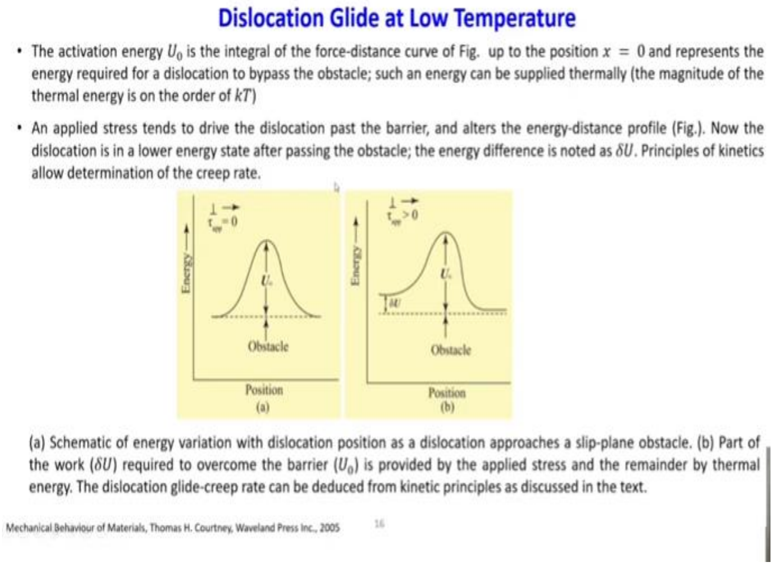
Mechanical Behavior of Materials
Prof. S. Sankaran
Department of Metallurgical and Materials Engineering
Indian Institute of Technology - Madras

Module No # 09
Lecture No # 45
Creep – III

Hello I am Professor S. Sankaran in the department of metrological and materials engineering.

(Refer Slide Time: 00:17)



Dislocation Glide at Low Temperature

- The activation energy U_0 is the integral of the force-distance curve of Fig. up to the position $x = 0$ and represents the energy required for a dislocation to bypass the obstacle; such an energy can be supplied thermally (the magnitude of the thermal energy is on the order of kT)
- An applied stress tends to drive the dislocation past the barrier, and alters the energy-distance profile (Fig.). Now the dislocation is in a lower energy state after passing the obstacle; the energy difference is noted as δU. Principles of kinetics allow determination of the creep rate.

(a) Schematic of energy variation with dislocation position as a dislocation approaches a slip-plane obstacle. (b) Part of the work (δU) required to overcome the barrier (U_0) is provided by the applied stress and the remainder by thermal energy. The dislocation glide-creep rate can be deduced from kinetic principles as discussed in the text.

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

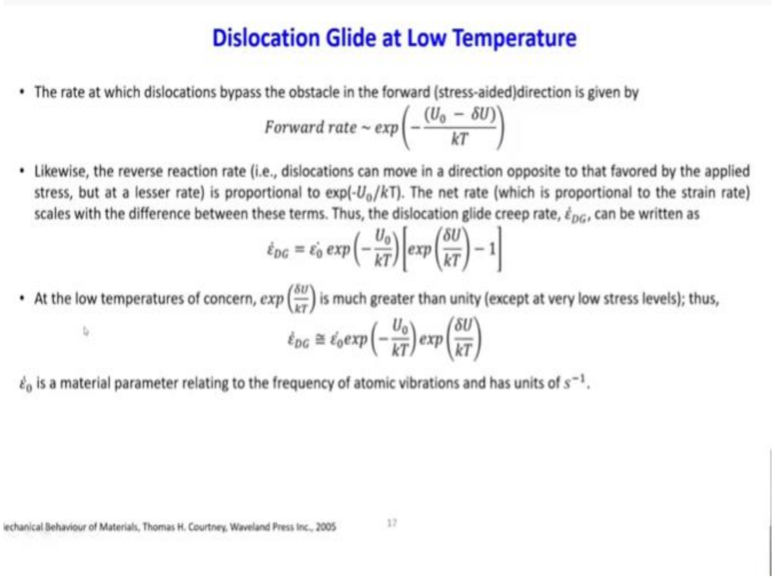
16

Hello everyone welcome back to this lecture and we will continue our discussion on the creep deformation. In the last class we looked at the introduction to the creep and the type of creep curve the various stages of the creep curve and so on. And today class we will discuss very specifically the important mechanisms. There are several mechanisms being reported in the literature depending upon the material. This is known the state of stress and strain rate and temperature combinations because it will be already seen that the treat deformation is a strong function of these parameters. So some of the prominent mechanisms we will go through and then see how we can comprehend the idea of the creep deformation in the very variety of material. So depending on the temperature and applied stress, dislocation glide, dislocation climb or diffusional creep flow mechanisms may dominate the deformation. This is very important so it is not one particular mechanism we are going to say that this is the mechanism because as you rightly see that this deformation highly depends on the applied stress and the dislocation climb or glide or dislocation mechanisms. So what is the plot shown here? It is the activation energy for self-diffusion which is Kilo joule/mol, and activation energy for the high temperature is, which is what is given. So the high temperature activation energy correlates closely with self-diffusion activation energy, so this is one proof that you know the self-diffusion activation energy is correlating very well with the high temperature which are creep. So this correlation indicates that creep deformation is associated with diffusional flow. So this is one experimental evidence clearly shows that high temperature deformation creep involves diffusional flow. So now that was kind of a proof but then we will see what kind of you know stress and temperature combination dictates, what kind of creep mechanisms dominates we can look at later. In that case we will first look at which is dislocation glide at low temperature, relatively low temperature. So what you see here in the block is very a simple one energy versus position where the dislocation approaches the clip plane and this is an obstacle as a plane so this is a barrier you notice the activation barrier that the dislocation as to cross through. So normally if you recall we have just looked at this exactly similar approach of thermally activation process, two times in fact we have seen. One, we have just seen that you know at very how the thermal energy k T assists the dislocation to cross the barrier. Otherwise the thermal activation alone has to do the job or the update stress has to be with that.

