Mechanical Behaviour of Materials-1
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Lecture – 42
Summary of Strengthening Mechanisms

Welcome back students, so, we have looked at various strengthening mechanisms that work in metals, alloys. So, in this lecture we will summarize all that but before that there were there is one particular aspect about the yield point phenomena that we missed earlier. So, we will complete that part which is called strain ageing. So, let us begin and thereafter, we will look at the overall summary.

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So, strain ageing if you remember the yield point phenomena it would it looks something like this. So, you have upper yield point. Then there is something like a fluctuation and then over here. So, what was described is that at this is the upper yield point. There is the lower yield point and there is loader band forming and at this point the loader band has formed throughout the sample.

And hence the material begins to deform uniformly after this. So, now, let us say if you are at this particular point and drop the stress, so, you will come back like this. Now, if you start; if you want to deform it again then this would look like this. This would look like a common usable material where you do not have any yield point phenomena. However, if you heat the material, what happens at the atomic level.

So, first of all, let us understand what happens in this particular case once you have dropped the stress and then try to remove the dislocations again. Now, there is enough number of mobile dislocations. And therefore this formation can take place smoothly, just like in material where you have sufficient number of mobile dislocations. But now, if you heat the material, what will happen is that the dislocations which were able to disconnect themselves from the interstitial solute atoms.

Will now the solute atoms will diffuse and because they have a lower energy or basically, there is a bonding between the two. There is a tendency to bond between the dislocation and the interstitial atoms. So, the interstitial atoms will diffuse and will bond with the dislocation or basically it will sit right below the dislocations and thereby pin the dislocations again. And therefore, the density of mobile dislocations would reduce.

And overall it would mean that you will again see the yield point phenomena. And therefore, if this is without heating, now, if you were to heat it so, you would see something like this, meaning the yield point phenomena reappears. And we know why it reappears? It reappears because the solute atoms diffuse and they have the tendency to form bond with the dislocation, are basically sit near the dislocation line.

And which will in the end result in immobility of the dislocation and thereby decreasing the overall density of mobile dislocations. And therefore, again you would see this kind of phenomena where first it will have to unpin some of the dislocation there will be a small band and then at a lower stress. This band keeps getting stretched to a wider and wider region until the all of the region has uniform fully distributed mobile dislocation density and thereafter it will uniformly deform. So, this phenomenon is called strain ageing.

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And this behavior is actually exploited in one particular type of material which is bake hardened steel. Now, bake hardened steel is basically a low manganese steel. And over here so basically, what happens here is that bake hardenable steel has very low concentration of interstitials. And therefore, initially it would behave as if there were no yield point phenomena.

However, if you bake it a little bit, meaning heat it a little bit then the yield point phenomena not assurance reappear, it appears. Because now those whatever small amount of solute atoms are present, they move diffuse and pin the dislocations. And therefore the material will now become harder. So, where it is used? For example if you want to form a shape of them from the material at a lower temperature and at a lower stress.

Then, you can easily deform the material, give it whatever shape and then just heat it a little bit. And in fact, in some cases, for example, when you are trying to make automobile bodies then sometimes during the painting process, there is automatically some amount of heating 150 degrees Celsius to 200 degree Celsius. And in that process that if automatically that diffusion process will take place or a bake hardening baking will take place.

What is called as bake hardening and in the process solid interstitial atoms will move and pin the dislocations and the yield point phenomena will appear. So, overall this would look something like this. So, initially the material has very low strength because it has very low fraction of interstitials. So, you can easily or with small amount of pre-straining it will form it will give you a stress strain curve like this.

So, you can say this is at the pre-straining and after some time once you have formed the shape, you can bake it or maybe the process itself involves some amount of heating like the painting process and in that process the baking will take place. And then interstitials will move and pin the dislocations. So, the overall new stress strength curve would look something like this.

So, here this is with only pre-straining and this one is pre-straining plus baking. And in the process what you get is this much increment in the sigma. So, this is bike hardened steel which is exploited in the industry. So that you can do the forming process and lower stresses then heat it a little bit and sometimes heating would itself be involved in the overall process. And thereafter the material; will form process formed component will become harder.

And less amenable to any deformation so, this is strain ageing and an application of strain ageing.

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Now, let us move on to some summarizing overall various processes that we have learned. So, here I have given you a table which gives you the most important governing equation which shows how the strength increases. This first one is work hardening or strain hardening which is given by Taylor relation and this column tells you that which dislocation interacts with which particular entity resulting which results in the strengthening of the material.

Because, as you remember; strengthening happens because in the end dislocation is interacting with some entity. So, in the case of work hardening or strain hardening this location is interacting with other dislocations and it is overall a strong strengthening process. And the relation is given by the Taylor relation which is alpha Gb root rho. Then there is also the grain size effect or the hall pretch relation where the dislocations interact with the grain boundaries.

And again this is a very strong effect and the relation is given by this. The increment, in the strength is given by k y by root d. Where d is the grain size and k y is proportionality constant. Then you have the solid solution where the dislocations interact with the solid solution solute atoms. And the overall effect is kind of weak, not very strong and this is the equal governing equation.

So, g is the modulus e is the strain and c is some factor. And then you have the precipitates, where you can have small precipitates or large precipitates. Small precipitates are coherent where cutting takes place for the large precipitates it is the loop that forms around it and also this is the governing equation for dispersoids. And for the small coherent particles the strengthening effect is weak.

But for the large incoherent particles, the straining effect is strong. And this is these are the governing equations that are given over here.

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So, now, let us quickly summarize what we know. So, first one is the strain hardening. So, strain hardening one of the primary effect is the dislocation interaction which is given by the peach coller relation which we saw was obtained from here. So, sigma xx sigma xy dot b, so, it is sigma dot b cross e, where e is the line vector. So, here sigma is a stress being generated which may be external stress or stresses from other dislocation.

