Defects in Crystalline Solids (Part-I)

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Lecture – 16
History of Dislocations

So now, we move on from point Defects to Dislocation. We move on from 0 D to 1 D defects But it does not mean that, we will forget our friend point defects. We will come back to it because, dislocation at many a places interacts with point defects and many of the phenomena that, we know are present because of the interaction of dislocation with these point effects. Particularly if, you remember or if you have been exposed to mechanical metallurgy then, you would know of the phenomena yield point yield point behavior.

So, that is some phenomena, that takes place because of the inter interaction of dislocation with point defects. So, we will come back to it every once in a while, but now our focus would be dislocations.

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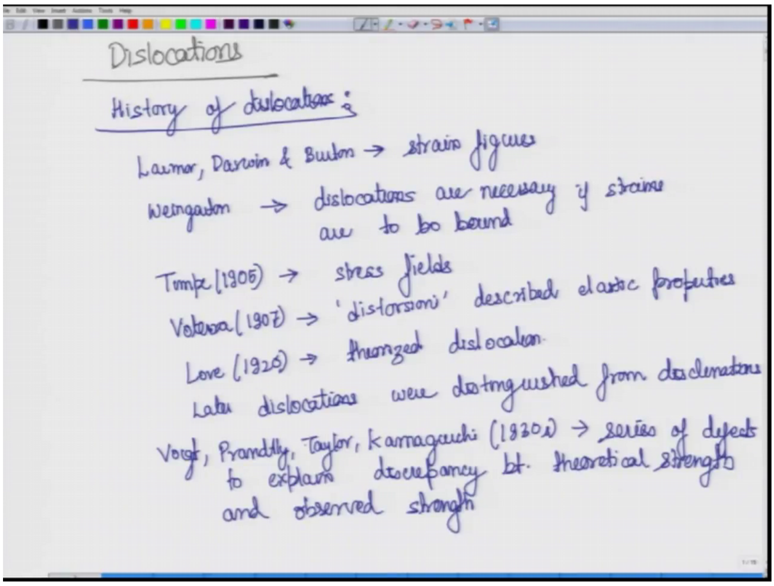

Dislocations

History of dislocations:

Larmor, Darwin & Burton → strain figures

Weingarten → dislocations are necessary if strains are to be bound

Timpe (1905) → stress fields

Volterra (1907) → 'distorsioni' described elastic properties

Love (1920) → theorized dislocation

Later dislocations were distinguished from disclinations

Voigt, Prandtl, Taylor, Kamaguchi (1930s) → series of defects to explain discrepancy bt. theoretical strength and observed strength

So, we will let us start with dislocations ok. So, the first thing that, you should be aware of when, we are talking about dislocation is a brief history of how the dislocations, the concept of dislocations were developed ok. So, the first thing or the most important thing, you should realize is that, dislocations were formulated and their properties developed in terms of elastic and plastic properties were understood long before they were even seen first time directly.

So, people were able to realize that, there is something called defects inside a crystal, even before they had long before the even they had seen it. So, why how was that possible; so that is what, we will look at briefly. So, there is a long history on how dislocations were developed. There were several people involved or several people contributed in steps, but most important of those were Orowan, Polyani and Taylor. We will come to them, but before that, who has contributed and what have they contributed we will see in a short note.

So, there were Larmor, Darwin and Burton, these were somewhere in the late 19th century. What did they contribute? They were the first to introduce something called a strain figures, which we can now relate to the concept that, we know of dislocation and strain that arises because of that. Later on Weingarton, he suggested that dislocations are necessary, meaning this concept of dislocations ok. Remember that we, people have not seen dislocations yet. He said that dislocations are necessary. So, that time people were not aware why or how the deformation takes place, they just know or observe the phenomena that deformation is taking place and they are hypothesizing several things.

So, someone suggested Larmor Darwin suggested strain figures, Weingarton suggested dislocations and he also suggested that dislocations are necessary, if strains are to be bound. If you do not consider what he meant was that, if you do not consider a dislocation like structure then, the strains can become infinite, which we know is not possible. Then Tempe in early 20th century, he introduced to the field or to the concept stress fields.