So this is kind of an activation barrier how the applied stress is going to pave this or modify this profile this is what we are going to see. (a) schematic; of energy variation with the dislocation position as dislocation approaches slip plane obstacle and what is shown in (b) suppose if the applied shear stress is greater than 0 then what happens is we just alters this profile. This energy required to cross this barrier is altered what does this show? Δ U is in applied stress so that means it reduces the barriers that means, it assists I mean the energy barrier which normally accommodated are circumvented by the thermal fluctuation. So it applies to us it reduces that energy required so that is what is shown here. The part of the work that is Δ U is required to overcome the barrier U_0 is provided by the applied stress that is tau applied here.

And the reminder by thermal energy that is k T the dislocation glide creep rate can be reduced from the kinetic principles as discussed in the text what we are going to see. So the activation energy U_0 is the integral of the force-distance curve. So this is integral this is already we have seen this we have enough background to understand this which is up to the position x – 0 and the represent the energy required for a dislocation to bypass the obstacle. Such an energy can be supplied thermally the magnitude of the thermal energy is in the order of k T. And applied stress tensed to drive the dislocation past the barrier and alters the energy obstacle and the energy distance profile which is shown in this figure. Now the dislocation is in the lower energy state after passing the obstacle. So you can see that now the dislocation energy is lowered as compared to the before it crossing the obstacle. The energy difference is noted as Δ U and principles of kinetics allows the determination of the creep rate. So how do we find the creep rate for the dislocation glide creep.

(Refer Slide Time: 06:39)



Dislocation Glide at Low Temperature

- The rate at which dislocations bypass the obstacle in the forward (stress-aided)direction is given by

$$Forward\ rate \sim exp\left(-\frac{(U_0 - \delta U)}{kT}\right)$$

- Likewise, the reverse reaction rate (i.e., dislocations can move in a direction opposite to that favored by the applied stress, but at a lesser rate) is proportional to exp(-U_0/kT). The net rate (which is proportional to the strain rate) scales with the difference between these terms. Thus, the dislocation glide creep rate, $\dot{\varepsilon}_{DG}$, can be written as

$$\dot{\varepsilon}_{DG} = \dot{\varepsilon_0}\, exp\left(-\frac{U_0}{kT}\right)\left[exp\left(\frac{\delta U}{kT}\right) - 1\right]$$

- At the low temperatures of concern, $exp\left(\frac{\delta U}{kT}\right)$ is much greater than unity (except at very low stress levels); thus,

$$\dot{\varepsilon}_{DG} \cong \dot{\varepsilon}_0 exp\left(-\frac{U_0}{kT}\right) exp\left(\frac{\delta U}{kT}\right)$$

$\dot{\varepsilon}_0$ is a material parameter relating to the frequency of atomic vibrations and has units of s^{-1}.

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

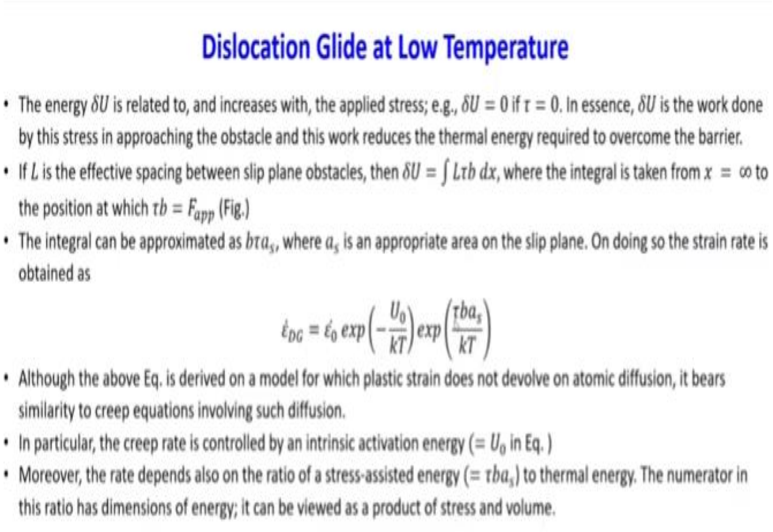
The rate at which the dislocation bypass the obstacle in the forward that is stress aided direction is given by forward rate is approximately equal to exp(- (U_0- δU)/ k T), this is the forward rate. likewise the reverse reaction rate that is dislocation can move in the direction opposite to the favoured by the applied stress but at a less rate is proportional to exponential (–U_0 /k T). So what we require is the net rate so the net rate which is proportional to this strain rate scales with the difference between these terms. So what is the difference that is the dislocation glide creep rate that is ε dot D G stand for dislocation like can be written like this.

$$\dot{\varepsilon}_{DG} = \dot{\varepsilon}_0 \exp\left(\frac{U_0}{kT}\right) \left[\exp\left(\frac{\delta U}{kT}\right) - 1\right]$$

at low temperatures of exp(δU/Kt) is much greater than unity except that very low stress levels.

We can rewrite this expression like this $\dot{\varepsilon}_{DG} = \dot{\varepsilon}_0 \exp\left(-\frac{U_0}{kT}\right) \exp\left(\frac{\delta U}{kT}\right)$. So this can be written like this after we modify this exponential term. $\dot{\varepsilon}_0$ is a material parameter relating to the frequency of atomic vibrations and as units of per second. So this is a material parameter.

