Welding Metallurgy

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Lecture - 12

Solid Solution Strengthening and Grain Refinement

Welcome to the lecture on solid solution strengthening and grain refinement. So in this lecture we are going to have the discussion about the strengthening mechanism in metals using the these 2, you know ways that is solid solution strengthening and grain refinement. So as we have discussed that you know if you talk about the pure metals, so pure metals are seldom used for the engineering applications.

And certainly we try to have the incorporation of more and more atoms type of different atoms which should be combined to have the better properties. So what happens that you know most of the time if you talk about the you know solid solutions, so in general the solid solutions will be offering the greater resistance to the dislocation motion means they have better strength, you know as compared to the pure crystals.

Now that will be basically because of the stress field which is you know present because of the presence of these foreign atoms, foreign solute atoms. So they will be creating one stress field because of different type of, different factors like it may be because of the size, you know, I mean size may be comparable or there will be you know changing in the sizes so what happens that when you have the solute atoms.

So you will have the presence of this stress field and there will be interaction of this stress field with the dislocation movement. So basically you require large amount of stress to move the dislocation. So solution strengthening is that you know by which basically when you do the solid solution strengthening then the stress required to you know to move that dislocation will be increased to as compared to the pure metals.

And then the next thing we will discuss about the grain refinement you know methods, so in that we will talk about that how when we do the grain refinement, when the grains are refined, when the grain sizes become small so that you know that offers more resistance to the movement of dislocation.

So you know these 2 methods we will be discussing. So you know as we discussed that in case of the solid solutions, the stress field around the solute atoms interact with the stress field of a moving dislocation.

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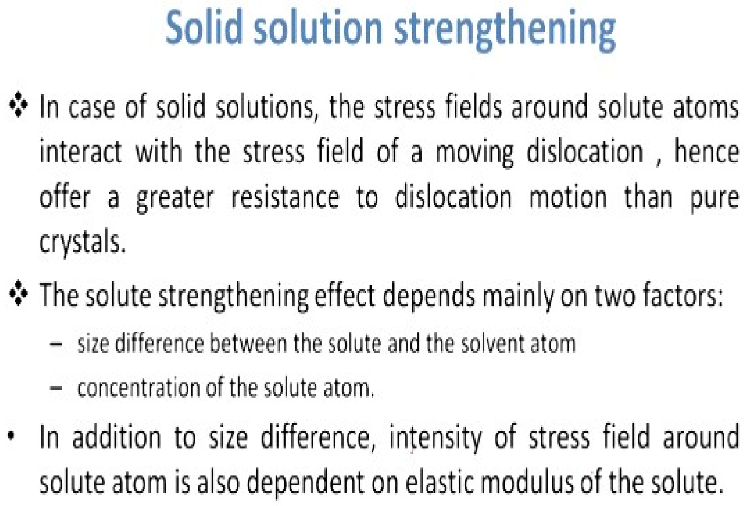

Solid solution strengthening

- In case of solid solutions, the stress fields around solute atoms interact with the stress field of a moving dislocation , hence offer a greater resistance to dislocation motion than pure crystals.
- The solute strengthening effect depends mainly on two factors:
  - size difference between the solute and the solvent atom
  - concentration of the solute atom.
- In addition to size difference, intensity of stress field around solute atom is also dependent on elastic modulus of the solute.

So you will have the these 2 stress fields and they will be interacting with each other and then in that process basically there is a greater resistance which is offered for the dislocation movement in case of solid solutions. You know then the pure metals, so basically you know when we talk about the you know solute strengthening, so that effect will be basically depending upon the 2 factors mainly.

One will be the size difference between the solute and the solvent atom. So you know the solute atom which we are using and dissolve it have solvent atoms these 2 atoms are there, so there may be the size difference between them and that will be affecting you know the strengthening effect and second is that the concentration of the solute atoms. So that these 2 you know factors are basically you know important. So if you talk about the size difference.

