Introduction to Polymer Physics
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Lecture – 18
Mechanical Properties of Polymers

Hello everyone. So, today we will be talking about Mechanical Properties of Polymers. So, in this lecture we will first talk about the some of the basics basic definitions related to some Mechanical Properties.

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So, we will start off with the definition of Stress; what are the different components of Stress that can be identified and similarly, we will also talk about the concept of Strain. So, Stress and Strain are some things that might be familiar to many of you, but we will talk about it in a more general sense and see that for in any given material there are many a different components of stress and strain that are possible.

And then, we will talk about the relationship between stress and strain. So, how a stress and strain are related; what kind of different mechanical properties like the different moduli which can the can be identified based on the relationship between different types of stress and strain. Then towards the end of this lecture will focus on the elastic deformation of polymeric materials; so, stress strain behavior of polymer materials of different kinds, that is what we will focus on towards end of this lecture.

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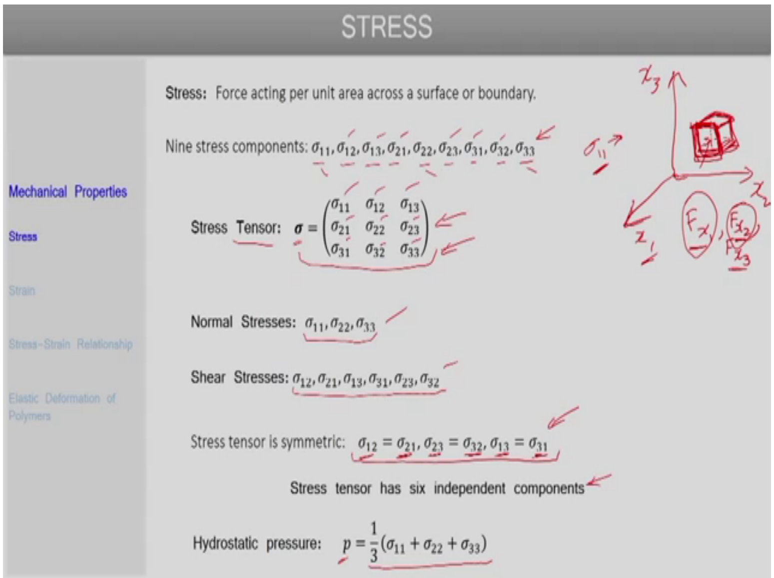

Stress as many of you might know is generally defined as a force acting on a unit area. So, force per unit area that is acting on the surface. So, it is acting across a surface. So, if we talk about let us say solid material and we take a section across the solid material and we focus on one of the surfaces.

Then, the stress basically can be identified as the force per unit area being exerted by part of this solid material or the collection of molecules within the solid material on a different part of or adjacent part of the solid material. Similarly, for fluids also such internal stress can be identified, it will have units of force per unit area which in SI units is Pascal or Newton per meter square.

So, if you have force acting per unit area on a when given surface as a definition of stress, then depending on the orientation of the surface relative to the direction of force that is acting; a several different components of a stress can be identified. So, if we talk about the stress at a given point in a given coordinate axis; so, if we let us say have a axis system defined by these three axis, where we will call them x 1 x 2 and x 3 and one can equality call them as xyz also.

So, that does not change anything about the fundamental definitions, if we consider any point in this coordinate system, then the stress around that point can be defined by first let us say constructing a small kind of cubic element around this point, and then, identifying the different stress components that are acting on the different phases of this cube.

So, if we talk about this phase, the phase which is perpendicular to x1. So, if we have some force acting on this phase in some arbitrary direction, we can resolve that force into 3 different components that is the components along the x 1 x 2 x 3 directions. And then, we can calculate the appropriate stress components by dividing the force components that we have identified by the corresponding area of the phase on which the force is acting.

So, on this front phase which is perpendicular to a this x 1axis, if we have some force affecting due to let us say the presence of surrounding material. Then this force can be broken down into the 3 components F x 1 F x 2 and F x 3, let us say which are the components along the 3 coordinate axis that we have drawn here. So, F x 1 will be the force component parallel to the x 1 axis, now the surface that we are talking about is perpendicular to the x 1 axis.

So, this force component F x 1 will also be perpendicular to the surface that we are talking about. So, this F x 1 force is the normal force on this surface; whereas, the other two forces F x 2 and F x 3, these will be parallel to the x 2 and x 3 axis and the again the surface that we are talking about this surface is also parallel to x 2 and x 3 axis.

So, the forces F x 1 F x 3 are actually parallel to the surface on which they are acting. So, these forces will are referred to a shear forces; so, the and the corresponding stresses due to these forces will be the shear stresses. So, the once we have broken down the forces into the different components, then the force per unit area for each of these force components will give the corresponding stress components.

