Creep Deformation of Materials
Metallurgy and Materials Science
Improving Creep Resistance of Materials

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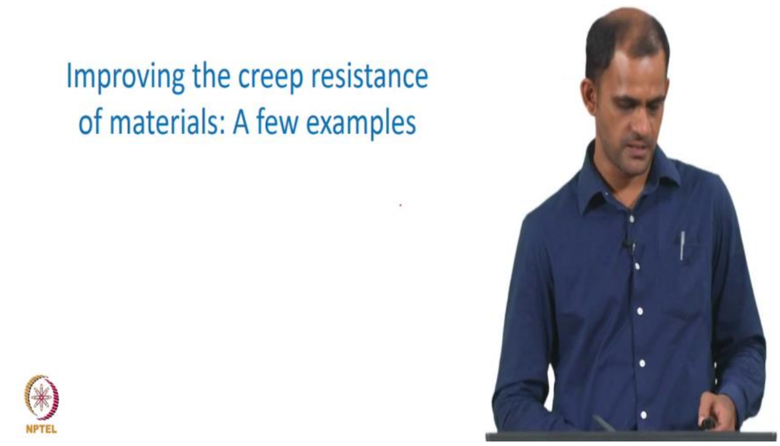

Improving the creep resistance of materials: A few examples

Now we will move onto the next portion, so the next portion is how do you improve the resistance of materials, now the significance of this portion is as follow, so we have learnt about creep, we understood how a creep curve looks like, how a creep curve can be modelled, what are the different mechanisms of plastic deformation that influence creep, how is a creep curve dependent on…

How dislocation motion leads to creep or how diffusion of vacancies leads to creep, so we learned all that and then we also talked about how you can model the useful life, creep life of material using all this knowledge, Larson-Miller parameter and the theta projection concept or continuum damage mechanics approach, so all these things we spoke about, of course having said that the important thing to remember is engineers by all means would like to limit the amount of creep deformation happening because higher the amount of creep faster is the progress of material on the path of failure and also if you have more amount of creep you are also going to lose the dimensional stability of your component.

So on account of this what is important is having now known how creep happens, so let us talk about ways of limiting the amount of creep deformation or improving the creep resistance of materials, so towards the end I will be talk or provide you a few examples and these are very selected examples, there is a lot of literature available on this topic. I have picked up a few examples just to demonstrate the importance of different parameters for improving the creep resistance of materials.

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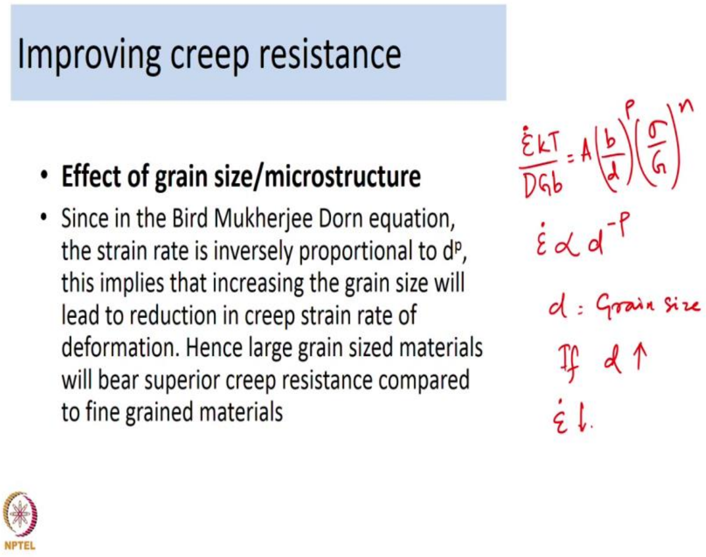

Improving creep resistance

- **Effect of grain size/microstructure**
- Since in the Bird Mukherjee Dorn equation, the strain rate is inversely proportional to d^p, this implies that increasing the grain size will lead to reduction in creep strain rate of deformation. Hence large grain sized materials will bear superior creep resistance compared to fine grained materials

$$\frac{\dot{\varepsilon}kT}{DGb} = A\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{G}\right)^n$$

$$\dot{\varepsilon} \propto d^{-p}$$

d : Grain size

If d ↑

$\dot{\varepsilon}$ ↓.