(Refer Slide Time: 08:38)



Dislocation Glide at Low Temperature

- The energy δU is related to, and increases with, the applied stress; e.g., $\delta U = 0$ if $\tau = 0$. In essence, δU is the work done by this stress in approaching the obstacle and this work reduces the thermal energy required to overcome the barrier.
- If L is the effective spacing between slip plane obstacles, then $\delta U = \int L\tau b\, dx$, where the integral is taken from $x = \infty$ to the position at which $\tau b = F_{app}$ (Fig.)
- The integral can be approximated as $b\tau a_s$, where a_s is an appropriate area on the slip plane. On doing so the strain rate is obtained as

$$\dot{\varepsilon}_{DG} = \dot{\varepsilon}_0\, exp\left(-\frac{U_0}{kT}\right) exp\left(\frac{\tau b a_s}{kT}\right)$$

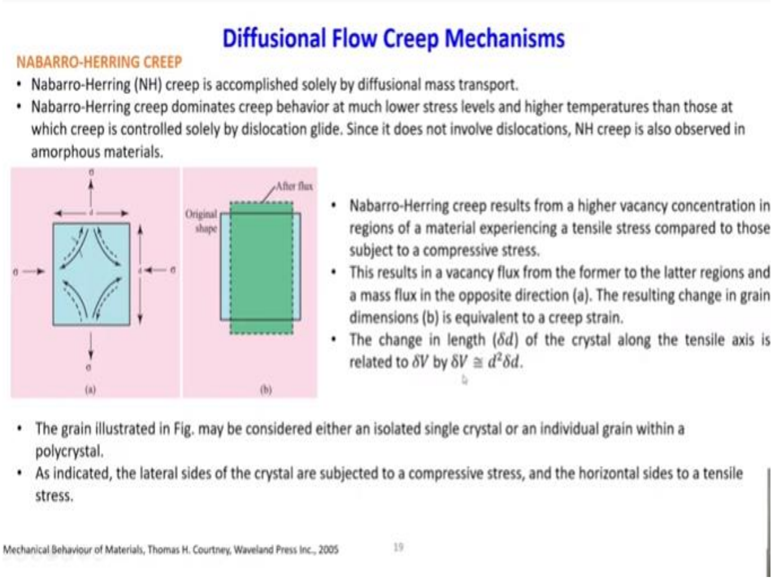
- Although the above Eq. is derived on a model for which plastic strain does not devolve on atomic diffusion, it bears similarity to creep equations involving such diffusion.
- In particular, the creep rate is controlled by an intrinsic activation energy (= U_0 in Eq.)
- Moreover, the rate depends also on the ratio of a stress-assisted energy (= $\tau b a_s$) to thermal energy. The numerator in this ratio has dimensions of energy; it can be viewed as a product of stress and volume.

The energy Δ U is related to and increase with the applied stress example Δ U = 0 if tau = 0. In essence Δ U is the work done by stress in approaching the obstacle and this work reduces the thermal energy required to overcome the barrier. This we have already stated if L is the effective spacing between the slip plan obstacles then Δ U is equal to integral of τbd x. Where the integral is taken from x is equal to infinity to position at which τ b which is equal to Fapp(fig). So this equation they are all very familiar to you we have already looked at it when we looked at the dislocation dynamic also we have seen that force where the b is a burst vector this is a stress creep. So the force required so we have seen that so this is also the similar expression so you know the L is the length effective spacing between the slip plane obstacles. And then it gives a kind of energy term.

The integral can be approximated as $b\tau a_s$ where a_s is an approximate area on the slip rate. On doing so the strain rate is obtained $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{DG}} = \dot{\varepsilon}_0 \,\mathbf{exp}\left(-\frac{U_0}{kT}\right)\, \mathbf{exp}\left(\frac{\tau b a_s}{kT}\right)$. So what is this term we know this is an energy barrier but this one is the complete again an energy. So this is a stress into area, so the intersect volume to stress into volume term it comes. So this is a ratio of stress into volume divided by the thermal energy term, so this term will keep in, repeating in this different kind of mechanisms. If you just keep a track of this although the above equation is derived on a model for which plastic strain does not devolve on atomic diffusion it bears. Similarity to creep equations involving such diffusion in particular the creep rate is controlled by an intrinsic activation energy that is U_0 in the equation.

Moreover the rate depends also on the ratio on stress assisted energy so that is what I just mentioned τba_s is nothing but the volume into stress to thermal energy. So stress assisted energy to thermal energy it is a ratio so this ratio is you know it is an additional term I mean additional term along with the intrinsic activation energy that is what it says. So the creep rate depends upon the ratio of stress assisted energy to thermal energy. The numerator in this ratio has a dimension of energy and it can be viewed as a product of stress and volume. So this is stress τ and ba_s is a volume.

(Refer Slide Time: 11:56)



Diffusional Flow Creep Mechanisms

NABARRO-HERRING CREEP

- Nabarro-Herring (NH) creep is accomplished solely by diffusional mass transport.
- Nabarro-Herring creep dominates creep behavior at much lower stress levels and higher temperatures than those at which creep is controlled solely by dislocation glide. Since it does not involve dislocations, NH creep is also observed in amorphous materials.

- Nabarro-Herring creep results from a higher vacancy concentration in regions of a material experiencing a tensile stress compared to those subject to a compressive stress.
- This results in a vacancy flux from the former to the latter regions and a mass flux in the opposite direction (a). The resulting change in grain dimensions (b) is equivalent to a creep strain.
- The change in length (δd) of the crystal along the tensile axis is related to δV by $\delta V \cong d^2 \delta d$.

- The grain illustrated in Fig. may be considered either an isolated single crystal or an individual grain within a polycrystal.
- As indicated, the lateral sides of the crystal are subjected to a compressive stress, and the horizontal sides to a tensile stress.

