Properties of Materials (Nature and Properties of Materials: III)
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Lecture 19 - Microscopic Mechanism of Plastic Deformation

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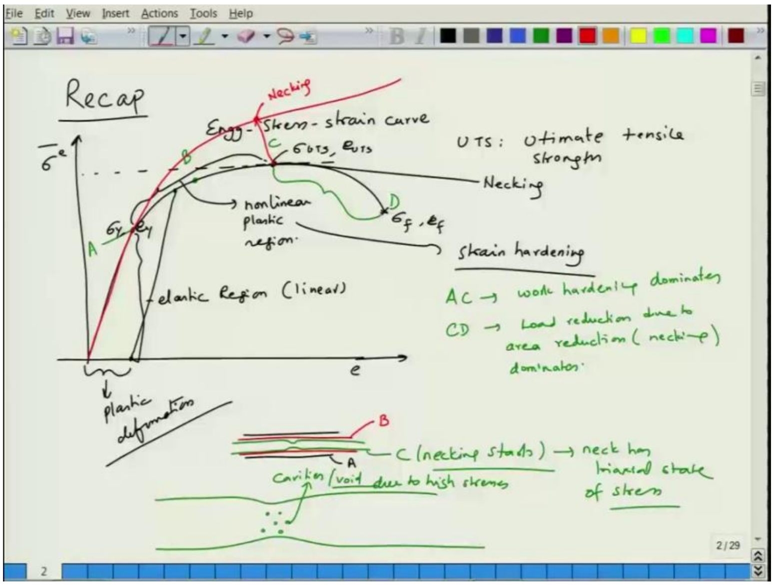

So, welcome to the new lecture of this course again, Properties of Materials. So, let us just briefly see what we did in the last class. So if we do a brief recap, we saw in the last class the, so stress-strain curve, and we saw what happens. So basically, we've been talking about it for a few lectures and basically, this is what is engineering stress-strain curve. And this curve shows few regions which are very clear in nature.

So up to this point, it shows the region which is elastic region, which is basically a linear region followed by a region, which is up to a point which is called as sigma UTS, which is ultimate tensile strength so UTS is ultimate tensile strength. So, there is a nonlinear increase in the stress, as a function of strain, this is nonlinear plastic region and then you have a point at which the stress is maximum. So, this is sigma Y this is sigma UTS followed by you have sigma fracture, okay and epsilon fracture. So, correspondingly, we will have epsilon Y and you will have epsilon UTS.

Now, so what happens in the elastic region, the sample gets elastically deformed, which is which means up to EY not epsilon sorry, so this should be EY, so up to EY this deformation will be recoverable. So, if you drop the load at any point below sigma Y, the sample will come back to its original dimensions. Beyond sigma Y or EY, we reach into a region which is plastic region where the deformation is permanent. So, if we drop a load at this point, you will get back at this point. So, this will be your plastic deformation.

So, the strain that is caused by plastic deformation is permanent in nature, it does, it cannot be recovered and this region is essentially a nonlinear region where strain hardening occurs. So, this is the region in which you have strain hardening. And then there comes a point at which the load is maximum, this point is called as ultimate tensile strength or maximum load point at which there is a phenomenon called as necking that occurs.

So, sample when you deform the sample, sample goes from this state to let us say this state, gets thinner and then somewhere after this it undergoes formation of a neck something like this. So, this black one you can say is A, the green one could be the point B. So, let us say this is point A, this is point B and then you are at point C. So, this sorry, the red one will be the point B and this will be point C, the green one. So, this is the point at which the neck starts to form and so this is where necking starts.

And when necking starts, basically that is where we start a region of let us say instability, the sample there is instability. And what happens at the necking is the area reduction at the center or the neck is far more, far higher than the other regions and the stress state in the neck is triaxial in nature, neck has triaxial state of stress so there is a non-uniform deformation in this region.

