

**Mechanical Behavior of Materials-1**  
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**Lecture - 16**  
**Dislocations: Discovery**

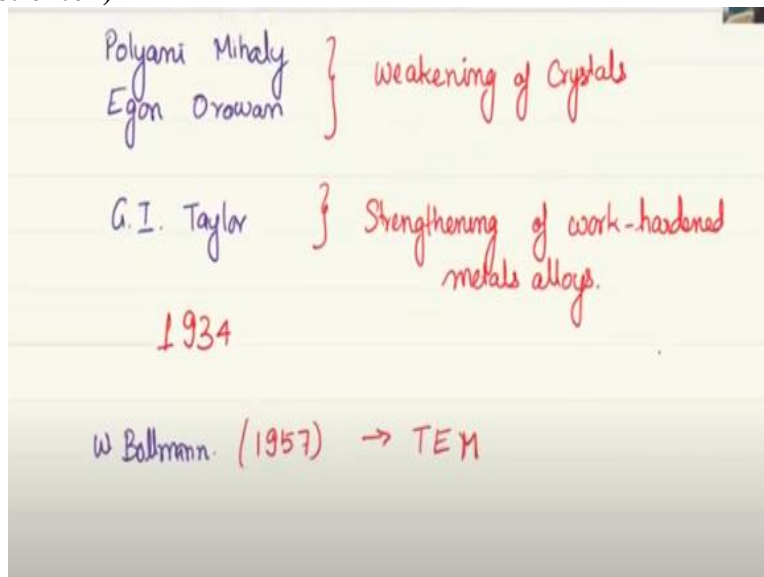
Welcome back students. So today we will be talking about dislocations. So we have seen so far that plastic deformation takes place in the material if you keep applying a higher and higher structures. However, this plastic deformation at first people thought happens by complete cleavage of bonds or between two different planes and there the planes slip apart on along each other.

However the experimental observations were very different. So what were these experimental observations? There were two main experimental observations and which were contradictory in nature. One is called a weakening of crystals and the other is called strengthening or work hardening of metals and alloys. So these two observations made people realize that the deformation does not take place like that.

And there must be some other mechanism operating. And as you would see, I will introduce some names who discovered or who hypothesized this concept of dislocations. And what is very intriguing is that they hypothesized in 1934 which itself was after quite some time of discussion in the scientific groups. And the real observation of dislocations was done much later. It was done in sometimes in 1950s, okay.

So with this small brief introduction, let us start our today's lecture. So like I said, there were different scientists who contributed to the discovery of dislocations. So who were these people? So let me, it will be very useful if you know the names.

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So the names are Polyani Mihaly, Egon Orowan. So these two work together and they primarily worked on the theory or trying to explain weakening of crystals. And then there was also G. I.

Taylor. We very well know, Taylor hardening or heard of this term Taylor hardening. So he worked on the other concept or trying to explain the other observed phenomenon which is strengthening or work hardening of metals.

We will explain those in couple of slides. So the first theory was about weakening of crystals and the second one was strengthening of work-hardened metals alloys. So this one like I said was done in the year 1934. And this itself happened after a lot of refinement, where people postulated the theory and then refined it, refined it further, until in 1934 we obtained what is now called as theory of dislocations.

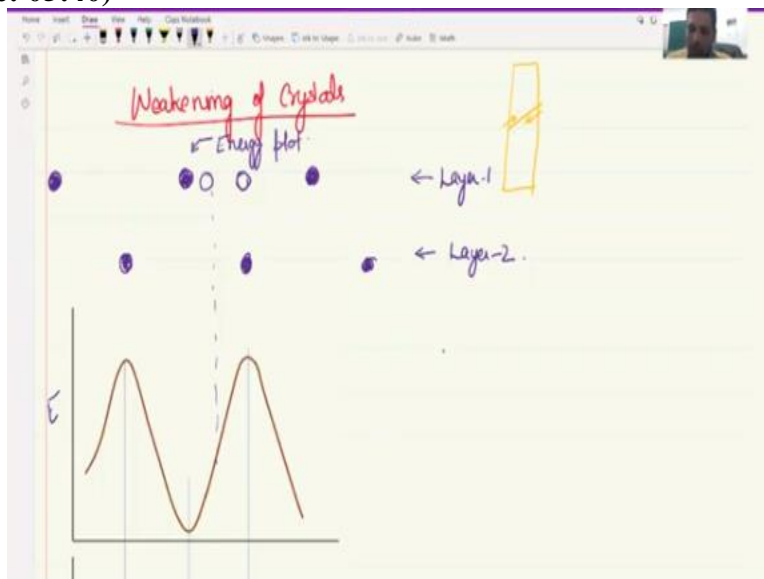
So here the theory was postulated in 1934. But the observation was made much later by Bollmann group of people particularly led by W. Bollmann and this was in the year 1957. They used TEM transmission electron microscopy to first observe dislocations. So you can look Google through the internet and for some dislocation videos and images which have been taken from PM.