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

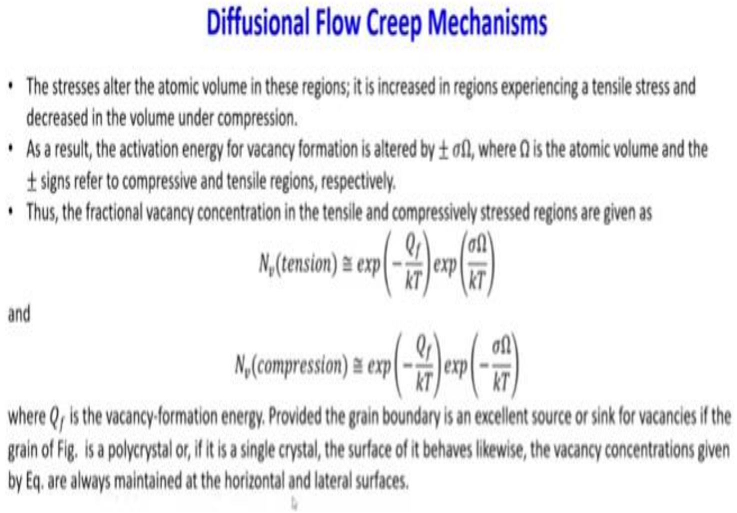
19

So now that is about the dislocation glide creep that is a creep rate, if it is completely controlled by dislocation glide that is relatively low temperature high stress. That is how we should do it now look at diffusion flow creep mechanism a popular one is Nabarro-Herring creep. So now we have to reverse the situation slightly high temperature low stress so high stress low temperature now it is reversed high temperature low stress. Nabarro-Herring creep is accompanied solely by diffusion mass transport and NH creep dominates creep behavior at much lower stress levels and higher temperature than those at which creep is controlled by solely by the dislocation glide. Since it does not involve dislocations Nabarro-Herring creep is also observed I amorphous materials. So this is one advantage since there is no dislocation activity this kind of formulation can be applied through amorphous materials also.

But we will now just look at the crystalline material context so what is the model so here is the model where you can consider a square type of a single crystal an which is being subjected to biaxial loading one is tension other is compression and the crystal width is d and then you can see the diffusion flux how it goes with respect in response to the stress and the temperature. So that is what it is given so we now describe the glide illustrated figure may be considered either an isolated single crystal or an individual grain within a poly crystal.

So both are possible as indicated the lateral sides of this crystal are subjected to a compressive stress and the horizontal sides to a tensile stress. So since it is a diffusional flow Nabarro-Herring creep results from a higher vacancy concentration in the regions of a material experiencing tensile strength compared to those subjected to compressive stress. This results in the vacancy flux from the format to the later region that is a tensile region to a compression region. And then and a mass flux in the opposite direction that is; what is shown here.So vacancy flux is one direction mass flux is opposite direction so you can see that dotted line and the solid line. So that is what it is shown here this results in the vacancy flux from the former that is from the tensile to compression region and latter that is the mass flux is going from sides to compression to tensile region. So this is what you have to appreciate the resulting change in the grain dimension is shown in the b is equal into the creep strength. So the resulting shape changes so the original shape is that this is an after flux so this change is the creep strain. The change in length Δ d so the d is this is the d so this is a Δ d of the crystal along the tensile axis is related to d v this is volume Δ v by Δ v is approximately equal to $D^2\Delta$ d. So this is a change in volume because of this diffusion flux is given by this expression.

(Refer Slide Time: 16:15)



Diffusional Flow Creep Mechanisms

- The stresses alter the atomic volume in these regions; it is increased in regions experiencing a tensile stress and decreased in the volume under compression.
- As a result, the activation energy for vacancy formation is altered by $\pm\sigma\Omega$, where Ω is the atomic volume and the $\pm$ signs refer to compressive and tensile regions, respectively.
- Thus, the fractional vacancy concentration in the tensile and compressively stressed regions are given as

$$N_v(tension) \cong exp\left(-\frac{Q_f}{kT}\right)exp\left(\frac{\sigma\Omega}{kT}\right)$$

and

$$N_v(compression) \cong exp\left(-\frac{Q_f}{kT}\right)exp\left(-\frac{\sigma\Omega}{kT}\right)$$

where Q_f is the vacancy-formation energy. Provided the grain boundary is an excellent source or sink for vacancies if the grain of Fig. is a polycrystal or, if it is a single crystal, the surface of it behaves likewise, the vacancy concentrations given by Eq. are always maintained at the horizontal and lateral surfaces.

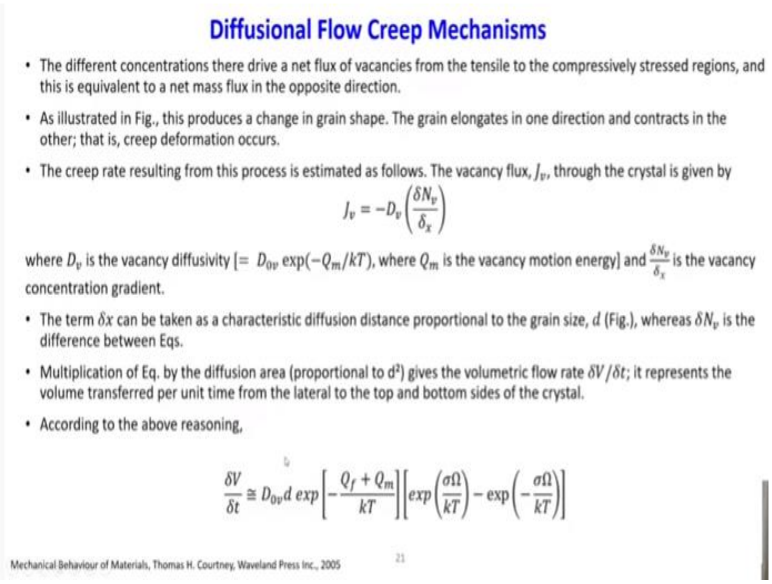
This stresses alter the atomic volume in this region, it is increased in the regions experiencing tensile stress and decreased in the volume the compression. So this we have seen the schematic as a result the activation energy for vacancy formation is altered by plus or minus $\sigma\Omega$, where Ω is the atomic volume. And plus or minus sign refers to compressive and tensile regions respectively. So now we are taking about the activation energy for the vacancy formation by the factor sigma times volume. So obviously we are looking at the microstructural dimensions here okay. So stress into volume even in the previous case we looked at stress into volume term. Thus the vacancy concentration in the tensile and compressively; stressed region are given by N v that is a fraction of vacancy in the tension is approximately equal to

