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

Module No # 09
Lecture No # 46
Creep – IV

Hello I am professor S.Sanakaran in the department of Metallurgical and materials engineering.

(Refer Slide Time: 00:17)

Creep mechanisms involving dislocation and diffusional flow so we just look at the previous two cases as an independent mechanism. But normally materials have undergo creep accompany several mechanism together. So one such popular mechanism is creep mechanism involving dislocation glide as well as diffusion flow, let us see. The linear dependence of creep rate on the stress for a diffusional creep is not observed under the conditions of moderate applied stress instead the value of the stress exponent; m′ in the primary equation. what is the primary equation? If you recall, before even discussing all this mechanism, I just showed one basic equation for the all type of creep mechanisms, power law equation. So that is what I am just mentioning here is a primary equation. And where the stress exponent can prime ranges from about 3 to 8. Under these conditions creep involves a dislocations as well as diffusional flow that dislocation creep and the power law creep (PLC), it is called power law creep being the most common. The term power law creep arise because the creep rate various with the stress to the

power greater than unity, very important. So the power law creep also, you know coming to this dislocation, I mean sorry creep mechanisms because the creep rate varies the stress to a power greater than unity. A number of mechanisms have been proposed for PLC that is power law creep. There are so many mechanisms have been proposed for PLC, two among them are solute drag creep and climb glide creep. So there are several mechanism reported to literature but we just look at these two, which are quite familiar to us solute drag creep. What is solute drag creep? First let us look at this terminology I mean creep rate formulation.

$$\dot{\varepsilon}_{SD} = A_{SD} \left(\frac{D_{sol}}{b^2}\right) \left(\frac{\sigma}{G}\right)^2 \left(\frac{\sigma\Omega}{kT}\right).$$

So what is new in this? Almost everything is known to us because every creep rate has got some constant depending upon these specific microstructural geometry and which is taken into account. Whatever the specific micro structural features here what is the microstructural features we have to consider is the solute drag.

That means the interaction between dislocation and the solute has to be taken into account. Any geometry where the involvement of solute interacting with dislocation. This we have already seen, in the several occasions in one of the primary expression seen in the strengthening mechanisms and also dislocation dynamics we have seen. How they so the physics is the same so that is what I am going to say here. We even microstructural feature and the physics are the same rest all the common other parameters like you have σ/G, this term and then remove this $\sigma\Omega/kT$ term. They are all familiar to us that is what I am trying to say, so the other mechanisms that is dislocation climb-glide creep it is not that well understood as compared to solute drag creep as per the literature. But then the physics is not that different because we are talking about the Climb-glide so a dislocation-dislocation interaction that physics is much more, you know familiar to other mechanisms. So, what is involved here you can see that the

$$\dot{\varepsilon}_{CG} = \left(\frac{A_{CG}D_L}{h^{3.5}M^{1/2}}\right) A_{CG} \left(\frac{\sigma\Omega}{kT}\right).$$

So what this particular model where, considered is M that is number of dislocation sources per unit in area. So, for example the most familiar dislocation source is a frank read source, which comes as a known content to open site. So such loop we considers that is number of dislocation source for per unit area that is M and h is the distance between the each sources it could be on same different level of paint so that is h, and the l is the distance of the loop so that is what it is. So it involves these parameters so basically it takes care of all the microstructural scale and its parameter and rest is the again the stress assisted energy term and thermal energy term that the

ratio that is formed, so this keeps coming so all the power law creep models have in common a correlation coming in between a microstructural scale and the applied stress that results in the greater stress dependence of climb-glide dependence combined to diffusional creep. So this is very important all the power law creep models whether it is you know dislocation glide or solute drag so many models have been reported depending upon material system and also the specific conditions. So they are all emphasizing one point primarily is the greater stress dependence of Climb-glide process creep process as compared to diffusional creep so the stress dependence to the primary focus here.

