Introduction to crystal elasticity and crystal plasticity
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Lecture-14

Hello everybody! Let us start with the another module with the crystal elasticity and crystal plasticity.

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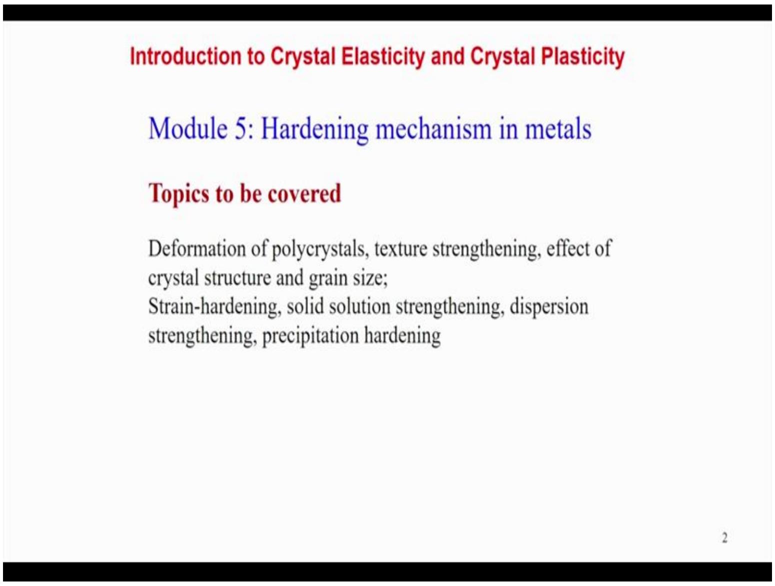

Introduction to Crystal Elasticity and Crystal Plasticity

Module 5: Hardening mechanism in metals

Topics to be covered

Deformation of polycrystals, texture strengthening, effect of crystal structure and grain size;
Strain-hardening, solid solution strengthening, dispersion strengthening, precipitation hardening

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It is a hardening mechanism in metals. So actually this topic is significant to analyze what that typical mechanism exist to explain the specifically the hardening behavior of the material. So this module we try to focus on the specific topic on the deformation of polycrystals structure strengthening that means presence of structure is there any strengthening affect on the microstructure or not. What is the effect of the crystal structure and grain size to impart the strain in the metal itself? Then strain hardening, solid solution strengthening, dispersion strengthening, precipitation hardening.

These all are the typical hardening, these are all the typical hardening mechanism, actually exist in the metals and that mechanism, using that mechanism specific always we try to explain that imparting the strength level or increasing the strength of a specific material and specifically all these are subjected to when we try to explain in the specifically in the plastic deformation zone of a material. So individually we will try to focus on the individual topic but to do that what are the basic philosophy that how to increase the strength of a material.

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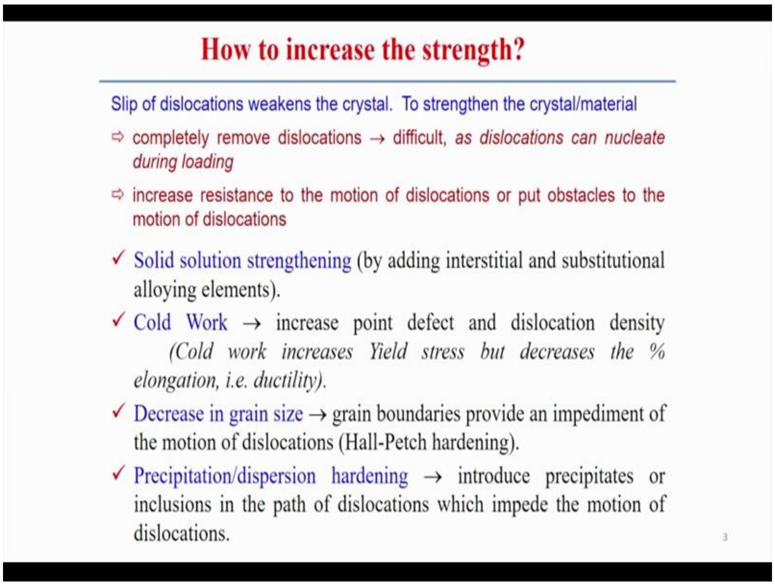

How to increase the strength?

Slip of dislocations weakens the crystal. To strengthen the crystal/material

⇨ completely remove dislocations → difficult, *as dislocations can nucleate during loading*

⇨ increase resistance to the motion of dislocations or put obstacles to the motion of dislocations

- ✓ Solid solution strengthening (by adding interstitial and substitutional alloying elements).
- ✓ Cold Work → increase point defect and dislocation density *(Cold work increases Yield stress but decreases the % elongation, i.e. ductility).*
- ✓ Decrease in grain size → grain boundaries provide an impediment of the motion of dislocations (Hall-Petch hardening).
- ✓ Precipitation/dispersion hardening → introduce precipitates or inclusions in the path of dislocations which impede the motion of dislocations.

So we start with the mechanism of the slip or maybe we try to link with the dislocation slip, all these typical elementary terms in the plastic deformation of a material. So first is the slip of dislocation actually weakens the crystal. So then what are the way to strengthen the crystal of material. There are two possible way probably first one is the if it is possible to completely remove the dislocation then in absence of dislocation the strength level maybe more, in case of crystals or materials. But practically it is very difficult as dislocations can be generated during the or during the deformation.

So ideally it is not possible to exactly on a specific structure defect free that means dislocation defect free. Another option is that increase resistance to the motion of the dislocation or if it is possible to put obstacles to the motion of the dislocation that actually imparts the strength or increase the strength level for a single crystal structure or polycrystalline structure or in general it is in metals of (())(3:42). So there are basically different type of strengthening mechanism we explain and of course in this case we will try to focus on that mostly in case of single crystal structure and we using in a single crystal structure how the strength can be increase of a structure looking into the different mechanism.

So there are basically 4 mechanism one is the solid solution strengthening. Solid solution strengthening means it is a simply by adding interstitial and subtitutional alloying elements. So alloys this strengthening mechanism that means with respect to the pure metal, if it is possible to add some alloying elements to the materials then in general that actually impart the some amount of the strength and that is called the solid solution strengthening. And second one is the cold working. Cold working means if we try to deform the amterail and there is a increase of the point defect and there is of course increment of the dislocation density number of dislocations, and if there is a number of dislocation that in case of the number of dislocation actually impart but not simply increment the number of dislocation and there interaction with each other, probably increase the amount of the strain. And that mechanism is called specifically cold work, due to the cold work.

Another is the decrease in grain size. So within the microstructure itself it is possible to decrease the grain size that means fine grain size actually produces more amount of the strain as compared to the coarse grain structure. So only difference is that in fine grain structure the number of grain boundaries actually increases and that grain boundary actually resist the dislocation motion and by that mechanism we can increase the strain by decreasing the grain size. This key is generally called Hall-Petch hardening mechanism. Fourth one if the precipitation of dispersion hardening, that means in general if it is possible to introduce the sum precipitates or inclusion in the part of the dislocation motion which actually impede the motion o the dislocation.

So here actually we try to explain all this typical mechanism of strengthening of a single crystal structure and that actually, broadly we can say all these cases there is a obstacles of the dislocation movements with this mechanism we can increase the strength level of the single crystal structure.

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How to increase the strength?

Usually there will be other sources of opposition/impediment to the motion of dislocations in the material

- Stress fields of other dislocations
- Stress fields from low angle grain boundaries
- Grain boundaries
- Effect of solute atoms and vacancies
- Stacking Faults
- Twin boundaries

- Some of these barriers (the short range obstacles) can be overcome by thermal activation (while other cannot be-the long range obstacles)
- These factors lead to the strengthening of the material

So usually there will be the other source of opposition or some obstacles to the motion of the dislocation in the materials, what are the other sources. So presence of the stress field of other dislocation. So stress field of other dislocation actually impart some amount of the obstacle to the movement of the dislocation. Stress field from lower angle grain boundaries, presence of the grain boundaries, effect of the solute atoms and vacancies, presence of the stacking faults and twin boundaries all actually contribute or maybe all actually responsible to increase the strain level by obstruct in the motion of the dislocation.

So sum of the barriers probably we can categorize it like that short range obstacle which is the short range obstacles that can be overcome by thermal activation. But that thermal activation may not be applicable for the long range of obstacle, so let us look into that categorize into whether short range or long range obstacles like that. So finally all these factors actually contribute to the strengthening of a material. Now obstacles to the motion of a dislocation, one is that long range internal stress field.

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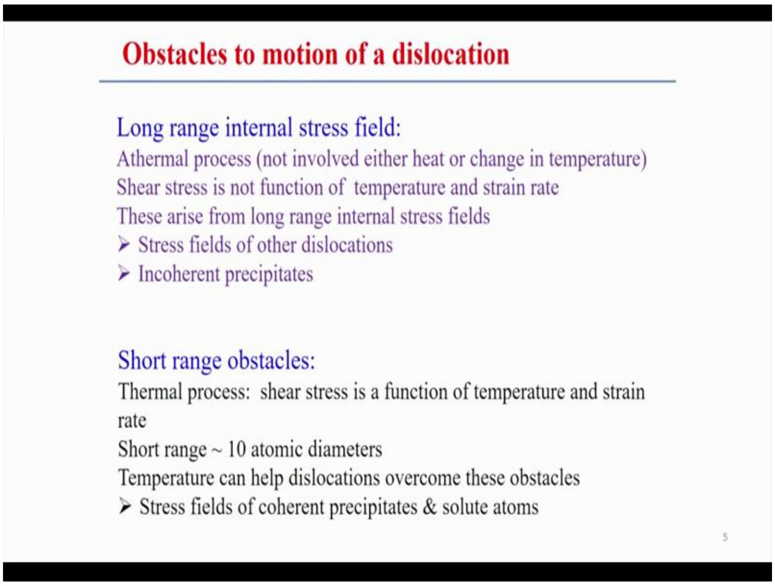

Obstacles to motion of a dislocation

Long range internal stress field:

Athermal process (not involved either heat or change in temperature)
Shear stress is not function of temperature and strain rate
These arise from long range internal stress fields
- Stress fields of other dislocations
- Incoherent precipitates

Short range obstacles:

Thermal process: shear stress is a function of temperature and strain rate
Short range ~ 10 atomic diameters
Temperature can help dislocations overcome these obstacles
- Stress fields of coherent precipitates & solute atoms

So how is it like that, a thermal process which is not involved either heat or change in temperature, that means the thermal, it is not thermal activated process, so in this case the shear stress is actually not the function of the temperature and the strain rate. And these arises from the long range internal strain field due to the stress field of the other dislocation or due to the presence of incoherent precipitates. So with the long range of internal stress field and now we see that what are the short range of obstacles and that obstacles for the motion of a dislocation. Thermal process, if it is thermally activated process in that case the shear stress is a function of the temperature and strain rate.

