Creep Deformation of Materials
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Mechanisms of Creep Part II

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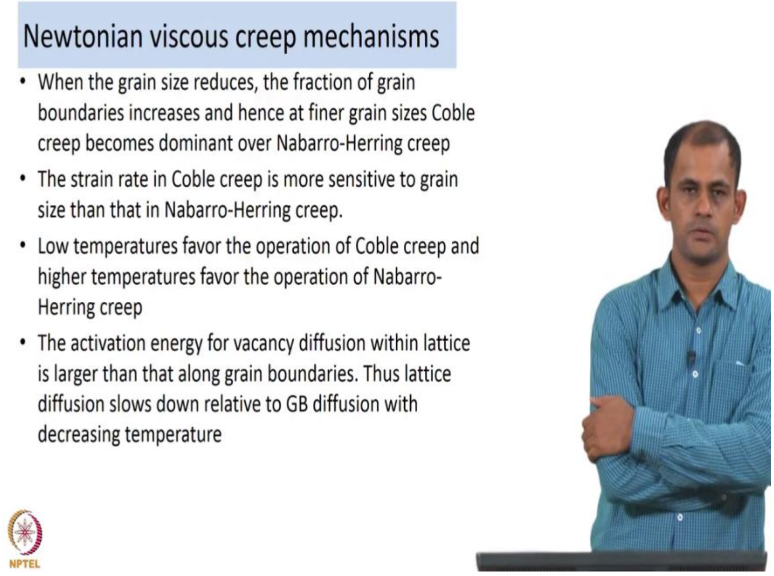

So we were talking about Nabarro-Herring and Coble creep and we were talking about how low temperatures favor the operation of Coble creep and high temperatures favor the operations of Nabarro-Herring creep. So which means as the temperature increases, you will slowly move away from Coble creep controlled creep deformation to Nabarro-Herring creep controlled deformation.

So how do you know at which temperature this transformation or transition from Coble creep controlled deformation to Nabarro-Herring controlled deformation would happen? So it is possible to determine that critical temperature or transition temperature at which the transition from Coble creep controlled deformation to Nabarro-Herring creep control deformation can happen.

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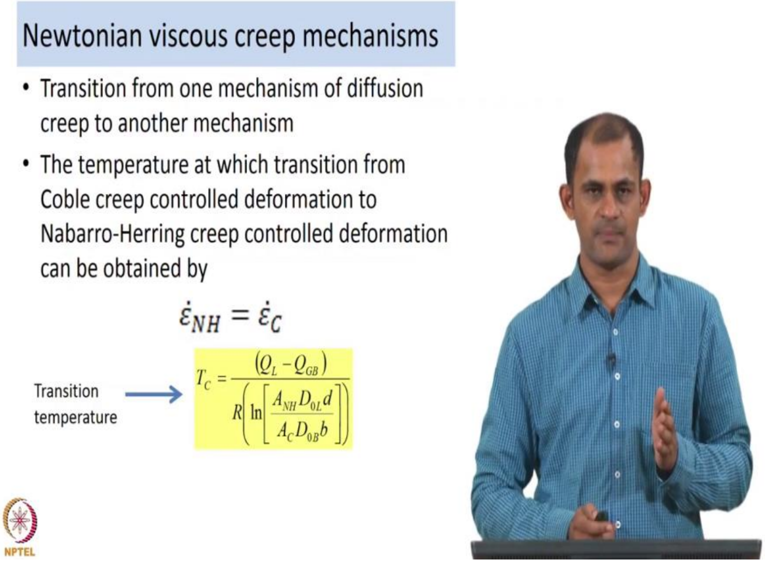

So this transition temperature can be obtained by equating the strain rates

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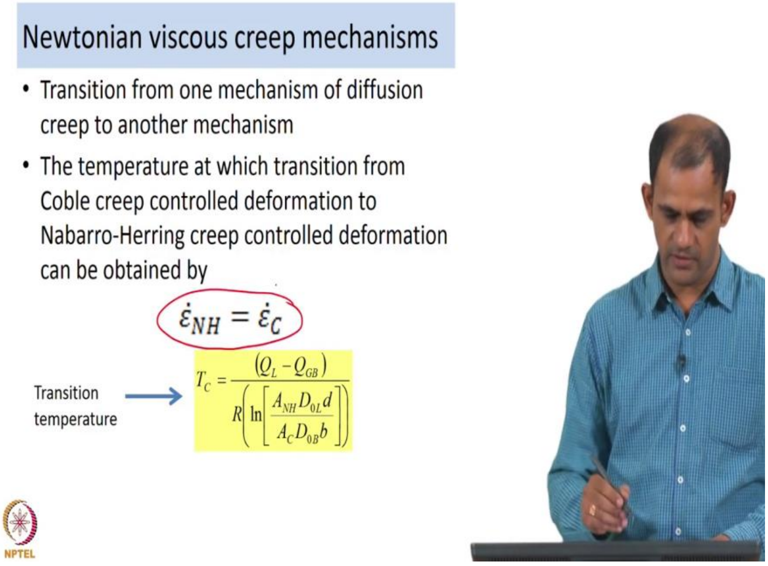

of deformation of Nabarro-Herring creep and Coble creep.

So as the material moves or starts deforming by Nabarro-Herring creep instead by Coble creep there is going to be a certain temperature where both Nabarro-Herring creep and Coble creep controlled deformation is going to be equal.

So if you do that, then you are going to arrive at this temperature T c which is equal to Q L minus Q g b and divided by these terms. So here D O B is also equal to,

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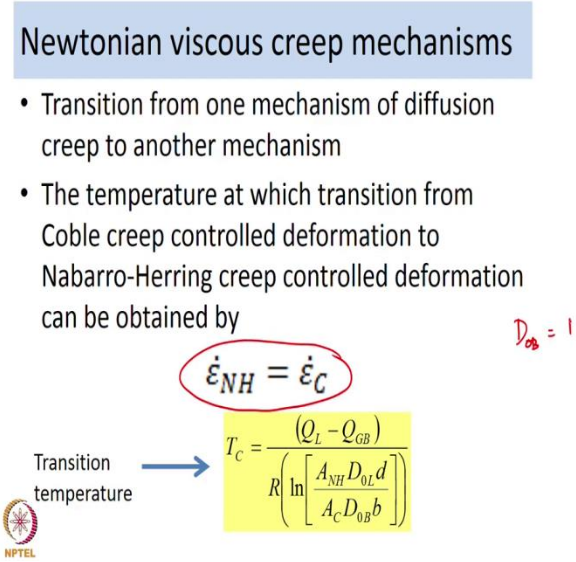

is basically the diffusion coefficient for grain boundary diffusion. And D O L is the

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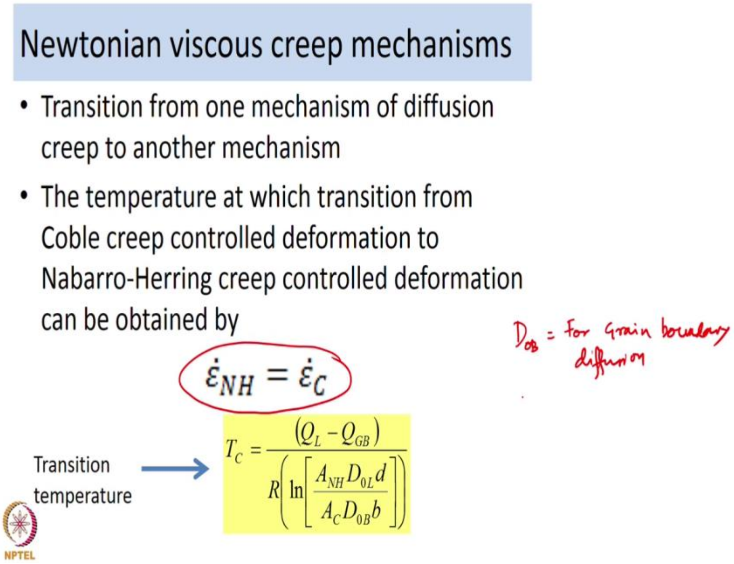

grain boundary coefficient; it is the diffusion coefficient for lattice diffusion.

And like I mentioned earlier,

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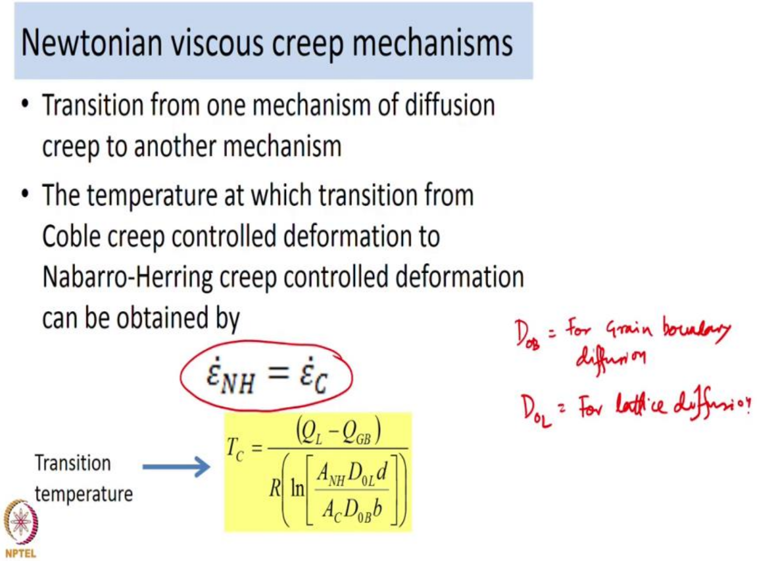

Q L is the activation energy for lattice diffusivity and Q g b is the activation energy for grain boundary diffusivity. Now similarly we also spoke about how grain size is important.

We said as the grain size becomes finer and finer the contribution of Coble creep to the deformation is going to be higher. So similar to critical temperature there is also going to be a critical grain size at which the deformation is going to move away from say Nabarro-Herring controlled deformation to Coble creep controlled deformation.

So how do you determine

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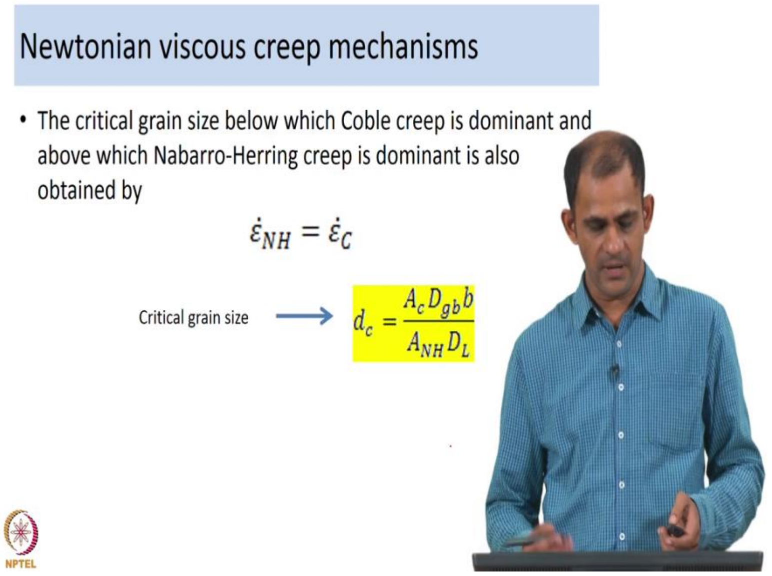

the grain size, the critical grain size at which such a transformation would happen?

Well we apply the same principle, essentially we equate the strain

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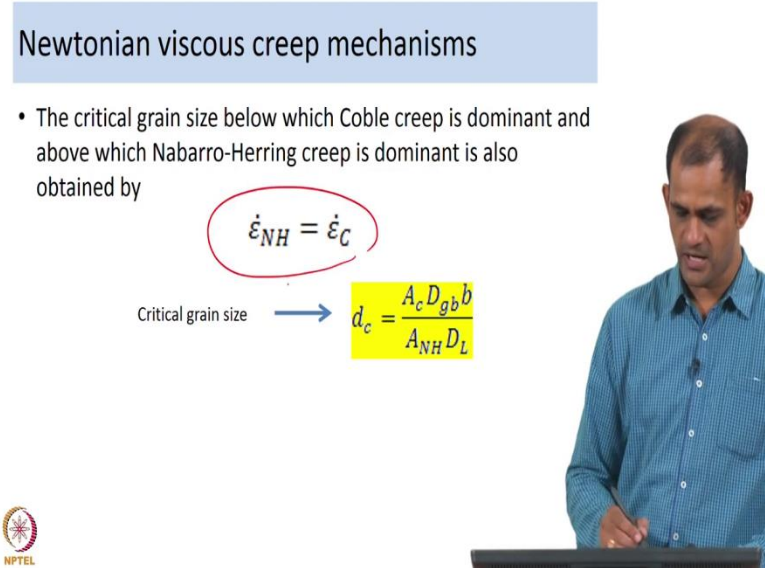

rate due to Nabarro-Herring creep to the strain rate due to Coble creep and if you do that then what you will arrive at is the critical grain size at which the deformation is going to move away from Nabarro-Herring creep controlled regime to Coble creep controlled regime.

So what will be interesting is for you to determine this, the critical transition temperature as well as the critical grain size by equating these two, if we are equating the strain rates of deformation. So one thing you would realize is there is a term b here

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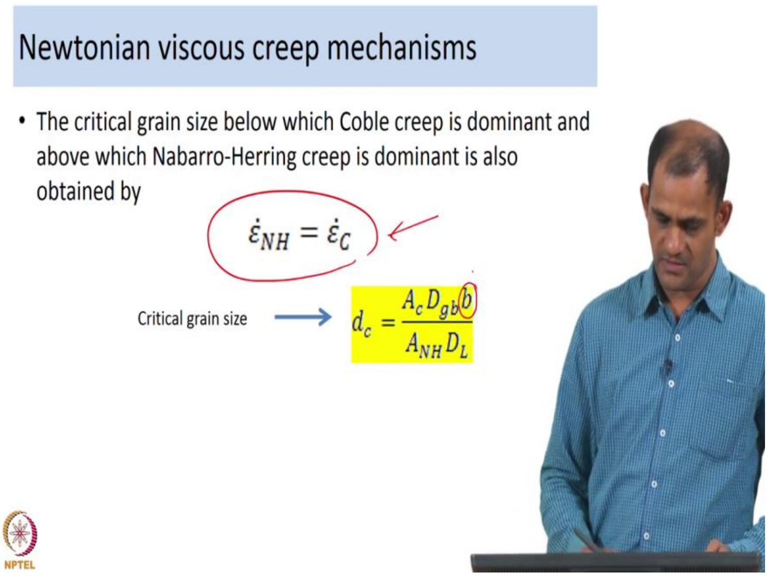

where as when you look at creep deformation due to Coble creep you are going to have a delta b delta g b term.