Then Volterra came and remember all of them were not using the term dislocations. For example; Volterra used the term distorsioni, which meant both dislocation and disclination. We will talk about what our dislocation and disclination, but what we are talking about now, as dislocation was not like I said was not known to them. So, they were talking in different terms, but most likely they were referring to these concepts.

And he described, Volterra described, elastic properties. Based on this model, which is all very very famous Volterra model, he described the elastic properties. Then Love in

1920, he theorized for the first time something, like a theory, he put together four dislocations. From this stage, there were several more improvement, where a lot of people in what lot of people contributed.

For example; later dislocations were distinguished from disclinations. So, far people were and you will see what, is the difference we will talk about Volterra model. But, so far whenever people talked about these defects as line defects, they were including both dislocation and disclinations. So, at this stage somewhere between 1920 to 1934 dislocation and disclination were distinguished.

Then came the contribution of Voigt, Prandtly, Taylor, Kamagurchi somewhere, somewhere around 1930's. They came up with series of defects, authorized series of defects, to explain discrepancy between theoretical actual strength and the observed strength. So, they came up with series of defects. So, they will soon see, what do we mean by we weakening of crystal.

But people observe these phenomena, weakening of crystal or basically much lower strength than the what is theoretically expected and they came they were trying to explain it. And this is the first time they put together a series of defects, which would be able to explain this weakness in the crystals.

So, they theorize series of defects, to explain discrepancy between theoretical strength and observed strength.

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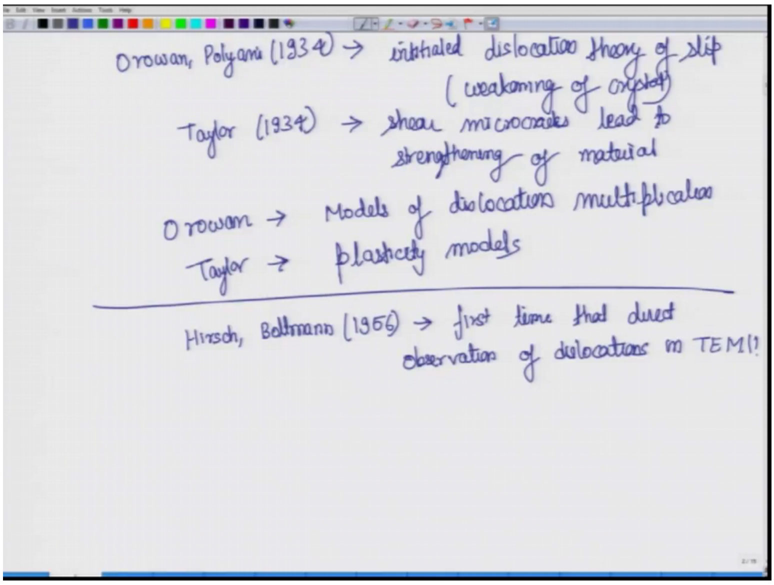

Orowan, Polyani (1934) → initiated dislocation theory of slip
(weakening of crystal)
Taylor (1934) → shear microcracks lead to
strengthening of material

Orowan → Models of dislocation multiplication
Taylor → plasticity models

Hirsch, Bollmann (1956) → first time that direct
observation of dislocations in TEM(!

Next came the most important of all these, where they where the theory was finally put in a most much more formal way and which, actually became the genesis of theory of dislocations. So, this was proposed by Orowan and Polyani in 1934. So, they initiated the theory of dislocation, theory of slip, so slip that occurs because of presence of dislocation.

And this was able to explain weakening of crystal. On the other hand in the same year Taylor came up with another model. Similar to this, what we know which says that, why the micro crash the shear micro cracks can lead to strain hardening. So, you see this is kind of contradictory work contradictory results, but the origin is same, that is the nature of dislocations.

So, Roman and Polyani they are talking about dislocation, to understand why their crystals are weaker and what they should be. On the other hand Taylor has theorized or used dislocation to explain, why there should be deformed materials should have higher strength. So, this is a kind of a contradictory and very interesting phase of dislocations, which led to the discovery of or the understanding of theory of dislocations.

So, this was the origin and later on, Orowan has also contributed in models of dislocation multiplication. And Taylor has contributed to plasticity models. So, this is the brief history of dislocations, that one should be aware of how they were discovered. Now let us yeah so, this is the model, but one thing that I missed here is that, when was it first observed. So, in 1934 it is still as a theory and when is it actually observed Hirsch and Boltmann, in the year 1956 that is, when first time that direct observation or dislocation was done in tem.

