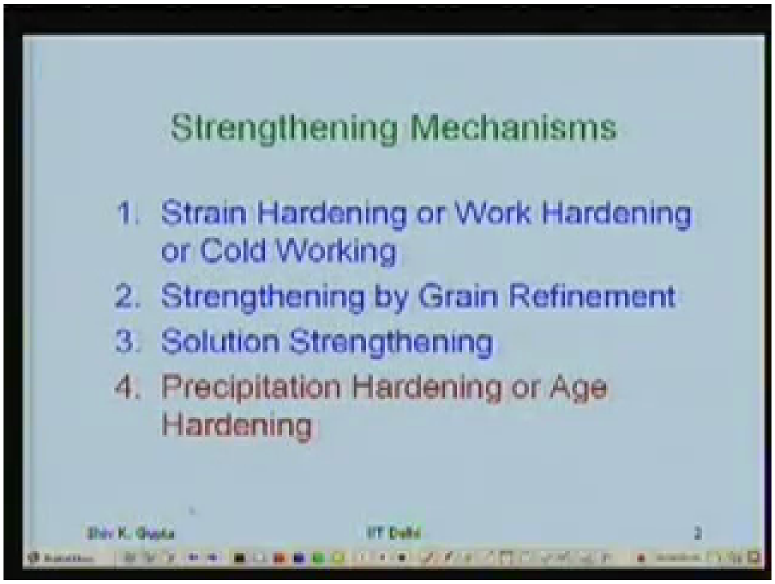
Materials Science
Prof. S. K. Gupta
Department of Applied Mechanics
Indian Institute of Technology Delhi
Lecture 31
Strengthening Mechanisms Creep

(Refer Slide Time: 1:04)



Strengthening Mechanisms

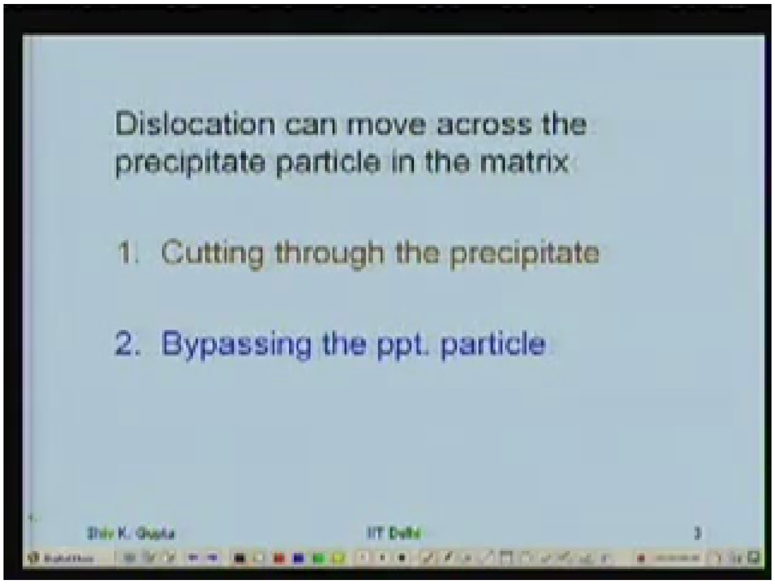
1. Strain Hardening or Work Hardening or Cold Working
2. Strengthening by Grain Refinement
3. Solution Strengthening
4. Precipitation Hardening or Age Hardening

Shiv K. Gupta IIT Delhi

In the last class we were talking about the strengthening mechanisms and we have looked at the mechanisms working for the strain hardening, mechanism for the grain size effect. That is if I have a fine grain material, it is more difficult to make the plastic deformation go on, that means the yield strength of material becomes higher. And so coarse grain material, yield strength is low. I have just seen the effect of the solutes and we said that martensite is one wonderful structure which provides all the three mechanisms working.

Prep mechanisms also works which we are going to discuss today in martensite, that we have seen and secondary hardening. During tampering if the carbide which forms is a very fine precipitate, it visualize to secondary hardening, right? We define precipitate that we shall understand today when we talk about the precipitation hardening or age hardening in materials. When the precipitate particles are present in the matrix, only with the volume, they form an interface with the matrix.

(Refer Slide Time: 2:26)



Dislocation can move across the precipitate particle in the matrix

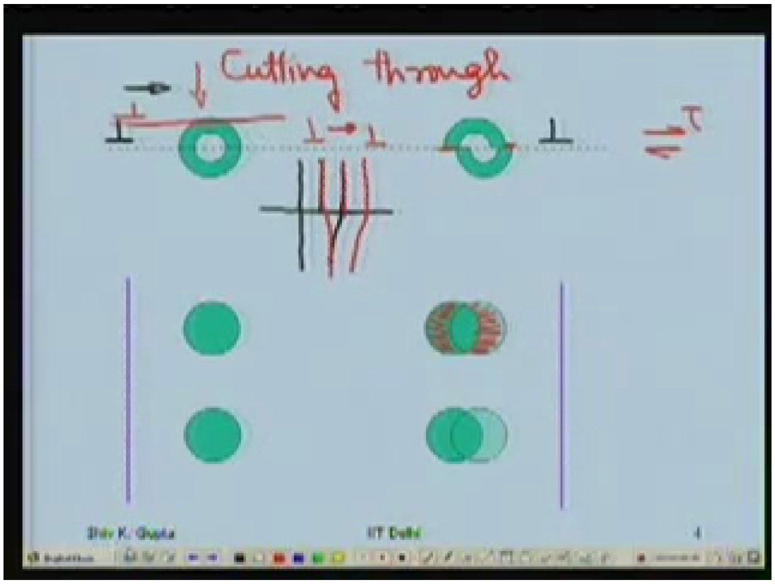
1. Cutting through the precipitate
2. Bypassing the ppt. particle

And the interface has an interfacial energy. Interfacial energy could be small, interfacial energy could be large depending upon what is a precipitate and what is the matrix. Now a dislocation which is moving, that is slipping in the matrix to cross the plastic deformation, has two options. It goes across the precipitate and cuts it through or it bypasses the precipitate. These two mechanisms, we shall look at. Cutting through the precipitate is possible generally if the precipitate is very small in size so that whatever the difference of the interface is, it provides even at same strain continuity of slip planes from the matrix to the precipitate.

The precipitate is a different structure ultimately. It can provide a continuity of the slip plane if it is small in size, (())(3:37). And depending upon the interfacial energy, well sizes to be also restricted by that. The high interfacial energy is there, size has to be very small which can be cut through and means the strains at the interface are going to be high. And the interfacial energy is small, strains are going to be small. Small strain means more matching planes, so that is what is happening. We will show you that.

And then if the precipitate becomes big enough, interface becomes incoherent. That is it does not provide me a continuity of slip plane. Dislocation cannot enter the precipitate, so it has no alternative but to bypass it. How does it bypass this, that we shall see today.

(Refer Slide Time: 4:35)



This is the cutting through mechanisms, let us see I have a let us say a dislocation here. A dislocation which is an edge dislocation, the positive edge dislocation let us say. And the applied stress it is slipping in this direction, why? If suppose this provides a continuity of slip plane which I have shown here, maybe some strain there at the interface. So dislocation will continue to move as if there is no precipitate there.

