Welding Metallurgy
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Lecture - 14
Strain Hardening and Strain Ageing

Welcome to the lecture on strain hardening and strain ageing. So again we are going to discuss about you know very 2 important strengthening mechanism in metals and that is strain hardening as well as strain ageing.

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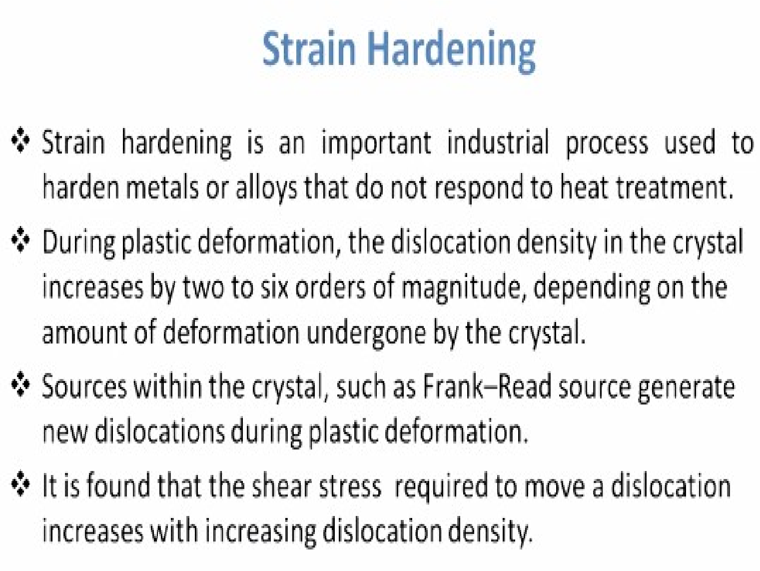

So strain hardening as we know it is an important industrial process used to harden metals or alloys that do not respond to heat treatment. So we have seen the flow stress curve not a stress-strain curve and in that you know as after the plastic deformation when you see the reason where the flow stress value goes on increasing basically that is indicative of the strain hardening zone.

So for those materials where you cannot do the you know hardening by the heat treatment that is may be by transformation hardening or so, in those cases you know the strain hardening becomes an important you know process and in this case basically what happens that when you do the plastic deformation in that case the dislocation density in the crystal will be increased by 2-6 orders of magnitude.

Depending upon the amount of deformation which is undergone by the crystal and since there will be increase in the dislocation density so that will be you know that leads to increase in the stress required you know for the plastic deformation. So the sources within the crystals like that of the Frank-Read source they generate the new dislocations during the plastic deformation.

And so your it is found that the shear stress required to move a dislocation increases with the increasing dislocation density. So what has been seen that you know the shear stress required that is to move a dislocation τ.

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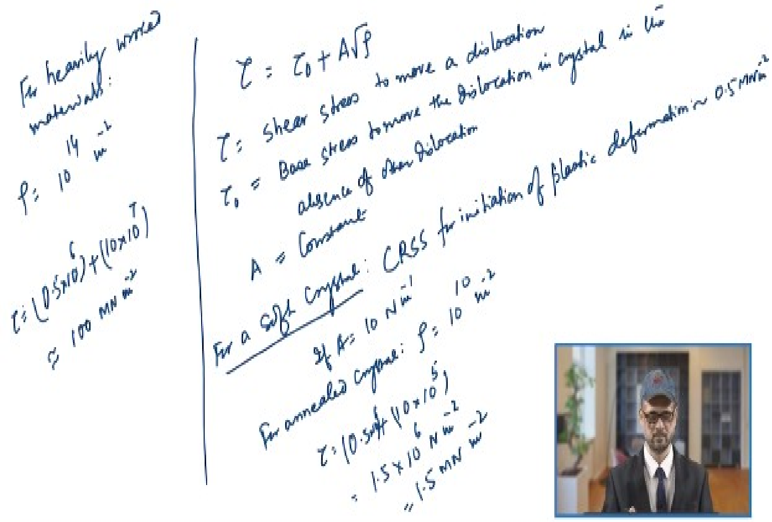

It is found to vary with the square root of the dislocation and keeping the constants we write it like $\tau_0 + A\sqrt{\rho}$. So basically what happens that this τ, τ is the shear stress to move a dislocation and you know this $\tau_0$this is basically the base stress to move the dislocation in crystal when there is no other dislocation. So in the absence of other dislocation.

