Introduction to Polymer Science
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Module No # 07
Lecture No # 34
Mechanical Properties, Amorphous State

So we have been discussing properties of polymers and we started with discussing thermal mechanical and viscoelastic properties. These three properties, thermal, mechanical and viscoelastic properties are very much related to each other, that is why they are clubbed together. And in this lecture, I will discuss about mechanical properties and then we will start the discussion on amorphous state of polymers, so let us begin with mechanical properties.

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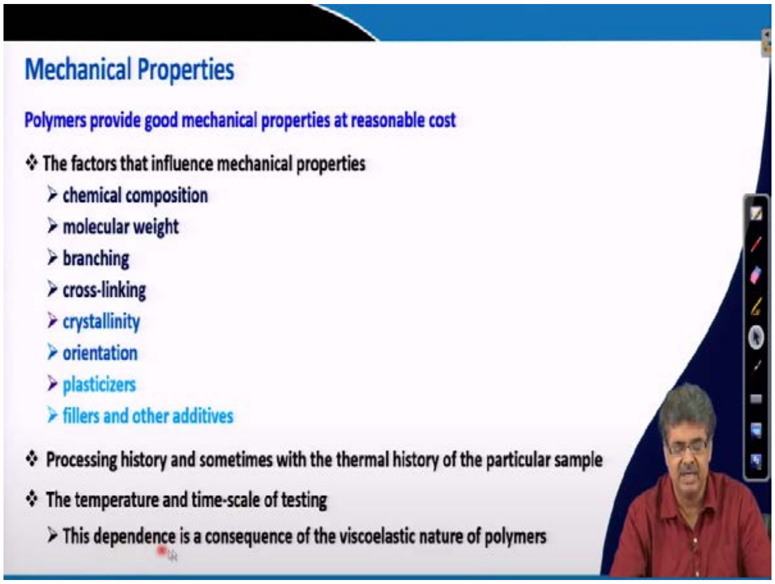

Advantage of polymer is that polymers provide very good mechanical properties at reasonable cost. That is why polymers are used everywhere nowadays because at a cheap price we can get good mechanical performance from polymer products. The factors that influence mechanical properties are chemical composition, molecular weight, branching, and cross-linking. These are the properties or characteristics for the polymer itself. The chemistry of polymer gives these properties. Therefore, you can control these properties during synthesis of the polymer. Once synthesis is done you have no control on these parameters, unless you are using a reaction molding type processing later on, which are not very common.

Other properties like crystallinity, orientation also effect mechanical properties and these properties like crystallinity, orientation depend both on the polymer chemistry and on chemical composition of the polymer. In addition, on the polymer processing steps, how you are carrying out the polymer processing. The mechanical properties also depend on the additives like plasticizers, or fillers, and other additives that are added on the polymer samples. Of course, the performance, mechanical performance of the final products depends on the processing history and sometimes on thermal history of a particular sample other than this all these parameters that I discussed.

Nevertheless, even if all these parameters are same for a particular product, the mechanical property or mechanical performance of that particular sample can also be dependent on the temperature of the testing and the time scale of the testing. How fast the testing is done or how slow the testing is done. Therefore, this is dependent on the testing process. The performance, mechanical performance or value of the mechanical properties also will depend on the temperature and the time scale. And this dependence is a consequence of viscoelastic nature of the polymers.

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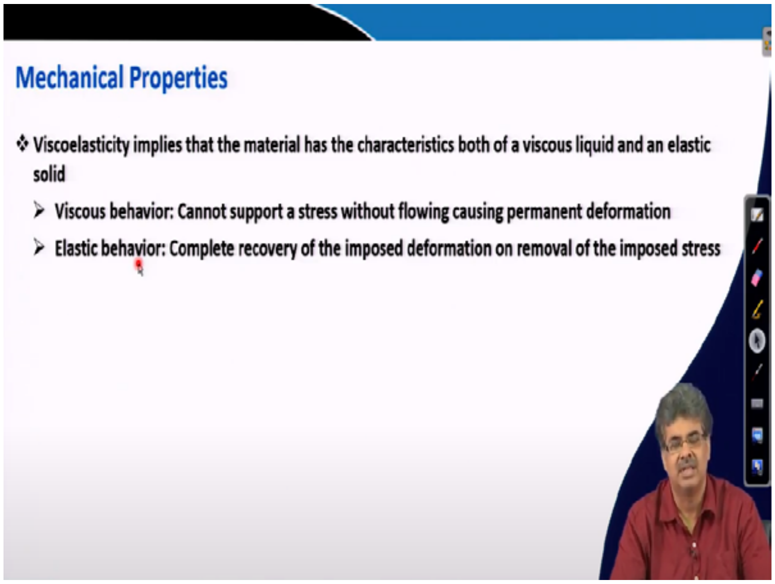

