Basics of Materials Engineering
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Lecture – 23
Defects in Crystalline Material – 6 (Strengthening Mechanisms)

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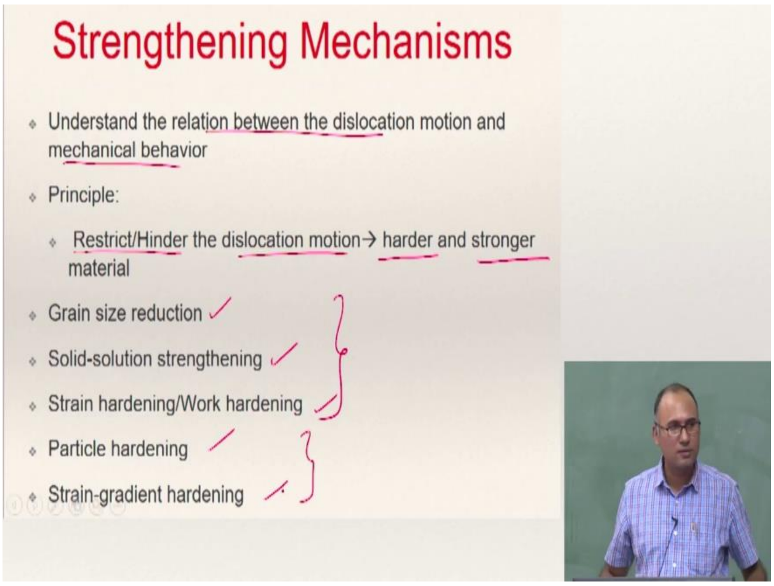

Strengthening Mechanisms

- Understand the relation between the dislocation motion and mechanical behavior
- Principle:
    - Restrict/Hinder the dislocation motion→ harder and stronger material
- Grain size reduction
- Solid-solution strengthening
- Strain hardening/Work hardening
- Particle hardening
- Strain-gradient hardening

So far, we have looked at point defects, and we have discussed why point defects exist in the first place in the materials. Then, we have discussed line defects, what is the meaning of dislocation motion, and what is the meaning of plastic deformation in a material. And then, we have discussed interfacial defects, and what are the different kinds of interface defects.

In the last module of this unit *Imperfections*, is strengthening mechanisms. Whenever you want your material science friend - the friend from metallurgical engineering, you want to discuss with him and ask him to develop material which has a better strength -- so immediately what happens, he will develop different alloys and he will say that I can increase the strength.

But again, you will go back and say that ok you can increase the strength, but I do not want to lose my ductility; you want good side of everything. You do not want to sacrifice your ductility for strength. But then your friend in metallurgical engineering will tell you, so I cannot do that. There should be a compromise. And as a mechanical engineer, you should be able to understand what he is talking about.

And that is the reason why we need to learn these basics of material science when you are talking to your friends in other departments, when you are in your real job, when you will be interacting with engineers from different disciplines, then you should be able to talk in the language that they can understand and you should be able to understand the language in which they are talking,.

That is why the strengthening mechanism is an important aspect particularly for mechanical engineers because we want to design structures which have higher strength, but at the same time they are not brittle. So, you will come up with a design and then say that, ok I want a material with such and such strength, but the ductility should be reasonably good. But if you do not know that such material is not possible, your design is not going to be useful, right? And hence, you should know why such systems are not possible. And if at all one can make such systems, what are the steps that one needs to take.

So, why a material gets strengthened when you do something to it, what are the different ways that I can enhance the strength of the material -- these are the aspects that we are going to study in this module. In order to understand the concept of strengthening mechanisms, the most important thing for us to understand is the relationship between the dislocation motion and the mechanical behaviour of the materials.

The moment we understand the connection between the dislocation motion and the mechanical behaviour, we sort of reasonably understand the various strengthening mechanisms that we are going to look at. So, how do you strengthen a material?

The basic principle is to restrict or hinder the dislocation motion. What happens if you restrict the dislocation motion? It becomes harder for you to impart plastic deformation. As a result, the yield strength of the material increases; that is what you mean by strengthening. So, all that you need to do is just to restrict the dislocation motion, right? By restricting the dislocation motion, you can actually make your material harder and stronger.

