Basics of Materials Engineering
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Lecture – 24
Defects in Crystalline Materials – 7
(Plastic deformation in polycrystalline materials, Softening Mechanisms)

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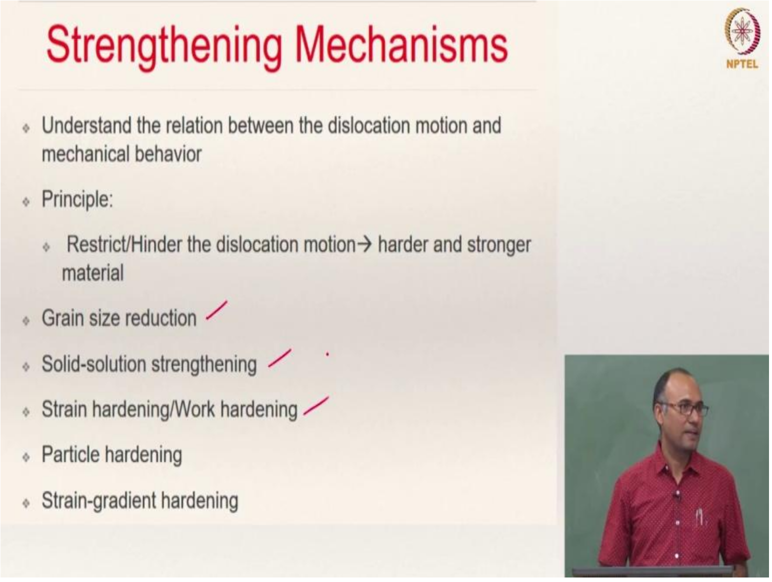

Strengthening Mechanisms

- 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, we have discussed about different strengthening mechanisms. One is grain boundary strengthening (or grain size reduction), solid-solution strengthening, and work hardening. We have discussed all these three mechanisms; how they are responsible for increasing strength of the material and we have also discussed that when you increase the strength of the material, you are going to lose its ductility. You cannot get both. If you increase strength, your ductility automatically goes down; that means, by increasing the strength of the material, you are actually making your material more brittle. That is an important consequence of strengthening.

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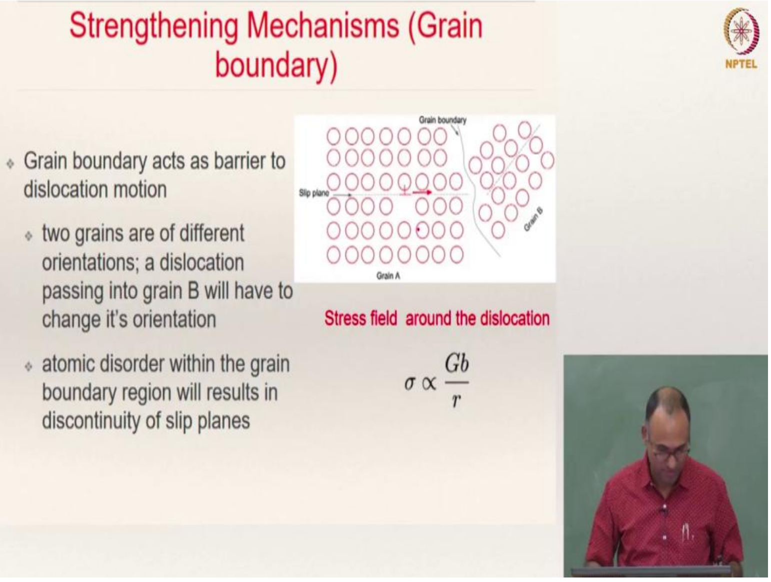

Strengthening Mechanisms (Grain boundary)

- 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

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

In grain boundary strengthening, the grain boundary acts as a barrier for dislocation motion and hence dislocation goes and gets pinned near the grain boundaries. Therefore, we need to apply a higher stress in order to continue the dislocation motion and that is how grain boundary strengthening happens.

Similarly, we have discussed that if you increase the area of grain boundaries in the material, you can actually enhance the strength of the material. So, one way to do that is to reduce the size of the grain. That is the reason why nano-crystalline materials are strong. For instance, between nano-crystalline copper and a coarse grain copper, because of the fact that the grain size is smaller in nano crystalline material, the grain boundary area is higher, and hence, there is a higher probability for the dislocations to go and get pinned near the grain boundary. Therefore, nano crystalline materials are stronger.