So, the nine stress components that we have written down here; these nine stress components corresponding to basically the normal as well as shear stress components that that will be acting on let us say surfaces that are perpendicular to x 1, surface perpendicular to x 2, this 1 as well as this top one surface perpendicular x 3. So, if we identify all the stresses acting on these surfaces, we will end up with nine such distinct components ok.

A typical stress description of stress in a given material involves nine different stress components. So, stress is normally called as a Tensor quantity and this Stress Tensor, which we have denoted as this bolt sigma here, this stress tensor can this be represented as a matrix of all the nine stress components that we have identified.

If we talk about let us say the stress components sigma 11 that will correspond to the force acting normal to the surface that is perpendicular to x 1. So, if we have this surface perpendicular to x 1 here, then the force normal force acting on this surface that will be F x 1. So, F x 1 divided by the surface surfaces area that will correspond to sigma 11. Sigma 12 will correspondingly be a stress component on that same surface, but due to the force F x 2 which is parallel to the surface area. So, sigma 12 will be a shear stress component.

Similarly, sigma 13, 21, 23, 31, 32 these will be shear stress components and 11, 22 and 33 these will be the normal stress components, because here the force is acting normal to the surface ok. So, normal stresses as we have identified as sigma 11 sigma 22 sigma 33 and these are the diagonal elements in this stress tensor and the off diagonal elements constitute at called the shear stresses. So, if we have we have pressing against the surface in this way, then the corresponding stress being generated is a shear stress.

So, it is a acting parallel to the surface and normal stress due to force acting perpendicular to the surface. We have 6 such shear stress components and 3 normal stress components. One thing to note again is that the shear stress all these 6 components are actually not independent of each other it turns out that the stress tensor is symmetric what; that means, is that sigma ij equal to sigma ji

or in other words, for this the stress tensor that we have written here the sigma 12 will be equal to sigma 21, sigma 23 will be equal to sigma 32 and same for sigma 13 and 31. So, this is a condition that results if an applies the a condition of rotational equilibrium on a given element and then, that equilibrium condition leads to the fact that the shears sorry, the stress tensor is symmetric and the shear stresses are not independent of each other; only three shear stress components are independent they are the shear stresses are related in this way to each other.

Another important thing to note about these normal stresses that typically when we talk about pressure lets inside a fluid; so, hydrostatic pressure inside a static fluid. So, that is also related to the normal stresses and the relation between the normal stresses and the hydrostatic pressure which is p is just 1 by 3 times sigma 11 plus sigma 22 plus sigma 33.

So, hydrostatic pressure can be thought of as just the average of the normal stresses at any point inside a fluid. And as we have already mentioned the shears the stress tensor has only six independent components because shear stress components are related to each other. So, this is some fundamental material about the quantity stress. Another important quantity that is that invariably comes up when we talk about mechanical properties is what is called the strain.

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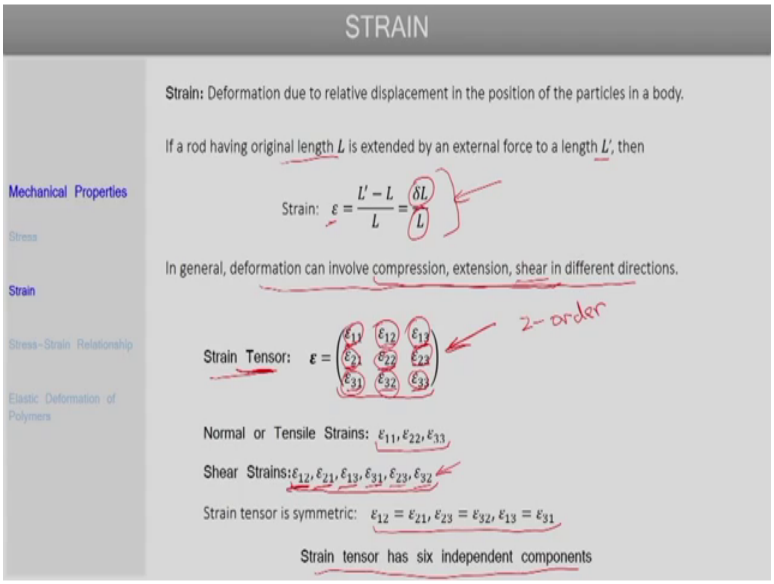

So, strain is again something that you would have come across earlier also. So, it can be thought of as a deformation resulting from the relative movement of particles or our atoms and molecules considering a given solid due to the action of certain let us say external element like external force or anything like that. And strain is typically defined as the change in the in any dimension produce divided by the original dimensions. So, if we are talking just about a simple Uniaxial tensile force acting on it is something.

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So, if we have let us say have this rod and if it is being pulled down along a fixed axis let us along the axis of this sort in a using a tensile kind of force it is being pull down. So, the corresponding strain produced will simply be the ratio of the change in length divided by the original length of this rod.

So, for simple cases if we let us say have as we discussed have a rod of original length L and it is extended to a length L prime due to the action of some external let us say tensile force. Then the strain is simply defined as the change in length divided by the original length.