And you would see that these dislocations appear like line and more like a very thin lines starting from 1.2 and ending at another point. And this is, this kind of observation is made in TEM. So what is the two theory that led people or two observation, actually this will also help you understand how the science works. So people made these observations and then they wanted to explain it.

And in the process they explained it using this phenomena or the this concept of dislocations, which was not observed until then, because technology or technology of TEM was not developed until then, which came up only in early 1950s. And once technology caught up then people were able to prove and show that yes indeed there is something like dislocations.

So overall, you can see this is also study about how science works. Okay, so now coming to what is the two theory that or two phenomena that people were trying to explain. So the first one is weakening of crystal.

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So let us say that you take a bar of single crystal metal, okay. Now earlier understanding was that when it is deforming, basically the whole plane is shearing against each other. And therefore, this whole bond, the atom, there will be atoms over here, and they are bonded with atoms on this side. So all the atoms must move with respect to each other. So if that is the theory, then let us look at how much stress would be required for the atoms to move.

So let us say that you have, so let me just push this figure a little bit lower, because I need to draw some atoms over here. Let us say we have two different layers shown over here. So this is one layer. So here will be another atom for this layer. And there is another layer over here. So this is in the center. In this layer the atoms are from the point of view where we are looking at this is in the center of these two atoms.

So this is layer 1 and this is layer 2. Now if we really think that the whole layer has to move, so it would mean that this layer of atoms must move across this, and therefore there is also one atom over here. So this one, let us say moves so this one if you look at now what will be the energy plot for this particular atom. So right now, this is the equilibrium position for this particular item. So let us draw this energy plot with respect to this particular atom.

So when it is in its equilibrium position that time it has the lowest energy. Now if I try to move it a little bit over here, so somewhere over here, its energy keeps on increasing. Now I bring it over here, it is somewhere in between these two atoms. So energy is highest, because this is the most unstable position.

And again, if you keep moving in this direction, then again when it comes back to this position, this is again a equilibrium position. And therefore it will be in equilibrium and the lowest energy state. Now if this is the energy plot, how would the force which is required to move the atoms along this particular plane would look like. So we know that force is basically the first derivative of energy. So we differentiate it and we will be able to get the energy plot and which is shown in over here.

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So this is force. And in both this plots, this is  $x$ . So now over here, if you look for the original position of the atom, where the energy is lowest, force is 0. Again when it comes back to this position, then again the force would be equal to 0. So these are the two force, the positions where the atom is in equilibrium, and hence over there, the force acting on it is 0 or force required is 0.

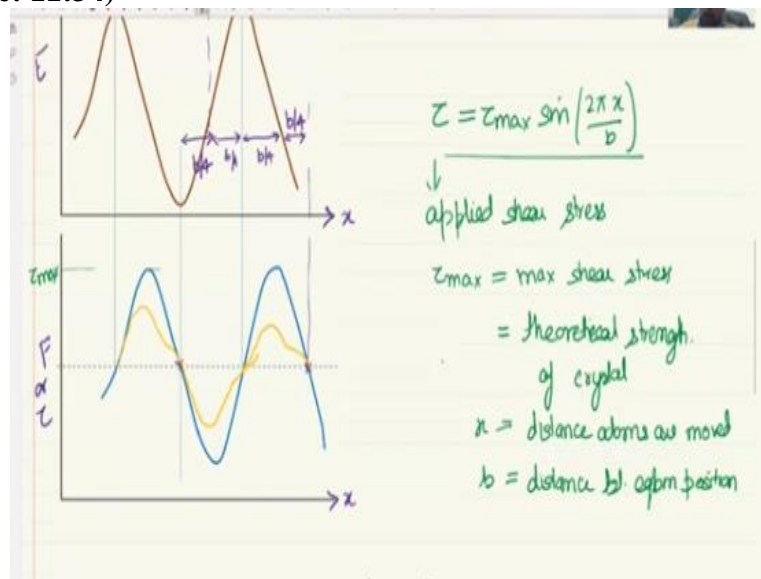
But if you want to move it from here to here, then there would be some force required. So let us say this direction, the force that is being applied is shown by negative. So in somewhere over here, when it reaches one about, so let us say that this whole length is  $b$ . So when it reaches  $b/4$  then the atom is over here. And it has the maximum amount of force required over here.

