Creep Deformation of Materials

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Part 1
Creep and different factors that influence creep deformation

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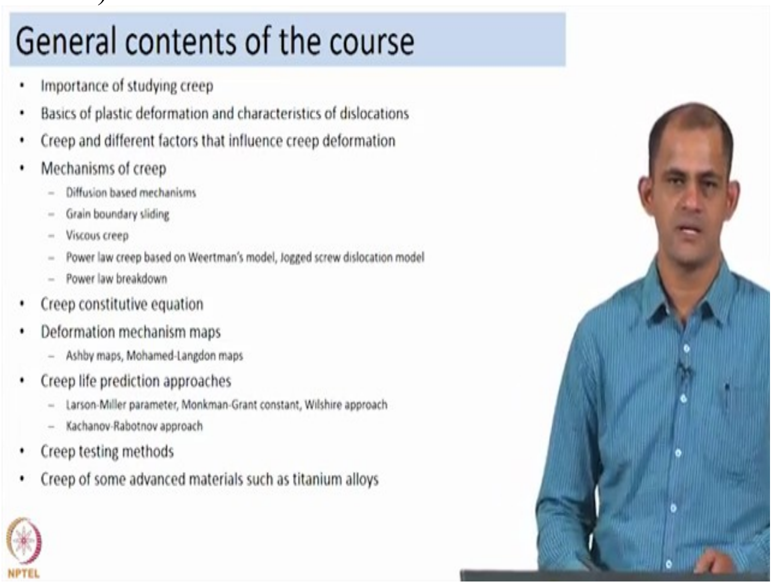

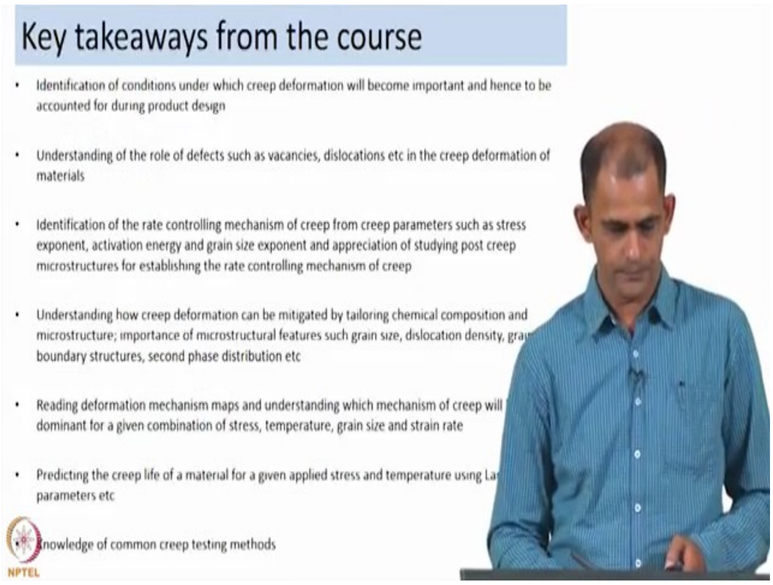

Ok, so in the last set of lectures we started of by introducing to the concept of creep and then I talked about the importance of studying creep and following that we talked about the basics of plastic deformation since creep is a plastic deformation process so it was important to touch upon concepts of plastic deformation and since plastic deformation in general involves the motion of dislocation.

We also discussed about some characteristic of dislocations and in todays class I will take you into more detail on creep, so we will go into the concept of creep and discuss it in greater detail. So today is class is about introducing you to creep and then gradually will talk about the different factors that influence creep deformation.

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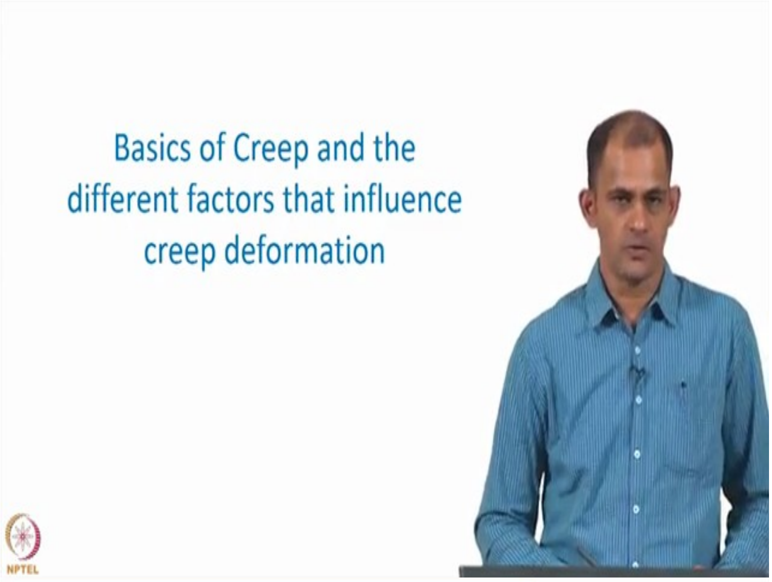

