavior. There is very negligible yielding. Hooke's law governs the stress-strain relation. Stiffness of such material is indicated by E.

Rigid plastic, figure b – has infinite value of E, Once stress level reaches yielding Y, it continues to deform at same stress level.

Elastic, perfectly plastic-fugure c - is combination of perfectly elastic and rigid plastic. This material will undergo elastic recovery upon unloading. Metals heated to high temperature behave this way. Lead has elastic, perfectly plastic at room temperature.

Elastic, linearly strain hardening material, figure d – It approximates many of engineering materials. Such material has linear elastic behavior and linear plastic behavior. Due to strain hardening, the flow stress increases with increasing strain.

3.3.4 Factors affecting the stress-strain behavior

Temperature and strain rate influence greatly the stress-strain behavior of materials. Increasing the temperature reduces the tensile strength, yield strength, increases ductility.

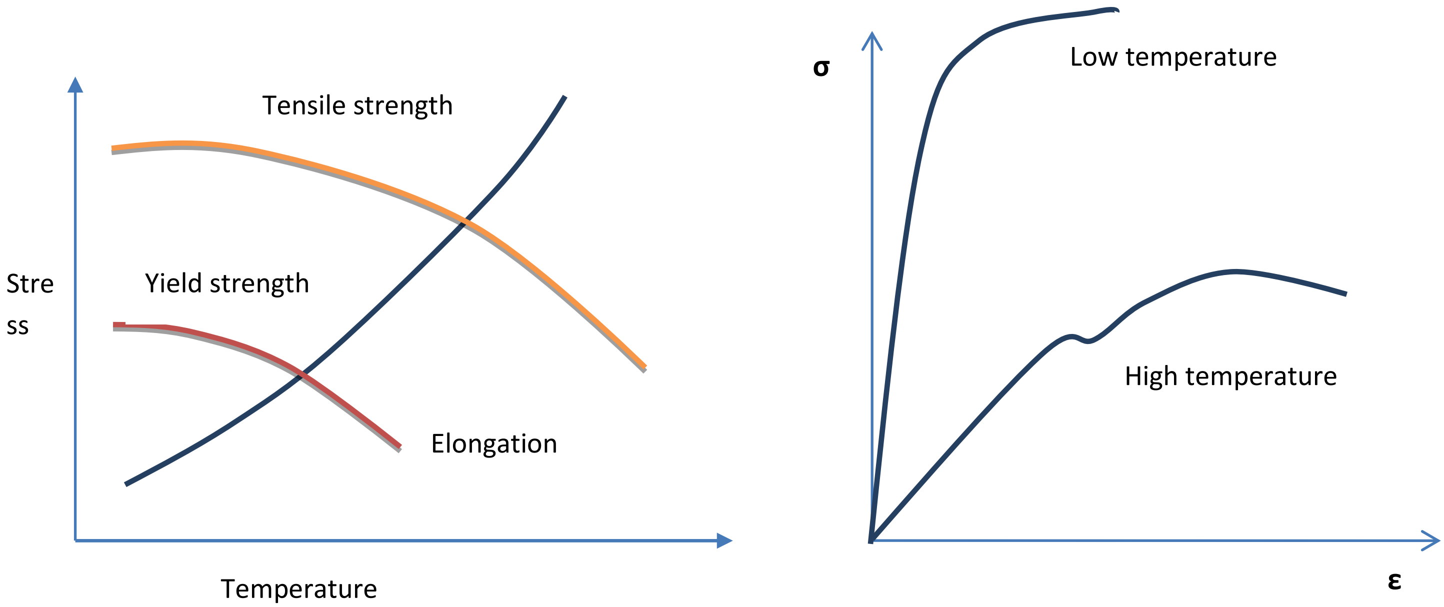


Fig. 3.3.4.1: Effect of temperature on mechanical properties and stress-strain behaviour

3.3.4.1 Strain rate effect

Strain rate is the rate at which material gets strained. Strain rate is expressed in s^{-1}.

Deformation speed of material in a process of forming is expressed in m/s.

Engineering strain rate is defined as $\dot{e} = \frac{de}{dT} = \frac{dl}{l_o\, dT} = \frac{v}{l_o}$, where v is velocity or deformation speed of the process, l_o is initial length. V is ram speed in tensile testing.