And after that what happens is that once the neck is formed, so, if you enlarge it in the neck region, you start forming these little voids, these are cavities or voids because of high stresses, because of due to high stresses. And these voids as you keep deforming, they grow in size, they merge into each other and finally, it leads to a fracture. So, in the region A to C, the strain hardening dominates over decrease in load due to reduction in area, and the region C let us say D, in the region CD, the decrease in the load as a due to reduction in area due to necking dominates over strain hardening.

So, there are two competing mechanisms which determine what will be the load at a particular point. So, within in AC the work hardening dominates and in CD, the load reduction due to area reduction and which is mainly determined by necking dominates. So, this is what we saw in the last class, last few lectures. And in contrast, if you plot the true stress-strain curve, true stress-strain curve will show a behaviour like this, where necking point, this point will be replicated somewhere here in this point, so, this will be necking.

So, we use engineering stress-strain curve, because you can see necking very explicitly in engineering stress-strain curve, but it is not very obvious in true stress-strain curve. So, that is why engineering stress-strain curve is more useful. And from the perspective of deformation, you do not go beyond the ultimate tensile strength or ultimate tensile strain you remain, you limit your deformation up to that point to prevent any cavitation or void formation in the sample. So, this is what we did in the last class. So, here we said that you have a triaxial state of stress.

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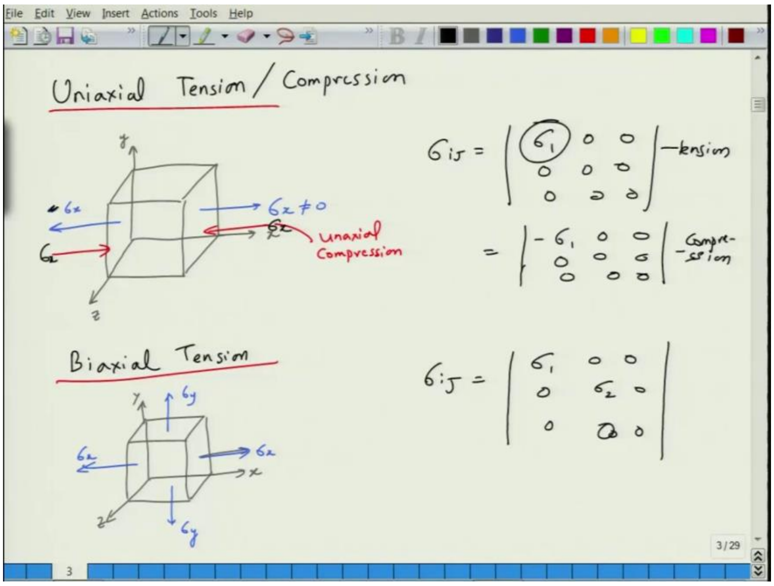

Let me just briefly explain what the state of stresses are so that you do not get confused. So, there are various states of stress so, you have uniaxial tension. So, uniaxial tension can be described by if you have a sample, let us say like if you have a cube like this, let us say this is x axis, this is y axis, this is z axis, then we say that along this direction sigma x is not equal to zero, okay.

So, we say that sigma i J can be written as sigma 1 in terms of principal stresses 0, 0, 0, 0, 0, 0. So, only one component is finite. This is the uniaxial tensile stress that we apply to the sample in the uniaxial testing. You can have biaxial tension and biaxial tension basically implies that you have a sample. So, the stress states, so this is x, this is y, this z, so, you have sigma x, sigma x, sigma y, sigma z is equal to 0. So, in terms of principal stresses you can write this as sigma i J is equal to sigma 1, 0, 0, 0, sigma 2, 0, 0, 0. So, this will be the stress tensor for….

Then we can write uniaxial. So, uniaxial compression on the other hand would be, so, if you have the stress like this, this will be uniaxial compression. So, for compression so this is for tension let us say if I just say compression, slash then for compression, I can write minus sigma 1, 0, 0, 0, 0, 0, and this will be the stress tensor for compression. Le us not remove, let us remove the sign as implicit, the moment you look at direction.