What are the different ways that you can do so? One of the ways that you can increase the strength of the material is by grain size reduction, solid-solution strengthening, strain hardening or work hardening, particle hardening, and strain-gradient hardening.

In this class, we will be talking about only these three mechanisms. I suggest you go back and read about these two mechanisms in the textbooks that are available on mechanical behaviour of materials.

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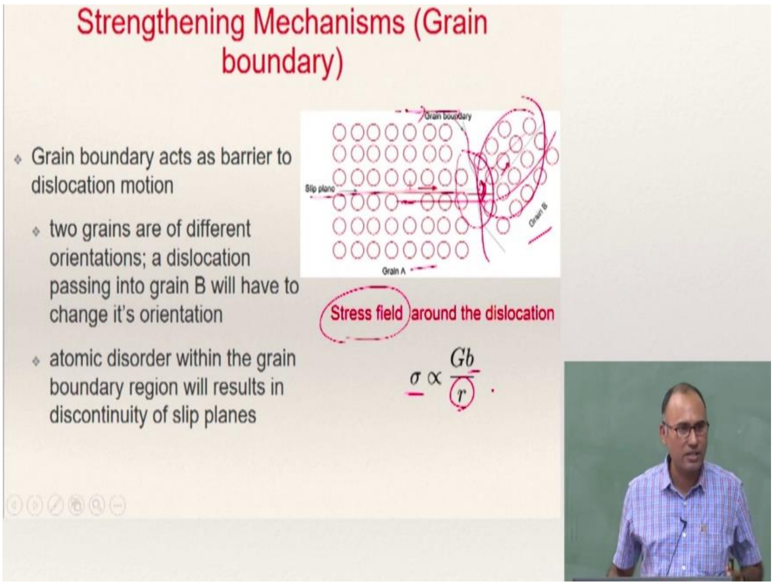

Strengthening Mechanisms (Grain boundary)

- Grain boundary acts as barrier to dislocation motion
  - two grains are of different orientations; a dislocation passing into grain B will have to change it's orientation
  - atomic disorder within the grain boundary region will results in discontinuity of slip planes

Stress field around the dislocation

$$\sigma \propto \frac{Gb}{r}$$

First of all, we will talk about strengthening mechanisms due to grain boundaries. The grain boundary, as we have discussed, is a defect in a crystalline material. What is the implication of that defect to the dislocation motion? Let us say you have a grain A and grain B. In grain A, this is your slip plane and the dislocation is moving in this direction, that is the slip direction -- that is your dislocation.

When you are applying shear stress, the dislocation moves in this direction. The moment it encounters a grain boundary, then the further slip is not possible, because there is a misorientation. The neighbouring grain is not having the same orientation. The slip plane is in the other direction; there is an orientation mismatch. As a result, the dislocation simply cannot move past the grain boundary. Then what happens?

The dislocation gets stuck near the grain boundary. You are applying the stress, but the dislocation is not able to move far across the grain boundary. As a result, you will have the stress generation, because you are putting in the stress, right? So here, you will have stress generation. For some time, you will have a resistance to dislocation motion; that means suddenly you see that in your force-displacement curve, the force keeps on increasing without not so much increase in the strain.

Because of the increase in the stress ahead of the grain boundary, the neighbouring grain's slip system gets activated. If there are some dislocations, then the dislocations in this grain start moving and so on. So, the atomic disorder within the grain boundary will result in discontinuity in the slip planes, and that is what hinders the dislocation motion; that is how you can actually stop the dislocation motion.

Whenever you have a grain boundary like that, there is a misorientation. Because of the misorientation, you will create a local stress field around the dislocation and that is usually proportional to the Burgers vector and the dislocation core radius.

