Physics of Functional Materials and Devices
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Lecture – 21, Week 5
Mechanical properties of solids

Welcome to the final lecture of week 5. Till now we have seen about solids, we have talked about their fabrications, then we have seen about phase transitions, we have seen the theory which are associated with phase transformations, then in the previous lecture we have seen the mechanism of diffusion and if there is diffusion then what happens we have seen diffusion in solids, we have seen in liquids and in gases. Let us move on and introduce the next concept which are associated with solids, that is stress and strain and because of this what type of deformations take place and finally what is the way of defining such deformations. Now what is the need of understanding such deformations. We have seen till now that you will not get ideal crystals or it is very very difficult to obtain ideal crystals. You will always have imperfections and because of these imperfections you do see some defects or deformations, but they are at the microscopic level that is you are seeing these imperfections at the atomic level or the molecular level at the lattice level, but is that defect similar to what will happen to a macroscopic level and if not then what are the ways of defining the effects which are deformations at macroscopic level which are quite evident and you can observe it.

So you can clearly see them and that have their own impact and during these fabrication of materials it is critical to understand such defects or deformations which can occur at the macroscopic level otherwise you will not be able to understand the modulations which are occurring in solids and when you go from one batch of material to the other they may have different electrical, mechanical, thermo mechanical or any other physical or chemical properties and then you do not understand why these materials are showing different properties even when they have the same molecular unit that is leading to that material. So, these kinds of properties are extremely important and you must understand these properties. So, if you have a material there are various ways in which load can be applied on it that can be tension, compression or shear. So, you have tension or the second set showing compression and the third set showing shear.

What is tension? It is the positive linear strain on the application of tensile stress. So, you have force which is leading to increase in the length. Compression, what is happening? It is a negative linear strain on the application of compressive stress. So, you are seeing negative coefficient of expansion. So, you are seeing decrease in the length rather than seeing increase in the length.

So, what is happening in compression? When you apply a force you have seen decrease in length rather than seeing a stretch which was seen in tension you are seeing compressive forces and then rather than applying a force in the upward direction or the downward direction leading to elongation or compression now you have a shear stress. So, you apply in a tangential direction. So, what will what is happening you are applying a force on the body in the tangential direction and then you are seeing certain deformation in the shape of the body because you are applying the force in the tangential direction. So, when a force is applied to such solids then it will lead to deformation. This is what we have seen.

The body will change the shape. When the shape changes obviously the associated size will also change. But by the concept of inertia a restoring force of equal magnitude and opposite in direction to the applied force will develop. This force per unit area is known as an engineering stress. But this is nowadays only referred to as stress.

So, stress given as σ is force per unit area and F is the load applied perpendicular to the cross sectional area A and the SI unit would be therefore Newton per meter square or Pascal. In the figure which was shown in the previous slide that is slide 4 you had seen the example that the material under a compressive or tensile stress is going to undergo longitudinal strain. The strain can be positive or negative. So, you can have either negative that is you can reduce the length of the body or you can increase the length of the body. The corresponding strain because of the applied stress is given by $\frac{\Delta L}{L_0}$ where L_0 is the original length and ΔL is the change in length.

So, you can have negative value or you can have positive value depending upon the compressive or tensile stresses respectively that are being applied. If two or equal opposite forces are applied parallel to the cross section area of a cylinder which we had seen in slide 4 then what will happen there would be opposite phases of the cylinder that will undergo relative displacement. The force that develops per unit area to restore the original shape of the cylinder which was getting deformed due to the applied tangential force is written as tangential or shearing stress. So, the shear stress is force by area, F/A_0, where F represents the load or force applied and A_0 is the surface area. So, now you are talking about in terms of surface area.

To the applied shear stress the object develops a shear strain. It is determined as the ratio of the length of the displacement of the original length of the object forming the strain angle delta which was shown earlier. So, you had the angle theta. So, because of this applied shear stress the object will develop a shear strain. We had seen that there would be a strain angle theta that will develop and because of this theta you will be then defining shear strain gamma as $\Delta x/L$ that is given by $\tan\theta$.

