Mechanical Behavior of Materials
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Module No # 10
Lecture No # 48
Creep – VI

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

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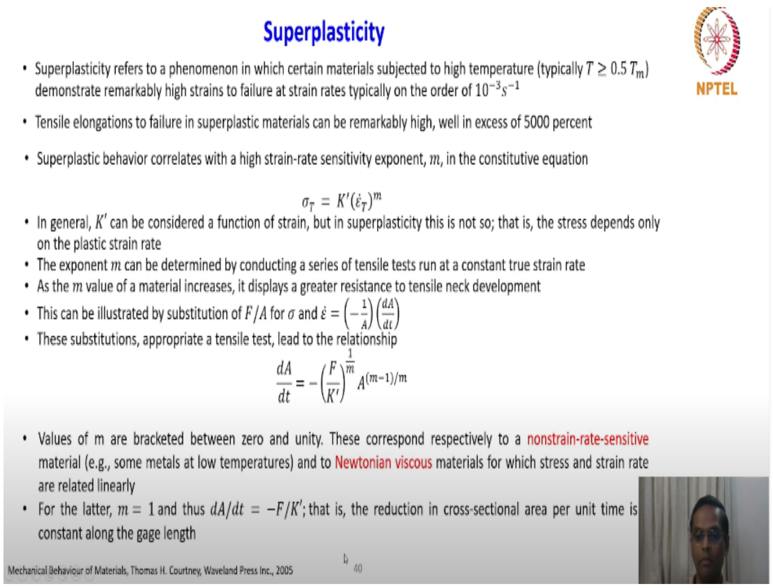

So now we move on to the one more final topic in the high temperature deformation called the super plasticity. We did have some introduction about this topic when we talked about right the stress exponent. Or while discussing the high temperature deformation we introduced a term called the strain rate sensitivity index or **s**train rate sensitivity. And we compared that parameter with the strain hardening exponent also. So now we will just look at little more detail about this concept. It is a phenomenon so super plasticity refers to a phenomenon in which certain materials subjected to high temperature typically temperature (greater than or equal to 0.5 T_m), demonstrate remarkably high strains to failure at strain rates typically in the order of 10 $^{-3}$ per second. So we are talking about material exhibiting remarkably high deformation uniform elongation, I would say uniform elongation without a necking that is called super plasticity, but that happens only with certain conditions your temperature of deformation should be in the order of 0.5 T_m and then strain rate also should be in the very slow strain rate. And we will later we will see that it will also have some influence on grain size. Tensile elongation to failure plastic material can be remarkably high well indexes of 5000%. So we are not talking about 100 or 200 it is you know in the order of thousands.

Superplastic behavior correlates with the high strain rate sensitivity exponent m in the constitutive equation. So the constitutive equation is we have already seen in the high temperature deformation $\sigma_T = K'(\dot{\varepsilon_T})^m$ $\sigma_T = K'(\dot{\varepsilon_T})^m$ is the strain rate to the power m. So you can also recall this you know similar equation we just seen as a fundamental equation a basic constitutive equation for a creep deformation, where we related the strain rate versus stress and then stress exponents, so it is here it is stress, strain rate and then strain rate exponent, I mean strain rate exponent. So they are all very closely related you can calculate that. In general K′ can be considered a function of strain but in super plasticity this is not so. That is the stress depends only on the plastic strain rate. The exponent m can be determined by conducting a series of tensile tests run at constant true strain rate. So, this plot also we have already seen how to determine the m the exponent? While we looked at the high temperature tensile deformation we specifically spent a lot of time on effect of strain rate and temperature in that context we have already seen this so I will not repeat that here again. As the m value of the material increases it displays a greater resistance to tensile net development. So this particular point you have to remember the value of m is an index of it is resistance to necking. So, this point we discussed already but you have to keep in that mind the depending upon the value you can just have a assessment about what mechanisms will follow m also will differ from the mechanisms we will see. This can be illustrated by substitution of by A force by area for A and $\dot{\varepsilon}$ = (-1/A) (dA/dt). So we can rewrite this equations for an appropriate tensile test that will relate to a relationship like this $(dA / dt) = -(F/K')^{1/m} A^{m - 1 / m}$ so this is. Values of m are bracketed between 0 to unity these correspond respectively to a non-strain rate sensitive material example some metals at low temperature to Newtonian viscous materials for which the stress and strain rate are related linearly. So, it covers the entire spectrum this just before I just said depending upon the mechanisms right or the basic structure. That means a non-strain rate sensitive materials metals at low temperature will behave you know highly brittle so, that means same strain rate sensitivity is 0 that is why it says 0 to unity or on the other hand if m = 1 then the material will be behave like a Newtonian flow it will adopt Newtonian flow the Newtonian stress material. So this is very important so one extreme to other extreme 0 to 1 m value. For the latter m = 1 and that d A/d t = -F/K′ that is the reduction in cross sectional area per unit time is a constant along the gage length, so this is very interesting so there is no necking so then what happen so the cross sectional area the reduction in cross sectional per unit time is a constant, along the gage length when m = 1 very interesting point.