What is viscoelastic nature? Viscoelasticity implies that the material has the characteristics of both a viscous liquid and an elastic solid. Viscous behavior means that if we apply stress, I apply force to a material; it cannot resist the stress without flowing. For example, if I tilt a water bottle, water will flow; it will not be able to sustain the force, gravitation force that is acting on it. Moreover, once it flows it will be permanently deformed.

Elastic behavior is that when a sample or a material is deformed, as soon as the force or the stress is removed, the material will come back to the original state on removal of the applied stress. So that is an example of perfectly elastic material. A polymer can have both; viscous or elastic behavior depending upon the temperature or time scale of the experiment or testing mechanism you are using.

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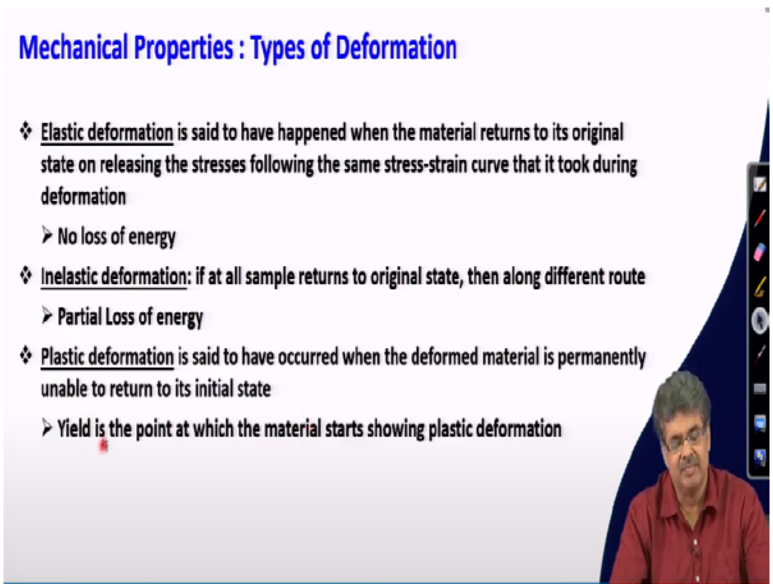

Now there are different types of deformation possible for a plastic material or polymer material. Elastic deformation: As I explained that perfect elastic deformation is said to have happened when the material returns to its original state on releasing the stress following the same stress strain curve that it took during deformation. So there is no loss of energy, whatever energy is applied, you can get it back. Inelastic deformation is said to have happened when the sample return to the original state but in this case, in different route. There will be some loss of energy or partial loss of energy. The third type of deformation is plastic deformation, in this case the sample will deformed permanently and it will not be able to come to the initial state and that generally happen at a point called yield point where the material start showing plastic deformation.

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Mechanical properties of polymer materials: Different types of test one can do like static test, like tensile, compressive, or shear test. These tests provide stress strain behaviors, stiffness, strength and toughness of materials. High strain tests like impact test give impact strength of the material. Creep test gives time dependent elongation of a material; it also gives the parameters of viscoelasticity. Dynamic mechanical test gives viscoelastic properties, the value for thermal transition like T_g, T_m, molecular relaxation. Fatigue test is applied when one need to find out the lifetime or durability of a particular sample in a particular application. Hardness gives the resistance to surface indentation. Abrasion resistance is a measure of the weight loss by an abrader or finely divided abrasive. Therefore, you can see that there are many tests are available to an engineer or a product specialist.

Now which test needs to be done will depend upon the final application for the material. If somebody wants to find out the scratch resistance or mar resistance of a plastic film then he or she should do a hardness measurement. Moreover, if somebody wants to use polymers as structural material, stiffness is a very important property. If, somebody wants to use for a long duration in some application then fatigue test must be done. So depending upon the application, the application engineer or polymer engineer should select the type of or more than one type of tests to find out the mechanical performance of a polymer sample.