But in general so, the strain can be thought of as a change in dimension divided by in the original dimension due to the action of some external applied stress. So, this is a simple definition of strain and is fine if you have a very simple kind of system where only at elongational kind of tensile force is acting and the deformation of the body is only along one direction.

But in general one can think of as a combination of stresses normally acting on given body, whether we can have either tensile or compressive stresses acting simultaneously in different directions along with shear stresses also acting on a material.

So, if you have such a general kind of case where many different kind of stresses are acting together on a given body, then the corresponding strains produce strain produced will also cannot also be defined by a single quantity, but instead it will also have many different components. So, in general a deformation can involve various different types of stresses and thereby, various different directional deformations. So, we can have shear deformation, extension compression in various directions.

Due to this proper description of strain in a material can be given by identifying again nine different components of strain and that is done through this strain tensor. So, strain tensor is also a tensor quantity and both stress and strain tensor has referred to as what is called the second order tensor; both of them have nine elements.

So, again if you talk about the diagonal elements say epsilon 11 22 and 33; these correspond to the normal strain. So, due to a normal forces or normal stresses acting whereas, the combination of stresses where shear stresses also might be present that can also produce angular deformation along with linear deformation.

So, this angular deformation are characterized by these in shear strains that we have here. So, again we have a three normal or tensile strains corresponding to the deformation in the 3 axis that we have defined. And we can also have shear strains which will be due to the action of usually shear stresses and these will correspond to some kind of angular deformation of a body.

So, if again we have a this rod if you have pull down the that will induce a normal strain in this material. On the other hand, if we have some again somebody like this and if we shear it by applying a shear stress on this surface and the body which initially is this it deforms changes its shape. So, that change in shape will correspond to some kind of an angular deformation and that will that is quantified by this shear strains here.

So, again like shear stress, the shear strain strains are also not independent. They are also related to each other and the strain tensor is also symmetric. So, sigma 21 and sigma 12 are equal sigma, similarly sigma 31 and 13 are equal and 32 and 23 are equal. So, strain tensor is symmetric just as a stress tensor is symmetric and we have these three conditions. So, again only three shear strain components are independent and overall we have only six independent strain components so, the strain tensor only a six independent components.

So, now that we have some idea about the stress and strain and the different components that are necessary to describe stress at a point of strain at a point inside body, we can move ahead now and talk about the relationship between the stress and strain ok. So, if there is a certain kind of external force applied resulting in certain stress in the material what kind of strain correspondingly will be produced and so on.

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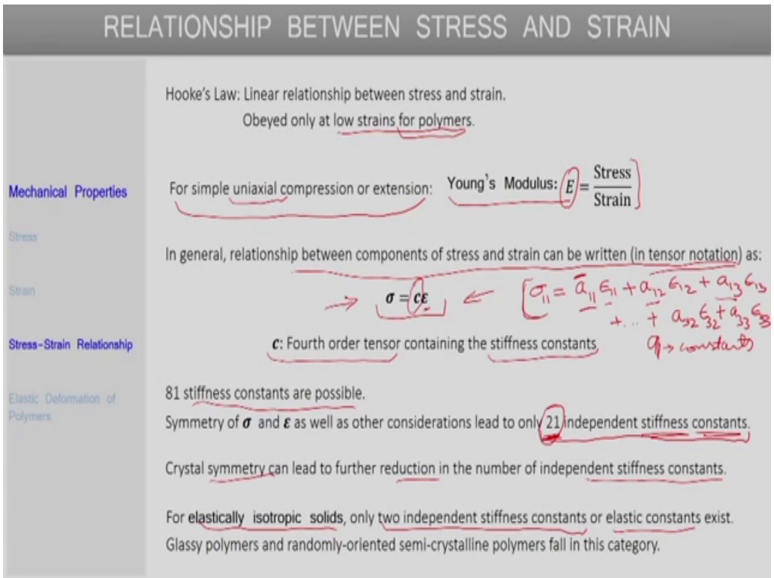

So, a very simple kind of relationship between stress and strain is something that most of you would have come across even in high school physics and that is what is referred to as the Hooke's law. So, Hooke's law is a linear relationship between the stress and strain. So, on the application of a certain force on a given body will which produce a certain amount of stress a proportional amount of strain is produced a that is what this Hooke's law predicts for elastic materials.

And what is observed is that for many materials is this kind of a law this linear relationship or a direct proportionality between stress and strain is found to be valid provided that the amount of strain produced is small. So, for small strains this kind of Hooke's law is obeyed by many different materials including many different polymers as well..

However, if the strains are large then deviation from Hooke's law and deviation from this elastic kind of a behavior is commonly observed. For low strains we can say that for many polymers this kind of Hooke's law behavior or a linear relationship between stress and strain will be observed.