Then you have A, A again is a constant, so as you know that when your dislocation density will increase, so its value will be ranging you know you have different values and you know now depending upon this increase in the dislocation density your, you know τ value will increase, so what happens that you know this equation basically will be deriving will be discussing about the work hardening behaviour.

So if the dislocation density will increase then the τ that is shear stress required to move the dislocation will go on increasing. So basically you know for you know for a soft crystal if you look at, so for a soft crystal, we have talked about the critical resolved shear stress. So critical resolved shear stress CRSS you know for initiation of the plastic deformation.

So as we discussed that this is the critical value which has to be reached for the initiation of plastic deformation and for you know a soft crystal which is very anneal one now this value is close to the 0.5 MN/m^2. So this is the critical resolved shear stress for a very soft crystal. Now if A is taken as you know 10 MN/m. Now in that case you know.

Now depending upon the value of rho now suppose you are taking you know for a anneal crystal so for annealed crystal if you look at, for annealed crystal basically rho is of the order of 10^{10} per m^2. So if you take this rho value of 10 per m^2, so if you see tau will be tau not. Now $\tau_0$is your, this is the value 0.5 and then A value is 10.

And then this will be multiplied by 10 raised to the power, now 5, so its root. This is 0.5 MN, so certainly into 10^6. So it will be coming in the term of Newton. So it will be you know if you look at this value so this will be 10^6 and then this is 0.5 10^6. So it will be 1.5 * 10^6, so that will be you know N/m^2.

So it will be 1.5 MN/m^2. So you see that this is a very small value for the annealed crystal. If you take heavily worked you know crystal, if you do the heavy working in that case this 10^{10}, it can go up to 10^{14} you know per meter square or sometimes may be many a times we talk in terms of per mm^2 so it will be divided by 10^6.

So if you take for heavily worked crystals, now in this case your ρbecomes 10^{14} per m^2. So if the material is heavily worked, now in that case if you find the τ , now τ will be A so that will be τ_0, τ_0 is anyway 0.5 MN. So this is again 10^6 N/m^2 + A, we know that it is 10 and then it is root will be 10^7.

So basically it will be 100 * 10^6, so it will be move 100 + 0.5. So it means close to 100 MN/m^2. So this way what we see that your dislocation value will be changing quite high when your dislocation you know I mean this shear stress required to move the dislocation value that will be changing and that indicates the increase in the strength of the material.

So suppose you may lean with some questions like you have we are talking about suppose you know the yield stress of a crystal.

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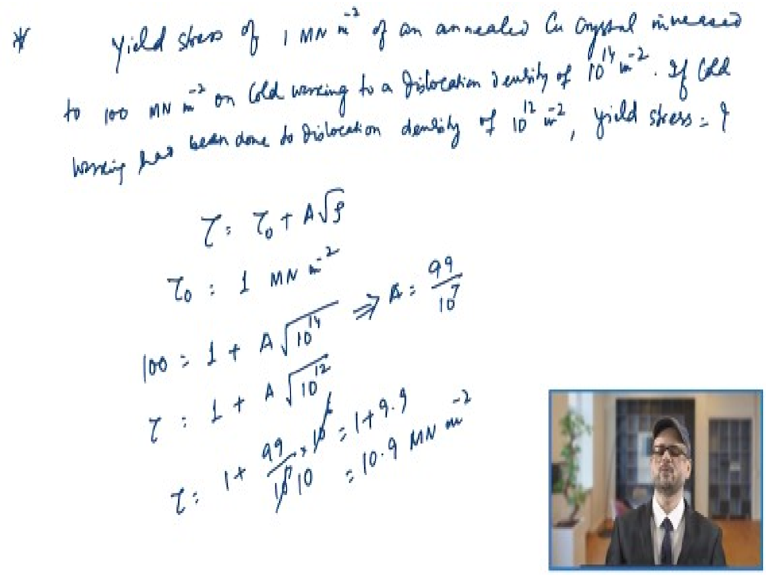

So if we say that the yield stress of you know 1 MN/m^2 of an annealed copper crystal, now if that is increasing, so if that increased you know to 100 MN/m^2 . Now so on cold working, so because we are cold working the material, so to a dislocation density of say suppose 10 ^{14} per m^2.