So the first parameter is the grain size or the microstructure of the material now you can manipulate or tailor the grain size in microstructure of material to improve the creep resistance. Let us take the example of grain size, now if you draw from the Bird Mukherjee Dorn equation Epsilon dot kT by DGb equal to a b by d to the power p and Sigma by G to the power n, so what this basically means is Epsilon dot is proportional to d to the power minus p so d is equal to grain size, so clearly if d increases Epsilon dot is going to come down.

So which means this implies that increase in the grain size will lead to reduction in the creep strain rate of deformation hence larger creep grain size materials will bear superior creep resistance compared to fine grain materials, so that is one of the key take away of this equation that you can play with the grain size to improve the creep resistance or you can increase your grain size to improve the creep resistance of your material, so that is one thing.

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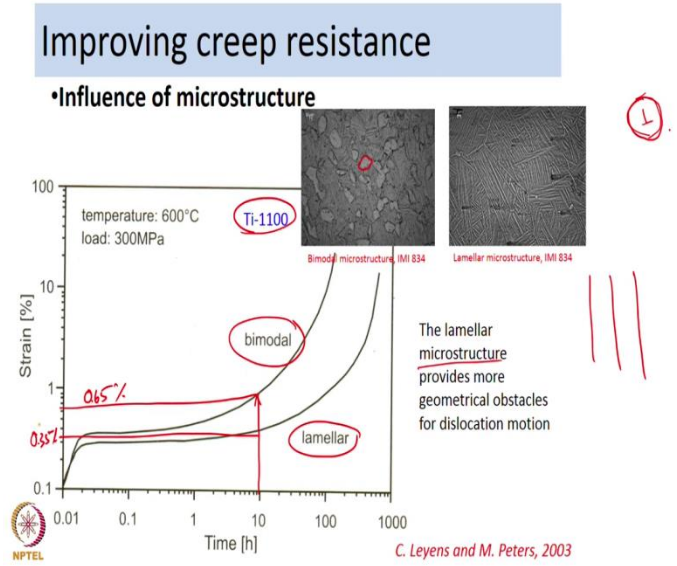

Improving creep resistance

- Influence of microstructure

The lamellar microstructure provides more geometrical obstacles for dislocation motion

C. Leyens and M. Peters, 2003

Now how what is the role of microstructure, so again microstructure also plays a very important role and here is an example from titanium alloys this is titanium 1100 alloy and the authors are talking about the creep behaviour of 2 different microstructures of this material, so in one case you could have a lamellar microstructure in another case you could have bimodal microstructure.

Here are couple of pictures to tell you what we understand by a bimodal microstructure and what we understand by a fully lamellar microstructure, so these microstructures can be attained based on suitable heat treatments, so your heat treatment will decide what kind of microstructure you achieve, so what is being shown in this slide is the lamellar microstructure is providing a higher creep resistance compared to the bimodal microstructure.

So let us take time t= 10 hours, so if you see a 10 hours' time the lamellar microstructure has probably deformed to 0.35 percent strain whereas the bimodal microstructure has deform to probably 0. 65 percent strain, so which means the bimodal microstructure is more amenable to creep deformation compared to the lamellar microstructure.

Now the reason for this is the lamellar microstructure as you can see from the microstructure there is a fine spacing of lamella and the lamellar boundaries, so the boundaries between the lamellas they act as geometrical obstacles to dislocation motion, so what happens is the dislocations find it difficult to overcome this boundaries and as a result plastic deformation is controlled and in the process you have higher creep resistance.

On the other hand in a bimodal microstructure you have this single phase alpha and you also have this lamellar microstructure. Now the single phase alpha is like a grain and there are no real boundaries accept for the phase boundary between alpha and the lamellar microstructure, so the dislocations find it a lot easier to travel there because the mean free length available for the dislocation to move is higher in the bimodal microstructure in comparison to the lamellar microstructure that is why bimodal microstructure is allowing greater creep strain compared to the lamellar microstructure. So this is an example of how microstructure can influence the creep behaviour of your material.