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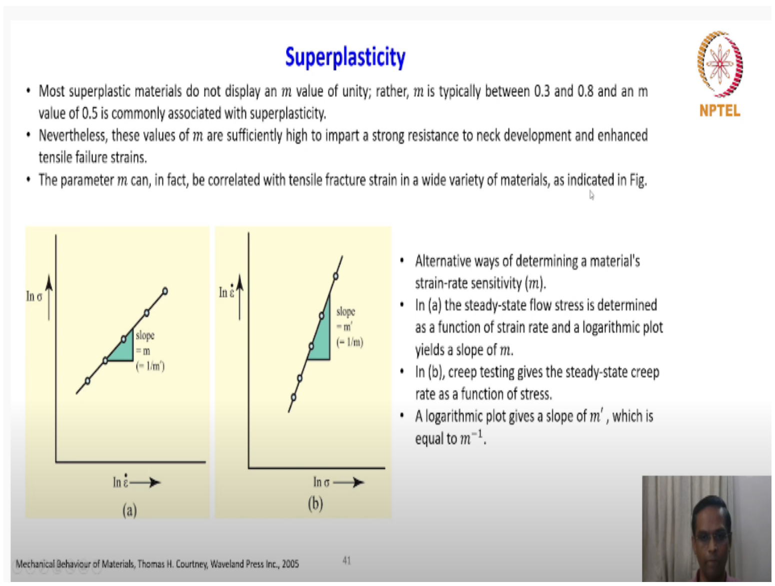

So how the m is determined there are two ways alternate ways of determining a materials strain rate sensitivity m. A first is stress versus strain rate plot in a steady state flow stress is determined as a function of strain rate and the logarithmic plot is a slope m. So, this is a well-known idea on the other hand a strain rate versus σ. So, this also we have looked at in the creep deformation right. So if you the basic constitutive relation I said you can write it in two forms that is σ is related to strain rate and strain rate related to σ. So both the terms have the exponents so this is what it is so m is nothing but I mean m′is nothing but 1/m that is what it is. So in the b the creep testing gives the steady state creep rate as a function of stress so typically in a creep test you will get this and then here is a high temperature tensile test you will get that. The logarithmic plot gives a slope of m′, which is equal to inverse of m.

Most superplastic materials do not display an m value of unity rather m is typically between, 0.3 to 0.8 and m value of 0.5 is commonly associated with super plasticity. Nevertheless these values of m are sufficiently high to impart a strong resistance to neck development and enhanced tensile various strings. The parameter m can in fact be correlated with the tensile fracture strain in a wide variety of materials as indicated in the figure this we have seen that.

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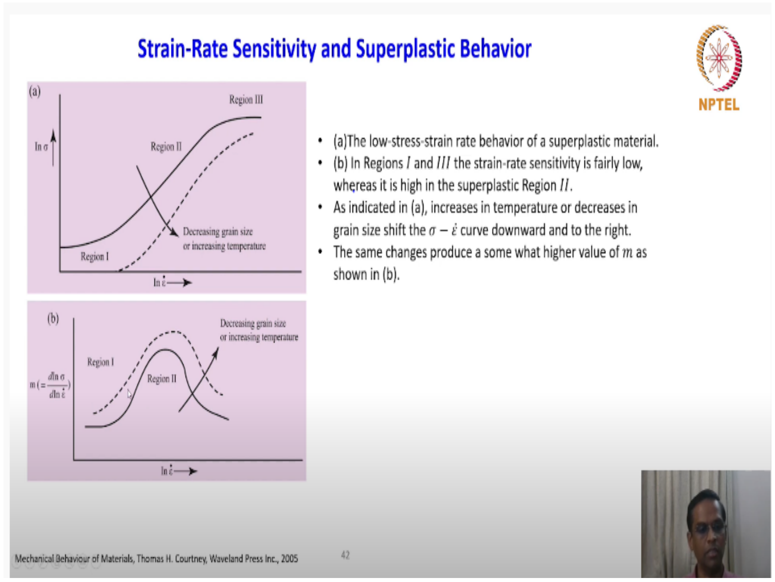