The delta g b term is basically the grain boundary thickness or the grain boundary width and

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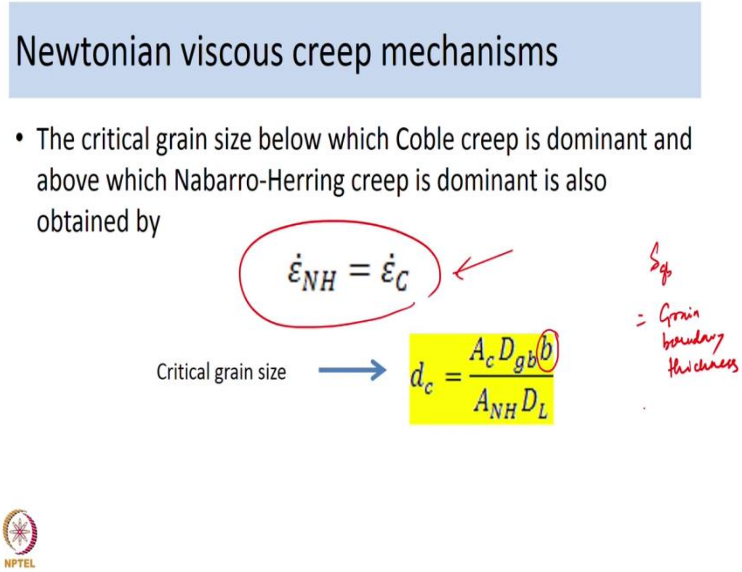

typically the grain boundary width is taken as almost equal to Burgers vector or about 1.5 times the,

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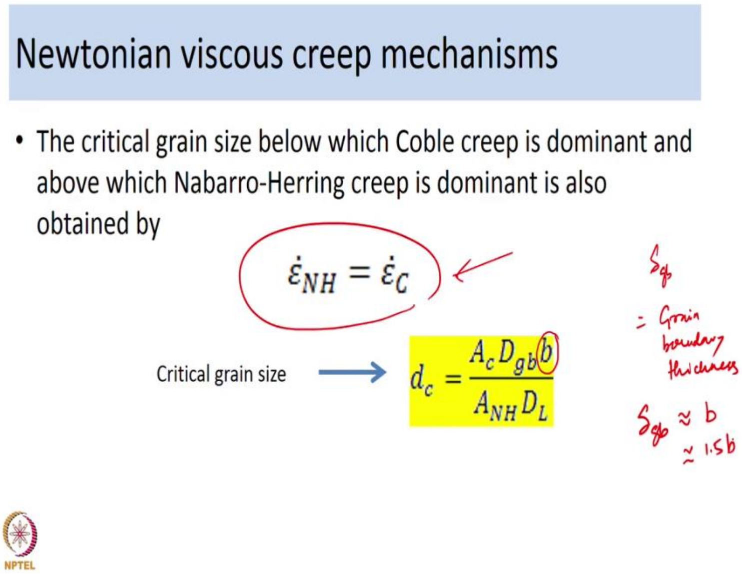

the Burgers vector.

So when you are doing this conversion from, so when you are doing this determination of critical grain size or critical temperature you will eventually end up with relation like this where instead of

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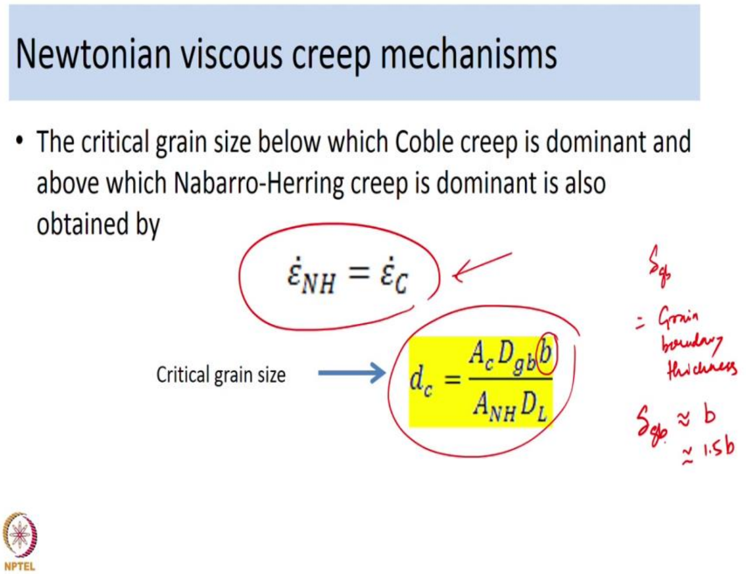

delta g b you are going to use Burgers vector.

So that was about identifying these two para/parameters, two properties, critical grain size and critical transition temperatures but now having said that one thing to understand is

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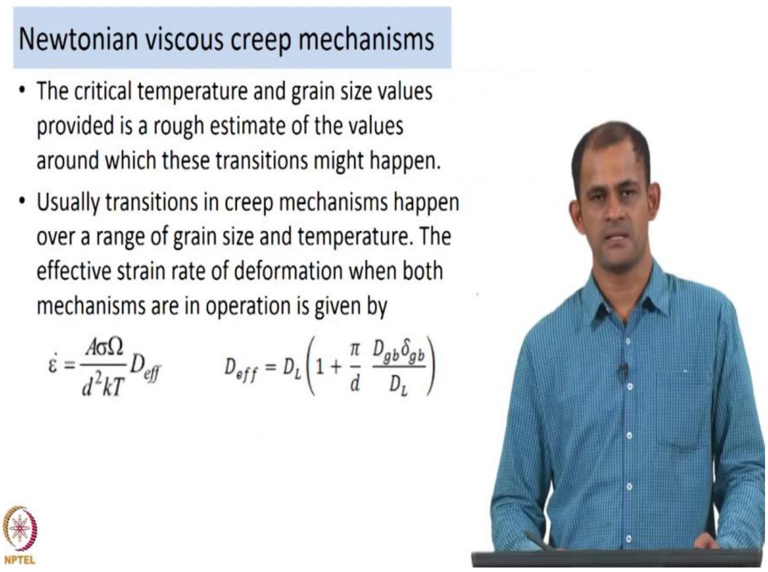

that these transitions are not going to be that sharp.

What I mean by that is, so you are, say you are moving from Nabarro-Herring to Coble creep at low temperatures or you are moving

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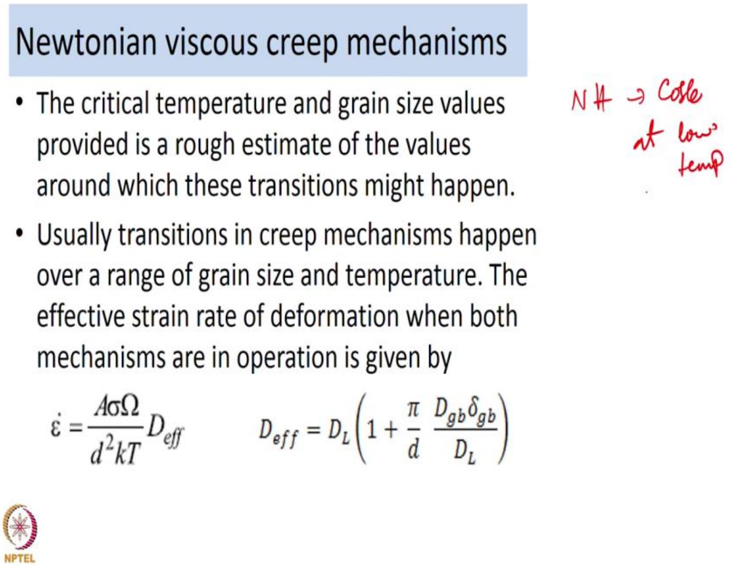

from Nabarro-Herring to Coble creep with grain size refinement, generally this

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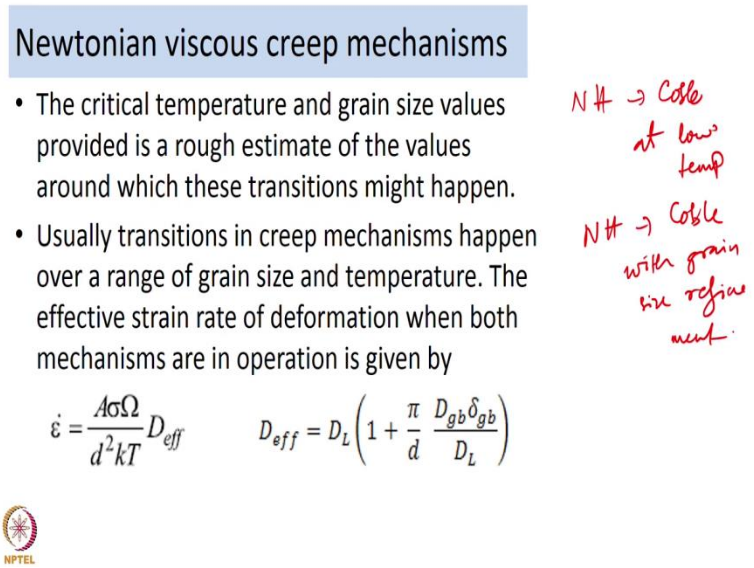

transition is not going to happen at one particular temperature or one particular grain size.

So the transitions typically happen gradually over a set of grain size values or over a set of temperature values, so the critical, so, but the point was that, but the point of introducing T c or d c was to just to give you a rough estimate or a ballpark estimate of where you may expect these transitions to happen.

But in real life scenarios these transitions are going to happen over slightly broader range of grain sizes or broader range of temperature values.

So what would happen is when you have that range of grain size, say d over which

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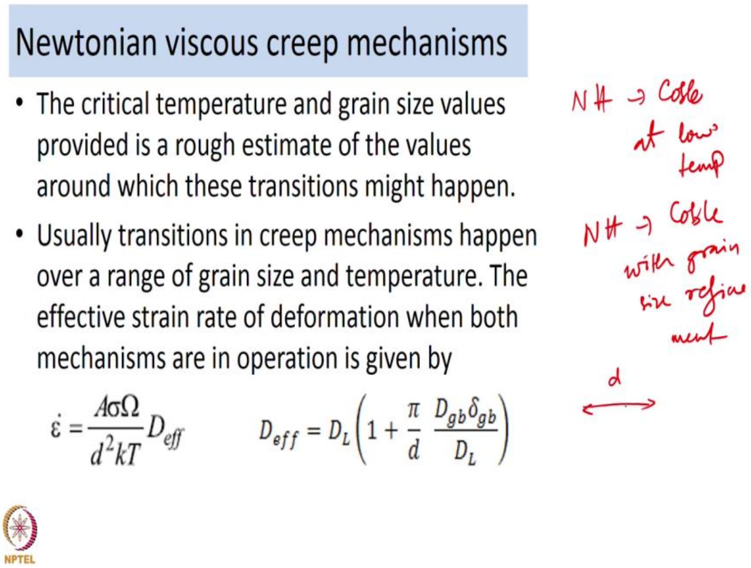

the transition is going to happen or the range of temperature over which Nabarro-Herring,

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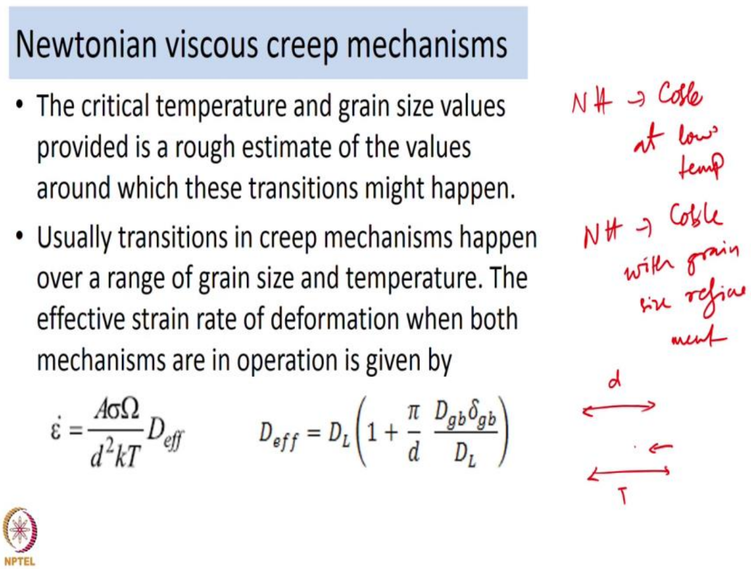

so if temperature is decreasing in this direction so the Nabarro-Herring moves to Coble creep, so it is going to happen

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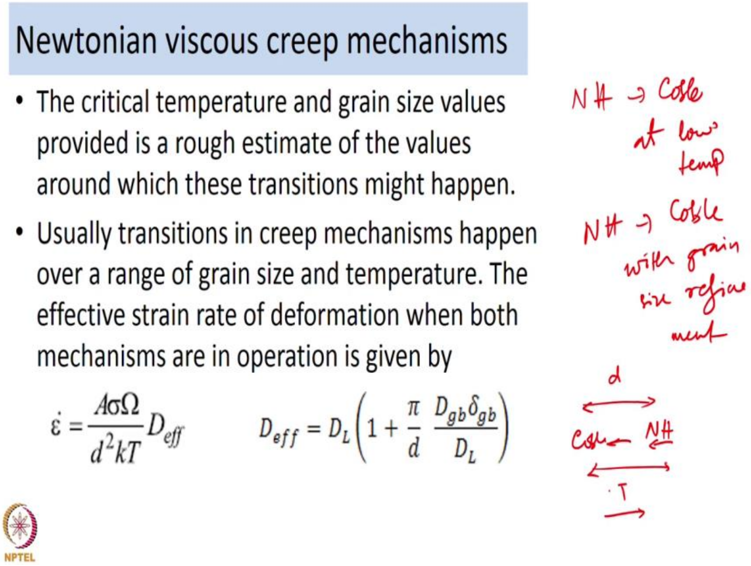

over a certain delta T value or a certain delta d value.

So typically what happens

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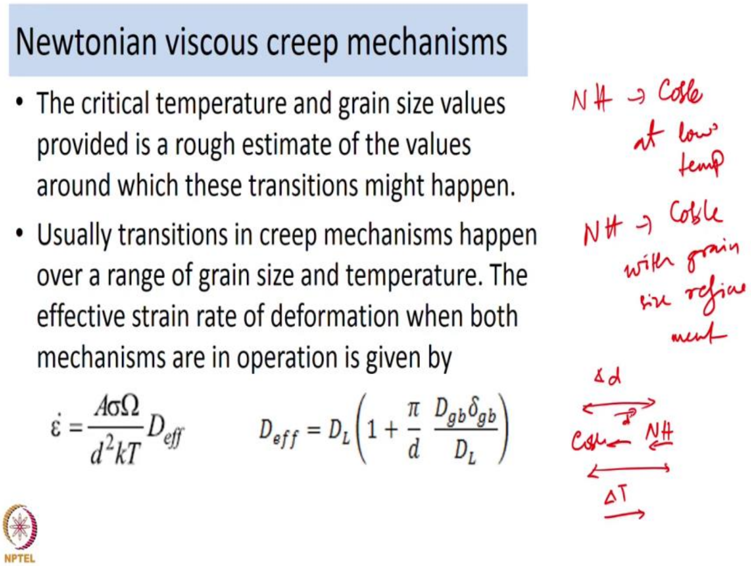

is during that transition regime, both Nabarro-Herring creep as well as Coble creep will have their contributions. So that means the deformation in that particular range of grain sizes or in that particular range of temperature values will have contribution from both, Nabarro-Herring creep as well as Coble creep.