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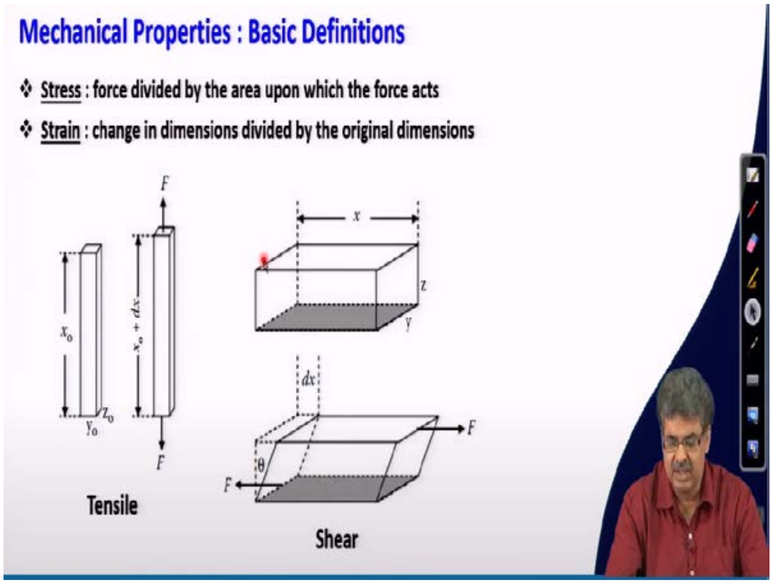

Some basic definition about mechanical properties: Stress is the force divided by the area on which the force is acting. And strain is the change in dimension divided by the original dimension. There are different types of stress like in this case a stress is applied in a longitudinal direction and this is called tensile stress and the deformation happens in a longitudinal direction or the length is increased in this case. This strain is called tensile strain.

In the second case, the force is applied in one direction keeping one of the sides fixed. So the deformation happened sidewise, horizontally, so this is called a shear stress and the deformation happened is called shear strain. So depending upon the type of sample and type of force, we can have different types of strains and stresses; two examples are given here are tensile and shear.

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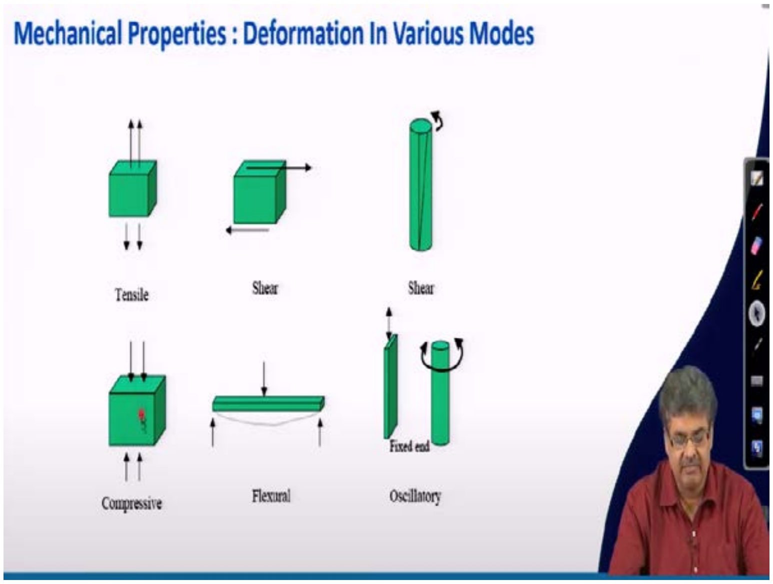

There are other possible deformations in various modes, there could be other types of shear where we are applying a circular force, if the compression is happening by applying force like this, the way it is shown this is compressive stress. This is a flexural stress where these two sides are fixed or supported and a force is applied in the middle. So it bends after applying the force like this dotted line and this is called flexural stress and this strain is called flexural strain.

Similarly in this case these samples are fixed at one end and an oscillatory stress is applied, oscillatory force is applied this way or up and down. So in this case we are talking about oscillatory stress or oscillatory strain. So again depending upon the application of the final product we need to or somebody need to basically identify which type of deformation mechanism he or she should choose to find out the performance of a material.

