Lecture - 39
Mechanical Testing – VII

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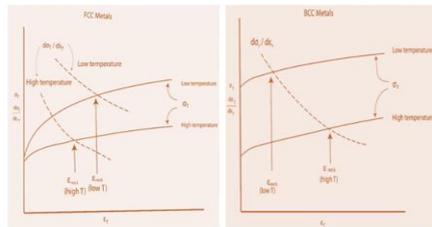
- Schematic true stress-true strain curves for (a) a "typical" fcc metal and (b) a "typical" bcc transition metal. Plots of $\frac{d\sigma_T}{d\varepsilon_T}$, the work-hardening rates of the respective metal classes, are shown in the Figure.
- For a fcc metal, σ_y is relatively insensitive to temperature, but the work-hardening rate increases with decreasing temperature.
- Since tensile geometrical instability occurs when $\frac{d\sigma_T}{d\varepsilon_T} = \sigma_T$, these features lead to a lesser necking strain with increasing temperature for fcc metals.
- For the bcc metals, the yield stress is highly temperature sensitive but the work-hardening is not.
- Thus, for these metals the tensile necking strain increases with increasing temperatures

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

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Hello, I am Professor Sankaran in the Department of Metallurgical and Materials Engineering. Hello everyone welcome, back to the lecture, we are looking at mechanical testing primarily we are looking at tensile behaviour and in the last lecture we discussed about the effect of strain rate and temperature and constitutive relations in terms of stress and strain how the material behaves so on. So, to complete that discussion, I just want to show a few more examples. What you are seeing here now is a plot of stress versus true strain plot and then you have also seen that ($d\sigma_T /d\varepsilon_T$), that is work-hardening rate is superimposed on this true stress true strain curve. So, what you are seeing this is what typically in FCC metals and also it shows the temperature effect the low temperature and then high temperature and then how the FCC metal response to the deformation and these conditions so, what is that we are seeing.

So, before we even we look at the description of this let us look at this this is a similar plot for BCC metals and again you are seeing the stress strain response two different temperatures similar to this. So, the primary purpose of this slide is to show the difference the kind of difference the two class of material exhibit. So, what are the primary differences? The

primary differences as we have already seen that FCC metals do not show any significant influence of yield stress. On the other hand, BCC metals exhibit significant influence of temperature. So, that is the first observation. Schematic of true stress true strain curves for a typical FCC metal and typical BCC transition metal plots of $(d\sigma_T /d\varepsilon_T)$, work-hardening rates of respective metric classes are shown in the figure. So, for FCC metal σ_y that is yield stress is relatively insensitive to temperature. So, we are almost a similar behaviour here but the work-hardening rate increases with increasing temperature.

So, the work-hardening rate if you look at it increases with the increasing increases with the decrease in temperature. So, this is work-hardening rate is higher here, but it is for the low temperature and then. So, you know the point of you know you can see that inflection. What is the meaning of meaning of this point of inflection that do you have already seen like so, but now, we have to compare this ε neck that is point of instability at these two junctures is quite interesting?

What is that since the tensile geometrical instability occurs when $(d\sigma_T /d\varepsilon_T)$, is equal to T that means that σ_T. These features lead to a lesser making strain with increasing temperature for FCC matter very important observation. So, we are looking at two point of inflection that is point of instability and the epsilon neck is you know lesser with the increase in temperature for FCC metals. This is quite interesting observation.

We can now relate this point with other fundamental quantities like second quadrant energy strain hardening exponent, strain rate sensitivity or strain temperature. If you put all of them together you will again get some more clarity upon this. If you look at the bcc metals the yield stress is highly temperature sensitive. So, you see that there is a huge gap between the yield point. So, highly temperature sensitive but the word-hardening rate is not. Similar unlike the FCC metals the work hardening rate does not get influenced by the temperature.

So, what does that mean, that is what these metals the tensile making strain increases with increasing temperatures. So, it is just opposite to what we are seen on FCC metals the neck strain that is point of instability increases with increasing temperature. So, these are all very important observations and which will be useful to interpret the, you know the high temperature behaviour of this class of material suggest.