So when you have such a case what happens is the strain rate of deformation in that scenario

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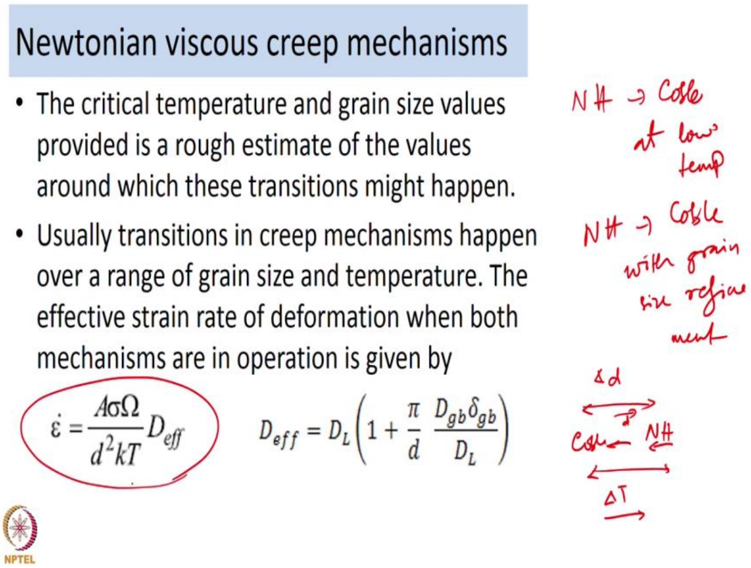

can be described by the following equation. So here you can, you still have epsilon dot as proportional to sigma to the power 1

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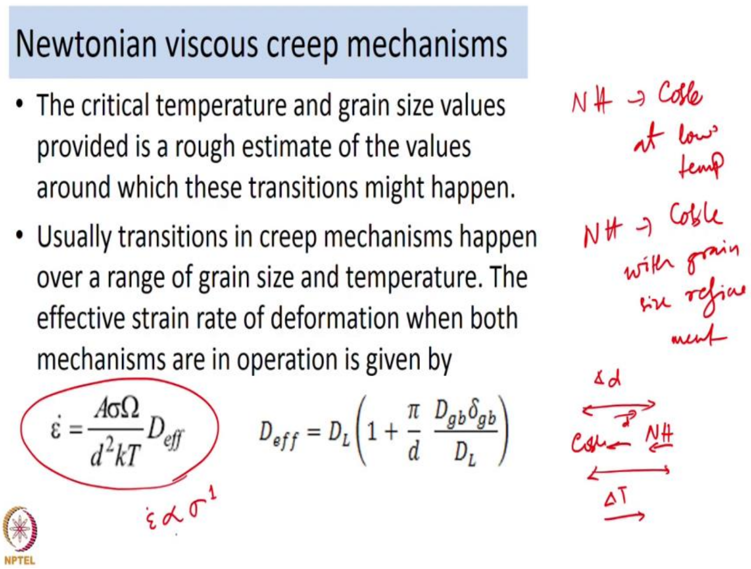

because this is n is equal to 1 for diffusion creep mechanisms.

So you will continue to have that but instead of D equal to D L or D equal to D g b, you are going

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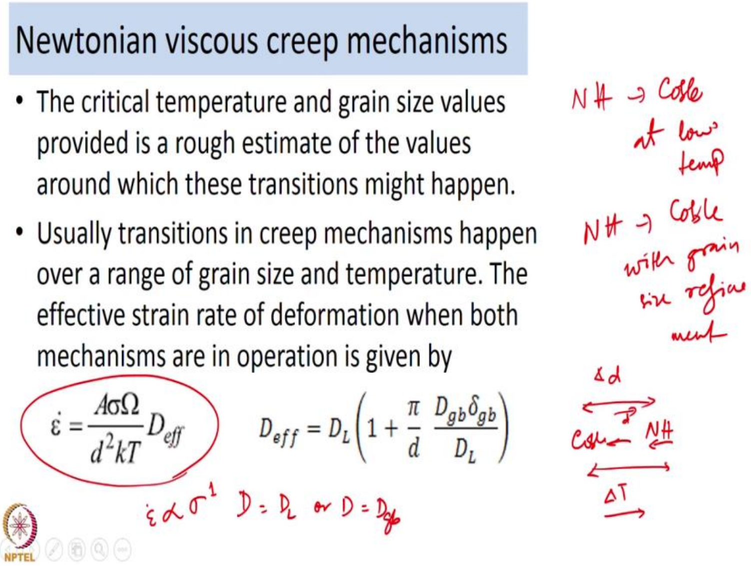

to use a effective diffusivity. So here the strain rate will be dependent on effective diffusivity which is given by the following relation.

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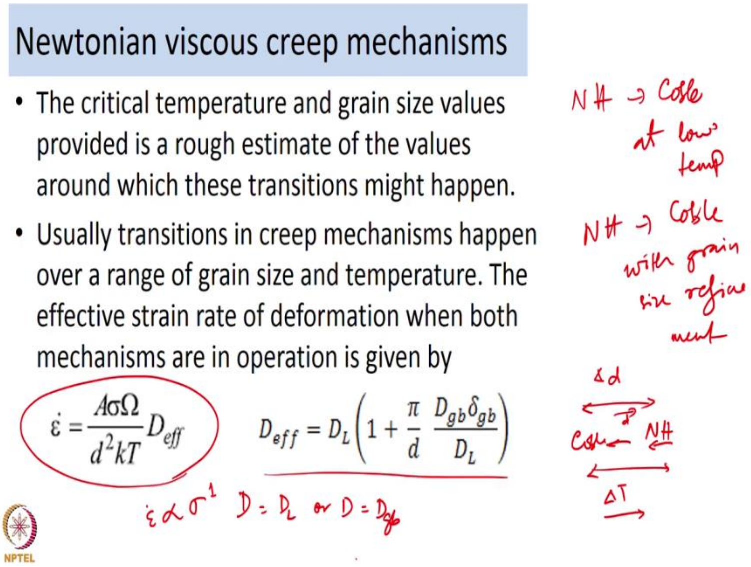

So D effective is given by, is going to depend on both D L, it is also going to depend on D g b and then delta g b something that I introduced earlier is grain boundary thickness. So this is how it is going to be for those temperature or grain size values where both Coble creep and Nabarro-Herring creep are going to operate simultaneously.

Now one of the things to note here is from this equation what you also realize is when D g b, if D g b by D L is large and if d is small, so if

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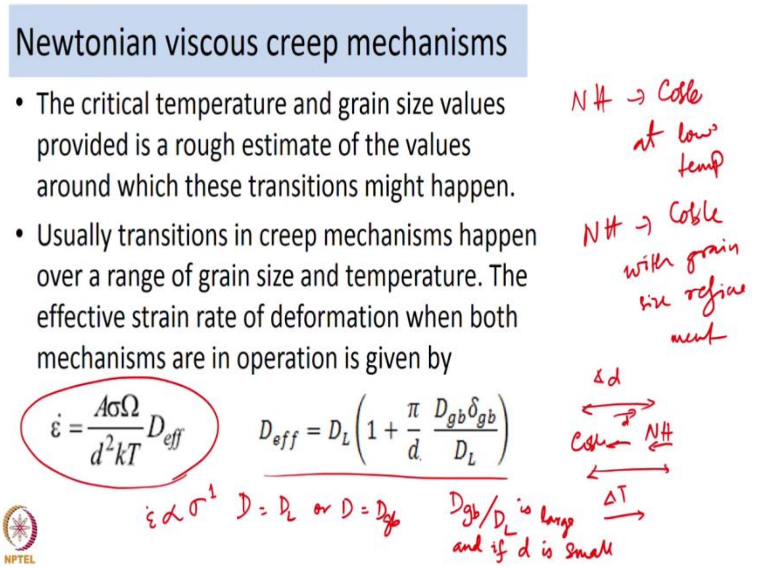

d is small and the ratio D g b by D L is large then your contribution of Coble creep to the effective diffusivity or the contribution of Coble creep to the total strain rate is going to be higher.

And the converse of it, that is if D g by, if D g b by D L is small and if d is large, if the grain size

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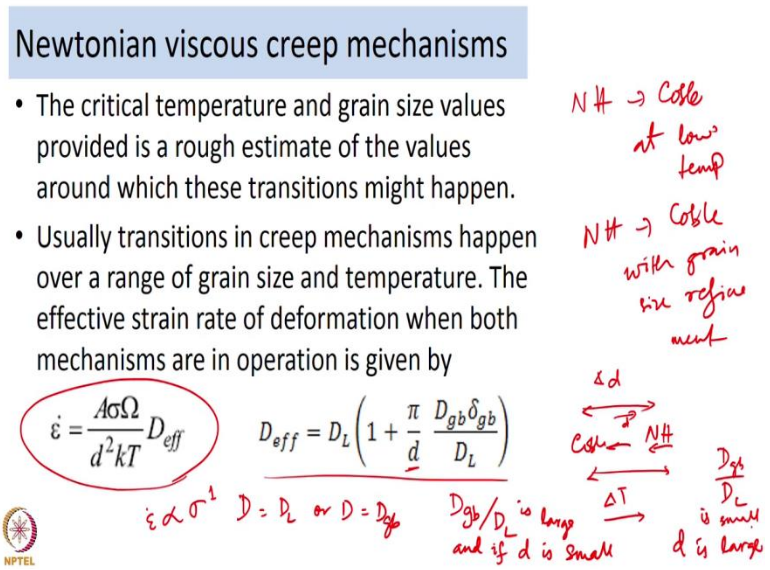

is large then the contribution of Nabarro-Herring creep to the total strain rate of deformation is going to be higher.

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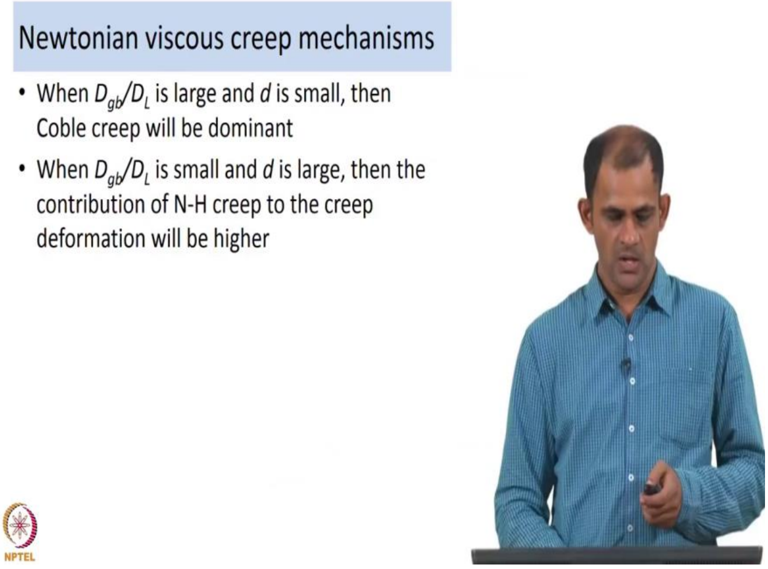

So that is what I am mentioning here. So when D g b by D L is large and the grain size d is small then Coble creep will be dominant

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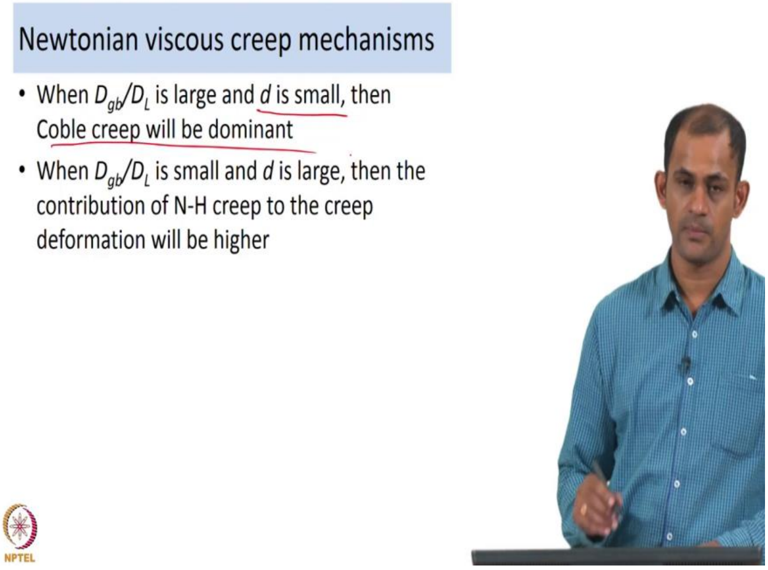

or the contribution of Coble creep to the total strain rate of deformation is going to be higher. And if D g b by D L is small and the grain size is large then the

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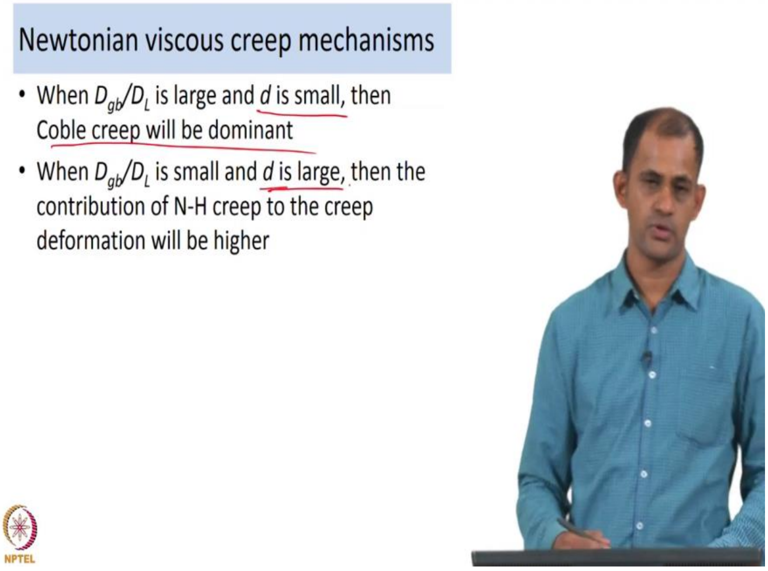

contribution of the Nabarro-Herring creep to the creep deformation will be higher.

So that was about the strain rate of deformations and how to determine the relations for Nabarro-Herring creep and what is, how is the relation for Coble creep going to look like? What are the critical transition temperatures and grain sizes and things like that?

Of course the way of identifying Nabarro-Herring creep or Coble creep is by identifying the values or determining the values of p, value of n and the value of Q and based on that you can know if Nabarro-Herring creep is operating or Coble creep is operating.

Now another way of looking at, and similarly in general when you talk of creep you are also going to, in order to see if diffusion creep is operating or not, or instead of diffusion creep if you have dislocation creep which is controlling, so how do you determine and find out which one was the rate controlling mechanism?

But one another way of doing it is also

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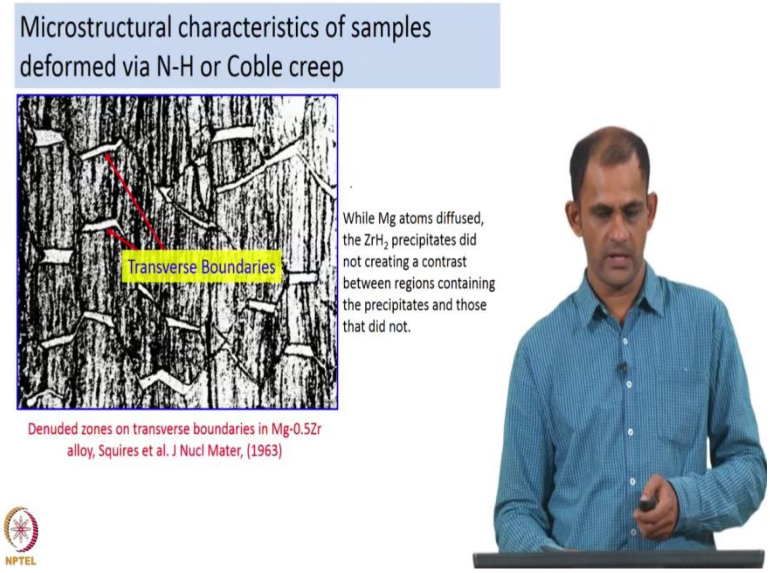

by looking at the microstructures that form during the creep deformation process. So what I am trying to say here in this slide is depending on whether the deformation process is controlled by diffusion-based mechanisms or if it is controlled by dislocation-based mechanisms you will have different characteristic microstructures.

So one of the earliest investigations on microstructures associated with samples that were crept under diffusion conditions or diffusion creep conditions was by this group Squires et al.