When it continues to move, crosses those new precipitate, what happens is when it comes out onto the other side like this, it cuts through the precipitate particle like this. Why does it do that? You have to recall how the dislocation slips. When this dislocation slips by one step, it forms a plane with that and this becomes a part plane. So this plane actually it is a part plane shifted to the left. That is what is happening. When these planes are shifted by one step, then interplanar spacing they are shifted to the left on the top, the atoms have gone to the right. It was a negative dislocation, it could be other way around. So when the dislocation goes across the precipitate, it cuts through, that is why call cutting through mechanism.

“Professor-student conversation starts.”

Student: Sir, what is the requirement for this?

Professor: Let us see. We will understand the (mecha), let me call (())(6:46).

Student: The early ones was 3 diameter.

Professor: Not necessarily.

Student: So dynamic content you can differentiate.

Professor: Yes, you get differently. It depends at what location it is. It can cut it through, suppose the dislocation is on this slip plane here, it can cut through here.

Student: The precipitate should be of same size of the grain material like (())(7:10).

Professor: No, it is not means such a small enough, it may be different crystalline arrangement than that crystalline arrangement also. That mid some strain, it provides continuity of the slip plane. That is because they are small in size, 10 to 20 Armstrong, that is what the kind of diameter I am talking about. It is a very small size.

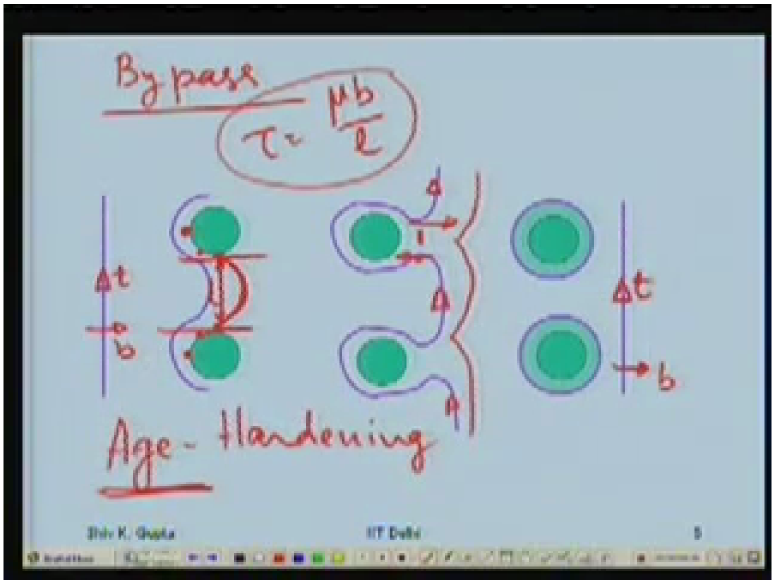
Now what has happened is when the dislocation, let us say I am showing the two precipitate particles, dislocation is here. This is the effect. Let us say I am seeing in that direction, now I see from the top view, that is, from that direction if I see in this direction here, that is a direction in which I view. Then it looks like this, this is the dislocation line. These are only two precipitate particles. When it cuts through them, the top has gone to the left and bottom has gone to the right.

As a result, just see carefully, this crescent area is an interface between the matrix and the precipitate which did not exist before. Similarly this crescent here is an interface between the matrix and the precipitate. This did not exist before which is shown here, this part and that part there. Interface, additional interface area, additional interfacial energy. So when the dislocation was here, that extra interface was not present. When the dislocations come out on this side, this interfacial area cannot out. Thereby no more interfacial energy is there.

That energy should come from where? It should come from the person who is making the dislocation move, person who is applying resolved shear stress. So resolved shear stress has to be increased. You may have to do this work so that this energy gets stayed here. So I have high stress required to make the dislocation move across rather than the stress required to make it slip in the matrix. Here I do not have to apply that additional stress but when I go across, I have to apply the high stress.

And that additional stress which I make is increase in strength. That is one and that is true when the interfacial energies are small usually. When interfacial energies become too high, normally I have lot of strain and I do not get any continuity of the slip plane. By that time probably the precipitate has become much bigger. It contains, instead of some 1500 atoms, it contains now 500-1,000 atoms. It has become much bigger in size. If that has happened, then it is possible for the dislocations to move still and cross the plastic deformation, thereby passing the precipitate particle.

(Refer Slide Time: 10:24)



We shall look at this process of bypassing. Let us say this is again a dislocation line here. t vector and the b vector, I consider same positive edge dislocation. This dislocation gets obstructed when it comes the, at near the interface of the precipitate in the matrix. So it starts to get pin down here and starts growing above the precipitate particle like this. But when it goes, the pinning climbs change. Pinning climbs keep changing and till now reached the pinning climb which is right here.

And then dislocation is pinned at between these climbs and we are trying to pull out it from the semi-circle for which you have to apply the maximum possible stress. Light defect it says after that further movement is automatic. So stress you need to apply here, this is the distance between two precipitate particles, center to center distance, it is from surface to surface. Let us call it L. Then the stress I need to apply is mu b by L.

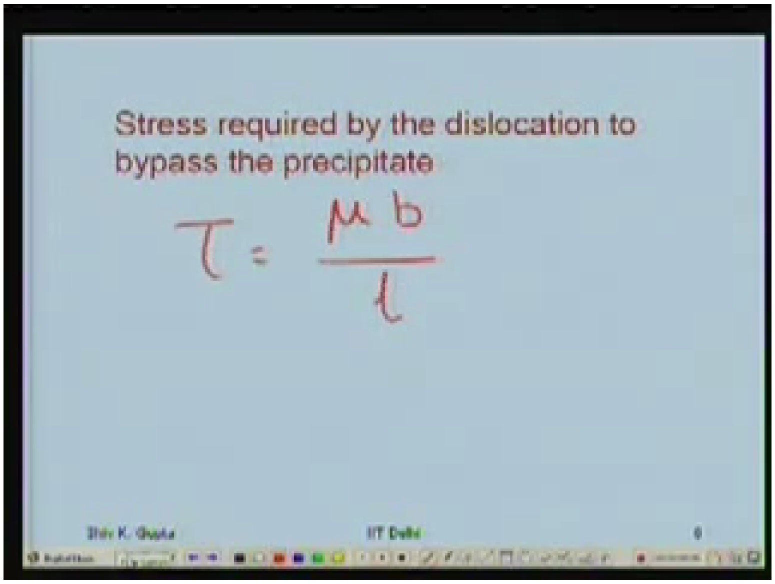
As a semi-circle, it automatically goes to the other contours. And when it comes here, you can have your dislocation line vector going like this. If this position, dislocation vector, t vector is here, here the dislocation vector is there and therefore the opposite dislocations on the same slip plane. They come closer and cancel each other, and form a loop like this. And the remaining part jumps like that, it jumps out and dislocation has come out. With the same sign, same character it comes out but it has left behind a loop.

So that is called the bypassing the precipitate particle, this is how a dislocation can bypass the precipitate particles and still slip. And the stress you need to apply is mu b by L. For this to be an effective strengthening mechanism, this L should be as small as possible. And that is what we discussed, we are talking about the precipitation hardening. As the time progresses, nucleation of more and more precipitate particles is taking place in the matrix and thereby the inter-particle spacing is decreasing.