So what is this plot shows this? Plot shows the σ versus the strain rate plot for a superplastic material. So the superplastic material going to involve this kind of behavior so this curve is divided into three regions. Region 1, region 2 and region 3, region 1 and 3 the strain rate sensitivity is fairly low so the plot is shown here before I just read it before I show the plot. So this plot is m versus strain rate block so you can see that σ versus strain rate shows 3 regions and m versus strain it shows also 3 regions and the strain rate sensitivity for region one and region 3 is fairly low. Whereas it is high in this superplastic region 2, so only in the region 2 the strain rate sensitivity index is high. So that means this plot this region steady state region. So this is one so as indicated in a increases in temperature or decreases in grain size shift σ versus epsilon dot curve downward and to the right.

So increases in temperature and decreasing in the grain size is shifting the curve downward and to right. So it is coming down and then shifting to the right so this is how the influence of temperature and grain size on this superplastic behavior is shown here. And you can clearly see that you know as a grain says increases you can see that there is an increase in the strain rate sensitivity index, so this is also very important.

The same change is produced on a somewhat higher value of m as shown in b. So this is a general behavior of super plasticity and it is response to the m.

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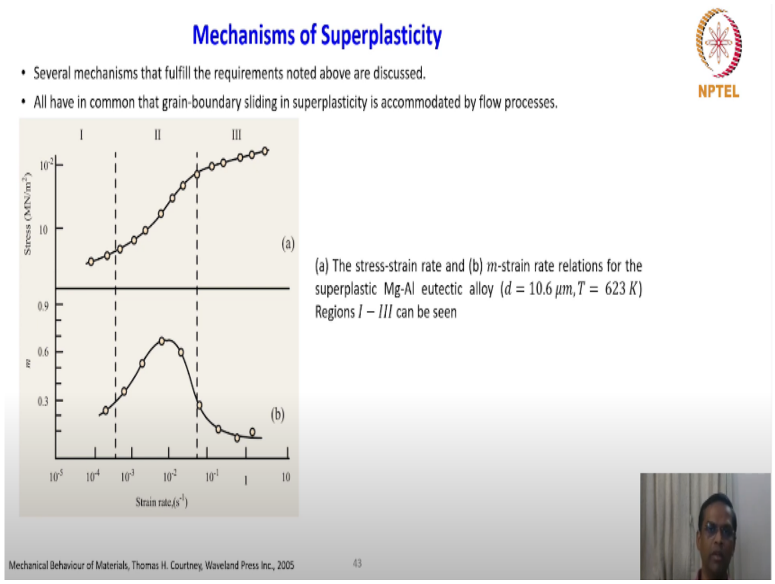

Now we will see one example several mechanisms that fulfill the requirements noted above are discussed. All have in common that grain boundary sliding in super plasticity is accommodated by flow processes. So this is one typical plot observed for a magnesium aluminum eutectic alloy with the grain size 10.6 micrometer tested at 623 kelvin. So what, is schematically shown in the previous slide it is also experimentally occured in terms of stress versus strain rate as well as m verses strain rate plot.

So what is that we are talking about so for this super plasticity several mechanisms like creep we discussed several mechanism right. For super plasticity also there are several mechanisms are posed depending upon the experimental condition and the materials and other parameters and so on. And all have in common that the grain boundary sliding is involved and this is not just grain boundary sliding but is accommodated by a flow processes.

There are different type of flow processes are accompanied by the grain the only sliding so what you need to understand is super plasticity mechanism involves primarily grain boundary sliding accommodated with other flow process. We will look at some of the primary mechanisms which is well known just for to for the completion.