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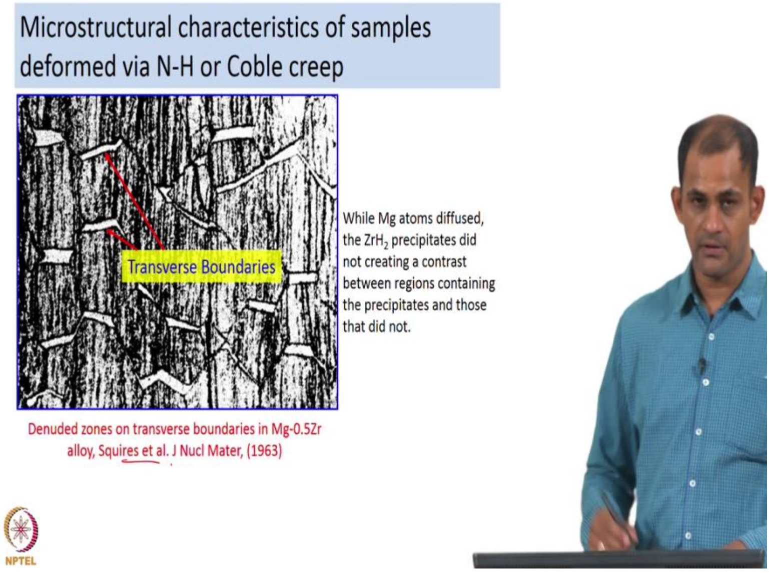

They were among the first few to; in fact they were the first to find out the microstructures that are generated during diffusion creep.

So what they did was they took Mg-0.5Zr alloy and these had some precipitates of Zirconium hydride. So zirconium hydride precipitates were present in this alloy and then they took the sample and they carried out diffusion creep. So say, this stress was applied in that direction and you had

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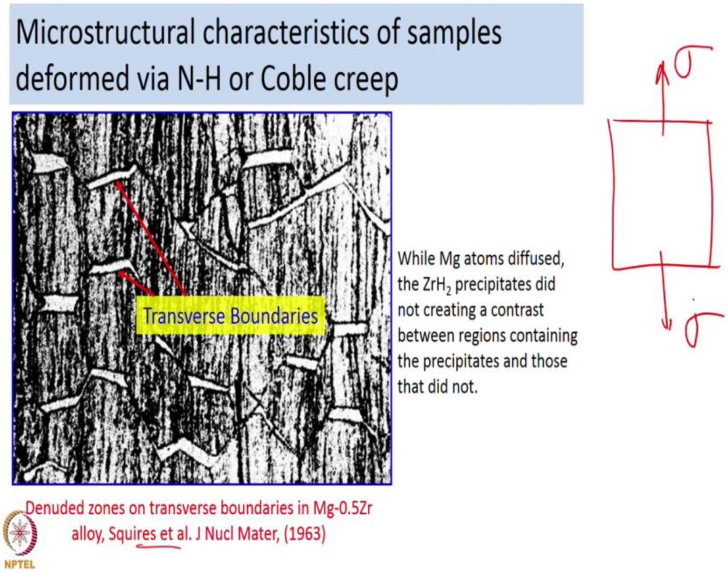

diffusion creep going on.

And now what we know is when the material is deforming by diffusion creep, so what we have learnt is there is going to be extension of the grains

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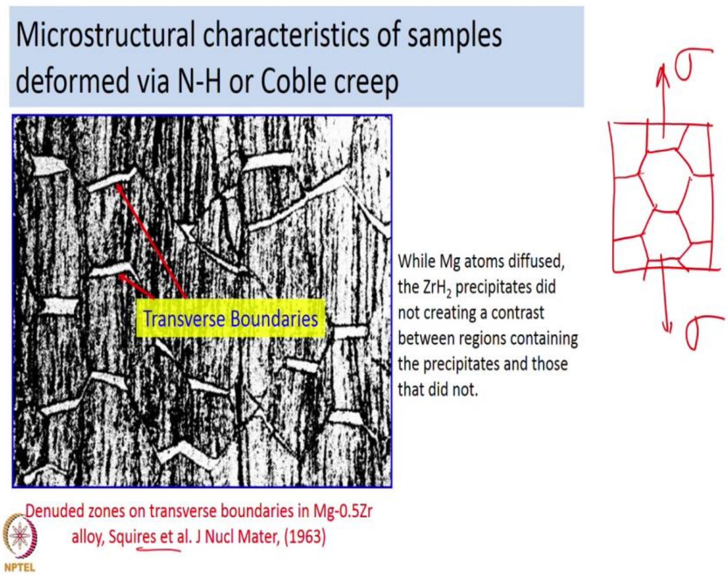

because the grain boundaries which are perpendicular to the applied stress will have higher vacancies and the grain boundaries almost parallel to the applied stress will have lower concentration of vacancies.

So vacancies are going to move from there to

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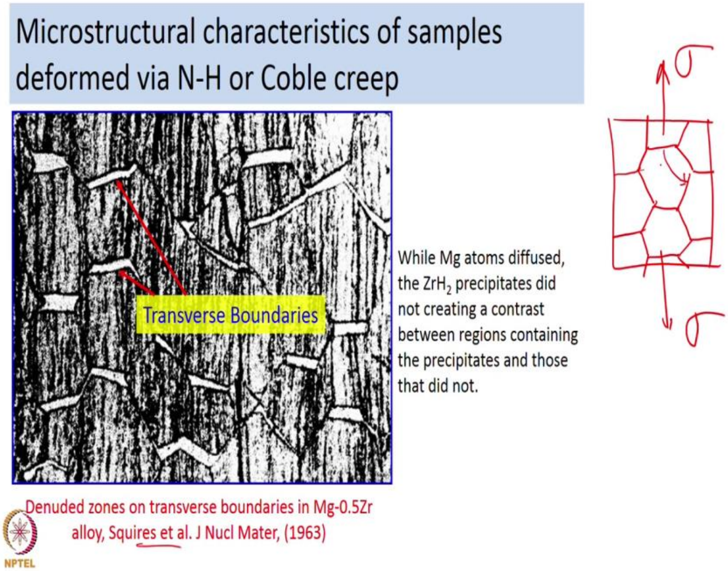

here and the reverse of it, the atoms are going to move from,

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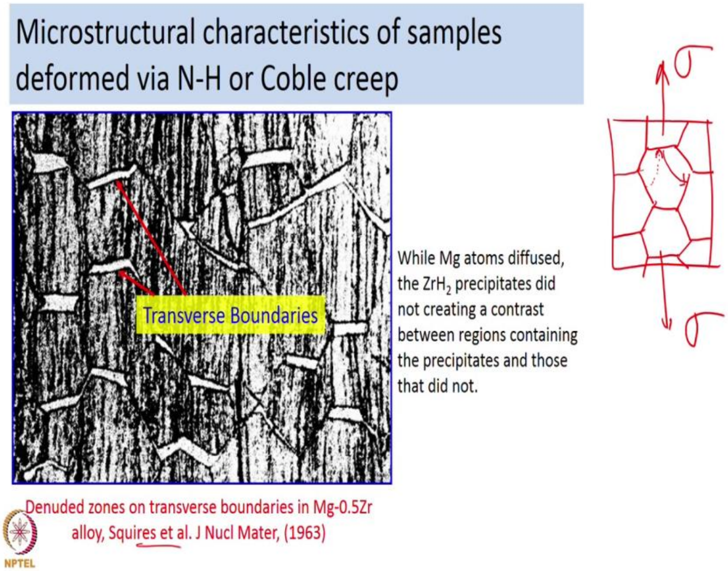

the atoms are going to move from the parallel grain boundaries to the perpendicular grain boundaries. So when you have atoms moving from the parallel grain boundaries to the perpendicular grain boundaries, obviously the grains are going to elongate.

So that is what we discussed is happening when you have a material experiencing diffusion creep.

Now in this particular case, since the alloy is magnesium point 5 zirconium so the matrix is magnesium, so the diffusion of atoms means the diffusion of magnesium atoms. So what happens is the magnesium atoms start diffusing from the grain boundaries which are almost parallel to the applied stress to the grain boundaries which are perpendicular.

But during the motion of magnesium atoms or the diffusion of magnesium atoms, the zirconium hydride precipitates which were uniformly distributed in the matrix, so if you understand, if you see that the matrix has uniform distribution of zirconium hydride precipitates these precipitates are not going to the, zirconium hydride precipitates do not participate in this diffusion process.

So you have only magnesium atoms

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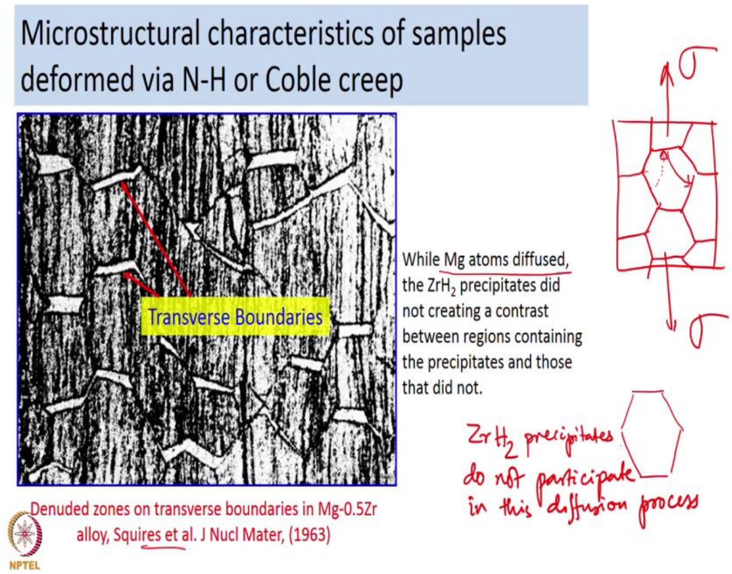

which are diffusing from parallel grain boundaries to the perpendicular grain boundaries, perpendicular here means

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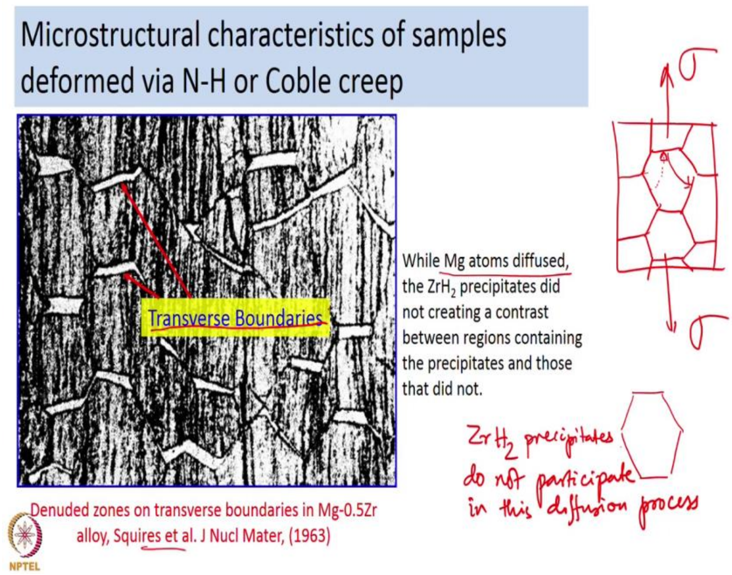

transverse, so the grain boundaries which are transverse to the applied stress.

So what happens is you have magnesium atoms moving in that direction, and

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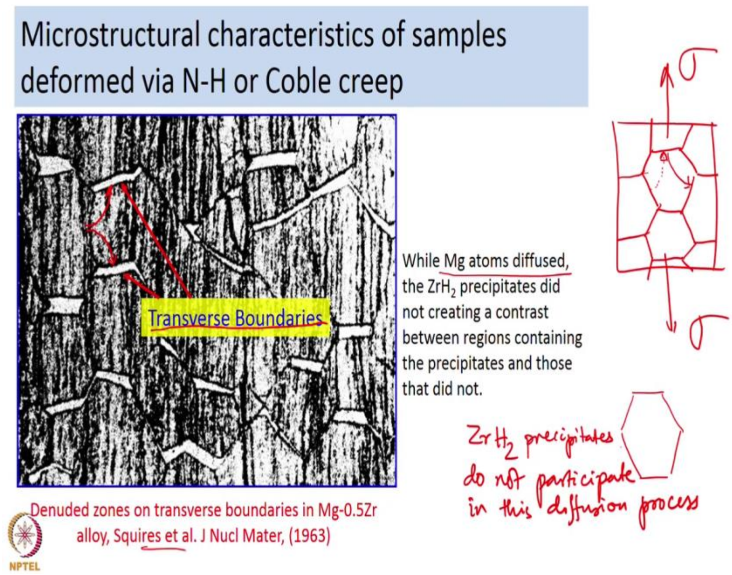

because the zirconium hydride precipitates did not move you eventually end up with regions like this which are devoid of any zirconium hydride

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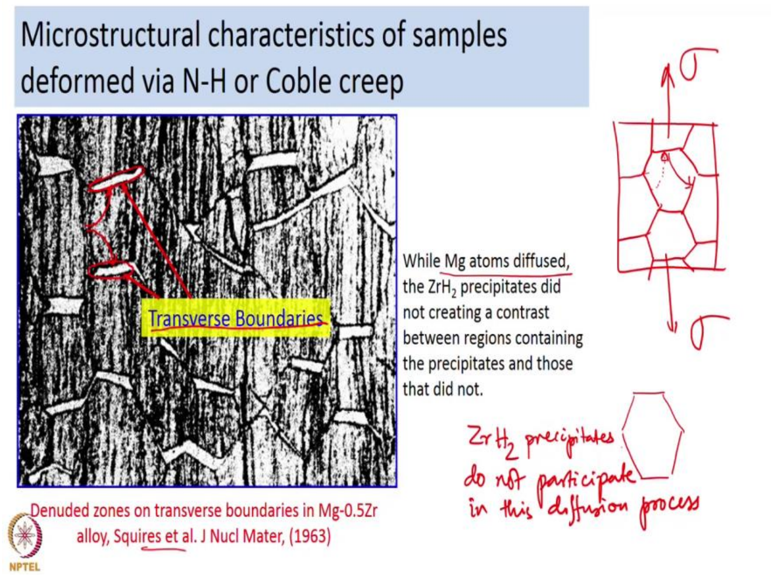

precipitates.

So these are also known as denuded zones.

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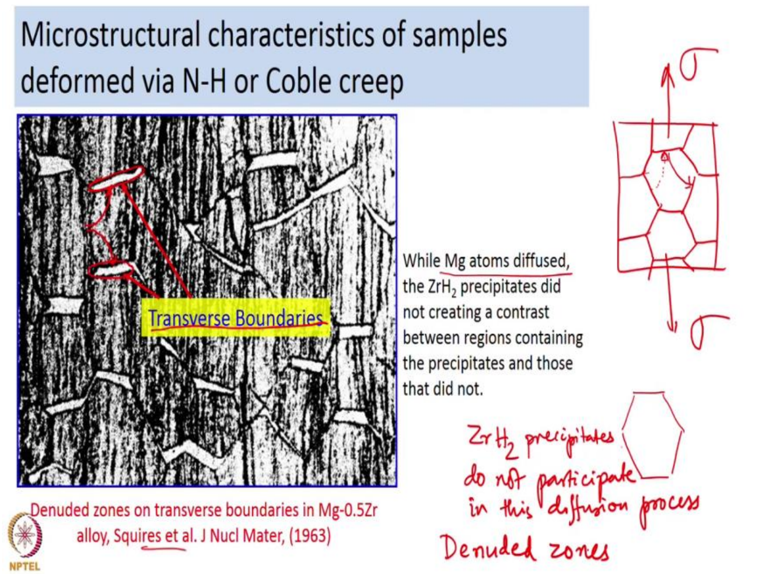

So you do not have any zirconium hydride precipitates moving into the region, so that is why that region is clear of the black spots or the black contrast that we are seeing at other locations. So this particular microstructure was taken as evidence for the operation of Nabarro-Herring creep or Coble creep.

The fact that magnesium atoms moved and they elongated the grains and you had regions which were free of the precipitates; that was taken as evidence for the diffusion of magnesium atoms and that causing diffusion creep. So this was one of the earliest evidence.