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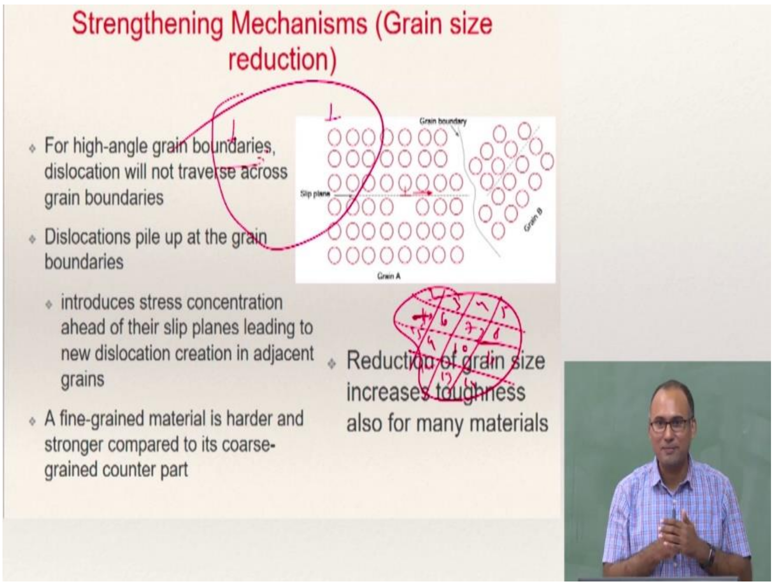

Strengthening Mechanisms (Grain size reduction)

- For high-angle grain boundaries, dislocation will not traverse across grain boundaries
- Dislocations pile up at the grain boundaries
  - introduces stress concentration ahead of their slip planes leading to new dislocation creation in adjacent grains
- A fine-grained material is harder and stronger compared to its coarse-grained counter part
- Reduction of grain size increases toughness also for many materials

If it is a high angle grain boundary, the misorientation is larger; if it is a low angle grain boundary, the misorientation is smaller; that means, the slip plane on grain A and grain B are misoriented, but the difference in orientation is not so much.

If it is high angle grain boundary, the dislocation will not cut open the grain boundary and move. It will rather create higher stress in the neighbouring grain boundary and create a new dislocation motion in the neighbouring grain boundary. If it is a low angle grain boundary, it is possible sometimes for the dislocations to cut open the grain boundary and go into the neighbouring grain. So, these are the different mechanisms.

Nevertheless, the mere presence of the grain boundary is creating obstruction to dislocation motion, eventually increasing the strength of the material. Is that clear why the grain boundaries increase the strength of the material?

If you have more grain boundary area within the material, then there are more obstructions to dislocation motion. If we increase the grain boundary area, you are increasing the probability of dislocations getting impeded near the grain boundary. So, one of the ways that you can increase the strength is by increasing the grain boundary area.

How can you increase the grain boundary area? You take a material and reduce the grain size. If you reduce the grain size you can actually put in a greater number of grains, and as a result you will have more grain boundary area. Suppose this is your material and let us say these are grain 1 and grain 2. This is the grain boundary area. It is length, but of course, if you take out-of-plane, you will have the area.

Now, if I want to increase the grain boundary area, what I can do is, I can make instead of two grains, now I have 1, 2, 3, 4, 5, 6, 7 8, 9, 10, 11, 12, 13, 14, 15 grains. So, what happened? I have reduced the grain size; as a result, the total grain boundary area has increased. Yes?

Student: (Refer Time: 09:54).

The moment you have an obstruction -- so, for instance let us say in these multiple grains, you have a dislocation getting activated here. For the sake of argument, let us say only dislocation is getting activated here and this gets obstructed there. And then the dislocation cannot move past, if it is high angle. Even if it is low angle grain boundary, it needs additional force in order to move past to the next grain.

Student: But then the density of such dislocation at the grain boundary increases (Refer Time: 10:27).

Then there are dislocations also in the other materials, they also move. But, if you imagine without any grain boundary, you have a dislocation here, you have a dislocation here. They have no resistance, they are freely moving, right? And hence, you have a nice easy glide plastic deformation that is happening. But when you have more grain boundaries what happens is all of them cannot move easily.

It is like this. Let us say you have a long bamboo stick. You are holding like this, and you are running with this bamboo stick in KV grounds here. What happens? You will be happily be able to run either KV grounds or our Manohar-Watsa stadium. You will be able to happily run.

Now, if I put you in the forest, in the campus, then what happens? You are running with this long bamboo stick running in the forest. Every time you will encounter a tree, and then what you need to do? You need to apply more force, so that your stick bends and goes, and you will be able to run.