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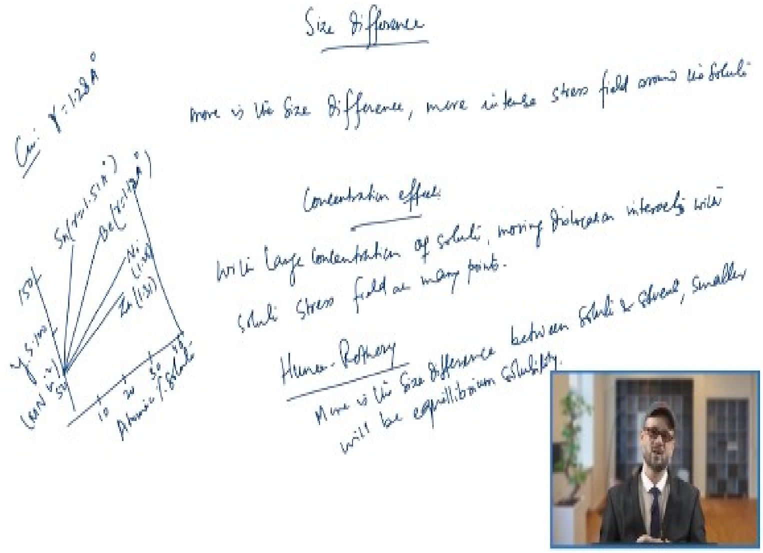

Size Difference

More is the size difference, more intense stress field around the solute

Concentration effect

With large concentration of solute, moving dislocation interacts with solute stress field at many points.

Hume-Rothery

More is the size difference between solute & solvent, smaller will be equilibrium solubility.

So if we see that if you talk about the effect of the size difference so what happens that a larger will be the you know size difference. So the more intense will be the stress field. So basically more is the size difference. So that will be creating you know more intense stress field around the solute. So you know more is the size difference between the solute and the solvent atoms more intense will be the stress field around the solute.

And then in that case you know once they interact then more will be the stress required for the moving dislocation. So you know so that will be stronger you know interaction and so more will be less stress required to move the you know dislocation. So what happens that if you are you know if you have the larger and then second factor is about the concentration of the solute.

So if you have so if you talk about the you know concentration effect, so with large concentration of solute again you know what happens that you know moving dislocation will be interacting basically with at many points because you have the stress field. So moving dislocation interacts with so interacts with solute stress fields at many points.

So that basically you know that happens that when you have you know large concentration of solute in that case you will have the moving dislocation interaction will be at you know more points because the concentration has become larger and in that case again you know your effect on the you know strength of the material will be there directly because in that case the stress required to move the dislocation will be you know larger.

So if you talk about the you know these effects and try to you know interpret in a graphical way. So if you try to draw the graph so if suppose you are talking about the you know on the y-axis you have yield strength that is in MN/m^2 and if suppose this is your atomic percent solute. So as there will be concentration of solute you know as you increase, suppose this is your concentration.

So it will we have you know 10%, 20%, 30% or 40% you know that way it may go. So this is percentage. So, what is seen you know in that case if you are using the copper crystal you know if your solute strengthening this copper crystal by the other you know atoms. So in that case if you look at suppose this is a 50 MN/m^2, you have 100 mega Newton per meter square, you have 150 mega Newton per meter square.

So what is seen is that you know the graph goes like if you go for zinc, so and if you go for nickel, so for nickel this is the graph. So what is seen is you know for copper if you talk about the copper, so if you take the copper it is radius is about you know radius is 1.28 Å. So if you have you know the other atoms are like zinc or nickel which has suppose, zinc has 1.31 and nickel has 1.25.

So what you see that you have not much of the change, but certainly when you increase the concentration you see that there will be you know increase in the yield strength of the material as you are increasing, now if you come to, so this is the showing basically the effect of the concentration of the solute. When concentration is increasing in that case I mean proportionally, your yield strength is increasing.