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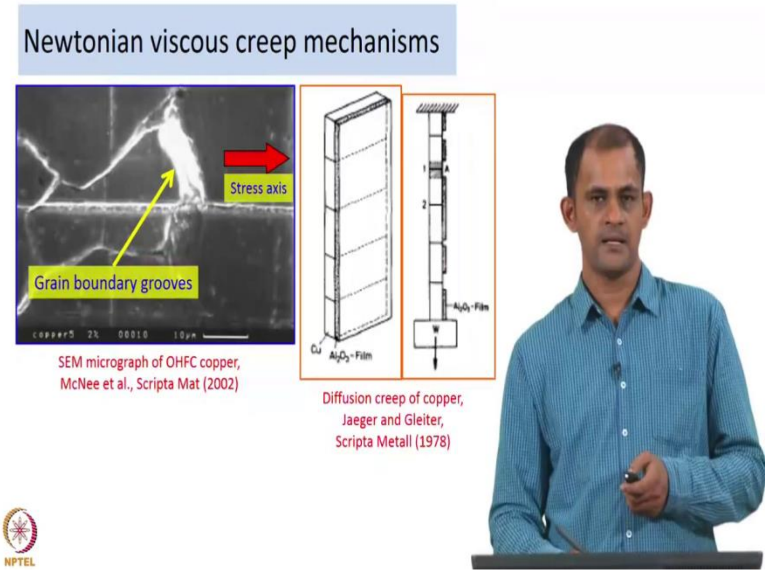

Another evidence was provided in, by Jaeger and Glieter in the year 1978.

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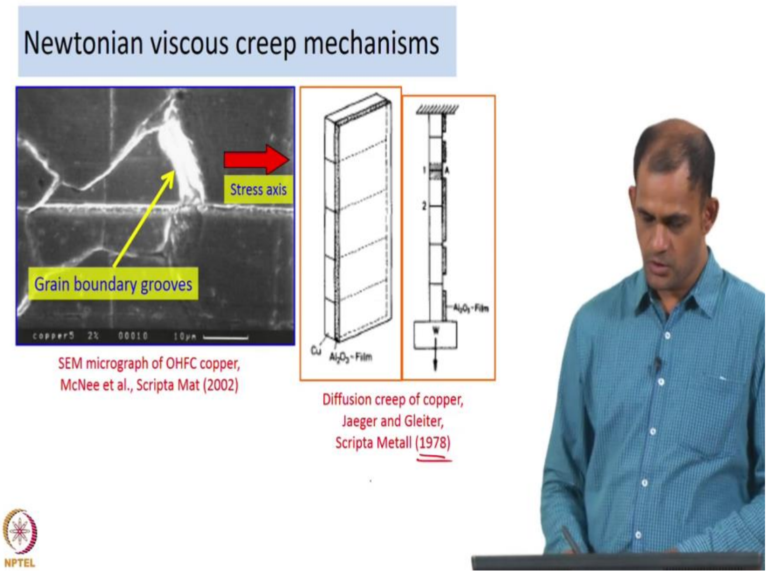

So what the group did was they took a piece of copper and coated it with alumina film. So alumina

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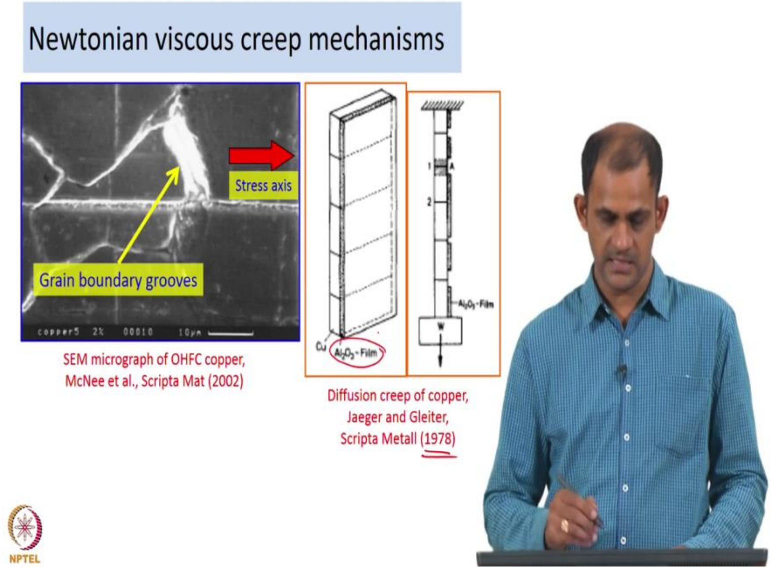

is a ceramic. So it is a hard, brittle material. So, and then they started deforming the material under conditions which are suitable for diffusion creep controlled deformation.

So the stress and the temperature values that they chose were such that the copper could deform under diffusion creep conditions. So after they carried out the experiment what they did was they noted, they looked at the sample post-deformation and what happened and what they noticed was there were these regions which were devoid of the alumina films.

So the alumina film which was originally continuous now had gaps between

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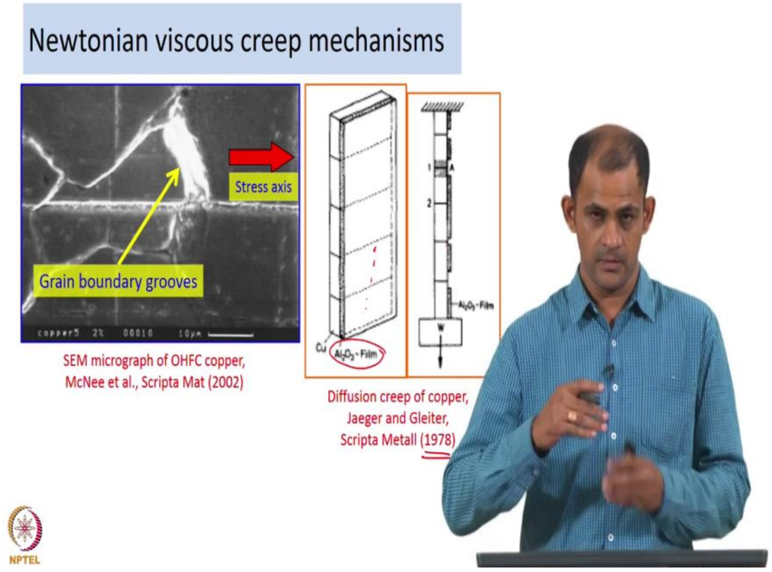

different portions. So you had alumina film at a gap and alumina film region at a gap so these gaps correspond or indicate the breakage of the alumina film.

So this breakage is going to happen because of plastic strain incompatibility, that is because the copper film, the copper material which was deforming under diffusion creep conditions was elongating, the grains were elongating but alumina which was not participating in this plastic deformation process did not stretch to the same extent and that is why you developed these gaps in the

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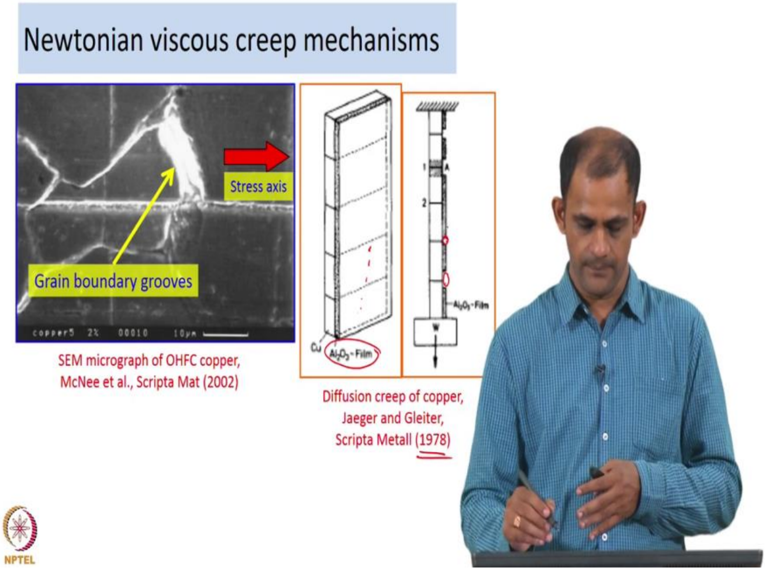

material.

So this is another example of how the concept of grains getting elongated and during diffusion creep was proven and, by these set of experiments.

Another set of microstructures that were reported in recent times were by McNee et al in this journal. So in this case you again see the grain boundaries have developed. So the authors call these as grooves.

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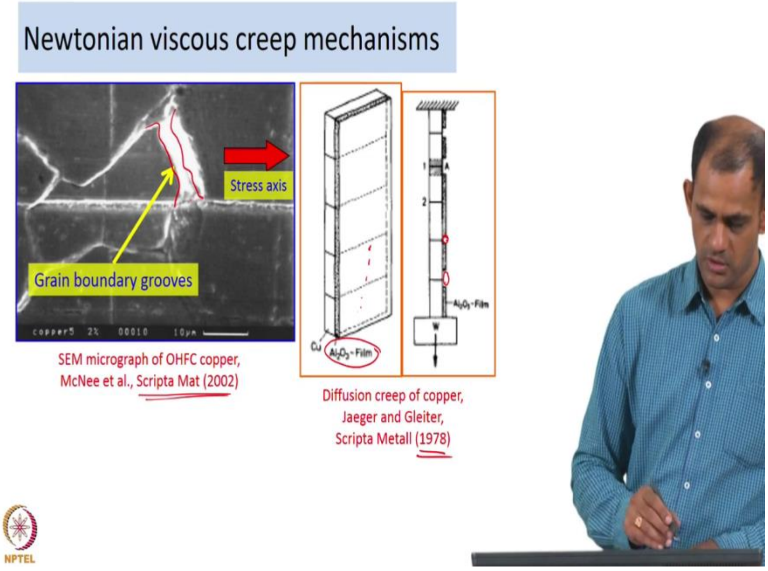

So there is a certain groove that is forming in the grain boundary and that is because of plastic strain incompatibility.

Such a situation could arise if the grain in front and the grain in back extend or stretch to different levels and again, the grain boundary was more or less perpendicular to the

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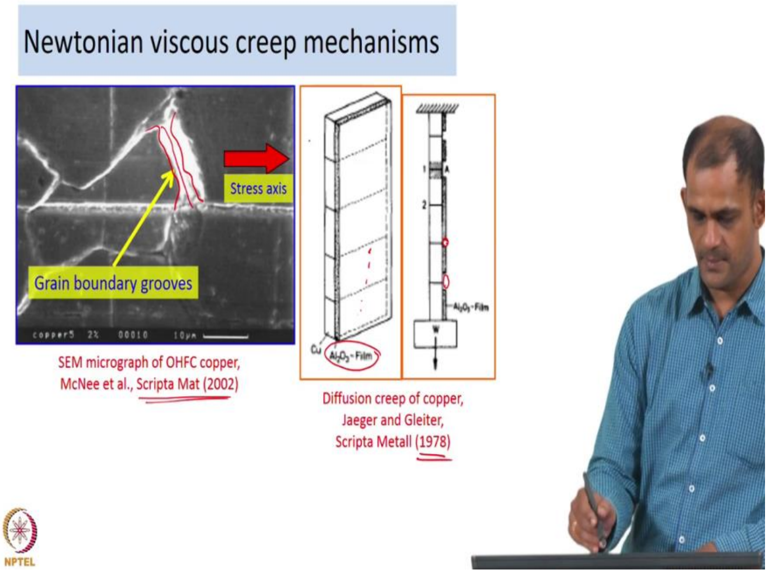

applied stress and this is again telling that you have some amount of grain elongation happening during the process of diffusion creep.

So these are all evidence or the type of microstructures or that you could observe during the diffusion creep conditions. So post-creep microstructure analysis can also tell you about the mechanism of creep that was in operation. So that was about

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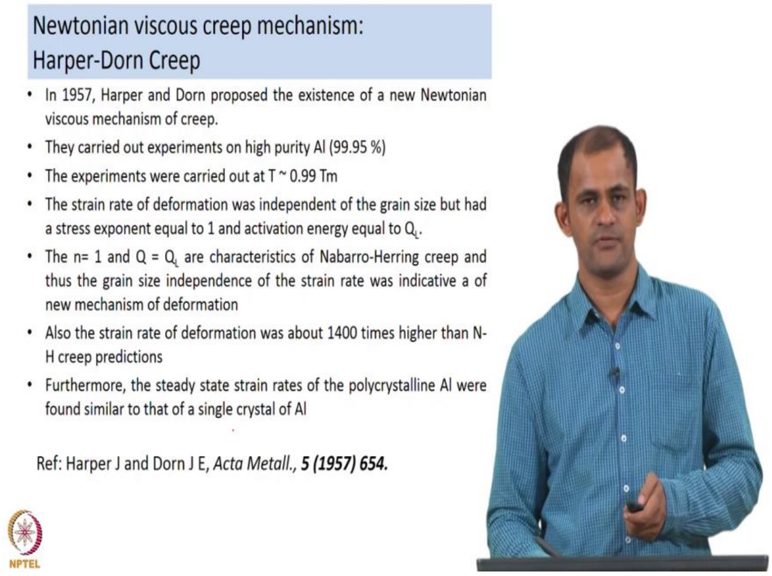

diffusion creep mechanisms, especially, so we talked about Nabarro-Herring and Coble creep as two primary or main diffusion creep

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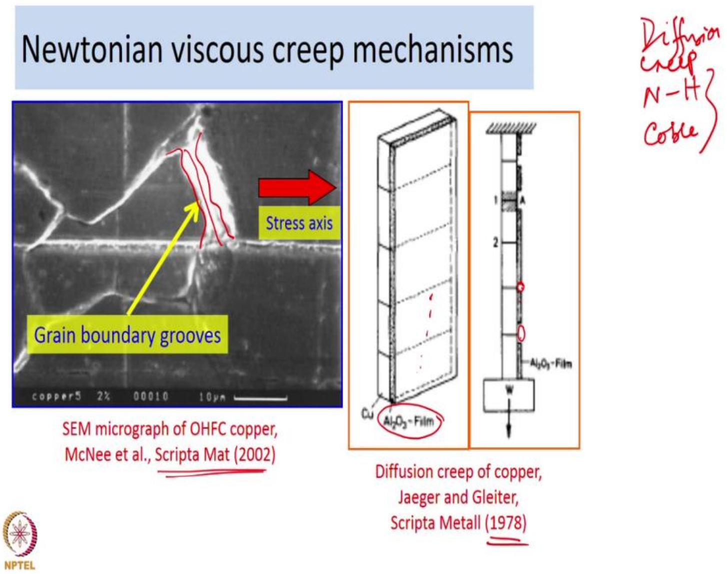

Now, under Newtonian viscous creep we also have a third category, the third category which is called the Harper-Dorn creep mechanism.

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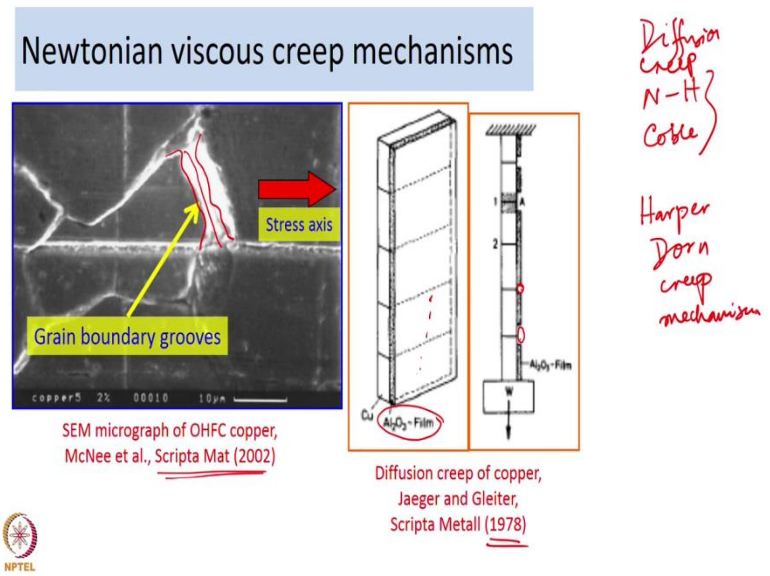

So we are now going to talk about the Harper-Dorn mechanism.

