Introduction to crystal elasticity and crystal plasticity

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Week-07

Lecture-15

Hello everybody! Let us start the strengthening mechanism due to the presence of the solid solution and dispersion, hardening at the same time precipitation hardening. Last time we had discussed the different strain hardening mechanism. Specifically in case of strain hardening there is a increment of the strength level by the application of the further straining or further plastic deformation of the single crystal structure as well as the polycrystalline structure. Now apart from we have discussed the several strain hardening mechanism, the effect of the crystal structure, we have discussed the effect of the texturing also we have discussed.

Now in today's class we will try to focus on the mechanism of solution strengthening and you know that solid solution probably in case of alloy and in case of alloy when there is a, when we add some alloying element to a pure metal then it becomes alloy and that actually, the strength level normally increases as compared to the pure metal. But what are the mechanism behind that.

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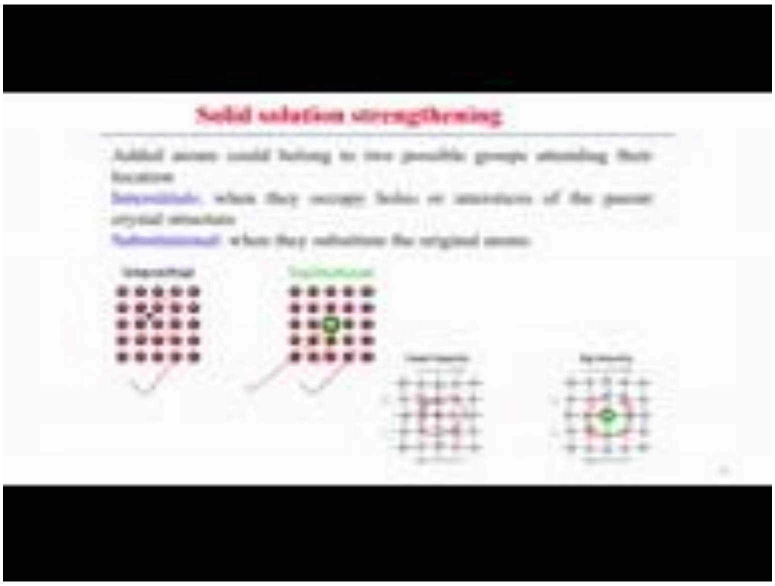

Solid solution strengthening

So when try to discuss the solid solution strengthening, probably we will look into that what are the possible way the atoms can be added with a pure crystal structure. So there are two ways, also we have discussed the defect that is the interstitial defect and subtitutional defect. So interstitial defects in the sense that when the space is occupied by the other atom and the interstitial specifically the interstitial space is occupied of a single crystal structure then that type of defect produces the interstitial defect and the mechanism related to that is called the strengthening, solid solution strengthening due to the interstitial size.

Second is the subtitutional solid solution. So in this case the actual position of the atom is substituted by the another atoms and if we see the both the figures the interstitial and solid solution arrangement of the atoms, CPC the interstitial the smaller in size atoms in takes the position of the interstitial, that we have also discussed that in crystal structure so along if we consider the unit cell though along with the atoms all the corner point of the unit cell there exist some interstitial size. Of course there is a difference in the ratio of the atoms size as well as the interstitial size and normally the interstitial size is smaller as compared to the parent atom in a unit cell.

So if the atoms take the interstitial position that kind of solution creates the interstitial solid solution or subtitutional solid solution when the one atoms completely substitutes the parent atom and it takes that position. So both way, normally this two way the strengthening mechanism is done by the formation of the solid solution. .Now point is that if there exist a small impurity so specifically if we see the stress level probably different in this case. So when the interstitial size is small smaller impurity is there that will try to create the stress field that is towards the size of the interstitial. But if big impurity present if you see the lattice distortion that actually reflects in such a way that you try to create the stress field which was outer direction.

Now we will try to focus on this thing, the presence of the interstitial, different type of stress generally we consider or how we can generate the stress state in specifically subjected to the presence of interstitial and subtitutional atoms in case of with reference to the pure atomic arrangement of a unit cell or of a crystal lattice.

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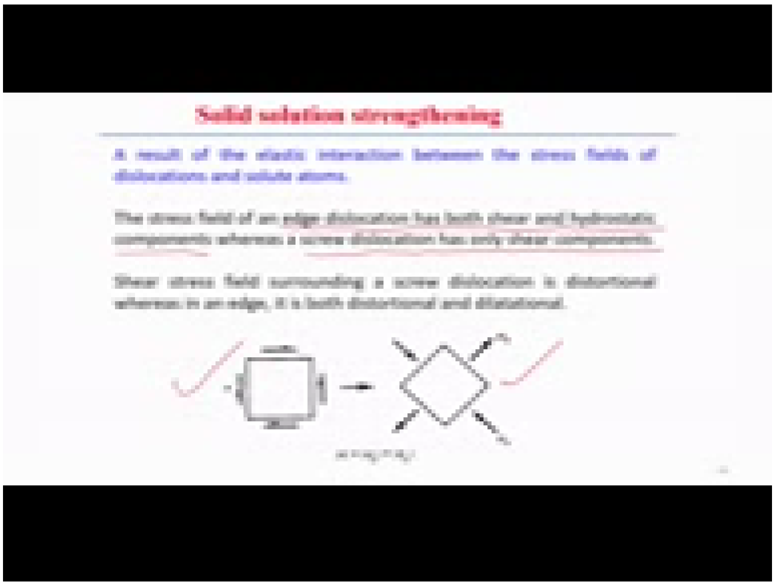

Solid solution strengthening

A result of the elastic interaction between the stress fields of dislocations and solute atoms.

The stress field of an edge dislocation has both shear and hydrostatic components whereas a screw dislocation has only shear components.

Shear stress field surrounding a screw dislocation is distortional whereas in an edge, it is both distortional and dilatational.

Now actually the solid solution strengthening is because of the result of the elastic interaction between the stress field of the dislocation and solute atoms. So, so far we have discussed due to the presence of the dislocation edge and screw dislocation what type of stress field can be generated and what are the interaction of the dislocation with the another stress field of the another dislocation that we have already discussed, and some basic idea we have provided that was related to the interaction of the stress field of the among the different types of dislocation. So basically two types of the dislocation edge and screw dislocation here. Now normally when you try to explain the strain hardening mechanism, so all mechanism are directed to in such a way that how the motion of the dislocation is obstructed by the presence of the other factor.

For example of the any other kind of particles, presence of the any another dislocation or any other obstacles that actually if that resistance of the dislocation motion can be created that actually impart in other way it actually replace the increment of the strength level for a specific crystal structure. So all description actually based on this phenomena, how the movement of the dislocation or dislocation of motion can be restricted. Now to do that so here what maybe the interaction between the stress field of the dislocation and the solute atoms that is responsible to bring to analyze the mechanism of the solid solution strengthening or solid solution hardening. If we see of we already if we recall the fact that the stress field of an edge dislocation actually having both the shear component as well as the hydrostatic component but whereas screw dislocation is merely subjected to shear component.

That is very important statement that edge dislocation has both shear and hydrostatic components whether screw dislocation is having only shear component. Accordingly the shear stress field surround screw dislocation is basically distortional whereas in edge dislocation both components are there that is both distortional as well as the volumetric. So first figure if we see that which is the it is subjected to pure shear component and second case if we see this is the subjected to the normal stress component. So to represents that interaction of the stress field and we have already discussed that when we analyze the volumetric strain associated with actually the edge dislocation whereas volumetric strain was 0 in case of screw dislocation.

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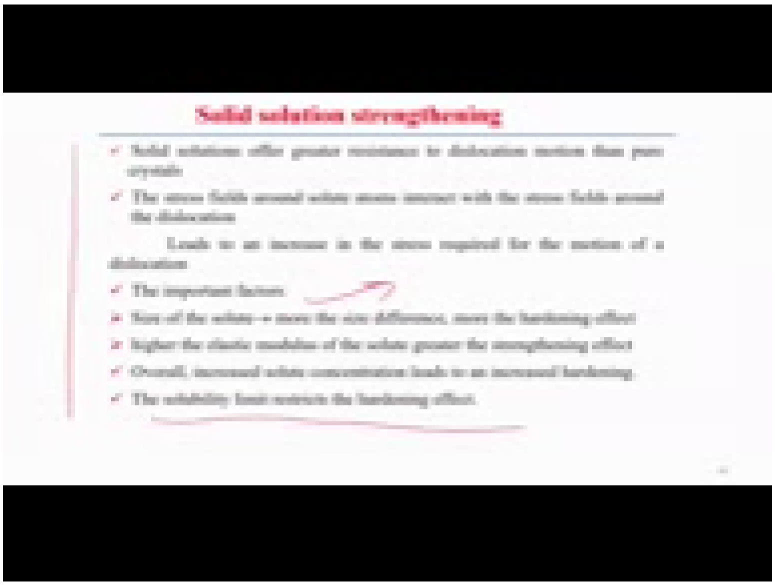

Solid solution strengthening

- ✓ Solid solutions offer greater resistance to dislocation motion than pure crystals
- ✓ The stress fields around solute atoms interact with the stress fields around the dislocation

Leads to an increase in the stress required for the motion of a dislocation

- ✓ The important factors
- ➢ Size of the solute → more the size difference, more the hardening effect
- ➢ higher the elastic modulus of the solute greater the strengthening effect
- ✓ Overall, increased solute concentration leads to an increased hardening
- ✓ The solubility limit restricts the hardening effect.

So to look into that fact we will try to analyze the further effect of this thing how we can bring the solid solution strengthening mechanism in this case. So if we see the solid solution offers greater resistance to dislocations motion that pure crystals because definitely the pure crystals probably the lattice arrangement is almost perfect in absence of any kind of defect. So here we assuming the defect in presence of only the solute atoms. So in absence of the solute atoms the resistance of the dislocation motion is very less in case of the pure metals. But whereas in case of alloys, in case of solid solution so it actually presents of the interstitial and subtitutional atoms that actually restricts the dislocation motion so definitely that will try to impart the some amount of the strain.

Now the stress field around the solid atoms interact with the stress field around the dislocation based on that actually leads to the increase in the stress required to the motion of the dislocation further. So the important factor in this case is first the what are the size of the solute atoms if the more the size difference probably the hardening effect will be increase more. Second point is the higher the elastic modulus of the solute atoms actually that impart more amount of the strengthening effect, but overall increase solute concentration actually leads to an increased hardening. So that amount of the or concentration of the solute atoms in the solid solution that actually finally more impactful to decide the hardening effect on a specific solid solution. But this hardening effect is actually restricted or limited by the solid limit, sorry solubility limit of a specific solute atoms to the solution. So this are the overall fact related to the solid solution strengthening. Now let us see how are the important factor here, actually imparts the strengthening mechanism in case of solid solution.

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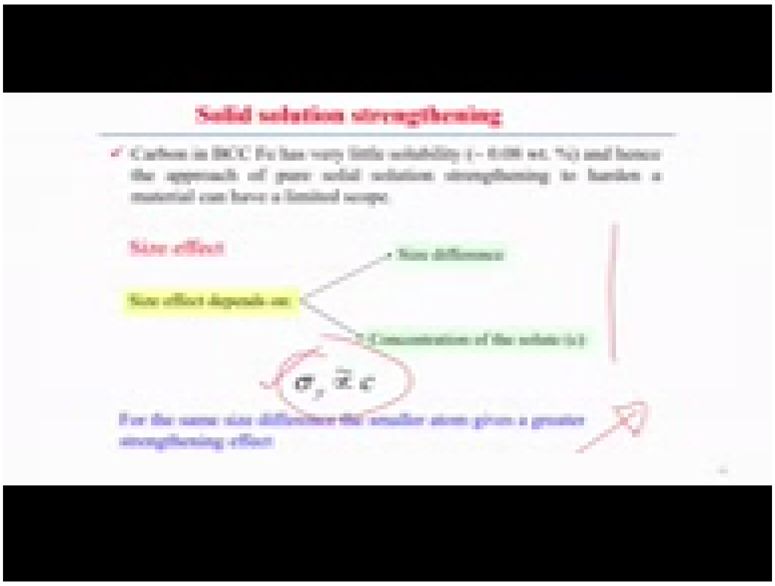

Solid solution strengthening

- ✓ Carbon in BCC Fe has very little solubility (~ 0.08 wt. %) and hence the approach of pure solid solution strengthening to harden a material can have a limited scope.

Size effect

Size effect depends on:

Size difference

Concentration of the solute (c)

$\sigma_y \propto c$

For the same size difference the smaller atom gives a greater strengthening effect

If we observe that presence of the Carbon in BCC iron actually having very little solubility, say less than around 0.08 percentage of carbon so therefore the approach of pure solid solution strengthening to harden a material may have a limited source, that point is here, the carbon percentage is very low in case of BCC iron or solubility limit is only 0.08 percent, so based on the solid solution strengthening mechanism probably having limitation to impart huge amount of the strain for the solid solution. Now what are the other factors, size effect, the size effect depends primarily on the size, what are the difference of the size, so that is size differences in the solution and another is the concentration of the solid. This two most important factor that finally affect the hardening mechanism in case of solid solution.

So the yield strength for the solid solution is more of less or almost proportional to the more on the concentration of the solute, so rather more rather less important here is the difference in sizes. Now for the same size difference the smaller atoms actually gives a greater strengthening effect as compared to the (())(12:33) atoms. So this are the secondary point here where the size difference but primary is basically from the concentration of the solute and of course that is limited up to the solubility limit. So we can do further analysis on that mechanism of solid solution.