(Refer Slide Time: 07:17)

Creep Mechanisms Involving Dislocation and Diffusional Flow

- In spite of the apparent diversity of the formulations of the several creep rates presented in this section, all of them can be expressed in a similar form, i.e.,

$$\dot{\varepsilon} = A\left(\frac{D}{\Omega^{2/3}}\right)\left(\frac{\sigma}{G}\right)^{m'}\left(\frac{\sigma\Omega}{kT}\right)\left(\frac{b}{d}\right)^{n'}$$

In Eq. the last three parameters on the right hand side are dimensionless as the constant A. The $\left(\frac{D}{\Omega^{2/3}}\right)$ has units of s^{-1} i.e., it has units of creep rate. The ratio $\frac{\sigma\Omega}{kT}$ is the ratio of a mechanical to a thermal energy. The parameter $\left(\frac{b}{d}\right)^{n'}$, where b is the Burgers vector (b is also equal to $\Omega^{1/3}$) represents a grain size- dependence of the creep rate; The term $\frac{\sigma}{G}$ is the ratio of the applied stress to the shear modulus; this ratio is important in determining the rate of power –law creep

Mechanism	Favored by	A	M"	N'
Nabarro-Herring creep	High temperature, low stress, and fine grain sizes	7	0	2
Coble creep	Low stress, fine grain sizes and temperatures less than those for which NH creep dominates	50	0	3
Power-law creep	High stress	*	2-6*	0

* The terms A and m" are strongly dependent on the mechanism controlling power –law creep at the substructural level. Values of A can range from several to several million

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005   27

In spite of the apparent diversity of the formulations of the several creep rates presented in the section, all of them can be expressed in a similar form what is that? So most of the mechanisms can be represented in the general form like creep rate that is $\varepsilon^{\cdot} = A\left(\frac{D}{\Omega^{2/3}}\right)\left(\frac{\sigma}{G}\right)^{m'}\left(\frac{\sigma\Omega}{kT}\right)\left(\frac{b}{d}\right)^{n'}$.

In the equation the last three parameters on the right hand side are dimensionless as a constant A. Similar to A so these three parameters also dimensionless the $\left(\frac{D}{\Omega^{2/3}}\right)$ as a, units of per second that is it has units of creep rate. The ratio $\sigma\Omega/kT$ is the ratio of mechanical to thermal energy this we have already seen. The parameter $\left(\frac{b}{d}\right)^{n'}$, where b is the burger vector, b is also equal to $\Omega^{1/2}$ represented a grain size dependence of the creep rate.

The term $\left(\frac{\sigma}{G}\right)^{m'}$ is the ratio of the applied stress to the shear modulus this ratio is important in determining the rate of power law creep. So this is you can see that m' is there stress exponent okay that is what it says the ratio is important in determining the rate of power law creep. So what is the significance of these stress exponents and other m' and all that you can see that. It is now tabulated here for Nabarro-Herring creep of mechanisms which is favored by high temperature, low stress and fine grains sizes.

You have the value of A is 7 and m'' is 0 and n' is 2 which is small m which is not a M, m there is a typo here(09:22) For a coble creep which is favoured by low stress fine grain sizes and temperature less than those for which Nabarro-Herring creep dominates. You see the value of A is 50 and m'' is 0 and n ' is 3. So power law creep in other hand which is always favored by very high stresses we will talk about the A value in a minute but then you see that it varies m ' varies between 2 to 6 for a power law creep and n' is 0. The terms A and m'' are strongly depend on mechanisms controlling power law creep at the structural sub structural level. So kind of you know, it heavily dependent on the microstructural features that develop during this deformation that is what you have to understand that. Values of A can range from several to several million so it is quite complex there nothing can be predicted as such.

So this is quite complicated because of the so many parameters involved depending upon the deformation condition. So this particular slide is the kind of summary for all creep mechanisms so any creep mechanisms you think off or new material always a combination of mechanisms takes place right dislocation glide and then diffusional flow and power law. So, all of them can be happen in a sequence manner so you need a very comprehensive idea about a creep head. So that is why this equation is useful so this is a general form depending upon a situation at the micro structural scale and what dimensions this is so that will be taken care by this first term the rest of the three terms will be almost same for the material involving different mechanisms in a sequence or parallel whatever maybe the case. So it gives you a overall idea about the creep rate in different materials.