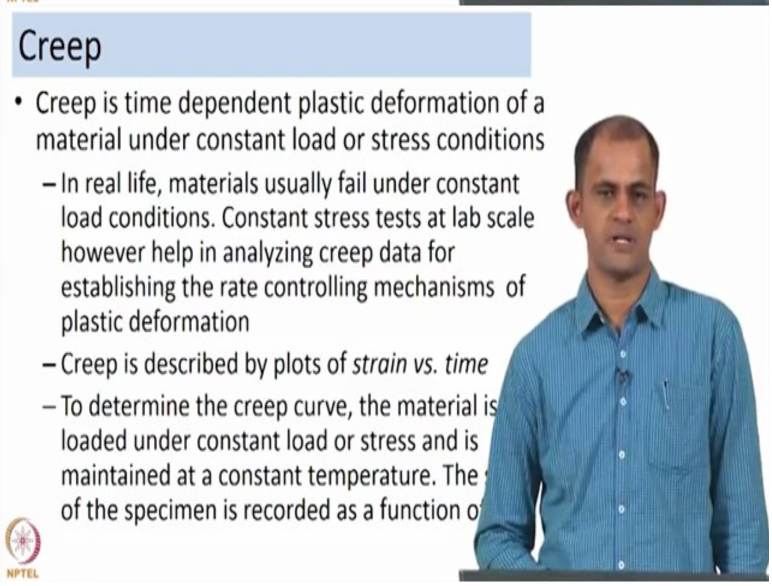

So, basics of creep and the different factors that influence creep deformation. So like I mentioned in the first class, creep is a time dependent plastic deformation process that happens in a material experiencing a constant load or constant stress condition in the presence of a temperature typically the temperature has to be fairly high it should be at least point four or point five times the melting point of the material.

Now, the test that we do at lab is usually at constant stress but in real life materials usually fail under constant load conditions, so materials creep as well as fail in real life under constant load conditions however the need of carrying out constant stress creep test comes from the fact that it becomes easier to analyze the creep data when the test are carried out under constant stress, so the data that is generated will be analyzed better as well as it becomes possible to understand the rate controlling mechanism of creep deformation when the tests are carried out at constant stress.

Having said that it is not that test nobody studies creep test under constant load there is a lot of work that happens where people study the creep behavior of materials under constant load conditions. Now creep is generally described by plots of strain versus time. So a typical creep curve is described by plots of strain versus time where strain is on the y axis and time is on the x axis. Like I mentioned the creep curve is a result of a test carried out under constant load or constant stress at a constant temperature and the strain is recorded as a function of time.

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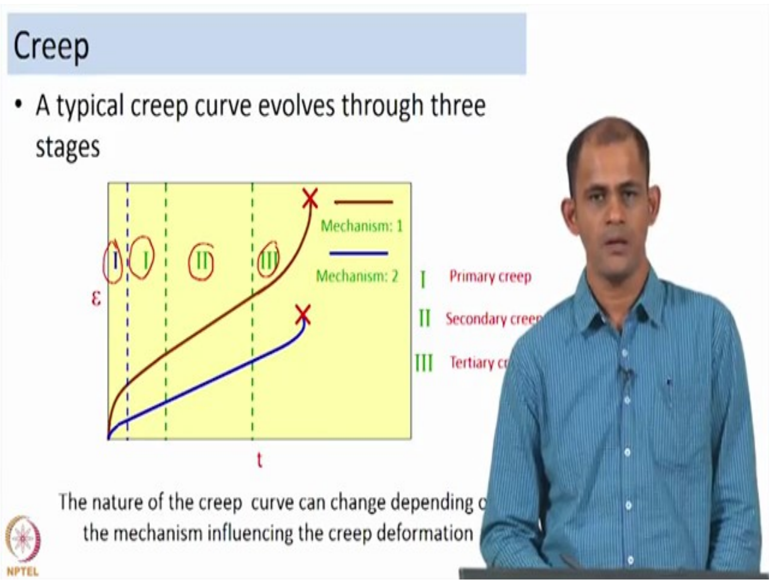

So this is how a typical creep curve looks like. So you have three stages marked as 1, 2 and 3 and the first stage is known as the primary creep stage, the second stage is known as secondary creep stage or also known as the steady state creep stage and the third stage is known as the tertiary creep stage. So in this plot I have delineated the three stages using these dotted lines. So the nature of the creep curve that you see here are could change depending on the mechanism in operation.

There are different mechanisms that have been proposed to explain creep deformation and depending on the mechanism that is controlling creep deformation the nature of the curve could change for example here is a curve where the curve in blue is a result of creep deformation being governed by another mechanism so let is call it mechanism 2, so the first curve that is a curve in brown is a result of mechanism 1 and the curve in blue is a result of mechanism 2 and if you see there is clearly a difference between curves produced by mechanism one and curves produced by mechanism two.

I will elaborate in detail during the subsequent classes why there is a change in the creep curve but the main point or the bottom line here is the nature of the creep curve by itself could also tell you if one type of mechanism is in operation versus another so here what we observed is stage 1 is actually very small when the creep curve is progressing by mechanism 2 whereas stage 1 is large when the creep curve is evolving because of mechanism 1. So the nature of creep curve also provides insights into deformation process.

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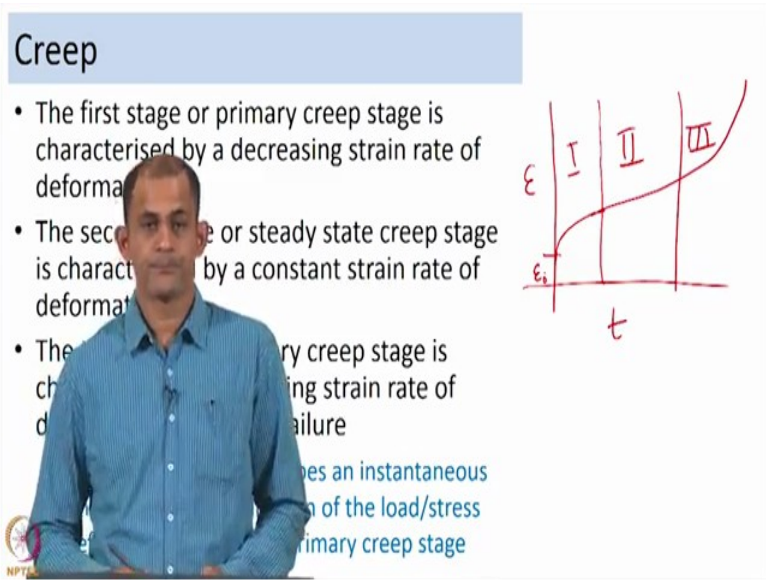