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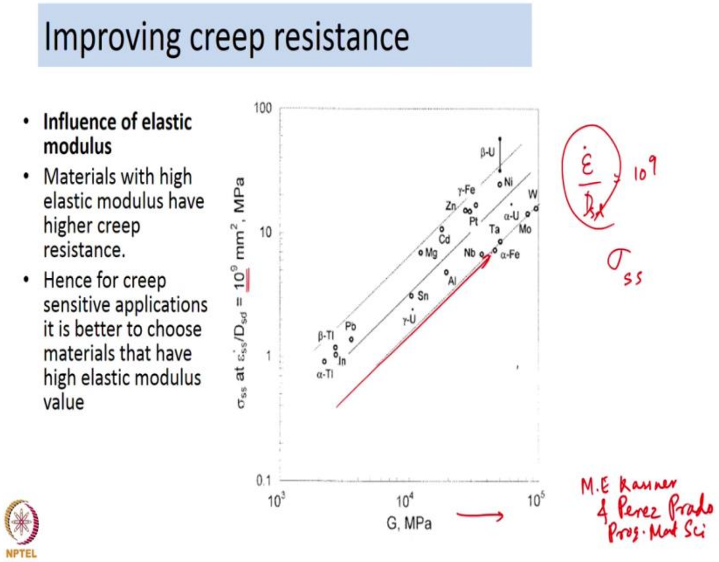

Improving creep resistance

- **Influence of elastic modulus**
- Materials with high elastic modulus have higher creep resistance.
- Hence for creep sensitive applications it is better to choose materials that have high elastic modulus value

M.E Kassner
& Perez Prado
Prog. Mat Sci

Now let us look at another case let us look at the influence of elastic modulus, so this is from review paper of Kassner from progress in material science, so Kassner and Perez-Prado talk about the influence of elastic modulus. This is a graph that we discussed even earlier, so when you talking about the role of elastic modulus, so what this graph is telling you is as your elastic modulus or your shear modulus is increasing the amount of stress required to generate a certain creep strain rate is also increasing.

So in this case they are talking about a creep strain rate of the order of 10 to the power 9, they are talking about creep strain rate normalised with a D_{sd} which is a self-diffusivity and to achieve a particular value of this parameter the amount of stress required is increasing as the shear modulus of the material is increasing which means you need to apply higher stresses for materials which have higher elastic modulus hence for creep sensitive applications if you have to choose a material, so it is better to choose a material that has high elastic modulus because that will ensure that the amount of creep deformation that you get in the process is going to be limited versus vis a vis a low elastic modulus material, the what this plot is suggesting.

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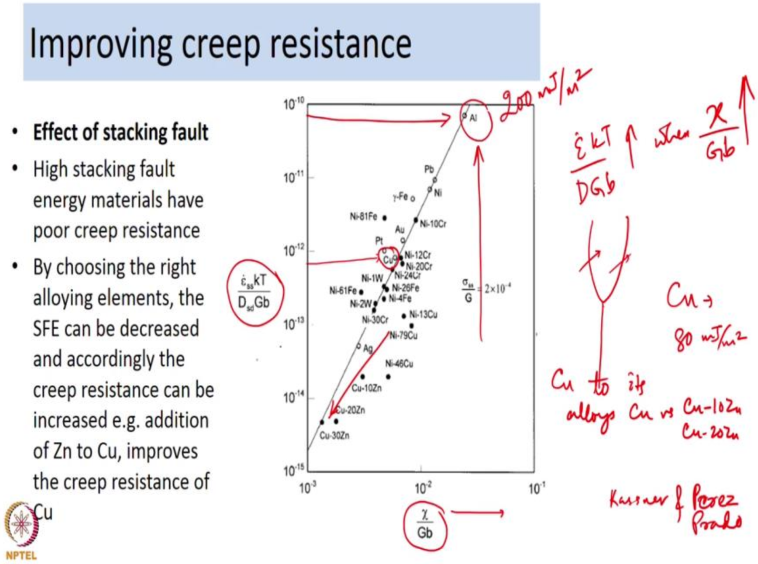

Improving creep resistance

- **Effect of stacking fault**
- High stacking fault energy materials have poor creep resistance
- By choosing the right alloying elements, the SFE can be decreased and accordingly the creep resistance can be increased e.g. addition of Zn to Cu, improves the creep resistance of Cu

In another plot in the same paper by Kassner and Perez-Prado they also talk about the role of stacking fault energy, so if you look at the normalised strain rate versus stacking fault energy normalised by Gb what is clearly emerging is as this term increases the strain rate of deformation or the normalised strain rate is also increasing, so Epsilon dot kT by DGb increases when stacking fault energy normalised stacking fault energy is increasing, so what this basically means is if your stacking fault energy is high then your creep resistance is going to be low.