Now in that case, now if you are told that if cold working had been done to dislocation density of say 10^{12} per m^2, now yield stress will be what? So such kind of situation may you know come you may face with that kind of problems. So you can just use this that formula that is τ will be equal to $\tau_0 + A\sqrt{\rho}$, so what you saw that when we are talking about the annealed crystal.

So it is completely annealed, you know without the absence of any dislocation, so your τ_0 is basically here given as 1 MN/m^2. So you can write that for this dislocation density of 10^{14}. So this value has gone to 100 MN/m^2, so 100 will be $1 + A\sqrt{10^{14}}$.

Now in that case you require to find the shear stress to move the dislocation when your density, dislocation density has gone to you know 10^{12}. So what we see that certainly it will be lesser than this value and you can solve these 2 equations and you can get the values. So what you can from here you can say so from this equation you will get that A will be 99/10^7.

So you can use in this formula, so τ will be $1 + 99/10^7*10^6$, so it will be cut, so it will be 10 here, so 1 + 9.9. So it will be 10.9 MN/m^2. So this way you know depending upon the type of question or you may have the question of different type. So you can always solve you know the problems which you may face or you may come across of different type and you can solve them with ease.

Now also if you try to see that what will be the effect of this cold working. So when you increase the cold work.

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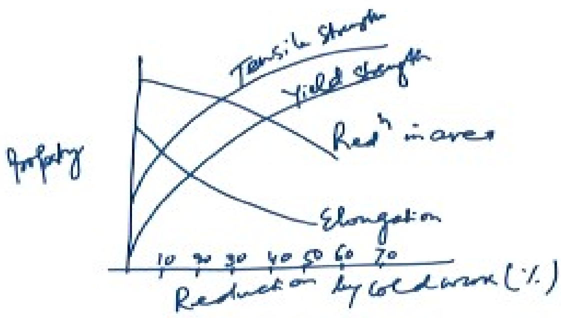

So if the degree of cold work is increased if it is the reduction you know by cold work and if you do it in terms of percentage and if you look at the property then in the property basically changes. So the tensile strength will be increasing similarly the yield strength also will be increasing and your elongation basically decreases and also the reduction in area that will be also is you know decreasing.

So this is elongation, this is reduction in area. So this will be something like 10%, 20, 30, 40, 50, 60, 70. So this is in terms of percentage so 10, 20, 30, 40, 50, 60 and 70. So this way if you increase the reduction you know by cold work, so in that case your you know this is the increase in it is tensile properties or you know yield strength, so this is tensile strength and this is your yield strength.

So very you know as you know that a very you know common example can be cited for the use of the strain-hardening process that if you have a wire and if you try to bend it many number of times and ultimately it breaks. So basically what happens that the dislocation density goes on increasing and the material becomes harder and harder and at one point of time there is not at all any ductility or elongation.

So you know the material breaks, so that way there is a fracture you know you have little type of fracture you know to the material. So this is the you know example of you know increase in the strain hardening because of the you know reduction. So when you do the cold working in that case you have you know the change in the properties or increase in the strain that is achieved.

Now we will come to the next you know the mechanism of strengthening and this is strain ageing.

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Strain Ageing

- Strain ageing is usually associated with the yield point phenomenon, in which the strength of a metal is increased and the ductility is decreased on heating at a relatively low temperature after cold working.

- If specimen Strained plastically beyond yield point elongation, further unloaded and retested without appreciable delay or any heat treatment, Yield point on relaoding does not appear.

So strain ageing is usually associated with the yield point phenomena in which the strength of metal is increased and the ductility is decreased on heating at a relatively low temperature after the cold working. So what happens that normally if you talk about you know if you try to see the flow curve of a low carbon steel. So we can have so what happens that initially what you see that it will go to the elastic zone and then after that it will go into the plastic zone.

So you will have yield point also they will be yield drop and then you will have the things you know the material will go into the plastic deformation zone. Now what happens that it was seen that when basically you are you know you are unloading it and then further reloading it then in that case that the citizens which you are seeing or the yield drop which you are yield point which is appearing that normally is not seen.