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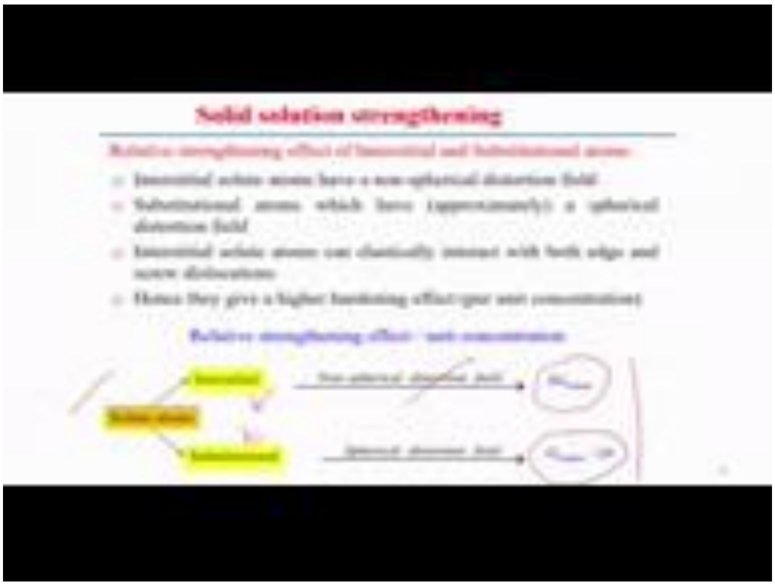

Solid solution strengthening

Here you can see relative strength effect can be represented with interstitial and subtitutional atoms first thing is that interstitial solute atoms actually have a non-spherical distortion field so in the sense that distortion field in presence of actually interstitial solid solution is not spherical in nature so that actually non spherical in the sense that distribution probably not very symmetric but in subtitutional atoms actually produce almost spherical distortion field that means approximately symmetry kind of field can be created in the presence of the subtitutional atoms. But interstitial solute atoms probably elastically interact with both the edge and screw dislocation but whereas the subtitutional atoms more only on for the screw dislocation.

Therefore the hardening effect probably in presence of the interstitial solute atoms more because that interstitial solute atoms actually interact elastically with both edge and screw dislocation. So when there is a, when it is interacting both edge and screw dislocation so in that case it is having the effect of the both distortional effect as well as the volumetric effect also there both. But subtitutional atoms probably spherical distortion field because in this case here it is interact mainly on the screw dislocation, so that why it is subjected to the pure shear the screw dislocation only the distortion field exist. So because of that two different type of solid solution having the hardening effect there is a difference on that.

So we look into that diagram in this figure that solute atoms probably based on the interstitial solid solution or subtitutional atoms both types but interstitial as per non-spherical distortion field and if we see the relative measure of that the relative strengthening effect with respect to unit concentration. So in that case if we see that in presence of the interstitial solute atoms the strengthening effect is more almost three times of the G solute just for approximate calculation and if we see the presence of the subtitutional solid solution the strengthening effect is around G by 10. So in second case since it creates the spherically distortion field probably in this case the effect of the strengthening is less as compared to the interstitial solid solution.

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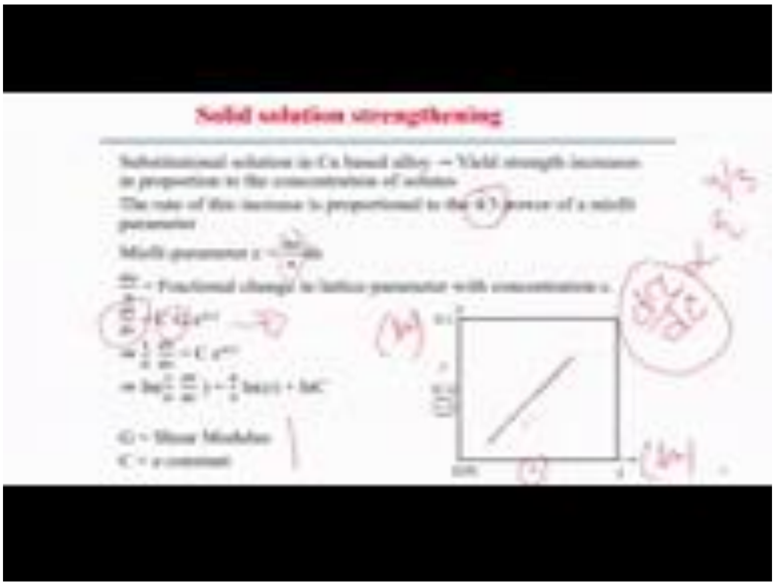

Solid solution strengthening

G = Shear Modulus

C = a constant

So further we can do the analysis, let us look into that subtitutional solid solution in copper based alloy. So in copper based alloy if we see that the yield strain actually in proportional to the concentration of the solutes, that we have already mentioned. That yield strain is more effective or proportional to the concentration, so in this case but the rate of this increase each proportional to the 4 by 3 power of a misfit parameter. So what is the misfit parameter? If you see the misfit parameter is actually the ratio of the fractional change in the lattice parameter with respect to the change of the concentration. So that can be defined as a misfit parameter here, so if you see it is a da by A divided by the dc. So da by A is the fractional change in the lattice parameter and dc is the change of the concentration.

So that misfit parameter actually related to that is proportional to the the rate of increase, rate of increase actually proportional to the misfit parameter, so if we see that d tau by debit card so that means changes of the or increment of the stress level as compared to the change of the concentration gradient is proportional to the misfit parameter and here 4 third power of the misfit parameter, so if we found out that it is proportional to this thing and if we introduce this two constant cg so finally this is the expression of change of the strength level and that if we 1 by G, d tau by debit card equal to c Epsilon to the power 4 by third, so if we do the logarithm scale we can find out the c as constant and g is the shear modulus.

So if you see that misfit parameter here and with respect to 1 by G, dow tau by dow c is actually in logarithm scale it is actually linear. So this graphically we can represent that increment of the strength level with respect to the misfit parameter that misfit parameter is again related to the fractional change in lattice parameter with respect to the concentration of the solute atoms. So the relation follow the linear relation in logarithm scale, here we see so that scale is actually represents in the logarithm scale and variation with respect to that is represent, it is a linear variation we observe from this figure.

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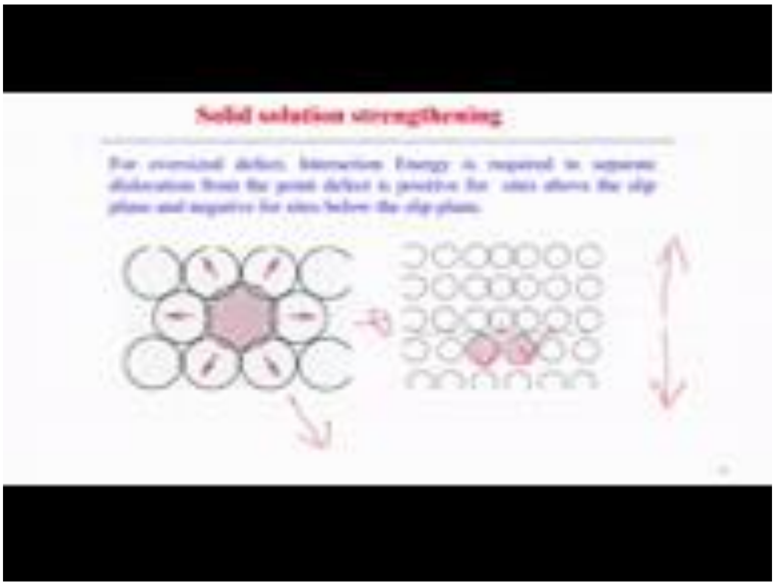

Solid solution strengthening

For oversized defect, Interaction Energy is required to separate dislocation from the point defect is positive for sites above the slip plane and negative for sites below the slip plane.

Now in solid solution strengthening probably you can look into that the oversize defect probably that the side if the occupied by the atom which is oversized, in that case the interaction energy is required to separate the dislocation from the point defect is actually positive. For size above the slip plane, positive above the slip plane and negative below the slip plane, so in this case that is oversized defect, if you see the stress field is basically the readily directed and this is the over fitted atoms that actually try to create the stress field which is, which shows the outward direction and with this configuration actually it will create the with respect to the slip plane positive side and negative side and accordingly the solute atoms will be occupied the position.

So here if we see the solute atoms is occupied below the slip plane so probably here we can considered the interaction energy in this case below the slip plane is negative so in that position the solute atoms is attracted.

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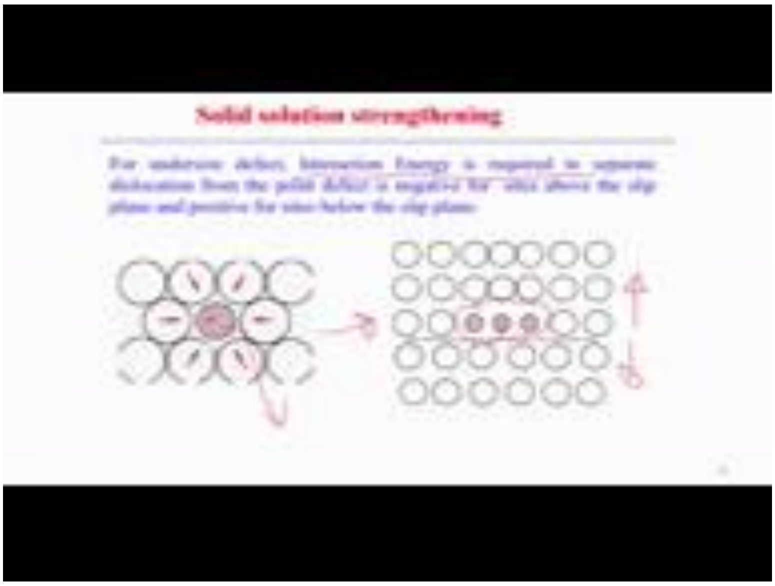

Solid solution strengthening

For undersize defect, Interaction Energy is required to separate dislocation from the point defect is negative for sites above the slip plane and positive for sites below the slip plane.

Now if it is a oversized effect but if it undersize defect then what will happen, if we see in the undersized effect the interaction energy is required to separate dislocation from the point defect is negative. So if we see the interaction here it a undersized defect so the stress field will be created which is towards the center point or towards the center point of the solute atoms and with the configuration we can find out that the slip plane for the positive or side above the slip plane and the positive side below the slip plane, so this is the positive side and above the slip plane actually this can be considered as a negative side so the solute atoms will be attracted that position and the the interaction energy can be represented accordingly whether it is positive or negative.

So these are the typical interaction for the undersized defect and oversized defect and with this interaction probably we can decide that in case of dislocation at the which point the above or below the dislocation plane the atoms will be attracted or try to take that solute atoms will try to take that position. So that we have already discussed due to the mechanism of the dislocation in that case we have analyze the stress field due to the presence of the dislocation whether it is with reference o the slip plane we can define above the slip below the slip plane the the positive field and the negative stress field and accordingly the other solute atoms will be attracted in that position.

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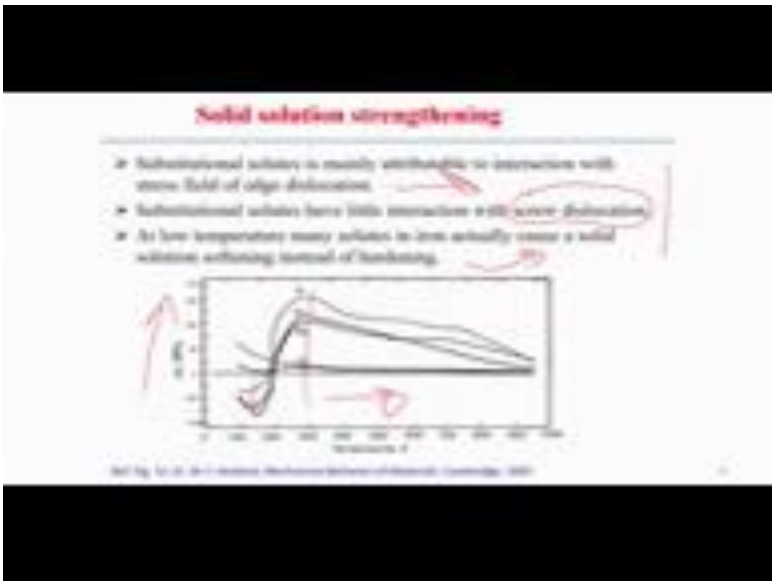

Solid solution strengthening

- Substitutional solutes is mainly attributable to interaction with stress field of edge dislocation.
- Substitutional solutes have little interaction with screw dislocation
- At low temperature many solutes in iron actually cause a solid solution softening instead of hardening.

Now if you see the solid solution strengthening mechanism and few fact for that, first thing is that, subtitutional solute is mainly attributed to interaction with stress field of the edge dislocation that we have already pointed that subtitutional solute atoms mainly the interaction with the stress field of the edge dislocation so that it can create more the distortion at the same time there must be associated with the volumetric change. Subtitutional solute atoms have little interaction with the screw dislocation so subtitutional solute atoms having very less with the screw dislocation but at low temperature many solutes in iron actually cause solid solution softening instead of the hardening .