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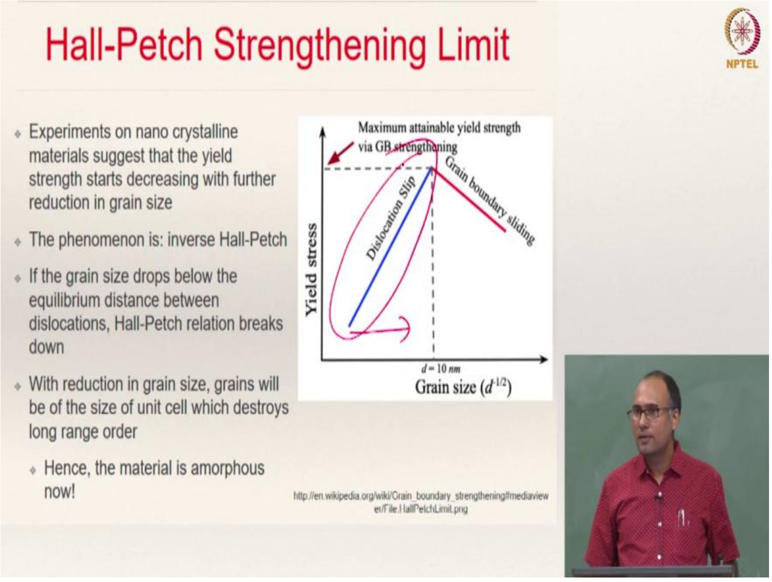

Hall-Petch Strengthening Limit

- 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#mediaviewer/File:HallPetchLimit.png

We have also discussed about Hall-Petch where in the yield strength increases with decrease in grain size up till a certain point beyond which, the relationship breaks down, and it starts decreasing again.

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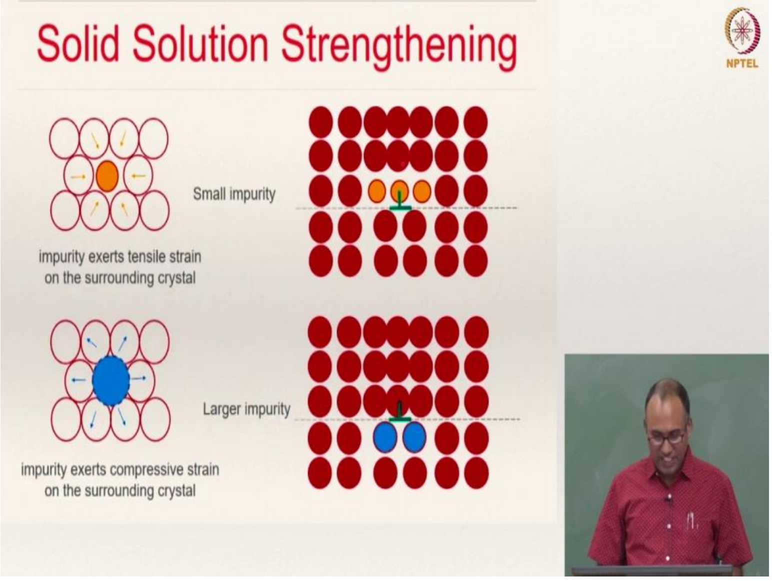

Solid Solution Strengthening

Small impurity

impurity exerts tensile strain on the surrounding crystal

Larger impurity

impurity exerts compressive strain on the surrounding crystal

Similarly, we have discusses solid solution strengthening.

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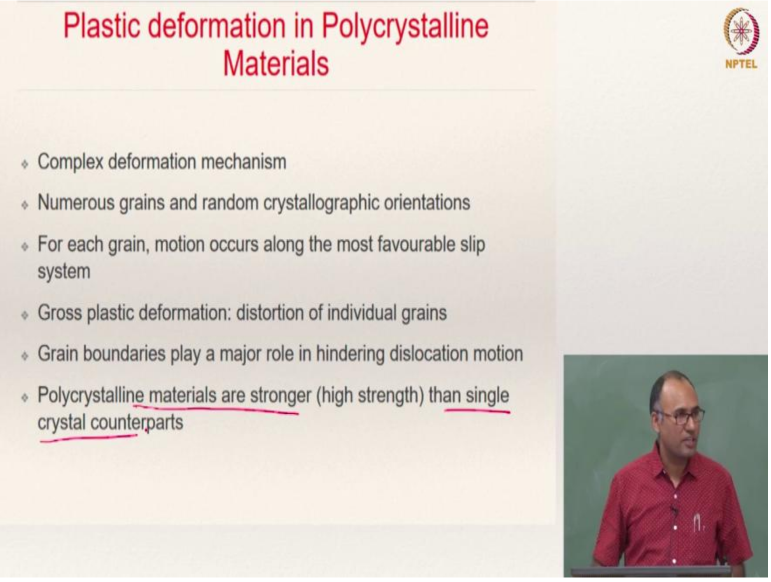