So we talked about three stages of creep stage 1, stage 2 and stage 3. So the first stage (also known) of creep known as the primary creep stage is generally characterised by decreasing strain rate of deformation and the second stage or the steady state creep stage is characterised by constant strain rate of deformation and third stage of creep known as tertiary creep stage is characterised by an increasing strain rate of deformation eventually leading to failure, these are the three stages.

So generally whenever the material is loaded what has been observed is that there is always an instantaneous elongation on the application of the load or stress. So only after the material has undergone this instantaneous elongation or instantaneous strain it is only then that it enters into the primary creep stage. So this how a creep curve would look like you have an instantaneous strain and then you have a primary creep, secondary creep and tertiary creep stage so this instantaneous strain generally is represented by epsilon$_0$.

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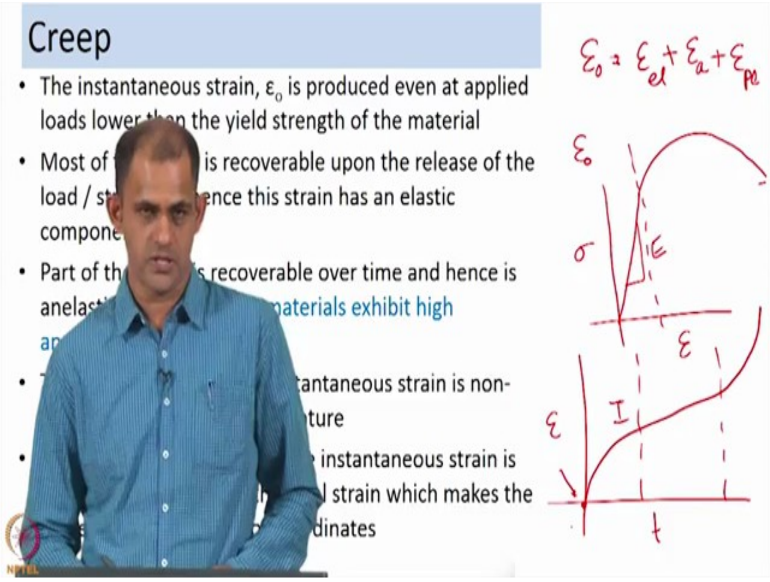

So the instantaneous strain epsilon0 has been observed that instantaneous strain epsilon0 is produced even at applied loads lower than the yield strength of the material and most of the strain is recoverable upon the release of the load or stress and hence this strain has an elastic component. So epsilon0 is not entirely elastic if you compare the creep curve to a regular stress strain curve.

In a regular stress strain curve you have an elastic region. A plastic region eventually leading to failure but and this elastic region is entirely recoverable when the load is released. In the case of a creep curve (by) instantaneous strain epsilon0 is not entirely elastic, so epsilon0 has a part or a component which is elastic so let us say we call it epsilon0 is equal to epsilon elastic and a portion which is not recoverable on the release of the load.

There is another part of epsilon not which is recoverable but not instantaneously this strain is recovered over time and hence it is anelastic so let us call this epsilon-a as anelastic, typically anelastic materials are materials such as polymeric materials where the plastic strain is recovered once the stress or load is removed but the recovery happens over a fairly long time and third component of epsilon0 is non-recoverable and this is the part which is plastic in nature, so epsilon0 will also have a plastic strain component epsilon-pl so epsilon0 consist of three items you have epsilon elastic which is recoverable on the removal of the load immediately and epsilon anelastic which is strain that is recovered after the removal of load but the recovery happens over a certain period of time and then you have a epsilon plastic which is strain that is not recovered on the removal of the load.

Generally for the purpose of analysis people in the scientific community they generally subtract the instantaneous strain from the total strain and that is why since the instantaneous strain is subtracted from the total strain so that is why when you have plot of epsilon versus t the creep curve generally starts from the origin of the coordinates. So the creep curve starts from here that is because epsilon0 is generally removed from the total strain.

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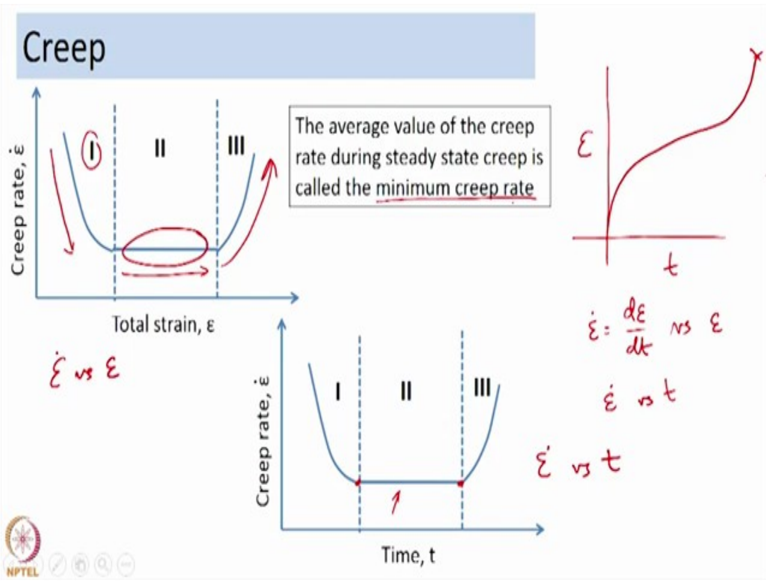

So the creep curve we talked about three stages primary, secondary and tertiary and we also said the characteristic of primary creep is that there is a decreasing strain rate of deformation in the primary creep stage. In the secondary creep stage you have a constant strain rate of deformation and in the tertiary creep stage you have increasing strain rate of deformation leading to failure.