Since the inter-particle spacing is decreasing, the strength is going up and up and up. However it reaches an optimum value that is when all the precipitate which is supposed to be formed as given by the lever rule is formed and no more transformation is possible. When the interfacial energy of the precipitate with the matrix is too high in such a situation and that becomes a driving force for a next step that is called the over ageing or the coarsening of the precipitate.

Precipitate begins to coarsen, thereby some precipitate particle dissolve in the matrix and they precipitate over the growing precipitate particles, so they grow in size. And thereby inter-particle spacing begins to increase, the step begins to decrease. That is why we also call it age hardening. As the time passes, the strength of the material initially increases. Once it reaches the optimum, it begins to decrease. Ageing process is this, that precipitate process or precipitation process is on. At close to completion, near the optimum and after that it begins coarsen, precipitate particles begin to coarsen and they become bigger in size.

(Refer Slide Time: 15:05)



Stress required by the dislocation to bypass the precipitate

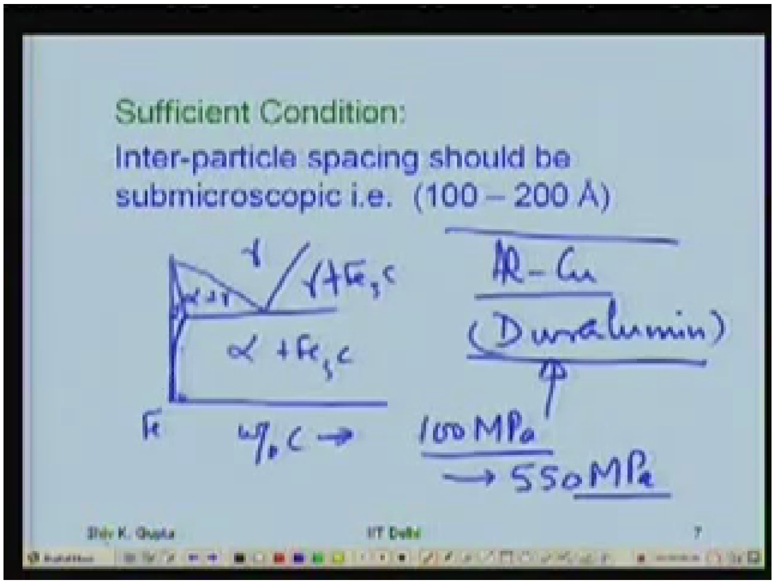
$$\tau = \frac{\mu b}{l}$$

Shiv K. Gupta IIT Delhi 6

All right, so that is what we have seen the stress required to bypass the precipitate particle. mu is the shear modulus, b is the magnitude of the Burgers vector and L is the space or distance between the two precipitate particles between which the dislocation has to go. And from that you need to apply this stress which we also saw for Frank-Read source, they have not derived it but this is what you take granted and discuss that which is the stress which we need to apply.

And from this it will be possible for us to see, I work on some numbers in a problem, that link L should be in the range of few hundred Armstrong. If it is more than that 1,000 or more, then it is not an effective strengthening mechanism. Certainly by the time it is 10,000, it is no effect. So I am looking for size between 100-200 Armstrong, precipitate or diameter and that shall be very effective. And this L will also be of the same order of magnitude as the diameter.

(Refer Slide Time: 16:44)



Sufficient Condition:

Inter-particle spacing should be submicroscopic i.e. (100 – 200 Å)

Al – Cu
(Duralumin)
100 MPa
→ 550 MPa

Shiv K. Gupta IIT Delhi 7

So therefore I am talking about the precipitation transformation. I said the necessary condition is you obtain first the super-saturated solid solution so that with time it goes to saturated solid solution and a precipitate forms, the second phase forms. The sufficient condition I left at that time and the sufficient condition now is the inter-particle spacing or center to center distance. Inter-particle spacing should be submicroscopic in size, that is in the range of 100 to 200 Armstrong could be effectively strengthening it.

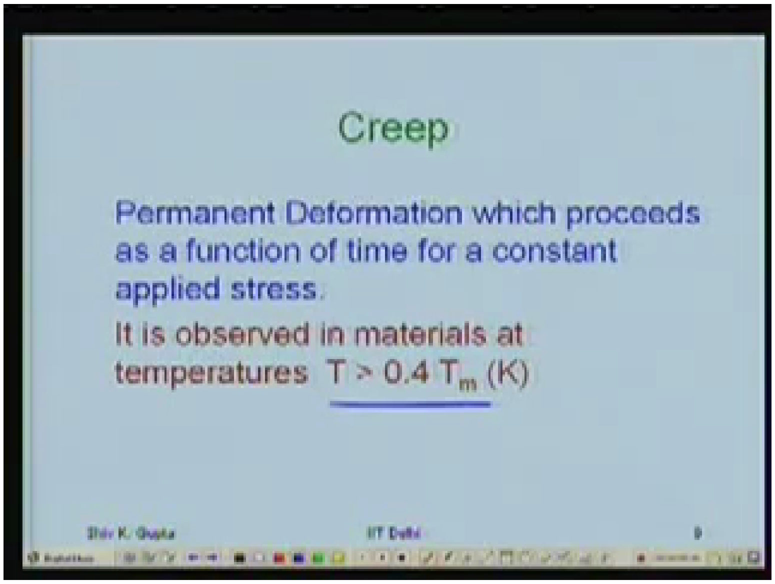
After no move, this is the kind of distance I get at the end or the optimum edging. Then less than optimum edging, it will be slightly lower than this because fewer particles are present. So that is the kind of distances and spacings which we require for hardening to take place by precipitation. Then such a situation is getting a super-saturated solid solution is present in almost all phase diagrams. But I do not get say for example, this diagram show the decreasing solubility with decreasing temperature.

Therefore it should be possible for me to have a solid solution here, I quench it to get super-saturated solid solution and all alloys do not show me the precipitation hardening or the age hardening. There is a necessary condition I write. I can quench it and keep it in solution or the solute but the precipitate forms does not provide me the fine inter-particle spacing what I am looking for in the range of 100 to 200 Armstrong. Sufficient condition is not satisfied, that is why we took the example of aluminum copper alloy which we call duralumin.

Some name for these alloys are producing this kind of precipitation hardening and the duralumin is less strong as compared to steel but you can get effective strengthening. And as a matter of fact, aluminum usually will be of the order of 100 megapascal strength, it can be made to go to 550 megapascal with alloying and giving the precipitation hardening. 4-5 increase in strength is possible and that is kind of thing which we get by precipitation hardening and some aluminum alloys.

With this strengthening mechanism and as I said the when we had alloying additions like vanadium, niobium, titanium or tungsten, molybdenum, things like that which produce very fine carbides during tampering, can give rise to secondary of hardening of steels. That is also same mechanism as the precipitation hardening. We shall look at the next deformation which is permanent deformation in materials, then this permanent deformation goes on as a function of time when I call the viscous flow of the material or the creep.

(Refer Slide Time: 20:40)



Creep

Permanent Deformation which proceeds as a function of time for a constant applied stress.