Some stress is acting and budgers vector and the line vector are the dislocation on to which this force is acting. So, this gives you the effect of these stresses on this particular dislocation. And we looked at special cases where we had two edge dislocations to screw dislocations. We were able to find. We have also looked at image dislocation that tells us that why whiskers are so strong.

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

And then we also looked at Taylor hardening which is based on the relation between two edge dislocations. So, we saw that the critical stress to overcome an array of dislocation, not array of dislocation when there are two dislocations if you want to move another dislocation then it is obtained at x, equal to 0.414 pi. And from here we obtained that tau c should be equal to Gb 1 by 8 pi 1 – nu.

What or this y becomes h, where h is the distance between the two dislocations. And from here we moved on to an array of dislocations, where we showed that rho which is the dislocation density, can be related to the distance h by the relation 1 over 2h square. Which implies that h can be written as 1 over root 2 times rho and from here we obtain the relation tau equal to alpha Gb root rho.

Now, this clearly established that as the dislocation density increases the strength of the material increases. Then we looked at why the dislocation density increases with increasing strain? Then we saw that there are multi dislocation multiplication taking place and those multiplication are taking place because if there are dislocations which are pinned. Then the dislocation and you keep applying the stresses the dislocation form loop and this leads to frank-reed source and in the context of dislocations, getting pinned.

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We also looked at dislocation-dislocation intersection. And here we found that there is energy cost, whenever there is a step formed and also that some of these steps are glissile in nature. So, overall the dislocations get pinned and then and there are also a step form when they intersect. So, the overall you need higher stresses to overcome this and which leads to work hardening or strain adding.

And then we also looked at four different types of intersection between edge-edge dislocations, edge this when the budgers vector parallel when the budgers vector perpendicular to each other. Then we looked at intersection of edge and screw dislocation and we also looked at screw-screw dislocation intersection.

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The other mechanism that we have discussed is the grain monitoring strengthening which leads to pile-up. So, we also showed a animation with respect to that where we showed that if you have a green boundary like this and there is a glide plane like this then there will be dislocation and you are applying stress like this. So, the dislocation would get piled up. And somewhere over here you have to have a source.

And at the end of it there is a stress multiplication. So, if there are n dislocations, there is n times that stress that is acting over here and because of this stress concentration, there are two different proposed mechanism: one either the dislocation will burst through or the dislocations would the stress concentration would lead to generation of odd dislocation source in the neighboring grade.

And based on the burst through mechanism proposed by hall pretch, we know that can be given by this relation. Where d is the grain size and tau 0 is the lattice the strain that shear strength required to overcome the lattice strain.

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And from this we follow the hall pretch relation which is then we also looked at solid solution strengthening and we have also showed that there are basically two types of interaction depending on whether it is edge dislocation or screw dislocation. So, edge dislocation interacts with both shear and tensile stress fields. Because it has both the components and therefore, it leads to both dilational and distortional strains.

On the other hand, screw dislocation has only shear stress field and it has no hydrostatic components and therefore it only results in distortional strains. Substitutional atoms have a spherical distortion field and hence they interact only with the edge dislocations. On the other hand, interstitial solute atoms have both the distortional and the dilational field and therefore they interact with both edge and screw dislocation. And therefore, the hardening effect per unit concentration is higher for interstitial atoms.

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But then the problem is that is the interstitial atoms cannot dissolve much in much larger quantities. On the other hand, solute atoms n the other hand, the substitutional atoms dissolve in a much larger quantity and hence you can dissolve much larger quantities and therefore you can get much more enhanced effect.

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$$\Delta\boldsymbol{\sigma} = \boldsymbol{6G}(\frac{\boldsymbol{r}}{\boldsymbol{b}})^{1/2}\, \boldsymbol{f}^{1/2} \in^{3/2}$$

And then we also looked at the yield point phenomenon which happens because of the patrol fields because of presence of the interstitial atoms near the dislocations. And which also leads to strain ageing which is something that we discussed in this lecture also. And another important strength mechanism was the precipitate strengthening which can actually be divided into two parts. First is when the precipitates are small and coherent.

So, in this case you have cutting and shearing of the precipitates and governing equation is given by this.

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$$\Delta\boldsymbol{\sigma} = \frac{\boldsymbol{\alpha G b}}{\boldsymbol{L - 2r}}$$

And when the precipitate sizes are very big and they are non-deformable like in this per-side then the dislocations bow around the precipitates and again pile-up kind of effect is obtained. And the governing equation here is Gb, where l is the distance between the precipitates. But if you want to be very accurate, you can say you can reduce the size of the precipitates. So, this in most cases may be very small, so, you can ignore that.

But if it is not small then you will also have to include this part. And the overall effect of the two types of precipitates is most visible in aluminum alloys, where we see ageing effect. So, up to a point where we see we see that at a particular temperature and time we see that we have the highest increase in the hardness. And if you keep decreasing the temperature, you may even optimize the process and get even higher strength.

So, this is increasing temperature meaning this is lower temperature. So, all these governing equations are captured in the first table that we saw over here. So, this is the strain hardening. This is for the grain size effect. This is for the solute solution, solid solution effect and this is when the precipitates are small and the cutting shearing is taking place. And this is when the precipitates are much larger and non-deforming.

So, like also in this dispersoid and like I said that this is the distance between the precipitates or the particles but if the precipitate or particle size is very large compared to l then you also need to reduce this or to subtract this and in some form of the equation, you may also get a proportionality constant which is alpha. So that brings to us that brings concludes overall strengthening mechanisms and with that we close this lecture. Thank you.