So this can be understood better if you make a plot of strain rate versus strain or strain rate versus time. So if you take the data from this creep curve and if you plot if you determine derivative of epsilon over derivative of t, then that is what strain rate is so if you determine d (epsilon) over dt and if you plot d(epsilon) over dt versus epsilon or d(epsilon) or epsilon-dot versus time then this is how the curve will look like.

So clearly in stage 1 the strain rate is decreasing, it retains constant value in the second stage that is a steady state creep stage and then continues to increase after the steady state in the tertiary creep stage this strain rate of deformation continues to increase and the same behavior is observed in both epsilon-dot versus epsilon and epsilon dot versus time plot.

The average value of the creep rate during steady state creep rate creep is also called the minimum creep rate that is because as it is evident from the picture the creep rate decreases and once it reaches the steady state it more or less stays constant and as you can observed from this figure this strain rate is the lowest in the entire plot and that is why the strain rate is also called the minimum creep rate.

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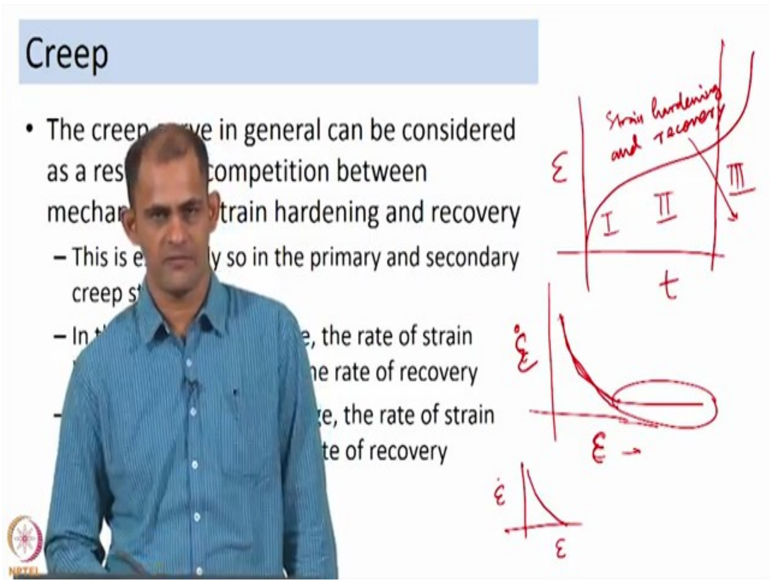

The creep curve in general can be considered as a result of a competition between mechanisms of strain hardening and recovery. So the creep curve that we have observed the nature of the creep curve can be considered to be the result of a competition between mechanisms of strain hardening and recovery. So there is some competition that is going on between strain hardening and recovery and that is why the creep curve has the following form, of course this concept that there is some form of competition going on between strain hardening and recovery is largely applicable to the first stage and second stage because in the third stage that is in the tertiary creep stage the material behavior is significantly different than that compare to in stage 1 and stage 2 that is why this concept of a competition between strain hardening and recovery is generally not applicable to stage 3.

Now coming back to this concept that there is a competition between strain hardening and recovery in the primary creep stage the rate of strain hardening is higher than the rate of recovery. So the material is strain hardening and because the rate of strain hardening is higher that is why the strain rate of deformation is coming down, so in the material slowly the rate of deformation is coming down the strain rate of deformation as strain progresses as we know when a material deforms plastically there is a strain hardening so because of strain hardening the material is becoming harder do deform further and that is why the strain rate of deformation that is epsilon dot is coming down but this is gradually balanced by the rate of recovery and when the rate of recovery is equal to the rate of strain hardening then you enter into the secondary creep stage.

If there was no recovery process then what would have happened is the strain rate would have eventually become equal to zero or very negligible, so the decrease in strain rate will continue to happen if there is no recovery and the decrease will happen to a point where the material stops deforming all together or deforms at so slow strain rate that it is not even perceptible.

So since this is not happening since we have a steady state of creep rate that means there is a some form of a restoration that is happening and that restoration is the rate of recovery, so in the secondary creep stage the rate of strain hardening is balanced by the rate of recovery which helps the material to continue to deform, plastically deform.