And short range means we assume the range which is equivalent to the 10 atomic diameter specific crystal, atoms of a specific crystal structure and actually temperature can help dislocation overcome this obstacles. But in case of the sources probably the stress field of the coherent precipitates and other solute atoms can be consider as a short range of obstacles for a dislocation movement. So overall we can divide the obstacles to the motion of a dislocation, it can be in the range of the long range or it can be in the short range of obstacles.

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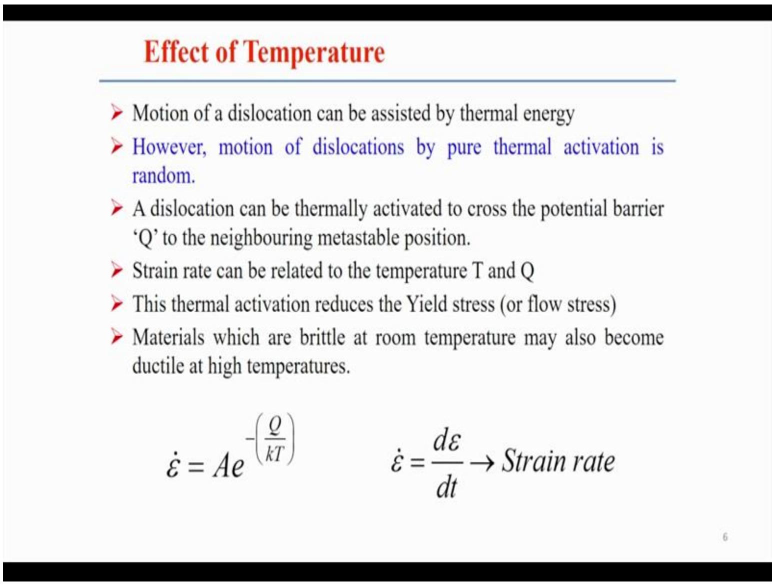

Effect of Temperature

- Motion of a dislocation can be assisted by thermal energy
- However, motion of dislocations by pure thermal activation is random.
- A dislocation can be thermally activated to cross the potential barrier 'Q' to the neighbouring metastable position.
- Strain rate can be related to the temperature T and Q
- This thermal activation reduces the Yield stress (or flow stress)
- Materials which are brittle at room temperature may also become ductile at high temperatures.

$$\dot{\varepsilon} = Ae^{-\left(\frac{Q}{kT}\right)} \qquad \dot{\varepsilon} = \frac{d\varepsilon}{dt} \rightarrow Strain\ rate$$

So let us look into that how actually impart the motions to the dislocation help or resist to that motion. Now what is the effect of the temperature on this dislocation motion. One thing is that motion of a dislocation can be assisted by the thermal energy. However the motion of dislocation by pure thermal activation is random, it is not very certain that if thermal activation is there definitely all types of short range obstacles can be overcome that means thermally activated process to against the resistance of the dislocation movement is purely random, so that means there is a probabilistic way we can estimate what is the amount of the dislocation obstacles can be overcome by application of the temperature.

If we look into that dislocation edge dislocation can be thermally activated process to cross the potential barrier if we define q which is generally called the activation energy to the neighboring metastable position. Now strain rate can be related to temperature and, temperature t and this q which is called activation energy. Now this thermal activation actually reduces the yield stress of flow stress because this thermally, this thermal activation actually smoothen, actually uses the resistance to the dislocation motion and by that way it actually reduces the amount of the flow stress or yield stress value. Materials which are brittle at room temperature probably may also become the ductile at very high temperature because at very high temperature the more slip system may be active or maybe it can accommodate large amount of the plastic deformation for a fix amount of the application of the stress.

So the strain rate temperature activation energy can be linked this way, the strain rate equal to some constant, e to the power q by kt, q is the activation energy and t is the temperature. So these are typically relation of the thermally activated process between the strain rate, temperature and the activation energy where strain is define d Epsilon by dt. So overall we can say that temperature is having some effect to reduce the motion of the dislocation which during the plastic deformation or a specific crystal structure.

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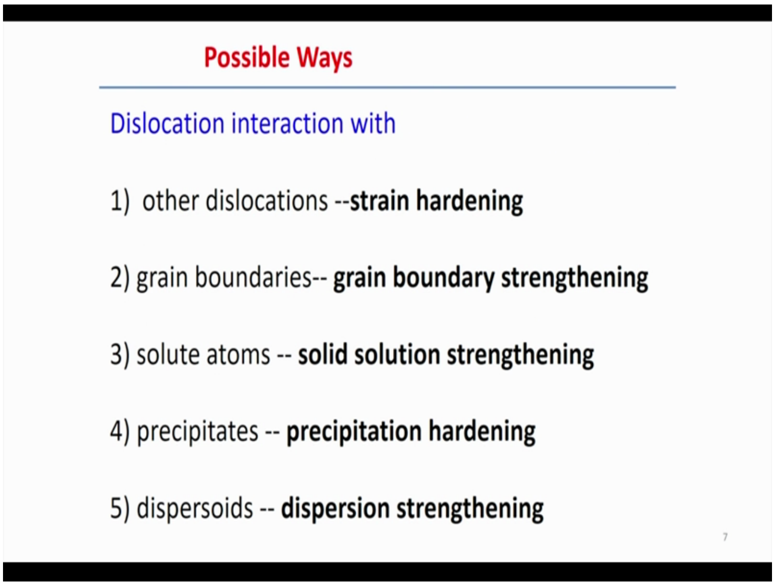

Possible Ways

Dislocation interaction with

1) other dislocations --**strain hardening**

2) grain boundaries-- **grain boundary strengthening**

3) solute atoms -- **solid solution strengthening**

4) precipitates -- **precipitation hardening**

5) dispersoids -- **dispersion strengthening**

Now what are the other way that means how dislocation can interact and what are the typical mechanism is called for the that impart the strain for a specific single crystal structure. So one is that dislocation interaction, how they are interacting with each other with respect to the other dislocation probably that is called strain hardening mechanism. When dislocation interaction happens with respect to the grain boundaries then we can say that grain boundaries strengthening. Actually the presence of the grain boundary creates some obstacle to the motion o the dislocation. Third when the dislocation interaction with the solute atoms that we can say the solid solution strengthening and then interaction with the precipitates then we can say the precipitation hardening and dislocation interaction with the dispersoids then we can call is the dispersion strengthening mechanism.

So all this typical mechanism exist and here we will try to explain all this typical mechanism, how the dislocation actually interact with the different phenomena with respect to other dislocation, with respect to grain boundary, with respect to the presence of the solute, presence of the precipitates and in presence of the dispersoids. So all these mechanisms are active, in general is effective to increase impart the strength of a single crystal structure.

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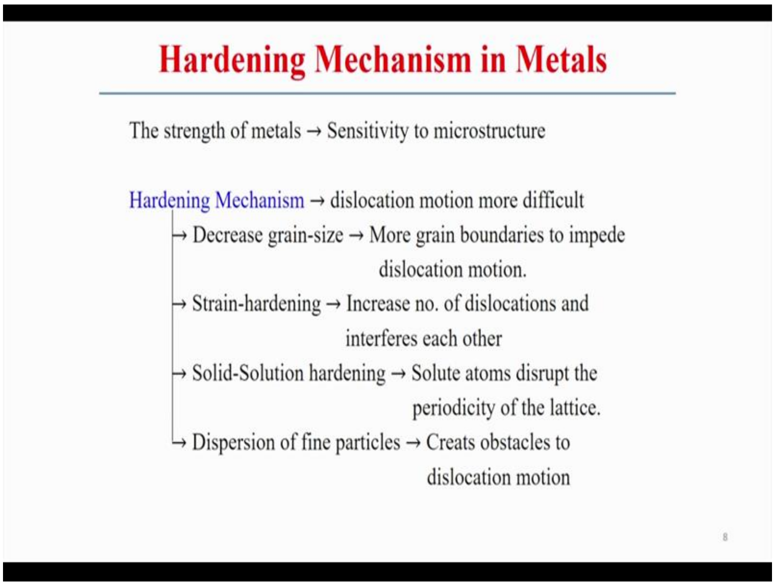

Hardening Mechanism in Metals

The strength of metals → Sensitivity to microstructure

Hardening Mechanism → dislocation motion more difficult
- → Decrease grain-size → More grain boundaries to impede dislocation motion.
- → Strain-hardening → Increase no. of dislocations and interferes each other
- → Solid-Solution hardening → Solute atoms disrupt the periodicity of the lattice.
- → Dispersion of fine particles → Creats obstacles to dislocation motion

Now in general the hardening mechanism or maybe strengthening, we can say the strengthening mechanism in metals, is basically explained in such a way that the strength of the metals is actually very much sensitive to the microstructure. So hardening mechanism exist that can be said that dislocation motion more difficult in general we can say or maybe strengthening mechanism reason is a mechanism is simply we can say that the dislocation motion becomes more difficult that actually impart the strain of hardening mechanism to the single crystal structure or polycrystal crystal structure or in general in metals. So decrease in grain size that means that is more related to the more grain boundaries to impede dislocation motion.