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Strain rate and Temperature
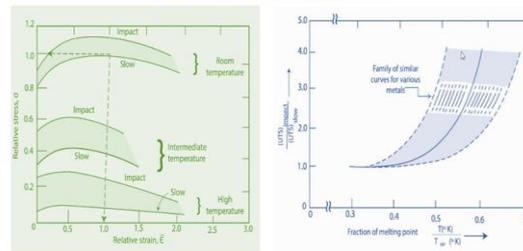
- The lowering of the stress-strain curve at elevated temperatures my be compensated by increasing the strain rate Although this compensation occurs only while the high strain rate persists, it may still be important for those applications where the required life of the part can be short
- If plastic flow occurs more rapidly than diffusion can eliminate its effects, the metal can then be used under rapid loading at high stress levels, even at high temperatures
- Although the static stress-strain curve may drop very rapidly with increasing temperature, the percentage increase in strength due to impact loading is much greater at elevated than at low temperatures
- The strength of metals at elevated temperature is greater under impact strain rates as compared to slow strain rates

The Structure and properties of Materials, John Wulff, John Wiley,1965   49

Now, again we will look at some combined plot of strain rate and temperature effect and this plot is not quite commonly reported in most of the texts but it is very interesting and important plot, what is that it is again the relative stress versus strain plot and again you have a stress-strain curve, slow strain rate as well as high strain rate. So, slow and impact and then at three different temperatures. This is room temperature data; this is the intermediate temperature data this is high temperature data.

So, what is the TRC here it is the mark here is the stress and strain at 1 the mark is the stress strain relation of material at room temperature the maximum stress at strain 1. You just keep a reference for this and then you look at it so, what is that we are seeing now, so, we generally know that as the temperature goes up the strength comes down the this is what you see in most of the stress-strain curve plots.

The level of stress-strain curves comes down as the temperature goes up, but something can be compensated but the strain rate as increasing strain rate it also increases the stress-strain curve. So, this is an opposite effect the strain rate has the opposite effect. So, it is a kind of you knows, we can make a comment like the decrease in the stress-strain behaviour can be compensated by the increase in the strain rate that kind of analogy we can bring in.

But what you see here is a room temperature the difference in the slow and the impact load this is quite different from other temperatures you see that the difference in the normal strain rate and the high strain rate deformation the difference is very high as compared to the room temperature. You can see that and it is much more higher in the high temperature. So, the difference between these two slow and impact loading at high temperature is the highest.

So, this is how we should compare and now we will see the lowering of the stress-strain curve at elevated temperatures may be compensated by increasing the strain rate. Although this compensation occurs only by the strain, high strain rate persists. It may still be important for those application where the required life of the plot can be short. So, this is a specific application where we can still this this will be of some use. So, this can be a solution.

If plastic flow occurs more rapidly than the diffusion can eliminate its effects. The metal can then be used under rapid loading at high stress levels even at high temperatures. So, what are the problems at high temperatures? High temperature means your diffusion rate will be very high and whatever the you know the recovery process no grain grow effect all this will influence the microstructure and which in turn reflects in the system behaviour. On the other hand, the high strain rate will compensate that, but then what is important here is if the plastic flow occurs more rapidly than diffusion it has the rate of plastic flow should be much more than the diffusion then those effects can be eliminated, I mean the microstructure will change whatever happens because of the high temperature can be compensated provided the plastic flow rate is much more than the diffusion that is the idea.

Although the static stress-strain curve may drop very rapidly with increasing temperature the percentage increase in strength due to impact loading is much greater at elevated temperature than at low temperatures. So, that is what is shown here, the percentage increase in strength due to impact is much greater at elevated temperature than at the low temperature. So, this is one nice information which predicts in one plot the effect of strain rate and temperatures in a multi strain material.

The strength of metals at elevated temperatures greater under impact strain rate as compared to the low strain rates and I am just showing an another very interesting plot. What is this plot shows? It is UTS the ratio of UTS $_{impact}$ to UTS $_{slow}$. With high strain rate to slow strain rate ratio versus fraction of melting point that is temperature in Kelvin divided by temperature that is melting point in Kelvin usually this fraction is called homologous temperature.

We will see it in the high temperature behaviour we will use the term homologous temperature normally this is called the homologous temperature. So, it shows very interesting trends like how the strain rate and the temperature you know influences the deformation behaviour what is that we are seeing here. So, the most of the material at least metals here we are referring to metals it starts you know responding to this high strain rate.