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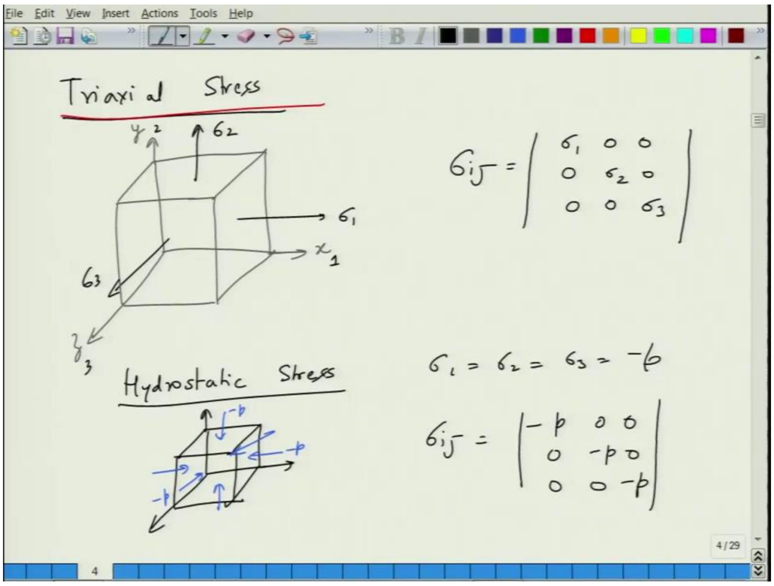

Now, the next case could be of, so what is, what do we mean by triaxial state of stresses, triaxial stress state is essentially you have, so what triaxial state of stress means you have sigma 1, sigma 2 and sigma 3. So, let us say this is 1, 2 and 3. So you can write the Sigma i J as sigma 1, 0, 0, 0, sigma 2, 0, sigma 3, this will be the triaxial state of stress.

There is analogue in terms of hydrostatic stress as well. So, if we write hydrostatic stress, in case of hydrostatic stress, sigma 1 is equal to sigma 2 is equal to sigma 3 is equal to minus P. So, essentially the sample is under compression from all the sides. So, basically we will have, so essentially, minus P, minus P, minus P, so we can write sigma i J here as minus P 0, 0, 0 minus P 0, 0, 0 minus P. These are the states of stress you can write. And then you have things like cylindrical stresses where sigma 1 and sigma 2 are equal, but they are not equal to sigma 3 and so on and so forth.

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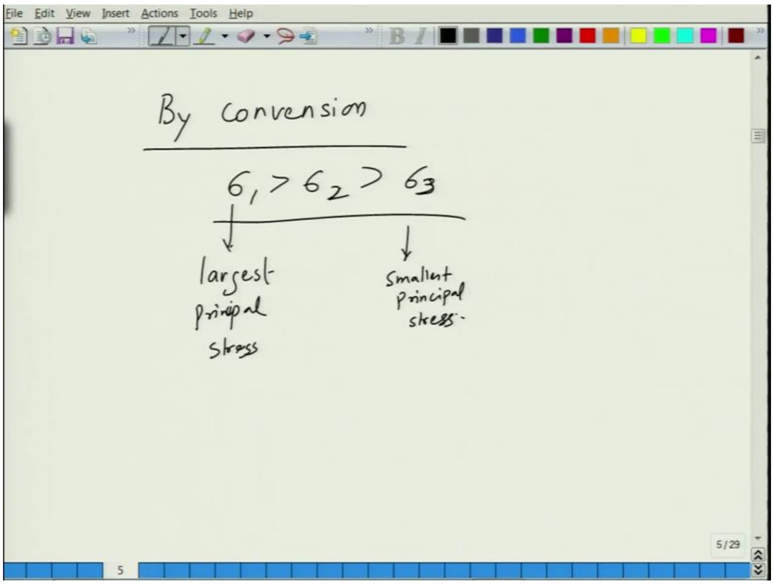