Plastic deformation in Polycrystalline Materials

- 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

We have also discussed strain hardening and work hardening. In a single crystalline material, it is typically the stage II where in when you increase the dislocation density, the dislocations starts interacting with each other. So, dislocation entanglement, dislocation annihilation, dislocation repulsion, etc. may happen. All these interactions will impede dislocation motion.

Now, we will look at plastic deformation in polycrystalline materials. In polycrystalline materials, it is a bit more complex than a single crystalline material, because in single crystalline material, firstly, you do not have grain boundaries. Additionally, in a polycrystalline material, you can have slip getting activated on several grains.

Easy glide is not something that is usually observed in polycrystalline materials. Immediately after crossing the yield strength, immediately strain hardening starts, because several dislocations and several slip systems start to activate and they start interacting with the grain boundary. The hardening kicks in quite early.

As a result polycrystalline materials are stronger than their single crystal counterparts. So, if you make a single crystal copper and a polycrystalline copper, single crystal copper is going to be softer compared to polycrystalline copper because of the impediment of dislocations in a polycrystalline material compared to a single crystal.

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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.

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

So, this is the micro graph showing plastic deformation in a polycrystalline material. In a single grain, you have several slip systems activate. In one grain, more than one slip system is active. Also, there are several grains in which several slip systems slip systems are active.

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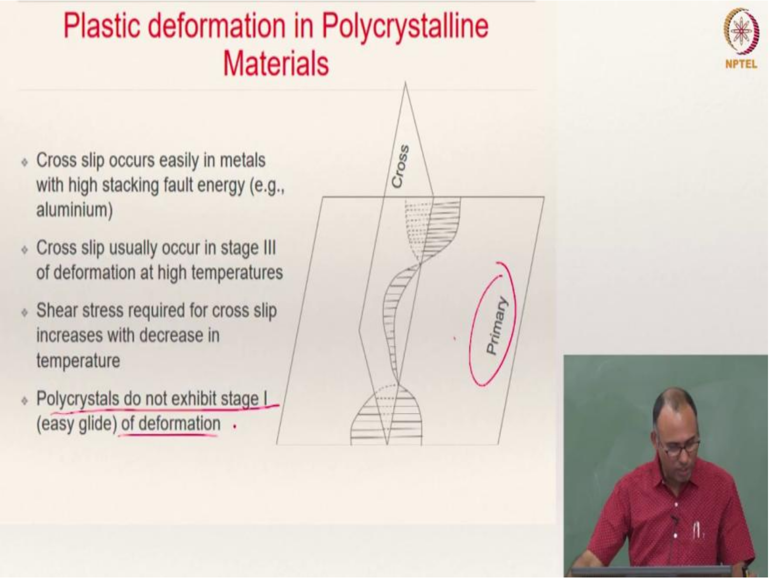

Plastic deformation in Polycrystalline Materials

- Cross slip occurs easily in metals with high stacking fault energy (e.g., aluminium)
- Cross slip usually occur in stage III of deformation at high temperatures
- Shear stress required for cross slip increases with decrease in temperature
- Polycrystals do not exhibit stage I (easy glide) of deformation

Another mechanism that is important in a polycrystalline material is something called cross slip. It typically occurs in stage III of deformation at high temperatures. When there are two slip systems, the dislocation might actually jump from one to another. So, there can be a slip from one slip system to another; this called cross slip.