If you remember in the table where I listed down p, n and Q values

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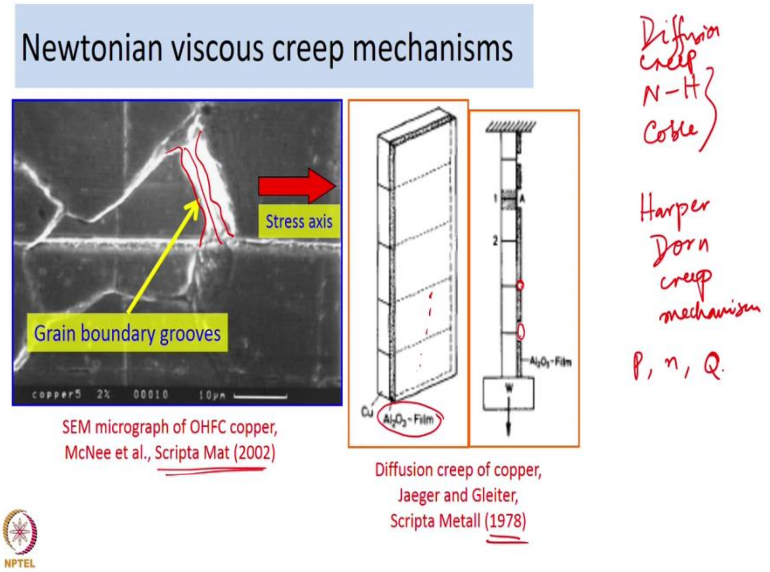

so what you will recall is n is equal to 1 for this mechanism and Q is equal to Q L.

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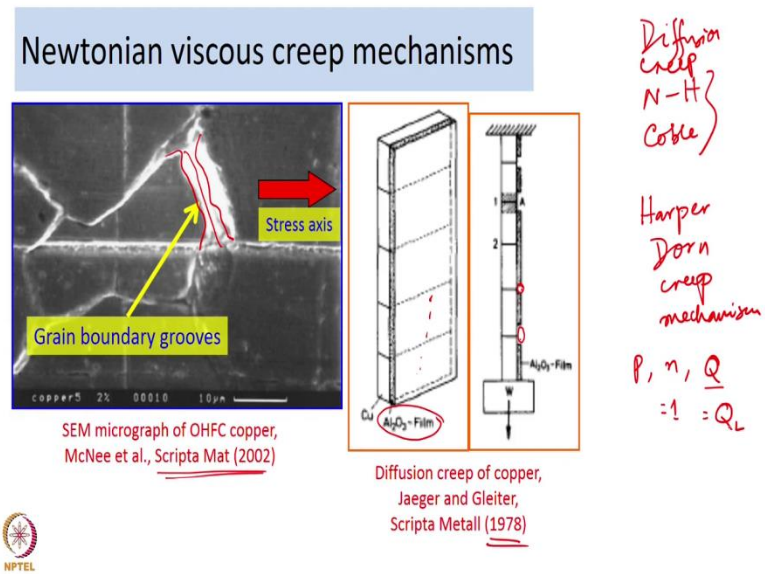

But there is no grain size dependence which means p is equal to 0.

So, so this mechanism was discovered about 60 years back in California so

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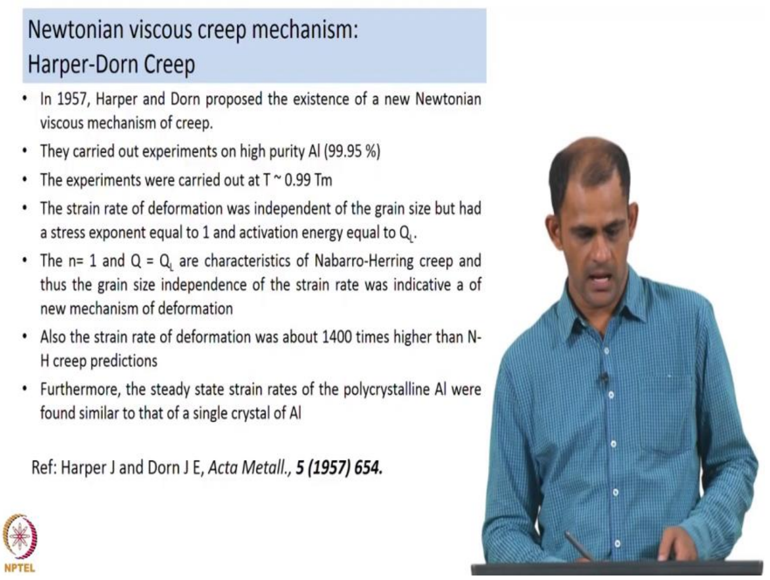

Harper and Dorn, based on their experiments proposed the existence of a new Newtonian viscous mechanism of creep. This creep mechanism came to be known as Harper-Dorn creep. So what they did in the study was they carried out experiments on high purity aluminum, so high purity aluminum with a purity of about 99.95 %

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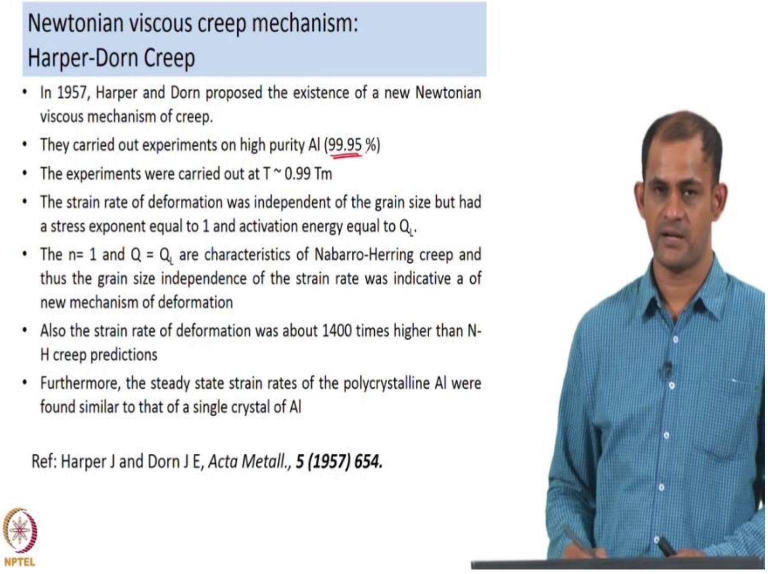

percentage was chosen for the experiments.

And the experiments were carried out at temperatures very close to the melting point of aluminum. So we know the melting point of aluminum is 1660 degrees Centigrade. So they chose temperatures which were about 0.99 times the melting point of aluminum.

And what they found out from the studies was, so they took the data and they plotted strain rate versus stress just to understand the stress exponent and what they found out during the process was that the stress exponent was equal to 1 and also

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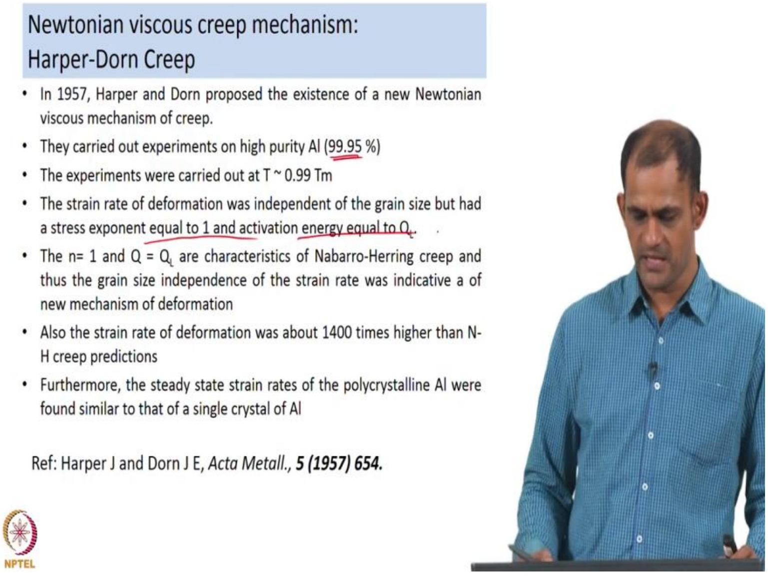

they determined the activation energy and found it equal to Q L.

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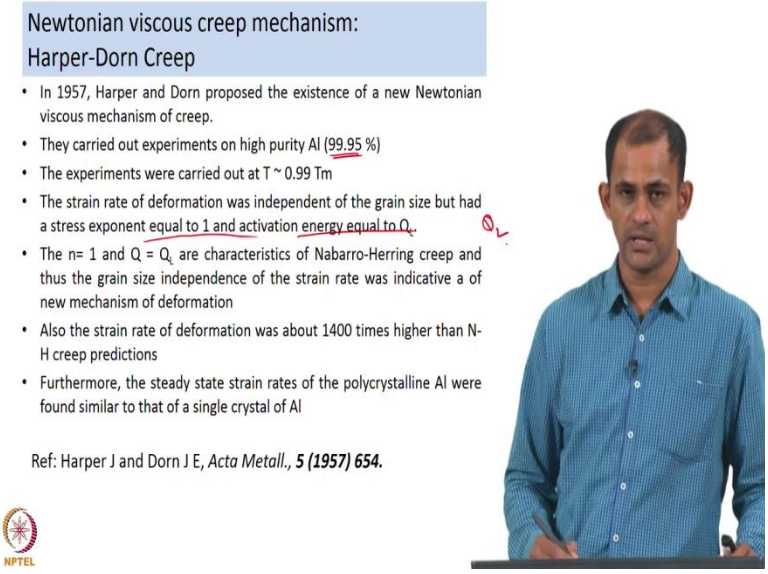

But what was of interest was that the strain rate of deformation was independent of the grain size. Now at that time, in 1948 and 1950, Nabarro and Herring came up with the concept of Nabarro-Herring creep and in 1953 Coble came up with the concept of Coble creep. And at that time n is equal to 1 and Q is equal to Q L were generally understood as characteristics of Nabarro-Herring creep.

However what was baffling to Harper and Dorn was the grain size independence of the strain rate. Because if it was Nabarro-Herring creep then the grain size exponent would be 2. And the fact that there was no dependence on the grain size, this was baffling to Harper and Dorn and they realized that perhaps they were looking at a new mechanism of deformation.

And just to validate their point, when they compared the strain rate of deformation that they achieved with their study to the Nabarro-Herring creep predictions, so if we use Nabarro-Herring equation, the strain rate of deformation predicted by Nabarro-Herring and if you calculate it, the strain rates as per that equation.

And what they did was they calculated; the experimental strain rates that they achieved were compared to that of Nabarro-Herring, so experimental strain rates were compared to Nabarro-Herring creep predictions and what they found out was

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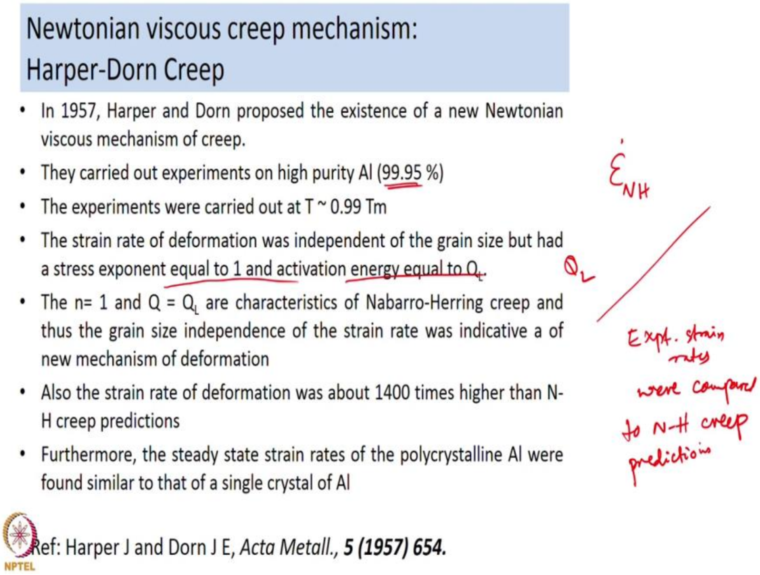

the values they were achieving in their experiments were about 1400

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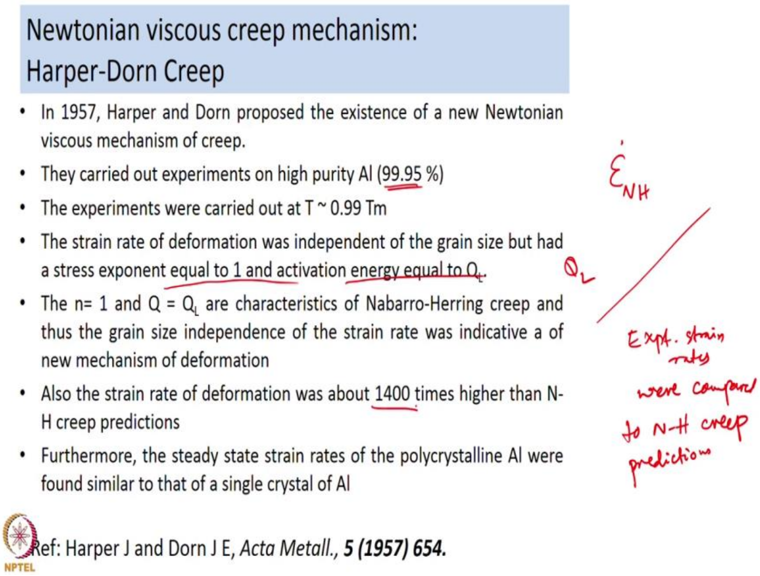

times higher than Nabarro-Herring creep predictions.

Another thing that they also noticed in their study was the strain rates of the deformation of the polycrystalline aluminum that they studied were found similar to that of a single crystal of aluminum.

So what is the significance of this?

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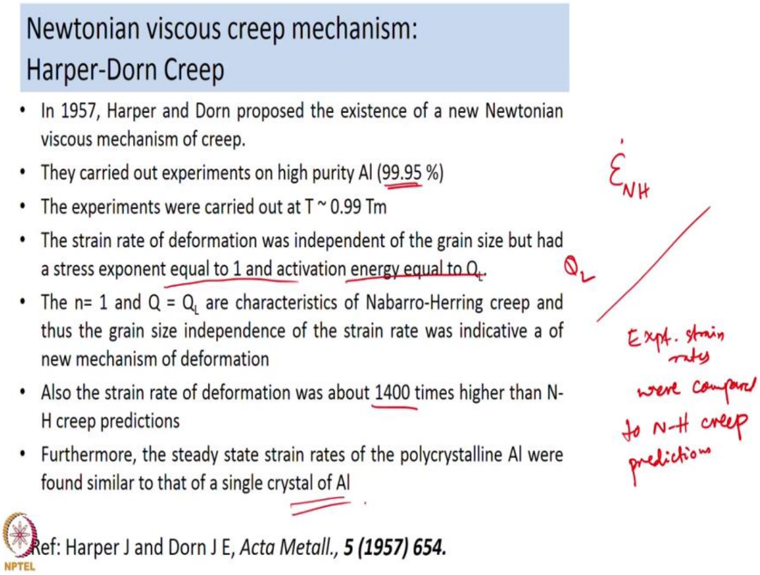

The significance of this is that if, if it was a grain boundary controlled deformation process like in Nabarro-Herring or Coble creep you need the grain boundaries to participate in the deformation process.

It is because when you apply the stress, the grain boundaries are either going to have an excess of vacancies or a reduction in vacancy concentration and that vacancy concentration gradient actually drives the mechanism forward.

So which means you need grain boundaries to participate in the deformation process. And if you have diffusion creep control mechanism then the behavior of a crystalline sample, polycrystalline sample and the behavior of a single crystal would be very different.

But in Harper-Dorn case what they noticed was the steady state strain rates that they achieved with polycrystalline aluminum were very similar to that of a single crystal of aluminum.

This also told them that the role of grain boundaries is not present in the mechanism of deformation and perhaps, and that also tried, that also told them that the mechanism of deformation that they were observing is very different from Nabarro-Herring.