Now if you keep moving again towards this somewhere over here, so it has equal amount of pull from both the directions and therefore the force is again 0. But this is unstable equilibrium. If you push it a little bit on this side, the atom would move to this side. If you push it a little bit to this side, the atom will move to this particular position.

But as long as you are at this particular position, it is a, the total amount of force required is 0 and it is unstable equilibrium. And if you again keep moving it then the force is now acting on it on the other direction. And eventually it will go to a peak value. Again this will be at, with respect to this, this will be  $b/4$ . This is again  $b/4$ . And this position, which is the minima, energy minima over here this is again  $b/4$ .

So this is how the energy varies and this is how the force varies. And if we look at this force, this is also how the stress would act, which would mean that we can say that this is how force or shear stress  $\tau$  acts and therefore, we can write the equation for stress like this.

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$\tau$  equal to  $\tau_{max}$  because it is sinusoidal. So let us say this is the maximum, so this is

$$\tau = \tau_{max} \sin\left(\frac{2\pi x}{b}\right)$$

So  $b$  is the overall length and if you keep moving by the distance  $x$  therefore it varies like this  $\sin\left(\frac{2\pi x}{b}\right)$ .

This is the usable form for a sinusoidal wave where  $\tau$  is the applied shear stress,  $\tau_{max}$  is the max of the shear stress, maximum shear stress, which also means that if you are able to apply this much, minimum this much of stress, then you can keep moving the atoms or the planes away from or past each other and therefore you can cause deformation. So in other words, this also represents the theoretical strength of crystal.

$x$  is equal to distance atoms are moved and  $b$  is the distance between equilibrium positions.

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The image shows a handwritten derivation on a yellow background. It starts with the equation  $z = z_{max} \sin\left(\frac{2\pi x}{b}\right)$ . Below this, it states  $x \ll b$ . Then, it approximates the sine function:  $z \approx z_{max} \cdot \frac{2\pi x}{b} = z_{max} \cdot 2\pi \cdot \gamma$ , with a note " $\gamma \leftarrow$  shear strain". Next, it equates this to the shear stress definition:  $z = G \cdot \gamma = z_{max} \cdot 2\pi \cdot \gamma$ . From this, it derives  $z_{max} = \frac{G}{2\pi}$ . To the right, a note says "Using more exact expression," followed by  $\tau_{max} = \frac{G}{30}$ .

So this is the equation where we will start. This is our

$$\tau \cong \tau_{max} \frac{2\pi x}{b}$$

Now when we are doing the deformation, let us say at the very beginning the  $x$  would be very small and therefore, for  $x$  much less than  $b$  we can say that this equation can be approximated as  $\tau$ , sorry now it is no more  $\sin$ . We can directly say  $\frac{2\pi x}{b}$ . And over here  $x/b$  is nothing but shear strain.

So this becomes  $\tau_{max}$  times  $2\pi\gamma$ , which is the shear strain. But then we also know that  $\tau$  is given by  $G$  which is the shear modulus times  $\gamma$  and therefore we can equate these two equations and we have  $\tau_{max} 2\pi\gamma$ . Now the strain is same on both the side and basically it is the same quantity and therefore, we have a relation or an equation which defines the value of  $\tau_{max}$  which is equal to  $G/2\pi$ .

Now this is a very rough calculation, but we have obtained some value and if we had taken a more appropriate representation of energy and the shear stress, so for the more appropriate form of this curve as you would see in some books is like this. And therefore, there will be some variation and based on that also people have calculated what should be the maximum shear stress or theoretical strength.

And people have found that, using more realistic expression people have obtained that  $\tau_{max}$  is equal to  $G$  by 30, okay. So this should be your and this is approximately  $G$  by 6. So somewhere in  $G$  by 6 to  $G$  by 30 should be your shear strength of the material. Now let us compare it with how does it compare with experimental values.

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	$G/2\pi$ (MPa)	Exp Str. (MPa)
Aluminum	4200	0.7-0.8
Silver	4800	0.4-0.5
Copper	7700	0.5-3
Nickel	12000	3-5

Our assumed model of deformation is incorrect.

So for example aluminum, here let us write  $G$  by  $2\pi$  in mega Pascal and experimental strength. So the  $G/2\pi$  for aluminum should be 4200 mega Pascal. Meaning this is the amount of stress that you need to apply for the material to plastically deform or somewhere close to this, this will be the yield strength of the material. On the other hand, what is the yield strength that we obtain for a single crystal? For silver.