It is observed in materials at temperatures $T > 0.4\ T_m$ (K)

Shiv K. Gupta

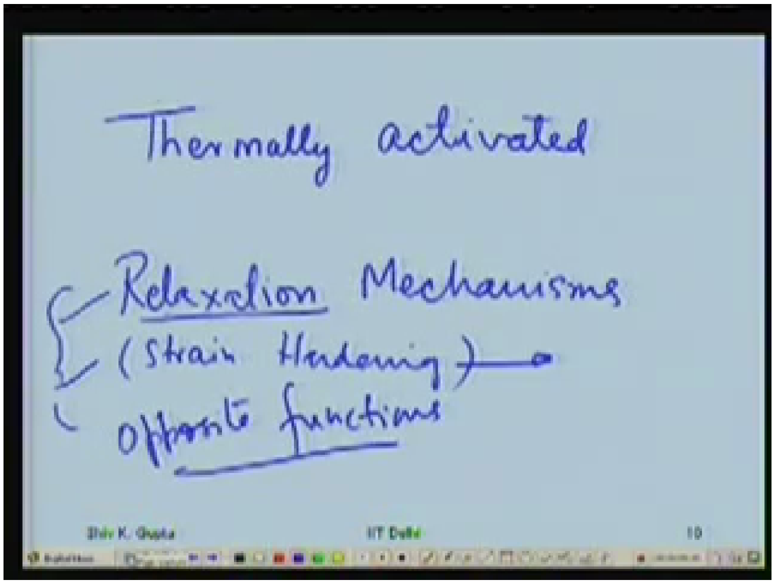
IIT Delhi

9

Creep as I already said is a permanent deformation and it seems as a function of time and I am not changing the applied stress. Stress is a constant and it means a kind of problem for engineers who are working in power plants, let us talk about the turbine. Turbine is functioning normally at high temperatures. And it is working constantly for years together, the material is at high temperature and there is a stress all the time, thus rotating in the tension blades go through the stresses, stress cycles. And it is all the time under stress and it is at high temperature.

The creep can take place, blade can deform plastically and if the blade increases by even a fraction of a (())(21:37) which crosses the clearance which you have between the casing and the blade, it will then jam. The moment it gets jam, it will break because there is a force acting already to make it move. And breaking of a blade is a very common problem in turbines. So that is the creep taking place in such a place, location or the temperature is high and this phenomenon is observed whenever the temperature exceeds 40 percent of the melting point. And the melting point is expressed in Kelvin. That shows that this phenomenon is a thermally activated process.

(Refer Slide Time: 22:26)



Thermally activated

Relaxation Mechanisms

(Strain Hardening) →

Opposite functions

Shiv K. Gupta

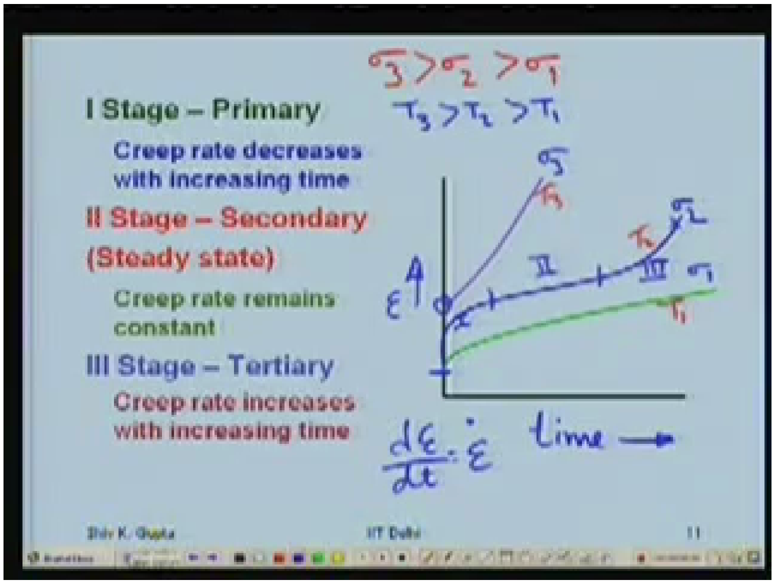
IIT Delhi

10

Creep is a thermally activated process. We have seen that when plastic deformation occurs in a material, by and large it is a slip motion of the dislocation. Dislocation slip can cause plastic deformation in the material and then that happens, no dislocations form because of dislocation sources and they start interfering with the moving dislocation, work hardening or the steel hardening takes place.

However this thermal energy is doing, it is probably allowing this obstructive dislocation to overcome this obstruction. And I call the dislocation is getting relaxed, for I refer to this as relaxation mechanisms. And there is already strain hardening taking place and the plastic deformation occurs. Therefore these are the two which are working opposite to each other. Once this hardening can be overcome with because of the relaxation, dislocation will continue to slip and deformation will go on. We shall try to look at these relaxation mechanisms in materials.

(Refer Slide Time: 24:23)



I Stage – Primary

Creep rate decreases with increasing time

II Stage – Secondary (Steady state)

Creep rate remains constant

III Stage – Tertiary

Creep rate increases with increasing time

Shiv K. Gupta IIT Delhi 11

Before that we shall look at the phenomena logically what happens when the creep occurs in the material. This is the observation, or this axis I have the strain and this axis I have the time. Time extends inverse, so we can choose the logarithmic scale. Well, this I have shown the three different curves, you can consider them at three different levels of stresses. Let us say sigma 1, sigma 2 and sigma 3. And I would say that sigma 3 is greater than sigma 2 is greater than sigma 1.

We could also consider that same level of stress sigma but different temperature. Then this can also be the effect of T1, T2 and T3. And what we have is T3 is greater than T2 is greater than T1. On this axis if you look at, when the load is applied and the temperature is greater than the 40 percent of the melting point, instantaneously you get the deformation in the material, that is called the time independent deformation. Time independent deformation could be elastic, it could be elastic and plastic depending upon what is the stress you are applying, what is the load value you are applying.

And with that once you leave it, as a function of time the strain keeps on, elongation keeps on going on, goes on. Well, there are three parts of the curve which can be seen very clear in the second one. First one here, second one there, and third one there. This is called the first stage, this is called the second stage and this is called the third stage. And differentially we faced this on the basis of the slope of the curve. In the first stage, slope of the curve is decreasing with increase in time.

In the second stage, the slope of the curve is constant, it is straightening. In the third stage, the slope of the curve increases with the increase in time. So I have the minimum strain rate which is called the minimum creep rate in the second stage. In the first stage I have a creep rate higher than that, creep rate is nothing but the slope of the curve which is called the strain rate because it strain and the slope will be the derivative of the strain versus time which is d epsilon upon dt, is written like epsilon bar which is called the strain rate.

This strain rate is minimum in the second stage. The first stage, initially when the slope is high and it continuously keeps on decreasing. And the second stage is also called the steady state because strain rate or the creep rate is a constant. It keeps on flowing on the same rate. And third stage and the tertiary stage, creep rate increases with increase in time. There are different things are happening in the three stages.

In the first stage, obviously there are two things which I said which are working. One is the strain hardening, other is a relaxation. Which one is more dominant than the other? Strain hardening is more dominant than the relaxation. By the time I come to the second stage, strain hardening and relaxation, they are going equally. If in the time, given time, 10 dislocations were obstructed in the same time, some more 10 dislocations are relaxed. So necessarily the same dislocation which is obstructing may be relaxed.