So there may be some other effect is obvious in this case but practically if you see that there is a change of the stress level in that direction. So here if you see that there is a up to as a function of temperature actually the 300 Kelvin room temperature the strength level is the increment of the stress level is maximum. But below that in certain cases it is subjected to the increment of the negative stress value so that means at very low temperature it is actually subjected to the solid solution softening rather than hardening, but above room temperature the hardening effect is obvious but increment of the stress level is actually decreases with increase the temperature. So temperature also having some effect on the solid solution strengthening effect.

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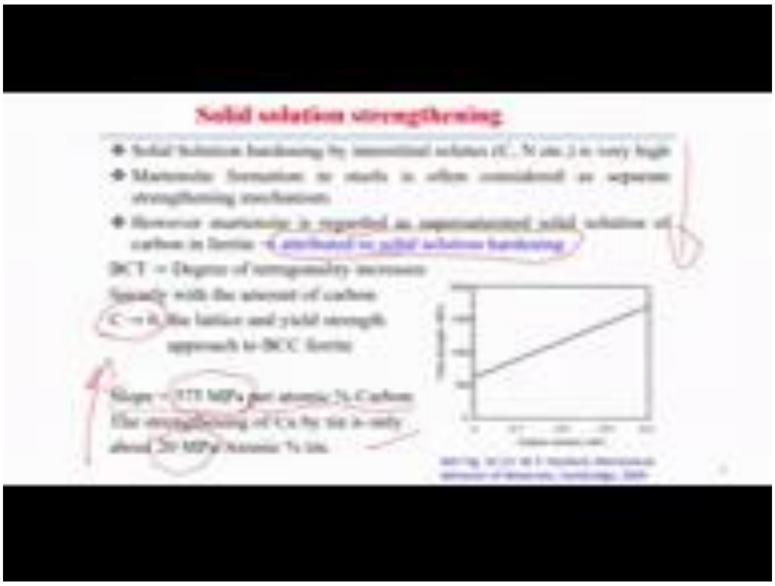

Solid solution strengthening

Now solid solution hardening by the interstitial solute normally we find out the carbon nitrogen they actually try to take the interstitial position which is the presence of the interstitial solute atoms the hardening mechanism is relatively higher as compared to the subtitutional solid solution but Martensitic formation in steel actually consider as a separate strengthening mechanism but Martensitic is regarded as the super saturated solid solution of the carbon ferrite which is attributed to the solid solution hardening. So formation of the Martensitic structure generally consider the super saturated solid solution of the carbon in ferrite and that can be considered as a solid solution hardening.

So what are the typical mechanism actually responsible for the increment of the strength level in case of the Martensitic structure then. If we see that BCT structure that is called Body centered Tetragonal structure and that is generally observed in case of Martensitic, the crystal structure of Martensite is generally considered as the body centered tetragonal structure. But degree of tetragonality actually increases linearly with the amount of the presence of carbon. So when carbon percentage is 0, if c tends to 0 the lattice and the yield strength actually equivalent to the BCC ferrite so strength is then equivalent to the strength of the BCC ferrite when carbon percent is tends to 0.

So here if you see that the percentage of carbon and corresponding the yield strength value also it is increases almost increases linearly that 0 carbon percentage to 0.4 carbon percentage, there is a huge increment of the yield strength, only simply presence of the carbon and carbon here in terms of the interstitial solid solution in iron. Now graphically we can see that the slope is around 5, 75 megaPascal per atomic carbon percentage. What does it mean? It means that with a change of the carbon percentage the increment of the with the per atomic carbon percentage is changes the increment of the yield strength is 575 megaPascal.

So but if we compare practically the other cases if you see that strengthening of copper by tin is only about 20 megaPascal per atomic carbon percentage of tin. So that means with the addition of the per atomic percentage of the tin the increment of the strength level is only 20 megaPascal but whereas here in this case of Martensite structure, here it is the slope is 575 is that, only increment is 575 megaPascal as compared to the 20 megaPascal in case of the strengthening of the copper alloy by tin. So that strengthening mechanism is more impactful when there is a production of the Martensitic structure and in that case we can correlate just roughly that with the carbon percentage there is a huge amount of the increment of the strength level can be achieved.

Now this we have discussed the basic idea about the mechanism of the solid solution and solid solution strengthening and how we can impart the strength by forming the different solid solution and whereas what are the type of solid solution, interstitial and subtitutional solid solution so increment of the strength level in these two cases are different probably interstitial solid solution generally produces more hardening effect as compared to the subtitutional solid solution and at the same time we have tried to interact with that the presence of the subtitutional solid solution or interstitial solid solution they are interact more with the screw dislocation or edge dislocation accordingly, the type of distortion level can be explained when they interact with the either edge or screw dislocation.

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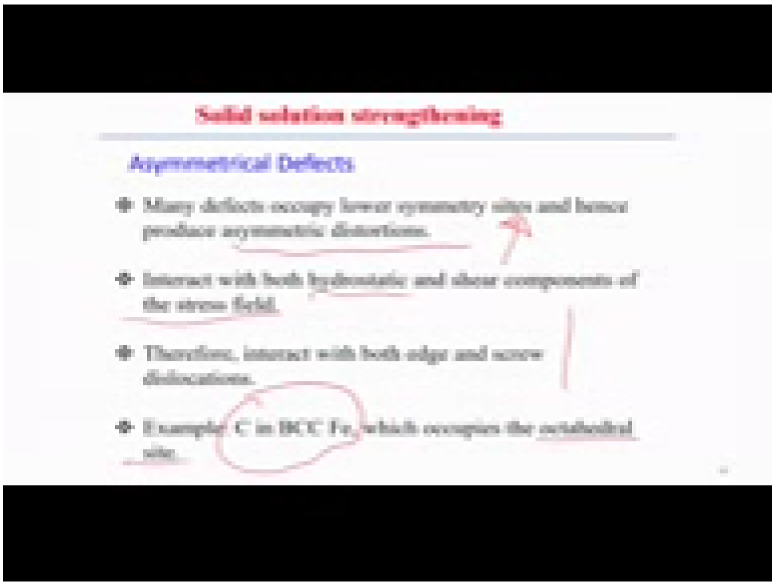

Solid solution strengthening

Asymmetrical Defects

- Many defects occupy lower symmetry sites and hence produce asymmetric distortions.
- Interact with both hydrostatic and shear components of the stress field.
- Therefore, interact with both edge and screw dislocations.
- Example: C in BCC Fe, which occupies the octahedral site.

So let us look into the other fact that Axisymmetric defect which is related to the solid solutions, so many defect occupy the lower symmetry side and hence produce the Axisymmetric distortion. So low symmetry side when the symmetric level, low symmetric side actually the subtitutional or interstitial atoms will take into that position that actually try to create the Axisymmetric distortion field. So therefore interact with the both hydrostatic component and the shear components of the stress filed occurs when they actually create the Axisymmetric distortion field. So both component present there, hydrostatic and shear stress field.

Therefore when the hydrostatic and shear component stress field actually produces the Axisymmetric distortion probably in that case therefore the interaction with the both edge and screw dislocation happens, because edge and screw dislocation both actually produces the either shear field and in edge dislocation creates the both shear as well as the volumetric strain field. So that’s why it is interact both the edge and screw dislocation. So one example is that carbon in BCC iron structure which occupies the octahedral side position, let us see how we can look, how the actually side position creates the Axisymmetric defects in case of the solid solution of BCC iron and carbon.

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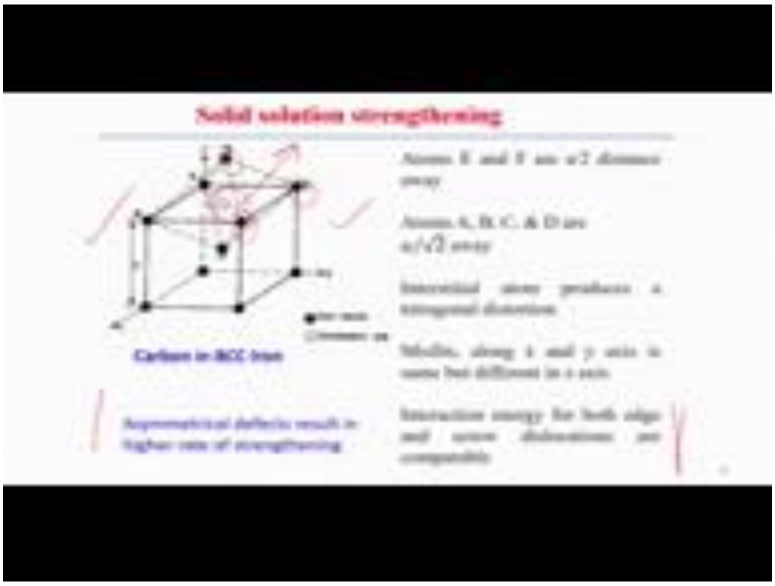

Solid solution strengthening

Carbon in BCC iron

Asymmetrical defects result in higher rate of strengthening

Atoms E and F are a/2 distance away

Atoms A, B, C, & D are $a/\sqrt{2}$ away

Interstitial atom produces a tetragonal distortion

Misfits along x and y axis is same but different in z axis

Interaction energy for both edge and screw dislocations are comparable

If we look into that figure here if we see that atoms actually E and F both are atoms at E and F. A by 2 distance actually this is the this structure represents the carbon in BCC iron and where Axisymmetrical defect results in basically higher rate of strengthening but when tried to explain this thing if we look into this structure this corner atoms actually represents the iron atoms and the this position actually indicates the octahedral side. So we have already discussed that in case of BCC and FCC where we can find out the octahedral and tetrahedral sides also. So with reference to that figure we can look back into this figure the this is presence of the one octahedral side and how it influence the making solid solution in case of carbon and BCC iron.

So probably carbon will try to take that octahedral side position and if you see that atoms presence in E and F is basically of the same distance A by 2 but atoms presence in ABCD are A by root a with respect to the interstitial side or presence of the octahedral side here. Now interstitial atoms produce are tetragonal distortion probably if you say is formed the tetragonal distortion, the location of the interstitial side with respect to the atomic arrangement in case of FCC structure this will try to clear the tetragonal distortion. Therefore the misfit corresponding to the x and y axis remains the same but the misfit along the z direction their distance r is different as compared to what is the distance of interstitial side with respect to the other atoms or same in corresponding to the x and y axis.

Therefore interaction energy for both the edge and screw dislocation are actually comparable here and both actually try to produce interact with the presence of the solute atoms, there is an interaction and maybe some change of the interaction energy level. But interaction energy with respect to the both edge and screw dislocation are comparable with each other. So this explain that this phenomena actually explain the Axisymmetric defect actually results basically the higher rate of strengthening mechanism.

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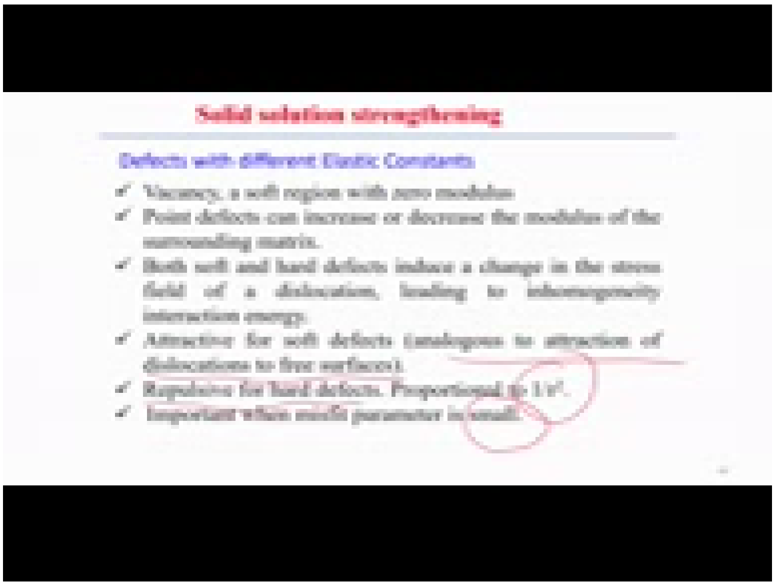

Solid solution strengthening

Defects with different Elastic Constants

- ✓ Vacancy, a soft region with zero modulus
- ✓ Point defects can increase or decrease the modulus of the surrounding matrix.
- ✓ Both soft and hard defects induce a change in the stress field of a dislocation, leading to inhomogeneity interaction energy.
- ✓ Attractive for soft defects (analogous to attraction of dislocations to free surfaces).
- ✓ Repulsive for hard defects. Proportional to $1/r^2$.
- ✓ Important when misfit parameter is small.

Now another fact is that the defect with other different types of elastic constant so vacancy when you look back into the crystal defect specifically a soft region with a 0 modulus, we can consider as a 0 modulus in presence of the vacancy. Now point defect can increase of decrease the modulus of the surrounding matrix. Third point is that both soft and hard defects actually induce our change in the stress field of a dislocation and that actually (())(34:52) inhomogeneity interaction energy. So both soft and hard defects actually influence on the stress field of a dislocation and that actually try to bring the inhomogeneity in the interaction energy.

Attractive for soft defect which is basically analogous to the abfraction of the dislocation of two free surfaces. But repulsive for the hard defects, we can find out the attractive force or repulsive force we can find out for the hard defects, but in this case it is proportional to the 1 by r square, the size of the vacancy. Important when the misfit parameter is specifically small. If misfit parameter is very small probably whether attractive or repulsive force or interaction energy is significant to analyze further. Now with this the different mechanism of the solid solution strengthening will try to shift to the hardening mechanism.