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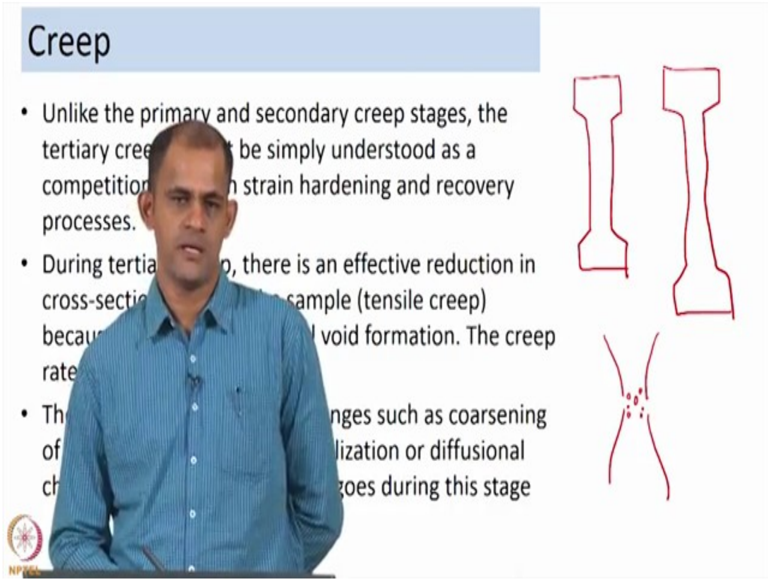

Like I said unlike the primary and secondary creep stage the tertiary creep cannot be simply understood as a competition between strain hardening and recovery processes that is because in tertiary creep or during tertiary creep there is an effective reduction in cross-sectional area of the sample especially so if you are caring out test in tension mode so if your creep test is being carried out in tensile creep mode instead of compression creep mode than you will see tertiary creep brought about by an effective reduction in the cross-sectional area. The reduction in cross-sectional area is because of necking or for that matter due to internal void formation.

So let us assume a dog bone sample experiencing creep strain so slowly the material is going to extend and then this extension will lead to necking and we know that during necking void formation can start happening locally within the material and because of this reduction in cross-sectional area or the formation of voids the creep rate of deformation is accelerated.

So as a material starts necking or internal void start forming the creep rates are accelerated and in addition to this there are also other metallurgical changes such as coarsening of precipitate particles or recrystallization or diffusional changes that the material could undergo in tertiary creep stage.

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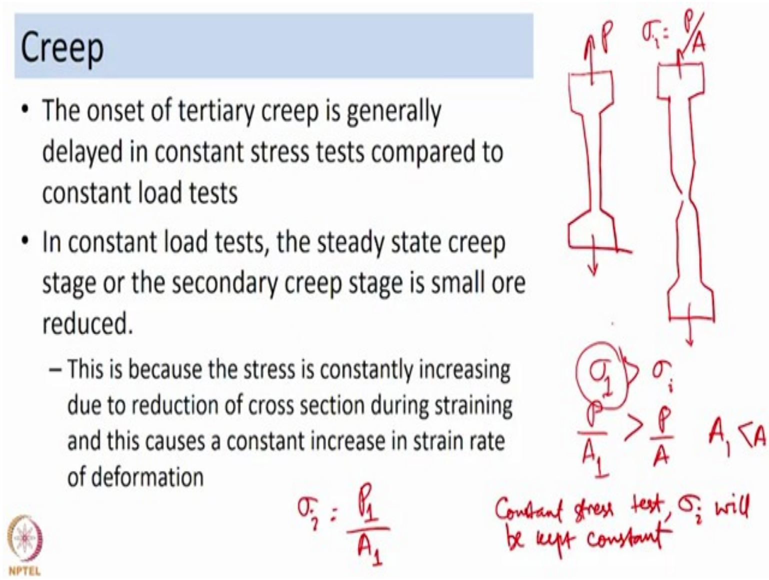

Now compared to a constant load test the onset of tertiary creep is generally delayed in constant stress tests the reason is when you have a constant load test so say you are carrying out a test under a constant load of P so initial apply stress is sigma is equal to P over A but as the material starts necking or starts experiencing a reduction in cross-sectional area this stress acting at any point of time at any given location will be higher than sigma-i that is because for the same load the new area A (let us say) let us called this A1 since A1 will be less than A that is why the stress acting on the material sigma 1 will be greater than sigma A.

So what this means is the material is going to enter into a tertiary creep region faster in a constant load test compare to a constant stress tests that is because in a constant stress test you are going to change the load applied in order to account for the change in cross-sectional area, so in a constant stress test sigma-i will be kept constant and that is done by reducing the load to P1 when the area of cross-sectional has reduced to A1.

So when the area of cross-sectional is reduced to A1 you can reduce the load to P1 so that the stress continues to remain constant but in the constant load test that is not the case so that is why sigma1 is higher than sigma-i and that is why you will have reached the tertiary creep region faster in a constant load test and also because of the reduction in cross-sectional area and the increase in applied stress the strain rate of deformation will also increase significantly that is why the material will reach into tertiary creep faster.

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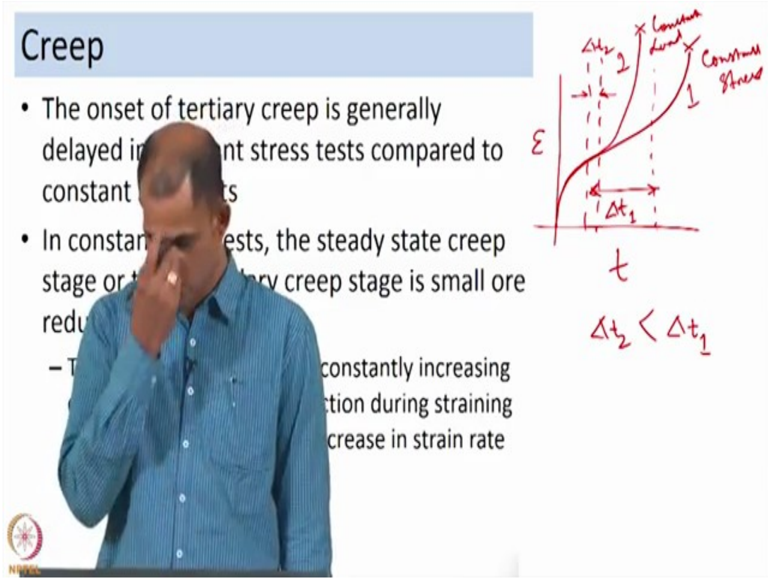