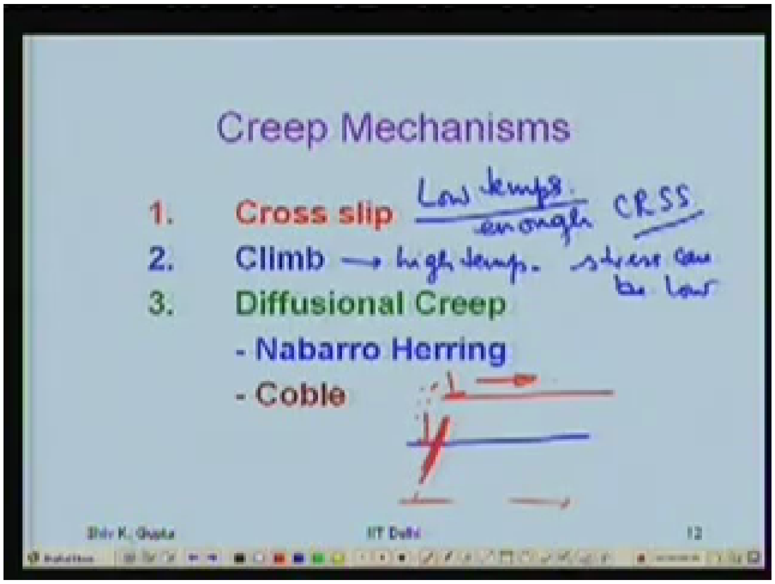
With the number of dislocations which are flowing, which are slipping, are never same and it remains same, so whatever is cut, obstructed, same number or same kind of a dislocation get relaxed somewhere else, is a material and deformation goes on at the same rate. By the time I have the third stage, the flow of the material has taken place to such an extent that the formation of void spaces at the grain junctions, grain boundaries, therefore any cross-sectional area effectively is reduced just like in making.

It can also get to such an extent there could be next formed in the specimen. And then the applied stress is no more, a constant value it becomes concentrated at those local regions where the area of cross-section is reduced. So now deformation will get localized. More stress, more strain and area of cross-section reduces because of the more strain, stress becomes more. So more strain, that is how the rate keeps on increasing with increase in time in the material fields or there is breaking taking place. It splits into two or more parts.

And this we have the curve, we obtained this first one which is at lower level of stress or let us say lower temperature. First stage is very long, and second stage begins after some time and it is going to be very, very long stage. Tertiary stage will start after a very, very long time. But when the stress and the temperature become high or stress or the temperature become high, I promise you only the third stage. First stage, second stage gets, applies right there. It is a very small time in which the first stage and second stage is completing. That is process of creep is very, very fast such a high temperature. So that is just kind of thing which we observe.

But the time scale depends upon the applied stress and the temperature, the time scale for the whole curve to be seen. In the low temperature, low stress, the time may be much much larger but in a high stress, high temperature, the same thing is reduced to a smaller time. So that is time is taken care of that manner.

(Refer Slide Time: 32:04)



Creep Mechanisms

1. Cross slip $\frac{\text{Low temps.}}{\text{enough}}$ CRSS
2. Climb → high temp. stress can be low
3. Diffusional Creep
   - Nabarro Herring
   - Coble

Now let us look at these relaxation mechanisms what we refer to the creep mechanism. Some of these things are already seen: cross slip of screw dislocation. It does not require temperature, it does not require the hype of, though slip motion or dislocation is self thermally activated process, it depends upon the temperature. Benefit of the screw dislocation which is obstructed, it can begin to cross slip over another slip plane, only thing is I have to apply enough stress so that there is a resolved shear stress good enough on that slip plane for it to slip there.

Resolved shear stress required should be critical value on the second plane where it is going to cross slip. This happens at low temperatures, it happens at low temperatures but I need enough resolved shear stress. It should be critical value on the second. Even when edge dislocation which is obstructed, it has to change the slip plane from there, it can only climb, either climb up or climb down. It require diffusion of atoms or the diffusion of vacancies either towards the edge of the part plane or away from the edge of the part plane. Therefore this is requires elevated temperature but stress can be low.

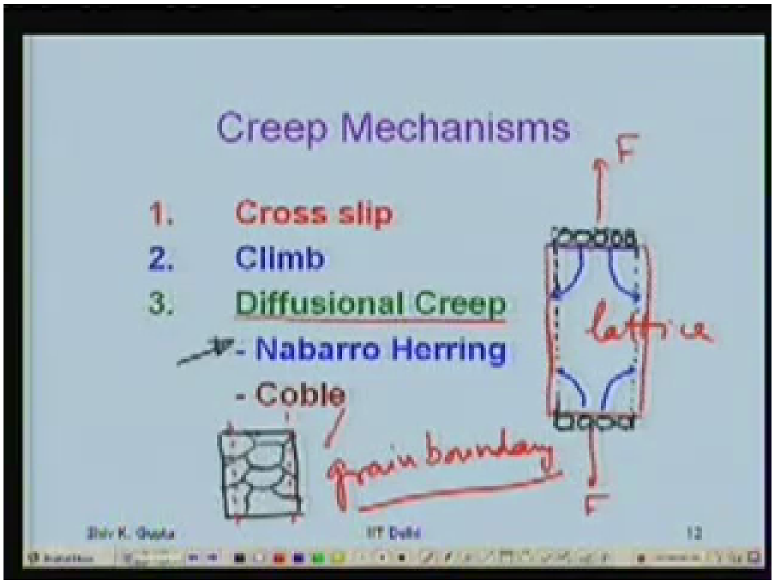
“Professor-student conversation starts.”

Student: Sir, how those climbing can cause plane to strain?

Professor: Climbing, see a dislocation which is moving here on this plane is obstructed right here. If it moves from here, goes over to this plane, it may not be any obstruction, it has jumped up and then it starts looking there. Obstruction is here, on this obstruction another strain field. Some strain field which is obstructing it here, may not be present a few planes away, five planes away. It can jump up by five planes and then start slipping. Or it can jump down the five planes and then start slipping. So that is where is decline and that high temperature is required because diffusion is required. Diffusion is relatively faster if the temperature is higher.

“Professor-student conversation ends.”

(Refer Slide Time: 34:53)



Creep Mechanisms

1. Cross slip
2. Climb
3. Diffusional Creep
   - Nabarro Herring
   - Coble

Shiv K. Gupta

IIT Delhi

Let us look at the diffusional creep. This diffusional creep is also going to take place by diffusion of atoms or diffusion of vacancies. Let us say this is the force which you applied or stress you applied and this is the material which is deforming. In this case vacancies have to move from these planes which are here perpendicular to applied stress and go over to the planes which are parallel to the applied stress.