Now if you look at the effect when you are alloying with or making this solute atoms you are you know adding like you are doing with suppose tin whose radius is about 1.51 Å or you are taking the beryllium whose radius is about 1.12 Å. Now in these cases if you look at these you know cases what you see that for zinc and nickel the difference is not so high.

So it is hardly 0.03 Å, you know in these cases; however, when the difference becomes more for beryllium. For beryllium you consider it is the difference is you know about 0.16 Å and if you see the tin, Sn, then it becomes even 0.23 Å, even larger, so in these cases what you see that you know strength becomes quite high, the slope of this line basically will be quite high in these cases.

And that is why you know what you see that the difference in the strength is quite you know that difference in the yield strength is becoming quite you know considerable. So this is basically you know the effect of the change in the size, so that you know can be seen that here you have the larger you know strength which is achieved when your size difference becomes you know larger.

Now if you look at the nickel or zinc so what you see that in case of nickel and zinc both way you have the size differences same; however, so what you see that in the case of nickel the strength is more. So that basically is depending upon the elastic modulus value of the nickel. So for nickel the elastic modulus value is higher that is why in this case what you see is that you know the increase in the value of the yield strength is higher as compared to when it is you know when the other solute which is present the zinc.

So in that case you know you will have the more intense stress field in case of nickel, you know when copper is with nickel as compared to copper with you know the zinc. So that is why you will have the you know more strength in nickel as compared to zinc even if their size difference is basically you know same. Now what is you know important is that you might have the idea about you know Hume-Rothery rules.

So what is seen from here that you know the size difference should be maximum as well as the concentration should be maximum, but then it means that you will get the best result when you have the maximum size difference and also you have the maximum concentration, but then that both these conditions cannot be satisfied simultaneously and that is you know in the line of the very famous rule that is Hume-Rothery rule.

And that tells so your Hume-Rothery rule basically is giving you, you know a limit on the conditions you know on both the conditions being satisfied and that Hume-Rothery rule tells that more will be the size difference so more is the size difference between solute and solvent so a smaller will be the equilibrium solubility.

So, basically you know that poses you know a limit because you cannot add large amount of those solutes which have larger size differences. So basically another you know the way what we follow is normally we do that you know we go to you know higher temperature so you normally try to get a supersaturated type of you know metastable solid solution and so you go at the higher temperature and then quench it.

You know you cool it fast so that you can get it trapped you know the larger concentration of the solute you know at room temperature otherwise which is not possible. So that is how we also try to have the strengthening by going into that zone where the solubility is more and then we are cooling it fast or quenching it. Another you know this effect of size difference, basically will be the you know apart from these substitutional solutes.

So you have basically there are 2 things, one is the substitutional solution that is your when your the 2 atoms which we are using solvent and solute atoms they are basically of the comparable sizes their size difference is not very high, but then you have the example of interstitial solute solutions which are very much you know this concept is very much used for very you know very popular type of materials like steel if you look at.

So in the steel as you see that we are able to get very high strength because of the interstitial solid solution strengthening. So as you know that you know the void you have the size of carbon which is very small and it is basically you know comparable to the size of the void which is there you know when we talk about the you know iron matrix.

So in that the way these let the structure of iron is so in that case you will have the 2 types of voids are there, you have the tetrahedral, you have octahedral voids. So as you know that when you have the larger solubility of carbon when you increase the temperature and then when you are decreasing you know from there so when you have the from austenite you are cooling and you are getting the martensite basically.

So basically there you know again you have the tetrahedral avoid, so you have the ferrite in those cases what you see is that in that case the void being smaller than even the size of the carbon. So in those case these interstitial solid you know atoms solute atom that is carbon plays an important role in the strengthening of you know the steel and as we know that you are you know getting very good engineering material in terms of steel.

