Basics of Materials Engineering
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Lecture – 13
Mechanical Properties (Tension Test - Elastic Deformation)

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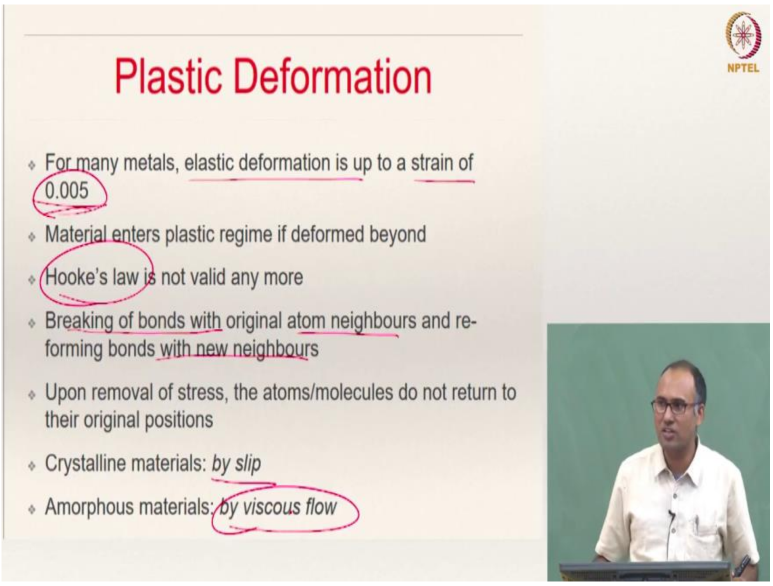

Let us move on to plastic deformation. As you load the specimen beyond elastic limits, the material gets into plastic regime. This means that you are activating the dislocation motion and thus the material plastically deforms. So, for many metals, the elastic deformation is only up to a strain of 0.005 beyond which it enters into the plastic regime. Note that this is only a thumb rule.

The moment that plastic deformation starts, Hooke's law is no longer applicable. The plastic deformation is a result of the breaking and reforming bonds between atoms. This was discussed in the case of dislocation motion. In other words, the bond between initially neighbouring atoms are broken and new bonds are formed with subsequent neighbours. When the material is unloaded, the atoms will not return to its original neighbours and you cannot regain the initial configuration. For crystalline materials, this plastic deformation happens by slip, as discussed.

For amorphous materials, it is by a process called viscous flow. You will also have plastic deformation in amorphous materials, but since there is no structure to amorphous materials, you cannot explain the deformation through slip. So, you have to resort to other mechanisms which can be used to explain the plastic deformation.

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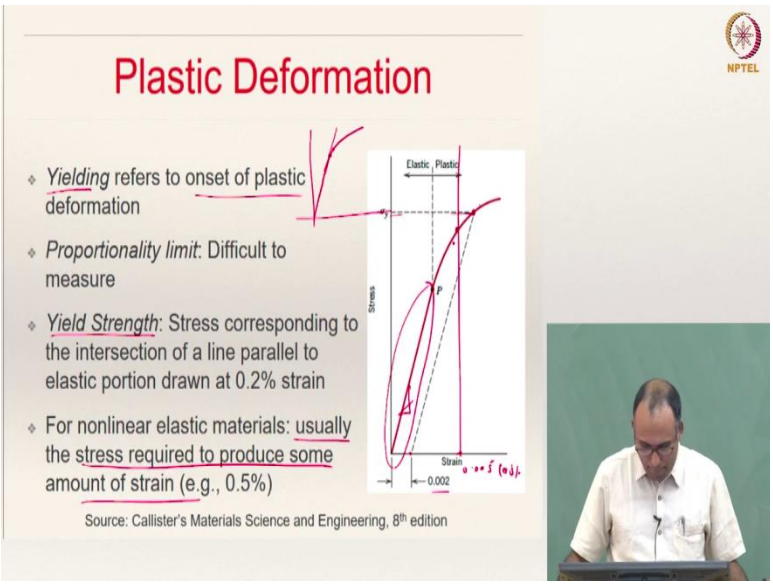

In the previous lecture, we saw the initial portion of the graph. Let us now look at the next portion. This region (marked) is the plastic deformation. Yielding refers to the onset of plastic deformation, i.e. the point at which your plastic deformation starts. This point is referred to as the yield point.