So, if θ is small then $\tan\theta$ is approximately equal to θ. So, you can immediately find out what is the magnitude of shear strain by just finding the change in the angle of the body

which is initially forming a 90 degree with the substrate or the base on which it was placed. The magnitude of the applied stress influences the extent of deformation or strain experienced by a structure. If you have less stress on the body then you will find the extent of deformation is much lower and if you increase the stress then the deformations would be much larger. There is no difficulty in understanding that.

In the case of minor levels of stress there exists a proportional relationship between stress and strain which can be expressed as:

$$\sigma = E\varepsilon$$

This is known as Hooke's law where **E** is the proportionality constant and this is the modulus of elasticity or also known as Young's modulus. Hooke's law fails if the stress increases beyond the elastic region that means the region beyond which if you pull the material further it cannot go back to its original shape. Below it the Hooke's law condition that is σ is equal to E into epsilon holds good. So, if you look into a typical stress strain curve then you have various regions. You have regions from 0 to A, A to B, B to C, D to E and these define the way you will be seeing deformation in solids.

So, if you have less than 1% of strain then you are in the proportional region. Then you have certain region where you go beyond and then you are in the region C to D you will move on and you will see significant deformation. So, what are these regions let us see into that and you will understand the stress strain curve more clearly. So, in the figure which we saw from point 0 to point A the slope of the curve gives the modulus of elasticity that is Hooke's law. So, $\sigma = E\varepsilon$ this is what we had seen and in this region from 0 to A you are seeing a elastic deformation that means if you take away the applied force the material regains this initial shape and size.

So, in this region Hooke's law is strictly followed and if you take the slope you will find that will give you the value of Young's modulus. If you go back and you have the region A to B then what is happening to A to B although the stress and strain are not proportional still the material is able to regain its original shape when you remove the load. Point B is known as the yield point that is the elastic limit and the stress is called the yield strength. So, remember when you go from A to B the material is able to regain its form but the change in strain and stress is not directly related by the Hooke's law and you see that you are going to see certain loss in proportionality but still the material is able to recover its original shape. You go on increasing the load and you apply a load which takes you beyond point B that is the value at which you have the yield point.

The stress exceeds the yield strength then what happens strain changes rapidly even for a slight change in stress. So, what is happening the material does not regain its original shape and it deforms and it goes to a new shape and this is then known as plastic deformation. So, you have actually forced the material to go to a new shape just by applying load and

you have gone beyond the yield point and you have lost the relationship being given by Hooke's law. If you go to point D then what happened this is the tensile strength of the material. Beyond this point any extra strain generated by the stress causes the material to fracture.

So, you actually disintegrate the whole material you can have material which can crack which can crumble or you will have a new kind of material all formed and that is not what you want. So, what you need if you want to have a material with desired properties you should be working within the limit where Hooke's law is maintained or if you still want to take it further try to be in the range where you have the performance that when you take away the load material regains its shape that means you can go from 0 to the point where you have the yield strength. Poisson ratio is actually the way you define the relationship between the extensions or elongations in various directions. So, this is a measure as to how the material responds to deformation in one direction when it is subjected to strain in the other direction. In simple terms it describes the tendency of a material to expand or contract when it is being stretched or compressed.