So if you are once you have done and then further you have unloaded and further reloaded without much of the delay, in that case you do not see the appearance of yield point; however, again if you unload it and then you are ageing it at some low temperature range and then if you are further you know so after this treatment if you are further putting it under loading in that case that is seen that there will be further appearance of the yield point.

And then there will be yield drop basically and then what you see that there is a decrease in the ductility also observed. So that is basically the process of you know process of strain ageing. So this ageing treatment basically will lead into you know certain you know traits, certain other observations are observed. So that we can see by looking at the you know the stress-strain curve for a low carbon steel.

So what was seen that if you have you know the if you look at the stress-strain curve for the low carbon steel, so initially when you strain it so it will go and then you will have this lead point observation.

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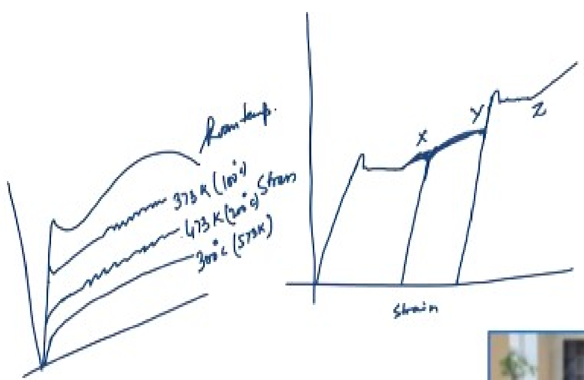

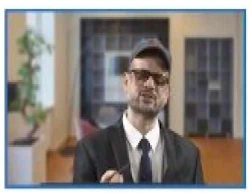

And then you will have further increase that will be observed, so this will be your stress and this will be strain. So this specimen is you know plastically strained through the you know yield point elongation and initially it is strained to say suppose point X. So after the yield point we have strain to point X and then after this point what we do is you know a specimen is further unloaded.

So we are unloading this you know this specimen, so now what we do is we try to you know further reload it. So it is retested without any appreciable delay, we are not doing any delay, we are further retesting. Now if you further retest then it will go and then further it will go from here and you will have this kind of you know the stress-strain curve.

So what you see that once you do the reloading then the yield point does not, the yield point which you have seen in the earlier case, now that does not you know appear this time because it is seen, it is expected that and what is has been found that in this case the dislocation which is you know they are thought of being torn away. So they are torn away from the atmosphere of carbon and nitrogen atoms.

So for that this yield point is not you know observed in such case. So if further suppose you go to this point Y you are straining and then now again what you do is you are unloading it and then you are further, so you want to reload it after you know many days of ageing and if you do the ageing you know ageing temperature may be the room temperature or it may be up to 400 Kelvin of temperature.

So it will be something like 120 ^{0}C, so if you do the ageing for many days and if you do the further testing then what you see that further you will have the increase in the yield and then again you will have this yield point occurrence. So that is further seen so from Y to you are now going to Z. So the yield point is further reappearing, so that is reappearance of this yield point.

And this is because of the diffusion of the carbon and nitrogen atoms you know to the dislocation. So in that region of ageing when you know when you have done the age, so during that ageing period this is because of the diffusion of the carbon and nitrogen atoms into the dislocation and they are forming the new atmosphere of interstitials which will be anchoring the dislocations and because of that again your you know appearance of yield point is you know observed you know in this case.

So that is what is known as the strain ageing and you know the specimen is strained plastically beyond yield point elongation, further unloaded and retested without appreciable delay then yield point on reloading does not appear, that is what we have seen that when you first go to point X then you are you know unloading and then reloading without much of delay, so you do not see any yield point elongation and yield point you know phenomena.

And but when you go further when you do the ageing in that case you know so once you go to point Y, then you unload and then reload it after some time of ageing normal you know ageing at room temperature or somewhat higher temperature then in that case again the yield point phenomena is observed and in this case this is basically because of the you know carbon and nitrogen that diffusion into the dislocation during the ageing period to form new atmospheres of interstitials anchoring these dislocations.