So another aspect of this is that the onset of tertiary creep is faster in constant load test and another observation is the steady state creep stage or the secondary creep stage accordingly is also small or reduced. So if you compare a constant load and constant stress test so let us assume this curve 1 is for constant stress, so curve 1 is for constant stress and curve 2 is for constant load so what we observed in this case is the steady state creep region which was occurring over a certain time say delta t1 is now reduced significantly so let us call this is delta t 2, so delta t2 that is the time range over which steady state creep is happening is lower for constant load test compare to delta t1 which is a time range over which the material is in steady state corresponding to constant stress test and the reason is because of the reduction in cross-sectional area.

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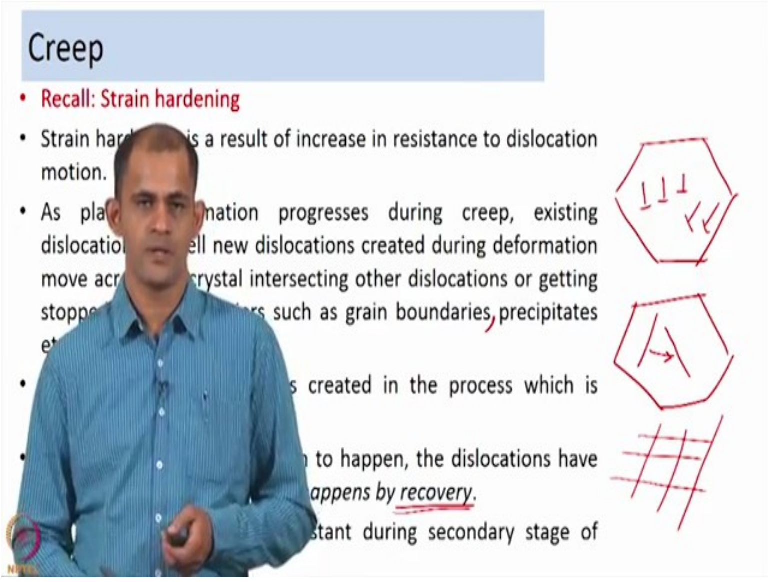

Now coming back to the creep curve being a result of a competition between strain hardening and recovery. So this a very interesting stage because this gives you an opportunity to recall the concepts of strain hardening that we talked in the previous lecture. So if you recall we discussed strain hardening is a result of increase in resistance to dislocation motion.

So during plastic deformation material experiences strain hardening and this strain hardening is because of different mechanisms such as it could be barriers to dislocation motion due to grain boundaries or could be barriers to dislocation motion due to solute atoms or barriers to dislocation motion coming from fellow dislocations intersecting each other and things like that.

So that concept those concepts are applicable to creep as well so as plastic deformation progresses during creep the existing dislocation as well as new dislocations created during deformation process move across the crystal and they start intersecting other dislocation or maybe they get stopped by the other barriers such as grain boundaries or precipitate etcetera.

So you have in the grain, dislocations moving and maybe they encountered other dislocations or better way of representing is this, so if you have one line then you have other line and say the dislocation moves and then it intersects this location and we know what happens when two dislocations intersect each other breaks in dislocation are produced this breaks could be jogs or kings and jogs on screw dislocation we know are difficult because they prevent the screw dislocation from cross slipping or moving easily.

So because of this process of dislocation moving around and intersecting with each other a dislocation substructure is created, so the dislocation are constantly ranging or configuring (each) themselves because say you have dislocations two dislocations that got intersected by another two is instruction, so now you have some form of a mesh that is forming and when you have multiples dislocation they are forming meshes so that is one example of a substructure could be forming in the material.

Now because there is a resistance to dislocation motion because of the strain hardening process for further plastic deformation to happen the dislocations have to overcome the barriers and these barriers can be overcome by mechanism of recovery. So we are going to talk about recovery but one point that I would like to make here is this competition between primary and the competition between strain hardening and recovery during the primary creep stage causes the evolution of a dislocations substructure and this dislocation substructure evolves and then retains a constant state during the secondary stage of creep.

So what is very interesting is the co-relation between the dislocation substructure and the strain rate of deformation. So we said primary creep stage is a stage where the strain rate of deformation is constantly decreasing and that is because of the rate of strain hardening being higher than the rate of recovery. During the decrease in strain rate we are also seeing that a dislocation substructure is getting evolved and when the rate of strain hardening is balanced by the rate of recovery creep rate comes to a constant value so that is the minimum creep rate and at that point what also happens is the dislocation substructure that was evolving till then now becomes constant and it stays constant during the secondary stage of creep.

So since I have introduced the term called recovery some going to talk a little bit about recovery in the next few slides.