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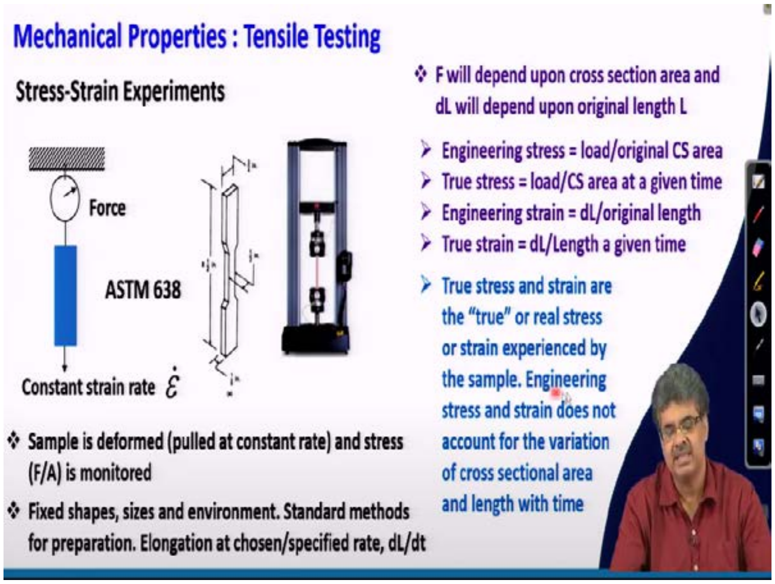

For example, let me discuss about tensile testing. I am repeatedly saying that in the lab, we cannot make the final products like a car headlamp or buckets, or we can think there are several things that we cannot make in the labs. Therefore, instead, what we do in the labs is that we make some standard samples. The standards are given by different standard organizations like ASTM, ISO, etc. ASTM is American standard organization, or ISO, international standard organization provide specific dimensions of the samples that need to be molded. And specific test conditions that need to be followed to generate meaningful data which can be used to compare or use to predict the performance of the final polymer product. In this particular case, ASTM 638 is a test that is used for measuring tensile properties.

In this case, the sample is mounted and then a constant strain rate is applied. This sample is deformed with the constant strain rate and the resulting stress is measured and stress is plotted against the strain. So typically, a dog-bone shape sample is molded for which dimensions are specified by the standard test conditions. These are available in literature. Once this material is molded in a particular shape, then it is taken to an equipment or instrument that we call a strain instrument or Instron or universal testing machine.

The sample is pulled in a longitudinal direction, so we are talking about the tensile test at a constant strain rate, and the resulting stress or the required stress is actually measured by the machine and stress is plotted versus strain. The sample is deformed, pulled at a constant rate and the stress, force by area, is monitored. Shape and size of the test specimen, testing environment and condition, need to be followed as per the standard, which is mentioned in the standard testing protocol.

The stress will depend on the area or cross sectional area of the sample and the change in length will depend on the original length. Now as the sample is pulled the cross sectional area will change so as the length. Hence, the force or the stress actually keeps on changing as the length of the sample increases, so does the, value of the strain. Hence, the stress vs strain behavior is also function of the moment when we are measuring. So we define engineering stress which is the load or the force divided by the original cross sectional area, but the true stress which varies at different times depends upon the force applied is defined as the force divided by the cross sectional area at a given time which keeps on changing as we increase the length of the sample.

Similarly engineering strain is the change in length divided by the original length. And true strain is a change in length divided by the length at a given time. Therefore, length will increase as the time increases, resulting in lower strain as the length or denominator value changes. True stress and true strain are the true or real stress or strain experienced by the sample. Whereas engineering stress and strain do not take account the variation in the cross sectional area and the length with time as I discussed.

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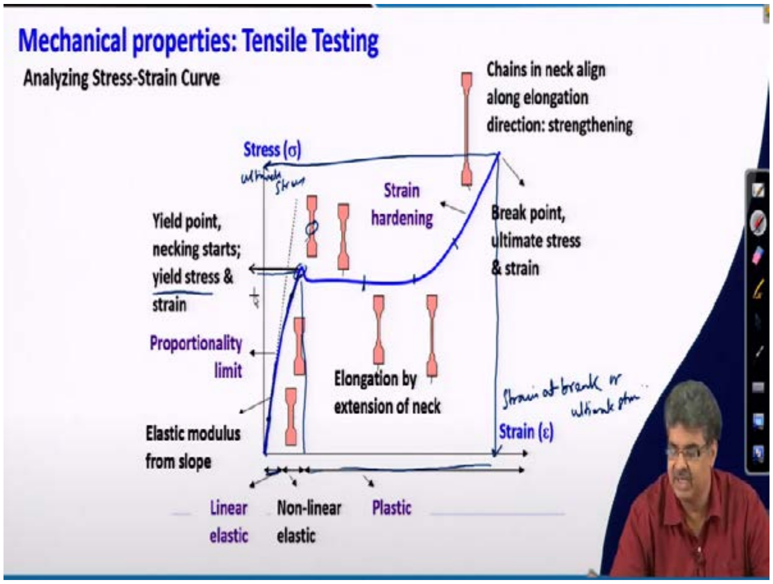