If your stick is strong enough and the tree is weaker, you can actually break open the tree and go. If it cannot break open, then it will have to bend otherwise it will break. Nevertheless, if there are only two trees, you will be able to break open and then move past.

But if there are so many trees in a real jungle, what happens? Every time you are trying to make a move, there is an obstruction. And then, you have to apply more and more stress; as a result, with smallest grain itself your strength has increased significantly right, and that is what is the strengthening mechanism that we are talking about.

So, the bottom line here is that if you reduce the size of the grain, you can increase the strength of the material, right? And yes.

Student: Still we say single crystal materials are harder. (Refer Time: 12:41).

Wait, no. We did not say single crystal materials are harder. When did we say?

Student: (Refer Time: 12:48).

Did I say that?

Student: (Refer Time: 12:51).

I never said single crystal material is harder than polycrystalline material. We only said that single crystal materials are better for high temperature applications. Because the thermal creep, there is another deformation mechanism that is detrimental when you have grain boundaries. Because the grain boundaries are your defects, near the grain boundaries your thermal creep becomes a problematic thing, and hence you do not want to have gain boundaries there.

But I did not say that single crystal material is stronger than a polycrystalline material. It is actually the other way around.

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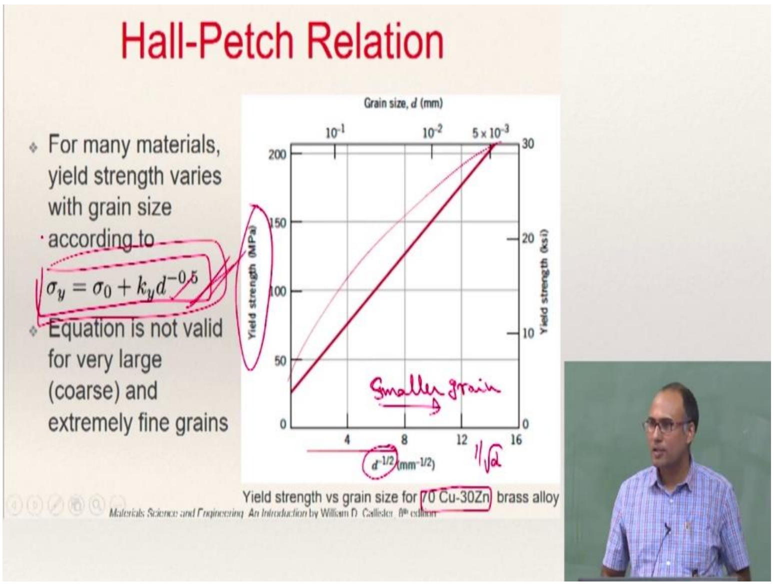

Hall-Petch Relation

- For many materials, yield strength varies with grain size according to $\sigma_y = \sigma_0 + k_y d^{-0.5}$
- Equation is not valid for very large (coarse) and extremely fine grains

Yield strength vs grain size for 70 Cu-30Zn brass alloy

Materials Science and Engineering: An Introduction by William D. Callister, 8th edition

So this is $d^{-\frac{1}{2}}$, that means, $\frac{1}{\sqrt{d}}$ as a function of yield strength of the material. This is for 70 Cu - 30 Zn brass alloy. As you reduce the grain size, which direction are we moving on the x-axis? To the right, it is smaller grain because it is $\frac{1}{\sqrt{d}}$.

As you reduce your grain size, the yield strength increases. Typically, you can write the expression for yield strength

$$\sigma_y = \sigma_0 + k_y d^{-0.5}$$

where d is the approximate grain size. This equation is valid only for grains of certain size; it is not valid for coarse grains and it is also not valid for extremely fine grains.

If you take this equation for yield strength, what should happen when d is 0? You should have infinite yield strength. What do you mean by $d = 0$?

Student: (Refer Time: 15:08).

There is no material, right? You are saying that if you take this equation, you can have infinite strength, if you do not have a material at all, so that is contradicting, right? Obviously, this cannot work. This has a range within which it works. And the behaviour that with the reduction in grain size, the yield strength of the material increases, is given by this relation, and it is called Hall-Petch relation.