True strain rate is $\dot{\varepsilon} = \frac{v}{l}$

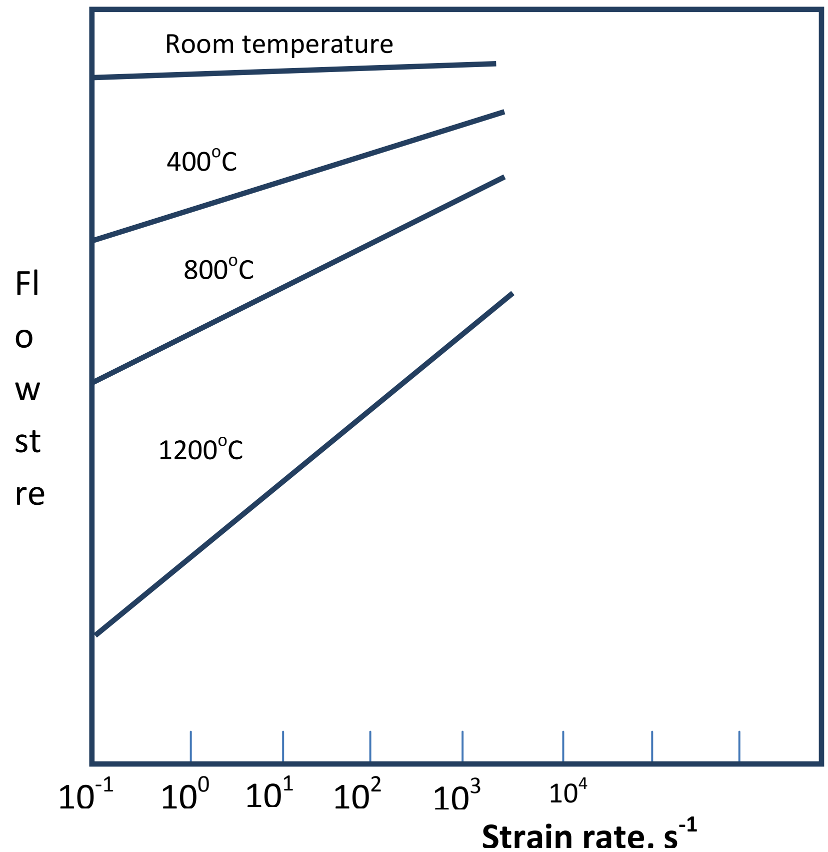
True strain rateis dependent on velocity and instantaneous length.

In order to maintain constant strain rate during tensile test, velocity of the cross head of the tensile machine has to be increased.

Increasing the strain rate increases the tensile strength. Increasing the temperature reduces the strength.

At higher temperatures, the sensitivity of strength to strain rate increases – strength becomes more sensitive to changes in strain rate. This is shown in figure below:

The flow stress is strongly dependent on strain rate at elevated temperatures.



Fir. 3.3.4.1.1: Variation of flow stress with temperature and strain rate

Velocity of deformation and strain rate of deformation during forming operations are deciding factors for selection of forming process and forming press. There are forming processes which are carried out at high strain rates and high velocities. Such processes are called high velocity forming. Example is explosive forming.

Strain rate and deformation velocity for some of the forming operations are given in table below:

Table 3.3.4.1.1: Strain rates and velocities in some forming operations

Process	True strain	Deformation speed, m/s	Strain rate, s^{-1}
Cold forging, rolling	0.1 – 0.5	0.1 - 100	1 - 10^3
Cold wire drawing	0.05 – 0.5	0.1 - 100	1 - 10^4
Hot forging, rolling	0.1 – 0.5	0.1 - 30	1 - 10^3
Hot extrusion	2 - 5	0.1 - 1	10^{-1} - 10^2
Sheet metal forming	1 - 10	0.05 - 2	1 - 10^2

Strain rate dependence of flow stress or tensile strength, can be represented by the expression: $\sigma = C(\dot{\varepsilon}^m)$, m is strain rate sensitivity parameter and $\dot{\varepsilon}$ is strain rate.

In general, the value of m decreases as strength increases.

With higher values of m, a material can undergo more plastic deformation before necking or failure.

The material near the necking becomes stronger due to work hardening, at the instance of necking. Strain rates near necking are also high. As a result, Necking gets delayed. There is large uniform deformation before failure.Elongation after necking also increases due to large values of m.

Superplastic behavior of some materials is possible only if the strain rate sensitivity for a material is high – 0.3 to 0. 85

Superplastic behavior is the ability of materials to undergo very large amounts of elongations – upto 1000% elongation, before failure. There is also no necking in such behavior as m values are high. Examples are thermoplastics, hot glass, fine grained titanium alloy, zinc-aluminium alloy.

Strain rate also affects the strain hardening exponent of materials. Strain hardening exponent decreases with increase in strain rate.

Generally ductility of materials is dependent on strain rate sensitivity parameter, m.

3.3.4.2 Hydrostatic stress:

Hydrostatic stress refers to a state of stress in which the stress acting along all the three directions is the same and of the same sign. Hydrostatic stress cannot cause yielding of conventional materials, because the plastic deformation of crystalline materials is caused by mechanism of slip. Slip is essentially caused by shear force.

Hydrostatic stressis found to influence the plastic deformation process by affecting material property. Hydrostatic stress leads to increase in ductility of a material. Hydrostatic stress increases true fracture strain. However, it has no effect on necking, maximum stress, strain. Hydrostatic stress is found to increase the ductility of brittle materials like cast iron, ceramics.

In metal forming operations, large strains are involved, true strains exceeding 3 to 4.

Therefore, simple tensile test and the results obtained from the same are not sufficient to predict the flow stress of materials. Homogeneous compression test, torsion test, plane strain compression test are some of the tests which are used for determination of the flow stress. These tests are discussed in next lecture.

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