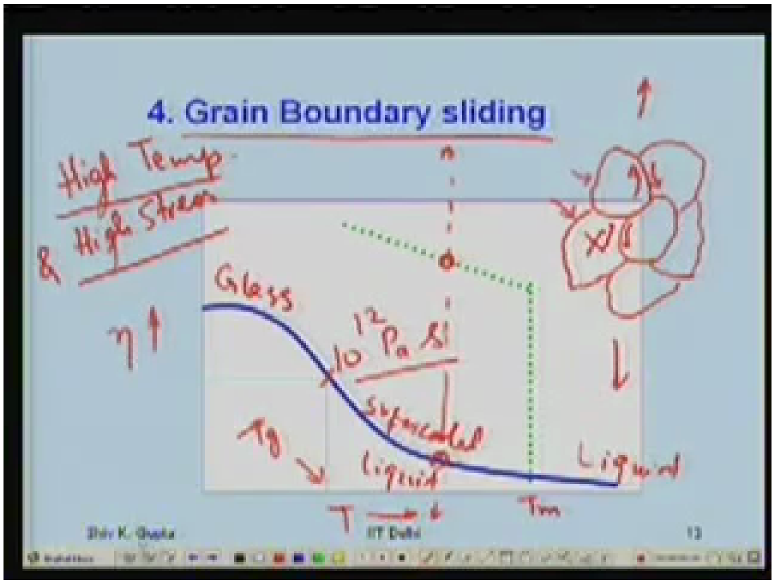
And when that happens, what is going to happen is these layers will move inwards because vacancies have come. And atoms on the other direction have gone upwards and they have increased the, atoms can come and here they are deposited like this. So area of cross-section is reducing, length is increasing, creep is going on, deformation is going on. And this is a time dependent phenomena. How many vacancies that are moved here, depends upon the time because the diffusion of vacancies.

This is going through the lattice and is referred to as Nabarro Herring creep. The same thing can also be achieved in the material if the diffusion occurs along the grain boundaries, polycrystalline solid. With diffusion occurs along the grain boundaries, effect is vacancies have to come to this low. Vacancies have to come and this is reduced but decides to go through the grain boundaries rather than the lattice. That is called Coble creep. So that is the diffusion caused along the grain boundaries, you know is going to be easier. But lattice diffusion is going to be slower than the grain boundary diffusion.

But the area of cross-section available for the grain boundary diffusion is less. That is why it becomes more effective at lower temperatures. So therefore this is the two kinds of diffusion of vacancies, is basically diffusion of vacancies only the path used. In this case it is a lattice which is used. In this case it is the grain boundaries which is used for diffusion and the result is the area of cross-sectional space reduces and the length increases. So plastic strain is going on and material continues to deform, so creep goes on.

There is another mechanism which is also working. But before I come to back, this diffusional creep is strongly temperature dependent. I should have very high temperature so that I can provide for diffusion of vacancies or diffusion of atoms. And applied stress need not be very high for this.

(Refer Slide Time: 39:08)



4. Grain Boundary sliding

Now there is another mechanism which also is working is called the grain boundary sliding. Let us see, here I am showing the curve which I showed you earlier, the viscosity versus temperature and that is the melting point. While for a crystalline solid, the viscosity, the liquid structure is small but it increases with decrease in temperature. The melting point suddenly increases by 18 to 20 order of magnitude and then in the crystalline solid it increases slowly, gradually with decrease in temperature.

But when it is glass like structure, non-crystalline structure, the viscosity gradually increases, passes through a glass tension temperature where the viscosity is 10 to the power 12 Pascal second which we defined arbitrarily as dividing line between the solid and the liquid and this is called the super-cooled liquid where it is liquid of course and there it is glass. What happens to the non-crystalline solids? Now in a solid where I have grains like these there is a region which is crystalline and it is going to behave like the dotted line. And there is a region which is non-crystalline and going to behave like this glassy material, non-crystalline structure.

“Professor-student conversation starts.”

Professor: Which is the non-crystalline region, which is the crystalline region in a polycrystalline solid?

Student: Along the grain boundaries there is non-crystalline.

Professor: Yes, along the grain boundaries there is no crystalline arrangement. It is a glassy matrix basically. And the grain boundaries are the, sorry the grains are the crystalline region.

“Professor-student conversation ends.”

So here I have crystalline region and here I have non-crystalline region, the grain boundaries. When I am at temperature which is above the 40 percent of the melting point, somewhere here below the melting point I am, at this temperature range, this is the viscosity of the crystalline solid and this is the viscosity of the grain boundary region. And we applied a stress. The situation at this high temperature, elevated temperature is like we have seen there are laying the carpet on the road, they bring the hot mix, hot mix is pebbles which is being heated and coated with tar. That is called the hot mix.

The lay it on the road and then they allow the road roller to move over this, it stacks it. And they allow sliding now. So this is the situation like that, we have a hot tar which is fluid and can flow. But inside pebble though they are hot, they are very rigid, but those pebbles unable to slip around and you can make a uniform carpet on the road. That is exactly what is happening here, quite similar to that. That you have these regions which are glassy or rather you can say in that high temperature there is a super-cool liquid state.

And the applied stress, they start to slide against each other. And because of the sliding taking place, deformation goes on. For here I meet high temperature so that the viscosity of the grain boundaries is very low. And secondly I meet high temperature because there should be a component of the applied stress which is a shear stress and can make the grain boundary slide. There could be a slip or the sliding motion taking place at the grain boundaries.

“Professor-student conversation starts.”

Student: Sir, even at the (())(43:51) slightly we want to change the shape of the gradient, that is purely be (())(43:56)?

Professor: Yes. Actually grain will not distort. They are not the, dislocation will take in part of this kind of thing.

Student: Sir how is creep going on, maybe in….?

Professor: Yeah, these grains when they slide, they get elongated in the direction of the applied stress. They start moving in the direction of the applied stress now, so they start shrinking on the lateral direction and the longitudinal direction they start extending.

Student: Penalty time.

Professor: Yes. Since it is a viscous flow, that is why (())(44:28), okay, it is a viscous flow because this is a viscous field basically. And it is not, the viscosity is not very low that you feel like water. Water has a very low viscosity. So it is only the applied stress, so it is flowing. So I need both, high temperature and high stress for this phenomenon to take place.

“Professor-student conversation ends.”

(Refer Slide Time: 45:16)

Resistance to Creep

Shiv K. Gupta IIT Delhi 14

Now let us look at the materials where I can develop the resistance to creep. All right, before I go over to this, I just now talked about the grain boundary sliding.

“Professor-student conversation starts.”

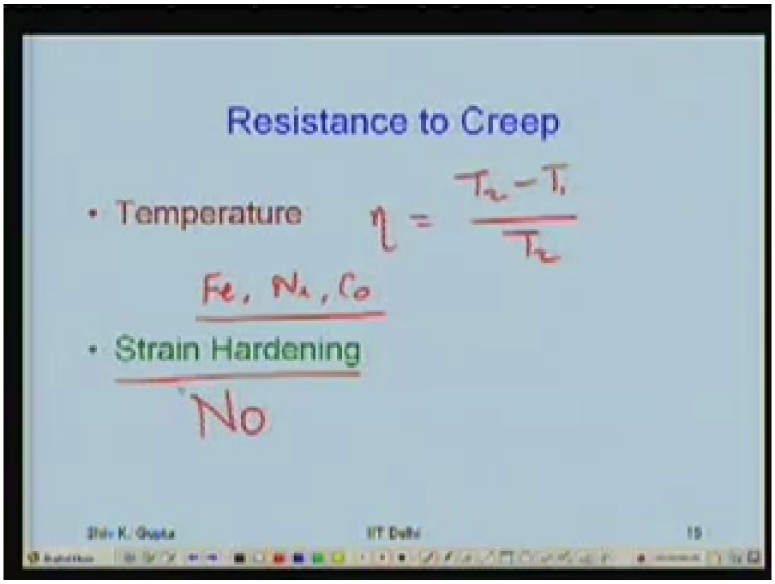
Professor: Now tell me if I have a fine grain material and I have a coarse grain material, where the grain boundary sliding can be more?