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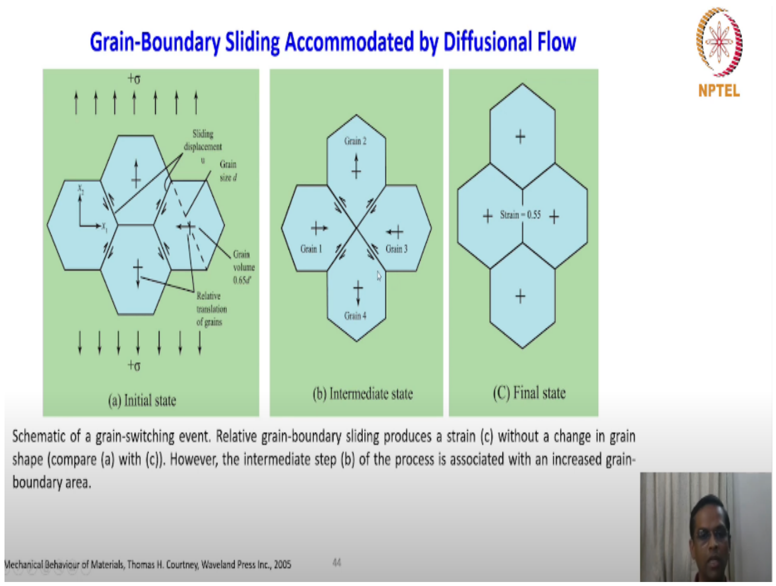

So this is a grain which is there in the initial state. this is one model, what is shown here is? The grain is being subjected to uniaxial tension in this manner and then what is shown here is? How this grain boundary you know displacements are accommodated? That is what shown here so this is a hexagonal schematic which also measures of grain size. And grain volume the model assumes to be 6.65 d′ and the relative translation of grains. So that this 2 grains are trying to move up and this grain is trying to come here because of you know the shear forces acting on this boundary so it goes to the intermediate stage like this. So grain 1, 2, 3, 4 so these interfaces have become like this and finally it becomes like this. So what is that we are seeing? It is kind of a, the grains which are in the horizontal form and now it become a vertical form. It is a kind of a grain switching that is what the model also describes.

Schematic of a grain switching event relative grain boundary sliding produces a strain in this. Eventually what happens? Because of this sliding event without you know just by gain switching it also accommodates the strain of 0.55 according to this model, without change in the grain shape. So if you look at the individual grain shape they are all the same so without changing the grain shape it is able to absorb so much of energy because of the grain boundary sliding limit.
However, the intermediate step of the process is associated with an increased grain boundary area. If you look at this grain boundary in the intermediate stage so obviously this is increased and then finally like this.

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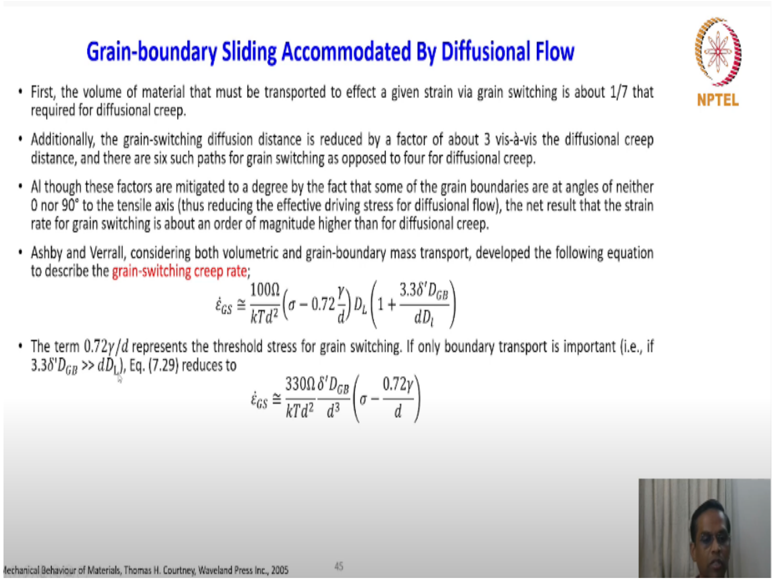

So how do we understand this, first the volume of material that must be transported to affect a given strain via grain switching is about 1/7 that are required for the diffusional creep. So we are now comparing the creep mechanism, because these mechanisms are very close to creep deformation. So, this is compared with the diffusional creep. Additionally, the grain switching diffusion distance is reduced by a factor of about 3 vis-à-vis for diffusional creep distance and there are six such paths for grain switching as opposed to for for diffusion creep, See all these points are I mean narrated here to accept the idea of this model they compare with the diffusion that what are the parameters what are the constraints they? Compare to this diffusional creep and what is this? What are the microstructural events or the mechanisms or steps which support the idea of grain switching that is how you have to look at it.