So, if we are again talk about a by simple kind of deformation where we have a uniaxial tension or compression. So, uniaxial means in one direction, and again if we consider a this rod then, then tensile is the force will be would be something that pulls it is this rod, whereas, the compressive force will be something that pushes on this rod, but this extension or compression that we are talking about is only uniaxial so only in one direction.

So, if we have such a case then the Young's modulus can be defined as the proportionality constant between stress and strain. So, if Hooke's law is valid and if we are talking about the uniaxial kind of deformation either extension or compression, then the stress is equal to the Young's modulus times the strain. In other words the Young's modulus's defined as the ratio of stress by strain stress and strain, of course within the limits of the validity Hooke's law this Young's modulus will have a constant value.

So, now we have talked about the way again a very simple case where we are only we have only discussed a uniaxial kind of deformation. In general, again we can have a deformation which can have many different components; so we can have deformation in different directions including both normal stresses as well as shear stresses. So, we can have a shearing shear stress action that can change the shape as well as we can have a normal stresses that can change the linear dimensions.

So, all these together when consider in combination for such a general case this simple kind of example that we have shown here will not work, and more generalized version of Hooke's law is needed. In general, the relationship between stress and strain components in tensor notation is written like this. So, this stress tensor is related to the strain tensor through another quantity C which itself is a tensor in this C is actually a fourth order tensor. And it can it contains all the stiffness constants that relate the stress components through the strain components.

So, such kind of description is commonly referred to a generalized Hooke's law because, in now we have considered all the kinds of deformation and the corresponding relation between all the stress components and strain components. So, here what is assumed is that all the stress components actually are functions linear functions of all the strain components are represent.

So, if we talk about sigma 11, one can say that it will be related to strain component epsilon 11 by some quantity a 11 which will be a corresponding stiffness constant. And it, but it would not just be related to this single strain component it will also be related to other strain components. So, a 12 epsilon 12 plus a 13 epsilon 13 and so on and so forth all the way up to a let us say a 32 epsilon 32 plus a 33 epsilon 33.

So, we will see that there are actually for the description of this single stress component terms of all the strain components their costed correspondingly 12 3 and if you count all the items say they actually 9 such constants. So, there will be nine constants these 9 constants are the 9 what you call stiffness constants or elastic constants and similarly for sigma 12 as well as similarly the relationship with all the different strain components will be there including other stiffness constants.

So, for sigma 11 we have 9 such constants appearing first in the expression for sigma 12 also 9 different constants can appear in for sigma 13 again 9 different constants can appear, because we are assuming that all the stress components are linear functions of all the strain components present. So similarly if we go on in this way, we will see that actually 9 times 9 that is 81 different stiffness constants or elastic constants are possible in this generalized Hooke's law kind of description of stress and strain relationship.

So, 81 stiffness constants are possible, but it turns out that we have seen that sigma and epsilon are actually symmetric tensors. So, the symmetry conditions actually reduced a number of stress stiffness constants that are independent to only 36 and then some further considerations are there which actually reduce a number of these stiffness constants to 21 independent constants.

So, ultimately if we take into account the fact that the stress and strain tensors are symmetric and the some other considerations then, it turns out that only 21 of the original 81 stiffness constants are independent. So this, 21 independent constants are other relevant part. Now depending on the specific to crystalline material that we are talking about the crystal structure that it has the symmetry of the crystal structure actually can further reduce the number of independent elastic or stiffness constants.

So, crystal symmetry can further reduce the number of stiffness constants. And for example, if you are talking about the cubic crystal system then, the symmetry of this cubic crystal system results in having results, in the fact that only three independent stiffness constants or elastic constants are present all the others are basically dependent on these three independent constants.

So, for a cubic crystal system only three independent elastic constants are there, for a another kind of crystal system which is not as symmetric that is the orthorhombic crystal system. There 9 independent elastic constants are there. And there these 9 independent elastic or stiffness constants are required to describe the elastic behavior of such orthorhombic crystals.

So, again depending on what kind of crystal system we have in how much symmetry it has the number of elastic constants actually goes further down, the another special case is if we have a material which is isotropic elastically. So, when we say isotropic elastically where we what is the mean is that in terms of the elastic properties a material is isotropic that is a elastic properties of the material are direction independent. The different elastic properties of the material do not depend on the direction in which the property is being measured.

So, if you have such isotropic elastic solids then that case only two independent stiffness constants or elastic constants actually exist all the others are dependent on these two. So, we when this isotropic it is a material which whose properties do not depend on the direction in which the property is being measured.

So, some examples of polymer systems which can be considered kind of a elastically isotropic is a glassy polymers as well as a semi crystalline polymers. So, semi crystalline polymers also to some extent can be considered as isotropic, because of course the amorphous matrix in that material will be a kind of isotropic material. And we can think of the crystalline domains as just randomly and regularly distributed in this amorphous matrix in the semi crystalline polymer. And overall we can think of this material as being kind of elastically isotropic as well.