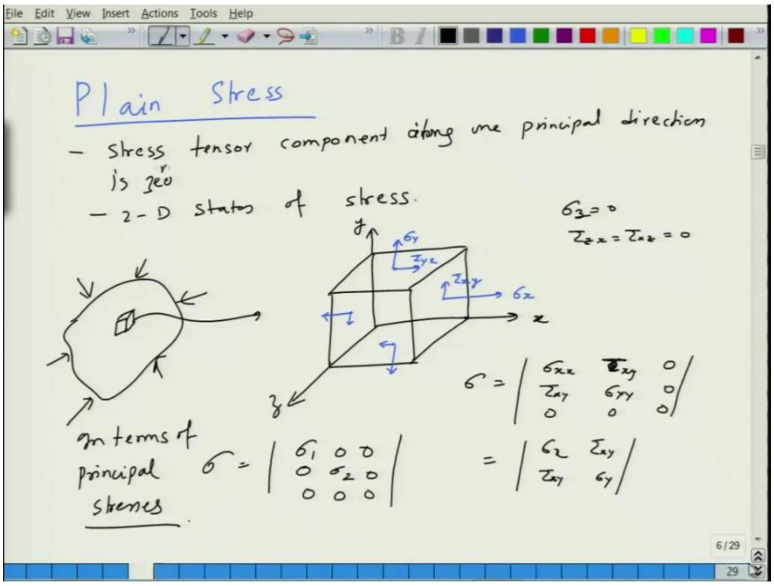

So, by convention, what we mean is that another thing that we notice is that by convention when we write these three stresses, principal stresses sigma 1, sigma 2 and sigma 3, by convention, we mean that sigma 1 is the largest stress, sigma 3 is the smallest stress, sigma 2 has intermediate value. So this is you can say largest principal stress, principal stress and this is smallest, okay. And then finally, there is another state of stress, which we probably did not look at was plane stress. We looked at it when we did the determination of relation between modulus. So here basically what we mean is that stress tensile component along one principal direction is 0.

So basically it is a two-dimensional state of stress. So, if you say, if you have let us say a plate, so this is a two-dimensional plane, that stresses are applied within the plane only. And if you take out a small element from it, and if you zoom it, this is how it will look like. So you have a cube. So, let us say this is x, this is y, this is z, so we have sigma x and then we have tau x, y, and we have sigma y and we have tau y, x. And similarly, you will have components along this as well.

And another thing that you notice sigma 3, sigma z is equal to 0 here, and tau z x is equal to tau x z that is also equal to 0. So, basically the stress tensor is written as sigma x x tau x y 0, tau x y, sigma y y 0, 0, 0, 0, so essentially you write the stress tensor in two by two matrix sigma x, tau x y, tau x y sigma y or if you write in terms of principal stresses, the principal stresses will be sigma 1, 0, 0, 0, sigma 2, 0, 0, 0 because in principal stresses the shear components are 0. So, this is in terms of principal. So, this is the stress states. We should have ideally discussed this in case of elastic deformation, but just to introduce that states of stresses.

Alright, so this is what it is in terms of plastic deformation that you have formation of a neck at UTS, sample undergoes non-uniform deformation, there is a cavitation at the UTS point and those cavities as you stretch the material further, those cavities coalesce or merge into each other forming a bigger cavity which sort of leads to rupture the material at 45 degree roughly to the tensile axis.