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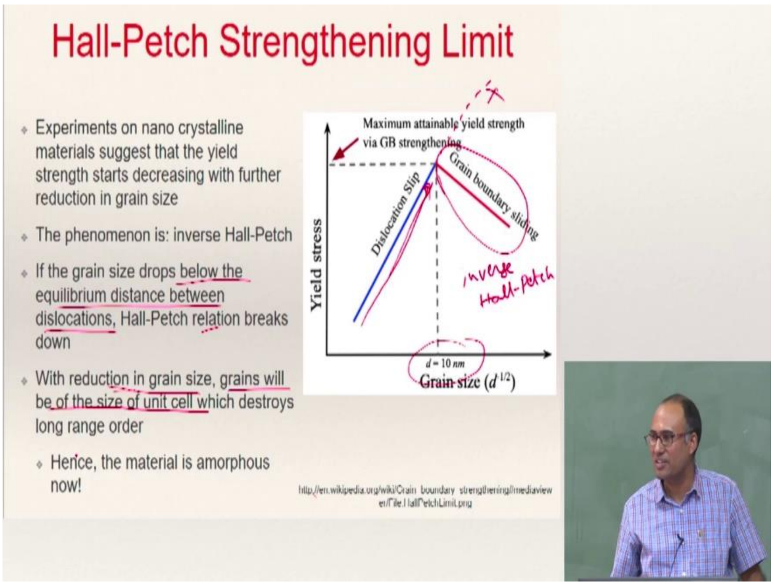

Hall-Petch Strengthening Limit

- Experiments on nano crystalline materials suggest that the yield strength starts decreasing with further reduction in grain size
- The phenomenon is: inverse Hall-Petch
- If the grain size drops below the equilibrium distance between dislocations, Hall-Petch relation breaks down
- With reduction in grain size, grains will be of the size of unit cell which destroys long range order
  - Hence, the material is amorphous now!

http://en.wikipedia.org/wiki/Grain_boundary_strengthening#/media/File:HallPetchLimit.png

Obviously, there is a limit; that is what you call Hall-Petch strengthening limit, typically of the order of your grains size being few nanometres. If you reduce the grain size initially, your dislocation slip mechanism comes into play; and as you are reducing the grain size, your yield strength increases - the blue line. But normally, if you use that Hall-Petch relation, you should continue to increase like that, but it will not do so.

After some time, if the size of the grain is below, say 10 nanometres, another mechanism comes into play, and as a result, your yield strength decreases. This is what is called inverse Hall-Petch relation. If the grain size drops below the equilibrium distance between dislocations this Hall-Petch relation breaks; that means, with the reduction in the grain size, grains will be of the size of the unit cell which destroys the long-range order.

Grain itself is becoming the size of the unit cell because you are reaching the size of the atom itself, and then there is no long-range order at all. Hence, the material itself is not crystalline anymore. So, the deformation mechanism is going to be completely different; that is one way.

Another mechanism is the grain boundary sliding. The moment you were reducing the grain smaller and smaller, the grain boundary starts to slide and that will make the material softer and softer instead of making it harder.

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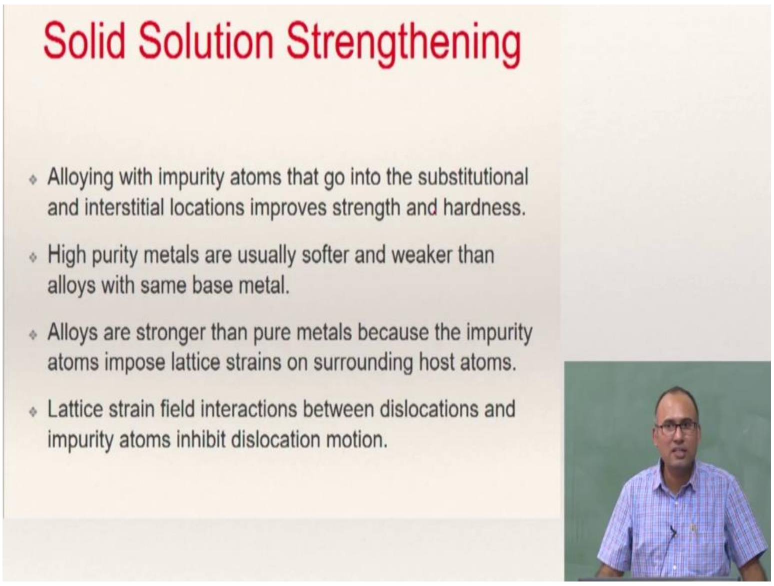