Approximately suddenly it just goes up approximately 40 to 50% of the melting point that is 0.4 to 0.5 T $_m$. That is this is the range the response is quite significantly raised most of the so, what is that microstructure change that will occur and under this temperature being that is 40 to 50% of the melting some most of the recrystallization no recovery all this process rapidly it would start taking place at the temperature.

So, it will have that is why it is also started responding significantly in this range. But here there is a division a range of you know temperature range is quite high. So, that means you have materials for example, light materials like aluminum, magnesium they will all which will respond to the, you know high temperature very slowly which will fall into this region, right hand side of the dash line.

But the materials which exhibit a sudden change in the structural features, they will fall at low, I mean, sudden change in the microstructure at relatively low temperature as compared to these light elements, they will fall into this category at very low temperature, the sudden changes there in the microstructure so they will all fall into this category. So, we can you can compare that iron, steel or something like that, just to give an example but this is a very general diagram.

But they extreme right this category all the light elements aluminum magnesium and so on. So, basically the insensitive note that the temperature sensitive temperature insensitive that is what we have seen in the previous slides and also how it responds to the strain rate. So, like I said we can put all these parameters together like stacking fault energy and you know strain hardening exponent, strain rate sensitivity, all these parameters we can put together and then compare. How these things are going to help and understand this. So, we have spent quite a bit of time on this interpretation of this stress-strain behaviour especially the tensile test.

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• Covalent chain configurations and strength:

Linear   Branched   Cross-Linked   Network
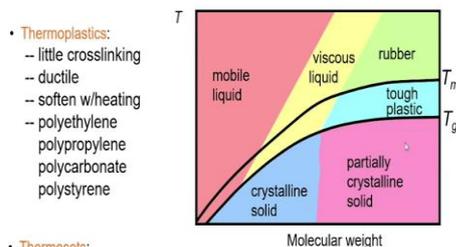
Direction of increasing strength
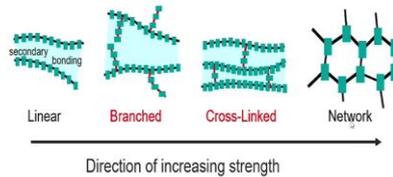
We will now move on to some other material classification mostly polymers. To start with we know that polymers are all made up of covalent chain molecules. So, there are covalent bond in the inter carbon link but they are also bonded by secondary bonding between the two chains, that and all we have already seen in the introduction. But then, this configuration chain configuration has got something to do with the strength how they are related.

So, if suppose if you classify this kind of a bonding nature as a linear and these are called branched chain molecules and this is crosslinked chains and configuration and then finally a network. So, interestingly you can see this the direction of increasing strength in polymeric materials like this. So, from linear to network the strength increases. So, how do we understand this in a simple tensile test.

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And before even looking at that we need to look at little more some properties about this polymer. Thermoplastics versus the thermoset polymers, what are thermoplastics they are all

characterized by little crosslinking they are ductile they softened while heating, for example, polyethylene, polypropylene, polycarbonate and polystyrene and what are thermo sets they are all large crosslinking molecules they are the primary bonding and 10 to 50% of the mers they are hard and brittle, they do not soften while heating.

Examples is vulcanized rubber, epoxies polyester resin phenolic resin. So, these are all the examples for thermosets and thermoplastics. But if you look at their general behaviour , temperature versus molecular weight, because we are talking about the chain configuration obviously, the molecular weight has the significant role to play. So, as the temperature increases, it forms a mobile liquid in this region and then it will look at the increasing volume of molecular weight then you have the crystalline solid and partially crystalline solid.

Which is there just below the T_g and below T_g and T_m that is very interesting and you have very tough plastic higher molecular weight and this region is tough plastic and then above this T_m then you have a rubber and complete viscous liquid and this is mobile liquid. So, this plot is depending upon the molecular weight and the temperature the polymeric behaviour is decided. So, that it will give us already it already gives us an idea how this is going to respond in deformation to some extent. So, that is why this like.