Now let us look at this, so stacking fault energy is basically corresponding to the energy between the 2 partial dislocations, so you have 2 partial dislocations and the area bounded by these 2 partial dislocations is the stacking fault energy. Now let us look at the case of aluminium which we know has a high stacking fault energy, it has around 200 milli joules per metre square, so on account of the high stacking fault energy actually aluminium finds it difficult to develop any stacking faults which means dissociation of a single dislocation into 2 partials is actually difficult in aluminium compared to copper, so in aluminium you see a lot of cross slip the dislocation finds it easy to move from one plane to another plane and does not to form any in faults.

On the other hand in copper you see a lot of stacking fault formation because in copper the stacking fault energy is around 80 millijoules per metre square. So if you see copper has lower creep strain rate of deformation compared to that of aluminium that means copper is more resistant to creep deformation. Now the role of stacking fault is coming up even nicely when we compare copper to its alloys, so if you look at copper versus copper 10 zinc or 20 zinc, et cetera if you see the stacking fault energy is coming down further.

So for copper as you increase the zinc content the stacking fault energy is coming down and as the stacking fault energy is coming down further you are seeing further improvement in creep resistance, so strain rate of deformation is continuing to come down. So what this tells us is by choosing the right elements, alloying elements you can play around with the stacking fault energy of the material and by reducing the stacking fault energy you can reduce this creep strain rate of deformation or in other words you can improve the creep resistance of the material, so that is the effect of stacking fault.

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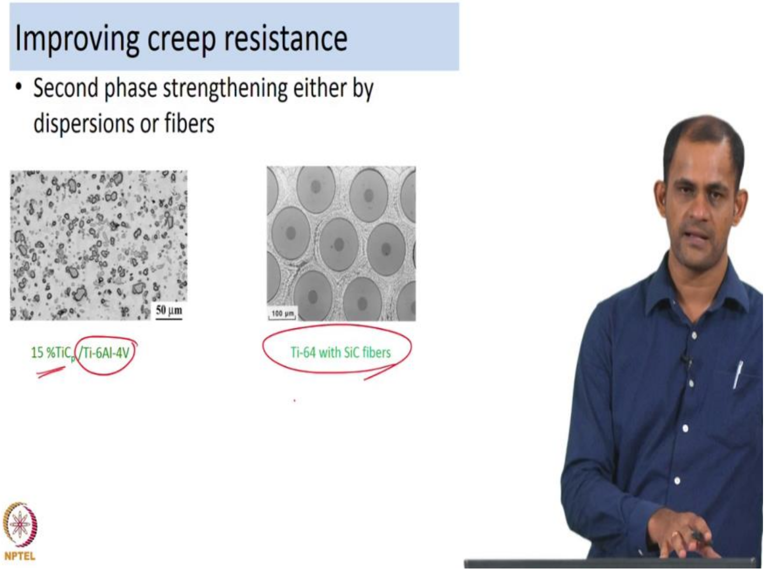

Improving creep resistance

- Second phase strengthening either by dispersions or fibers

Let us look at another aspect, so this is about improving the creep resistance of material by introducing some second phases into the matrix, so the second phase either could be dispersions or it could be fibres, so this is a microstructure of titanium 6 aluminium 4 vanadium with a dispersion of titanium carbide precipitate and this is another case where it is titanium 6 aluminium 4 vanadium reinforced with silicon carbide fibres. These microstructures are for the sake of illustration to tell you how a fibre reinforced system would look like and how a particle reinforced system would look like.

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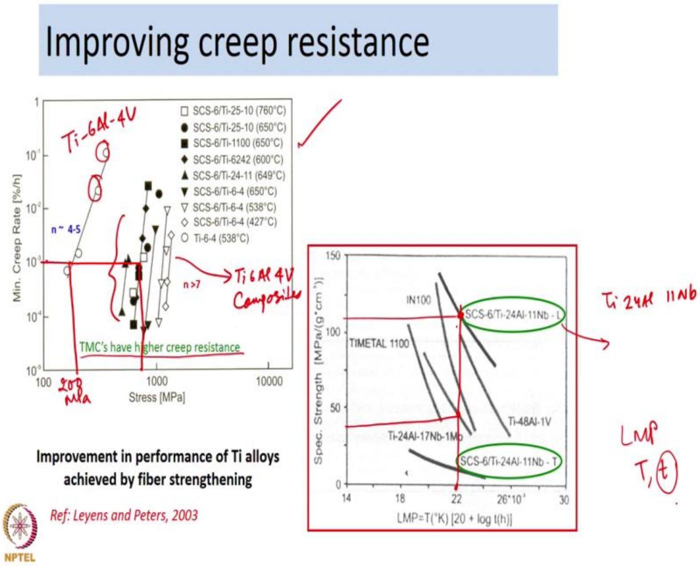