The proportionality limit is the region in which the stress remains proportional to the strain. Beyond the proportionality limit and below the yield point, you still have elastic deformation but the stress and strain need not be proportional. The gap between the two, however, is extremely small and cannot be easily distinguished.

It is extremely difficult to identify the exact point at which plastic deformation commences. It may be possible for certain materials, but impossible for others. We, however, need a consistent standard by which to define the yield strength so that it is not prone to ambiguity. The definitions and measurements must not be person-specific. It must be universal, so that anyone measuring it reports the same value.

Therefore, the stress corresponding to 0.2% offset strain is defined as the yield point. A line drawn parallel to the initial elastic portion of the curve, starting at a point offset by a strain of 0.002 from the origin, intersect the stress strain curve at a specific point. This point is then defined as the yield point. The slope of this line will be the elastic modulus. This is the standard definition of the yield point.

This works very well for linear elastic materials, since there exists a unique elastic modulus. However, for nonlinear elastic materials, we cannot use the same definition given that the elastic modulus is not a constant and keeps changing with deformation. Therefore, for nonlinear elastic materials, the stress required to produce a particular strain (say, 0.5% strain) is defined as the yield point. In other words, it is the point of intersection of a vertical line drawn at the chosen strain value with the stress strain curve.

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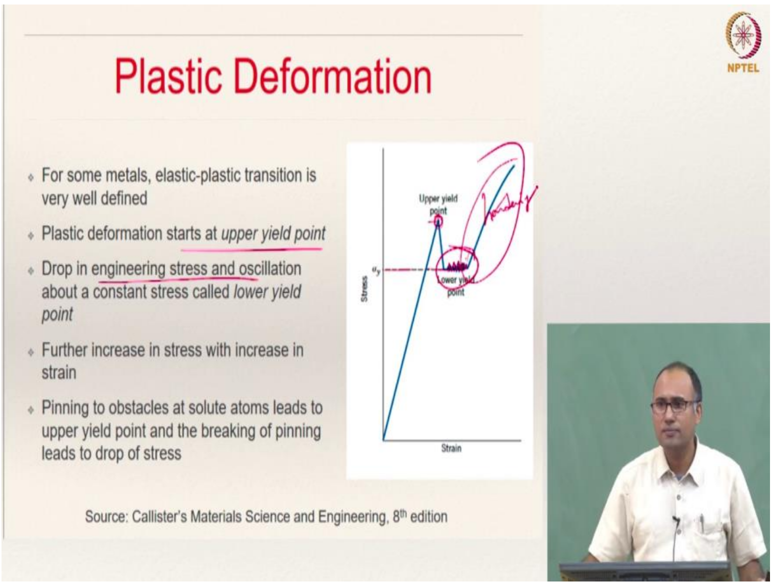

This is the typical yield behavior that one would have seen for mild steel. So, you will have something called upper-yield point. Then, there will be a certain drop in stress to the lower yield point. About this lower yield stress, at almost a constant stress value, you will have oscillations. Beyond this, further hardening occurs. This does not occur for all materials. Typically, this is observed in mild steel. The actual yield starts at the upper yield point, but the yield value that is reported is the lower yield point. So, plastic deformation actually starts at upper yield point, and immediately, there is a drop in engineering stress. Then there is an oscillation about a constant stress value called the lower yield point which is reported as the yield point of the material. Why does this happen?

Mild steel is an alloy of iron and carbon; there are no other solute atoms other than carbon. Compared to the size of the iron, carbon atoms are smaller. When the dislocations are moving, you will have solute atoms of carbon (which is dispersed everywhere) interacting with these dislocations. These dislocations, therefore, get pinned near the solute atoms. In other words, the carbon atom is actually restricting the motion of the dislocations. On application of further load, since the solute atoms are small compared to the solvent, the dislocations can break the pinning. However, there may be other dislocations which are getting pinned by other solutants and so on. The many such interactions are what causes the oscillations.