Because if you look at the you know normal solubility of carbon, so it will be about 0.02% you know and then it becomes 0.8% at the eutectoid temperature. So it is about 40 times you know the solubility is increasing when you are increasing the temperature. So that is how you can and then you are cooling it at that temperature highly. So basically intense stress field is generated and then there will be interaction with the stress field of dislocation movement.

So you know that way you have the effective hindrance to the movement of the dislocation and that way you are achieving the strengthening effect you know in the case of steel. So that is how what you see the effect of these you know in solid solution strengthening in the materials to be very effective you know and this is a very important way to have the strengthening in many alloy systems.

Now we will move towards another effect you know of that is grain refinement on strengthening. So grain refinement is basically another way to increase the strength of the material and what we see that if you talk about the structure of the material or microstructure of the material what you see that you have the grains and then grains are separated by the grain boundaries.

And when you know these grain boundaries because you know the orientation of the crystals so if you look at the grain boundaries on the either side of the crystal the orientation of the crystal will be different. So basically the dislocation which is moving you know so you know which is moving on a common slip plane. So it will be finding difficult to you know progress so easily.

So you know it cannot you know so it will be rarely moving you know on to the similar slip plane in the adjacent crystal. So basically that you know inculcates the one type of strengthening you know in the matter and it is because of the presence of these grain boundaries and having more sites like that means increasing the number of grains in the matrix.

So sort of a strengthening which is achieved because of this is you know normally called as the grain boundary you know strengthening because of the grain refinement. So what happens that if you look at the electron micrograph of you know the dislocation piled up against the boundaries. So what happens that if you see the normal TEM, so you will have basically if you look at any particular TEM of the you know alloy.

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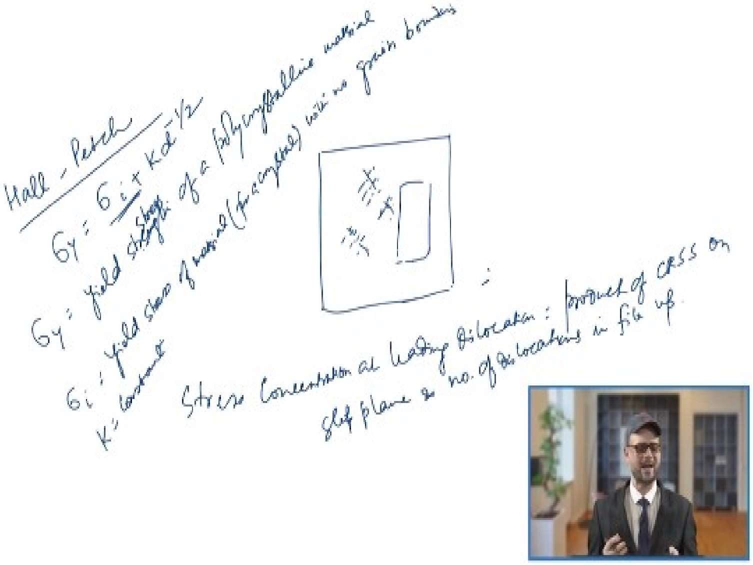

Hall - Petch

$\sigma_y = \sigma_i + K d^{-1/2}$

σ_y : yield ~~strength~~ stress of a polycrystalline material

σ_i : yield stress of material (for a crystal) with no grain boundary

K: constant

Stress Concentration at leading dislocation : product of CRSS on slip plane & no. of dislocations in pile up.

And normally it has been seen that you will have so you will have piling up of the dislocations so what you see along these you know grain boundaries. So this way what you see so you will have the piling of you can see from on these 2 sides there will be re-piling up of these you know dislocation lines and that is and also you will have, you may have the twin boundary also sometimes what you see in a copper crystal it has been shown that how the dislocations pile up basically against these boundaries.

So what happens that when you have the pilation of these you know dislocation, dislocation so in that case the stress which is you know stress concentration which is there at the you know leading dislocation, so when you have.