So, glassy polymers are semi crystalline polymers can be thought of as isotropic elastic materials. And when we say glassy it is important to note that glassy is still a completely amorphous material it does not have any order of crystallinity.

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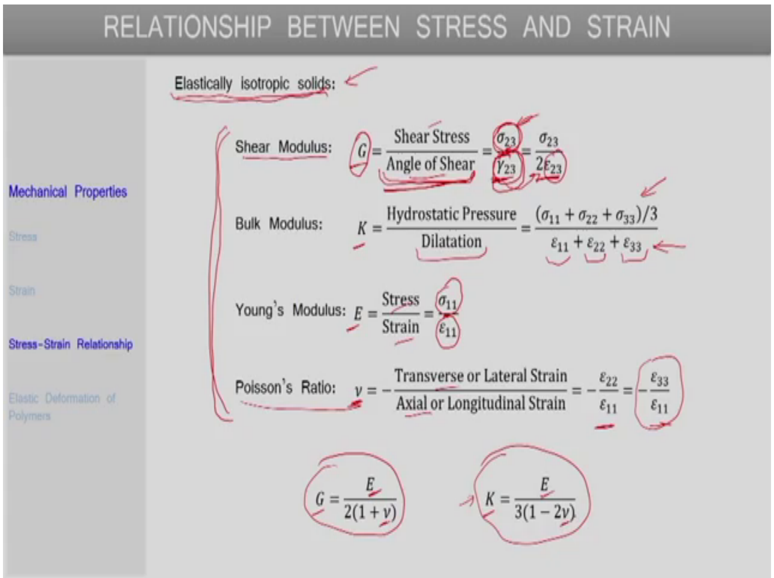

Now if he focused specifically on elastically isotropic solids. So, let us first define a few quantities which character is a mechanical properties of materials. And then we will try to relate or will discuss the relationship between these quantities that is valid for elastically isotropic solids. So, the first continue that will define is what is called the shear modulus of a material and the shear modulus is defined as the linear kind of proportionality constant between the shear stress acting and the corresponding what is call shear strain that is produced. So, specifically the ratio is between shear stress and what is called the angle of shear so, as we discussed this a shear kind of deformations are actually angular deformation.

So, if you have a surface if it is been sheared it will be angularly deformed in a way. So, this kind of angular deformation can also be quantified by what is called the angle of shear and represented by the symbol gamma here and this angle of shear is nothing, but 2 times the corresponding shear strain.

So, for a shear stress in the material represented by sigma 23; so sigma 23 will be a shear stress where the force is parallel to the force is parallel to let us axis x 3 that we have discussed earlier and the surface itself is also parallel to this axis actually what is a surface is perpendicular to axis x 2.

So, the corresponding shear stress due to this kind of a force and surface arrangement that is where the sigma 23 and corresponding shear strain is epsilon 23 and the angle of shear which will be just twice of this shear strain that is gamma 23. So, this ratio is how the shear modulus is defined, and of course then can have other kind of shear stresses also so, this is the only one component of shear stress we have actually three independent shear stresses.

So, their corresponding ratio the corresponding shear stress and the a corresponding angle of shear they will also constitute this shear modulus and since we have a elastically isotropic material. All these shear moduli measured using different components of the shear stresses they were they should come out to be equal because, the material is isotropic.

So, in general this shear modulus is a shear stress by angle of shear where angle of shear is directly related to the shear strain by a factor of two. In many cases, where this instead of angle of shear the shear strain itself is considering this definition and there in such cases the shear strain that is defined is equivalent to the angle of shear that we have discussed here. Another kind of important mechanical property of a material is what is called the bulk modulus and it is represented typically by K and it is a ratio for the hydrostatic pressure and what is called dilatation.

So, dilatation is basically a change in volume or the fractional change in volume due to the action of this uniform surrounding pressure on the material. So, if we let us say have a body and we submerge it in a fade, then typically in a static case uniform hydrostatic pressure will be acting on this material on from all directions in a compressive way and that will tend to or try to compress the material and reduce its volume.

So, the pressure acting divided by the fractional change in volume that is produced that that is what this bulk modulus measures. And we have already discussed that the hydrostatic pressure is the average normal stress at a point. And these dilatation are the fractional change in volume that is in that can be given by just the sum of the all three normal strains produced.

So, this ratio is where the bulk are the bulk modulus is defined similarly, we have already discussed Young’s modulus. So, if a body is subjected to a uniaxial extension or compression then, the normal stress divided by the corresponding normal stress in the direction of extension that that is how the Young’s modulus is defined. So, it is a stress by strain and if let us say deform if we are deforming the body along the x 1 axis.

So, the corresponding normal stress is sigma 11 and the normal strain or tensile strain is sigma epsilon 11 and their ratio corresponds to the Young's modulus one more important property is what is called a Poisson's ratio. So, Poisson's ratio this is represented by a nu and it is defined as the ratio of the lateral or transverse strain produced by the way by the longitudinal or axial strain produced.