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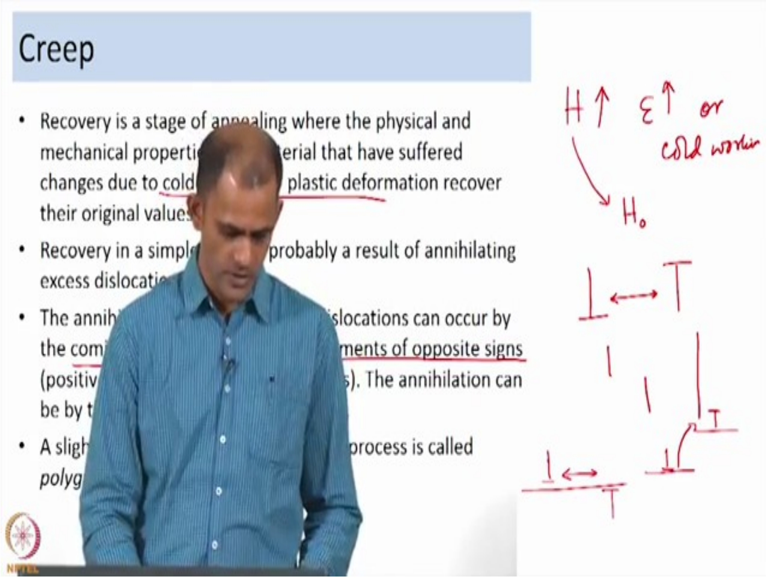

So recovery is a stage of annealing so we know annealing is heating a material inside a furnace heating a material at high temperature and annealing consist of three stages you can have the first stage of annealing is recovery, the second stage of annealing is recrystallization, the third stage of annealing is grain growth. In the first stage of annealing which is a recovery what happens is the physical and mechanical properties of a material start recovering.

So let us take the example of strength or hardness of a material we know when the material is experiencing cold working or plastic deformation the strength of the material is going to increase because of strain hardening, so say hardness increased because of plastic deformation or cold working now during recovery what happens is the hardness comes back to it is original value the value that the material had before it is started experiencing plastic deformation so that original value is recovered .

So the properties basically are recovered during the recovery process. Now recovery in a very simple sense is a result of annihilation of excess dislocation, so the concept of annihilation comes into play because strain hardening happens because of the dislocation stopping each other from moving and recovery helps the dislocation to move again and that movement happen only when dislocation start annihilating each other.

The of annihilation of excess dislocation can occur by the coming together of dislocation segments of opposite signs, so if you have a positive edge dislocation versus negative edge dislocation and say if the all these dislocation are trapped somehow if these two dislocations can come together then the positive and the negative dislocation can annihilate each other and restore the original structure.

So for the annihilation to happen you need both the processes of slip and climb that is because two dislocations of opposite sign for them to come closer to each other you need them to slip or glide on the slip plane and then if they are on different slip planes one of the dislocation could climb up into the other slip plane and then annihilate the dislocation of opposite sign. So the annihilation process (requers) requires both glide and climb of dislocation.

So this is a very simple way of looking at the process of recovery; a slightly complicated form of recovery process is known as polygonization.

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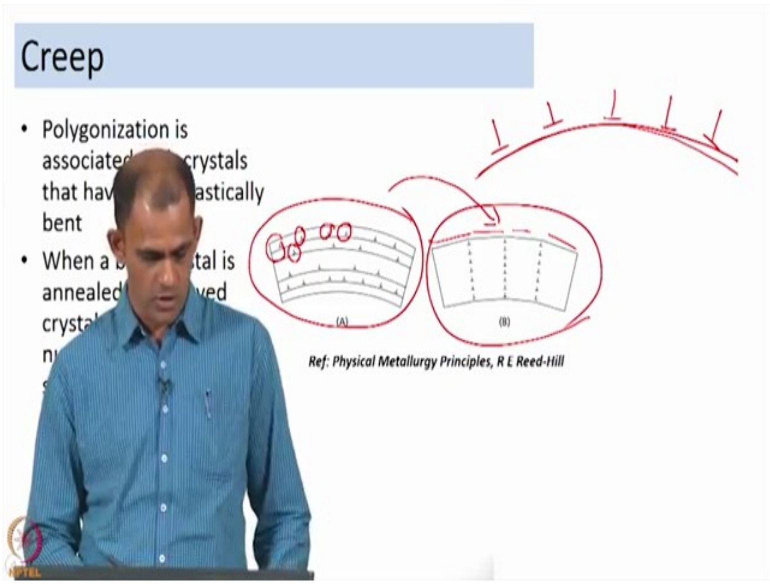

So polygonization is also again result of recovery process of a strain harden crystal. So (when you are strain hard) when you are plastically deforming a crystal under certain circumstances this crystals can become bent. So let us assume this is one grain or a crystal that is plastically bent and (when there is plastically) when the material has plastically bent you will have dislocations forming between the materials so these are all dislocations.

So say that is lattice plane that is bent you can have dislocations, the dislocations are the cause of the bending of the crystal, so you will have dislocations arrangement like that. Now when this bent crystal is annealed what happens is these bent crystal now breaks up into a number of closely related small perfect crystal segments, so this bent crystal goes from that stage to this stage so where you had a continuous (plane) lattice plane (is now) it now takes the shape of a more segmented, if you see segments of the crystal so the curved crystal now breaks up into a number of closely related small perfect crystal segments.

So this is what happens during recovery crystal assumes a slightly newer shape and this processes called polygonization.