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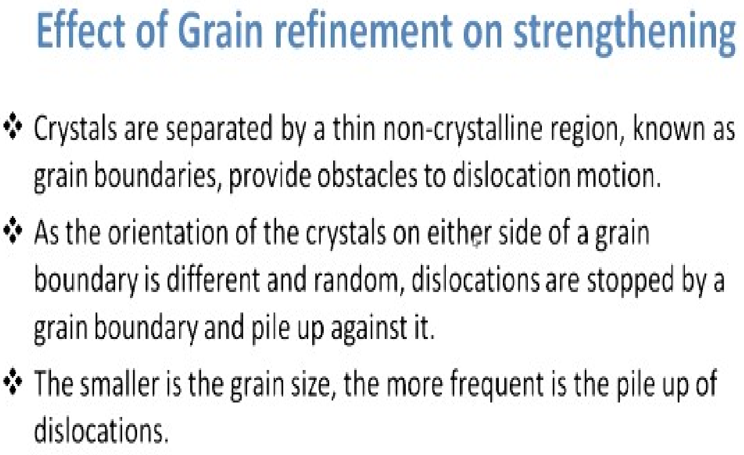

Effect of Grain refinement on strengthening

- Crystals are separated by a thin non-crystalline region, known as grain boundaries, provide obstacles to dislocation motion.
- As the orientation of the crystals on either side of a grain boundary is different and random, dislocations are stopped by a grain boundary and pile up against it.
- The smaller is the grain size, the more frequent is the pile up of dislocations.

So what you can see that so crystals you know are separated by a thin non crystalline region that is your you know grain boundaries and they will be providing the obstacles to the dislocation motion and these orientation of the crystals on either side of the grain boundary is basically different and random and these dislocations are you know stopped by the grain boundary and they are piled up against it,

So that is so normally if you look at the TEM micrograph so you can see only at that magnification you can see that how they are you know piled up against you know those boundaries on both the side of the boundary. Now so what is happening that you know so this will be basically when you have the piled up you know area of dislocation. So the stress concentration which will be there at the you know leading dislocation.

So your stress concentration at leading dislocation will be product of critical resolved shear stress so indeed that is on the slip plane and number of dislocations in pileup, so this way you know you will have so stress concentration that will be at these leading dislocation which is you know this pileup, in case of pileup of the dislocation. So that will be depending upon these you know number of dislocations that is in the you know pileup.

And this magnitude of this concentration now this magnitude of the concentration it will be depending upon the grain size as you will see that you will have you know if the grain size is you know smaller, so you will have the larger you know larger pileup. So I mean when these concentration basically will be the function of the grain size and grain size being larger you know will have these you know larger concentration.

So in those cases you know the stress concentration being higher, I mean then you require the lower value of a stress to initiate the plastic deformation whereas when you have you know the smaller grain sizes in those cases you require you know larger stress to initiate that plastic deformation. So in that line basically there has been a very you know popular formula which has been given, equation has been given.

And that is given by Hall and Petch, so based on his name this Hall and Petch equation basically is suggested and this question tells that you have the $\sigma_y = \sigma_i + K_d^{-0.5}$. So the σ_y is the yield strength of a poly crystalline material, so it is yield strength of a polycrystalline material. So for that material the σ_y will be σ_i.

So σ_i basically will be the yield strength of the material, yield stress you know this is yield stress basically you can say. So yield stress of material or it is for a crystal, you know with no grain boundaries. So basically if you see you know you know σ_y, so when you do not have any grain boundary you have this, this is the $\sigma_i$and when you have the grain boundaries, more number of grain boundaries in that case d will be smaller.

Now in that case this value will go on increasing so you have another constant K and this K is known as a constant. So from this expression it is quite clear that if the grain size will be smaller in that case the yield strength will be larger. So that is what is you know clear from here. Now as we see that normally we specify the grain sizes in terms of the a number and it is normally given by the ASTM number.