So, in general case if again we consider this as kind of a rod and if you are pulling it down, then some longitudinal or axial strain will be produced in the this direction and direction of the force that is acting, but that can also lead to transverse strain produced in a perpendicular plane ok. So, the longitudinal or axial strain will be produced like this, but the corresponding transverse or lateral strain in a perpendicular plane is can also be produced. So, the ratio of this lateral to longitudinal strain that is what this Poisson's ratio is a measure of.

And if we have a longitudinal strain which is positive. So, in the case of tensile stress in that case usually the transverse strain will be negative. And on the other hand if the longitudinal strain is compressive then usually the transverse strain will be positive. So, there is a minus sign here and in most of the cases the sign of the transverse and axial strains are opposite. So, Poisson's ratio many times is positive.

So, these are some of the important mechanical properties which are related to the stress and behavior of a material and for elastically isotropic solids as we have discussed there are only two a independent stiffness or elastic constants. So, using that condition what it can be shown that these four properties are actually related to each other.

So, will not going to the derivation of those relations, but we will just write down the relationship between these properties that is valid for isotropic elastic solids where only two independent stiffness constants are present. So, the relationship between the shear modulus and the Young's modulus is through this expression where the Possion's ratio appears here.

The relationship between the bulk modulus and Young's modulus also is through this relation expression and here Poisson's ratio again appears here. So, these are some of the important a mechanical properties of a material related to the stress strain behavior and we see that for elastic isotropic solids. These properties are actually are not independent, but are interrelated. And we have also discussed that certain kind of polymers like glassy polymers or some semi crystalline polymers can be thought of as behaving like elastically isotropic. So, for such polymers such expressions I expected to hold.

Next, let us talk about the elastic response of these polymeric materials and different types of polymeric materials. So, when we say elastic the responsible elastic deformation when specifically talk about the elastic deformation of these polymeric materials; what we mean is how the stress and strain are related to basically.

So, basically a stress strain kind of a diagram where the strain measure is a measure of the deformation and stress is measure of the amount of force were being a subjected or applied on the polymeric material.

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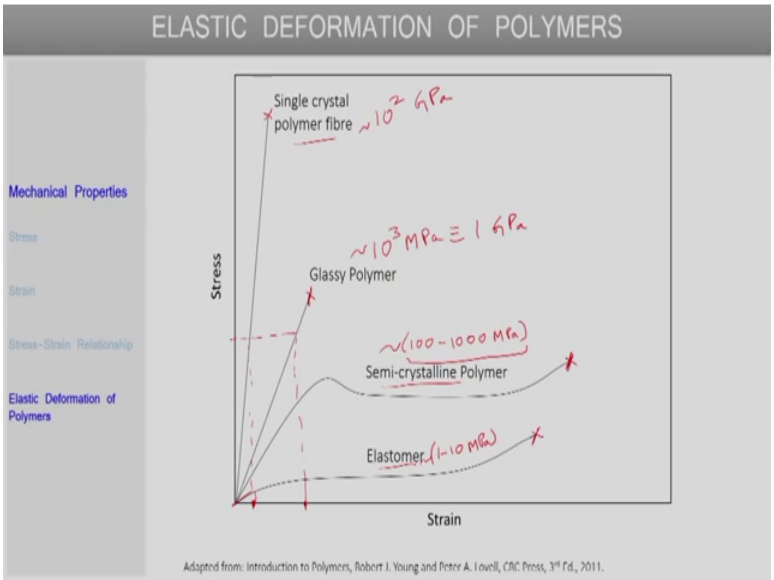

So, if we consider the first the case of what is called the single crystal polymer fibers. So, these are polymer fibers where the chains are highly oriented along the fiber axis ok. So, again if we can say this has a fiber the polymer chains are oriented along the fiber axis and the polymer chains are in a crystalline kind of arrangement. So, these are highly crystalline materials where the chain polymer chains are also highly oriented in one direction. So, because of the this strong chain orientation the axial direction this materials show the stress strain behavior where very large amount of stress only produces very small amount of strain.

So, the deformations produced for large amounts of forces are acting on it will still be very small for such materials. So, these materials typically will show the kind of behavior that is shown here and at high enough stresses they will exhibit failure which means that mechanical fracture of this material will take place if the applied stress exceeds a certain point. But, we will see that even at the failure point the amount of strain or elongation produced in the material is very small ok. So, these are very rigid kind of materials.

Next we can consider the case of glassy polymers. So, we have talked about to glassy polymers when we discussed a glass transition temperature in the amorphous phase of polymers. So, these glassy polymers are amorphous polymer structures which are rigid because, the polymer chains are kind of trapped in due to the absence of enough free volume and the polymer chains are mostly immobile and this leads to a kind of hard regent kind of these glassy polymers. So, this glassy polymers again show a behavior where the stress large amounts of stress a also do not produce significant amount of strain, but compared to this single crystal polymer fibers the corresponding strain produced for a given stress is higher as we can see here.