So, you can see that until 1956 people did not know that, this there is something as this like really exists like dislocation. But just based on the external nature, external observation they were able to theorize such a perfect theory for dislocations.

Now, let us move on to what we have been calling as weakening of crystal. So, we know that there were two different aspects, which led to the understanding or theory of dislocation; one was the weakening of crystal and the other was strengthening of the material, because of dislocation.

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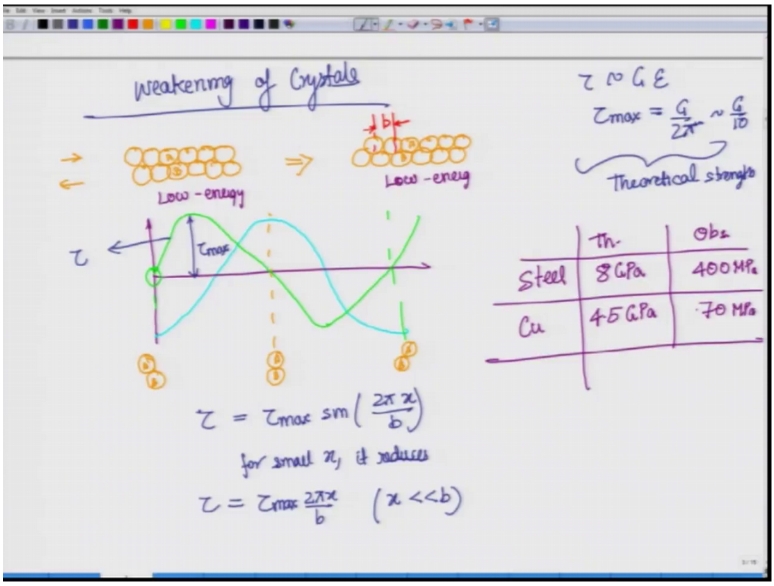

Weakening of Crystals

$\tau \propto G\varepsilon$

$$\underbrace{\tau_{max} = \frac{G}{2\pi} \sim \frac{G}{10}}_{\text{Theoretical strength}}$$

	Th.	Obs.
Steel	8 GPa	400 MPa
Cu	45 GPa	70 MPa

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

for small x, it reduces

$$\tau = \tau_{max} \frac{2\pi x}{b} \quad (x << b)$$

So, what is the weakening, what is the theory that we are talking about which is weakening of crystals.

Ok so, assume that, you are in the era of 1930’s where, people have not observed dislocation, but what you know is that, materials deform at certain strength, so you know or basically you know the yield point of the material. Now you would think how would, how is this phenomena occurring a domestically. So, one of the models that people said, that should lead to deformation is let say you have crystals like this.

So, now if you are applying some shearing on to this then, what is some kind of tension or stress onto it, then for the deformation to occur atoms must move relative to each other. And that relative motion would mean that, one plane should move with respect to the other plane. And therefore, if you are applying at some local level, this layer of atom would move to the right, this or with respect to this or this layer of atom would move to the left and you will have final structure like this. This is just a very very small strain associated with this movement, but several such movement, would lead to the overall large deformation; that is the theory. And therefore, if you look at it, this will become we can call this as b some vector b.

Now let us look at how, this stress and strain stress and energy should look like. Over here, if we look at the energy, then this is low energy state and this is low energy state, and in between these two there would be a high energy state. So, this energy plot if we want to plot, it should look like, so most likely this is representing when the atoms, so let us say we are talking about a and b, which becomes a and b over here. So, this is a, this is b and over here, this is a, this is b and in between somewhere, you will have configuration where the energy is highest sitting just over b.

So, this is the transition mode over here. And if you take a derivative of this, you will get the shear stress, that is acting on to it and you will get some relation like this. So, what you can see here is that, somewhere over here, you have 0 stress required, not somewhere, but the region where you have a and b in the lowest energy position. You have 0 stress required when the, a and b are again in the final position, then you again you have 0 stress required. Somewhere over here, there is 0 stress, but it does not mean it is stable position. If you just push it a little bit then negative stress is required or it will automatically come down to this position. This is what, this is this implies this plot implies.