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Hardening Mechanism in Metals

For other type of hardening mechanism generally we observe in the metals. So that is consider the precipitation hardening, so if we see that precipitates actually maybe coherent, semi-coherent or incoherent. This three types probable type of precipitates, we can found out coherent or semi-coherent precipitates are associated with the coherency stresses. So point is that precipitation when you try to mechanism try to understand the precipitation so there must be we look into in terms of the coherency with the metric structure with the base metal but the coherence with respect to the base metal and accordingly we can analyze the effect of the precipitates in hardening mechanism of metals.

So dislocation cannot glide through incoherenet precipitates, so gliding mechanism, gliding of the dislocation mechanism generally it cannot happen in case of the incoherent precipitates but inclusion we have similar two incoherent precipitates in this regard, so precipitates are the part of the system while the inclusion are the external to the alloy system. So with respect to our pin dislocation or maybe at a precipitate either climb over it which becomes favorable at a high temperature so that climbing mechanism probably occurs at the very high temperature or has to bow around it.

That means in the sense the dislocation either can glide through the precipitates or dislocation can get pinned by the precipitates. So there are the two possibilities there, the interaction of the dislocation with the precipitate and here if you see if dislocation glide through the precipitate, if the precipitate is coherent with the matrix. So try to, here you can try that further explanation of the this mechanism how the dislocation actually interact in presence of the precipitates.

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Dispersion strengthening

Dispersion of fine particles – effective in strengthening

- Several ways to produce dispersions
  - → Precipitation for super saturated solid solution (age hardening)
  - → Pressing and sintering of metals powder mixed with fine particles
  - → Internal oxidation (ex. precipitation of MgO in silver based Mg alloy)
- Hard particles on slip plane creates the barrier to dislocation motion

→ To continue slip:

(a) Either dislocations bow out between the particles

(b) Or dislocation cut through the particles

So to look into that if we see being into that dispersion strengthening probably we can correlate into the precipitation strengthening so here also dispersion of fine particles is actually effective in the strengthening mechanism, but what are the different way to produce the dispersion. So one way is the precipitation of the super saturated solid solution, this is basically happening in case of edge hardening, second thing is that pressing and sintering of the metals powder mixed with fine particles that actually try to produce the dispersion. Third internal oxide for example magnesium oxide in silver based magnesium alloy that internal oxide actually creates the very fine particles and actually to produce the dispersion.

So all these three different ways we can produce the dispersion and that can be effective in strengthening of the structure, strengthening of the metals and alloys. But hard particles on slip plane creates barrier to dislocation so this presence of the hard particles that actually creates the obstacles to the motion of the dislocation, so by this basic mechanism we can impart, we can strength level in presence of the dispersion particles. Now to continue to the slip, probably to continue the slip then, two possibilities there are either dislocation going out or go out between the particles or dislocation cut through the particles, let us see these two possible ways to continue the slip, what are the mechanism is responsible to create whether going or it simply cut the particles. So first we will try to look into the mechanism or typical condition where the dislocation bowing between the particles.

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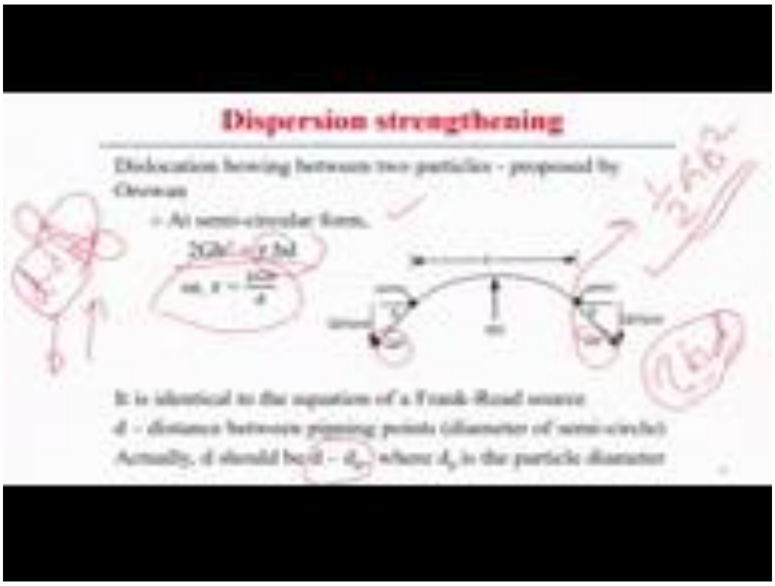

Dispersion strengthening

Dislocation bowing between two particles - proposed by Orowan

- At semi-circular form,

$2Gb^2 = \tau bd$

or, $\tau = \frac{2Gb}{d}$

It is identical to the equation of a Frank-Read source

d – distance between pinning points (diameter of semi-circle)

Actually, d should be $d - d_p$, where d_p is the particle diameter

Dislocation bowing between the two particles actually the mechanism is proposed by Orowan, we have already discussed the mechanism but here we try to modify little bit to fit further analysis of the dislocation bowing in presence of the particles. Now if we look into this figure that is dislocation energy per unit length is represented by the this amount Gb square. If we assume this is the Gb square and this is side is the Gb square and the semi circular form this dislocation, this dislocation of length d actually subjected to the force tau b into d, b is the Burgers vector here and d is the total segmented length of the dislocation and tau is the shear stress so that actually indicates the force, that actually try to bows the dislocation surrounding the particles.

Now mathematically we have seen that the amount of dislocation energy per unit length which is equivalent when it exactly take the semicircular form then we can balance this force the tau bt the vertical direction and other corresponding to the 2 Gb square so tau can be represented 2 Gb by d. So here maybe sometimes it may create some confusion that instead of Gb square sometime we can use the half of Gb square that can also be used in certain cases or Gb square we can use it but with this configuration if we assume the dislocation energy per unit length equal to Gb square here, then we can make it balance at the semicircular form the vertical force, then you can found out the shear stress is in terms of twice Gb by d, so in terms of the shear modulus Burgers vector and the segmented length of the dislocation.

Actually it is identical to the equation what we observe in the when you try to analyze the Frank Reed source of dislocation generation, but here we can modify the length d, actually we can see the d is the distance in the pinning point so basically the diameter of the semicircle. So actually the d should d minus dp, because dp is the particle diameter, that means (())(43:43) in the particle size, this is the effective diameter we can use that is corresponding to d minus dp. This should be the actual size of the segmented length dislocation with reference to the analysis what we did in case of the Frank Reed source of dislocation generation.

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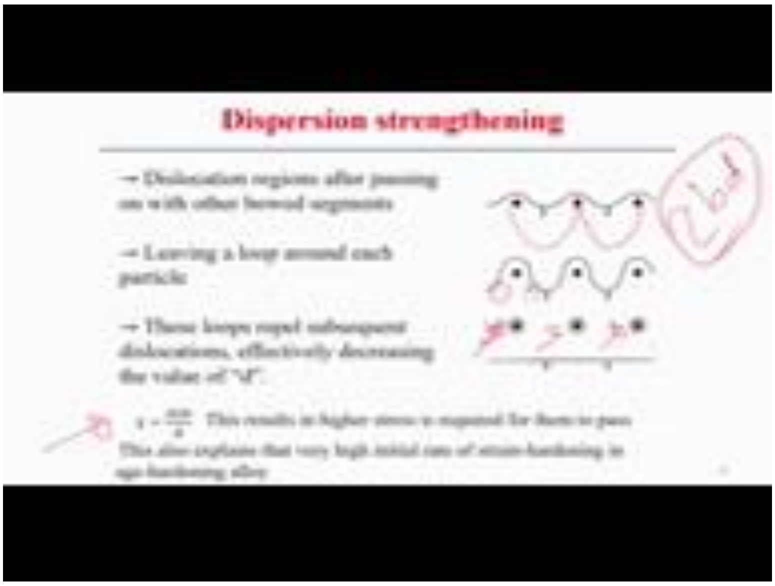

Dispersion strengthening

Now the mechanism is like that dislocation this is the particles presence of the particles if you see and this is the dislocation and it is subjected to the dislocation force or dislocation force per unit length and that total dislocation force we can see tau b into d, so stress field is basically the shear stress tau, so you need to subjected to that kind of stress field or dislocation , stress field or the force tau bd, then if you see that it is try to bow around the particles with the further increase that the particle is bowing, sorry the dislocation is bowing around the particles and actually try to leave a loop around each particle and if you see further bowing is the positive and the negative side probably taken (())(45:06) and they can produce the one loop.

This figure if you see they will try to produce the loop, so that create with the consequence deformation or during the plastic deformation and in presence of the particles and each particle it creates the one loop. So this loop actually remain subsequent dislocation and actually the loop actually effectively decreasing the value of d, so what was the initial value, now effective value of the d actually decreases with the a creation of that such loop, therefore we use to predict the what is the amount of the shear stress required in this case it corresponds to the twice Gb by d. so when d is, effective values of the d actually decreases then this actually results in the higher stress is required to form to the path.

So that actually when there is a requirement of the higher stress that means that is imparting of the strength level because of the presence of the dislocation bowing around the particles. Now this also explains that very high initial rate of the strain hardening generally observe in edge (())(46:28) alloy, so very initial stage the strain hardening, rate of the strain hardening is very high afterwards it actually decreases.

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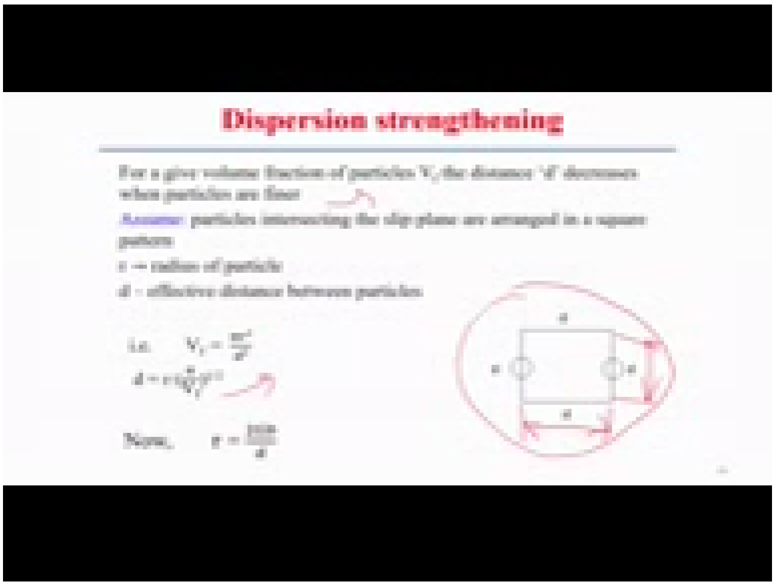

Dispersion strengthening

For a give volume fraction of particles V_f the distance 'd' decreases when particles are finer

Assume: particles intersecting the slip plane are arranged in a square pattern

r → radius of particle

d – effective distance between particles

i.e. $V_f = \frac{\pi r^2}{d^2}$

$d = r\left(\frac{\pi}{V_f}\right)^{1/2}$

Now, $\tau = \frac{2Gb}{d}$

Now for given volume fraction of particles vf the distance d actually decreases when the particles become finer that is true. For a fixed volume fraction if we consider the distribution of the particles. If the particle size is less effectively that actually increases the amount of the dislocation segment length between these two particles. Now consider that particle intersecting the slip plane are arranged in the square pattern. Probably we can consider this configuration, so the distance between these two particles assume this is the d and this, with this configuration if I consider the square arrange so within that two particles are there and the distance, the edge is basically d.

So with this configuration if we see that if small r is the radius of the particles and small d is the effective distance between these particles therefore volume fraction can estimated like that, so definitely you are talking about the volume fraction over a unit thickness that area occupied by the particles if we see over this area occupied by particles, the area of one particle that is pi r square, and the distance or the area of this square is basically d square. So here we can find out the d equal to in terms of the volume fraction and once we find out the volume fraction probably in that case we can use the shear stress equal to twice Gb by d.

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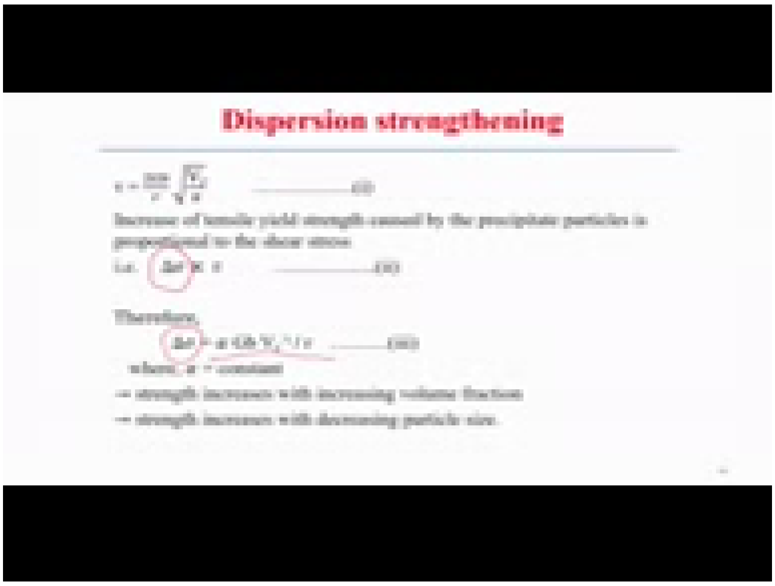

Dispersion strengthening

And by using this equation we can further find out that shear stress equal to in terms of the volume fraction, shear modulus, Burgers vector particle size. So here equation number 1 if we see that increase of the tensile yield strain actually caused by the precipitate particle is proportional to the again shear stress value that means that increment of the strength level yield strength is proportional to the shear stress value, so if we do that therefore increment of the stress is basically we can represent that alpha Gb pf to the power half divided by r, so that means the increment of the yield strength actually as a function of the volume fraction, main function of the volume fraction and the particle size, so other terms are constant for a specific metal or specific alloy system.