(Please refer the figure on the slide) Now this is the outcome of a tensile test - a stress-strain curve. In this case, stress is plotted in the y axis, and strain is plotted in the x axis. As I described, the sample is strained at a constant rate and the required stress is plotted in the y axis. Now in the beginning, upto a certain strain the deformation is elastic deformation that means if we leave the stress it will come back to the original shape.

So this limit is for this particular experiment is up to this point. This is the proportionality limit, and the slope of this stress strain curve is the modulus. In this particular tensile test, we call this slope as elastic modulus. Now when you strain above this point there is deformation. But in this case if we release the stress then it may come back to the or may come back to the original shape but in a different path. Therefore, this is an example of inelastic deformation. After a particular strain, depending upon the sample, some sample will break here; some sample may actually form a neck here. And when you apply further force then the neck will become bigger and bigger. Now little force which will be required to elongate this neck. So the stress almost remains same and the sample becomes elongated as shown here.

Once the sample is elongated quite an extent then it requires much more stress to further elongate the sample and this is called strain hardening. Now this is the force or the stress it requires initially to overcome the intermolecular forces between the polymer chains. Once it overcomes, then the polymer chains can easily move, that is why you require less strain. But at this moment when polymer chains are elongated enough then elongating the chains further becomes much more difficult. So it requires much more stress to elongate further. And this is the point where it breaks and this is, this value is called ultimate stress. And this strain, corresponding strain value is called the strain at break or ultimate strain. So this value of corresponding stress is called ultimate stress. And this corresponding strain value is called strain at break or ultimate strain. This corresponding point is called yield stress and of course the strain corresponding is yield strain.

This is the point where this necking start place and once this necking happens then it becomes easier for further elongation till it gets elongated to a such an extent that further elongation becomes, it becomes much more difficult and this is the region we call strain hardening. So this region is elastic deformation, this part is non-linear elastic deformation or inelastic deformation and this entire region is plastic deformation.

So if any time we release the stress from this point or this point it will not come back to the original state. Whereas if we release the stress from this point; it will come back to this original point. If we release the stress from this point then it may come back but in a different path. We will now learn about the different other different parameters form this stress strain curve.

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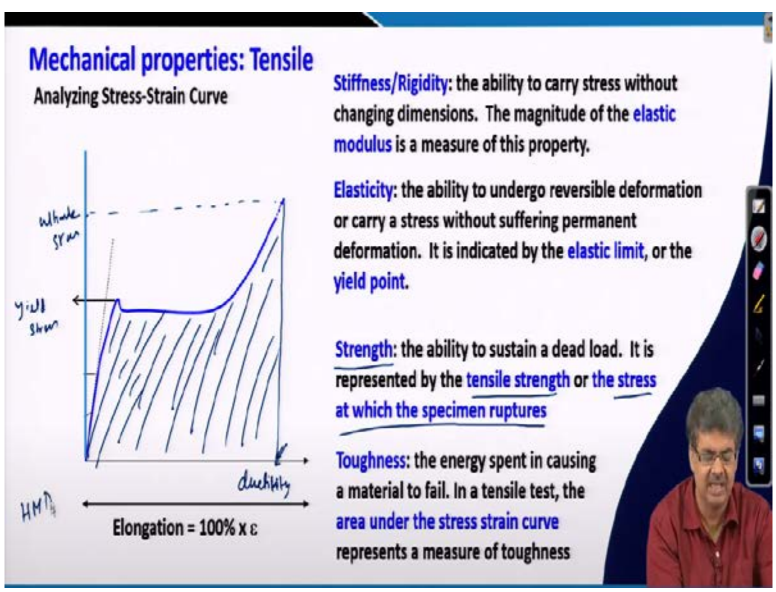

So as we shown here this is a yield stress. These are common terms we come across, stiffness or rigidity. It means the ability of the material to carry stress without changing dimension. It is given by the value of stiffness or rigidity, rigidity or stiffness is obtained from the value of elastic modulus. If the elastic modulus is higher, we say the sample or the material is stiff or rigid material. When we say stiffness or rigidity, we must remember what is the underline property, in this particular case elastic modulus need to be quantified. Similarly, elasticity is the ability to undergo reversible deformation to carry a stress or carry a stress without suffering permanent deformation. Till the yield point we have elasticity; this strain is the elastic limit.