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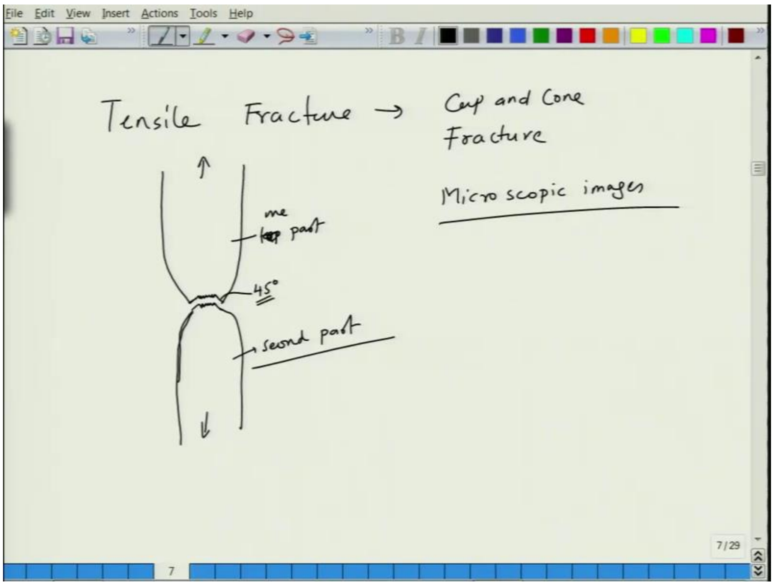

So, this fracture which it leads to basically, so tensile fracture leads to what we call as cup and cone kind of fracture. So, what we basically will have is sample will show sort of facets and this top part will be something which will fit in directly there. So, this is the top part or one part, this is the second part. So we can see the microscopic images of fracture, we will see them in the next class. So this is how tensile fracture will be. It is a cup and cone kind of fracture, so this is the tensile axis, these are the 45 degree facets, which are created at the neck. And it is a very rough fracture in morphology.

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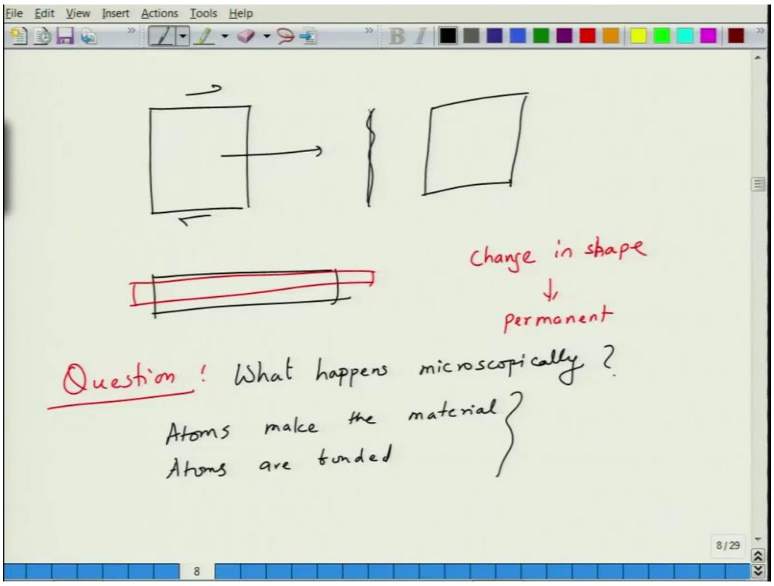

Now, let us ask a question that we see that you know, when you deform the material, there is elongation, there is increase in stress and so on and so forth. Question is, and there is a change in shape. So if you start from this shape, let us say and if you apply stresses, it may deform in this fashion, let us say something like this, okay? So, they could be change in shapes. So, for example, this can become, this become that. So, basically you have change in shape that is permanent. So, the question we ask is what happens microscopically. So, within the material because material is made up of atoms….So, atoms make the material, atoms are bonded. So, what happens, what are the internal mechanisms which actually lead to the plastic deformation?

