Fundamentals of Materials Processing (Part- II)
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Lecture – 10
Effect of Temperature

So, welcome back and we will continue our discussion with effect of temperature on flow stress. So we saw that we could verify by plotting this aligned strain rate versus 1 over t and not only verify, but we were also able to get values like strain rate and also q over r and z values. Now what we will do is, we will actually plot the same thing but in a different way which is what is more easier to obtain data and much easier to extract information from that.

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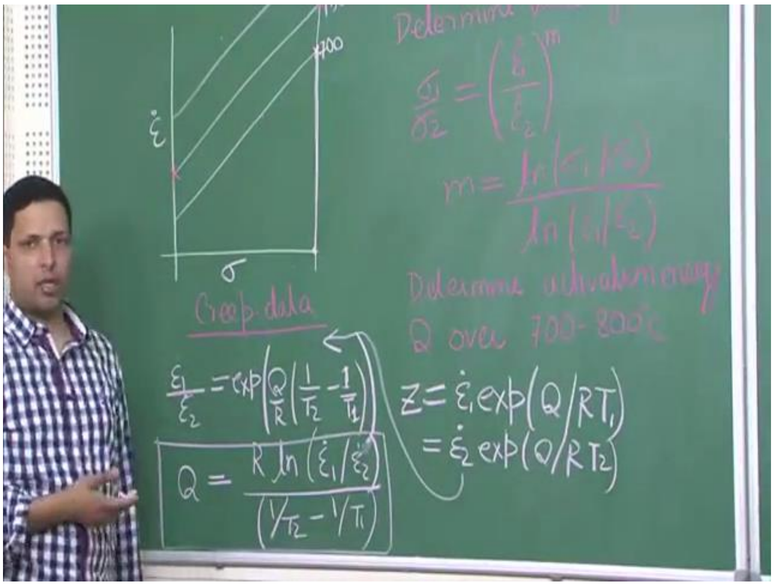

So, that is for that what we have here is data that you usually obtain from creep. So, if you are doing a creep experiment; creep experiment is where you put a constant stress on a material and then at a higher temperature you see how much deformation is taking place as a function of different strain rate. So, the plot for strain rate versus flow stress in this kind of experiment would come out something like this. So, you will have straight lines more or less straight lines data. So, these are not what you will get are basically data points on this and I have combined those to get one straight line. So, you will get some straight lines there may be a little bit variation in the slope because again you will see that slope is related to Q, but assuming that the temperature range we are talking about the slopes are not changing much.

For example let us say this particular experiment was done for three different experiments; 700, 750 and 800 degree Celsius and in that temperature range, let us assume that the mechanism of deformation or the mass transport phenomena does not change. Now here if someone asked you determine the value of m for this material at some particular temperature let say for one of these let say at 750 then what you need to do. So, what you need to do here is to get the value of m, you will compare for that particular temperature, you will take the plot. Now you will have two flow stress values and two strain rate values and you can see that since we are assuming that m is also constant in that range that is another assumption that we have to make because we are talking about a very small temperature range.

So when we are talking about 750, let us assume that we are within a very small range we are not changing the temperature by much. Now sigma 1 by sigma 2 is equal to strain rate, this is our old equation where we know that flow stress depends on strain rate and from here we can take a log on both sides and you can show that m will be equal to now like I said you have data points from this slope, you have stain rate 1 sigma 1, stain rate 2 sigma 2. So, for that particular temperature you can get m value, so whatever temperature as many temperature you have recorded the data, you will m values and then you can even plot m as a function of temperature and then you can see that it actually increases slightly up to 0.5 Tm and then suddenly takes up after 0.5 Tm, so that is one information that you can extract from this; so let me write it again, this is creep data.

So, experiment like creep you can obtain values like this and our make a plot like this and from those plots, you will be able to extract information. So, this is one thing another thing that we can do from this data is for example, someone ask you that determine activation energy Q. Now this activation energy Q has to be calculated over a temperature range. So, you would you would may be asked so calculate over temperature range 700 to 800, now when you are doing this calculation you have to first assume that activation energy does not change from here or that is the mechanism of deformation does not change from this temperature range 700 to 800 range, if it is changing then you may have to obtain the values at for the two different temperature ranges.