Now alpha is a constant, now if we look into that equation 3, here if you see the strength actually increases with increase in the volume fractoin, whereas that means the volume fraction of the particles, if the particle volume actually increases within the sample that actually increases the strength level, that means strain hardening effect is more with a increment of the volume fraction of the particles, but at the same time strength increases with decrease in the particle size, if particle size becomes smaller and smaller in that case strength level can also be increased. So these are the both way it is possible to increment the imparting the strengthening mechanism in case of dispersion strengthening. That means strengthening by the presence of the particles.

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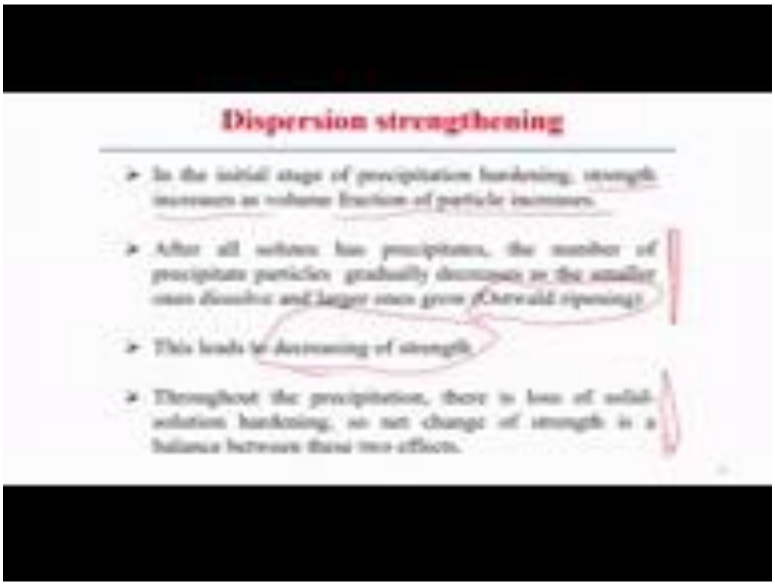

Dispersion strengthening

- In the initial stage of precipitation hardening, strength increases as volume fraction of particle increases.
- After all solutes has precipitates, the number of precipitate particles gradually decreases as the smaller ones dissolve and larger ones grow (Ostwald ripening).
- This leads to decreasing of strength.
- Throughout the precipitation, there is loss of solid-solution hardening, so net change of strength is a balance between these two effects.

Therefore in the initial stage of precipitation hardening actually strain increases at the volume fraction of particle increases. That is true that we have theoretically we have shown the strength increases as the volume fraction of particles actually increases. But after all solute has precipitate out the number of precipitate particles gradually decreases as the smaller one actually dissolve and the large one grow, so that means the large particles will try to grow by consuming the smaller particle so with that effect there is a decrement of the strength level so that is typically called Ostwald ripening effect. So by this effect the strength actually decreases.

So therefore if we see that we have observed, we have already discussed that solute particles, particles having the either large volume fraction impart the strength level, at the same time small particle size actually impart the strength level but if you see overall this thing for a specific sample so there is a there is a solubility limit of the solute atoms, so therefore well it is reached all the solute atoms will precipitate out at that time probably the bigger atoms or bigger solute atoms or probably the bigger particle size will try to consume the smaller particle size so that actually in other way overall particle size actually increases, with that effect there is a decrement of the strength in the presence of the bigger particle size.

Throughout the precipitation there is a another effect also, because throughout the precipitation there will be the loss of the solid solution hardening, presence of the solid solution hardening will be losing throughout the precipitation so net effect of the strength level or the net effective change of the strength probably the balance between these two effects, one is the precipitation another is the solid solution hardening, loss of the solid solution hardening. So by compromising these kind of mechanism that actually defines the final increment of the strength level in case of the dispersion strengthening.

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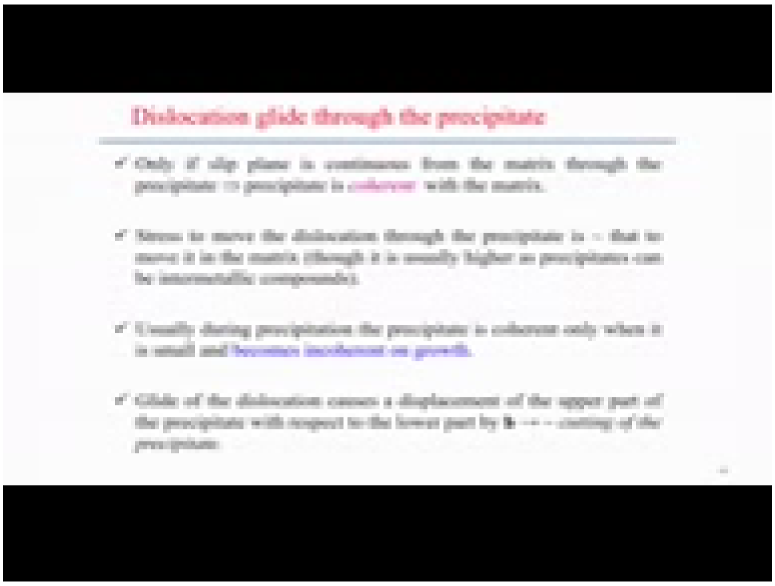

Dislocation glide through the precipitate

How dislocation glides through the precipitate? Now we have come to the second mechanism, if there is a dislocation glide through the precipitate out, so, so far we have discussed that dislocation bowing around the particles, now we will try to discuss on the dislocation glide through the precipitate or through the particles. So only if the slip plane is continuous, if slip plane is continuous from the matrix through the precipitate therefore precipitate is coherent with the matrix, that we can consider the coherent with the matrix. Stress to move the dislocation through the precipitate is that to move in the matrix though it is usually higher as precipitate can be intermetallic compound.

So coherency should be maintained here, when we try to explain this mechanism of the dislocation glide through the precipitate, usually during the precipitation the precipitate is coherent only when the it is in the small and becomes incoherent on the growth. So therefore we will try to explain this mechanism, we can neglect the growth mechanism of the precipitate. Now glide of the dislocation causes a displacement of the upper part of the precipitate with respect to the lower part and cutting the precipitate. So in general presence of the dislocation we will try to cut the precipitate although hit is very hard.

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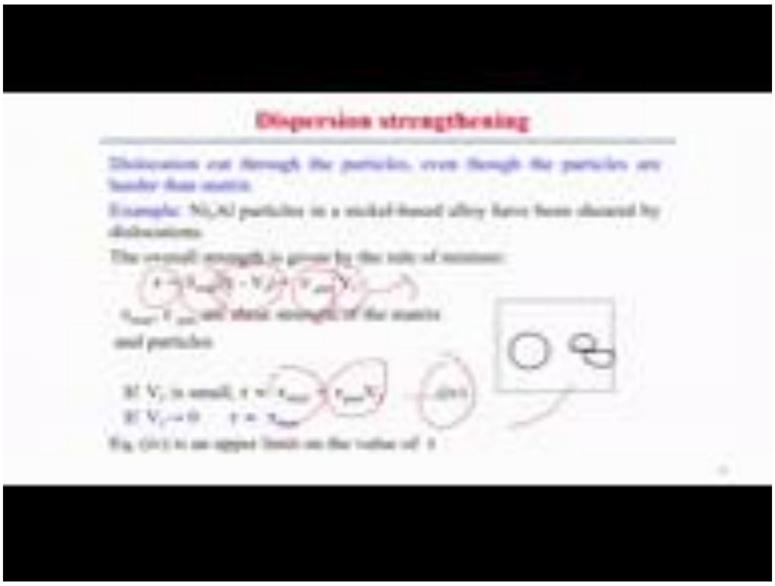

Dispersion strengthening

So here see the dislocation cut through the particles, even the particles are actually harder than the matrix, so let us see how it works. Experimentally observed that Ni3Al particles is a basically nickel based alloy has been sheared by the dislocation. So if you see the mathematically the overall strength is given by the role of mixture. So overall strength of the, we can see the tau, it is the particle and the matrix strength tau mat and the particle strength is tau particle, it is like that and we can distribute and consider this strength level bases on the proportionate way what are the volume fraction of the particles. So Vf is the volume fraction of the particles here and 1 minus Vf is the remaining matrix.

So if we see that Vf is small probably we can find out that if Vf is small, so 1 minus Vf is actually tends to 1 and overall strength consist of the strength part from the matrix and strength part from the particles. So by combining this thing we can find out that the strength level of the matrix is, that is represented by equation 4. So equation 4 is actually in upper limit at the value of the overall strength level. Now the figure shows this is the one particles, and presence of the dislocation in such that actually dislocation try to cut the particles and based on that we can find out, we can predict the strength level mathematically by follwing this equation and logical reasoning on that.

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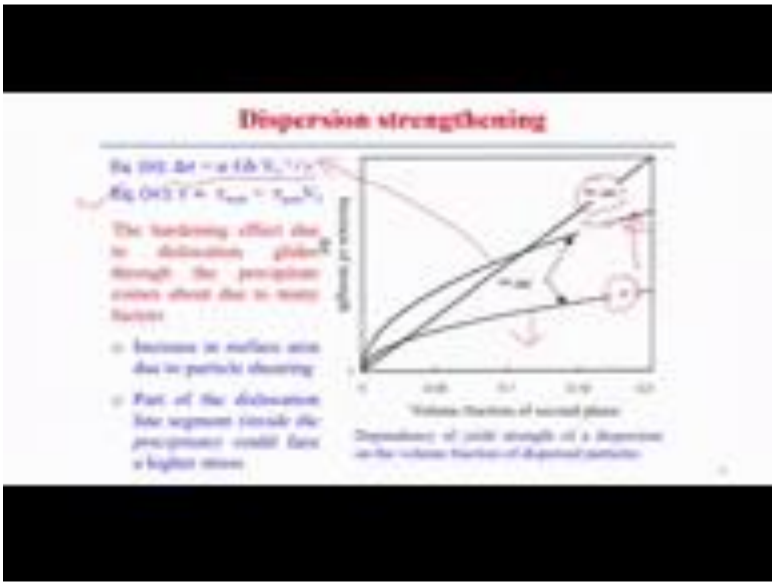

Dispersion strengthening

The hardening effect due to dislocation glides through the precipitate comes about due to many factors

- Increase in surface area due to particle shearing
- Part of the dislocation line segment (inside the precipitate) could face a higher stress

Dependency of yield strength of a dispersion on the volume fraction of dispersed particles

Now we try to explain this thing, if you see that volume fraction of the second phase that means volume fraction of the particles represents the x axis and increment of the strain represents y axis. So here we see that equation 4, that means equation 4 is represented by the simple straight line, so linear relation between the represent the volume fraction of the second phase particles and we can represent this thing. But equation 3 if we see the increase of the strength is proportional to the volume fraction and it also depends on the size of the particles. So this is the particle size, if particle size is bigger probably the increment of the strength level is in the lower side, but if particle size is smaller the volume fraction of the second phase actually variation the increment level or the increment of the strength actually more since in this case the particle size is more and that nature of the curve actually follow the equation number 3 in this case.

So here we can see that the hardening effect due to the dislocation glides through the precipitate comes out due to the many factors one of that, increase in the surface area due to particles shearing that is the one factor that actually affect the increment of the strength level is in the dislocation always try to cut the particles. And the second explanation is like that part of the dislocation like segment inside the precipitate could face a higher stress level. So that two mechanism is actually responsible for the increment of the strength level in case of when dislocation will try to cut the particle.

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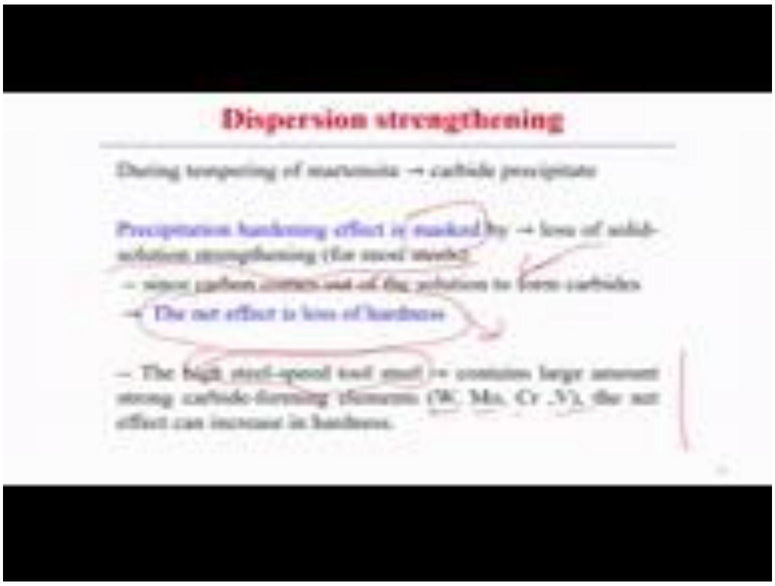

Dispersion strengthening

During tempering of martensite → carbide precipitate

Precipitation hardening effect is masked by → loss of solid-solution strengthening (for most steels)

→ since carbon comes out of the solution to form carbides

→ The net effect is loss of hardness

→ The high steel-speed tool steel → contains large amount strong carbide-forming elements (W, Mo, Cr ,V), the net effect can increase in hardness.