So in this case what has been found that it is found that this nitrogen is playing important role in the strain ageing of iron than carbon because of the higher solubility and diffusion coefficient of nitrogen as compared to carbon.

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- If specimen is further unloaded and reloaded after aging for several days at above room temperature (400K), yield point reappear and increased because of ageing treatment.
- Reappearance of the yield point is said to be due to diffusion of C and N atoms to the dislocations during the aging period to form new atmospheres of interstitials anchoring dislocations.
- Nitrogen plays a more important role in the strain aging of iron than carbon because of higher solubility and diffusion coefficient and also produces less complete precipitation during slow cooling.

And also it produces less complete precipitation during the slow cooling. So because of that this nitrogen is considered to be more important than you know that of the you know carbon in that case. So basically it is very important you know to avoid this strain ageing especially when you go for the phenomena like deep drawing.

So in those cases if there will be reappearance of this yield point in that case that may lead to you know the improper surface finish because there will be, so because reappearance of the yield point that may lead to the marks on the product. So these marks you know they are known as the stressor strains, so that is observed. So basically normally we try to avoid this.

So you know for controlling this strain ageing normally we try to have you have to control the amount of carbon or nitrogen and for that many a times we try to you know add elements which can form carbides or nitrites so that you know they can precipitate out so that way you can you know avoid this phenomena of strain ageing. Now you know it is very difficult to you know have you completely avoid this strain ageing.

So in that case what industrially what they do is that normally you will have you have to deform the metal to point X, you know by roller leveling or skin pass rolling operation and then further so in that case you know up to this point X, you go you go for the you know roller levelling or skin pass rolling and then use it immediately you know before it can age, so you have not to give time for ageing.

So that is what you know the remedy is, now so what actually the effect of the strain ageing is that one is that it is increasing the yield point and also it leads to the decrease in the ductility and also a low value of strain rate sensitivity. So these are basically the effect of the strain rate sensitivity. Also because of the strain ageing you will have the serrations in the you know stress strain curve also.

So you know this is known as the dynamic strain ageing behaviour. So if you look at the stress-strain curve for you know for iron so in the iron it is seen that when you do at room temperature you know it goes like this; however, if you, you know, if you do the ageing at different temperatures in those cases what you see that if you do at 100 ^{0}C, so it will be you know going and then then you will have this strain you know these serrations observed.

So this is at 373 Kelvin, so that is your 100 ^{0}C , this is at you know room temperature. So you know this is you know that is known as so this is basically known as the Portevin–Le

Chatelier effect because these are the scientists who have discussed about it. If you go to 200 ^{0}C so your curve will look like this and then you will have again the serrations will coming up, so this is 473 Kelvin that is 200 ^{0}C .

And you know at 300 ^{0}C it will be you know going like this, so it will be at you know so 300 ^{0}C or it is 573 Kelvin. So you know so ultimately basically you have you know tensile ductility is basically reduced in those cases. So this effect which is seen, now in this cases you know what we see that this effect basically is known as the Portevin–Le Chatelier effect.

So basically you know we can understand this from this point that in such cases when you are increasing the temperature suppose in this case 373 or 473 you know Kelvin in those cases what happens that these solute atoms they are you know able to diffuse in the specimen at a faster rate as compared to the movement of the dislocations and so as to catch or lock them. So what happens that in that case the load has to be increased.

And you know so that when the dislocations are torn away from the solute atoms and so ultimately there is a load drops, so that is how you know dropping and then increasing that continues, that leads to the formation of these serrations. So that is not desirable in fact. So that is why what we do is normally we try to have such a condition.

So that you know the effect of you know this carbon and nitrogen which is there which shows you know which is responsible for the reappearance of the yield point and also you know if you look at these you know serrations. So especially in those operations you will have to have lower amount of carbon and nitrogen or you will have you know you have to do these operations once you go to you know the region X, then you should finish there forming operation without you know giving that time for ageing or without much of the delay.

So that way so what we see that this is also a strengthening, it is increasing the strength. So basically strain ageing is another way you know to increase the strength of the material. So that is you know that is about the strain ageing. So we discussed mainly in this lecture about the strain hardening mechanism and also the strain ageing effect. We will have the discussion about few of these topics and the question solving you know on these topics in our coming lectures. Thank you very much.