Similarly, strength, when you say material is having high strength, this means the ultimate stress. This value corresponds to the ultimate stress. So this value determines the strength of a material. So higher is the value of tensile strength or ultimate strength, which is given by the higher value of this particular stress. When we say a material is having high strength we will know that it has a higher tensile strength or the stress at which at which the specimen ruptures.

Similarly, when we talk about toughness, toughness is the energy spent in causing a material to fall or fail. So at this point the material breaks. The energy it has absorbed before it breaks is given by the area under this stress-strain curve. So this area gives the toughness of a material. The higher is the value of this area, higher is the toughness of the material. So when you say material is tough, that means it consumes or it absorbs much more energy than a material which is less tough before it breaks.

The elongation at break is generally represented as a percentage, is sometimes also used to quantify a term called ductility. The higher is the elongation until it breaks, we call that sample is more ductile. It is generally seen that the samples that are having high modulus, have low ductility, and the sample which are highly ductile, have low modulus value or more low stiffness value. For example, elastomers have high ductility, provide a high elongation but they can resist very little force. So their stiffness is lower. Similarly, for fiber, the stiffness is higher but the elongation is lower. It has been always a challenge and remains a challenge to make a material that is having high modulus and ductility.

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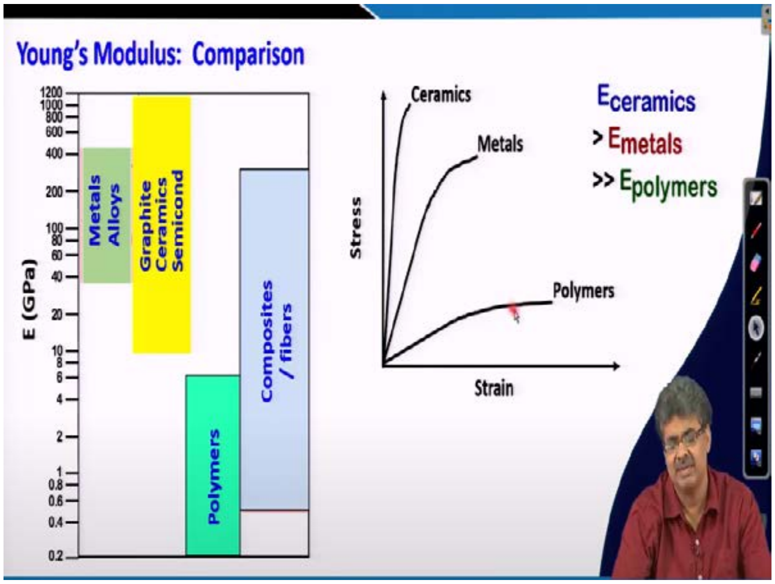

So now, let us compare some of the Young modulus values or tensile modulus values for different materials. Polymers are having lower than metals, ceramic, or composite. However, if you compare the modulus divided by the mass, then polymers will having higher value. Therefore, we can get more stiffness or more mechanical performance for a given amount of material in case of polymer that is why it is useful. And so if you see typical stress strain curves, ceramic we look like this, metal will look like this, and polymers will look like this. So compared to metal and ceramic, polymers have low modulus but higher ductility.

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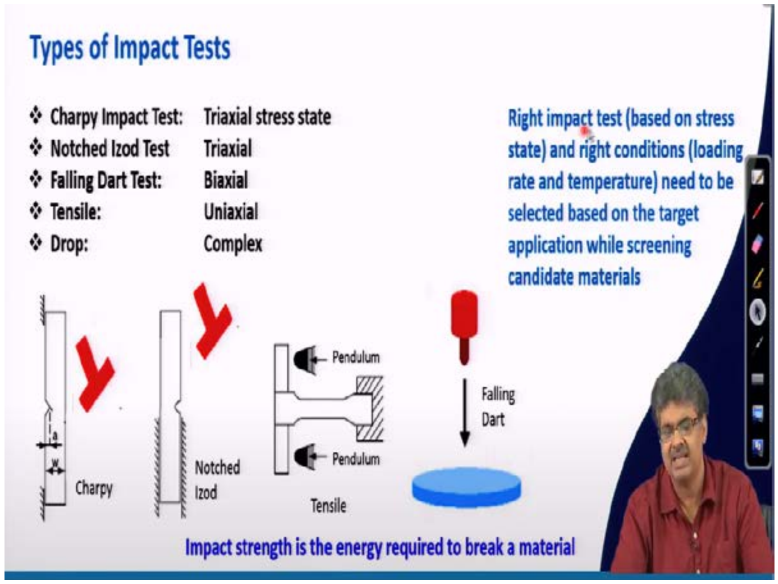