So, if we consider a particular value of stress the strain produced in this polymer fiber is here whereas, the strain produced in the glassy polymer is here. So, we see the larger amount of strain is produced but still these middles are quite rigid. And if enough stress is applied ultimately the material will fail or exhibit mechanical fracture.

Another kind the class of important polymeric materials has semi crystalline polymers. So, we have discussed the fact that most of the polymers or most of polymers in use can be thought of a semi crystalline polymers where which have different degrees of crystallinity and the polymer itself consists of amorphous phase along with the crystalline phase present together.

So, first semi crystalline polymers the stress strain behavior actually is a bit different and initially if we see there is a linear kind of stress strain relationship. But beyond a certain amount of stress the linear stress in relationship does not hold and the elastic instead of an elastic kind of deformation we see a inelastic or plastic kind of deformation of the material.

And material can another long elongations and ultimately might exhibit failure at high enough strains although the stress is address the failure is exhibited need not be very high ok. So, another important class of polymers is elastomers which are this rubbery polymers could be cross linked kind of polymers, and these polymers are captures way fact that they show a large amount of reversible extensibility or reversible elongation.

So, here we see that even for small amount of stresses in the case of elastomer a very large strains can be produced and up to very high strain values are actually, if the external force is removed the material will revert back to it is original dimension. So, the elongation is reversible at work quite a large strain value.

But at again high enough stresses and correspondingly large enough strains the material will exhibit failure. So, typically in the stress strain curve that we have shown here, if we measure the slope of this curve side very small values of strain that slope will correspond to the Young's modulus of this material. So, typically for elastomers the Young's modulus is of the order of 1-10 mega Pascal.

So, we see that the initial slope is quite small and the Young's modulus also is quite small for elastomeric materials. For semi crystalline polymers the Young's modulus is typically in the range of 100-1000 MPa, where MPa is mega Pascal. So, 100 MPa is essentially one Giga Pascal.

Now, the depending on the whether the semi crystalline the amount of crystalline crystal phase present inside the semi crystalline polymer. As well as whether the amorphous phase is in a glassy kind of state or not these are the factors that will dictate exactly what will be the Young's modulus, but typically the range observed is of is between 100 and 1000 mega Pascal.

For glassy polymer the Young's modulus is generally high and it is of the order of 10 to power 3 mega Pascal which is equivalent to 1 Giga Pascal. For polymer fibers, we see that it the curve shows a very high slope or very small strains at even very high stresses so, here the Young's modulus is of the order of 10 to the power 2 Giga Pascals or 10 to the power 5 mega Pascals.

So, this is just the order it is not the exact value the values of Young's modulus lie in this order of magnitude. So, far crystal the further polymer single crystal fibers an important thing to note is that although we have written the Young's modulus to be of the other 100 100's of Giga Pascals, but that is valid only in the longitudinal direction or in the fiber axis direction because, that is the action which the chains are oriented or aligned.

So, that is the direction which shows a high Young's modulus, but this polymer crystals this fibers are quite an isotropic and if one measures the transverse elastic modulus or the kind of Young's modulus in the direction perpendicular to the fiber axis. Then this transverse modulus values actually are much lower transverse modulus values are of the order of 1 Giga Pascal, whereas, the axial or longitudinal modulus as of the order of 100's of Giga Pascal.

So, due to the strong anisotropy moduli measured in different directions for polymer fibers are actually different. And finally, will just discuss the case of semi crystalline polymers in a bit more detail, because in many cases the polymeric material actually exists as a semi crystalline a polymer where both amorphous and crystalline phases are present.

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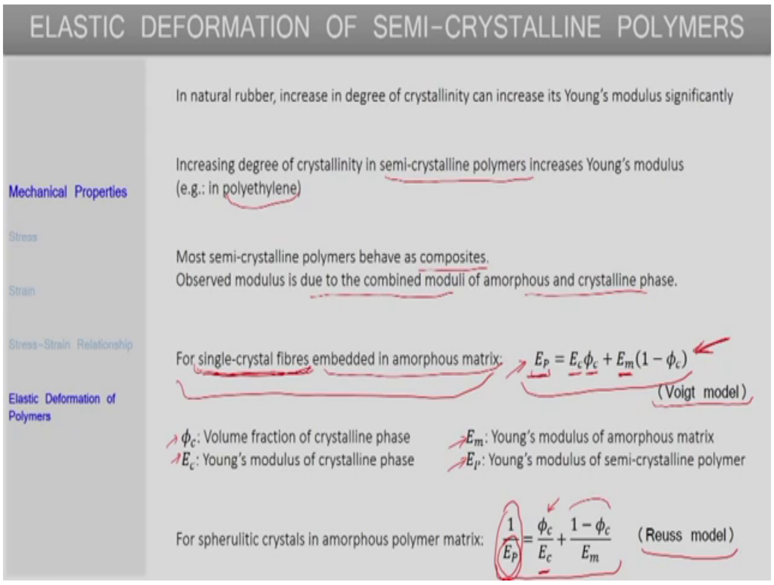

So, if we consider a few examples: so, in national level it has been observed that if we have a completely on alpha sample of natural rubber, it shows let us say Young's modulus of the order of one mega Pascal. But, if we if crystallization takes place and if the degree of crystallinity increases to let us say 20 or 25 percent in this natural rubber.