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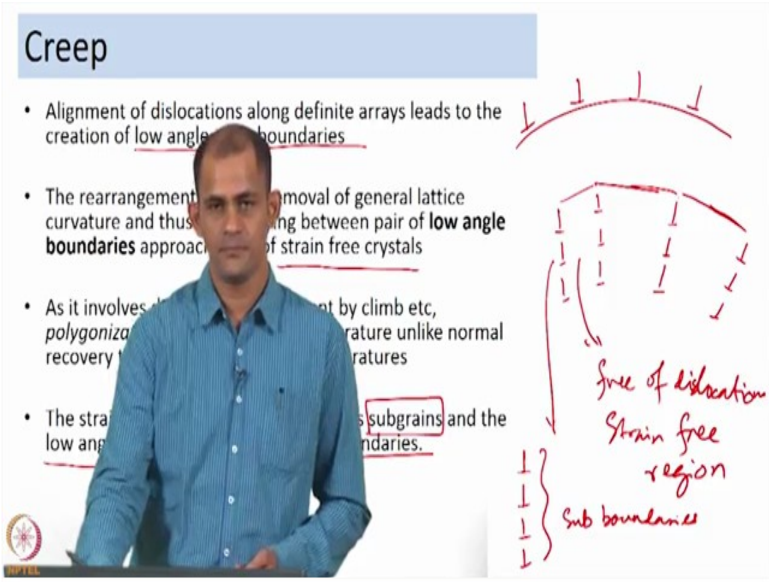

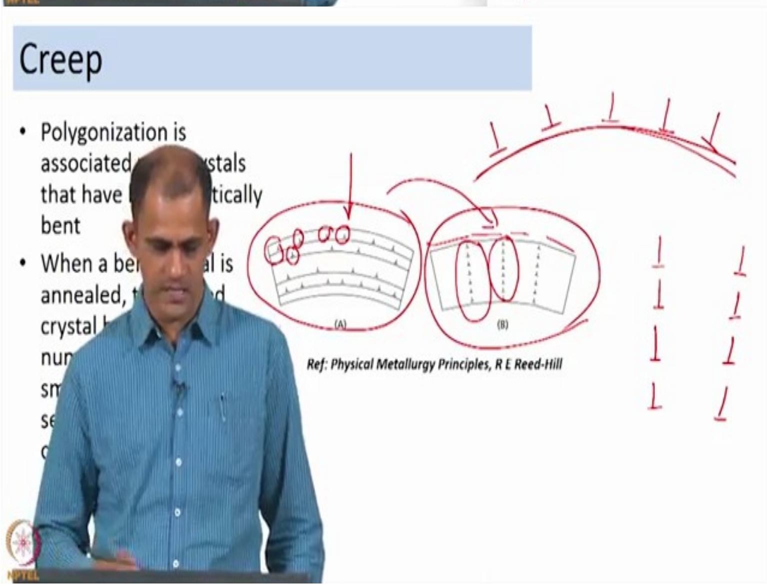

Now what exactly happens here is the dislocation that we are present along the curve plane they start re aligning themselves so the alignment of dislocations along definite arrays leads to the creation of low angle grain boundaries. So what you see here is these are all dislocations that have started ordering themselves so the dislocation that were present randomly along the slip plane have now started ordering themselves in certain arrays.

So they form some form of an array which looks like a wall, so these arrays are known as low angle grain boundaries. So the alignment of dislocations along definite arrays leads to the creation of low angle grain boundaries. What happens is when the dislocation start re arranging into these boundaries that leads to the removal of the lattice curvature, so the curvature that you saw is now removed and the crystals align between pair of low angle grain boundaries approach a state of strain free crystals.

So unlike the lattice plane where the dislocations where (())(32:38) randomly when the dislocations start ordering themselves into definite arrays the region between two definite arrays is free of dislocations and that is why it becomes a strain free crystal. So in the first case your dislocations are all along the lattice plane in the second case the dislocations started ordering themselves in certain arrays and the region between two arrays is free dislocations and hence can be considered a strain free region.

So this rearrangement requires help of dislocation climb, so the dislocations need to climb and move around for further rearrangement to happen and that is why the process of polygonization can happen and totally temperatures which encourage recovery. So polygonization is a high temperature process and this strain free crystals are also known as subgrains.

So the strain free crystals that you see the strain free crystals are known as subgrains and the low angle grain boundaries low angle boundaries are also called sub-boundaries.

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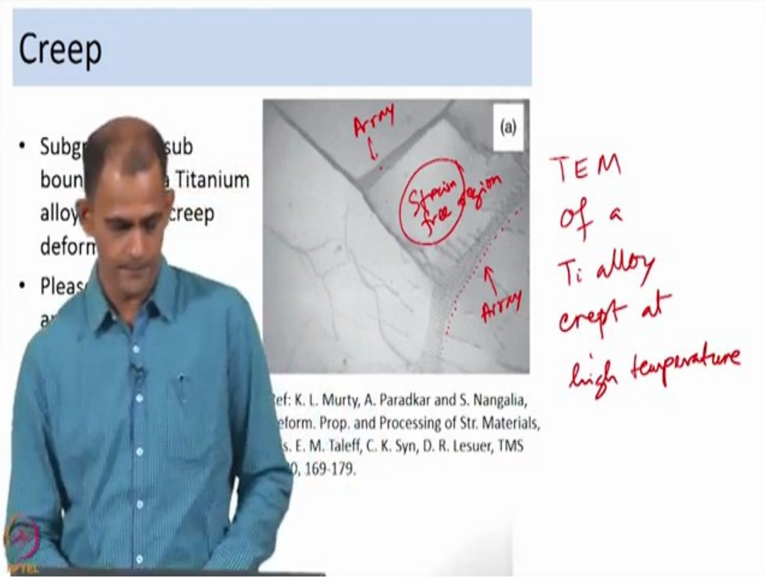

An example of a subgrain and sub-boundary shown in this micrograph is a transmission electron micrograph of a titanium alloy crept at high temperature and what comes out from this figure is the neat arrangement of dislocations so if you see these are all dislocations that have arrange themselves in a very neat fashion and if you look so this is one array of dislocation this is another array of dislocation so these are sub-boundaries and the region separated if you can see it is free of any dislocations so it is a strain free region. So these boundaries are sub-boundaries and this is a subgrain.