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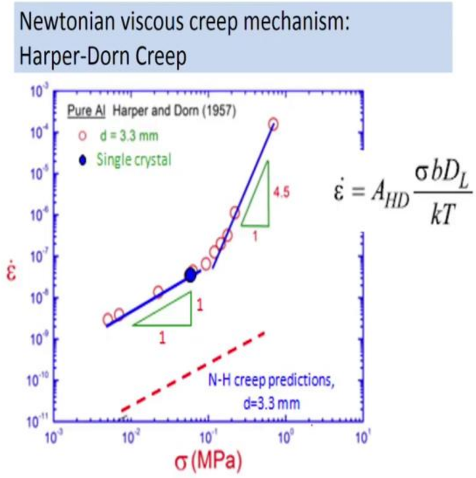

So here in this plot I am showing the data that Nabarro-Herring had generated from their experiments. So in this regime where they have

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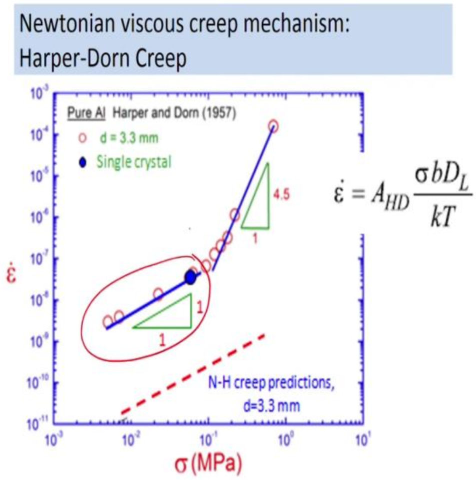

n equal to 1, so when you plot strain rate as a function of sigma so i

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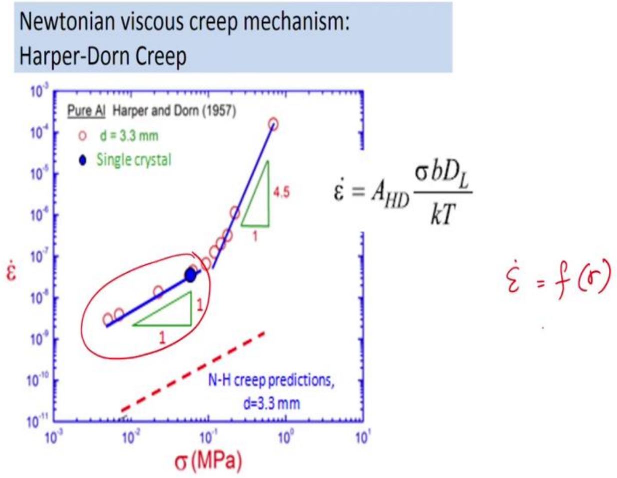

if, so we know it is, it is basically some constant times sigma to the power

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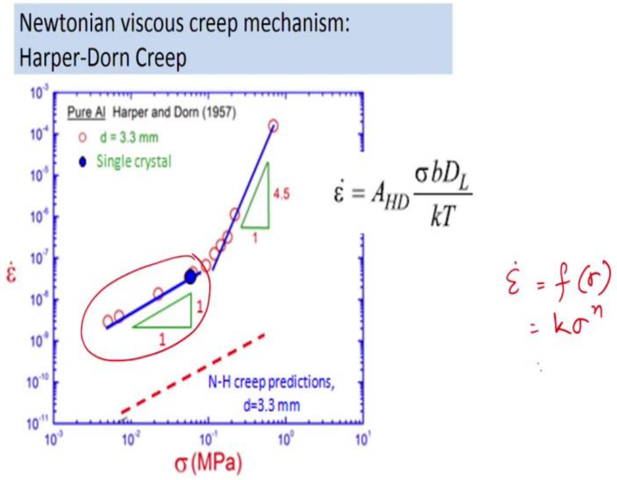

n, and since n is

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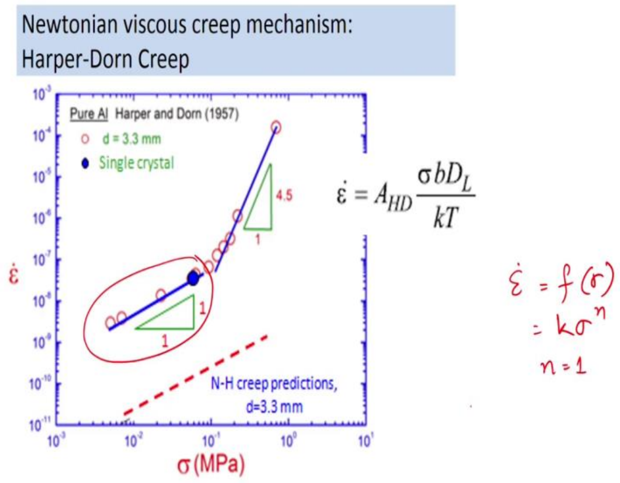

equal to 1 so if you do a log sig/sigma epsilon dot versus log sigma,

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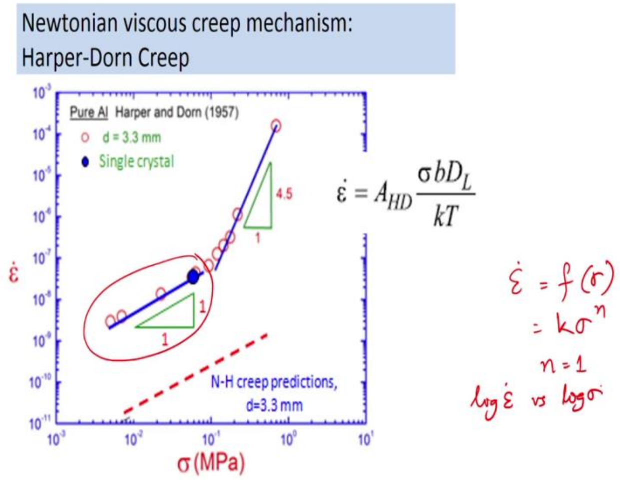

the slope will give you the n value.

So the slope n is equal to 1, that is what they observed, and when they compared the strain rates of deformation here, so these data are all experimental data.

So when they compared the strain rate of deformation to Nabarro-Herring creep predictions

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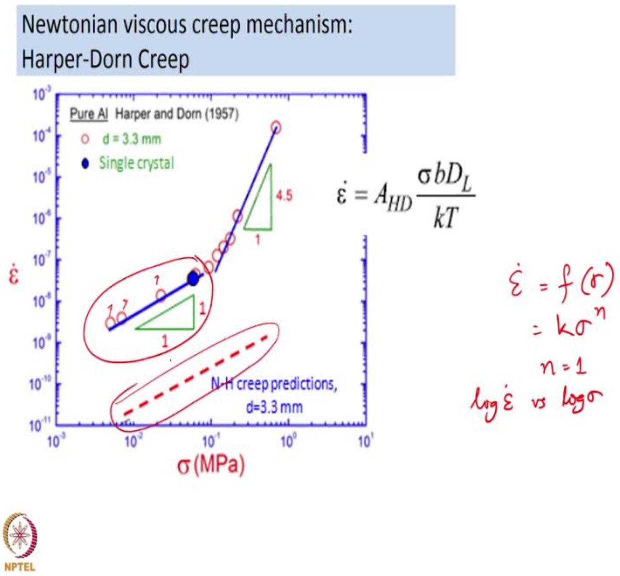

for the grain size of the material they had, there is a vast, at least 3 orders of difference in magnitude, so you are around some 7 to the power 10, 7 into 10 to the power or 8 into 10 to the power minus 11

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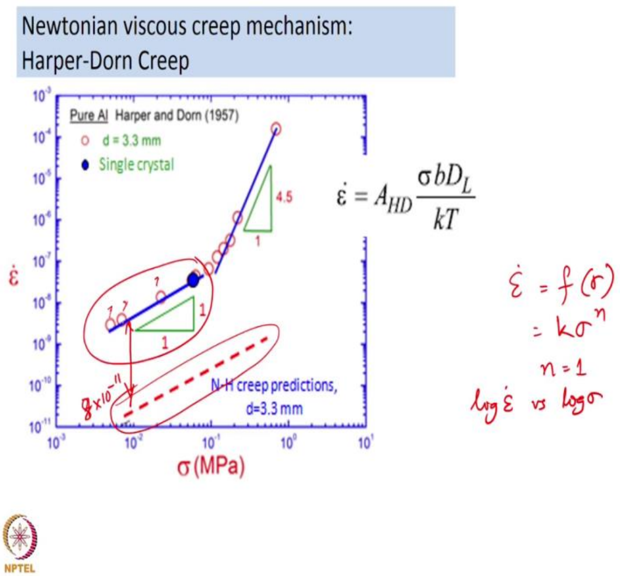

up to 8 into 10 the power minus 9 or above.

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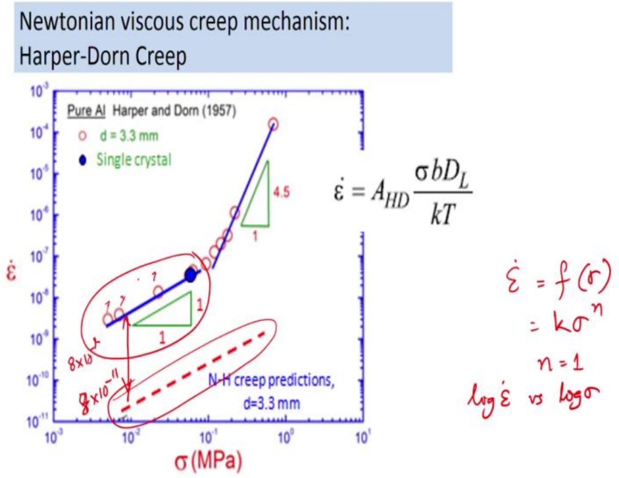

So you have at least 2 to 3 orders of magnitude, there is a difference of at least 2 to 3 orders of magnitude difference between the predictions of Nabarro-Herring and what they observed experimentally.

So that was the first thing and like I mentioned earlier, the strain rates of deformation that

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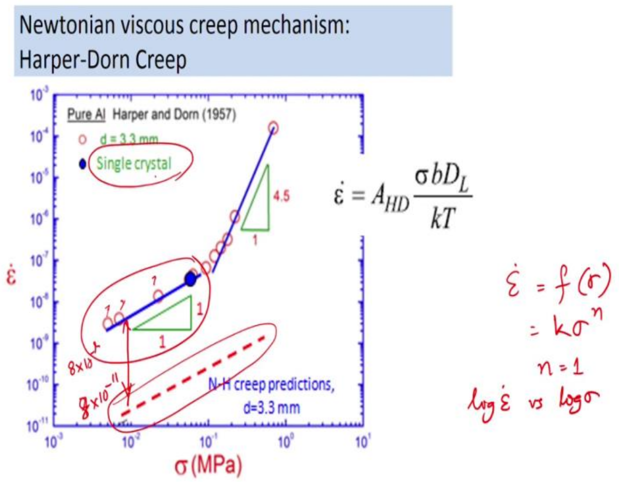

they achieved with the polycrystalline sample. So they had a 3.3 mm grain size

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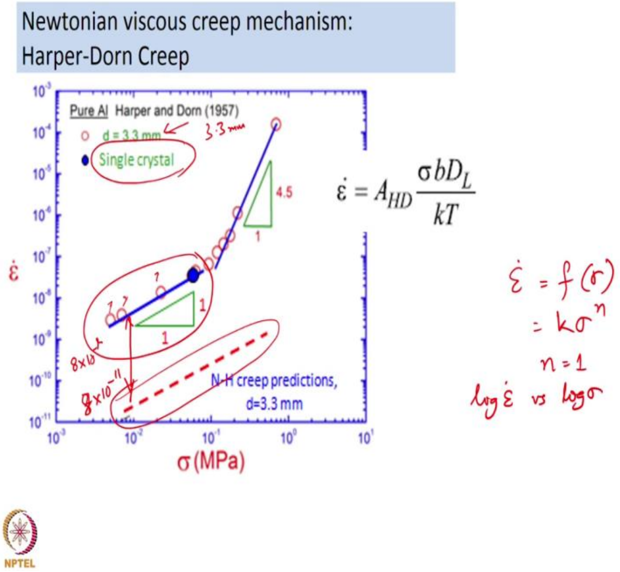

and the strain rates of deformation they observed with this is very similar to what they got with a single crystal.

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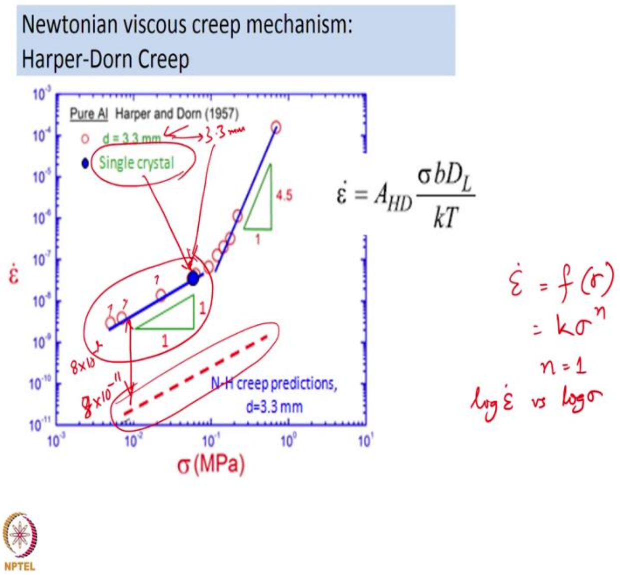

So the strain rates of deformation were very similar. So this also tells them that the grain boundaries are not participating in this deformation process. So that basically led them to propose that this is a new mechanism of creep and it would be called as the Harper-Dorn creep mechanism.

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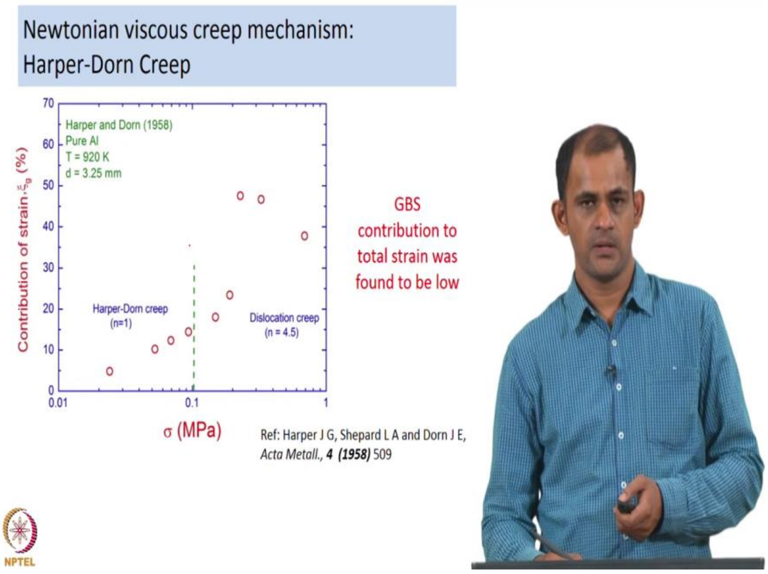

Another validation of their observations was through, in a subsequent work they also tried to determine the contribution of sliding, or the contribution of strain from the grain boundaries. So they carried out something called as marker experiments so they conducted some marker experiments and they looked at the marker displacements in the center of the grain and close to the grain boundary.

Now what is generally known is if your grain boundaries are playing an important role, if the grain boundaries are participating in the plastic deformation process then you are going to have a lot of strain concentrated in the region of the grain boundaries, so you will have a lot of strain there.