$$N_v(tension) = \exp\left(-\frac{Q_f}{kT}\right)\ \exp\left(\frac{\sigma\Omega}{kT}\right)$$

So it is the same type of expressions we will get and in compression is equal to $N_v(compression) = \exp\left(-\frac{Q_f}{kT}\right)\ \exp\left(-\frac{\sigma\Omega}{kT}\right)$, minus sign is because of the compression here. So just to make a difference between these two where Q_f is the vacancy formation energy provided the grain boundary is an excellent source or sink for; vacancies the grain in the figure.

If you can see that figure it is a poly crystal if you consider that figure as a poly crystal then the grain boundary can act as a sink, this is a well-known fact. Or if it is single crystal the surface of it behaves likewise. So there are two things if you consider the single crystal then the surface of the single crystal will act as a boundary and if it is a poly crystal then you can look at the any boundary which will act as a sink for vacancies. The vacancy concentration given by the equation is always maintained at horizontal and lateral surfaces.

(Refer Slide Time: 18:51)



Diffusional Flow Creep Mechanisms

- The different concentrations there drive a net flux of vacancies from the tensile to the compressively stressed regions, and this is equivalent to a net mass flux in the opposite direction.
- As illustrated in Fig., this produces a change in grain shape. The grain elongates in one direction and contracts in the other; that is, creep deformation occurs.
- The creep rate resulting from this process is estimated as follows. The vacancy flux, J_v, through the crystal is given by

$$J_v = -D_v\left(\frac{\delta N_v}{\delta_x}\right)$$

where D_v is the vacancy diffusivity [= $D_{0v}\exp(-Q_m/kT)$, where Q_m is the vacancy motion energy] and $\frac{\delta N_v}{\delta_x}$ is the vacancy concentration gradient.

- The term δx can be taken as a characteristic diffusion distance proportional to the grain size, d (Fig.), whereas δN_v is the difference between Eqs.
- Multiplication of Eq. by the diffusion area (proportional to d^2) gives the volumetric flow rate $\delta V/\delta t$; it represents the volume transferred per unit time from the lateral to the top and bottom sides of the crystal.
- According to the above reasoning,

$$\frac{\delta V}{\delta t} \cong D_{0v} d\, exp\left[-\frac{Q_f + Q_m}{kT}\right]\left[exp\left(\frac{\sigma\Omega}{kT}\right) - \exp\left(-\frac{\sigma\Omega}{kT}\right)\right]$$

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

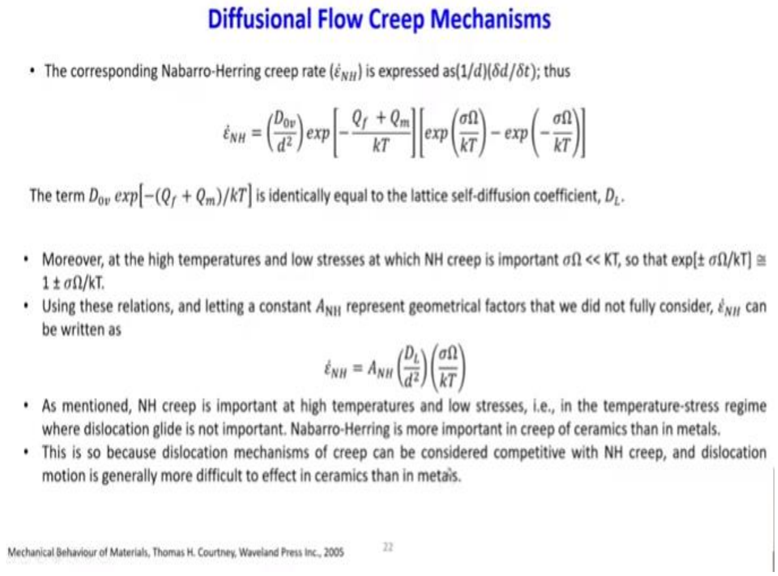
The different concentrations there drive a net flux of vacancies from the tensile to compressively stressed region and this is equal to a net mass flux in the opposite direction. That is what the schematic also shows with the dotted arrow and the solid error. As illustrated in figure this produces a change in the grain shape the grain elongates in one direction and contracts in the other that is creep deformation occurs.