Strain hardening actually increases the number of dislocation and also interferes with respect to each other and that with the number of dislocation actually with that mechanism actually this mechanism is generally called the imparting the strength by the mechanism of the strain hardening. Solid solution hardening solid, solid atom disrupt the periodicity of the lattice presence of the solute atoms in an alloy as compared to the pure metal, actually impart some amount of the obstacles of the dislocation motion, so this also that is called the solid solution hardening or solid solution strengthening mechanism.

Dispersion of the fine particles basically creates obstacles to the dislocation motion in the presence of the fine particles and that presence of the fine particles actually impart some amount of the obstacles of the dislocation and this mechanism is called dispersion strengthening mechanism. So all this difficult strengthening mechnism we will try to explain the each and every mechanism one by one. So first we will try to look into that.

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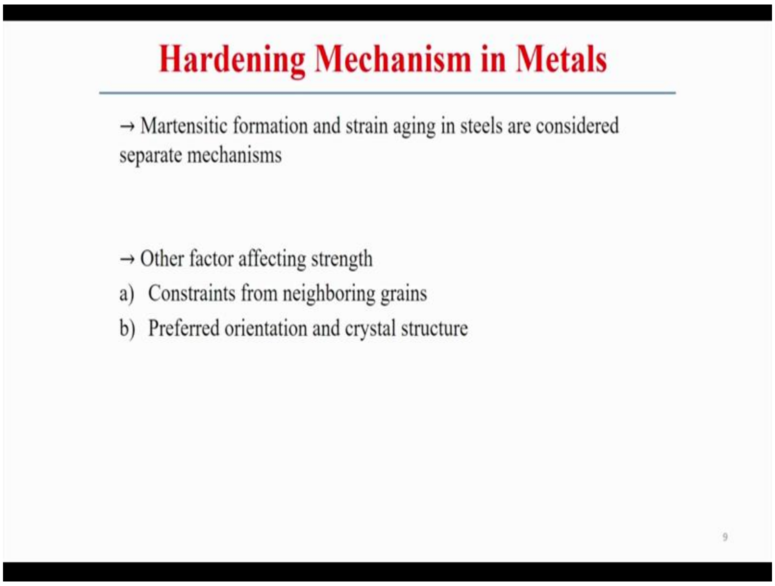

Hardening Mechanism in Metals

→ Martensitic formation and strain aging in steels are considered separate mechanisms

→ Other factor affecting strength

a) Constraints from neighboring grains

b) Preferred orientation and crystal structure

Before that we can say that Martensitic formation and the strain aging in steels are also considered the separate mechanism which is not in the same class we have classified the strengthening mechanism or hardening mechanism metal excluded the martensitic formation and strain aging effect in steels. Other factors that affect the strain basically the on strain from the neighboring atoms, neighboring grains in case of polycrystalline structure and of course the preferred orientation and type of the crystal structure is the another affecting factor that actually brings or that actually influence the strength of the microstructure or single crystal structure.

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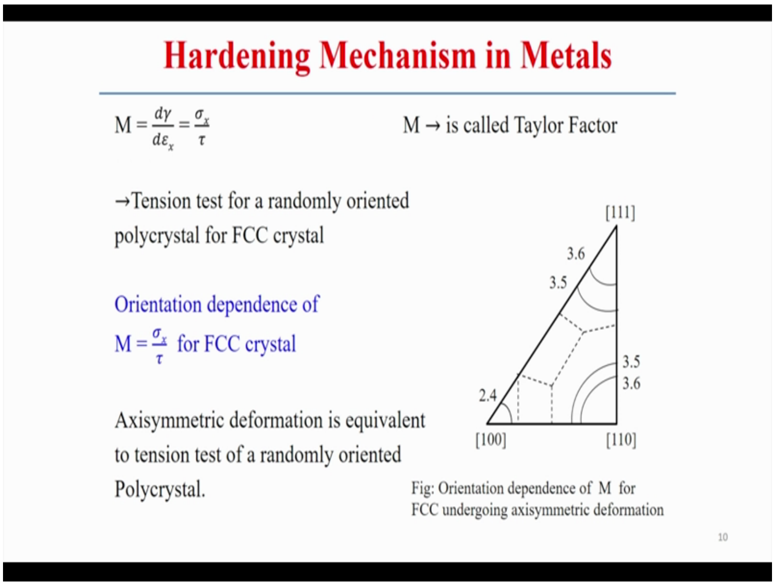

Hardening Mechanism in Metals

$M = \frac{d\gamma}{d\varepsilon_x} = \frac{\sigma_x}{\tau}$

M → is called Taylor Factor

→Tension test for a randomly oriented polycrystal for FCC crystal

Orientation dependence of $M = \frac{\sigma_x}{\tau}$ for FCC crystal

Axisymmetric deformation is equivalent to tension test of a randomly oriented Polycrystal.

Fig: Orientation dependence of M for FCC undergoing axisymmetric deformation

So we have this already discussed the Taylor factor and this m is defined and here figure actually represents the orientation dependences of m the Taylor factor per FCC undergoing Axisymmetric deformation. Actually this factor or individual contours is comes that depending upon orientation of the application of the load or orientation, different orientation of the slip. So here we consider the along the three specific axis, 100, 110 and 111, in this three axis we consider as a corner point of a triangle and within this triangle for the different direction the deformation behavior we are trying to, the deformation behavior may not be the same in between this three directions and we are plotting the orientation dependences of this deformation represented by this three triangle and we try to represent the variation of all these things, in terms of the contour plots.

So basically this isocontour, the variation from this point to that point it is basically that represent 3.5, 3.6 this are the simple number that represents the isocontour between the two axis. So that orientation dependences of the m we have consider and most of the cases when you try to analyze the behavior of the polycrystalline material probably we can consider the average value of m and in that case we estimate the relation between the shear stress strain of a single crystal structure with respect to the polycrystalline structure. And in this case this actually orientation dependences on this Taylor factor actually is very much effective when we have the deformation behavior of the polycrystalline structure and by looking into the average value of the m we can produce the deformation behavior of the stress strain curve of a single crystal structure.

But tension test for the randomly oriented polycrystal for FCC and for this case we need to define this Taylor factor m and orientation dependence m or FCC crystal structure is represented here that m is the ratio of the shear stress by the sorry normal stress by the shear stress component. So Axisymmetric deformation here we have mentioned that is equivalent to the tension test of a randomly oriented polycrystals. So looking into the concept of this using the Taylor factor probably we can use to explain the hardening behavior here.

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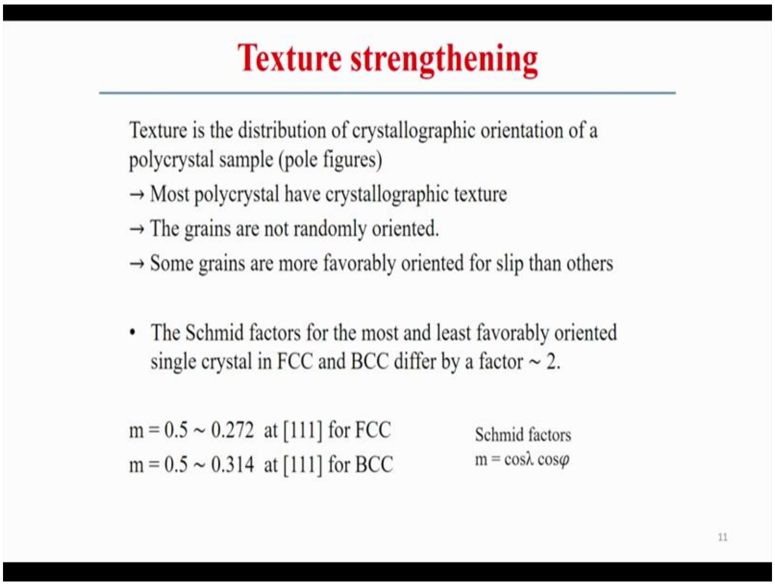

Texture strengthening

Texture is the distribution of crystallographic orientation of a polycrystal sample (pole figures)

→ Most polycrystal have crystallographic texture

→ The grains are not randomly oriented.

→ Some grains are more favorably oriented for slip than others

- The Schmid factors for the most and least favorably oriented single crystal in FCC and BCC differ by a factor ~ 2.

$m = 0.5 \sim 0.272$ at [111] for FCC

$m = 0.5 \sim 0.314$ at [111] for BCC

Schmid factors

$m = \cos\lambda \cos\varphi$

That is called the Texture strengthening mechanism. Texture is the distribution of the crystallographic orientation of a polycrystal sample and that is better explained by the pole figures, so I am not focusing on the pole figures here, but just to idea about this thing the structure strengthening, here most of the polycrystal have crystallographic texture. So orientation in one direction there is a crystallographic orientation we generally consider. The grains are not randomly oriented in that case if we consider this thing and some grains are probably most favorably oriented for the slip system then with respect to others. So this orientation of this grain and with respect to slip direction or their difference probably bring some that actually bring some amount of the strengthening in the crystal structure, in the deformation of the polycrystalline structure.

Since some grains maybe more favorably oriented and some grains may not be, so that is the is the structure is having some influence on the strengthening mechanism. So it is observed that the Schmid factor for most of the, most and the least favorably oriented single crystal in FCC and BCC actually differs by the factor 2. Just approximately factor 2, if you see that m along the direction 111 for FCC, the resolve factor m actually vary between 0.5 to 0.27 so ratio is approximately to, for BCC structure for the same direction the ratio is varies m from 0.5 to 0.314, so there is a huge variation of this m can vary depending upon the application of the slip system or slip direction or application of which direction the load is acting. And we represent x equal to cos phi cos lambda. So here the significant point is that the m actually varies over a wide range so in FCC and BCC probably it is near about 2. There is a huge variation of this thing, so this variation, this variable can be used to represents the mechanism of the structure strengthening.