Now, here if you look at, so this is tau, which is, the shear stress and therefore, this amplitude would be called tau max. So, this tau which has a sinusoidal relation, can be written like; tau max sm 2 pi x by b. For small x, this can be it reduces to tau equal to tau max 2 pi x by b. So, this is if this is a very small quantity, we can say this tau is equal to tau mx 2 pi x b or this is only when x is much less than b. But we also know that the useful relation, which is tau is approximately equal to g, which is the modulus times the strain.

And therefore, when you compare this, what we see is that tau max is equal to g by 2 pi. So, the shear strength of the material that is, what you would need, if you want deformation because, you must apply at least this much of stress for the atom to move .And if you apply continuously, this kind of stress, then the atoms can keep moving So, this is the this tau max is related to g by 2 pi and you must have this g, this relation shows that this minimum stress, that is required for deformation, to keep occurring this should be equal to tau should be equal to g by 2 pi.

Now, what is the actually the case, this is where what will be called as the theoretical strength and g by 2 pi can be approximated as, g by 10 taking into account some other factors we have missed So, now, let us look at what is really the observed case. Let us talk about steel, what is the theoretical, what is the observed. If you look at the g by 2 pi then, the theoretical strength should be 8 giga Pascal. If we talk about even something like copper then its strength should be 4.5 giga Pascal.

Now, do you know, what is the actual observed strength of these materials? For steel it is somewhere of the order of 400 mega Pascal and we consider it to be a very strong material. Copper is not so strong, it is of the order of 70 mega Pascal. What do we see, we see that the actual or observed strength is much much lower than, what we would assume or what we will theoretically calculate, assuming that dislocate or deformation takes by slip of the planes.

So, certainly this is not the way, so this is the slip is taking place and something else is adding into that. And what is it what is it that is adding into that.

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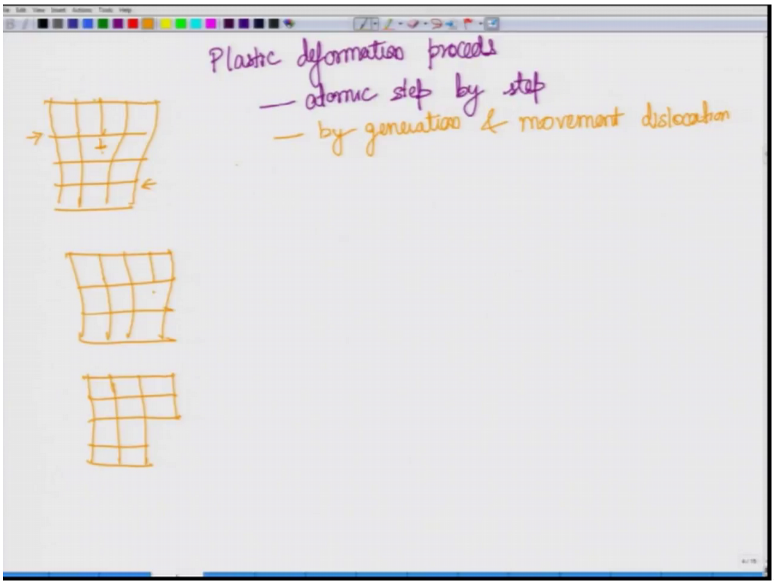

Plastic deformation proceeds

— atomic step by step

— by generation & movement dislocation

So, plastic deformation proceeds atomic step by step, meaning we will show it in a minute. So, now, if we will come back to our more descriptive model of dislocation, but for now, let us say this is the crystal, now you can imagine that, this is a dislocation which is, it is a defect because, this plane is not going all the way to the end displaying terminates inside it. In a perfect crystal this plane should go all the way to the other end and this is a line because, we are looking at 2 d if, you go 3 d then this is a line.

So, this is a 1 d defect and this is a defect that is first for sure. Now what how can this actually move, it can move in steps. So, if you apply stress on the from left to right, on the top side and on the bottom side, from right to left then, what will happen. So, what do we see here that, this dislocation in steps has moved from here to the next plane to the last plane. And this is the phenomena that lead to the deformation. And you can see that, you do not need to shear whole plane, only one line, one line of plane one line of defects is being broken and being moved. And therefore, that the energy required, which will be much much not energy but, the stress required would be much smaller.