So we are talking about single crystal. So yield strength is not really a appropriate term here. It is the minimum critical shear stress required for deformation of the single crystal. For silver it should be 4800 and what we get is 0.4 to 0.5. So even if you take this as  $G/6$  as an exaggeration and you go for  $G/30$ , which would mean divided by 5, but still what we see that we are orders of magnitude away.

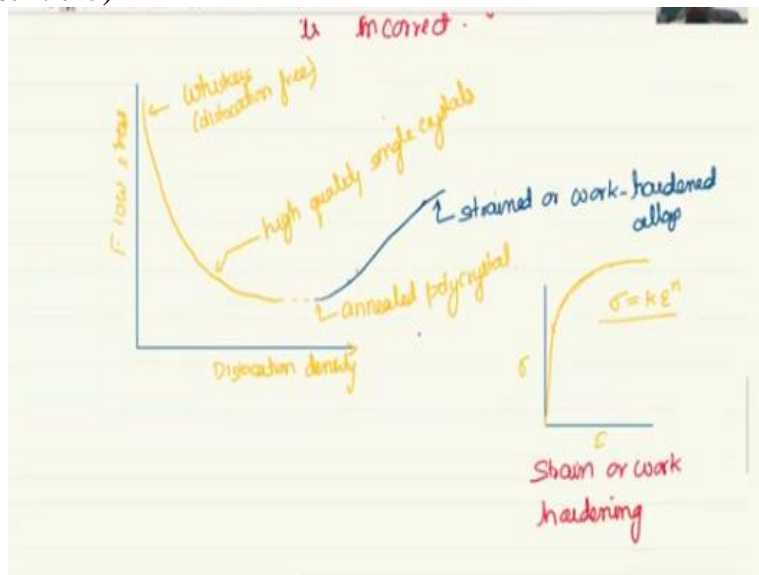
So this is the experimental strength and this is what theory predicts based on assuming that this is how the deformation is taking place by slipping of planes past each other, which clearly implies that our assumption is wrong. So which assumption is wrong? Most likely that is not how the deformation is taking place. This is not how the material is deforming. So just to further emphasize that, let me put some more examples here.

Copper 7700 should be the theoretical strength and what we get is 0.5 to 3. Even if you go for nickel which has much higher experimental strength, which is of the order of 3 to 5, but theoretical strength is even higher, 12,000. Meaning 12 Giga Pascal. Just imagine, if we had really materials like this, it would have been really good from some point of view.

But then you would also realize later on when you understand the importance of dislocation, that it would also have been bad for us. So what it clearly emphasizes is that our assumed model of or

model of deformation is incorrect. Moreover, if you look at the value of flow stress as a function of what is called a dislocation density, of course we have not yet defined it.

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But if you look at it, now just going a little bit ahead of ourselves. So this is how it looks like. We are on the x axis. We have increasing dislocation density and on the y axis we have flow stress. So when the dislocation density is very low, then the flow stresses are very high. In fact, it can reach the theoretical values that we just talked about. But in general annealed polycrystal would be somewhere over here which would have  $10^{14}$  per meter cube of density of dislocations.

Somewhere here you would have high quality single crystals. And here you will have what is called as whiskers. So these are mostly free of dislocations or nearly free I should say. So when you do not have dislocations then the flow stresses are very high. Orders of magnitude higher, close to the experimental, sorry the theoretical strength that we have come to expect.

On the other hand, if you keep increasing dislocation density in this direction then what we get are strained or work hardened alloys. So just imagine that if the deformation was taking place just by shearing of the planes, then why applying a strain in the material should increase its strength? This is also evident in our uniaxial tensile stress-strain curve. If you remember the uniaxial stress-strain curve, then it looks something like this.

So somewhere over here we have plastic deformation that begins and as you keep increasing strain, then we see that the flow stress required is higher and higher, which is also expressed by the relation power law hardening behavior which clearly shows that as strain increases flow stress increases. But if it were just as shearing of the plane, why should the flow stress increase, it does not make sense.