So, let us say that the temperature in this particular temperature range the mechanism is not changing and therefore, the activation energy is not changing. Now we can use another important point about point that you must keep in mind is that there is no negative over here, this is not the rate constant equation; the rate constant equation is in the strain rate. So, if you were to use it in terms of strain rate and you put it on the left hand side then it will have a minus sign. So, many a times students make a mistake of assuming from you are old Arrhenius form of equation that you may put a negative sign. So, you must remember there is no negative sign when you a put when you are writing the equation in this form.

Now, from here if we have what we need to do is compare for example, a particular stress. So, let us say this is the flow stress at which we are calculating or at which we are we are using for calculation of Q. So, you will have two values over here, where this is the strain rate 1 for one temperature and this will be the strain rate 2 at another temperature and we are using the same stress value, it would mean that z value for these two points would also remain same therefore, if this was e 1 and this was T 1 then this will become easy this same z equal to for second point where you have same flow stress and once you have this then we get; now beyond this it is just a matter of manipulation manipulating this equation and you can show that Q would be equal to R align strain rate 1 or strain rate 2 divided by 1 over t 2 minus 1 over T 1. So, you see all the values that you need for calculate Q are already over there like I said we have strain rate 1, strain rate 2 for these two different points and T 2 and T 1, so 700 and 800 and R is the universal constant, so you will be able to get Q value.

So, thus, again shows that you can extract a lot of information from this plot from this experimental data and at the same time it is showing you the effect of temperature. So, now, we have seen the effect of temperature in couple of different ways, but we are still not completely done with effect of temperature, there is still one more aspect of temperature and that is on the micro structure which actually leads to increased ductility or reduced strength.

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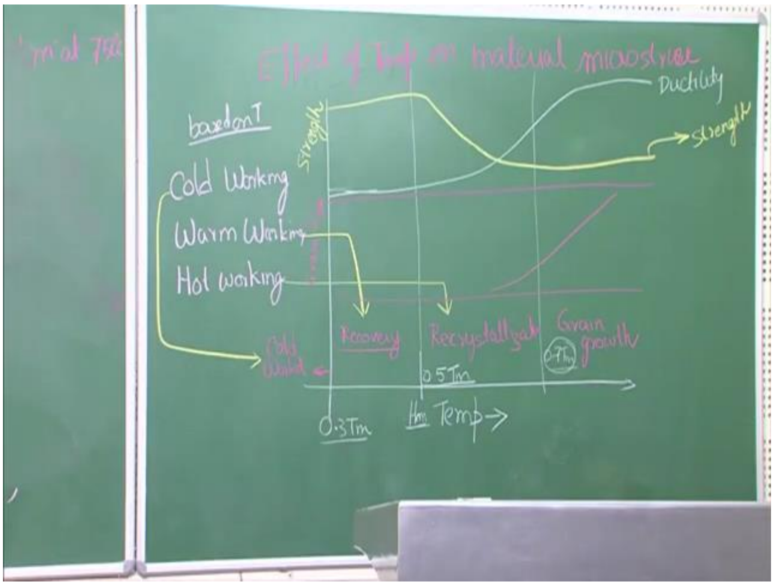

So, now next what we will see is effect of temperature on material. If some of you have not been exposed to the term microstructure, let me briefly describe it; so microstructure is basically structure at the micro level and what are those structures; some non equilibrium structures for example, defects like grain boundaries even other defects like dislocations would come in microstructure, but you may not able see those using optical microscope. So, grains, grain boundaries, phases, phase boundaries inclusions all those things constitute microstructure.

Now, if you look at the microstructure level for a deformed material the microstructure would be different, for anneal material there are microstructure would be different and from that microstructure itself you can actually predict a lot of material behavior and temperature itself effects the microstructure directly and therefore, through that micro structure also some of the properties of the material change. So, that is what we will see what are those properties that change and along with that what are the micro structural parameters that change which lead to those properties change in properties.

So, let me plot again over here on the x axis I have temperature, this is not 1 over T; it is temperature. So, this is increasing in this direction and the way I have drawn is that the point where the temp this y axis is crossing, it is 0.3 Tm again I am using homologous temperature; remember homologous temperature as a lot of utility because using homologous temperature the behavior of several materials can be shown in a group.

So, for example, when I say point Tm, if I do not need to say the separately for a different material for example, aluminum have a melting point of 660 while copper may have 110. So, their behavior will be different when we are looking at 300 for both of them, but when we look at 0.3 Tm; their behavior will be similar and therefore, it is easier to group them together when we use homologous temperature. So, another marker that I drawn here is 0.5 and some higher temperature something of the order of let us say 0.7 Tm, this value is little arbitrary and there is no exact value, but what are the exact value or actually bookish text book values or 0.3 Tm and 0.5 Tm these are the more important values that we should be concerned about, but we also have a third division which you can say is approximately above 0.7 Tm temperature.