Eventually, other strengthening mechanisms come into play. For instance, they can get pinned near the grain boundary. You then need a much higher force to continue plastic deformation. That is why you see that it is getting harder and harder to continue plastic deformation. That is why it is called hardening regime.

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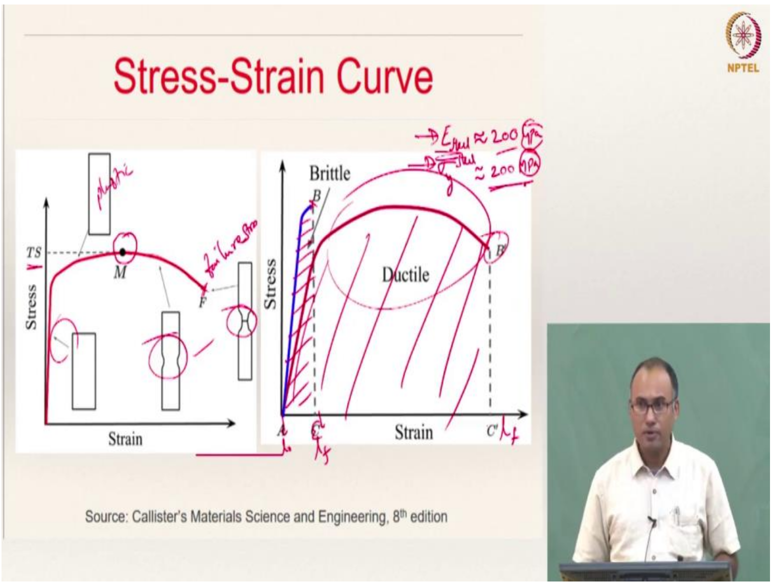

So, this is a typical complete stress strain curve, which is called the engineering stress strain curve. The elastic and plastic regimes are shown. Also, the ultimate stress has been indicated. That is what is defined as the tensile strength of the material, another material property. The tensile strength is the maximum stress that the material can resist before the material begins necking. Necking means the localized deformation, as indicated. Finally, after necking, the stress strain curve drops and eventually, you will have failure.

The typical stress-strain diagrams of a brittle and ductile material are shown. In the case of ductile material, you will have elastic deformation and an extended plastic deformation; a lot of energy is dissipated through plastic deformation before eventually breaking. Whereas, in the case of brittle materials, the yield strength is higher, meaning it can resist higher stresses, but it cannot store more energy. The amount of energy it can store is lesser and it will break without any signs. So, for a brittle material, you cannot define something called yield strength. You will only have ultimate strength; that is where the failure happens directly. Whereas, for ductile material, you will have a well defined yield strength.

Elastic modulus of steel is approximately 200 GPa. Yield strength, σ_y, of mild steel is 200 MPa.

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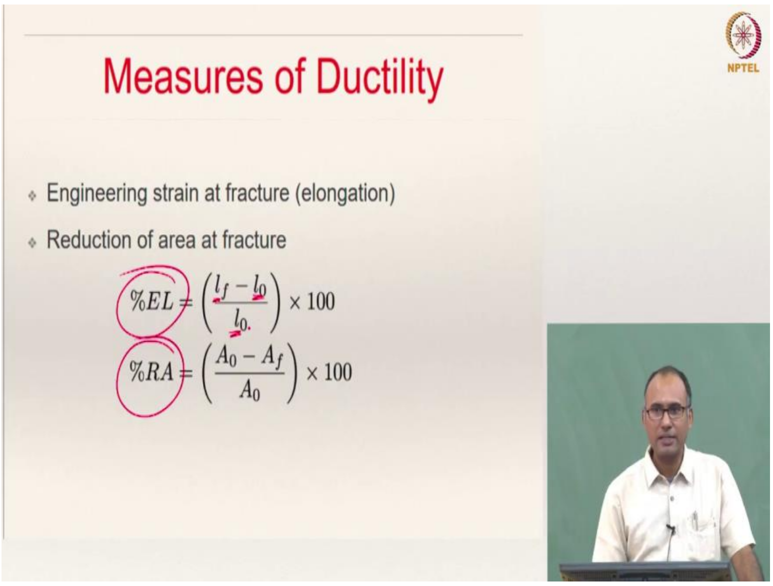

Ductility is the ability of the material to undergo deformation. The ductility of a material is defined by something called percentage elongation or percentage reduction in area.