Improving creep resistance

Improvement in performance of Ti alloys achieved by fiber strengthening

Ref: Leyens and Peters, 2003

Now let us look at the creep performance of these materials reinforced with either particles, heart particles or hard fibres, so these are basically titanium matrix composite, so you can call them as a composite because you have added the second phase it is a composite, so what this plot is telling you is that titanium matrix composite have higher creep resistance, so this data corresponds to vote titanium 6 aluminium 4 vanadium whereas all this data corresponds to the composites.

Titanium 6 aluminium 4 vanadium compositions, so if you look at the data to achieve a certain creep strain rate let us say 10 to the power minus 3, to achieve that creep strain rate let us look at the stress level required for Ti 64 and Ti 64 composite. So clearly to achieve a creep strain rate of 10 to the power minus 3 Ti 64 may need around 200 MPa applied stress whereas the composites will require at least 800 to 900 MPa applied stress.

So the composite required higher applied stress to produce the same strain rate of deformation, so naturally there is an improvement in the performance of the titanium 6 aluminium 4 vanadium by the introduction of these particle strengtheners or the fiber strengtheners. Let us also look at another example, so here you have Silicon Carbide fibres reinforced titanium 24 aluminium 11 niobium alloy and in one case they tested the samples along the longitudinal along the length of the fibres in another case.

They tested the sample perpendicular to the fibres so you have L and T, now what you see is the samples which tested along the length of the fibres but the same Larson Miller parameter of 24 or let us look at these alloys, so this will be alloy without the fibres and this is the alloy for the composite with fibres, so clearly the amount of stress required for the alloy without fibres and the alloy with fibres there is a large difference, so you need to apply higher stresses so the strength of the material with the fibres is higher, so you need to apply higher stresses to achieve the same rupture life as in the material without the strengtheners.

So you have Larson Miller parameter versus strength, so Larson Miller parameter will tell you the time or temperature for a given value of 22 let us say the temperature is constant, so to achieve a certain rupture life you need higher stresses, you need to apply higher stresses for the composite against the material without the fibres strengtheners, so that is the impact of adding fibres or dispersoids into a material and they also improve creep resistance.

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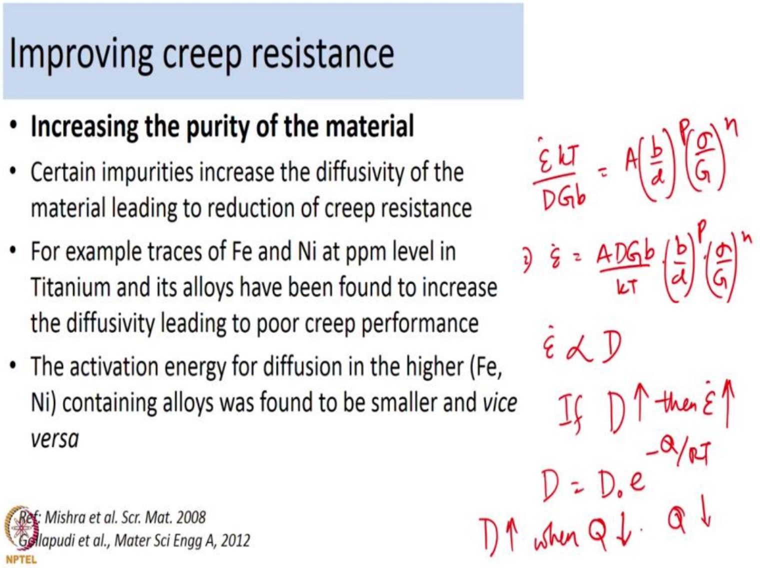