(Refer Slide Time: 11:52)

Deformation Mechanism Maps
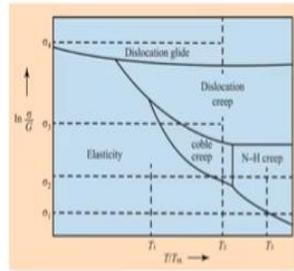
- A schematic deformation mechanism map. The axes of the map are homologous temperature (T/T_m) and stress (normalized by the shear modulus).
- The stress-temperature combination determines the primary deformation mode.
- At the boundary lines, deformation is due equally to two mechanisms and, at the intersection of the lines, to three mechanisms.

- A deformation mechanism map has axes of homologous temperature $(T/T_m$ where T is the absolute temperature and T_m is the absolute melting temperature of the material considered) and stress.
- Several deformation mechanism regions are included in the figure; these are the dominant deformation mechanisms at stress temperature combinations for which they are listed.
- The lines separating the regions represent stress-temperature combinations at which two mechanisms contribute equally to material deformation.
- Similarly, triple points-the intersection of three such lines-represent a particular stress-temperature combination at which three mechanisms contribute equally to the deformation.
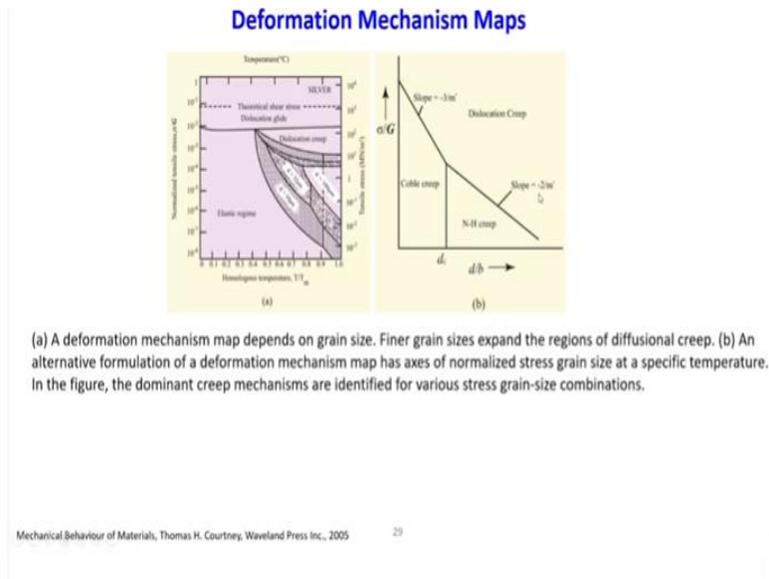
28

So now we will look at something called a deformation mechanism maps so we are looking at different mechanism maps how do we comprehend the idea? How do we summarize? You see this plot is quite popular plot deformation which is the lnσ that is stress normalized will be shear modulus G and the temperature normalize the melting point that is (12:17) with the temperature and then you see the all the deformation. I mean the creep mechanisms are demarked with different different boundary so dislocation glide and elastic region and the temperature T_1 and T_2 you have a coble creep, Nabarro-Herring creep, relatively high stresses and high temperatures. You have dislocation creep and very high stresses and relatively a low temperature stress it is only a dislocation glide. So it gives an idea what kind of mechanisms one can look, suppose of it traces this, If I start deforming this or this temperature keeps on increasing the stress how I have to overcome or I will come across different creep mechanisms. So it gives us an idea about it a schematic deformation mechanism map, the axes of the map are homologous temperature and the stress normalized by the shear modulus. The stress temperature combination determines the primary deformation mode obviously, stress temperature combination is it is key for a creep.