The creep rate resulting from this process is estimated as follows the vacancy flux J v through the crystal is given by $J_v = -D_v (\partial N_v / \delta_x)$. There is a typo here this is not substitute x this is a δ_x where D v is the vacancy diffusivity which is equal to D_{0v} exp(–Q_m/ k T where Q_m is the vacancy motion energy and the ($\partial N_v / \delta_x$. If the vacancy concentration gradient just you are familiar with this. We have seen this gradient in several occasions in the previous discussion so here it is a vacancy concentration gradient. The term δ_x can be taken as a characteristic diffusion distance proportional to the grain size very important idea. So the Δ x here is considered as a grain size d whereas ∂N_v the difference between the equation. So what we have given to compression and tension direction we have given vacancy concentration the difference is taken as in ∂N_v. Multiplication of the equation by the diffusion area that is proportional to d square is the volumetric flow rate. What is volumetric flow rate, δV/δt, so the vacancy flux is now related now equated to volumetric flow rate it represents the volume transferred per unit time that is δV/δt from the lateral to the top and bottom sides of the crystal. So according to the above reasoning you can write the expression like this δV/δt.

That is volume transferred per unit time which is equal$\frac{\delta V}{\delta t} = D_{0v} d \, exp \left[-\frac{(Q_f - Q_m)}{kT}\right] \left[exp\left(\frac{\sigma\Omega}{kT}\right) - exp\left(-\frac{\sigma\Omega}{kT}\right)\right]$.

This expression we are simply substituting from the previous equations you do not get confused that you know the equation is becoming bigger. We have just seen one by one then we have now putting everything together. So nothing is new here all the terms we have discussed right all the terms we have discussed.

(Refer Slide Time: 22:14)



Diffusional Flow Creep Mechanisms

- The corresponding Nabarro-Herring creep rate ($\dot{\varepsilon}_{NH}$) is expressed as$(1/d)(\delta d/\delta t)$; thus

$$\dot{\varepsilon}_{NH} = \left(\frac{D_{0v}}{d^2}\right) exp\left[-\frac{Q_f + Q_m}{kT}\right]\left[exp\left(\frac{\sigma\Omega}{kT}\right) - exp\left(-\frac{\sigma\Omega}{kT}\right)\right]$$

The term $D_{0v}\, exp[-(Q_f + Q_m)/kT]$ is identically equal to the lattice self-diffusion coefficient, D_L.

- Moreover, at the high temperatures and low stresses at which NH creep is important $\sigma\Omega << KT$, so that $exp[\pm \sigma\Omega/kT] \cong 1 \pm \sigma\Omega/kT$.
- Using these relations, and letting a constant A_{NH} represent geometrical factors that we did not fully consider, $\dot{\varepsilon}_{NH}$ can be written as

$$\dot{\varepsilon}_{NH} = A_{NH}\left(\frac{D_L}{d^2}\right)\left(\frac{\sigma\Omega}{kT}\right)$$

- As mentioned, NH creep is important at high temperatures and low stresses, i.e., in the temperature-stress regime where dislocation glide is not important. Nabarro-Herring is more important in creep of ceramics than in metals.
- This is so because dislocation mechanisms of creep can be considered competitive with NH creep, and dislocation motion is generally more difficult to effect in ceramics than in metals.

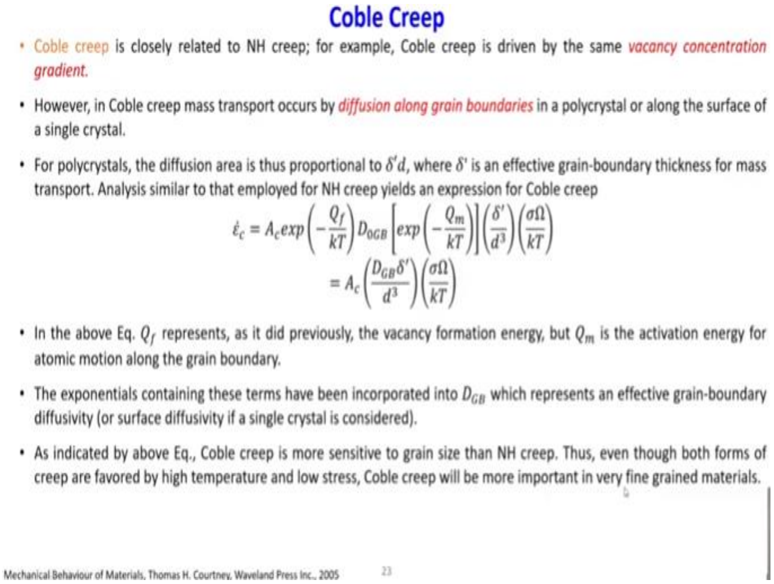
Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

The corresponding Nabarro-Herring creep rate that is ε dot and H is expressed as $\dot{\varepsilon}_{NH} = D_{0v} d \left(\frac{D_{0v}}{d^2}\right) exp\left[-\frac{(Q_f - Q_m)}{kT}\right]\left[exp\left(\frac{\sigma\Omega}{kT}\right) - exp\left(-\frac{\sigma\Omega}{kT}\right)\right]$. So same equation so this is the at creep rate Nabarro-Herring creep rate. The $D_{0v}\, exp\left[-\frac{(Q_f - Q_m)}{kT}\right]$ is identically equal to the lattice self-diffusion coefficient D $_L$. So this can be just replaced by this more over at high temperature and low stresses at which Nabarro-Herring creep is important σΩ is always less than the k T. That means the stress assisted energy is significantly smaller than the thermal energy that is how you have to read this. We have just talked about it so that the exponential plus or minus sigma omega by k T can be written like this one plus or minus sigma omega by k T.

So this is very simple idea using these relations and letting a constant A_{NH} represents the geometrical factors that we did not fully consider $\dot{\varepsilon}_{NH} = A_{NH} \left(\frac{D_L}{d^2}\right) \left(\frac{\sigma\Omega}{kT}\right)$. So this is a final expression for this Nabarro-Herring creep as mentioned Nabarro-Herring creep is important at high temperatures and low stresses that is in the temperature stress reaching where the dislocation glide is not important very you know important point to note also.