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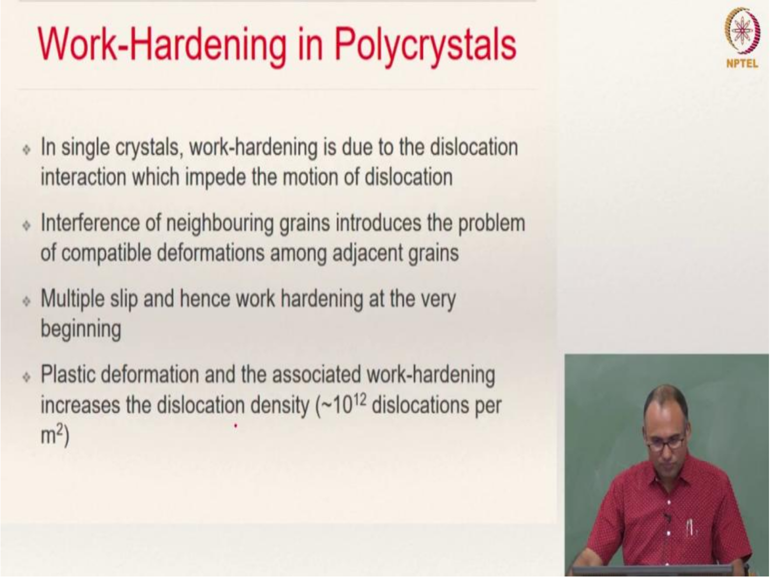

Work-Hardening in Polycrystals

- 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)

Since there are multiple slips there is going to be more resistance to dislocation motion

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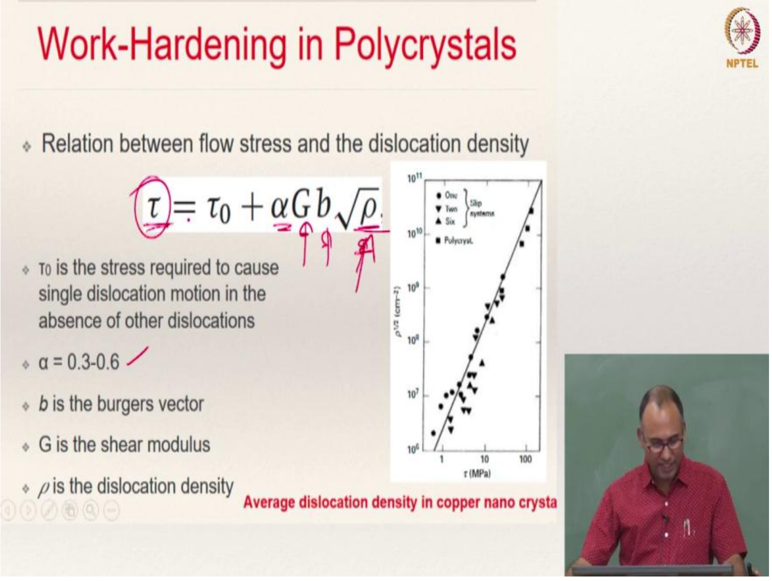

Work-Hardening in Polycrystals

- Relation between flow stress and the dislocation density

$$\tau = \tau_0 + \alpha G b \sqrt{\rho}$$

- τ_0 is the stress required to cause single dislocation motion in the absence of other dislocations
- α = 0.3-0.6
- b is the burgers vector
- G is the shear modulus
- ρ is the dislocation density

Average dislocation density in copper nano crysta

The relationship between flow stress and dislocation density is given by

$$\tau = \tau_0 + \alpha G b \sqrt{\rho}$$

Where, ρ is the dislocation density and alpha is a material parameter. Typically, for metals it is between 0.3 and 0.6. G is your shear modulus and b is the Burgers vector and then, as you continue to load the system, the dislocation density increases because the number of dislocations are multiplying as you continue to load the system. So, because of the fact that the dislocation density is increasing, the shear stress required to cause further deformation increases. And that is how the dislocation density and flow stress in a material are connected.