Then the Young's modulus has been shown has been seen to increase by as I as much as a 100 times.

So, this presence of crystalline phase in the polymer actually can lead to significant change in the elastic properties, especially the Young's modulus. And another example would be as order as a semi crystalline polymers like polyethylene where, clearly the increase in the degree of crystallinity in the material has been seen to a lead to an increase in the Young's modulus of the material.

So, what we can infer from these observations is that the elastic property is or elastic behavior of this polymeric semi crystalline polymeric materials actually depends on the, stronger depends on the degree of crystallinity in the material as well. Normally, the overall elastic property of the material, let us say the Young's modulus of the material that will be a reflection of both the elastic modulus of the amorphous phase and the elastic modulus of the crystalline phase in the semi crystalline polymer.

Semi crystalline polymer can be thought of as behaving as composites where both the crystalline and amorphous phases they contribute to the elastic overall elastic modulus of the material. But the way in which the in individual elastic moduli of the amorphous and the crystalline phases combine to produce the overall elastic modulus of the material, that usually is something that that is not known and it that is not something which can be readily a predicted.

So, that is a challenge so, the overall modulus is a combined moduli of both the phases, but how these two combine that is something which is not known for most of the materials. If we talk about few specific cases, because if you have a semi crystalline polymer then depending on the size of the crystalline phases present the also the shape of the crystal phases present and other factors the individual behavior can vary significantly.

So, what we will do is just focus on a couple of specific cases and try to see, try to discuss a couple of equations that to some extent can model the Young's modulus behavior of this semi crystalline polymers. So, if you are talking about system where we have five the crystalline phase exists as a semi a single crystal fibers and it is embedded in an amorphous matrix.

So, if you are considering a case where the crystalline phase exists as a in the fiber kind of morphology and it is assumed to be embedded in the polymer matrix which is a otherwise amorphous. So, for such a case the Young's modulus of the semi crystalline polymer E p that can be related to the Young's modulus of the crystalline part and the Young's modulus of the amorphous matrix, as well as the volume fraction of crystalline part by what is called this Voigt model? So, this Voigt model can be used to relate or estimate the Young's modulus of semi crystalline polymers of this kind of a morphology. So, as we have discussed the symbols have the corresponding meaning so, just written here.

And this kind of model can be thought of as representing a case where we have a two components in our system. So, our semi crystalline polymer we consist of as having a crystalline component and an amorphous component. And in this Voigt model what is assumed is that when its subjected to a stress then the strain producing both the components is equal. So, for such a case an equation like this can be shown to be valid, but it must be mentioned that such equations can only approximately model this kind of semi crystalline polymeric morphology. And exact are very quantitative mash may need not may not be obtained.

Finally, if we it or consider a case where the crystalline phase exist as paralytic kind of domains. So, that is what we discussed in mostly in the previous lecture that in most of the cases and polymeric is crystallized from a melt spherulitic kinds of crystalline domains basically grow and impinge on each other.

So, if we have a case where the crystalline domains has spherulitic and of course, we have an amorphous polymer matrix as well and this crystalline domains are assumed to be embedded in this amorphous phase. So, that we have this two phase semi crystalline polymer then, this Reuss kind of model is something that that can gives some reasonable estimates of the Young's modulus of the semi crystalline polymer.

So, here we see that the reciprocal of the Young's modulus of a semi crystalline polymer is related to the volume fraction of the crystalline part by the Young's modulus of the crystalline part plus, this volume fraction of the amorphous part by Young's modulus of the amorphous matrix. These are some of the models which are not really that accurate, but which allows some kind of rough estimation of the Young’s modulus of semi crystalline polymers.

So, in today‘s class what we have done is just gone through some fundamental concepts related to mechanical properties and then we have briefly discussed the mechanical properties and the elastic deformation behavior of polymeric materials. In the next week the material that will cover we in that material will draw upon some of the concepts that we have discussed today.

And we will specifically discuss some interesting mechanical behavior and flow behavior exhibited by a polymeric materials. So, we will talk about the visco visco elasticity, as well as the non Newtonian flow behavior of polymer solutions and melts that say. And we will also discuss the case of rubber elasticity which is exhibited by elastomers ok.

These some of the things that will be discussing in the next week, and hopefully the material that we have covered today will come in handy in understanding those concepts.

Thank you.