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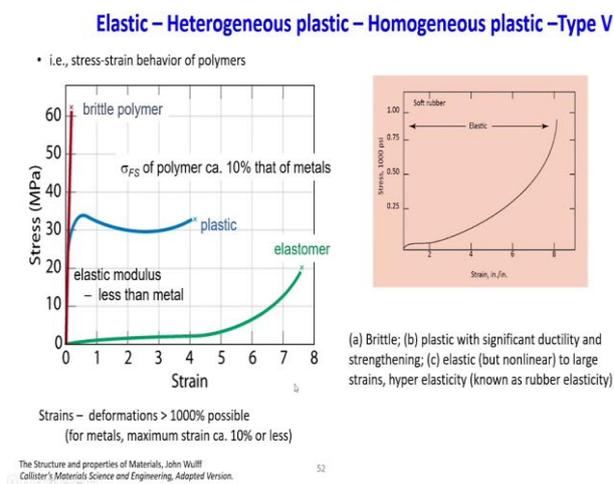
So, the type of tensile deformation which we are going to see is in line with the previous classification. This is elastic, heterogeneous plastic and then homogeneous plastic type 5. So, this is the typical we are talking about this type of behaviour elastic, heterogeneous plastic and then homogeneous plastic. So, we are talking about only this and other two are already seen linear we have already seen and this one is we are going to see now.

So, this is a stress-strain plot for typical polymers and there are the three types we are showing one is brittle polymer and is a plastic polymer and an elastomer. So, the soft rubber is also considered as an elastomer here. So, this curve is almost similar to this. So, brittle means, we can simply relate that with the networking of chains and we have seen that characteristic in the previous slide and then you have the plastic with significant ductility and strengthening.

So, this is a plastic and significant strengthening means it is it can go up again after coming down that is why it is plastic and significant ductility and then strengthen that is that is how this is described and this type of curve is described as elastic but nonlinear to large strain this is called something called hyper elasticity also known as a rubber elasticity. So, there is no load drop in the rubber elasticity with something you can witness which is quite different from the other stress strain curve we have seen.

There is no load drop in the hyper elasticity or elastomer deformation it just increases and it keeps on increasing still fracture. But on the other hand, this polymer shows a slow drop and then that will exhibit significant ductile behaviour and then strength. So, strains are possible up to 1000 or more than 1000%. So, you can see the kind of deformation possible in this kind of materials.

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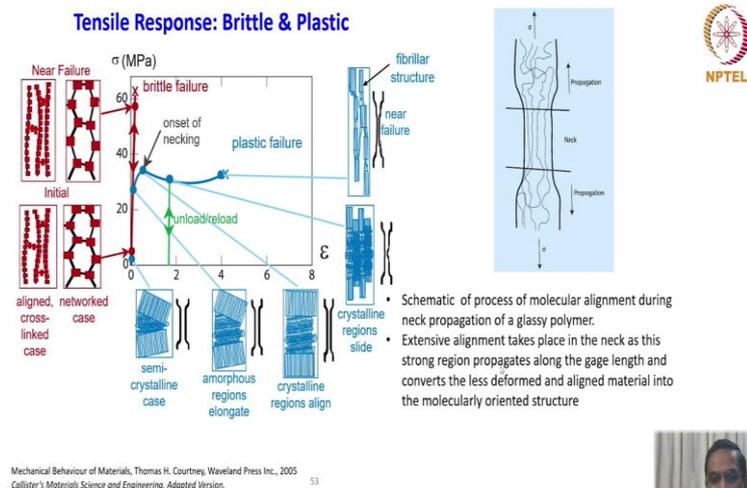
So, what is responsible for this kind of behaviour? So, we will just see one by one, we will first look at the brittle failure of this polymer. So, as I just mentioned that to start with, they

are all network polymeric chain and they are all aligned and cross linked to start with. So, what happens as the load goes up that is the idea. So, it is initial and this is a near failure. So, nothing happens. So, no literally no movement so, it just breaks, it is all intact nothing happens to this network, very strong network.

On the other hand, like you start with this semi crystalline polymer which exhibits you know elastic, heterogeneous plastic and homogeneous plastic type, five strain behaviour. They to start with they are all semi-crystalline in nature. So, you see that crystalline region and then in between there are some semi-crystalline or amorphous regions, these chains are all you know, randomly oriented here as these strain increases the schematic clearly shows that elongation.

So, this this point is before the yield point, still in the elastics so exactly on the onset of making. So, crystalline regions align. So, basically the alignment of this chains takes the load up to this point. Then, after the necking, the load drops significantly that is because of the crystalline region start to slide with each other. So, you can see that all broken into small segment and then start sliding with each other.