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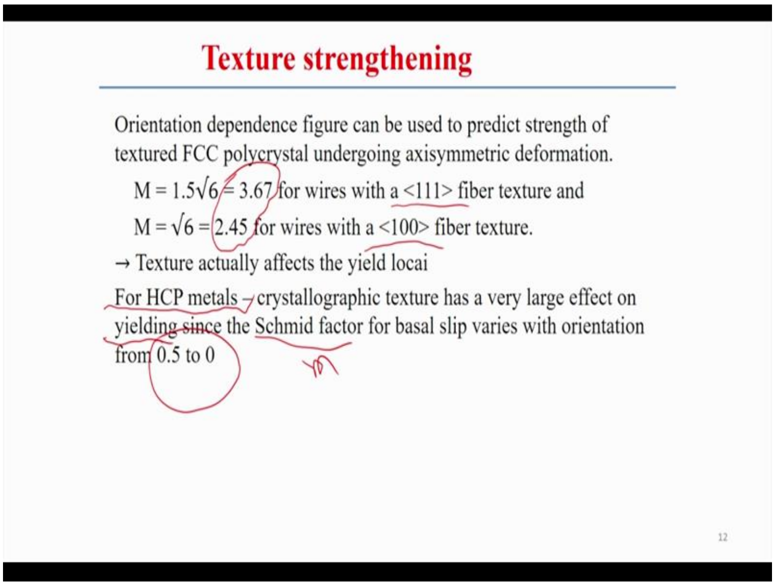

Texture strengthening

Orientation dependence figure can be used to predict strength of textured FCC polycrystal undergoing axisymmetric deformation.

M = 1.5√6 = 3.67 for wires with a <111> fiber texture and

M = √6 = 2.45 for wires with a <100> fiber texture.

→ Texture actually affects the yield locai

For HCP metals – crystallographic texture has a very large effect on yielding since the Schmid factor for basal slip varies with orientation from 0.5 to 0

So orientation dependence figure can be used to predict the strength of a texture FCC polycrystal under going Axisymmetric deformation. For example the for wire of fiber texture is along 111 direction, m can be considered as the value of 3.67, but wires with the 100 fiber texture m can be 2.45. That means if orientation of the single crystal, if orientation is more favorably oriented along 111 direction or if orientation is along 100 direction, in this two cases the values of the Taylor factor is you see there is difference in the Taylor factor, so actually and this difference Taylor factor present because of the texturing in specified direction. So that means texture actually affect the yield and probably this presence of the texture is the being some not in the anisotropy plastic behavior in the deformation of a polycrystalline structure.

If we observe for HCP metals, for HCP crystal structure metals the crystallographic texture has a very large effect on yielding, so on yielding it is having very huge effect since the

Shmid factor that means m for basal slip plane actually varies with orientation form 0.5 to 0. So that means there is a huge variation due to the presence of the texture in HCP crystal structure where the m varies 0.5 to 0. So with this variance there is a variation so that signifies that the presence of the texture actually imparts presence of the consideration of the texture or presence of the texture is basically impart some amount of the strain in case of the crystal structure. So if we consdier the plastic behavior of the material or specifically polycrystalline material is necessary to consider the effect of texturing and the presence of the texturing actually brings some anisotropy behavior of the polycrystalline structure.

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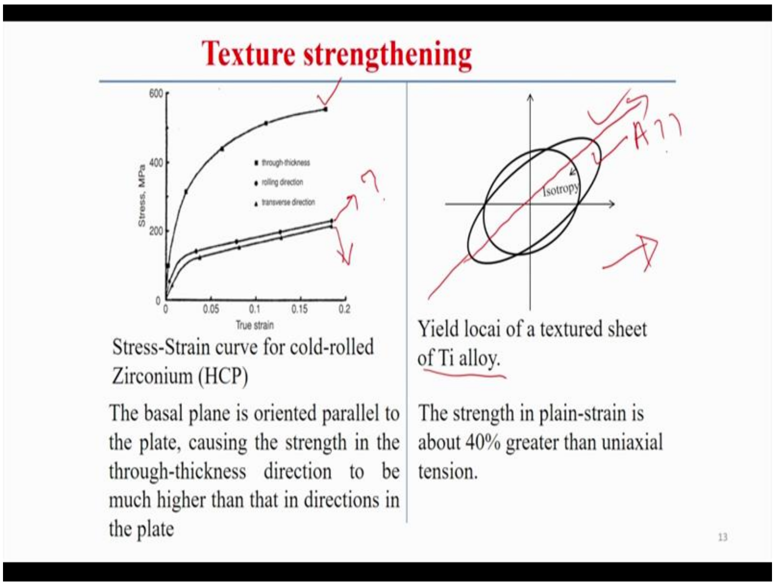

Texture strengthening

Stress-Strain curve for cold-rolled Zirconium (HCP)

The basal plane is oriented parallel to the plate, causing the strength in the through-thickness direction to be much higher than that in directions in the plate

Yield locai of a textured sheet of Ti alloy.

The strength in plain-strain is about 40% greater than uniaxial tension.

So in that sense if we plot the stress cold rolled Zirconium, if we see that the several rolling direction that this curve actually represents the rolling direction, so we are trying to explain the rolling process here and if we see there is a stress versus two stress versus two strain curve, we see this is a rolling direction that transfers direction, if we see the transfer direction, the second figure and the third figure is the through thickness direction. So we observe in a rolling process that three different direction there are stress strain behavior is completely different. So probably with this deformation, with this deformation behavior and the presence of the texture in this specific structure probably the strengthening effect is more in case of in the through thickness direction.

So in this case actually the basal plane is oriented parallel to the plate causing the strain in the through thickness direction to be the much higher than that in the direction in the plate. So message is that presence of the texture one specific direction probably impart some strength thickening mechanism with respect to the amount of the other direction. So through thickness direction here in this case through thickness direction is the more amount of the strain is produced and this happens due to the presence of the texture which is oriented parallel to the plate. Now efinitely the presence of texture also affects the isotropic behavior of the metal structure and if we see the yield locai of a textured sheet or titanium alloy. The figure represents that yield locai of a titanium alloy.

Here see the isotropic behavior and anisotropy behavior. This curve actually represents the anisotropy behavior and we see the strain in plane strain is above 40% greater than that uniaxial tension. So on the plane strain, in case of the plane strain condition there strain is 40% greater than that of uniaxial tension and see, and that happens due to the presence of the amount of the texture and that anisotropy we see that the strain level is very high or yield locus is more as compared to the isotropic behavior of the metal and that is because of the presence of the textures.

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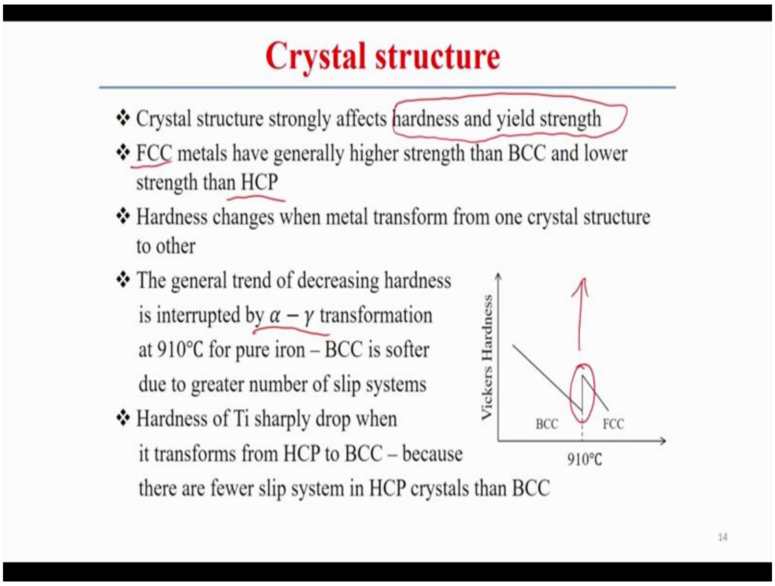

Crystal structure

- Crystal structure strongly affects hardness and yield strength
- FCC metals have generally higher strength than BCC and lower strength than HCP
- Hardness changes when metal transform from one crystal structure to other
- The general trend of decreasing hardness is interrupted by $\alpha - \gamma$ transformation at 910°C for pure iron – BCC is softer due to greater number of slip systems
- Hardness of Ti sharply drop when it transforms from HCP to BCC – because there are fewer slip system in HCP crystals than BCC

So with this effect of the strengthening due to the presence of the texture in a crystal structure. Now we will try to focus on that mechanism. Because of the crystal structure, so differences in the crystal structure also bring some amount, also brings the different in the stress level. Let us look into that, first crystal structure actually strongly affects the hardness and the yield strength. Mainly happens on that strongly. FCC metals have generally higher strength than BCC and lower strength than HCP. So FCC, that but hardness changes when the metal transforms that is more important from one crystal structure to other. So the electrofic transformation in this case the general trend of the decreasing hardness is interrupted alpha to gamma, so two different phase transformation at 910 degree for pure iron.

So if see the figure that actually at this temperature 910 degree centigrade for pure iron, the crystal structure changes from BCC to FCC. So at this joint BCC to FCC, so at the joint BCC structure is softer sue to the greater number of the slip system. We know that in BCC structure there are 48 slip system but in FCC structure there are 12 slip system, probably that is the reason for that. BCC is the softer and FCC is the harder, FCC impart more amount of the strain particularly at this temperature when there is a transformation happens from BCC to FCC structure in case of pure iron.