So, now let us see what are the changes that take place above 0.3 Tm, but less 0.5 Tm in terms of microstructure, we have phenomena which are called recovery. It is because of this, you remember we had three different zones of working and I will come back come to in a moment. So, this is recovery and above 0.5 Tm, what we have is recrystallization and at a much higher temperature what we have region or the micro, the changes that take place in a micro structure is defined by grain growth. So, there are three or in fact you can say less than this is what you can cold working region meaning no change in the micro structure at all, it is as it is and since we have these different micro structural transformation zones, we describe you remember we had three different forms of working based on temperature, it was cold working warm working and hot working.

If you are talking about cold working, it is when you are doing at a temperature less than 0.3 Tm, so let me relate it. So, cold working is this zone when you are less than 0.3 Tm, warm working is when you are above 0.3 Tm, but less than 0.5 Tm meaning some amount of microstructural changes are taking place over here.

Hot working is when you are above 0.5 Tm usually these are the only zones you do not need to go beyond 0.6 or 0.7 Tm because in this region you are not gaining anything everything that you can gain is limited up to this point and therefore, this particular region is not related with any kind of working for deformation. This is you can say this one is if at all related to it is related to annealing so that you can get rid of all the previous defects or pervious strain history and get the material as good as fresh.

So, for deform from the point of view of deformation or metal processing, we are limited only up to this temperature region or little bit higher than 0.5 Tm and this is called hot working recovery region, we have minor changes will take place as well show right. Now is related to warm working and the cold work region were nothing no new changes take place is cold working. Now if we were to understand what exactly are the parameters that are changing, so now let us look that.

So, first parameter that I would like to describe is grain size, grain size is a very important parameter as you can see grain growth we also have called a region as a grain growth here of course, the grain size would be much larger because that is why this region as named as grain growth, but even in the other two regions you may see some amount of changes and if you were look at variation of grain size, it would follow something like this. So, most of the grain size increased it starts to take place from the region in the recrystallization zone and all most negligible changes in grain size will take place in the recovery or in the cold work zone, so this is our bridge variation in grain size.

Now, grain size like I said is one of the very important parameters that describes the strength of the material and therefore, now let us look at the strength value; the variation in the strength value. If you are in the recovery zone or less than the recovery zone which is the cold work zone then in those zones, the change in the temperature will not influence the strength at all and that is because the grain size remains constant until this point when you get to the recrystallization what is happening is that the old deformed strained grains start to get replaced by new strained free grains and those strained free grains lead to a reduced strength of course, they have some additional advantages, but they also had disadvantage that they have less strength and therefore, the overall strength of the material starts to decrease. So, you can see that the strength decrease against to decrease from the onset of recrystallization and by the time you get to the grain growth region where all the strain free grains have replaced the old deformed grains your strength as dropped to a base level.

So, this is your base level strength, so this is how the strength will vary and along with the strength we also have another important parameter related to mechanical property. So, this is strength and there is another important parameter like I said which is ductility. So, ductility is in effect in words of strength whenever you have large strength, the ductility of the material goes down and when the strength or stain free grains start to form when ductility starts to increase. So, your ductility starts to increase again in the recrystallization zone and it regains complete ductility in the grain growth soon. What is important here is that in the cold work zone and in the recovery zone you do not see any change in grain size or the strength or the ductility, you see the changes in strength and ductility only in the recrystallization zones. So, grain size is start to increase here strength starts to decrease and ductility starts to increase.

So, these are some of the important parameters even beyond this we have some more important parameters to discus and those are residual stresses and another is the change in a microstructure. So, these are the micro structural parameters, but I will draw a schematically, how the microstructure actually changes with temperature.