Student: Sir, in fine.

Professor: In the fine grain because there is no grain boundary area for the given volume of the solid. Probably no grain boundary sliding in the fine grain material. I said fine grain materials have mechanical properties, creep is at least the bad, worse. I need poor strain material if I want to have effective creep, we will talk about the resistance now, so see that. The resistance to creep, I must be able to stop these mechanisms which are working. That shall develop the resistance to creep.

“Professor-student conversation ends.”

(Refer Slide Time: 46:17)



Resistance to Creep

- Temperature $\eta = \frac{T_2 - T_1}{T_2}$

Fe, Ni, Co

- Strain Hardening

No

Shiv K. Gupta IIT Delhi 15

It is effective, the creep is effective or relaxation mechanisms are effective when temperature exceeds 40 percent of the melting point. So use the material, use melting point and use it below the 40 percent of the melting. Where is the need for you to worry about the creep if you are using the material below 40 percent of the melting point? Engineers have got serious problem. To get the efficiency in your (())(46:53) cycles, you have studied temperature of the source where you are operating should be high and temperature sink should be low.

And the efficiency of the cycle you have studied is T2 minus T1 by T2. That is the operating temperature is T2. T1 is the sink where the heat is exhausted, that could be room temperature or could be higher than the room temperature. Particularly in turbines, there are different stages. First stage T1 may be high, maybe 700 degree centigrade. Second stage it may be less, third stage may be still less and so on and so forth.

The starting temperature, initially the operation could be at high temperature like 1400-1500 degree centigrade where the efficiency should become high. If you have the T2 as 1400-1500 degree centigrade, efficiency will be more. Like the turbine not working less than 70 percent efficiency. So that is why you need the temperature to be high. Then try to find the material which has a high melting point. If I am working at 1500 degree centigrade which means about 1800 Kelvin, how much should be the temperature? 4500 Kelvin.

4500 Kelvin means more than 4000 degree centigrade should be the melting point, difficult to get a material. Tungsten is 3410 degree centigrade. But then if I make any object out of tungsten, I have to melt tungsten first or would have keep it, the molten metal. I must have a temperature which has a melting point more than that, it is very difficult to form objects from tungsten. So we use normally powder metallurgy route for making objects from tungsten.

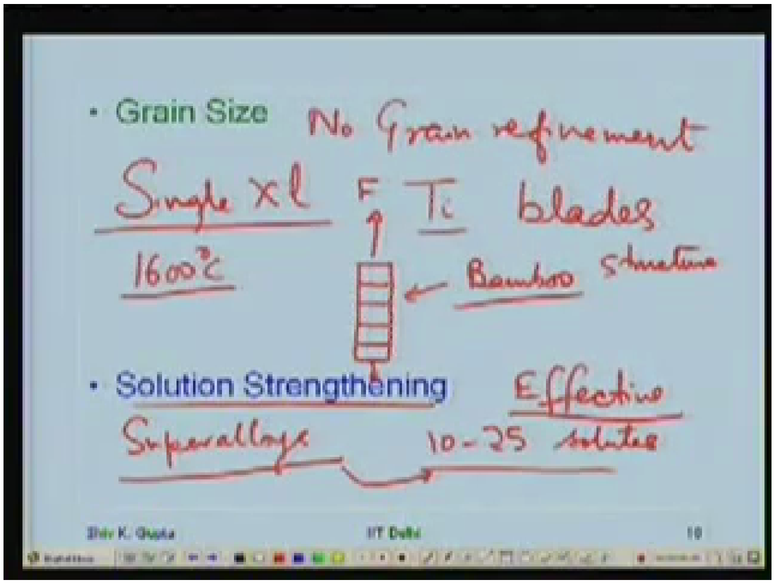
As a result, we have to live with materials with low melting points than 3000 degree centigrade. And most of them are either rarely found elements if they are in the range of metals and alloys and they are oxides. The problem with oxides which are available and I can make objects out of them, they cannot be used for structural application. They cannot be used for structural application because they are very brittle materials. Also their oxides could be acidic or could be basic in nature. So if I am using them somewhere where the medium is going to be acidic and uses the basic lining, it will not work like in a reactor.

Now chemical engineers are used to using reactors at high temperature. Still medium will strain the temperature but you put a lining inside which acts as an insulator for the steel case in the outside, at the same time it can work at high temperature. So there these oxides bricks which we use, magnesium oxide or iron oxide, these bricks or silica bricks, they have, they are brittle and can be used in the compression. So that is why I can use for lining. Only thing I do not show that what is the reactants or the products, if they are acidic, the lining should also be acidic in nature so that it does not corrodes or erodes with time in a faster manner.

So this problem of temperature, I have to use the materials at high temperature. And I need the structural materials which can withstand the some ductility, some deformation. I am to restrict myself to first long period where I have iron, nickel and cobalt. These are the base metals which we use for materials that, which are for creep resistant materials where all three of them have the melting points around 1500 degree centigrade. It is good enough temperature, again they have to live with it. But then we try to see now can we improve their creep resistance further, anywhere in the temperature, temperature I have no control over now. So that is what I have to see other mechanism.

The mechanisms which increase the strain, we talked about is strain hardening. Will it work? Why? 40 percent of the temperature is also the weak size in temperature, 40 percent of the melting point. So whatever research you dropped, the dislocation density, crystallization will overcome that effect and it will be a very soft material. It will not be effective at all, so I cannot use that.

(Refer Slide Time: 52:03)



- Grain Size No Grain refinement

Single xl F Ti blades

1600°C Bamboo structure

- Solution Strengthening Effective

Superalloys 10-25 solutes

Shiv K. Gupta IIT Delhi 10

Creating a grain refinement, no, I cannot use the grain refinement, no because there will be grain boundary sliding. Here what I can have, a single crystal, yes. They are making the single crystal, if I have to make a turbine blade, if you have ever seen this shape of the turbine blade, very complicated shape, then in the laboratory they made a small turbine with titanium single crystal blades.

And below its melting point or 1600 degree centigrade, for years it has worked. If not shown the creep, so it is possible to use single crystal, grain single crystals is very difficult. If so, then try to see that there is no grain boundary sliding. Grain boundaries are present but they do not slide. It is possible if you know where the force or the stress is coming. If force is coming in this direction, align the grain boundaries but probably go to the first and they will not slide.

“Professor-student conversation starts.”

Student: (())(53:18) grain boundaries are in?

Professor: Right, this is called a bamboo structure, you have to develop it by crystal growing. But most serious problem is there is no single direction of force in the material when I am using it whether it is a turbine or any other application. Force can come in any direction, so not very effective but this can also work. Attempts have been made in the bamboo structure, it does not slide, it does not show the creep.