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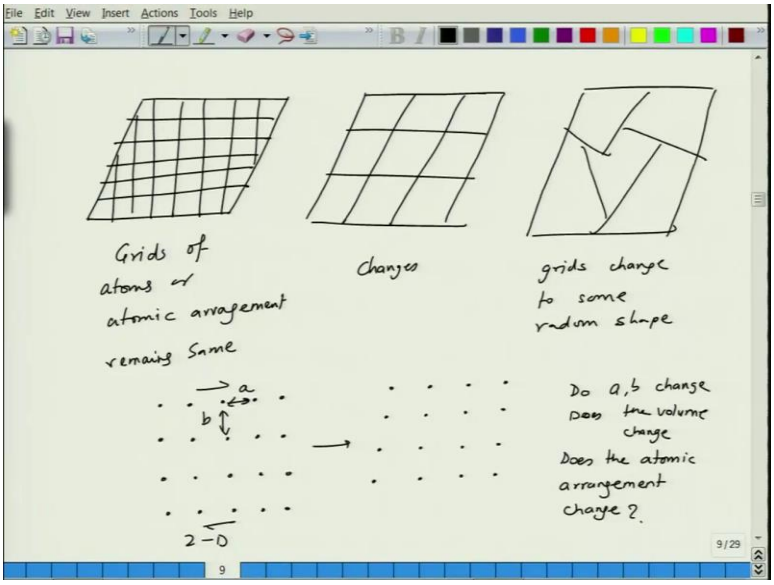

So that is our next goal. So when we deform the material plastically, what happens internally? So for example, you can have, let us say, if you deform the material to this shape, is it possible that you may have situation like this? Let us say we had these grids, atomic grids that represent earlier, will remain the same as they were earlier, or they become bigger or smaller. So let us say grids of atoms or atomic arrangement remains same, changes let us say gets bigger here, or does it become, all these grids become at sudden random angle. So grids change to some random shape.

Because from our Structures of Materials course, we have seen that atoms let us say adopt a structure adopt a uniform structure like this, let us say this is a two-dimensional grid of atoms. So, this is a two-dimensional grid of atoms. When you apply stress to it, let us say you apply a shear stress. So, one way is it may become like this. So, here we can see the, we have changed a dimension or is it that does this side become longer, this side becomes shorter? So do, let us say this is A and B, do A, B change?

Does the volume change, does the atomic arrangement change? So, these are the questions that we ask.

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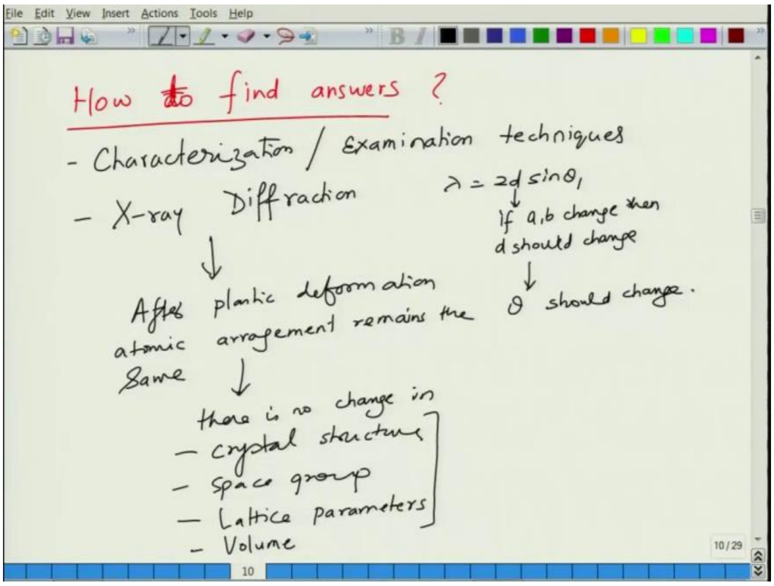

And how do we find the answers? The answers, how to find answers? So, basically, we use what we call as characterization techniques, characterization or examination techniques, which can examine the material at atomic level. So, what are the techniques? For example, one technique that we learnt is X-ray diffraction. So, X-ray diffraction is nothing but lambda is equal 2d sin theta. So, let us say you have a peak for a given material at certain value theta 1 for certain d spacing. If you are changing the atomic lattice parameter which means that if A, B change then d should change, which means theta should change.