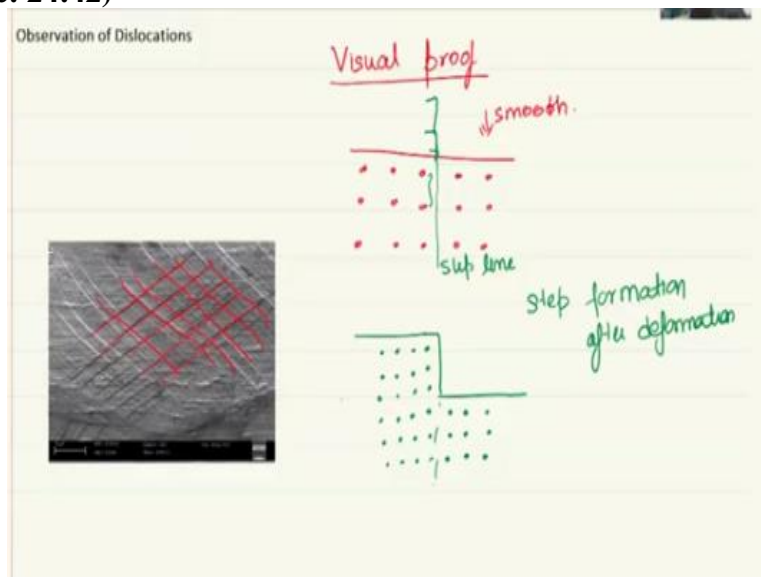
Therefore, again this emphasized to Taylor that there must be something more than we understand. And based on that, together they came up with the model of dislocations. And when you have a dislocations, so a strain hardening what is happening is dislocation density is increasing and from annealed material, which is somewhere over here to this particular point dislocation density again increases and here you get a much higher strength.

Of course, it is nowhere close to the viscous, but it is much higher than the annealed material. And that is why you see that most of these sheets, sheet metals that are used are in the rolled condition. Because in the rolled condition, you get higher strength in the material. So this is what is strain work hardening which cannot be again explained by our earlier model.

So these two things clearly emphasize that there must be some other mechanism for deformation and hence the two people Polyani and Orowan worked on theory of dislocation based on the observation that the theoretical strength and experimental strengths do not match and Taylor saw that when you deform a material, when you do some metal working on it, then their strength increases.

So again he emphasized or hypothesized that there must be something else. And therefore, he came up with the concept of what we now call as dislocations. And so together these three are credited with the theory of dislocations.

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So now we have talked about dislocations, let us quickly take a look at how would the dislocations look like? Not dislocations but it is an artifact. How would you just by looking in optical micrograph or somewhere how can you say that yes dislocations are there. And one quick visual proof for dislocation is obtained if you slightly deform a polished material.

So let us say you take a polished surface, okay. So you take a polished surface and therefore the atoms inside it are very well arranged and they are and from when you look from the top it will look like a very smooth surface. But now, let us deform it a little bit. For example, you may compress the surfaces and therefore what will happen is that there may be certain slip planes.

And because what we now, what we will later introduce the dislocations, dislocations move and they move in steps causing step rises. So one step would be equal to the distance of atoms. So it will rise like this, rise like this, this one and when you will have tens and thousands of this then it will become observable to a naked eye. And what you would see is something like step.

So this step is not by just one layer of atoms, it is actually if you are able to observe it, it is most likely being formed by tens of thousands of such dislocations accumulating and causing or making this very large step. And therefore it will this slip line, so this is a slip line where dislocations have moved and formed steps and therefore you have.

So I have not drawn it to the same scale as you can see, because I wanted to emphasize the fact that the steps are not just one layer of atoms, but several layers of atoms. And this is a SEM micrograph. And here what you see these lines these are basically slip lines, where tens of thousands of dislocations have accumulated. And when they ended up on the surface, you were able to see a large step.

So these were not happening just along this direction, but they were also happening along this direction. So eventually, we start to, it become so large that we can observe it with naked eyes. And we can see it like this. If you polish it again then again it will go away. And then again if you deform it or cause some any other way, another type of deformation where dislocations have to move, which will eventually come to the surface and therefore you would be again able to see this.

So if you keep polishing again and again it will keep disappearing and if you keep deforming again, you will see again. And this will also be observable in your tensile samples. So when you are doing the tensile samples, you have polished it very cleanly very nicely. Now after some amount of deformation, let us after 5% deformation, just look at the surface very closely and you would be able to see those slip lines.

But there you have to be a little bit careful, because over there you are not talking about one single grain, but there are multiple grains. So you will have to look closely so that you are looking inside one particular grain. But these slip lines may also be basically this may, this will happen, this slipping will happen across the grains and so overall you would see that these will cross the grain boundaries and across the grains.

So eventually you would be able to see it throughout your bulk sample. So with that we will come to an end for this first very initial introduction of dislocation or basically discovery of dislocations. Thank you.