Improving creep resistance

- **Increasing the purity of the material**
- Certain impurities increase the diffusivity of the material leading to reduction of creep resistance
- For example traces of Fe and Ni at ppm level in Titanium and its alloys have been found to increase the diffusivity leading to poor creep performance
- The activation energy for diffusion in the higher (Fe, Ni) containing alloys was found to be smaller and *vice versa*

$$\frac{\dot{\varepsilon} kT}{DGb} = A\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{n}$$

$$\Rightarrow \dot{\varepsilon} = \frac{ADGb}{kT}\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{n}$$

$$\dot{\varepsilon} \propto D$$

If $D \uparrow$ then $\dot{\varepsilon} \uparrow$

$$D = D_0 e^{-Q/RT}$$

$D \uparrow$ when $Q \downarrow$. $Q \downarrow$

Ref: Mishra et al. Scr. Mat. 2008
Gollapudi et al., Mater Sci Engg A, 2012

Now let us look at the purity of the material, so this is one example where we are talking about how impurities can lead to deterioration of the creep properties, so certain impurities can increase the diffusivity of the material leading to a reduction of creep resistance, so again let us go back to the equation Epsilon dot kT by DGb is equal to a b by d P Sigma by G n, so this implies Epsilon dot kT or Epsilon dot can be written as ADGB by kT b by d P Sigma by G to the power n so Epsilon dot is directly proportional to D which is the diffusivity, so if D increases then the strain rate of deformation also increases.

So what has been observed is the presence of certain impurities for example even impurities such as iron and nickel at trace levels that means even at ppm level when they are present in titanium it has been found to increase the diffusivity of titanium and in turn that leads to poor creep performance because the moment your diffusivity increases than your strain rate of deformation also increases, so elements such as iron and nickel even in small quantities tend to deteriorate the creep performance of titanium.

So what happens is when you have the trace elements the activation energy for diffusion actually comes down, so D is D_0 e to the power minus Q over RT. If Q comes down D increases when Q comes down, so what happens is when you have the trace elements they actually reduce the activation energy for diffusion and this in turn increases diffusivity which in turn increases the strain rate of deformation, so you need smaller quantities or you need an alloy or a material which is free of trace elements or you need a titanium alloy which is free of this iron and nickel impurities.

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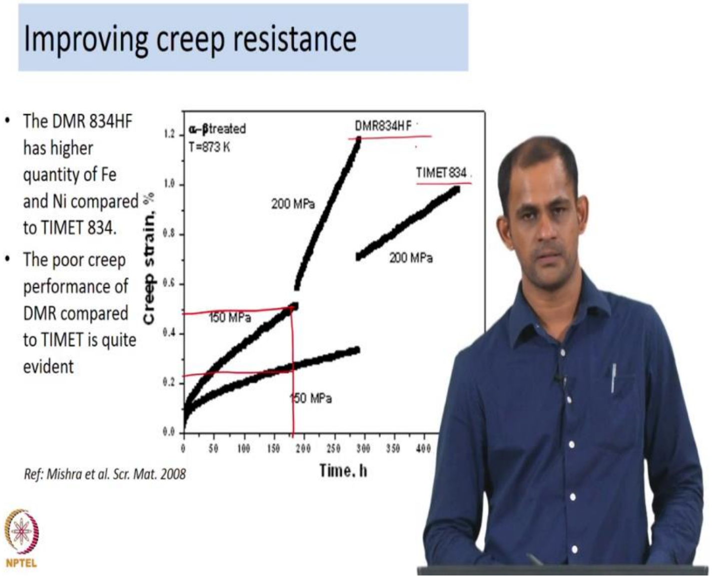

Improving creep resistance

- The DMR 834HF has higher quantity of Fe and Ni compared to TIMET 834.
- The poor creep performance of DMR compared to TIMET is quite evident

Ref: Mishra et al. Scr. Mat. 2008

So to illustrate the importance of iron and nickel impurities let us look at the data from 2 titanium alloys one is TIMET834 and the other one is DMR834, so this has high iron nickel and this has low iron nickel, so clearly the TIMET alloy for the same applied stress the DMR alloy is giving you around 0.5 percent creep strain in a time of around 175 hours whereas the TIMET alloy is exhibiting a plastic deformation of around 0.25 creep strain so almost half the creep strain provided by DMR alloy. So this poor creep performance is because of the presence of iron and nickel which have reduced the activation energy of deformation for the DMR alloy compared to the TIMET alloy. So that is the role of impurities and so that is why impurities have to be taken into account when you are designing a creep resistant material you have to be careful that you do not have any impurities which can increase the diffusivity of the material.