The other mechanical tests will depend on the type of material and type of application. For example, impact test is to quantify when a material face an impact like a car running hits something and then it is a sudden impact. Therefore, to test the materials′ capability to resist this impact force, different types of testing are done and they are called impact test.

There are different types of impact tests that depend on the final application of the polymer. For example this called Charpy impact test where one notch is made in this type of sample, these are fixed here and one hammer hit this and the samples gets broken in this area. Another test is notched izod test where a sample is molded in this shape with a notch, these are fixed on this part, and then it is hammered on the top part. And the amount of energy which is required to break this upper part is called notched izod impact strength. In addition, in fact, depending upon the surface of this broken species we can actually detect the type of failure, whether it is a ductile failure or a brittle failure of the materials. If the energy required to break this sample is high, typically it represents a ductile failure. And you can see this on the surface of the broken species. I am not going in detail on those this. Similarly, this is tensile impact test; the test is done as shown here using a tensile sample. Another test is like falling dirt test, and there are some other tests like dynatop test. These tests are designed or tailored as per the final application requirement for the particular sample. Right condition, loading rate and temperature need to be selected based on the target application while screening the candidates for material.

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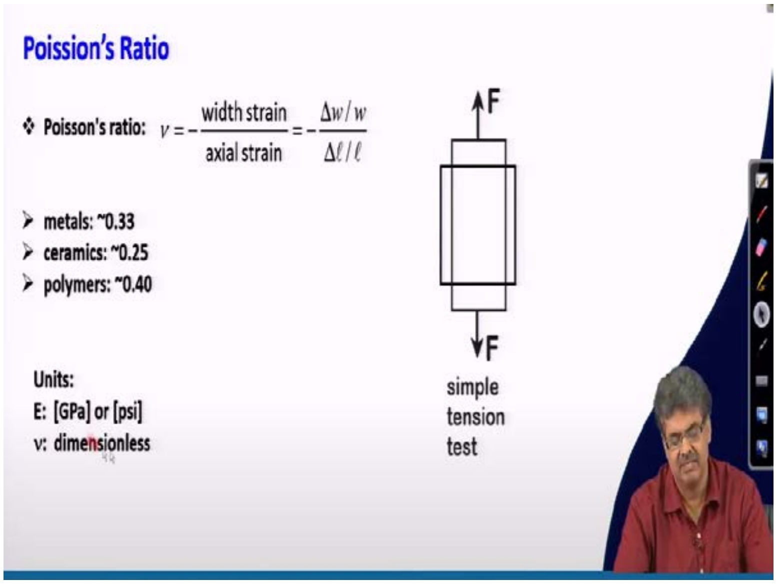

This is another information which we might require is Poisson's ratio. We need these discussed about engineering stress and true stress as the width or the cross sectional area might change during elongation. Generally, as we elongate a sample the cross sectional area decreases. Poisson's ratio is defined as the width strain, how much deformation happen in the width relative to the original width, divided by the axial strain or the strain it he longitudinal direction.

$$\nu = -\frac{width\ strain}{axial\ strain} = -\frac{\Delta w/w}{\Delta l/l}$$

The minus sign is to make this number positive because Δw and Δl have opposite sign. Typical values for metal, ceramic, and polymer are shown here. Obviously, ν is a unit less quantity and the units for modulus is Pascal (Pa), or GPa or mega Pascal, or psi.

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Next, we will move to the thermal properties of polymers and as I said that mechanical properties or thermal properties are related to each other and we need to understand the thermal properties, it is very important in terms of processing as well as product performance. As I said that, it is interlinked with mechanical, rheological behavior. So in next class I will start from here and discuss thermal properties of polymer.