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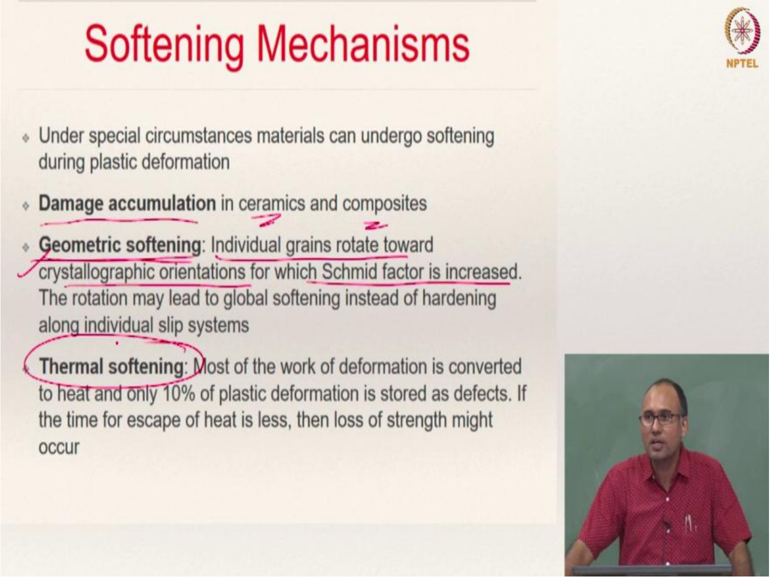

Softening Mechanisms

- 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

We have discussed about hardening mechanisms, but in materials, it is also possible that there are certain mechanisms which makes the material soft. Under special circumstances, they can undergo softening during plastic deformation. That happens when you have damage.

Hardening implies that the materials becoming more and stiffer. If you have a damage in the material; that means, during the deformation you are imparting damage to the material, and that damage actually is going to reduce the overall elastic stiffness of the material. And, that is what you mean by softening the material. So, damage accumulation, one of the mechanisms. This is typically observed in ceramics and composites. In ceramics, you can clearly see that there is no plastic deformation. Ceramics fail by damage accumulation. Typically, there will be a brittle fracture.

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We also have something called geometric softening. Enhancing the dislocation motion is what causes softening. When you are applying a load, some of the slip systems are active. We know that as you are deforming the materials, the slip system orientations are changing. The slip systems will be rotated, and during this process, it is possible that there are more and more slip systems that are changing their orientations in such a way that you are enhancing the dislocation motion That means, there are more slip systems that are becoming favorable or active because of the geometric orientation changes. Such a softening mechanism is called geometric softening.

So, the individual grains rotate toward crystallographic orientations for which Schmid factor is increased. When your Schmid factor is increased, then it becomes easier for you to cause plastic deformation or dislocation motion, and that is geometric softening. This typically happens in several materials, but many times, the hardening effect is more predominant compared to the geometric softening.

Even during the hardening response, the crystal orientations are changing, but the effect caused by reorientation of the grains is actually much lesser compare to the effect caused by the obstacles in the crystal systems, which are hindering the dislocation.

Another way that you can impart softening is thermal softening. Plastic deformations cause local heat generation. The local heat generation might actually reduce the strength of the material, and that is what we call thermal softening. So, the heat generated because of the plastic deformation is what helps the enhancement of the dislocation motion.

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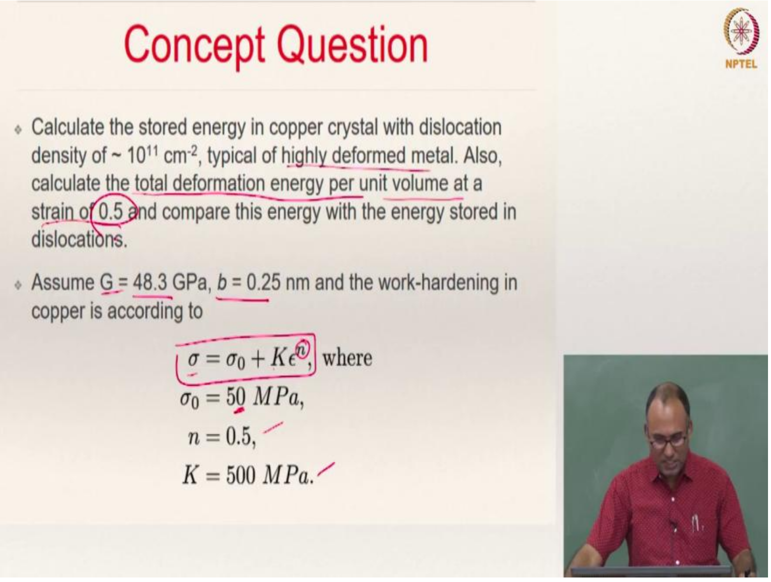

Concept Question

- Calculate the stored energy in copper crystal with dislocation density of ~ 10^{11} cm^{-2}, typical of highly deformed metal. Also, calculate the total deformation energy per unit volume at a strain of 0.5 and compare this energy with the energy stored in dislocations.
- Assume G = 48.3 GPa, b = 0.25 nm and the work-hardening in copper is according to

$$\sigma = \sigma_0 + K\epsilon^n, \text{ where}$$
$$\sigma_0 = 50\ MPa,$$
$$n = 0.5,$$
$$K = 500\ MPa.$$

Calculate the stored energy in copper crystal with dislocations density of $\sim 10^{11} cm^{-2}$, typical of a highly deformed metal. Also, calculate the total deformation energy per unit volume at a strain of 0.5 and compare this energy with energy stored in dislocations.