Similarly if we consider another example that hardness of the titanium actually sharply drop when it transforms HCP structure to BCC structure. Because there are few slip system in HCP crystals. Probably slip system is very, number of it is very less as compared to the BCC structure and actually observes in the titanium alloy. So here we can say that crystal structure actually brings and the presence of the different slip system also responsible to differentiate in the strength level to differentiate the change of the hardness or change of the strength level can also be observed in case of the different type of crystals. And that is more or less related to that transformation as a specified temperature when it transforms from one typical crystal structure to the another structure because during the transformation one structure to another structure system, so there is a difference in the slip system in this case and that difference in the slip system impart whether there is a increment of whether there is a decrement of the hardness or strength level for a specific crystal structure.

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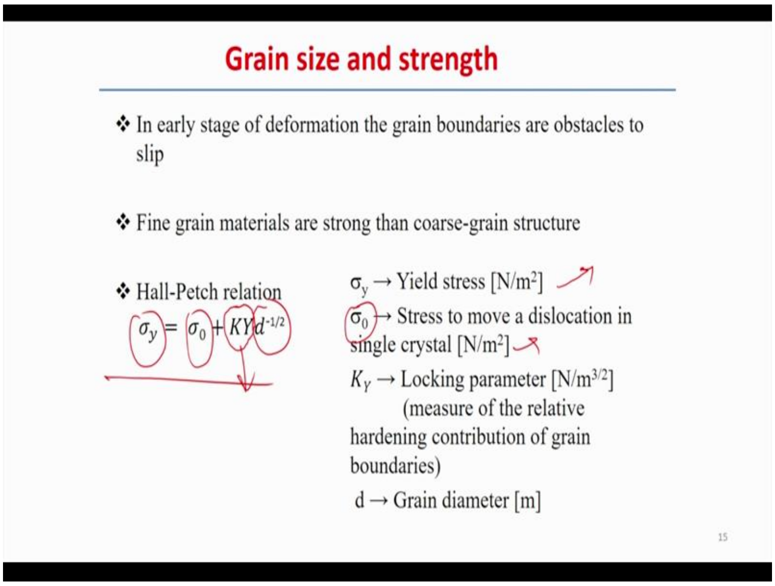

Grain size and strength

- ❖ In early stage of deformation the grain boundaries are obstacles to slip
- ❖ Fine grain materials are strong than coarse-grain structure
- ❖ Hall-Petch relation

$$\sigma_y = \sigma_0 + K_Y d^{-1/2}$$

σ_y → Yield stress [N/m^2]

σ_0 → Stress to move a dislocation in single crystal [N/m^2]

K_Y → Locking parameter [N/m$^{3/2}$] (measure of the relative hardening contribution of grain boundaries)

d → Grain diameter [m]

So after discussing on the effect of the crystal structure on a strengthening mechanism, now we shift to that effect of the grain size and how it can be presence of the grain size, how grain size can linked with a strain of a single crystal or polycrystalline structure. In early stage of deformation actually the grain boundaries create the obstacles to the slip system. Fine grain materials are stronger than that of the coarse grain structure only because of that fine grain structure, the total grain boundary area is more as compared to the coarse grain structure and when there is a grain boundary area is more probably that gets more amount of the obstacles to the dislocation movement.

So this, the relation between the strain and grain size probably bette explained by the Hall-Petch relation, here if we see what is their relation, sigma y, sigma y is basically yield stress and maybe we can represent in the yield stress in the SI unit, Netwon per meter square. Sigma 0, actually the stress to move a dislocation in single crystal structure that is the amount of the stress require, that is the fixed amount of the stress required to move the dislocation and that is sigma 0, that is represents the Newton per meter square and the KY is the locking parameter measure of the relative hardening contribution of the grain boundary, so it is basically constant term used depending upon the type of grain and d is the grain size or grain diameter. So this are the very important equation we generally relate the yield stress value in terms of the grain size.

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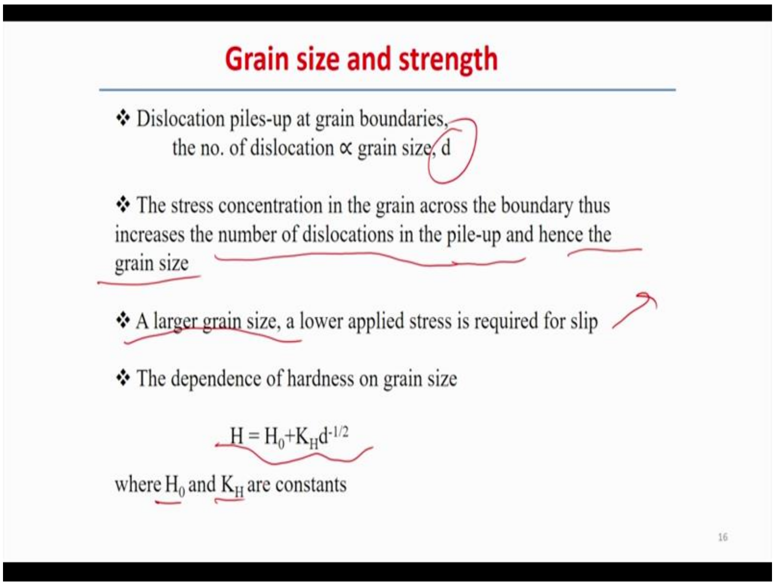

Grain size and strength

- ❖ Dislocation piles-up at grain boundaries, the no. of dislocation ∝ grain size, d
- ❖ The stress concentration in the grain across the boundary thus increases the number of dislocations in the pile-up and hence the grain size
- ❖ A larger grain size, a lower applied stress is required for slip
- ❖ The dependence of hardness on grain size

$$H = H_0 + K_H d^{-1/2}$$

where H_0 and K_H are constants

Now what are the typical mechanism for the increment or strain, the presence of the grain or presence of the grain boundary so actually the dislocation piles up at grain boundaries and this number of dislocations in the pile up is actually proportional to the grain size that is grain diameter. But the stress concentration in the grain across the boundary actually increases the number of dislocation in the pile and hence the grain size. So the number of dislocation in the pile up is responsible to increase the grain size and a larger grain size lower applied stress is required for slip. And the depend similar way, the dependence of the hardness can also be relate with respect to the grain size H equal to H0 and with the similarly philosophy when you try to react the strain to the grain size and here H0 and HK are constant terms.

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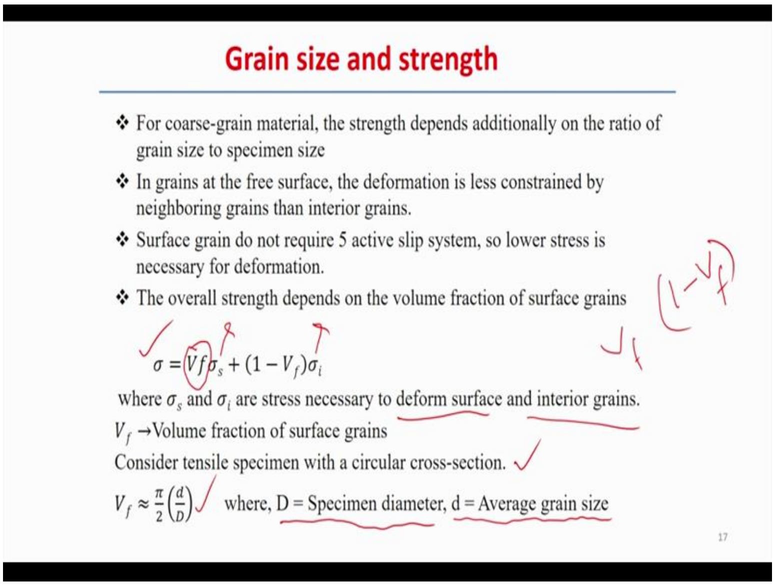

Grain size and strength

- ❖ For coarse-grain material, the strength depends additionally on the ratio of grain size to specimen size
- ❖ In grains at the free surface, the deformation is less constrained by neighboring grains than interior grains.
- ❖ Surface grain do not require 5 active slip system, so lower stress is necessary for deformation.
- ❖ The overall strength depends on the volume fraction of surface grains

$(1-V_f)$

$$\sigma = V_f \sigma_s + (1 - V_f)\sigma_i$$

V_f

where σ_s and σ_i are stress necessary to deform surface and interior grains.

V_f →Volume fraction of surface grains

Consider tensile specimen with a circular cross-section.

$V_f \approx \frac{\pi}{2}\left(\frac{d}{D}\right)$ where, D = Specimen diameter, d = Average grain size

Now more fact on the grain size relation between grain size and the strain we can say that for coarse grain material the strength depends additionally on the ratio of the grain size to the specimen size. When there is a coarse grain structure the effort from the motion to the dislocation movement it the strength level actually depend on the ratio of the grain size to the specimen size. So let us look into that fact that the grains at the free surface, the deformation is less constrained by neighboring grain than interior grains. So the deformation level on the surface grains is different from the deformation level of the interior grain for a specific sample. And that actually influence the strengthening mechanism at in that way that surface grain actually do not require except the 5 active slip system so lower stress is necessary for the deformation.

So low amount of the stress can deform the surface grain as compared to the interior grain of the sample. Therefore the overall strain can be represented of the volume fraction of the surface grains can be represented like this, sigma equal to Vf sigma s plus 1 minus Vf sigmai. So proportionate way if it is possible to estimate the volume fraction of the surface grains as compared to the interior grains so we can estimate the overall strain of a sample and that actually depends on the amount of the surface grain or basically the amount of the surface area presence in the specific sample. So this is the stress for the surface grain and this is the stress level for interior grain and we can multiply this proportionate percentage of the volume fraction.