And which means the contribution of grain boundaries to the overall strain is going to be high. But what Harper-Dorn observed in their experiments is

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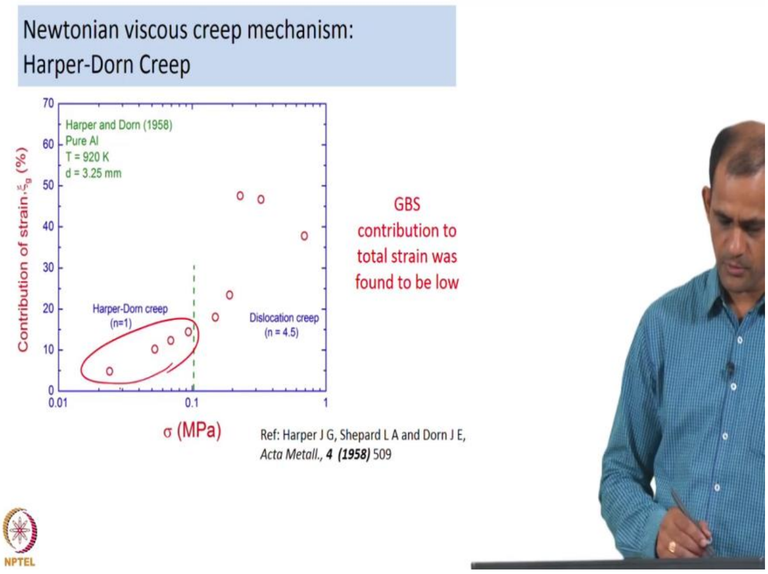

the contribution of grains boundaries towards the total strain is very small, it is less than 20 percent.

So this was also taken as an evidence for the lack of grain boundaries participation in the creep process. Furthermore

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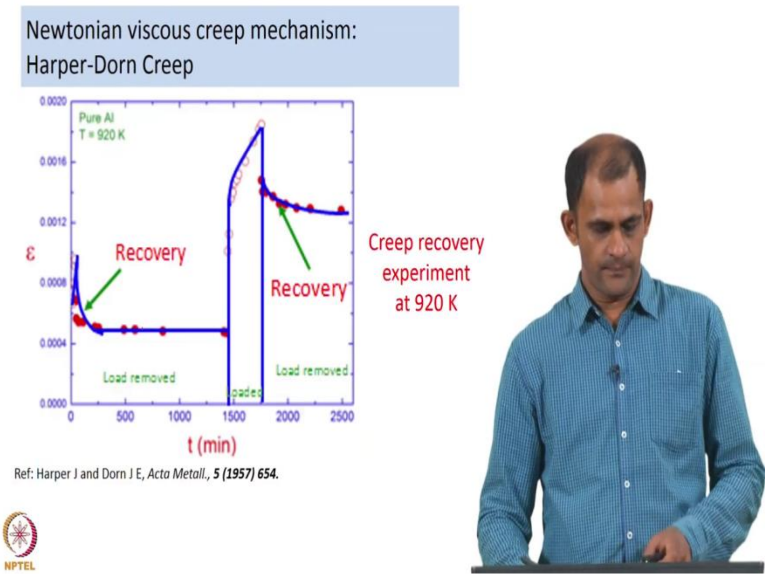

they also carried out something called creep recovery experiment. So basically in this set of experiments, when you have creep, when you have a typical creep curve of plastic strain versus time, you load it and then you unload it.

When the load is removed, if it is a dislocation-based mechanism then you will always have some amount of recovery, strain recovery and that is what they observed. So they loaded the sample to some strain value and then they removed the load and there was recovery and this is basically what is being shown in this.

So the fact that they saw recovery, creep recovery was also taken as evidence that this mechanism of creep involved, say dislocations instead of diffusion of vacancies and things like that.

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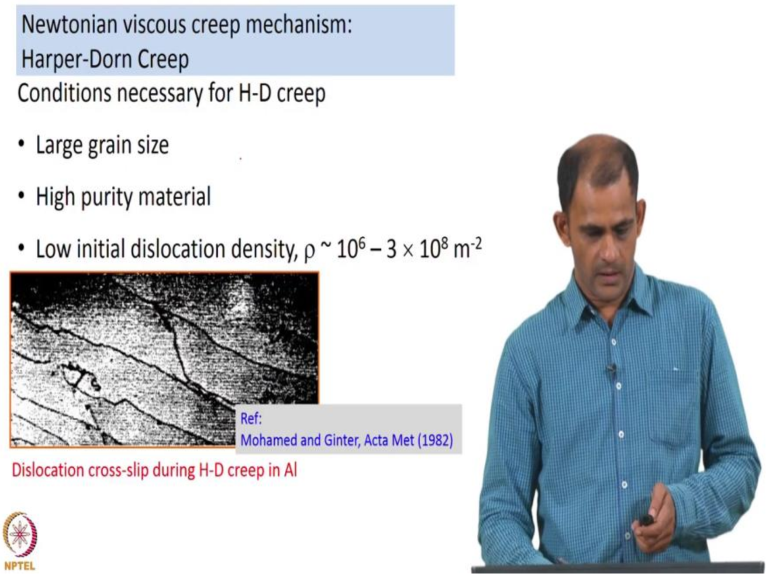

Now over the years what has been observed is the, the Harper-Dorn, Harper and Dorn were located in California in U S and that is where they carried out these experiments.

And over the years very interestingly, only groups which carried out their experiment in California were observing Harper-Dorn creep whereas groups which were carrying out these experiments in other parts of the world did not come across Harper-Dorn creep.

And so interestingly, people started saying may be this is a Californian artifact and probably there is nothing called a Harper-Dorn creep mechanism.

But in a later time, by, after carrying out some very systematic experiments,

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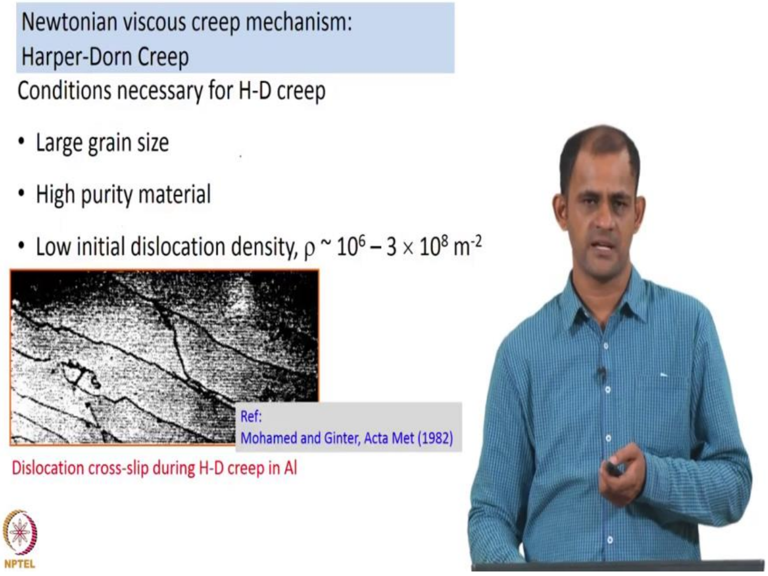

Mohamed and Ginter in one of their articles, in one article mentioned that there are certain conditions which have to be followed or certain experimental conditions which have to followed for the material to be deforming as per Harper-Dorn creep.

So if these conditions or experimental conditions are not met or if they are not satisfied then probably the material will not exhibit Harper-Dorn creep. So the main conditions for Harper-Dorn creep are the material should have a very large

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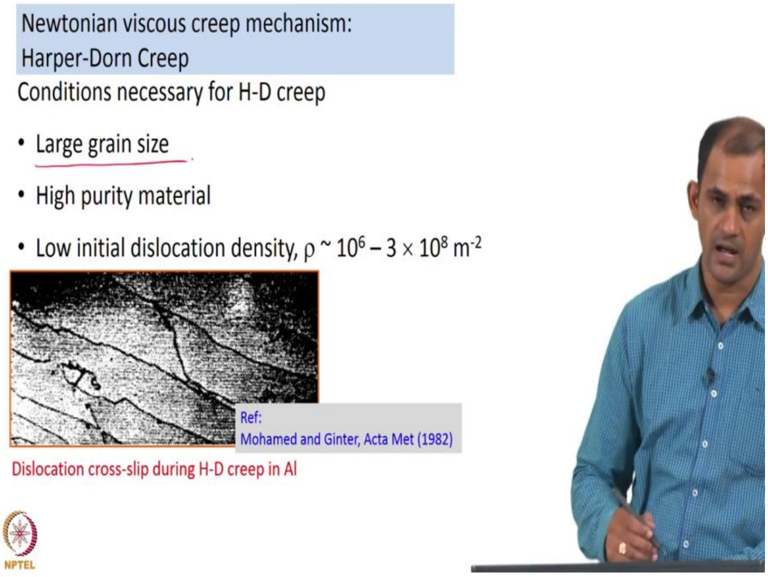

grain size.

So if you see Harper and Dorn in their experiments used polycrystalline aluminum with a grain size of 3.3 mm which is a significantly large grain size and so one of the necessary prerequisites is that the material should have a large grain size.

Secondly the purity of the material has to be very high. So again Harper and Dorn used the material which had purity of 99.95 percent. So aluminum with the purity of 99.95 percent was used

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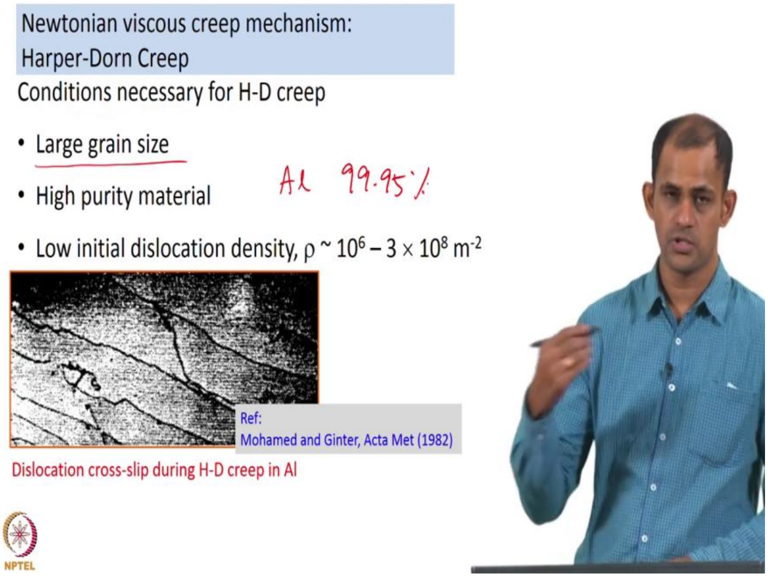

in their set of, was used by Harper and Dorn in their experiments. So Mohamed and Ginter said that this criterion should also be met.

And finally the initial, the dislocation density of the material to start with should be low. So the dislocation density that Mohamed and Ginter are saying, that the material should have is in the range of 10 to the power 6 to 10 to the power 8 per meter square.

So if you have dislocation densities higher than this, then probably dislocations will also play very important role and the mechanism of creep can then move towards probably dislocation creep based mechanism or something like that.

So dislocation creep we are going to talk about, that under Power law creep so, in the coming portions, so what Mohamed and Ginter said is that these three criteria have to be met

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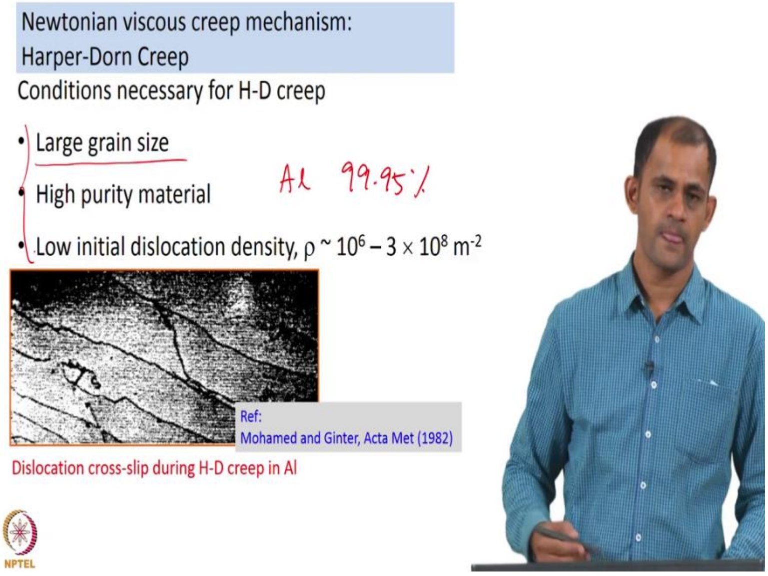

for the material to display Harper-Dorn creep mechanism.

And Mohamed and Ginter also, through their experiments they showed that the material which is crept under Harper-Dorn creep conditions will have the microstructure such as this. So they said dislocations definitely are participating in the deformation process which is also,

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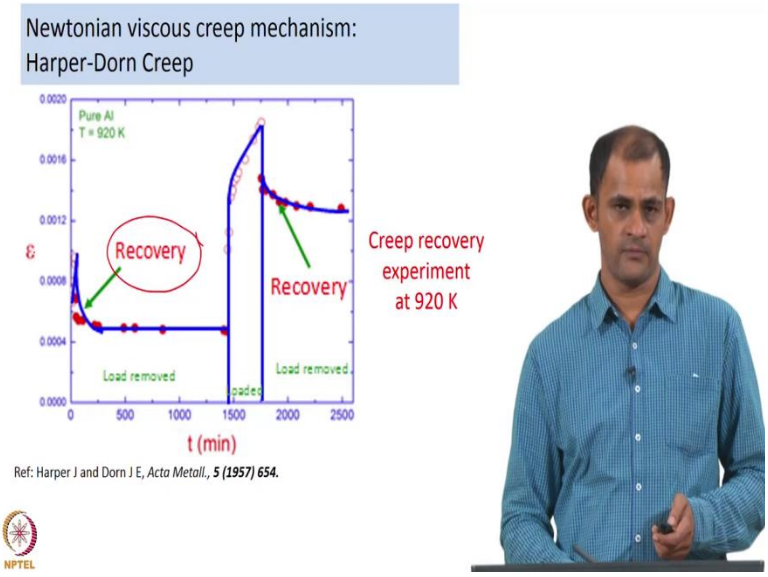

which as Harper and Dorn said from their recovery experiments, there are dislocations that are participating in the deformation process.

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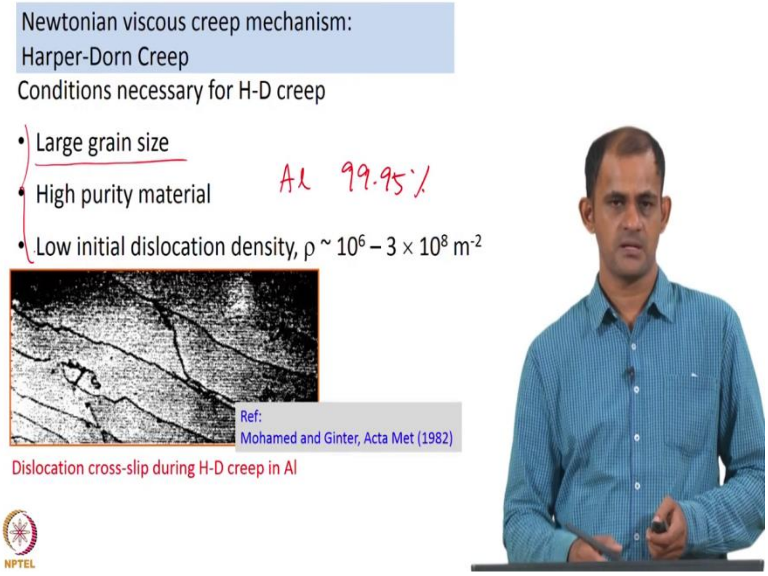

So Mohamed and Ginter from their T E M experiments, they showed that there are dislocation cross-slip happening and during Harper-Dorn creep and so they said that, indeed dislocations are participating during Harper-Dorn creep.