So, that belongs that is the rest of the load drop is because of that and then finally, it hardens why it hardens, because it is trying to stretch completely. It becomes fibrillar structure. No it is no longer crystalline and amorphous combination. It becomes a single line almost fibrillar structure, they are all getting stretched on this molecule chain. So, this clearly you know brings all the mechanisms of deformation in the brittle and the plastic polymers as compared to metals and other materials what we have seen.

It is quite different from what we have seen before. So, here also we talk about necking. So, if you look at the necking, what happens in this region you see that it is a complete molecular arrangement during neck propagation of plastic polymer. So, necking here means that all the, you know non-crystalline region becomes straight alignment basically pulling the strain straight into one direction that is stress direction.

Extensive alignment takes place in the neck as this strong region propagates along the gage length and converts the less deformed and aligned material into molecularly oriented structure. So, it is something similar to a loader band you know we were talking about the here also does it propagates the necking propagates throughout this and then finally, it stretches. So, that is about this polymer very interesting.

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Predeformation by Drawing

- Drawing...(ex: monofilament fishline)
  -- stretches the polymer prior to use
  -- aligns chains in the stretching direction
- Results of drawing:
  -- increases the elastic modulus (E) in the stretching direction
  -- increases the tensile strength (TS) in the stretching direction
  -- decreases ductility (%EL)
- Annealing after drawing...
  -- decreases alignment
  -- reverses effects of drawing.
- Compare to cold working in metals!

Callister's Materials Science and Engineering, Adapted Version.   54

And what kind of deformation process people you know, engage these polymers. So, drawing is one of the primary processes is called it is also called the monofilament the fishline stretches the polymer prior to us aligns chains in stretching direction that is one operation. Why do we do this because to increase because this operation increases the elastic modulus in the stretching direction increases the tensile strength in the stretching direction and obviously, it will reduce the ductility. So, this kind of configuration just we have seen at the point of fracture. So, this operation is called drawing operations just it is connected to a deformation. We can also anneal them like metals, these materials can also be subjected to annealing and then it will produce it results in or this operational linear operational decision decreasing the element and it also reverses it effects of drawing. So, to get back to the some of the original contribution, this can be simply combined with the cold working of metals.

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Tensile Response: Elastomer Case
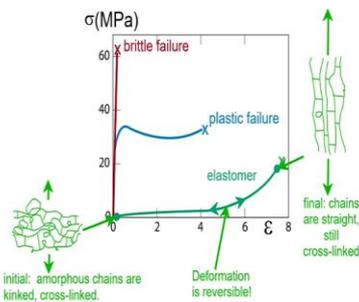
- Compare to responses of other polymers:
  -- brittle response (aligned, crosslinked & networked polymer)
  -- plastic response (semi-crystalline polymers)

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If you talk about the brittle and plastic behaviour, now, we talk about the elastomers. So, elastomers to start with they are all amorphous chains entangled in a to be completely kinked under crosslinked chain molecules that is a starting point and as the deformation proceeds it is going to absorb quite a bit of a strain after this point, which is still reversible then at that point of fracture and then again, the chain alignment takes place chains are straight and then still cross linked.

So, the significant amount of strain is absorbed in the process of basically aligning this, kinked and cross-linked chains. So, that is what is shown. Compared to other polymers, they are showing brittle response aligned and crosslinked network polymer and plastic responses mostly from these semi crystalline polymers.

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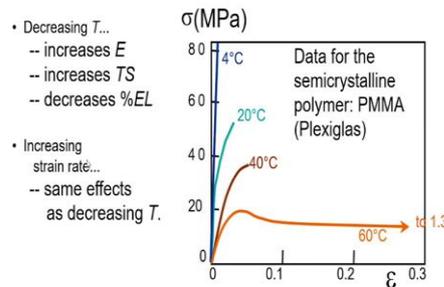
So, how what is the temperature and strain rate effect here. So, here also you can see that low temperature, making them highly brittle and high temperature, relatively high temperatures the more ductile similar to metallic materials. Decreasing temperature, increases E tensile strength and decreases elongation and increasing strain rate, same effect as decreasing temperature. So that is about a brief presentation of polymeric tensile tests or deformations tensile deformation. Now we will focus on the Torsion test.