So as sigma x and sigma I are stress necessary to deform the surface and interior grains. Vf is the volume fraction of the surface grains, so since volume fraction of the surface grain, so volume fraction of the interior grain it will be 1 minus Vf. So if we consider the tensile specimen with a circular cross section in this case we can roughly estimate the volume fraction is pi by 2 d by D is the ratio, capital D is the specimen diameter, and small d is the average grain size. So this volume fraction depends on this ratio and we can estimate the overall strain.

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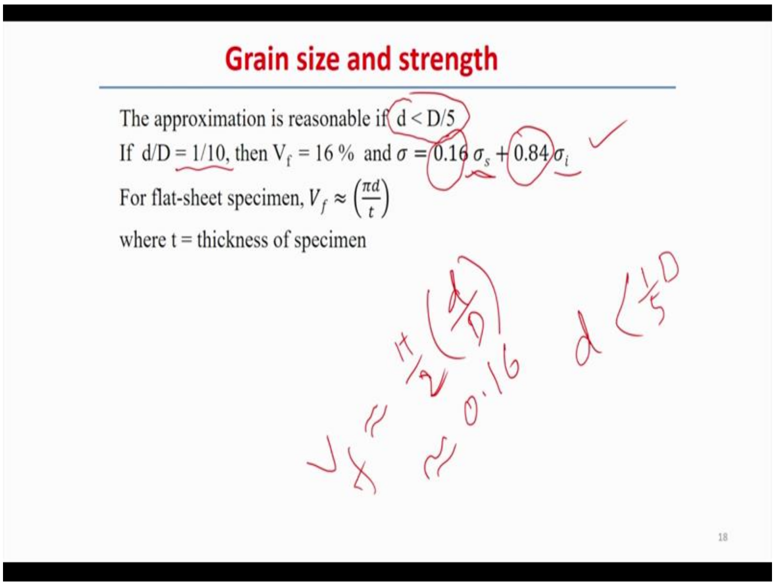

Grain size and strength

The approximation is reasonable if $d < D/5$

If $d/D = 1/10$, then $V_f = 16\ \%$ and $\sigma = 0.16\,\sigma_s + 0.84\,\sigma_i$

For flat-sheet specimen, $V_f \approx \left(\frac{\pi d}{t}\right)$

where t = thickness of specimen

$V_f \approx \frac{\pi}{2}\left(\frac{d}{D}\right) \approx 0.16$

$d < \frac{1}{5}D$

But the estimation is reasonable if d, at least d less than the diameter is less than one fifth of the specimen diameter. Then the this approximation is applicable. Let us look into that one example, d by D equal to 1 by 10 so in this case we can estimate the volume fraction by (())(39:19) pi by 2 into d by D so in this case we can roughly estimate, small d by capital D is 1 by 10, probably in this case it is approximately 0.16. So we can find out that 0.16 into the stress value for the surface stress and this is the stress value for the interior grains. So this is the typical estimation of that. But if the flat, we consider the flat-sheet specimen, in this case the volume fraction can be roughly estimated that pi d by D, here t is the thickness of the specimen so that volume fraction depends on the grain size and the thickness ratio.

So this is the typical calculation we can show that the effect of the grain size or to link between the grain size and strength level we use the Hall-Petch equation also to relate the strain or flow stress value in terms of the average grain size or similar we can relate the hardness of a material in terms of the average grain size that follow the similar kind of relation.

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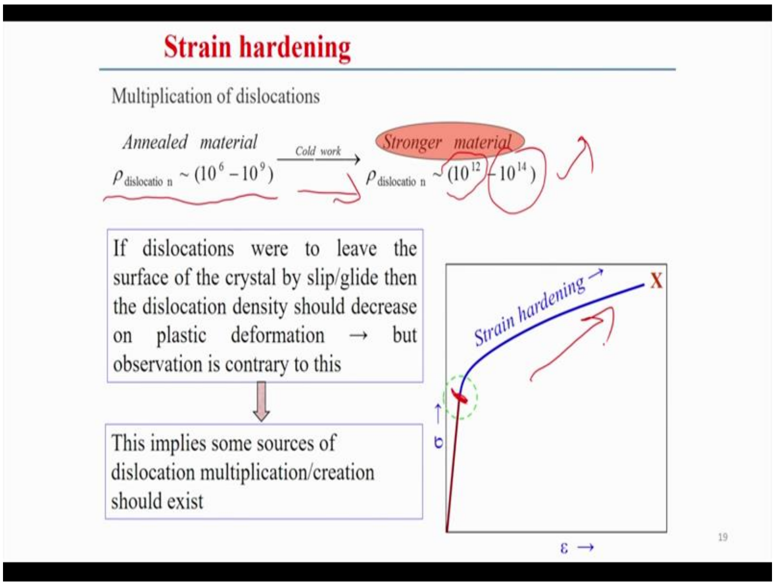

Strain hardening

Multiplication of dislocations

Annealed material $\rho_{dislocation} \sim (10^{6} - 10^{9})$ $\xrightarrow{\text{Cold work}}$ *Stronger material* $\rho_{dislocation} \sim (10^{12} - 10^{14})$

If dislocations were to leave the surface of the crystal by slip/glide then the dislocation density should decrease on plastic deformation → but observation is contrary to this

This implies some sources of dislocation multiplication/creation should exist

Now we will try to focus on strain hardening mechanism, how this mechanism impart the strain to a specific start or specific single crystal structure or polycrystalline structure. So basic mechanism for the strain hardening is that during the deformation there is a increment of the dislocation so there is a dislocation generation and dislocation density actually increases with a deformation of the metal, so that increment amount of the dislocation impart the strength, let us look into some physical data on that, so dislocation density of a annealed material probably in the normality range in the 10 to the power 6 to 10 to the power 9.

But with the application of the cold work, if you try to deform that sample then the dislocation density increases 10 to the power 12 to and the range of 10 to the power 14. So the increment of the strain, the second when there is a increment of the dislocation density this becomes more stronger material as compared to the annealed metal work. So that differentiate we can bring in terms of the dislocation density. There is a increment of the dislocation density. Now if dislocation were to the leave the surface of the crystal by slip or glide then the dislocation density should decrease on plastic deformation but observation is contrary to this.

So if we look into that so up to, when we just start the plastic deformation beyond that there is a with the due to the strain hardening mechanism there is a increment of the dislocation density and that actually impart the amount of the strain to the material. So this implies some source of the dislocation multiplication or creation should exist so because of that the dislocation generation mechanism there is a we know that there is a Frank Reed source of dislocation generation so that means with a further cold working on the material or the deformation of the material there is a increment of the dislocation density and that dislocation density actually the interaction between them or the dislocation density as a bulb some amount to impart the movement of the dislocation more difficult and that is responsible to increase the strength. So that is increase the strength due to the mechanism of the strain hardening.

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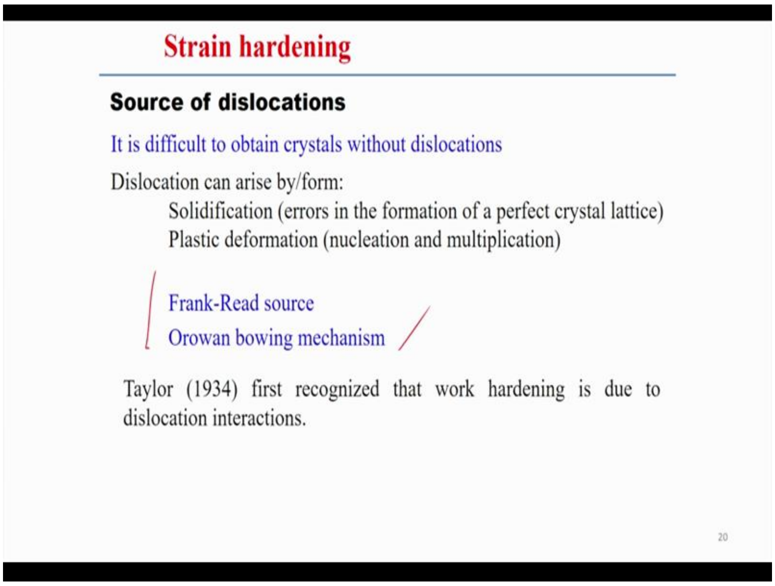

Strain hardening

Source of dislocations

It is difficult to obtain crystals without dislocations

Dislocation can arise by/form:

- Solidification (errors in the formation of a perfect crystal lattice)
- Plastic deformation (nucleation and multiplication)

Frank-Read source

Orowan bowing mechanism

Taylor (1934) first recognized that work hardening is due to dislocation interactions.

But what are the source of the dislocation, so it is difficult to obtain crystal without dislocation so it is difficult the obtain the being crystal without the presence of making any, if we consider a single grain it is difficult to presence of difficult to produce the grains without any dislocation, but what maybe the typical source of the dislocation. Probably practically we can say the solidification, because errors in the formation of the perfect crystal lattice is happens during the solidification of the material and solicitation, after solicitation there metal the sample is subjected to some amount of the dislocation.

Another source of the dislocation is the plastic deformation. If we further strain the material or there is or if we try to deform the material so there is a, there must be some nucleation and the multiplication of the dislocation happens so that is better explained in terms of the two basic element theory, the Frank Reed course of the dislocation, how we can impart or generate the dislocation during the plastic deformation of a material and Orowan bowing mechanism also responsible for that. But the hardening mechanism can be better explained which is started by Taylor in 1934 that the work hardening is due to the dislocation interaction. So basic mechanism of the work hardening is the dislocation interaction, so let us see how the, what are the prediction of the Taylor theory.