But few fact on the dispersion strengthening during the tempering of Martensite is also, there we observes the carbide precipitate and precipitate hardening effect is actually masked by the loss of solid solution strengthening for most of the steels. So it is obvious that precipitation hardening effect is masked compensated or maybe restricted by the loss of the solid solution strengthening and it is of the for the most of the steels. So there is a two contracting effect, one is the precipitation hardening effect due to the precipitates out at the same time there is a loss of the hardness due to the solid solution strengthening effect.

Therefore carbon comes out of the because the loss of the hardness because carbon comes out from the solution that actually tired to loosen the hardness due to the mechanism of the solid solution hardening at the same time carbon from the carbides that actually other way it increases the hardness level. So therefore there is net effect can be a loss of the hardness, with this two mechanism, but in case of high speed steel (())(59:55) steel it is having the continuous large amount of the strong carbide forming elements so the (())(60:02), Chromium and vanadium , this actually try to impact the mechanism of the had mechanism by the precipitation hardening by formation of the carbide is more as compared to the loss of the hardening due to the solid solution strengthening effect by losing the carbon atoms from the solution.

So here it is more the high speed steel the net hardening effect is positive, we can say the more what in case of normal carbon steel the net hardening effect is sometimes the loss of the hardness during the two opposing effect of the hardening.

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Precipitate hardening effect

So the hardening effect of precipitate can arise from many other sources also or many other mechanism also is responsible for that, one of is that lattice resistance actually the dislocation (())(60:58) and increase lattice friction stress in the precipitate that is called the lattice resistance. That actually impart the hardening effect, chemical strengthening, this actually arises from the additional interface created on shearing. Stacking fault strengthening is happening due to the difference of the stacking fault energy between the particles and the matrix and when this both FCC and HCP are these are both presence in FCC and HCP kind of structure, when the dislocation are split into the partial.

So stacking fault strengthening another is the modulus hardening, coherency strengthening and order strain hardening all are the typical mechanism actually observed that actually impart the hardening effect of precipitate. Now this we can the way we presented this thing, the hardening effect due to the precipitate and we have analyzed the positive thing, mostly we in general we can find out the hardening effect due to precipitate so definitely try to due to the formation of the precipitate or carbide particles, specifically formation of the carbide particles impart the hardness but at the same time there is a loose of the hardness because of the solid, because of the solid solution. In the solid solution there is a exist on the carbon atoms of the solid solution and that try to form the carbide.

So there is opposing effect or this one effect actually increase the hardness level, another level actually decreases the hardness level. So the net effect actually depends on the relative amount of the this thing whether we can say the solid solution softening probably due to the exit of carbon atoms from the solute or formation of the precipitate and that is due to the precipitation hardening effect.

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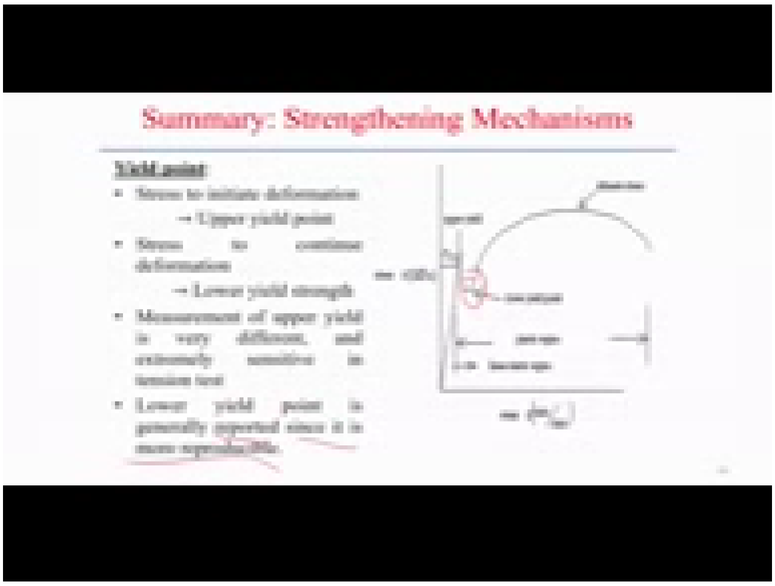

Summary: Strengthening Mechanisms

Yield point:
- Stress to initiate deformation
  → Upper yield point
- Stress to continue deformation
  → Lower yield strength
- Measurement of upper yield is very difficult, and extremely sensitive in tension test
- Lower yield point is generally reported since it is more reproducible.

So now in summary we can find out that the typical strengthening mechanism is first we have tried to explain the yield point, if we see the right hand side figure, so the typical stress strain diagram for specifically low carbon strength and here if we see the strain to imitate the deformation that is upper yield point and the stress to continue the deformation that is corresponds to the lower yield point and the measurement of the upper yield point is generally difficult and extremely sensitive in tension test therefore lower yield is the more in most of the cases is generally reported since it is more reproducible, more stable, point is the lower yield point. So here we are trying to summarize overall effect of the strengthening mechanism, probably we can look all these things in the continuum scale.

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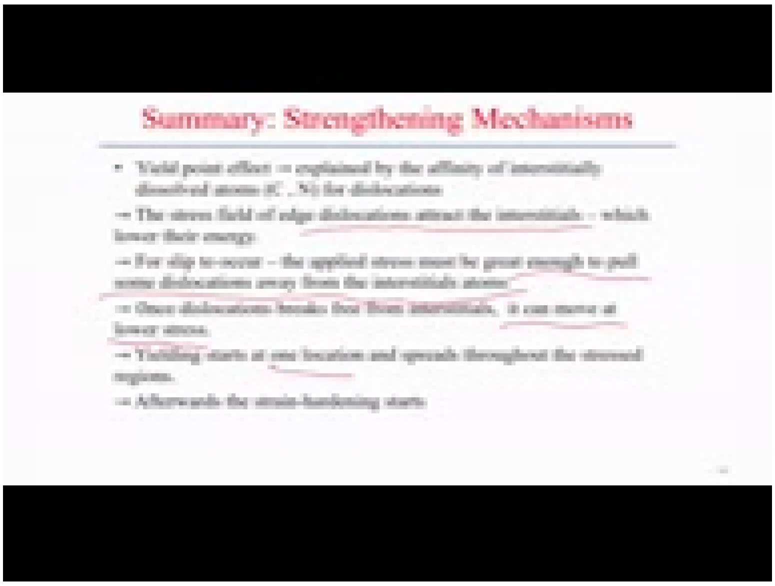

Summary: Strengthening Mechanisms

Now we have seen that yield point effect, probably we can explain by the affinity of the interstitial, interstitially dissolved atoms carbon or nitrogen for dislocation, the stress field for the edge dislocation actually attract the interstitial which lower than effective energy, but for slip to occur, the applied stress must be great enough therefore to pull the dislocation away from the interstitial atoms. So therefore when there is lower energy, therefore the applied stress should be more enough, much enough to pull the some dislocation away from the interstitial atoms. Third point is that once dislocation breaks free from interstitial it can move in the lower stress level, that we observe in the stress strain diagram. Once dislocation breaks free from the interstitial actually it creates the moves to the lower stress level, therefore yielding start at one location and spreads actually throughout the stressed region, afterwards the strain hardening effect actually comes and that all with this phenomena analogous to this corresponding to the microscopically or macroscopically if you see that are stress strain diagram of a specific material.

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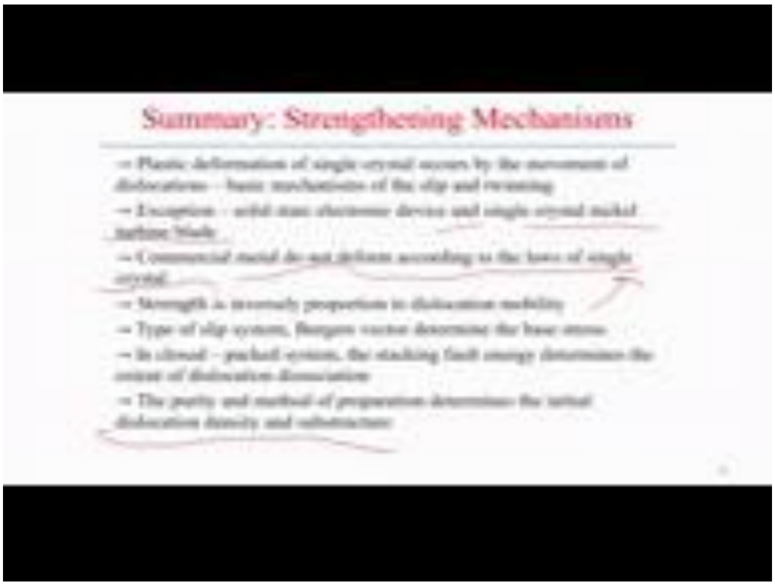

Summary: Strengthening Mechanisms

So plastic deformation of single structure by the movement of the dislocation so that we have explained that is the basic mechanism of the slip and twining, exception if the solid state electronic device and the single crystal turbine blade, but most of the commercial metals actually follows the basic mechanism of the hardening through the movement of the dislocation. But commercial metals do not deform according to the loss of the single crystal, therefore strength is inversely proportional to the dislocation mobility. Now type of the slip system, Burgers vector actually determine the amount of the base stress and then in close packed system the stacking fault energy actually determines the extent of the dislocation dissociation so the purity and the method of preparation determines the initial dislocation density and the substructure.

So in the summary we can say that there is a in case of commercial metals probably not exactly the following the theory with is subjective to the single crystal structure, so there are several effects, dislocation interaction, interaction between the dislocation and how the basic mechanism we are explaining all the hardening mechanism that what is the stress field generated by the dislocation interaction of the dislocation, or interaction of the stress field of the dislocation with the presence of the solute and the subtitutional atoms, based on that we can explain all this basic phenomena of the hardening mechanism. These are the typical fact related to the hardening effect in summary.

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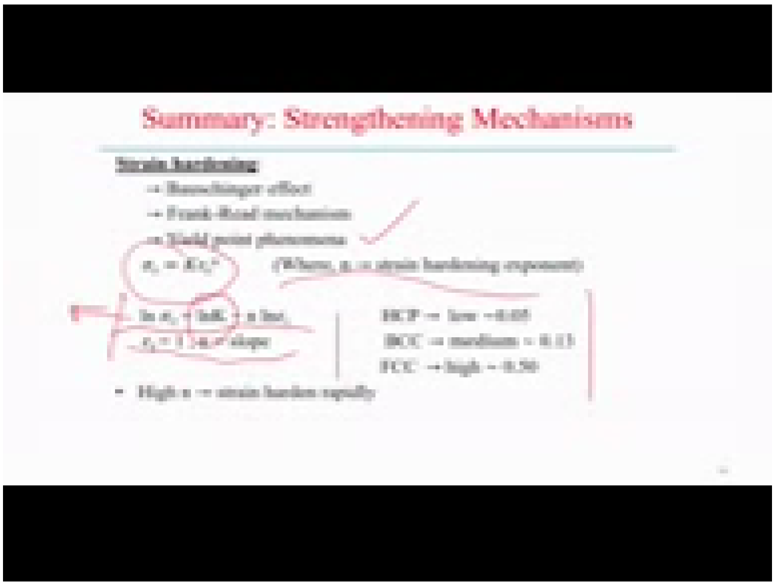

Summary: Strengthening Mechanisms

Strain hardening:

→ Bauschinger effect

→ Frank-Read mechanism

→ Yield point phenomena

$\sigma_t = K\varepsilon_t^n$ (Where, n → strain hardening exponent)

$\ln\sigma_t = \ln K + n\ln\varepsilon_t$

$\varepsilon_t = 1$, n → slope

HCP → low ~0.05

BCC → medium ~ 0.15

FCC → high ~ 0.50

- High n → strain harden rapidly

Now strain hardening, we have discussed the Bauschinger effect, Frank Reed source of dislocation generation mechanism by this, what was the mechanism of the Frank Reed that we have already discussed and yield point phenomena is the mainly we have discussed on the reference to the interstitial sides presence in the structure and how the energy level actually changes based on that we have explained the yield point phenomena but in general in continuum mechanism we represents the stress versus strain in the Hollomon type of equation where sigma t equal to two stress is equal to some constant into strain to the power n. This is the basic law here the constant term k and n depends on the type of material where any (())(68:08) strain hardening exponent and we have seen that in logarithm scale we can represent the logarithm of sigma t equal to logarithm K plus n into logarithm of Epsilon that means strain.

So in the logarithm scale it is the linear where that strain end actually represent the flow and L and K this represents the intercept along the axis. Now n for the different materials, n can be like that, for HCP material low n, BCC generally medium and FCC is the very high values of the n, so high n means that actually strain harden more rapidly. So these are the just overall overall idea of the strain hardening mechanism in case of the polycrystalline structure or we can say that in continuum scale we can use this type of equation.