Assume $G = 48.3\ GPa, b = 0.25\ nm$

Also, work hardening in copper is according to the following

$$\sigma = \sigma_0 + K\epsilon^n$$

Where $\sigma_0 = 50 MPa,\ n = 0.5,\ K = 500\ MPa$

Solution: The energy associated with dislocation per unit volume is given by

$$U = \rho \frac{Gb^2}{2}$$

$$U = \frac{1}{2} \times 10^{15} \times 48.3 \times 10^9 \times (0.25 \times 10^{-9})^2 = 1.5 \times 10^6\ J/m^3$$

The total deformation energy per unit volume at a strain of 0.5 is given as

$$U = \int_0^{\epsilon} \sigma d\epsilon = \int_0^{\epsilon_1} (\sigma_0 + K e^n) d\epsilon$$

$$= \sigma_0 \epsilon_1 + K \frac{\epsilon_1^{n+1}}{n+1}$$

$$= 50 \times 10^6 \times 0.5 + 500 \times 10^6 \times \frac{(0.5)^{1.5}}{1.5}$$

$$= 1.41 \times 10^8 \frac{J}{m^3}$$

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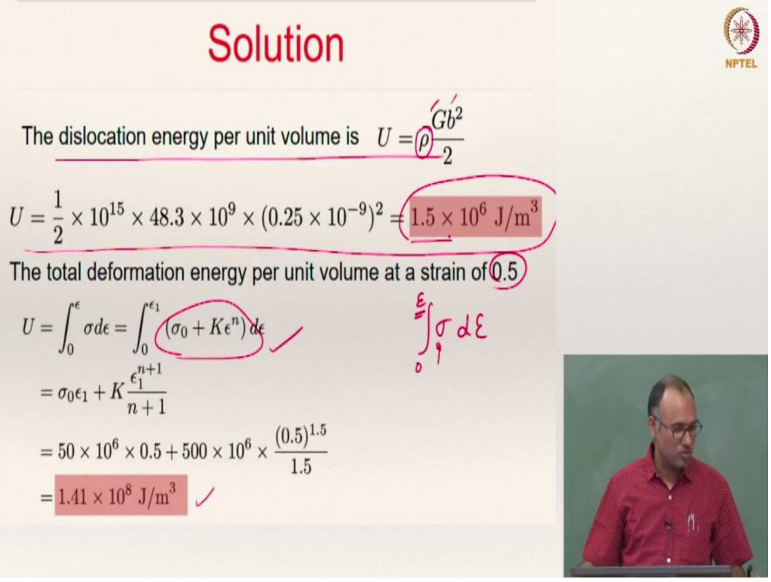

Solution

The dislocation energy per unit volume is $U = \rho \frac{Gb^2}{2}$

$$U = \frac{1}{2} \times 10^{15} \times 48.3 \times 10^9 \times (0.25 \times 10^{-9})^2 = 1.5 \times 10^6 \text{ J/m}^3$$

The total deformation energy per unit volume at a strain of 0.5

$$U = \int_0^{\epsilon} \sigma d\epsilon = \int_0^{\epsilon_1} (\sigma_0 + K\epsilon^n) d\epsilon \checkmark$$

$$\int_0^{\varepsilon} \sigma \, d\varepsilon$$

$$= \sigma_0 \epsilon_1 + K \frac{\epsilon_1^{n+1}}{n+1}$$

$$= 50 \times 10^6 \times 0.5 + 500 \times 10^6 \times \frac{(0.5)^{1.5}}{1.5}$$

$$= 1.41 \times 10^8 \text{ J/m}^3 \checkmark$$

Out of 140 $\mathrm{MJ/m^3}$, only 1.5 MJ/m^3 is actually responsible for creating dislocation motion or multiplying dislocation motion. The total energy stored in the dislocations is only 1.4% of the total deformation energy. The remaining work is dissipated as heat raising the temperature of the specimen.