It is given by

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

$$\%RA = \left(\frac{A_0 - A_f}{l_0}\right) \times 100$$

The percentage elongation in ductile materials can be seen to be much higher than those for brittle materials.

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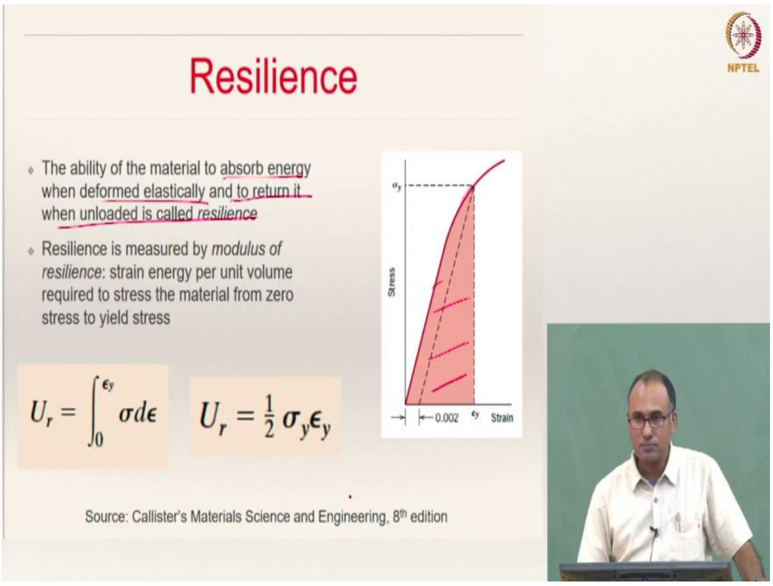

Resilience is defined as the ability of the material to absorb energy when deformed elastically and to return it when unloaded. This is an important property to consider in the design of springs, for instance.

Resilience is measured by modulus of resilience which is the strain energy per unit volume required to stress the material from zero stress to yield stress. This is basically the area under the stress strain curve up to elastic limit or yield strength just before yielding.

This is given by

$$U_r = \int_0^{\epsilon_t} \sigma d\epsilon$$

For elastic materials

$$U_r = \frac{1}{2}\sigma_y \epsilon_y$$

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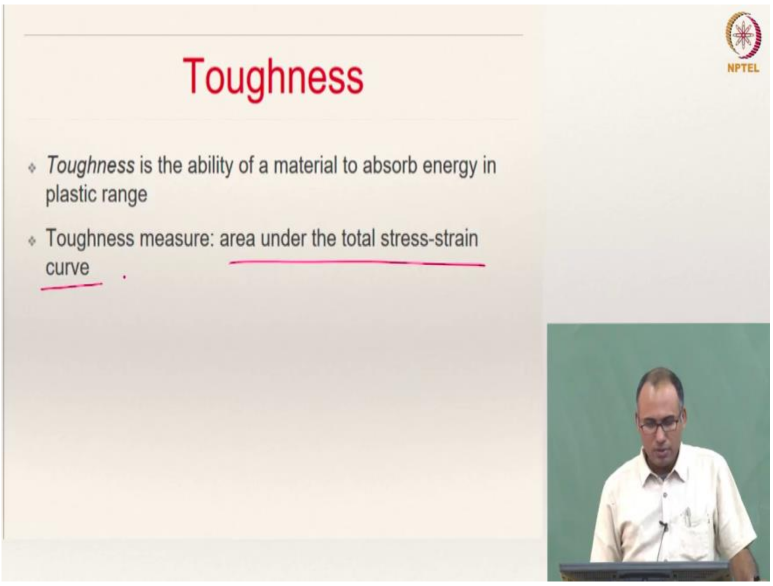

Toughness is the ability of a material to absorb energy in the plastic range. It is the area under the total stress strain curve.