So, if you stretch a material in one direction then the in the other direction it will contract and if you apply load from the top the material tends to expand in the x direction that is what it means. So, when you apply in one direction the load what happens on the other direction this is defined by the Poisson ratio. Poisson ratio is defined as $-\varepsilon_x/\varepsilon_z$ which is equal to $-\varepsilon_y/\varepsilon_z$ where $\varepsilon_x \; and \; \varepsilon_z$ are of opposite sign therefore you have the negative sign coming into picture. Why? Because if you elongate in one direction you are compressing in other direction and that is why in one direction if you are seeing elongation the other direction you are seeing compression So, the sign which you see here is coming because of the contrasting nature of force or strain which is developing in the two directions. If you write $-\varepsilon_z \; \varepsilon_x$ of length then what you will get? So, if you write ε_z So, if you write in terms you take the length and the breadth values So, if you write in terms of ε_z and ε_x you have ε_z equal to $\frac{\Delta L}{L_0}$ and ε_x equal to $\frac{\Delta W}{W_0}$.

One of them is positive the other is negative and hence the Poisson ratio is equal to $\varepsilon_x/\varepsilon_z$ with a negative sign. So, I hope you have understood the concept of Poisson ratio. If you are applying a stress which is uniaxial that means only in the z direction then if you also consider the case that the material is isotropic that means it behaves similarly in all the three directions then $\varepsilon_x = \varepsilon_y$ that would be equal to minus of nu epsilon z. Now let us consider a case of parallel piped fig shaped body the volume would be x y and z. Now this body is exposed to stresses and they are σ_x, σ_y and σ_z.

What will happen to the corresponding strain values that is epsilon x epsilon y and epsilon z respectively. The body experiences stress from all sides So, the total strain in the x direction would be epsilon x would be σx by e minus nu σ y by e minus σ z by e. Hence

you can write the expressions of epsilon x epsilon y or epsilon z in terms of Poisson ratio and σ y and z. So, you can get the same relationship which you were getting earlier what you were getting was σ equal to e into epsilon here also you get one term equals to e into epsilon So, that is why you will get the generalized Hooke's law. Now rather than taking in terms of lower nu talk in terms of pressure changes So, at a given temperature the volume change is negative producing a strain this is called as volumetric strain.

The ratio of the stress that is developed because of this strain is called the bulk modulus and is given by minus delta p by change in volume by volume So, minus delta p by delta v by v and the SI unit of bulk moduli is again Pascal and the reciprocal of bulk modulus is called compressibility and is denoted by small k and it is defined as fractional change in volume per unit increase in pressure. So, you have k is equal to 1 by v that is equal to minus 1 by delta p into delta v by v. What is happening here? What you see suppose a material and you is undergoing certain kind of evaluation as a function of temperature when you are heating this material the volume of the unit cell or the material itself will change you can have positive thermal expansion or you can have negative thermal expansion and because of that the value of V initial and V final will go on changing and if that changes what is happening the bulk modulus will change and if the bulk modulus changes the mechanical strength or the mechanical properties of the material will change and that is why you will find that as a function of temperature or pressure the properties of the materials change quite significantly because the modulus Young's modulus or even bulk modulus change significantly and you will now understand why when you have a material then each material has its own characteristics mechanical properties because it has its own shape the particle sizes are different the porosities are different the densities are different and because of that their capacity to react or respond to tensile compressive or shear forces are different and hence their mechanical properties are different because of tension compression or shear forces you have also seen today how do we define stress and because of the change in the applied force direction you will have appearance of strain and that leads to various kind of modifications in the body you can have plastic or elastic deformations as long as you are in the elastic deformation range if you remove the applied load the body will recover its original shape but if you go to plastic region then if you apply that force then the body will go to a new shape and cannot go back to its original shape and size and if you apply a longitudinal strain the lateral dimensions will also undergo small changes and the values are then defined by Poisson ratio and why materials have different Young's modulus or bulk modulus was also discussed and now you will understand the way you will make materials and how to change the mechanical properties of functional materials you can change their densities you can change their shape you can change their size and the mechanical properties would be different and if you do that what you can do you can make different types of mechanical sensors So, you can choose what type of sensing you require and based on that you can make different types of mechanical sensors these are the books which were used to prepare the lecture notes for today and you can read

them further to develop more understanding about the topics and with this we come to the lectures of week 5 and I will see you next week with the next sets of lectures. Thank you very much.