At the boundary lines the deformation is due- equally to two mechanisms so any boundary we have the possibility is 2 or even to 3 mechanisms there is a triple junction then you have possibility of coble Nabarro-Herring and then other or it is very clear. It could be a dislocation creep or to coble or could be Nabarro-Herring creep. So it is completely in this triple junction it is the elastic deformation.

A deformation mechanism map has axes of homologous temperature but this is already known. Several deformation mechanisms regions are included in the figure these are all dominant deformation mechanism at the stress temperature combinations for which they are listed. The lines separating the regions represent stress temperature combination at which two mechanisms contribute equally to the material deformation, this also we have seen. So this is again a redundant statement what I have already shown here.

(Refer Slide Time: 14:45)

(a) A deformation mechanism map depends on grain size. Finer grain sizes expand the regions of diffusional creep. (b) An alternative formulation of a deformation mechanism map has axes of normalized stress grain size at a specific temperature. In the figure, the dominant creep mechanisms are identified for various stress grain-size combinations.

Another, very interesting information about this, is people have looked at beyond the influence of stress and temperature. And here what you see here is the different grain sizes. So for the different grain sizes how is the regions get modified along the this is we are talking about 100 micron to 32 micron and the 10 micron how this boundaries are, you know bit changed. So that means a grain size significantly influence the slip creep behavior of course it is the (15:24) a given stress and temperature combination.

So that is something you have to appreciate a deformation mechanism map depends on the gain size. Finer grain size is expand the regions of the diffusional creep so what is being consumed by region wise is the diffusion creep is getting reduced the region is getting reduced. Then alternative formulation of a deformation mechanism has the axes of normalized stress grain size at a specific temperature that is given here this is for one temperature then what happens?

The dominant creep mechanisms are identified for various stress grain size combinations so here we are taking about the grain stress versus the stress and you can see that how the different mechanisms will apply a role. So this is basically for a constant temperature you can look at what are the mechanisms so this is another way of looking at which creep mechanism will dominate for influence of grain size.

(Refer Slide Time: 16:31)

Engineering Estimates of Creep Behavior

- The fundamentals underlying extrapolation techniques are contained in the empirical Eq. relating strain rate to stress and temperature. On taking natural logarithms of both sides of this equation, it can be written as

$$In\ \dot{\varepsilon} = \frac{-Q_c}{RT} + g(\sigma)$$

where $g(\sigma)$, a function of the applied stress, is the natural logarithm of all terms on the right-hand side of Eq. excepting the term $\exp(-Q_c/RT)$.

- Stress-rupture tests, in which the time to (fracture) rupture, t_f, is measured as a function of the stress and temperature are commonly performed for short-time material evaluation.

- Provided t_f is inversely proportional to the steady-state creep rate, we can substitute $t_f = k/\dot{\varepsilon}$ in Eq. to obtain

$$In\ t_f - In\ k + g(\sigma) = \frac{Q_c}{RT}$$

Or

$$T[In\ t_f + g(\sigma) - In\ k] = \frac{Q_c}{R}$$

- As $\frac{Q_c}{R}$ is a material constant, the terms on the left-hand side of Eq., which are related to the Larson-Miller (LM) parameter, can be used to assess a material's creep resistance. The parameter is frequently expressed as

$$LM = T[\log t_f + C]$$

where $\log t_f$ represents the logarithm to the base 10 of t_f (when it is expressed in hours) and C is an empirically determined constant

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005   30

So now we come to very important parameter the engineering estimates of creep behavior. How people use the engineering data I mean the creep data? As I said in the beginning of the creep class so the steady state creep that is being know that is the design parameter so how it is being used, we have to just? The fundamentals underline extrapolation techniques are contained in the empirical equation relating strain rate to the stress and the temperature.

So what is that again? I will refer to the basic equation, the stress exponent equation strain rate the very basic equation we are going to take. On taking natural logarithm of both side of that equation it can be written like this (()) (17:25) $ln\varepsilon^{\cdot} = \frac{-Q_c}{RT} + g(\sigma)$, where $g(\sigma)$ a function of applied stress is the natural logarithm of all types of right hand side of the equation excepting to the term exponential $-Q_c$/ R T.