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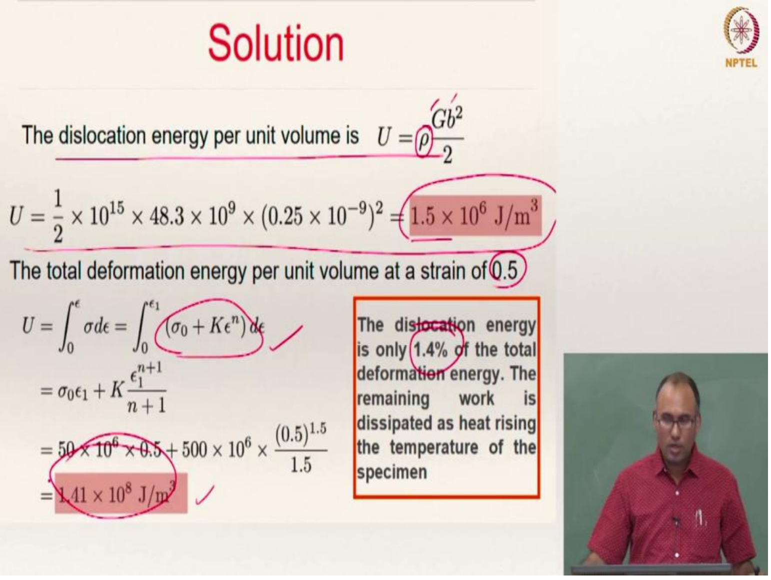

Solution

The dislocation energy per unit volume is $U = \rho \frac{Gb^2}{2}$

$$U = \frac{1}{2} \times 10^{15} \times 48.3 \times 10^{9} \times (0.25 \times 10^{-9})^2 = 1.5 \times 10^{6}\ \mathrm{J/m^3}$$

The total deformation energy per unit volume at a strain of 0.5

$$U = \int_0^{\epsilon} \sigma d\epsilon = \int_0^{\epsilon_1} (\sigma_0 + K\epsilon^n) d\epsilon$$

$$= \sigma_0 \epsilon_1 + K \frac{\epsilon_1^{n+1}}{n+1}$$

$$= 50 \times 10^6 \times 0.5 + 500 \times 10^6 \times \frac{(0.5)^{1.5}}{1.5}$$

$$= 1.41 \times 10^8\ \mathrm{J/m^3}$$

The dislocation energy is only 1.4% of the total deformation energy. The remaining work is dissipated as heat rising the temperature of the specimen

Not all the work that you are putting in is actually going into creating dislocation, lot of it is dissipated as heat and that is precisely the reason why if you have done a uniaxial tension test and immediately try to touch the sample, the sample will be very hot. Where is this heat coming from? This is the energy that is dissipated.

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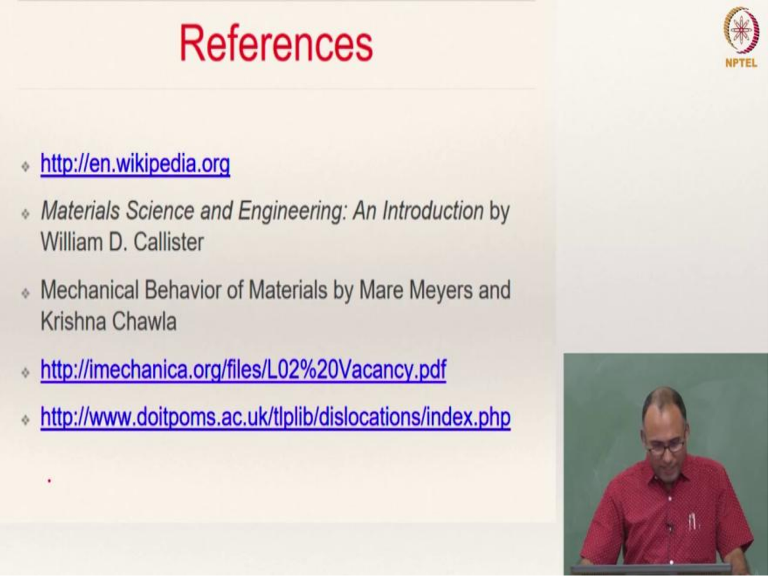

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