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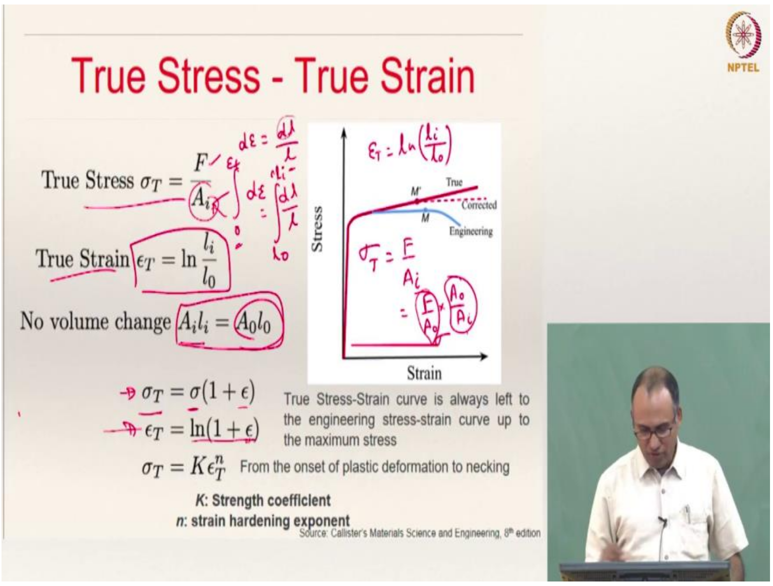

We now define something called the true stress-strain curve. The area that was considered in the calculation of stress in the engineering stress strain curve is the original cross-sectional area. However, we know that when the length changes, the lateral dimensions also are changing. This means that the cross-sectional area is evolving and a stress defined using this instantaneous area is called the true stress. Similarly, if the strain is defined with respect to the instantaneous length, it is called the true strain. Therefore, we have

True stress is given by

$$\sigma_t = \frac{F}{A_i}$$

Where A_i is the instantaneous area.

The incremental strain is given by

$$d\epsilon = \frac{dl}{l}$$

Therefore, the true strain is

$$\epsilon_t = \int_0^{\epsilon_t} d\epsilon = \int_{l_0}^{l_i} \frac{dl}{l} = ln\frac{l_i}{l_0}$$

Since there is no volume change in the plastic regime

$$A_i l_i = A_0 l_0$$

The relationship between the true and engineering components are given by

$$\sigma_t = \sigma(1 + \epsilon)$$

$$\epsilon_t = \ln(1 + \epsilon)$$

$\sigma_t = K\epsilon_t^n$ from onset of plastic deformation to necking, where K is strength coefficient and n is the strain hardening parameter.

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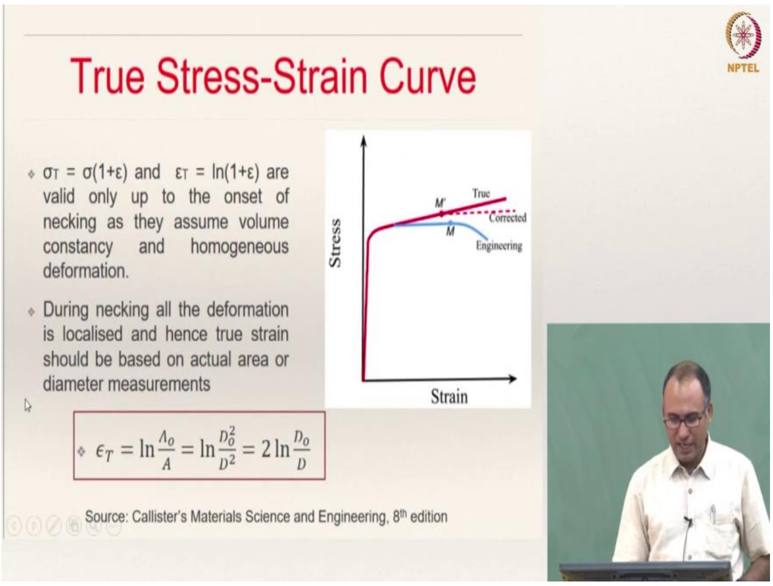

The first 2 expressions are valid only till the onset of necking as they assume volume constancy and homogenous deformation. So, similarly, you can also write a relation between true strain and the engineering strain.