So, when we do X-ray diffraction, we find that after plastic deformation, atomic arrangement remains the same, there is no change in crystal structure, space group and lattice parameters maybe slight change, but there is no appreciable change in the lattice parameters. So, basically, there is no change in the internal crystal structure, but there is a change in shape there is no change in volume as well. So, that is volume remains the constant. So, there is no change in lattice volume, there is no change in lattice parameter, there is no change in space group, there is no change in crystal structure.

So, the question is, what happens to the material? So, essentially, these are questions that we are going to answer in the next few lectures. So, what we see is that first the answers are…So, some of the clues are there is no change in crystal structure. There is no change in space group, there is no change lattice parameter, there is no change in volume.

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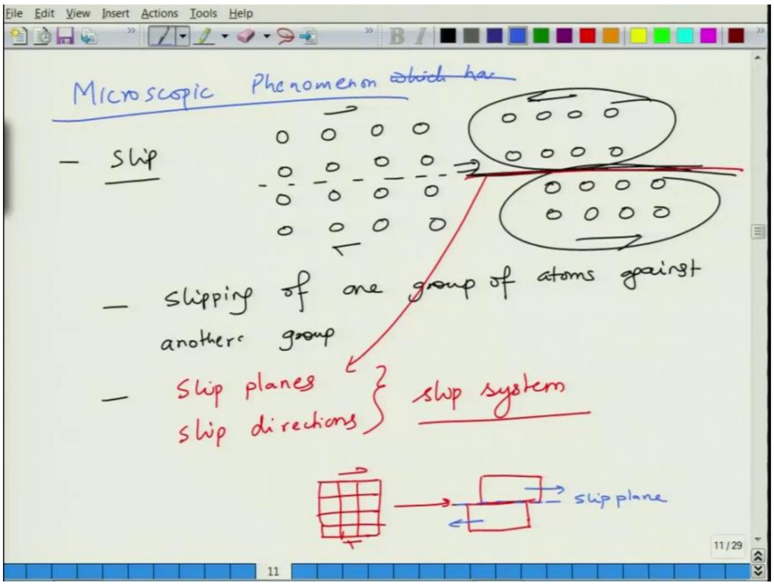

So, there are two microscopic phenomena. So, which have been, so the first is slip. So essentially, you have atom, series of atoms let us say, you have a material with ordered array of atoms. Pardon me for a little bit of changes there. Let me just probably make it a little better. So, this is here, alright. And when we apply stress, what happens is that this leads to the atom slip past each other. So without changing the crystal structure, the top part remains like this. Across this plane the bottom part becomes like this before it moves to sorry, let me draw the final position.

So, before so, then these atoms the bottom part moves with respect to top part by one step. So, this is the top part slipping against the bottom part. So, this side moves, so there is a relative movement in the direction of shear stress of one-half of the atomic plane with respect to other half. So, this is called a slip, slip of atoms against each other.

So, how does this phenomena of sleep happens, that we will see. So, basically, it is a slipping of one group of atoms against another group and this happens in a very coordinated manner. It does not happen on any plane, it happens across the plane. So, the planes across which the slip happens, sorry, the planes across which slip happens, these are called as slip planes. And it happens only along certain direction, it does not happen along every direction.

So, it happens along on certain slip planes and certain slip directions. So, we will, together they make what we call as slip system. So, for every given crystal structure, there is a specific set of planes and directions on which atoms tend to slip against each other. So, this is the phenomena of slip, okay, so, essentially if you have a, you have a bunch of, you have a crystal like this, let us say and when you apply shear stress, the top half of the crystal goes against bottom of the crystal against a certain plane, which is let us say the slip plane.

This is the slip plane, so this side has moved in this direction with respect to the top. So, there is relative movement of different parts of the crystals. This is slip, we will see the microscopic details a little later.