Nabarro-Herring is more important in creep of ceramics than in metals because ceramics you know they deform only at very high temperatures. So that is where it is important this is so because dislocation mechanisms of creep can be considered competitive with Nabarro-Herring and dislocation motion is generally more difficult to effect in ceramics than in metals. This aspects also we know this location activity is very limited we have discussed that aspect several times.

(Refer Slide Time: 25:08)



Coble Creep

- Coble creep is closely related to NH creep; for example, Coble creep is driven by the same *vacancy concentration gradient.*
- However, in Coble creep mass transport occurs by *diffusion along grain boundaries* in a polycrystal or along the surface of a single crystal.
- For polycrystals, the diffusion area is thus proportional to $\delta' d$, where δ' is an effective grain-boundary thickness for mass transport. Analysis similar to that employed for NH creep yields an expression for Coble creep

$$\dot{\varepsilon}_c = A_c exp\left(-\frac{Q_f}{kT}\right) D_{0GB}\left[exp\left(-\frac{Q_m}{kT}\right)\right]\left(\frac{\delta'}{d^3}\right)\left(\frac{\sigma\Omega}{kT}\right)$$
$$= A_c\left(\frac{D_{GB}\delta'}{d^3}\right)\left(\frac{\sigma\Omega}{kT}\right)$$

- In the above Eq. Q_f represents, as it did previously, the vacancy formation energy, but Q_m is the activation energy for atomic motion along the grain boundary.
- The exponentials containing these terms have been incorporated into D_{GB} which represents an effective grain-boundary diffusivity (or surface diffusivity if a single crystal is considered).
- As indicated by above Eq., Coble creep is more sensitive to grain size than NH creep. Thus, even though both forms of creep are favored by high temperature and low stress, Coble creep will be more important in very fine grained materials.

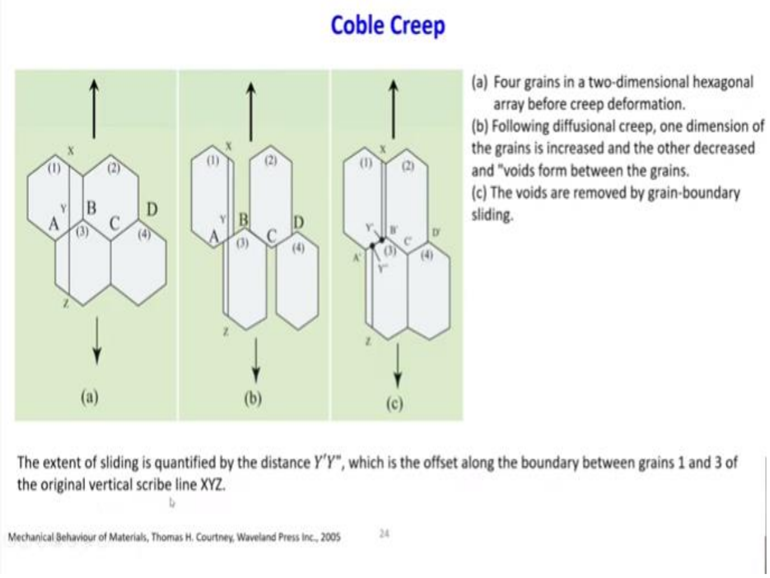
Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

So the next is coble creep is closely related to Nabarro-Herring creep for example coble creep is driven by the same vacancy concentration gradient. So that is ∂NB/∂t, that is concentration gradient so then what is the difference however in coble creep mass transport occurs by diffusion along grain boundaries very important to note. We are looking at only the grain boundary here in the poly crystal or along the surface of the single crystal. So we not the lattice diffusion is not considered here the diffusion along the grain boundary is only considered that is how you should look at it. For a poly crystal the diffusion area is thus proportional to δ′d, where δ′ is an effective grain boundary thickness for mass transport. Analysis similar to that employed in number of Nabarro-Herring creep yields and expression for probability like this in this form which is $\dot{\varepsilon}_c$ stands for coble which is equal $\dot{\varepsilon}_c = A_C\left(\frac{D_{GB}\delta'}{d^3}\right)\left(\frac{\sigma\Omega}{kT}\right)$.

So what is the difference primary difference here you will see one by one in the above equation Q_f represents as it did previously and the vacancy formation energy. But Q_m is the activation energy for the atomic motion along the grain boundary. So the motion is the lattice motion previous case but here it is motion along the grain boundary. The exponentials containing these terms have been incorporated into D_{GB}. All the exponential terms have observed into this constant I mean D_{GB} parameter which represents the effective grain boundary diffusivity or surface diffusivity if a single crystal is considered.

As indicated by above equation coble creep is more sensitive to gain size than Nabarro-Herring creep, how are we saying this? You can see that it is a d^3 terms here right so it is very important for the fine grained material thus even though both forms of creep are favoured by high temperature and low stress. Coble creep will be more important in very find grained material so this is a very presentable observation d cube the creep rate is inversely proportional to d cube. That means it is very much depend on the grained size.

(Refer Slide Time: 28:04)



Coble Creep

(a) Four grains in a two-dimensional hexagonal array before creep deformation.
(b) Following diffusional creep, one dimension of the grains is increased and the other decreased and "voids form between the grains.
(c) The voids are removed by grain-boundary sliding.

The extent of sliding is quantified by the distance $Y'Y"$, which is the offset along the boundary between grains 1 and 3 of the original vertical scribe line XYZ.

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

24

So now we see some schematic which will explain this coble creep in much more effectively what is shown here? These are the grains and which are subjected to high temperature deformation. You are seeing that you know in a x y z that line we were going to trace it as the deformation proceeds. You just look at this triple junction a, b, c, d there are four triple junctions we are going to trace as the deformation proceeds that is why it is marked here.