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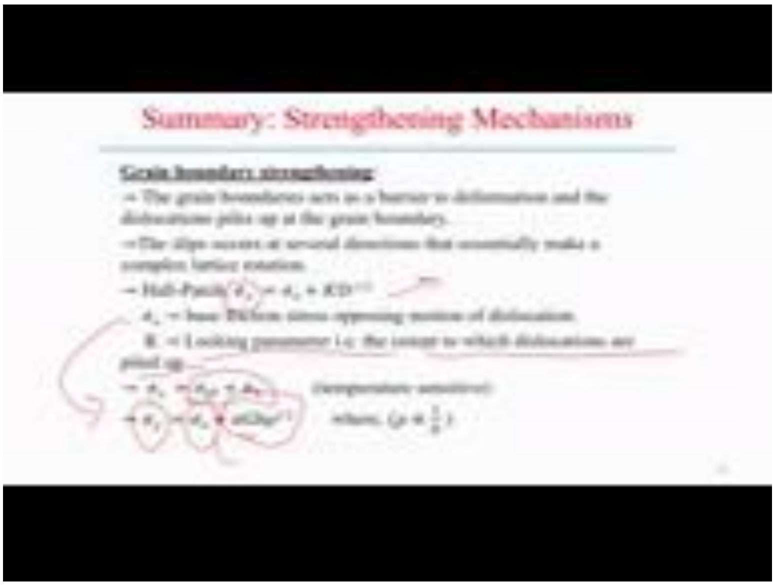

Summary: Strengthening Mechanisms

Now grain boundary strengthening we have discussed, that the grain boundary actually acts as a barrier to deform and the dislocation piles up at the grain boundary. So the slip occurs at the several direction and that essentially make a complex lattice rotation and the presence of the grain boundary actually impart the dislocation movement and these actually try to increase the strength of the, yield strength of the material, polycrystalline structure and that is strength can be predicted by using the Hall Petch equation where yield strength of the material sigma (())(69:04) equal to sigma 0 plus K into d to the power minus half that means where the sigma 0 equal to base fix some stress opposing motion of the dislocation and K is basically the locking parameter that means extent to the which the dislocation of R actually piled up and it is the function of the size of the grain size d.

Then if sigma 0 is temperature sensitive then sigma 0 can be consist of the two component, one is the temperature sensitive and the static component, we can further decompose into two component and probably by following any kind of mechanism we can find out this two component. Also the yield strain can be represented in terms of the dislocation density, so that again the dislocation density is proportional to the 1 by d that means it is proportional, inversely proportional to the grain size. So these are the typical mechanism related to the grain boundary strengthening.

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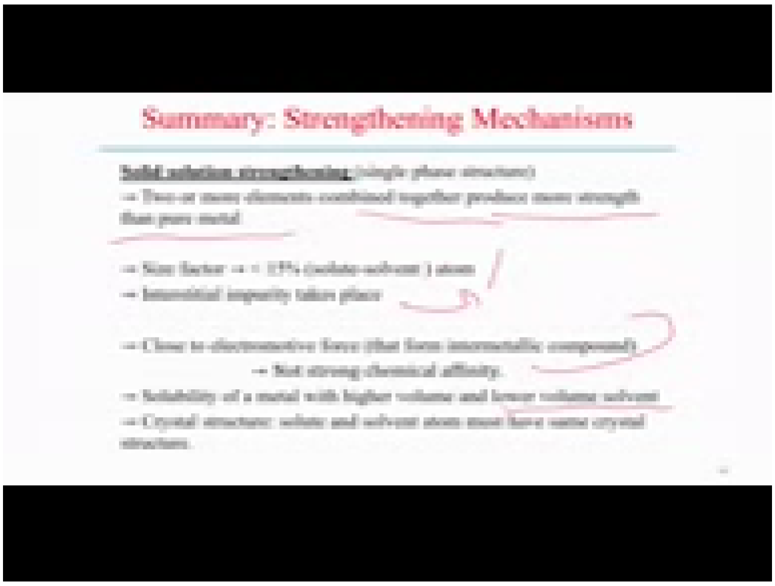

Summary: Strengthening Mechanisms

Solid solution strengthening (single phase structure)

→ Two or more elements combined together produce more strength than pure metal

→ Size factor → < 15% (solute-solvent) atom

→ Interstitial impurity takes place

→ Close to electronegative force (that form intermetallic compound)

→ Not strong chemical affinity.

→ Solubility of a metal with higher volume and lower volume solvent

→ Crystal structure: solute and solvent atom must have same crystal structure.

Then we observe the solid solution strengthening, specific solid solution strengthening we assuming all the mechanism, we try to assume that it produces the kind of the single phase structure where two or more elements combine together that actually produce more strength that pure metal that is the basic philosophy of the solid solution strengthening and size factor is also important here. Generally the ratio between the solid and solvent is less than 15% then the strengthening mechanism more active and probably more interstitial impurity take place and that actually impact more on the strengthening mechanism in case of the solid solution strengthening.

Close to the electrometric force that from the intermetallic compound and that is not strong, not produce the strong chemical affinity. Suitability, solubility of a metal with the higher volume and the lower volume solvent that actually impart the strengthening mechanism of that and also the crystal structure solute and solvent atom must have the similar kind of crystal structure that means it is having the, that is also having the effect on the hardening of the by the solid solution strengthening mechanism.

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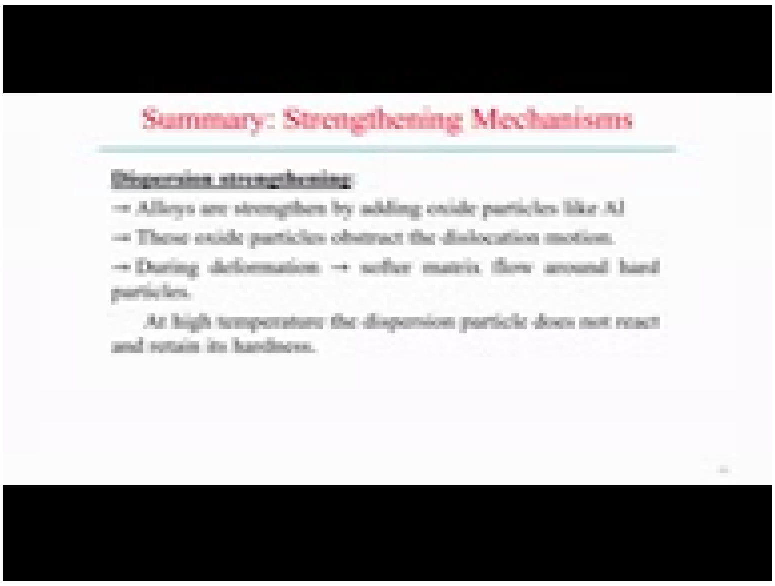

Summary: Strengthening Mechanisms

Dispersion strengthening:

→ Alloys are strengthen by adding oxide particles like Al

→ These oxide particles obstruct the dislocation motion.

→ During deformation → softer matrix flow around hard particles.

At high temperature the dispersion particle does not react and retain its hardness.

Finally dispersion strengthening, here if we see that alloys are strengthens by the adding of the oxide particles like aluminum oxide, actually this oxide particles obstruct the dislocation motion and during the deformation the soften matrix actually try to flow around the particles but at high temperature the dispersion particles does react and may or may not retain its hardness. So the hardness of the particles into the some extent influence the strengthening mechanism by the dispersion.

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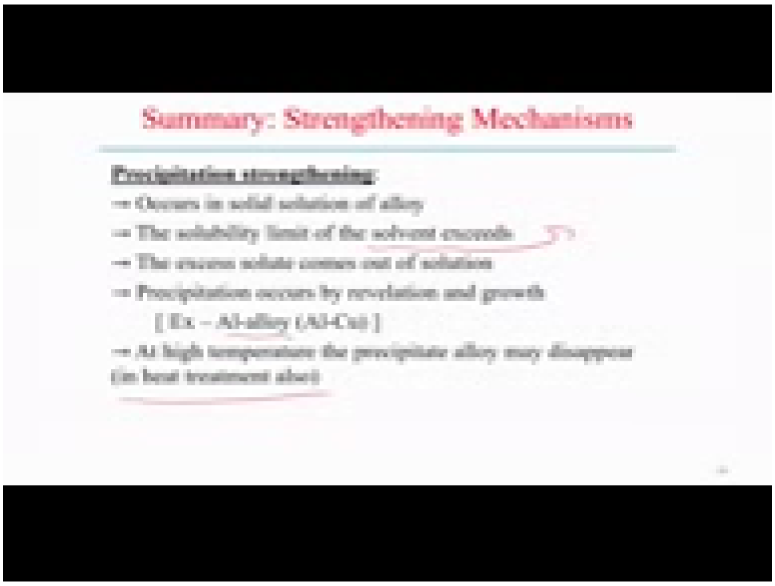

Summary: Strengthening Mechanisms

Precipitation strengthening:

→ Occurs in solid solution of alloy

→ The solubility limit of the solvent exceeds

→ The excess solute comes out of solution

→ Precipitation occurs by nucleation and growth

[Ex – Al-alloy (Al-Cu)]

→ At high temperature the precipitate alloy may disappear (in heat treatment also)

Finally the precipitation strengthening, it occurs in the solid solution of the alloys, of course the important point is the solubility limit of the solvent is the exceeds and the excess solute comes from the solution and that actually try to impart strengthening mechanism in terms of the precipitation strengthening, for example aluminum alloy probably is between aluminum in copper but at the high temperature the precipitate alloy may disappear and that is the case of the in heat treatment.

So this are the, I have tried to here the explain of the difference basic mechanism of the strengthening mechanism that actually we observe and the single crystal structure and the polycrystalline structure and we have tried to explain all the phenomena in terms of the stress field generated by the precipitation hardening and solid solution strengthening, to some extent it is related to the motion of the dislocation or interaction with the stress field generated by the edge and screw dislocation and that interaction of the edge and screw dislocation with the presence of the interstitial and subtitutional solute atoms.

Apart from that we have discussed the while strengthening and strain hardening texture strengthening, also we have discussed the strengthening mechanism effect on the mechanism for the different types of the crystal structure. So with this, by this explanation all this theory we will try to look into few problems related to all this theory.

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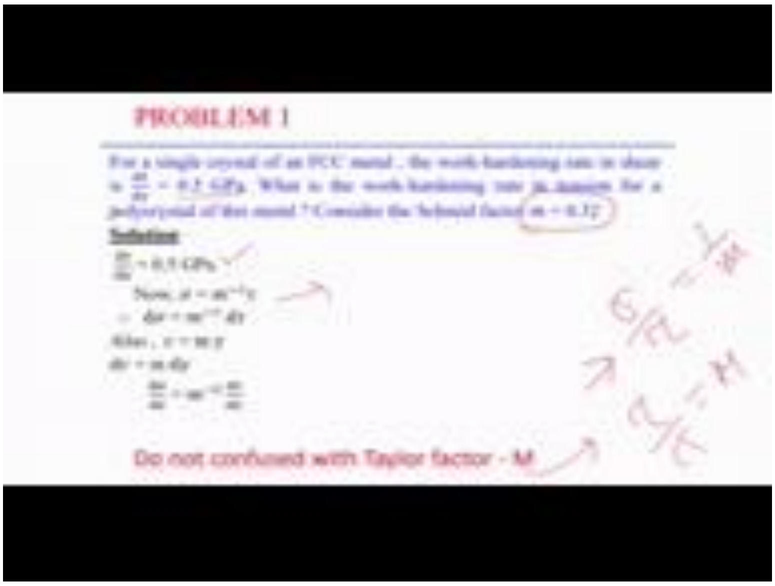
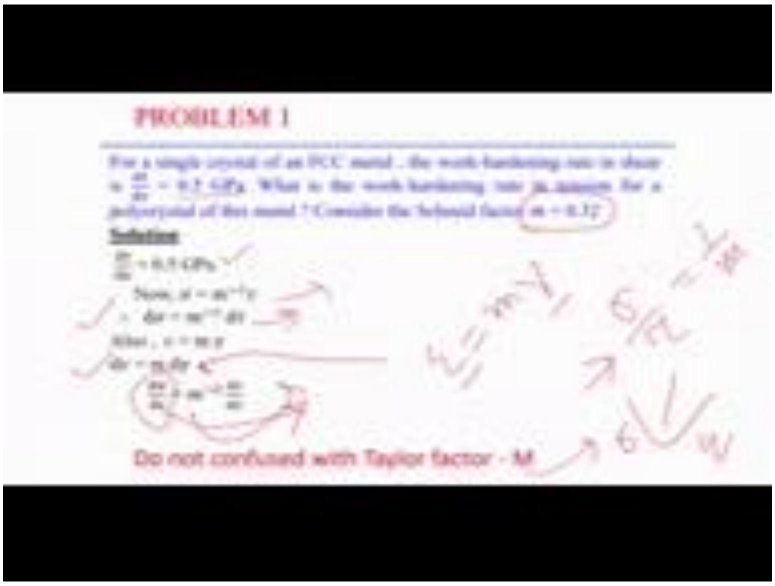


PROBLEM 1

Solution

Do not confused with Taylor factor - M



PROBLEM 1

Do not confused with Taylor factor - M

Let us look into that first numerical problem, here if you see that for a single crystal of an FCC metal the work hardening rate in shear is given 0.5 gigaPascal. What is the work hardening rate in tension for a polycrystal of this metal, consider the Schmid factor m equal to 0.32, so single crystal structure FCC metal and we have given the work hardening rate in shear so this is the d tau by d gamma is basically represent the work hardening rate in shear in case of crystal structure. Now it is given 0.5 gigaPascal. Now in terms of the Schmid factor if we observe that the relation between the stress and strain, we see that, so this is the relation actually between the normal and the shear stress and in terms of the Schmid factor, actually should be confused with the Taylor factor m, because when you try to consider the Taylor factor m for the orientation dependence in that case we consider that (())(76:26) is actually m.