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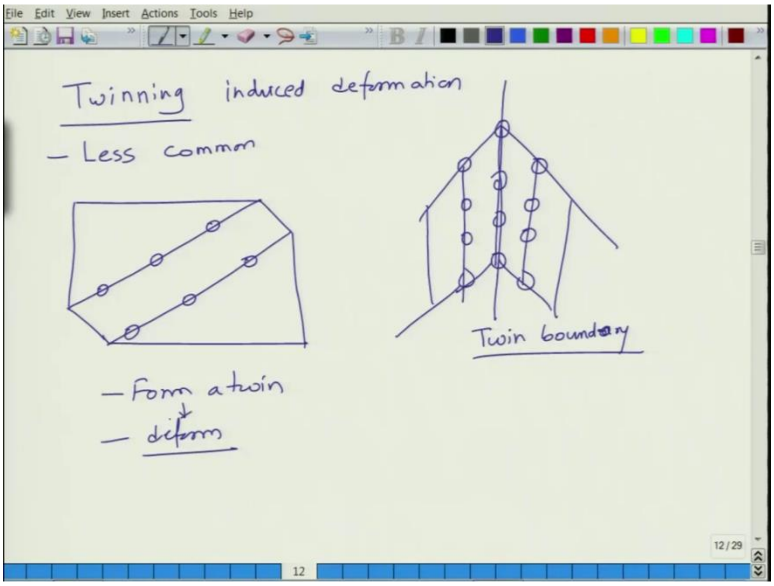

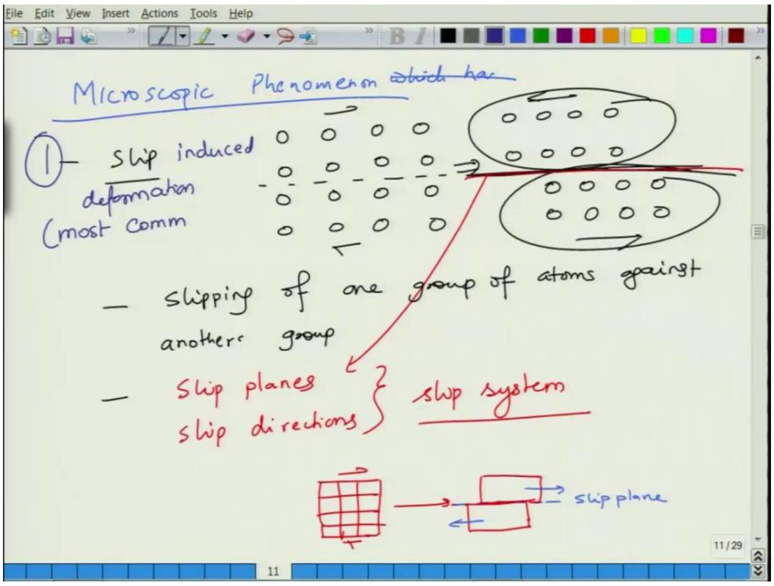

Second phenomena is called as twinning, twinning induced deformation. The first one is called as slip, this is the first one, slip induced deformation. This is the most common one. Most common, in by and large every case you have this.

The less common mechanism is twinning induced. And twinning induced what we have is, we have a slip of, we have a series of, okay. So, basically what we have is, we have a region in which this half, let us say this half they are identical to each other. And in between we have what we call as a twin. So, essentially or rather if you look at the twin boundary, let us say this is one plane of atoms, this is another plane of atoms. So if you draw the atoms in this fashion, so here, here, here, here, here, here, here, here, here, here, here, here, so this is the let us say twin boundary.

Because the orientation of crystals or grains is, regions is similar across this boundary. So basically, first you form a twin and then deform. So, again, there is no change in crystal structure of the material, there is no change in volume of crystal, all you form is twins and these twins lead to deformation in the material, but this is a very less common mode of deformation materials. In most materials, materials deform by a phenomena called a slip.

So, in the next lecture what we will do is that we will look at the microscopic details of slip, what are the planes along which the slip occurs, what are the directions along with the slip occur and what are the stresses which are required to carry out the slip on these slip planes and slip along the slip directions. So, we will stop here. We will do that in the next class. Thank you.