In fact, even this model will have more and as we will develop more understanding; even in these line defects you develop steps which are called kinks and jogs. So, those kinks and jogs are what lead to the movement of this whole dislocation. So, the real stress required is even much even further lower than, what we know. So, the plastic deformation proceeds atomic step by step by generation and movement of dislocation.

So, somewhere you will also get generation of dislocation, in case they are not sufficient and even if it is sufficient for larger deformation, you may need larger number of deformation, large number of dislocations. And therefore, generation has to take place and generation and movement of dislocation is what leads to plastic deformation over all of the material.

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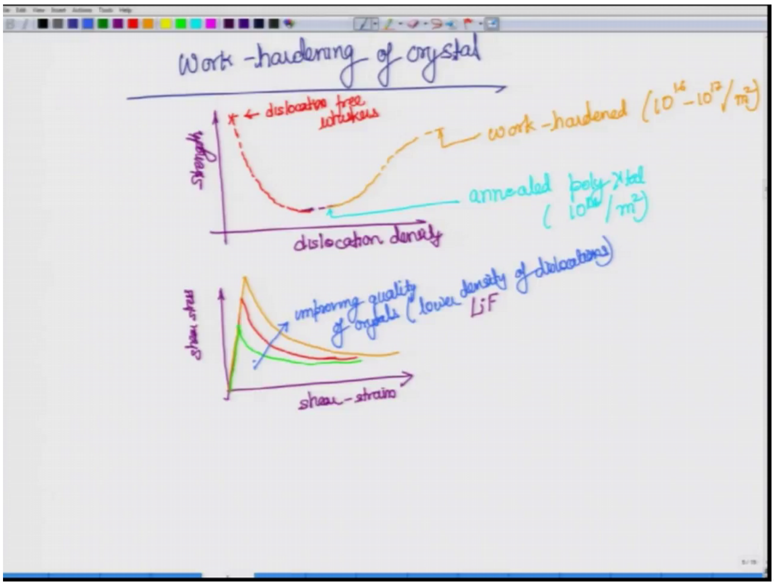

So, now, what we will look at, what we have looked at is the weakening of the crystal. Next we will look at the work hardening of crystal, so we said that, so we said that, there are two different and contradictory phenomena, which led to the understanding of dislocation. One was the weakening of the crystal that we have explained and now we also explained how the presence of dislocation can explain that, why the observed strength is lower than theoretical strength.

Now we will see that, wider presence of dislocation no not why I actually write this stage will just show, what do we mean by work hardening of crystals. So, let us say you have an yield sample. So somewhere the dislocation if, we draw the dislocation density versus strength at this stage, will not be able to understand why, but well just understand what this means. We will come back to the why in later stages.

So, this is the let us say the annealed sample and we what do we mean by anneal sample, one which has very minimal amount of dislocation density. And how do we do that, basically, we put it at high temperature, so that whatever stresses are there, they get relieved. And when the stresses get relieved, it means that the dislocations have annihilated and you have strain free crystals.

So, annealed poly crystalline sample or material they have, but that does not mean that they have 0 dislocations, that is something you must understand. That dislocations although not thermodynamically stable defect like point defect, they are always present in a material. And even in a annealed crystal strain free crystals, you will have dislocations of the order of 10 to the power 14. per meter square

Now, what is the anomaly over here? Anomaly is that, if you keep increasing the dislocation density then, it is observed that the strength increases. So, your strength you know for example; if you wrote do rolling, if you do forging, if you do severe plastic deformation in all these cases dislocation density is increasing and concomitant with that simultaneous to that, strength of the material increases. So, this is your work hardened material. As the name suggests, it is hardened, the meaning it has higher hardness higher strength.

And over here, you will have dislocation density something 10 to the power 16 in to 10 to power 17 depending on, what kind of or how much deformation has been given So, this is what we mean, when we say work hardening of crystal. However, now let us also include our earlier understanding, which is the weakening of crystal. Now if the dislocation density were very very small, somewhere like this, over here which is, almost a what is called as, defect free whiskers or dislocation free whiskers. Then from our earlier part we know that, now the deformation has to take place by slipping of the whole plane. And therefore, the strength is now, so much much much higher; in fact, even higher than work hardened samples.