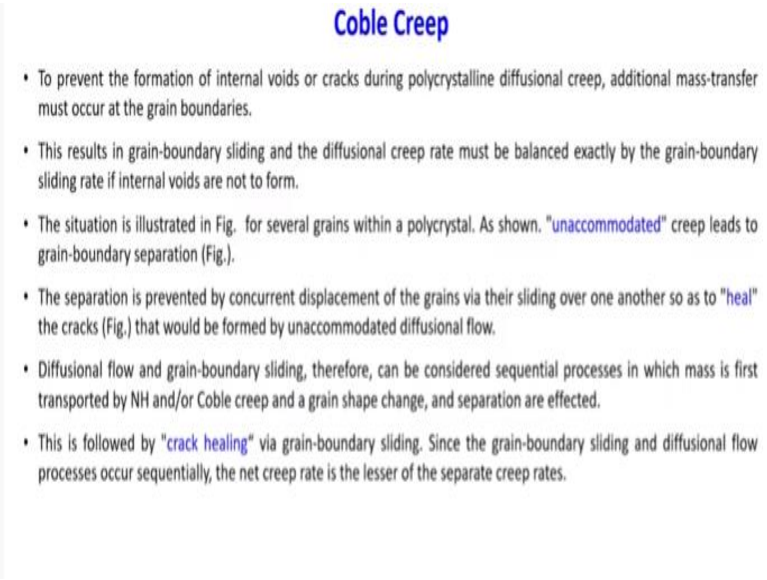
So grain (1),(2), (3), (4) after a deformation what happens? First we read this caption, four grains in a two dimensional hexagonal array before cream deformation following the diffusional creep 1 dimensional of the grain in increased and the other decreased and voids form between the grains. Suppose you assume that you know you pulling this tensile direction then what happens all this grain will try to elongate in this tensile axis.

Then because of this what happens? The voids are getting created here so how this is getting accommodated during the creep deformation. If voids are happening immediately then the material will fly fail right the creep deformation will result in the fracture because in the creep deformation we are just measuring only the strain not the fracture time. So how the deformation is proceeds with this? How this void formation is compensated? How it is accommodated? That is what is shown here.

So what is shown here the voids are removed by grain boundary sliding? We are introducing the term here grain boundary sliding. That means this grain 2 slides towards I mean this point junction b and the grain 1 is also trying to slide towards junction b so that is why you can see that there is a breakage in the x y this is a line becomes x, y′ and y′y double ′z. So it got split that means the glide 1 has just slide through this boundary and reach the point b that b becomes b′ now and a, becomes a′now.

Similarly this grain 4 and grain 3 they are also sliding along this grain boundary so then it becomes homogenous. So how will you understand this? The extent of sliding is quantified by the distance y, y double prime where is that y′, y ′′now gives the sliding distance how much the? Because it is the homogenous deformation each grain will slide the similar distance. Which; is the offset along the boundary between grain 1 and 3 of the original vertical stripe line x, y, z.

(Refer Slide Time: 31:40)



Coble Creep

- To prevent the formation of internal voids or cracks during polycrystalline diffusional creep, additional mass-transfer must occur at the grain boundaries.
- This results in grain-boundary sliding and the diffusional creep rate must be balanced exactly by the grain-boundary sliding rate if internal voids are not to form.
- The situation is illustrated in Fig. for several grains within a polycrystal. As shown. "unaccommodated" creep leads to grain-boundary separation (Fig.).
- The separation is prevented by concurrent displacement of the grains via their sliding over one another so as to "heal" the cracks (Fig.) that would be formed by unaccommodated diffusional flow.
- Diffusional flow and grain-boundary sliding, therefore, can be considered sequential processes in which mass is first transported by NH and/or Coble creep and a grain shape change, and separation are effected.
- This is followed by "crack healing" via grain-boundary sliding. Since the grain-boundary sliding and diffusional flow processes occur sequentially, the net creep rate is the lesser of the separate creep rates.

So how do we understand this? To prevent the formation of internal voids or cracks during poly crystalline diffusional creep additional mass transfer must occur and at the grain boundaries. Obviously if you want to avoid the voids or crack how to fill unless the diffusional flow happens this cannot be fill these results in grain boundary sliding and diffusion creep rate must be balanced exactly by the grain boundary sliding rate.

If the internal voids are not so this is a dynamical process it is not just a it has to take in place a quickly to avoid the void formation. So it has to balance these two rates has to balance with each other. The situation is illustrated in the previous figure for several grains within a poly crystal as shown un-accommodated creep lead to grain boundary separation. This is what the figure b that is where the voids and cracks forms along the boundary that is called un-accommodated creep.

The separation is prevented by concurrent displacement of grains they are sliding over one another so as to heal the tracks so we are it is kind of a nice description we are giving healing the cracks that would be formed by un-accommodated flow. First diffusional flow and grain boundary sliding therefore can be considered as sequential processes. The first diffusional flow causes the elongation and void formation and the subsequent grain boundary sliding heals it.

So there is no void formation prevails after this is what it means in which mass is first transported by Nabarro-Herring creep and our coble creep and a grain shape change and a separation are effected. So these are all sequence of events this is followed by crack healing via grain boundary sliding. Since the grain boundary sliding and the diffusional flow process occurs sequentially that net creep rate is lesser of the separate creep rates.

So this is quite understandable the net creep rate is considering all this activity Nabarro-Herring coble creep and then grain boundary slide. All these events have to be taken into account so that is why that is called a net creep rate which is lesser than the individual creep rate. So depending upon the stress and local stress and temperature and other facts so many other factors each mechanisms of the creep can dominate and the net one is much less than the individual events that is what it is.