Stress rupture test in which the time to fracture or rupture t_f is measured as a function of stress and temperature are commonly performed for short time material evaluation this point we have discussed in the beginning. Provided t of this inversely proportional to the steady state creep rate

we can substitute $t_f = k$ by epsilon dot in that equation. So we can rewrite this lon t of $ln t_f - \ln k + g(\sigma) = \frac{Q_c}{RT}$.

$T[ln t_f - \ln k + g(\sigma)] = \frac{Q_c}{R}$ as the Q_c / R is a material constant. The terms on the left hand side of the equation which are related to the Larson-Miller parameter this is popularly known as LM parameter this is called Larson-Miller parameter can be used to assess a material creep resistance the parameter is frequency expressed as LM = T[log t_f + C] so this is the Larson-Miller parameter.

So this should being used that is the question where log t_f represent the logarithm to the base 10 of t f and it is expressed in hours and C is an empirically determined consent.

(Refer Slide Time: 19:29)

Engineering Estimates of Creep Behavior
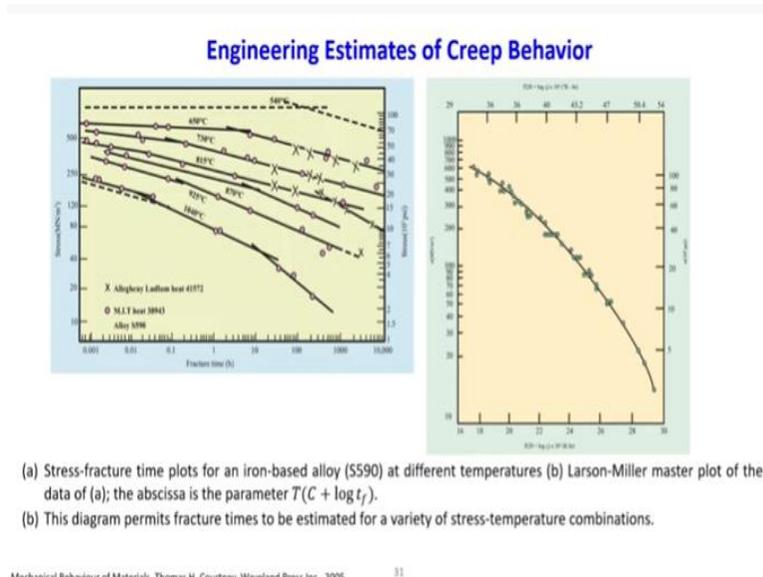
(a) Stress-fracture time plots for an iron-based alloy (S590) at different temperatures (b) Larson-Miller master plot of the data of (a); the abscissa is the parameter $T(C + \log t_f)$.
(b) This diagram permits fracture times to be estimated for a variety of stress-temperature combinations.

So now we look at the stress versus the t f it is (19:36) for the different temperature. You can see for a particular alloy system commercial alloy system is given here in this illustration. And then stress fracture time plots for iron based alloy S590 at different temperatures and then the Larson and Miller master plot of the data of a the abscissa is the parameter T[log t_f + C] so this is LM parameter and this is a stress, so what you are seeing is from these plots then you will be able to calculate the time required to fracture. The diagram permits fracture times to be estimated for a variety of stress temperature combinations. So this is one very crude way of I mean very simple I would say why I am saying crude means? Because there are so many other things complications

being takes place because this is only empirical relation. So it gives the rough idea about the time to fracture for any item as well (()) (21:03), So this is one way of looking at it but there are several other methods advanced methods but my intention is not to get into all the details. Because it is completely out of this performance course but then at least how but since I said that the creep rate is defined parameter how people try to use that basic equation to arrive at the last parameter. So that was my only intention not do any other calculation or getting into the details of the advancement of this estimation.

This is very old and reported in most of the text. So will stop here we will continue from that creep behavior of amorphous and solute estimation details in the next class thank you.