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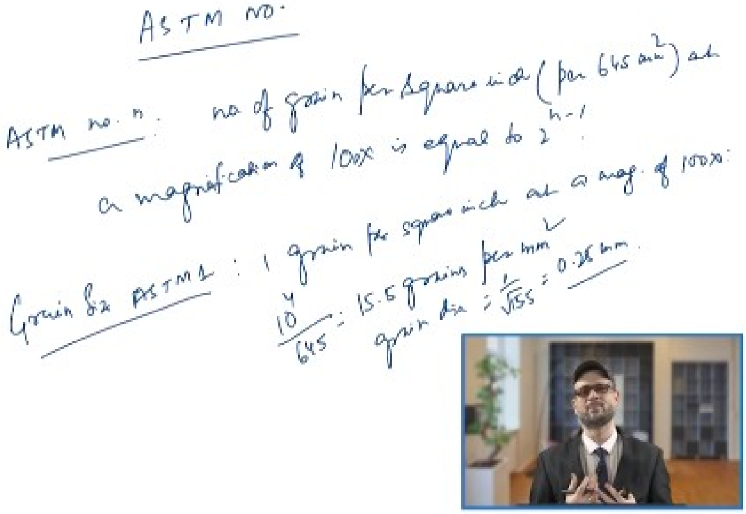

ASTM no.

ASTM no. n: no of grain per square inch (per 645 mm^2) at a magnification of 100X is equal to 2^{n-1}.

Grain size ASTM 1: 1 grain per square inch at a mag. of 100X:

$\frac{10^4}{645}$ = 15.5 grains per mm^2

grain dia = $\frac{1}{\sqrt{155}}$ = 0.25 mm.

So if you have the suppose ASTM number n, so ASTM number n means it means the number of grains per square inch that is per 645 mm^2 at a magnification of 100X and so number of grains will be is equal to 2^{n-1}. So this is basically the definition for the ASTM number n. So if you take this you know by 100 X 100 so you will have if you take any area so you will have the you know you are doing the magnification at 100 X 100.

And that too for the 645mm^2, so if you look at the you know, if you go for the grain size you know ASTM 1, so it will be 1 grain per square inch. So 2^{1-10}, so 2^0 that is 1, so it will be 1 grain per square inch and so it will be 1 grain per square inch at a magnification of 100X. So you will have $10^{400X100}$ in that area and divided by 645.

So you will have 15.5 grains you know per mm^2, will be basically the you know size so this will be ASTM 1 and if you talk about the you know grain diameter so grain diameter will be something like you know, so it will be 1 by under root 15.5, so it will be something close to 0.25 millimetre. So it will be 250 you know micrometre that will be the size of the you know the ASTM 1.

You can go for ASTM 2, 3, so every time it will be going by under root 2 like that it will be you know changing. So that way you will have the change in the grain sizes and if you go to larger you know ASTM, so you will have the ASTM value going from ASTM 1 to 8 and then you can have even for the you know so then we can have the solution, we can solve the problems based on these numbers.

And we can see that how you know when we decrease the grain size. So how the strength is basically you know changing so that even can be understood when we solve the problems based on that and there are many ways by which you can do the grain strength I mean grain size reduction many a times we have the micro alloy steels or many kind of steels where we are putting these you know alloying elements.

So that they have the form as they work as the heterogeneous nucleating agent so they form the nucleation and that way you can increase the number of grains so grain sizes are basically reduced. So you know if you talk about the ASTM 14 to 15 size it will be something you know very very small in those cases, so that way from 250 micrometre it may go to about 2 to 3 micrometre.

So that way you know you can go you know in those cases because 250 and then you have a 2 raised to the power something close to 8 will be you know that is 256. So somewhere close to that so before that if you come, so it will be somewhere ASTM about if you take 14 to 15 it will be about 2 to 3 micrometre size.

So if you go you get very small you know as you go on increasing the ASTM number the grain size becomes smaller and smaller. So we will have you know more discussions about you know we will have the solution of these problems in our coming lectures. Thank you very much.