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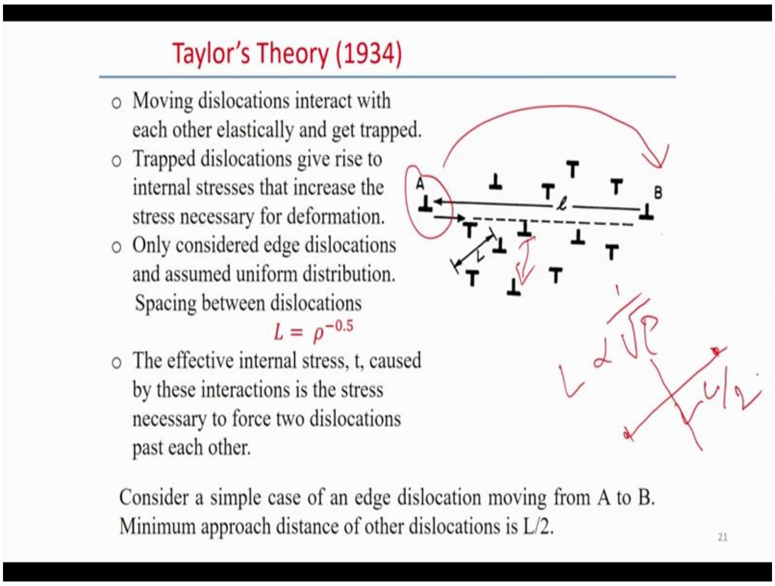

Taylor's Theory (1934)

- Moving dislocations interact with each other elastically and get trapped.
- Trapped dislocations give rise to internal stresses that increase the stress necessary for deformation.
- Only considered edge dislocations and assumed uniform distribution. Spacing between dislocations

$$L = \rho^{-0.5}$$

- The effective internal stress, t, caused by these interactions is the stress necessary to force two dislocations past each other.

Consider a simple case of an edge dislocation moving from A to B. Minimum approach distance of other dislocations is L/2.

It is as we say the moving dislocation interact with each other elastically and get trapped. Probably we are trying to explain the elastic deformation here that is the assumptions of this theory. Now trapped dislocation give rise to the internal stresses that actually increase the stress necessary for deformation. So only consider edge dislocation, let us consider only edge dislocation, and assume there is a uniform distribution of the dislocation and the spacing between dislocation can be represent as in terms of the, this is the L probably represents the 1 by dislocation density. So if we look into this figure, here if you see that the several dislocation are there and the distance between the two dislocations is L and this is the elemental length to total to similar A and B, the simple case of edge dislocation is moving from point A to point B over a length small l.

Now the effective internal stress caused by this interaction is stress necessary to force two dislocation pass each other. When one dislocation at point A will try to move point B so the interaction, it will try to cannot, it is not possible to avoid the interaction with the presence of the other dislocations. So presence of the other dislocation and their interaction with this dislocation presence at A during the travel from point A to point B having some effect or that actually impart some amount of the stress to move from A to B. If we consider it is free from other dislocation so maybe some minimum amount of stress is necessary to move from A to B, but presence of other dislocation in that path with different orientation actually makes more complicate or makes it is necessary to large amount of the stress is required to move from point A to point B.

That means presence of other dislocation actually interact to the initiation of the movement of the dislocation from one point to another point and that is represents the what is the amount of the extra stress is necessary to move from point A to B in the presence of the other dislocation. So of course as a bulk the presence of the other dislocation, it is better to represent or representation of the so many dislocation on specified zone in terms of the dislocation density other than individual dislocation. So spacing between this dislocation probably between two dislocation and it is a average value, let us consider as capital A.

Now consider the simple case of edge dislocation from point A to B and now minimum approach dislocation of other dislocation is L by 2. So that means between two distance, between two dislocation if we assume the average distance is L so at least effect of the 1 dislocation can be half of this, so that is L by 2 and that is called the minimum approach distance of other dislocation is the half of the average distance between the two dislocation that is Capital L by 2.

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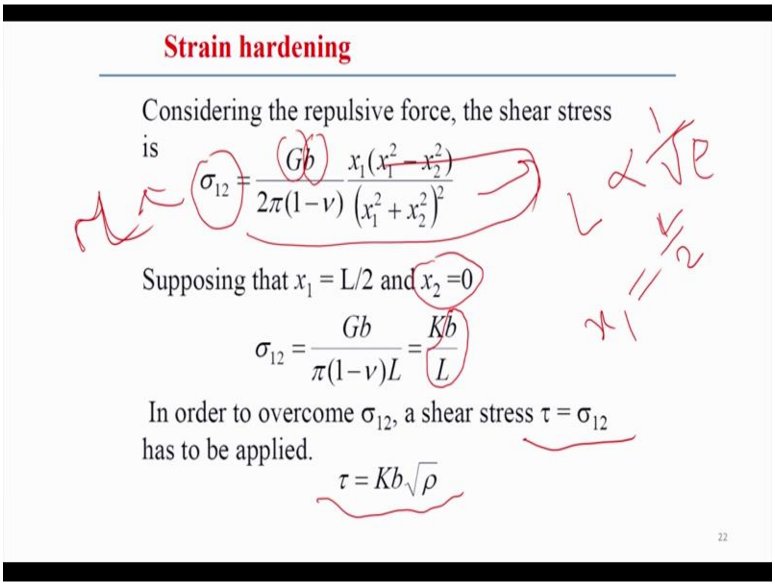

Strain hardening

Considering the repulsive force, the shear stress is

$$\sigma_{12} = \frac{Gb}{2\pi(1-\nu)} \frac{x_1(x_1^2 - x_2^2)}{(x_1^2 + x_2^2)^2}$$

Supposing that $x_1 = L/2$ and $x_2 = 0$

$$\sigma_{12} = \frac{Gb}{\pi(1-\nu)L} = \frac{Kb}{L}$$

In order to overcome σ_{12}, a shear stress $\tau = \sigma_{12}$ has to be applied.

$$\tau = Kb\sqrt{\rho}$$

$L \propto \frac{1}{\sqrt{\rho}}$

$x_1 = L/2$

Considering the repulsive force the shear stress between this, between the interaction of the two dislocation we can represented in that things that we have discussed when we try to explain the interaction of the dislocations and corresponding the stress field we represented in terms of this coordinate x1 x2 and the Burgers vector and the shear modulus G and the Poisson ratio in this case. So now suppose if we consider x1 is that minimum distance of basically L by 2 half of the average distance of the dislocation and if we consider X2 equal to 0 then we can estimate the amount of the shear stress is actually Gb by pi 1 minus mu into L. So that is basically some constant term and Burgers vector and the distance between the two dislocation.

So in order to overcome this amount of the shear stress value, here shear stress represents the tau equal to sigma b, if we equate it and if we apply that then we can say that the shear stress is actually Gb into root the power of L because distance is actually proportional to the 1 by dislocation density that we have already used that region. So using that we can find out the L, and if we replace L so it is say that the shear stress is actually proportional to the depends on the dislocation density and the Burgers vector in this case.

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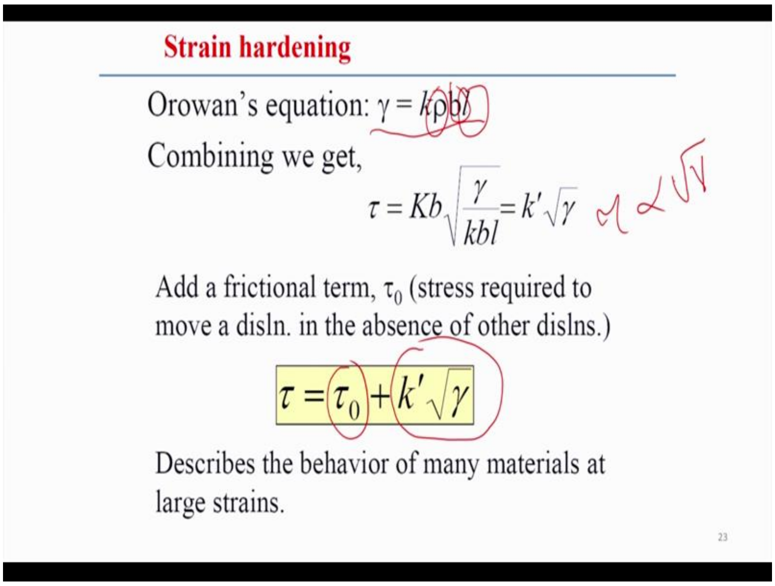

Strain hardening

Orowan's equation: $\gamma = k\rho b l$

Combining we get,

$$\tau = Kb\sqrt{\frac{\gamma}{kbl}} = k'\sqrt{\gamma}$$

$\tau \propto \sqrt{\gamma}$

Add a frictional term, τ_0 (stress required to move a disln. in the absence of other dislns.)

$$\boxed{\tau = \tau_0 + k'\sqrt{\gamma}}$$

Describes the behavior of many materials at large strains.

Now Orowan's equation states that amount of the shear strain some constant terms, dislocation density, Burgers vector and the length between the movement from one point to the another point. So that Lb and rho so by combining this relation and Orowan's equation we can find out that shear stress is specifically proportional to the amount of the shear strain so sometimes this relation can also be used to link that the what is the amount of the shear stress required to move the dislocation which is proportional to the amount of the square root amount of the shear strain.

So in general the equation can be written like that, we need to add a fictional term, tau 0 stress required to move the dislocation in the absence of the other dislocation that means it ideal condition in the absence of the other dislocation, if we introduce that term, that constant term plus this is the some constant term into this which is proportional to the amount of the shear strain to the movement of the dislocation from one point to the another point. So this equation actually describes the behavior of the many materials specifically at the large strain amount so this equation we can use to predict the amount of the shear strain to move the dislocation from one point to another point.