Solid Solution Strengthening

- Alloying with impurity atoms that go into the substitutional and interstitial locations improves strength and hardness.
- High purity metals are usually softer and weaker than alloys with same base metal.
- Alloys are stronger than pure metals because the impurity atoms impose lattice strains on surrounding host atoms.
- Lattice strain field interactions between dislocations and impurity atoms inhibit dislocation motion.

Another mechanism is solid solution strengthening; that means you put in impurities in the material.

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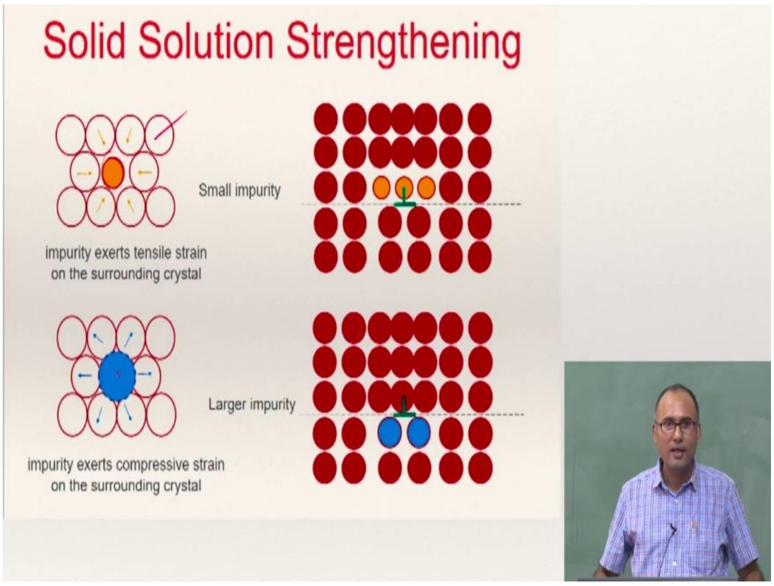

Solid Solution Strengthening

For instance, if this is your crystalline lattice, you put a small impurity, and that creates a local stress state around the crystalline lattice. If it is a small impurity, then it will create sort of tensile stress; if you put a larger impunity, then it will sort of create a compressive stress. And that local stress state will obstruct the dislocation motion.

The moment you have a grain boundary, you have a local stress field created and the dislocations interact with the local stress field, and that is what hinders the dislocation motion. Similarly, if you have an impurity, the impurities, hinders dislocation motion.

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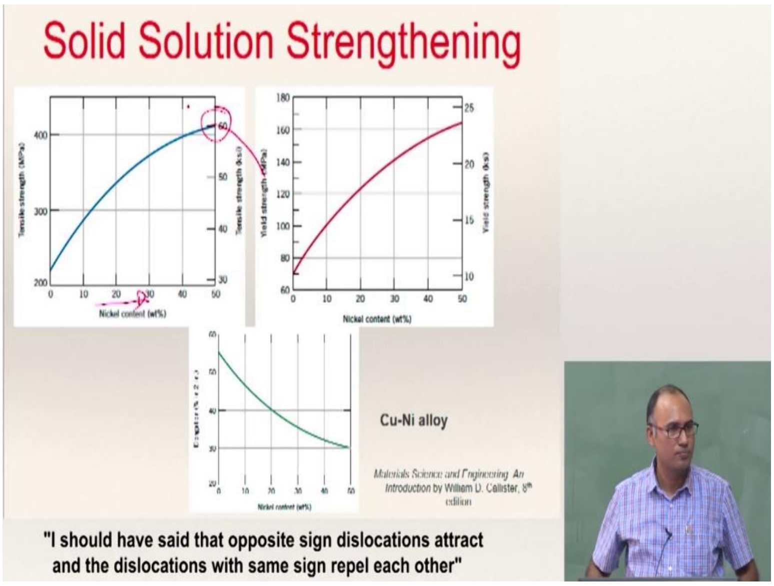