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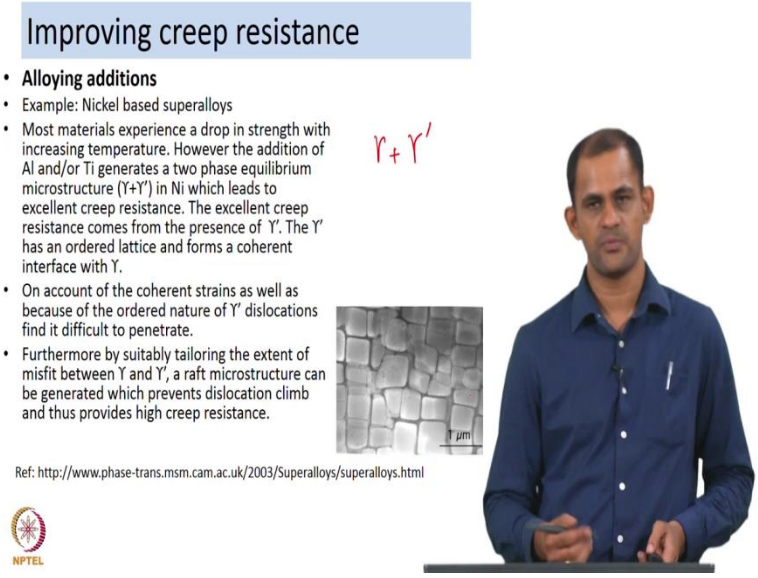

Improving creep resistance

- **Alloying additions**
- Example: Nickel based superalloys
- Most materials experience a drop in strength with increasing temperature. However the addition of Al and/or Ti generates a two phase equilibrium microstructure (Υ+Υ′) in Ni which leads to excellent creep resistance. The excellent creep resistance comes from the presence of Υ′. The Υ′ has an ordered lattice and forms a coherent interface with Υ.
- On account of the coherent strains as well as because of the ordered nature of Υ′ dislocations find it difficult to penetrate.
- Furthermore by suitably tailoring the extent of misfit between Υ and Υ′, a raft microstructure can be generated which prevents dislocation climb and thus provides high creep resistance.

$\gamma + \gamma'$

Ref: http://www.phase-trans.msm.cam.ac.uk/2003/Superalloys/superalloys.html

So we talked about impurities but if you are talking of alloying addition where you are intentionally adding elements into the material with the specific objective in mind then that can also lead to improvement in creep performance. Let us talk of this nickel based super alloys. The nickel-based super alloys are used in gas turbine engines especially in the high temperature region and the reason is these alloys have excellent high temperature strength, so compared to most materials which experience a drop in strength with increasing temperature nickel based super alloys continue to retain their strength up to higher temperatures and this is on account of the addition of aluminium or titanium.

The aluminium and titanium elements when they are added to nickel they allow the development of a 2 phase equilibrium microstructure, so you have a 2 phase microstructure, the matrix is gamma and your second phase which is known as gamma dash, so this 2 phase microstructure leads the development of an excellent creep resistance, so here the aluminium and titanium addition is causing the development of a microstructure which is creep resistant and the creep resistance come from the presence of gamma dash because gamma dash it is an ordered structure and gamma dash forms a coherent interface with gamma.

So coherency strains lead to strengthening of the material to start with, so that is why gamma dash helps in the improvement in strength of the material and when in addition to the coherent strain, gamma dash is also a ordered lattice and because of the order the nature of the lattice dislocation find it very difficult to penetrate the gamma dash material. So it is a strong material on account of the ordered lattice that it has and so dislocation finds it very difficult to move from the matrix that is gamma in to the gamma dash phase.

Furthermore on account of its ordered lattice structure the dislocation tends to get locked with in the gamma-gamma dash interfaces at higher temperatures and that has something to do with the anti-phase boundary, anti-phase boundary energy of the gamma dash. This is the advantage of generating gamma in the nickel matrix.

Now it has also been observed that if you by suitably tailoring the extent of misfit, so gamma and gamma dash although they have a very good matching there is still some amount of misfit between the 2 phases and if you play around with this misfit then a raft microstructure is generated, so raft microstructure as shown here, raft microstructure can be developed within the nickel based super alloy and what has been observed is this raft microstructure prevents dislocation climb and because it prevents or restricts dislocation climb it enables higher creep resistance.