Although these factors are mitigated to a degree by the fact that some of the grain boundaries are at angles of neither 0 nor 90° to the tensile axis. Thus, reducing the effective driving stress for the diffusional flow. The net result that the strain rate for; a grain switching is about an order of magnitude higher compare to the diffusion creep. The only difference coming out from the diffusional creep, I mean the sense which is a slightly contrasting requirement is that the strain rate for the grain switching is about is higher compared to the diffusional creep. So, the model is proposed basically by Ashby and Verrall, considering both volumetric and grain boundary mass transport developed the following equation to describe the grain switching creep rate. So the above mechanism is called grain switching creep rate, which is given by this expression. So like we have seen several strain rate during creep. So similarly they have used this $\dot{\varepsilon}_{GS} \cong \frac{100\Omega}{kTd^2}\left(\sigma - 0.72\ \frac{\gamma}{d}\right) D_L \left(1 + \frac{3.3\delta D_{GB}}{dD_t}\right)$ $\dot{\varepsilon}_{GS} \cong \frac{100\Omega}{kTd^2}\left(\sigma - 0.72\ \frac{\gamma}{d}\right) D_L \left(1 + \frac{3.3\delta D_{GB}}{dD_t}\right)$.

It is nothing none of this parameter is new if you just compare the previous mechanisms all these parameters, already we have seen. So, do not have to worry about this. Just to get an idea how these mechanisms are you know understood just for the completion I just want to bring all this information. So that you can refer it and then read it further if you are interested. The term $0.72\ \frac{\gamma}{d}$ $0.72\ \frac{\gamma}{d}$ represent this threshold stress for the grain switch so the grain switching mechanism is not just going to happen for all the stresses people are talking about threshold stress. So, beyond this certain stress only this is going to happen if only boundary transport is important then this term $3.3\delta D_{GB}$ $3.3\delta D_{GB}$ which is greater than the dD_L. So the equation the above equation will reduce to this point of the equation.

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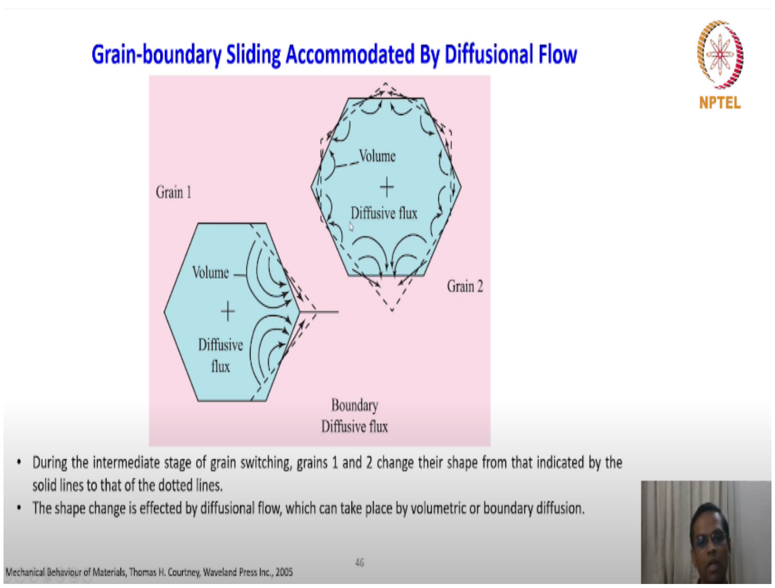

So what happens in the intermediate stage that also we will show here, so during the intermediate stage before the complete grain switching what happens? Grain 1 and 2 change their shape from that indicated by the solid lines to that of the dotted lines. So first, the initial grain is like this with the solid line. And because of the volume and diffusion flux this becomes like the dotted line. In both the cases the solid line becomes a dotted line which is due to the volume flux which is nicely shown by this arrow.