So do not confuse with that, so with the Schmid factor m this is the relation between this two, now if we do the derivative or the increment of the stress and strain we can find out d sigma equal to 1 by m d tau but at the same time the relation between the shear strain and shear strain also related to this way and here if you also see, sorry this is the shear strain, this is the normal strain this is the shear strain in terms of the Shcmid factor, we can correlate between the shear strain and if you see that increment of the of the normal strain in terms of the shear strain with the correlation and if we find out d sigma y, and equation this and from equation this, from this two the d sigma by d Epsilon equal to 1 by m square d tau by d gamma. So that is the relation between the, now this actually represents the work hardening rate in tension.

So work hardening rate tension that means in tension we need to define the work hardening rate that is the basically slope of the curve, slope of the curve in the stress and strain, that actually represent the work hardening rate mathematically. Now you can find out if we put the value of the m we can numerically estimate what is the work hardening rate. So this is the typical problem, we can find out the work hardening rate in the shear in terms of the Schmid factor, that we can find out the work hardening rate in case of tension for the, because of work hardening rate in case of shear we can easily find out for single crystal structure but work hardening rate of the polycrystalline structure using that value and using the simple Schmid factor we can find out the work hardening rate in case of the polycrystalline structure. So this one typical example.

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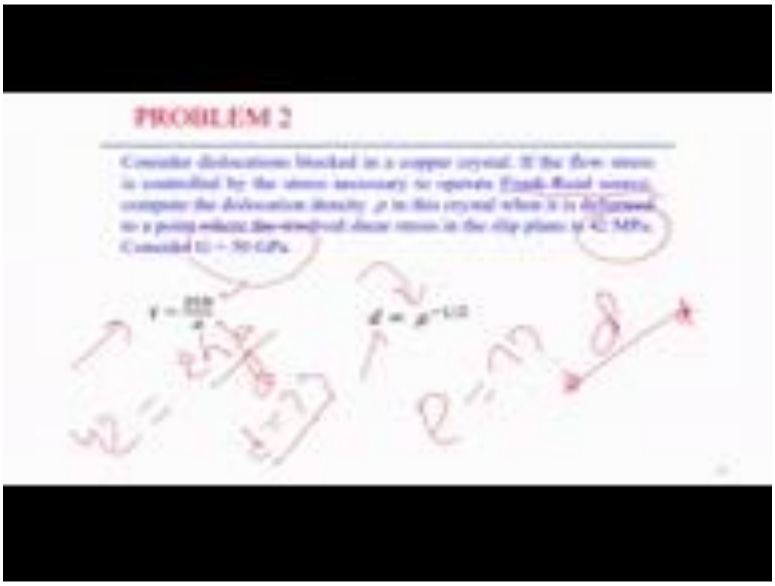

PROBLEM 2

$d = \rho^{-1/2}$

Now we can look into that another example that consider dislocation blocked in a copper crystal if the flow stress if controlled by the stress necessary to operate Frank Reed source, compute the dislocation density rho in the crystal when it is deform to a point where the resolved shear stress in the slip plane is 42 megaPascal. So here we need to consider the shear modulus G equal to to 50 megaPascal. Now here it is mentioned that stress necessary to operate Frank Reed source, so according to the when we consider the mechanism of the Frank Reed source of the dislocation generation and at the semicircular form we can directly estimate the shear stress to make the dislocation bows the semicircular form the relation between the shear stress and the shear modulus, Burgers vector and d equal to actually distance between the two point of the dislocation, sorry this is the d distance between these two points.

Here if we see that we can estimate the easily the shear stress required in this case, or maybe shear stress is given and twice G I think for the copper I think we can easily estimate the b and now from here we can find out what should be the distance d, distance d means the segment of the dislocation d we can estimate by looking into all the on that slip plane the resolved shear stress and the resolved shear stress and shear modulus and the Burgers vector we need to calculate in case of the copper by the available data we can easily find out the what is the Burgers vector in this case, and then we can find out what is the d. so once we estimate the d so from there we can find out, by estimating the d we can find out the dislocation density by looking into the relation between the d and the dislocation density.

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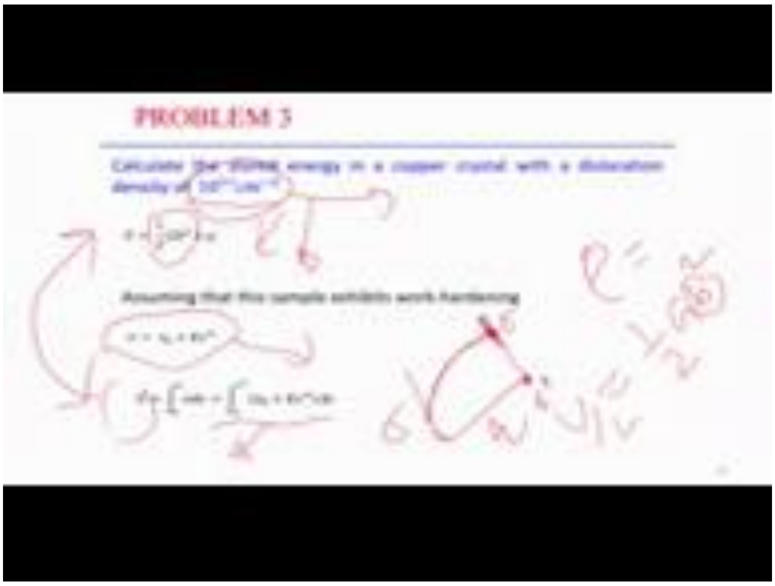

PROBLEM 3

Calculate the stored energy in a copper crystal with a dislocation density of $10^{11}\,cm^{-2}$

Assuming that this sample exhibits work hardening

Now if we look into the problem 3, here we need to estimate the calculate the stored energy in copper crystal with a dislocation density of 10 to the power 11 centimeter square, so dislocation density is given here. Now here we need to find out stored energy, so we know the stored energy approximately calculated by the dislocation energy per unit length is 1 half of Gb square, so once if we estimate the b for copper you can easily estimate the Burgers vector b and from there we can find out the dislocation energy per unit length so here we can find out half Gb square actually dislocation energy per unit length. Now if we multiply by the dislocation density so here we can find out what is the energy associated for a specific sample.

That means if one sample, one sample over the volume if we can if the dislocation density is estimated that means dislocation density is given here so for that sample we can find out the amount of the dislocation energy associated with the total number of dislocation with the sample. But this is the one way we can estimate the directly straight forward that what is the amount of the energy associated with this. Now there is another way to estimate this thing, but you need to know completely the stress strain behavior in the second case. If we assume the stress strain behavior of copper crystal or follow this thing, or of course considering the strain hardening or work hardening effect, sigma equal to sigma 0 and K Epsilon to the power N, this is the typical stress strain diagram in case of the copper crystal.

So if we completely define the stress strain and at a specific point suppose this is the point at this point if we know that strain equal to e1 for example, amount of the strain e1 and at this point the strain equal to sigma. So that here at this specific point sigma the stress we reach at that point from the base stress sigma and remaining part by the work hardening mechanism through the work hardening mechanism the strain actually increases up to that point. So at that point sigma is given. So once the stress strain curve is define for the specific material or for the in this specific case in that case the energy per unit volume can be estimated like this, 0 to Epsilon sigma d sigma so from here we can find out that the amount of the energy that if we put it sigma equal to in terms of the sigma 0, and intrication limit from 0 to Epsilon 1 and k Epsilon to the power n d Epsilon.

So here we can estimate that energy per unit volume in this case from the strain hardening mechanism. So if the sample volume size is define multiply by the total volume, so total amount of the energy associated with this can be estimated, now we can compare this thing that which cases the amount of the energy is more or less or both way we can estimate the total amount of energy, stored energy in a copper crystal with a dislocation of density specifically with this amount of the dislocation density is heavily deformaterial. So highly deformaterial this amount of dislocation density generally exist. So these are way we can estimate the amount of the energy associated with the specific sample.

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PROBLEM 4

Now if we look into the problem 4, here if you see consider a material strengthen of precipitation of fine particles, suppose shear yield strength of the particle is G by 10 that is the theoretical strength that we discuss that theoretical strength G by 10, G is the strength of the matrix is G by 500, so these are two strength level are given, also assume that the volume fraction of the particles is only percent that means volume fraction of the particles is 1% that means Vf one by 100 and have the diameter of 0.01 micro meter. So d the particle diameter is equal to 0.01 micro meter, Assume that B equal to 0.2 nanometer that means Burgers vector is given 0.2 nanometer need to estimate the applied shear stress which is necessary to bow the dislocation beet particles.

So what maybe the applied shear stress so that bow the dislocation between particles and would dislocation bow between the particles or it will try to shear them. So first we will look into that that, first question what will be the applied shear stress that will try to bow the dislocation between the particles. So in this case we assume the situation is like that, during the bowing the dislocation will try to form the semicircular form, so when you try to form the semicircular form in that case the shear stress is required, shear is equal to twice Gb by D. So here if you see the G shear modulus is define b Burgers vector is also define. But we need to find out the d, so d can be found out because of the volume fraction is given here and if we assume the volume fraction of Vg and probably over a sample with this configuration of a square element, with the configuration of the particles of the square element so here if we assume that the distance this two equal to d, so in that case volume fraction can be represented by pi r square by d square.

So pi r square is the surface area per unit thickness, surface area of the particles and d square is the surface area of the square. So this ratio indicates the volume fraction, so volume fraction is given and particle size also given. So from here we can find out the length, dislocation length between the length of the, segmented length of the dislocation or distance between the two particles. So once we start the d and if we put the d value then we find out the shear stress value requirement. Now this shear stress value again we can find out also the other way if we assuming the the particle is cut by the dislocation so in that case the shear stress is required to cut the particles is the mixture of, linear mixture of this component, one is the volume fraction of the matrix, volume fraction of the particles, so both the strength of the matrix and strength of the particle is also given and volume fraction is also given, so from there we can find out what maybe the shear stress vaule.

So now this shear stress value and this both the shear value we can compare. Now if the shear stress, which case if the shear stress value is actually cross the shear stress to cut the particles then we can say that the dislocation, so therefore the dislocation bow between the particles or shear them accordingly we can take the decision by comparing the shear stress value on the first case and in the second case.

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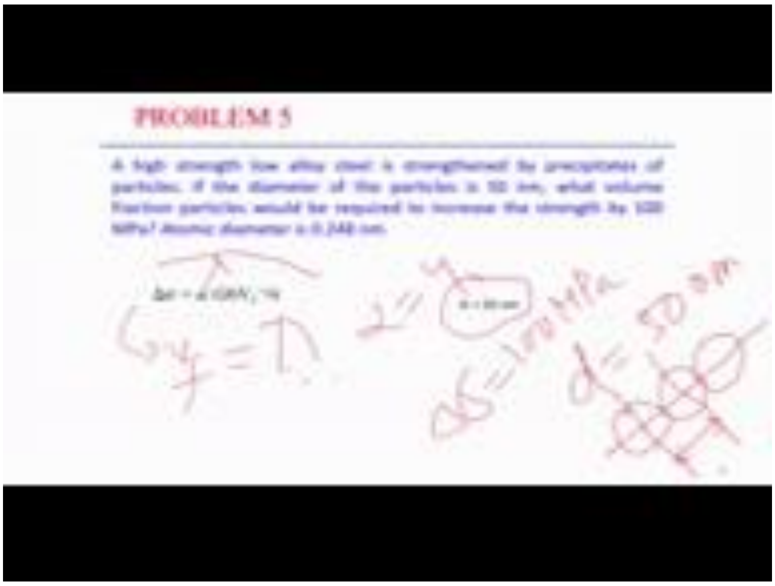

PROBLEM 5

A high strength low alloy steel is strengthened by precipitates of particles. If the diameter of the particles is 50 nm, what volume fraction particles would be required to increase the strength by 100 MPa? Atomic diameter is 0.248 nm.

So let us look into the another problem related to the strengthening mechanism but the high strength low alloy steel is strengthen by precipitates of particles if the diameter of the particles is 50 nanometer, what volume fraction particles would be required to increase the strength by 100 megaPascal atomic diameter is given, so if you see the high strength low value steel is strengthen by precipitate of particles so diameter of the particle is given so diameter d of the particle is given 50 nanometer. What volume fraction would be required to increase the strength by 100. So the increment of the increment of the strength is requirement so delta sigma equal to 100 megaPascal here. Now we need to find out from here what should be the volume fraction requirement.

So if this equation if you see the particle size is given R the radius of the particle is given, shear modulus you know the high strength, shear modulus is generally known, alpha probably in this case we can use alpha equal to 4 and b Burgers vector, I think here d is equal to the 50 nanometer, so d Burgers vector in this case we can consider the atomic diameter, so atomic diameter means probably we assume the close packed direction, so in this case full Burgers vector can be represented the shortest repeat distance which is equivalent to the atomic diameter in this case so b is the Burgers vector is the Burgers vector is the basically the atomic diameter. Now we need to find out, once G is given we need to find out Vf from this equation. So probably with the several problem related to this strengthening mechanism actually this will try to make the more clear understanding of the strengthening mechanism specific generally we apply either in single crystal structure or in polycrystalline structure or in general in case of metals.

Thank you very much for your kind attention.