So that is one of the things that can be achieved so the raft microstructure that can be achieved by addition of aluminium and titanium and with some suitable heat treatment this raft microstructure prevents the dislocation from climbing easily and in turn controls the creep deformation of the material. So that is an example of how alloying additions can bring about an improvement in the creep performance of a material.

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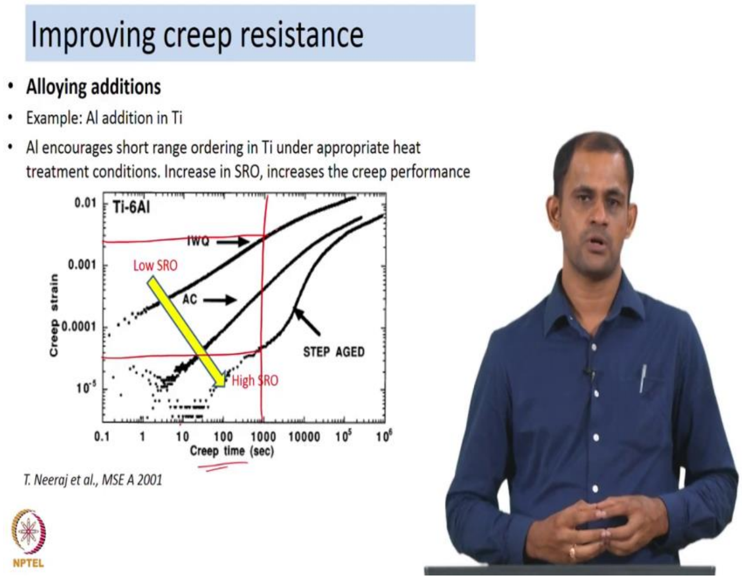

Improving creep resistance

- **Alloying additions**
  - Example: Al addition in Ti
  - Al encourages short range ordering in Ti under appropriate heat treatment conditions. Increase in SRO, increases the creep performance

T. Neeraj et al., MSE A 2001

Another example is the addition of aluminium in titanium, so aluminium is added to titanium as a strengthener and people have observed that aluminium encourages short-range ordering, the development of a short-range order in titanium under appropriate heat conditions, so this particular graph plot is between creep strain versus time so it is a creep curve and what people have noticed is if you somehow increase the amount of short-range order within the material and the amount of short-range order within the material can be improved by appropriate heat treatments.

So if increase the amount of short-range order and then there seems to be an improvement in the creep resistance of the material, so at the same time let us say for the same duration the amount of strain experienced by the material with higher short-range order is lower compared to the material with lower short-range order. So aluminium addition and combined with some appropriate heat treatments can allow us to tailor the short-range order within the material and that in turn can improve the creep resistance of the material, so that is the significance of alloying additions. Of course you can also look at alloying additions from a point of view of controlling the dislocation glide behaviour.

We know that solute atmosphere can form around dislocations, so solutes preferentially segregate around dislocation course and the trapping of dislocation by the solute atmosphere can limit the amount of dislocation glide for example in aluminium magnesium system, the magnesium atoms limit the amount of dislocation glide that happens within the aluminium matrix and as a result creep resistance is also increased, so that is the role of alloying additions. So to summarise, and just to point out one more example alloying additions can also play or can influence the diffusivity of materials, so we spoke about iron and nickel trace impurities increasing the diffusivity of titanium leading to poor creep performance.

A converse of this is…if you add alloying elements which reduce the diffusivity of your matrix element, so which means so typically diffusivity happens by the motion of vacancy or the motion of atoms from one location to another that is what is happening, so you need atoms to move around for diffusion to happen. If the atoms are prevented from moving easily then what would happen is your diffusivity will come down and what people have noticed is if you add atoms with large atomic radii compared to the host element or the matrix element then these large atoms prevent the motion of, the easy diffusion of the matrix element and because of which the diffusivity comes down.

So typical example is you can add molybdenum to some of the materials or you can add niobium to some of these different elements because these materials have large atomic radii and they prevent the motion of easy diffusion of vacancies and in turn improve the creep performance, so that is how you can improve the creep performance of materials, so we spoke about the role of grains size, the role of microstructure, we spoke about role of elastic modular and we spoke about the role of stacking fault energy and then allowing additions, so these are many different approaches by which people either separately or in combination you can play around with these factors to improve the creep performance of your material. So with that and conclude the lectures on creep deformation of material.