Solid Solution Strengthening

Cu-Ni alloy

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"I should have said that opposite sign dislocations attract and the dislocations with same sign repel each other"

This is a typical material property landscape. When you increase the nickel content in a copper-nickel system, your tensile strength increases, but after sometime it again decreases. We have not shown the decreasing part. As the solute and solvent are changing, there will be a peak always, it cannot continue to increase.

there is another mechanism which I have not written here, that is work hardening or strain hardening. This also happens in single crystal material. The stage-2 is primarily due to work hardening in single crystal material. What is stage-2 deformation?

In a single crystal material, we have a stage-1, stage-2 and stage-, right? Stage-1 was easy glide; stage-2 is what we called as work hardening. What is happening? Why do you call this as work hardening? By the time you are in stage-2, there are several dislocations; as you are increasing the load, your dislocation density in the material increases, and these dislocations start to interact with each other.

You have one dislocation and another dislocation; they are moving, and they get locked. We have discussed about it something called Lomer Lock. Opposite sign dislocations repel each other, and same size dislocations attract and they become perfect, and then there is no dislocation motion, and the dislocations entangling with each other -- all these cause the work hardening in the material; that can also happen in the polycrystalline material too.

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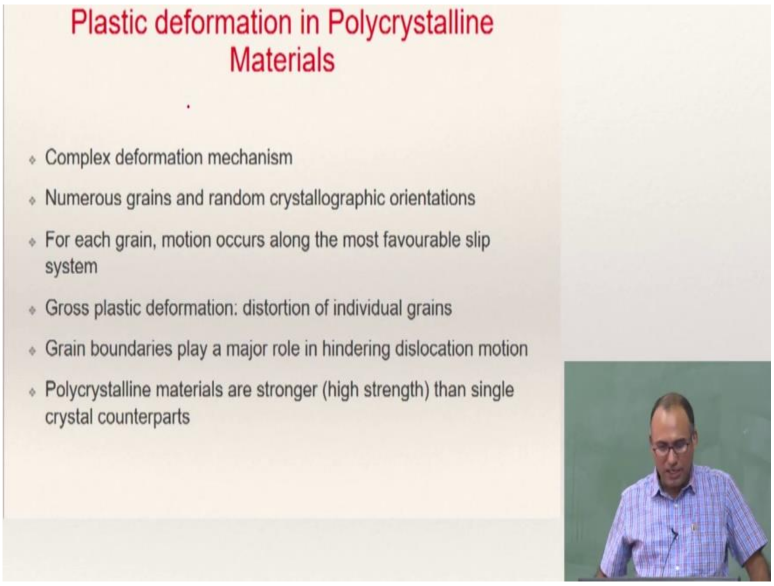

Plastic deformation in Polycrystalline Materials

- Complex deformation mechanism
- Numerous grains and random crystallographic orientations
- For each grain, motion occurs along the most favourable slip system
- Gross plastic deformation: distortion of individual grains
- Grain boundaries play a major role in hindering dislocation motion
- Polycrystalline materials are stronger (high strength) than single crystal counterparts

In the polycrystalline materials, typically the deformation mechanism is little bit more complex. If it is a polycrystalline material, you have many grains; you can have several slip systems active at the same time in each of the grains, right? And hence, at the same time, these dislocations are looking at the grain boundary.

The moment they move, immediately they try to see the grain boundaries or some impurities. As a result, you will not have this easy glide. It is extremely difficult to observe easy glide or you may not observe easy glide that you have observed in single crystal material in case of polycrystalline materials because of the numerous grains and random crystallographic orientations and these things are interacting with each other. As a result, polycrystalline materials are usually stronger because there are more obstructions than the single crystal counterparts

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Plastic deformation in Polycrystalline Materials

Polycrystalline copper surface after deformation. The slip lines are visible and they are produced by dislocations that exited at the surface. Slip lines are analogous to macroscopic steps found on the surface of single crystals.