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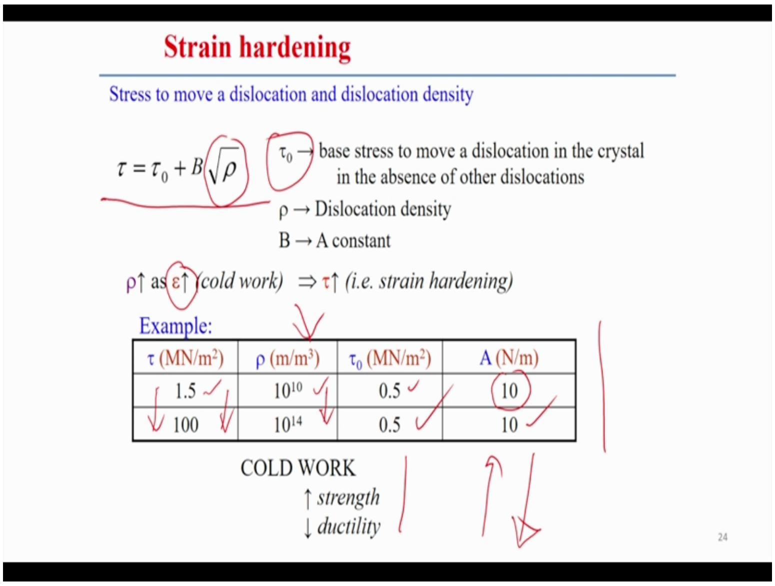

Strain hardening

Stress to move a dislocation and dislocation density

$$\tau = \tau_0 + B\sqrt{\rho}$$

τ_0 → base stress to move a dislocation in the crystal in the absence of other dislocations

ρ → Dislocation density

B → A constant

ρ↑ as ε↑ *(cold work)* ⇒ τ↑ *(i.e. strain hardening)*

Example:

τ (MN/m²)	ρ (m/m³)	τ_0 (MN/m²)	A (N/m)
1.5	10^{10}	0.5	10
100	10^{14}	0.5	10

COLD WORK

↑ *strength*

↓ *ductility*

So in general apart from that equation we can link that finally the amount of the shear stress to move the dislocation and the in terms of the dislocation density probably we can represent the tau equal to tau 0 plus B into root to power of rho. So here tau 0 is specifically base stress to move dislocation in the crystals in the absence of the other dislocation. Rho is the dislocation density and B is the a constant term. So this equation probably we can link that the stress to move the dislocation. Now it is obvious if we do the reasoning of the equation when there is a increment of the dislocation density during in specifically the increment of the dislocation density during the cold work process in this case, there is a amount of the increment of the strain that means deformation, amount of the deformation and that actually correlate directly that (())(53:13) of the shear stress.

So if we look into that (())(53:14) of this dislocation density with application of the cold work increment of the shear stress value tau. That means the increment of the shear stress in the tau means this is the effect of the strain hardening due to the increment of the dislocation density and that happens at the plastic deformation of a single crystal or polycrystalline structure. Now this is just for an example, numerical example to look the physical parameter we can see that shear stress is 1.5, dislocation density is corresponding to 10 to the power 10 1 by meter square and if we consider tau 0 as a constant term we can find out the constant a equal to 10.

Now this becomes 100 when dislocation density changes from 10 to the power 10 to 10 to the power 14, with the change of this amount of the dislocation density there is a increment of the strain from 1.5 megaNewton per meter square to 100. So there is a huge keeping all other parameter the constant term remains the same. So that means only practically there is a increment of the number of dislocation density and that happens practically there is a huge amount of the increment of the strength level. So that is the physical interpretation of the strain hardening. Now of course other point is there during the cold work by increment of the amount of the dislocation density the strength level is increased but the same time the ductility level actually decreases.

So that means material can deform up to certain limit so that after that it cannot sustain the deformation and it (())(55:14) to create the fracture at that point. So point is that with the increment of the strength level there is a decrement of the ductility, that is because of the basic mechanism of the strain hardening in case of single crystal structure and polycrystalline structure.

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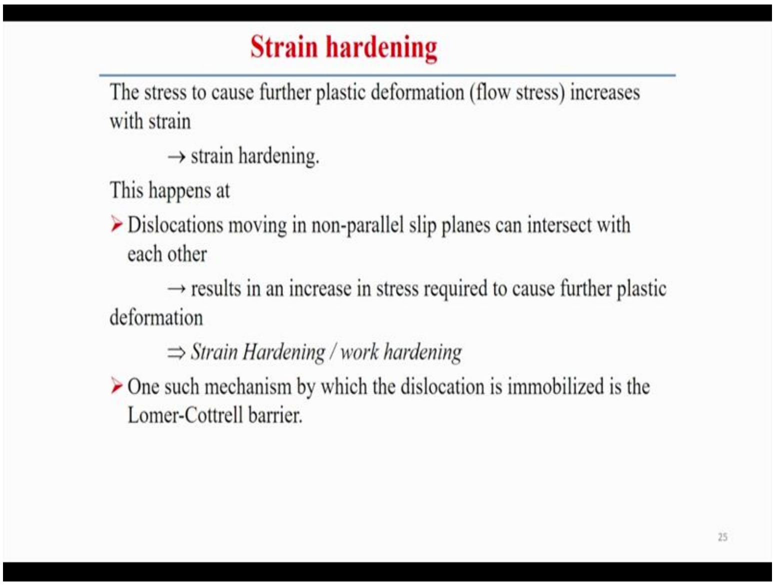

Strain hardening

The stress to cause further plastic deformation (flow stress) increases with strain

→ strain hardening.

This happens at

- Dislocations moving in non-parallel slip planes can intersect with each other

→ results in an increase in stress required to cause further plastic deformation

⇒ *Strain Hardening / work hardening*

- One such mechanism by which the dislocation is immobilized is the Lomer-Cottrell barrier.

Now strain hardening behavior can be explained like that the stress to cause further plastic deformation and that can define sometime use the term the flow stress value and that actually increases with strain and that it can said as the strain hardening but this happens at dislocations moving in non parallel slip planes and when they can intersect with respect to each other. Finally results in an increase in the stress required to cause further plastic deformation and that mechanism is generally called strain hardening or work hardening. One such mechanism by which the dislocation is immobilized is actually is the Lomer Cottrell barrier. So that strain hardening mechanism is sometime is better to explain by the, by this mechanism by which the dislocation becomes immobilized. So I am not going into the detail discussion of this mechanism of strain hardening.

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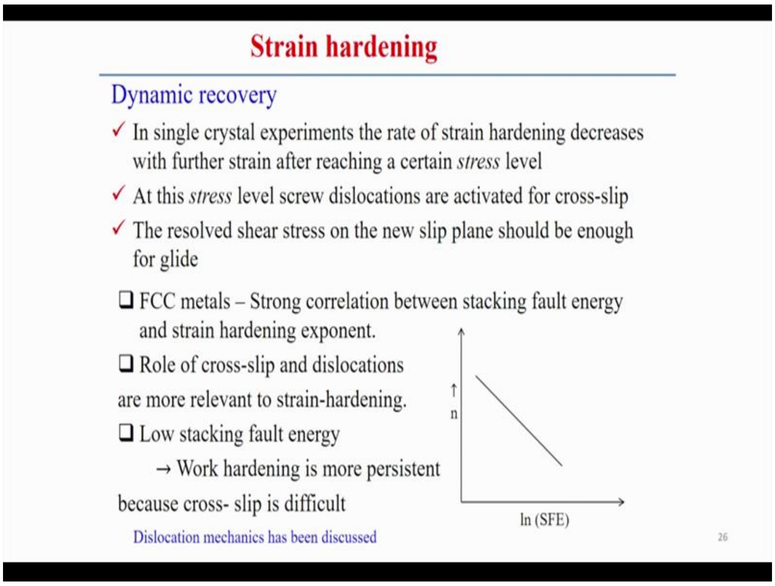

Strain hardening

Dynamic recovery

- ✓ In single crystal experiments the rate of strain hardening decreases with further strain after reaching a certain *stress* level
- ✓ At this *stress* level screw dislocations are activated for cross-slip
- ✓ The resolved shear stress on the new slip plane should be enough for glide

❑ FCC metals – Strong correlation between stacking fault energy and strain hardening exponent.

❑ Role of cross-slip and dislocations are more relevant to strain-hardening.

❑ Low stacking fault energy

→ Work hardening is more persistent because cross- slip is difficult

Dislocation mechanics has been discussed

Now if we look into typical stress strain diagram of a polycrystalline material so specifically after the making there is a dynamic recovery also happens so in single crystal experiment the rate of strain hardening actually decreases with the further straining and specifically at the stress slip and after reaching a certain stress level. At this stress level screw dislocation are actually active for the cross slip because presence of the dislocation actually more prone to the occurrence of the cross slip so in that case the resolved shear stress on the new slip plane should be in enough for glide so that activation of the cross slip actually imparts the dynamic recovery of a specific material and that happens when it is resist to the optimum stress level or maybe after certain stress or maybe after certain stress level the dynamic recovery actually happens.

Now in fact that FCC metals probably having strong correlations between the stacking fault energy and strain hardening exponent, so that is why figure actually represent the relation between the stacking fault energy and the strain hardening coefficient specific in case of FCC metal and here if we see that with increase of the stacking fault energy actually the strain hardening coefficient decreases that means the role of the cross slip and the dislocation are actually more relevant to the effect of the strain hardening when you try to incorporate or try to link what is the effect of the stacking fault energy in the strain hardening mechanism.

So low stacking fault energy in that case work hardening is more persistent because in the low stacking fault energy the cross slip is actually difficult when there is a high stacking fault energy probably in that case cross slip is more easier to form. So when there is a activation of the cross slip or the occurrence of the cross slip the probability is more so in the case there is a chances of the dynamic recovery so that actually effectively reduces the strain hardening effect. But dislocation mechanics related to this different work hardening that means we have already discussed that related to this mechanism dislocation movement probably the dislocation basic mechanism, dislocation pile up, cross slip that we have already discuss edge discussed on this so I am not repeating the same thing again.

So with this effect of the strain hardening to impart of the strength level of a single crystal or polycrystalline structure, today I can stop here so next class I will try to explain the other hardening mechanism, maybe focused on the either single crystal structure as well as the polycrystalline structure. Thank you very much for your kind attention.