Student: Is it easy to arrange the wafer in what you have shown there?

Professor: Yeah, it is possible, you can do that. You have to keep the depletion side such that they go direct to each other. You have to do that.

Student: Sir, you know arrange this particle in large size, they will also restrict the grain boundaries?

Professor: They are applied in grain boundary themselves, interface. Okay, I will talk about these precipitate particles also.

Student: But there are atoms, so then (())(54:26)?

Professor: The other things also. I am just talking about the grain size effect because grain will affect probably the grain boundary sliding. Grain boundary if it is present, it is going to affect only grain boundary sliding, nothing else. That is why I am discussing that. You must understand why I am discussing it. Grain is going to control only the mechanism of grain boundary sliding. Now if the solution is present, solute is present, it will provide the strain, arrange the solute like it is providing at room temperature, it provide high temperature also. So it shall keep interacting with their moving dislocation to be very effective.

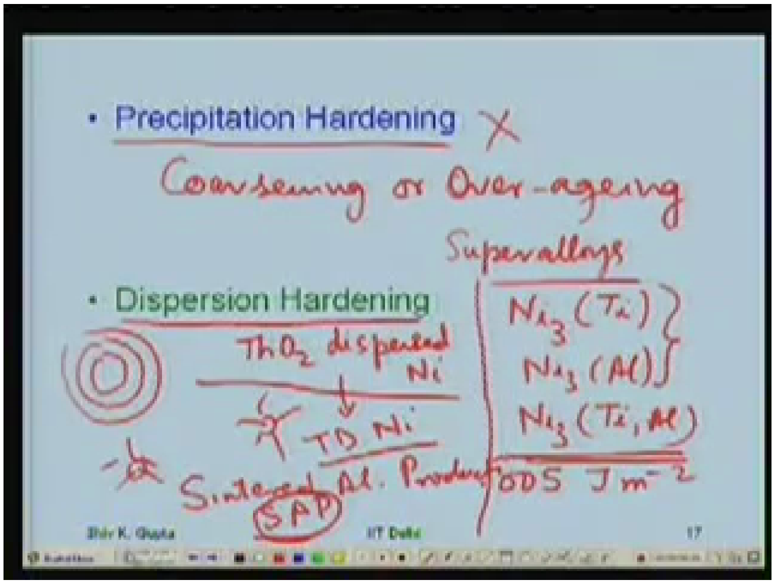
As a matter of fact, some of the super-alloys, super-alloys they are called super-alloys because they can resist creep. Developed, development took some time like 25 years and having 10 to 25 solutes. Then they should blend solution, that is important. Something is added just 0.2 percent, something is added 0.5 percent, something is added 1.5 percent, whatever can go in solution and they will all resist. The some super-alloys are the compositions like that, they have large number of alloying additions made.

Student: They resist creep. What is the property that they have?

Professor: They will stop the motion of the, slip motion of the dislocation, obstruct because that is probably continuing to provide the strain field and the solute whether the temperature is low, temperature is high. If the matrix is expanding with temperature, bond length is increasing. It will increase for the solute also. Steam around the solute shall continue to be there at high temperatures, so it will be effective.

“Professor-student conversation ends.”

(Refer Slide Time: 56:29)



- Precipitation Hardening ×

Coarsening or Over-ageing

Superalloys

- Dispersion Hardening

ThO$_2$ dispersed Ni

TD Ni

Sintered Al. Product

SAP

$Ni_3(Ti)$

$Ni_3(Al)$

$Ni_3(Ti, Al)$

.005 J m^{-2}

Shiv K. Gupta

IIT Delhi

17

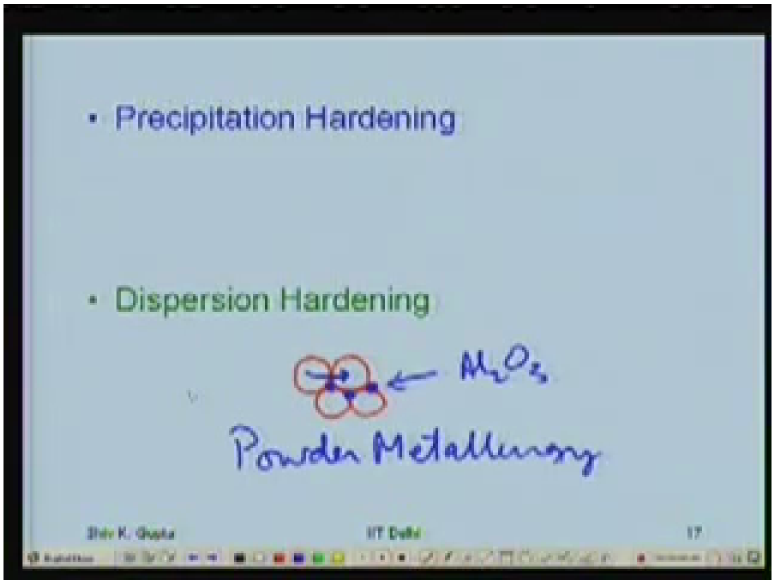
The last one I think we talked about the precipitation hardening. Precipitation hardening will not work, why? Temperature is so high that coarsening or what we call over-ageing can be very fast. However it can be effective if there is no coarsening. Coarsening would not take place if there is no driving force for coarsening and what is the driving force? Energy of the interface between the precipitate and the matrix. Like they have developed some super-alloys which provide the precipitate Ni3Ti or Ni3Al. Both are soluble in each other and therefore I can write this as Ni3TiAl.

This precipitate in the nickel matrix provides an interfacial energy of the order of 0.005 joule per square meter. Not less than that of even the grain boundary, it is much less than that. So the driving force is not there and it will continue to provide the creep resistance. Some of the super-alloys are doing that, nickel based super-alloys. Then second is the mechanism of coarsening. Particle, the solute has to go back into the matrix and that solute atoms have to go and deposit on the neighboring particle which is growing, like this.

And these are then dissolved back into the matrix. If it is insoluble on the matrix, it will not be able to dissolve, it will not be able to go and deposit there. But if it is insoluble, how do it convert as precipitate? Then it is not a precipitate, then it is a dispersed particle, what we call the dispersion hardening. Solid particles, fine powder, very fine powder like the size of 200 Armstrong as I said, in the form a powder we mix it to molten metal and then solidify it.

When a sample of this is thorium dioxide which is called Thoria, disperse nickel. In the market commercially it is called TD Nickel. And then the otherwise which are called the SAP alloys, Sintered Aluminum Products. What happens here is we know that aluminum is very reactive material. There is alumina, aluminum oxide formed on each aluminum particle.

(Refer Slide Time: 60:15)



- Precipitation Hardening
- Dispersion Hardening

$\leftarrow Al_2O_3$

Powder Metallurgy

Shiv K. Gupta IIT Delhi 17

When you sinter such a material, diffusion causes Al2O3 to move from the surface and cluster here at the junctions. Like this alumina gets deposited and then aluminum can diffuse like this and the bond can form. This is the powder metallurgy technique. Alumina is not soluble in aluminum matrix and this provides the dispersion hardening. Right? Okay, we shall stop here.