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This is a typical micrograph of a polycrystalline material which is deformed plastically. These serrations are your slips that are happening in the material. Slip system 1, slip system 2 and so on. Alright. So, work hardening I have discussed.

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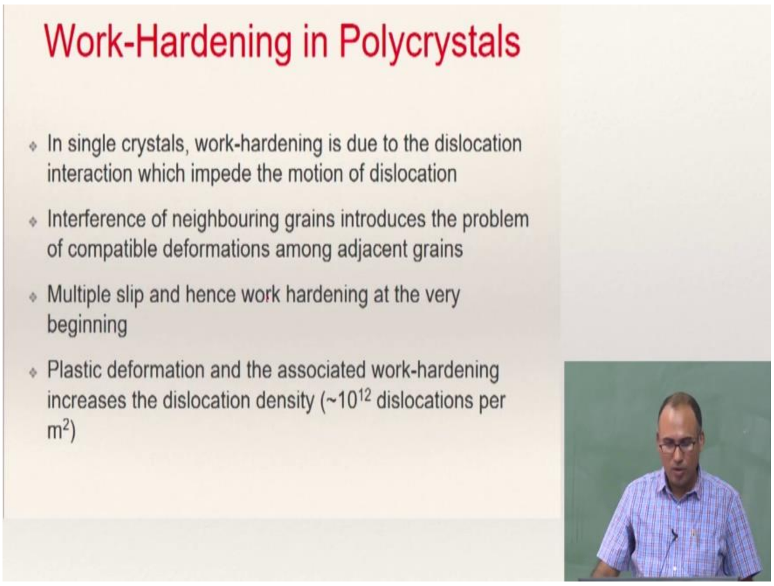

Work-Hardening in Polycrystals

- In single crystals, work-hardening is due to the dislocation interaction which impede the motion of dislocation
- Interference of neighbouring grains introduces the problem of compatible deformations among adjacent grains
- Multiple slip and hence work hardening at the very beginning
- Plastic deformation and the associated work-hardening increases the dislocation density (~10^{12} dislocations per m^2)

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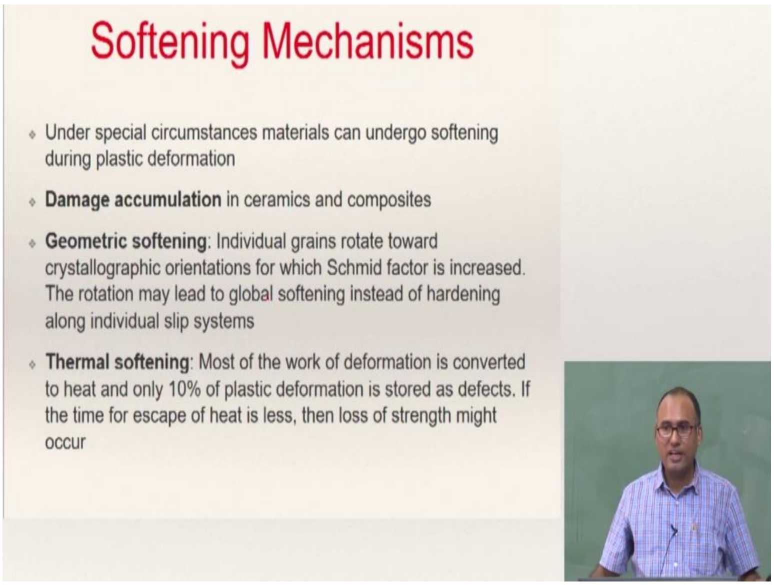

Softening Mechanisms

- Under special circumstances materials can undergo softening during plastic deformation
- **Damage accumulation** in ceramics and composites
- **Geometric softening**: Individual grains rotate toward crystallographic orientations for which Schmid factor is increased. The rotation may lead to global softening instead of hardening along individual slip systems
- **Thermal softening**: Most of the work of deformation is converted to heat and only 10% of plastic deformation is stored as defects. If the time for escape of heat is less, then loss of strength might occur

In addition to hardening mechanisms, you will also have several softening mechanisms which I am not going to discuss in this class. You please go through that. You can also have materials getting softened and just not hardened.