So, this is another, you can say anomaly or the part of the same understanding whether, when we said that weakening of the crystal as well as work hardening of the crystal, both of them led to understanding of dislocation. So, this is the weakening of the crystal, meaning when you are defect free whiskers, you have very high strength, but in our usual annealed material, where the defect density is of the order of 10 to the power 14 per meter square strength is lower. And again if you beyond if you go beyond this then again it starts to gain strength.

But, this particular strength is much much higher; this is orders of magnitude higher than these and these. And similarly if, you keep increasing the dislocation, it is sudden it drops very sharply, but still it will have a continuous distribution and you will have strength versus dislocation density plot something like this. Now to further expand our understanding on to the density of dislocations, let us understand what happens to lithium fluoride crystals.

Now, in lithium fluoride, initially their main the density of mobile dislocations what is called as mobile because, these are the ones that will contribute to hardening. They are very small, so if you take a very high density or sorry high purity lithium fluoride crystal, you will get strength something like this.

So, this is ok, if to last me just, so here we have shear strain and then we have shear stress. So, if you are talking about a very high purity crystal, then the dislocation density is very small then, shear strength would be very high. And it will be like this, but once you have started deforming then, the dislocation density starts to increase and therefore, the therefore, the shear stress drops.

Now, if you take a material with a little lesser quality, meaning it has to begin with some dislocation density then, it will show a little less increase in the strength in the beginning and very soon, it will start to add dislocations and it will drop like this. And if you take even poorer quality dislocation poor quality lithium fluoride crystals, it will start to deform at a much lower shear stress and at a much lower strain and dislocations would get to start to generate it and it will drop as expected because, now the dislocation density starts to increase.

So, here what we have is, so when you go in this direction, improving quality of crystals. When we say improving quality what we mean is, lower density of dislocations So, this is again something, that helps us understand, what is the phenomena that is taking place over here.

So, now we have understood the basic history of dislocation and the two contradicting aspects that, led to this discovery. Now let us move on to begin our understanding for this dislocation. But like I said, one of the other things that, people were always relating dislocations with was disclination. So, what we look at next is the model of the Volterra model, which describes dislocations and disclinations.

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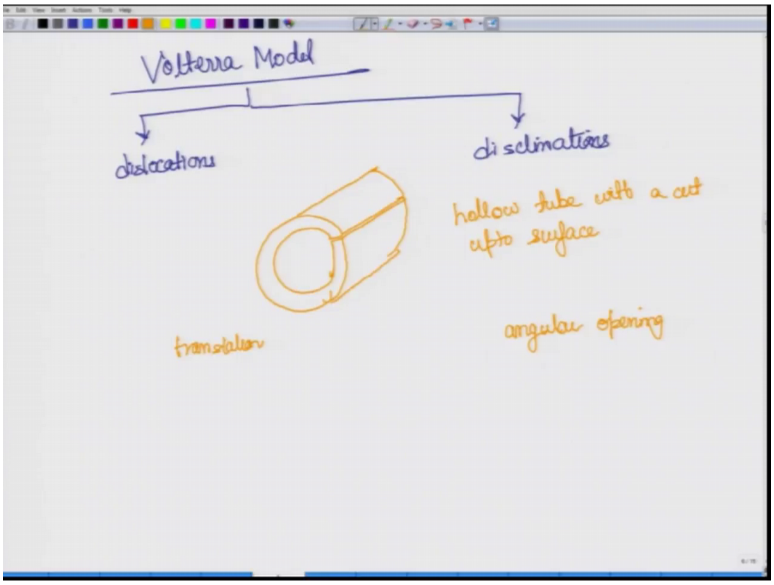

Now when in the volterra model, what is done is basically we you take a hollow tube of material. So, it is probably somewhere, from inside a crystal and you assume that, the crystal is broken along this line or it is in it is cut along this line. So, this is a hollow tube, so this is in this particular model, we take a hollow tube with a cut on up to the edge.

Now, you can realize that there are two phases to this. How you would deform the two phases, it will lead to either dislocation or disclination. If the two phases are just being translated, then you get dislocations. And if you are giving some kind of angular opening to it then, it leads to disclination. So, with this basic definition or basic understanding of dislocation and disclination with respect to volterra model, I will leave it here and we will pick up from this point in the next lecture.