You can just imagine it is logically it looks very good if you really take all, these arrows then this dotted line will automatically will emerge that is the good thing about this schematic. If you just follow the arrow you will land at the dotted line. So, the grain 1 and grain 2 will become like this and then these two lines if you join then you will get that final switching. The shape change is affected by diffusional flow which can take place by volumetric and boundary diffusion so this is a called volumetric and boundary diffusion flux. So this is nice schematic.

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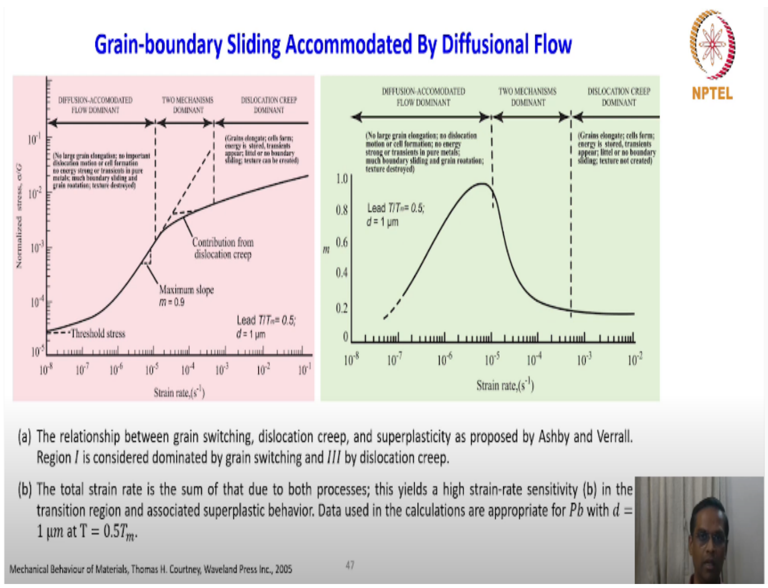

So what Ashby and Verrall, finally says that you know? If you plot the normalized stress versus strain rate and then if you generate this superplastic deformation curve. Then they divide this region 1, 2, 3 and associated that into different kind of mechanisms. So this is what it is written here the relationship between grain switching dislocation creep and super plasticity as proposed by Ashby Verrall. Region 1 is considered dominated by the grain switching and three by dislocation creep. So, the region 1 where you know it is just above the threshold stress then only the grain switching can take place. So, which is involving no large grain elongation no important dislocation motion or cell formation no energy strong or transient in the pure metals much boundary sliding and grain rotation texture destroy. So, all this small, I mean not small I mean different parameters, microstructural parameters which supports the diffusional accommodated flow. So, they propose that the region one is dominated by the diffusion accommodated flow which is devoid of all these microstructural points. No large grain elongation no cell formation and so on. And in the intermediate stage there are two mechanisms dominant so what is second

mechanics? Second mechanism is a dislocation feed dominant that means grains elongates, cell form, energy is stored transients appear a little or no boundary sliding texture can be created.
So, this is a little high stress event, right. So that means the dislocation creep dominates here as compared to diffusion. So in between the two mechanisms dominate. So that is what it is shown here. So in fact this is the slope is also compared between, where you know dislocation creep contribution is there and the other one is we will see that next one, then we will discuss this. So, this is again m versus strain rate same idea and what is shown here is?
This is for the lead this data is I mean, similar I mean appears to be match very well with this data the grain size is about a micron and then you can see this plot similarly. So where you see the grain, region 2 is here which both the mechanism is supposed to be dominant. The total strain rate is a sum of that due to both processes this yields a high strain rate sensitivity that means. So when you say the both dominant so you can see that almost it is you know it is the peak where the strain rate sensitivity is the maximum that is what is shown here.

So it takes all the way up to maximum to the lower value of this end. In the transition region and the associated superplastic behavior of light data used in the calculations are appropriate for lead with the grain size of 1 micrometer at 0.5 T_m. So what I just wanted to show was? That some basic idea about superplastic deformation and their mechanisms important parameters and some microstructural feature, just it can be just an introduction to the phenomena.
All that you have to appreciate is this is also very close to the creep deformation, that is why most of the semi empirical relations several of them we have seen. And then this deformation is also similar to I mean the strain rate expression is similar to one of the creep deformation empirical relations. And this; case study of you know superplastic behavior of a lead clearly shows what we have already seen in the schematic.

And this is an actual superplastic behavior it gives you an idea about the phenomenon. This is what my intention I will stop here and we will continue in the next lecture thank you.