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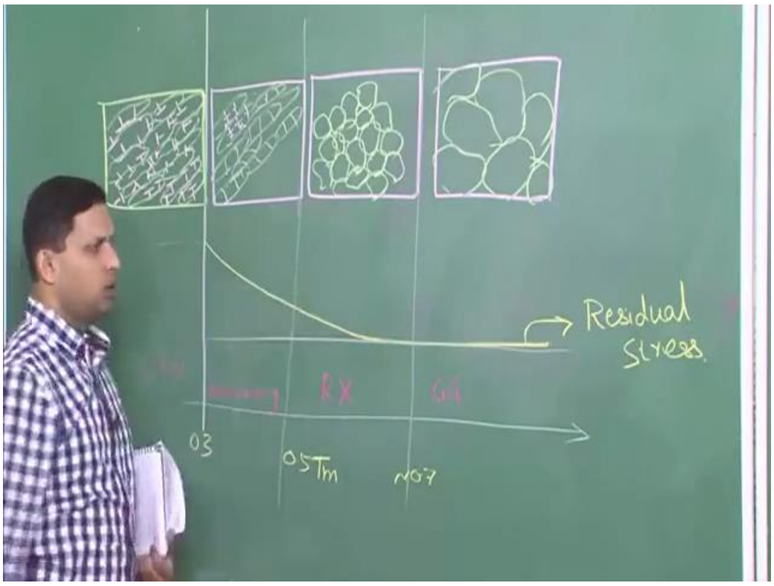

So, I will extend that plot over here, so we have like we said recovery cold worked recrystallization and grain growth and let me divide it again as earlier. Now, residual stress; residual stress are some amount some kind of stresses that are ruminant or left behind you after you have completed with a deformation and these residual stresses have a very deleterious effect on the overall properties; most of the time. Of course, you can find some particular applications where these residual stresses have advantages application or advantage to the material property, but in general the residual stresses that are generated during deformation have very deleterious properties and these residual stresses you would see actually also change, but they all they start to decrease from the recovery zone itself.

So, if you were to look at the residual stresses; the residual stress remains constant below 0.3 Tm. So, below this temperature there will be no drop in this residual stresses, but it does start to decrease when you reach recovery zone. So, we have again let me mark 0.3, 0.5 and approximately 0.7 Tm. So, if you are in the recovery zone there is now the drop in the residual stress starts to take place. Now it is time to take a look at how the micro structure changes when we go from this temperature over this to the higher temperature.

So, let me now draw a rough sketch; what is happening at you can say the microstructure level. In a cold work region what happens is that there are lots of dislocations generated. So, I am representing this T is these are actually way to represent dislocations. So, these are dislocations which are spread or trivalent throughout the microstructure in a random way and during the deformation the grain boundaries further break down and therefore, the grains become elongated and much smaller in size and inside each of these grains you have scores thousands actually millions of these dislocations.

So, in this temperature range this is the kind of microstructure you would expect, dislocations would be randomly distributed throughout and it is because of these dislocations you have high strength, but since the dislocations are randomly distributed you also have very low properties, some of the properties like low ductility and at the same time since it is cold worked and no residual stress has been removed, there are some limited ductility to the material that you have deformed at cold work.

So, there are several aspects to cold working positive and negative and we will look at them separately, but for now from this figure alone what I am trying to convey is that you will have dislocations randomly distributed because of which there will be high strength and low ductility and there will be high residual stresses because of which the material will have again low limited ductility and some deleterious properties.

Now when you get to the recovery zone and let us say there are these elongated grains somewhere like this. So, these are elongated grains and when you are in the recovery zone what happens is that the grain sizes do not change, we have already shown that. So, the grain sizes will remain same like this, but the dislocations that we saw they get a little bit rearranged and what you will see is that they will form sub cell; sub grains or cells and these dislocation will be at boundaries. So, I will just draw as lines these cell walls and because of this rearrangement, you see a slight improve in ductility; when you are in the recovery zone although I have not drawn it over there, but you do see some amount of improvement in ductility.

In the recrystallization zones what happens is that now you start to see some new grains, small new grains all over and therefore, you can see that these are what are called as equiaxed meaning in one any particular direction it does not have longer growth. Here you could see these are in longer in this direction, but when you are recrystallization these are all new grains and there are strain free, you can see there is strain free because there no more dislocation structure inside the grains and when you move on even further to the grain growth region which is not of much interest from the point of view of deformation or metal forming, what you have are very very large grains. So, whatever good properties you could achieve are only limited up to this point and therefore, the deformation is almost always limited up to this range and we do not want to get into the grain growth region.

So, we will leave it over here and we will come back and discuss a little bit more about the different types of cold working, warm working and hot working that we have seen today and these are the two different plots to show what different variations take place and these variation can actually will related to the microstructure that you see over here.

Thank you.