Material Science

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Lecture No 26

Phase Transformations; Precipitation Hardening Age Hardening (Contd.)

So we are talking about the precipitation hardening which is also referred to as the age hardening and just quickly go over what we did yesterday.

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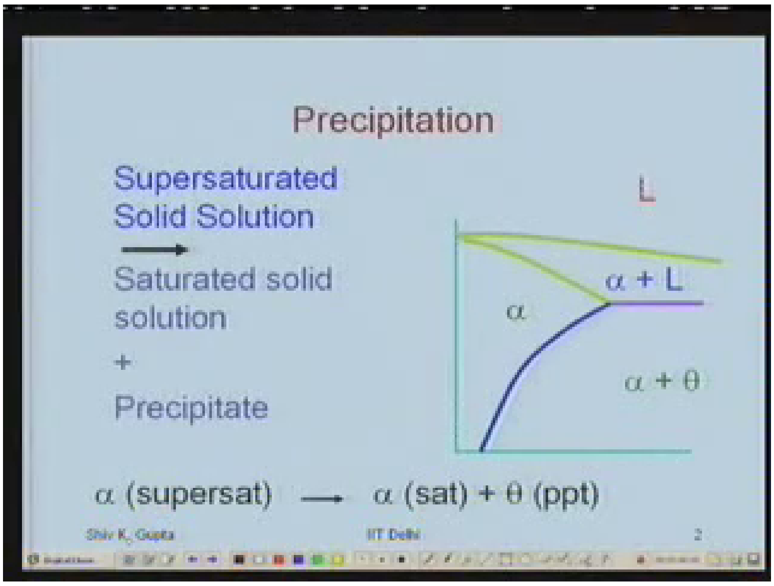

Precipitation

Supersaturated Solid Solution

⟶

Saturated solid solution

\+

Precipitate

α (supersat) ⟶ α (sat) + θ (ppt)

The process of precipitation is a reaction where you have a super saturated solid solution at a given temperature and with time its goes to the saturated solid solution and the second phase precipitates out. In the process of precipitation that occurs is taking place at the lower temperature and having super saturate is must at that temperature so the solubility of the solute must decrease in temperature and as I said about the sufficient condition we shall arrive after we understand how the hardening occurs. But only thing as I said yesterday was that the statement when the inter-particle spacing is small the hardness is more, inter-particle spacing is large the hardness would be small.

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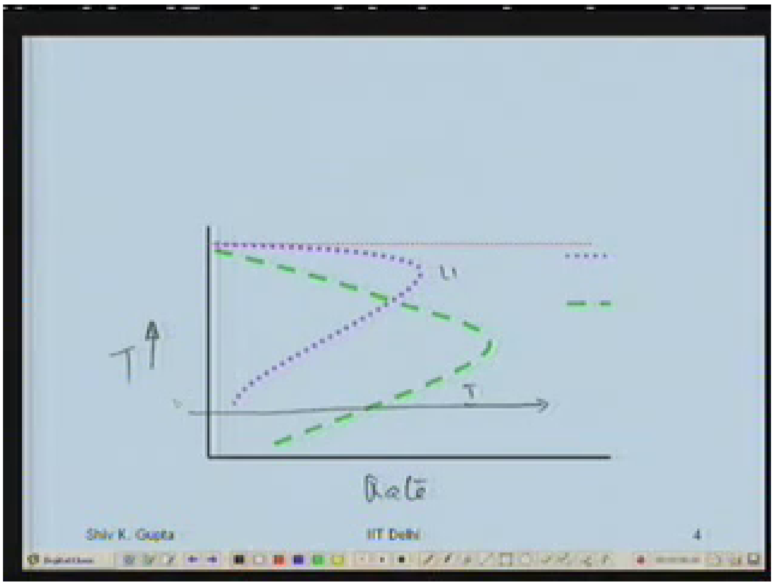

And this is the nucleation rate, that is the growth rate and this is somewhere we are working, in this temperature range where both nucleation rate and growth rate are very small and growth rate is much much smaller than the nucleation rate.

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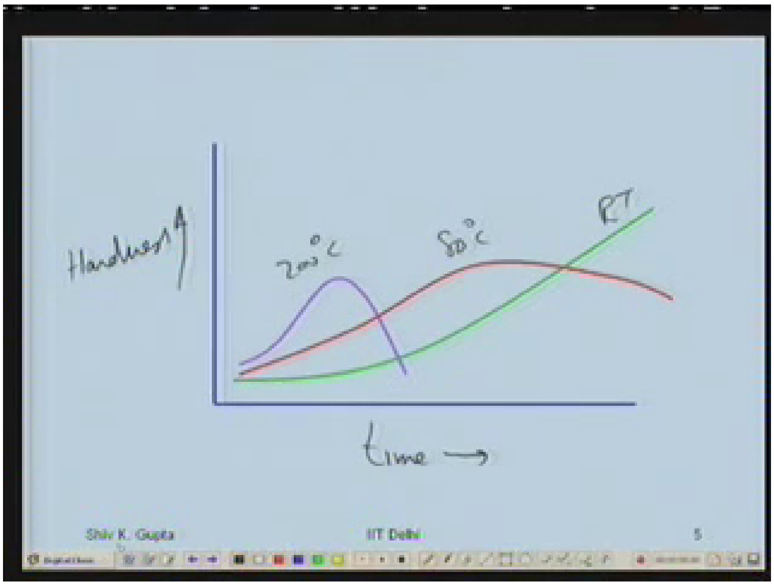

And this is how the hardness varies with time. This is at room temperature that is about 80 degrees centigrade and that is about 200 degrees centigrade, example we took that as of aluminum 4% copper alloy, as in more and more nucleation occurs, more and more particle will be forming so inter particle spacing in a given volume will keep on decreasing to hardness keeps on increasing.

However this does not go on increasing indefinitely because the amount of precipitate which has to be formed in a equilibrium is given by a Lever rule. Once that amount is formed we reach op, maximum which is called the optimum hardening, after the optimum hardening is reached there is an over ageing process, the driving process for the over ageing is stored interfacial energy between the precipitate and the matrix.

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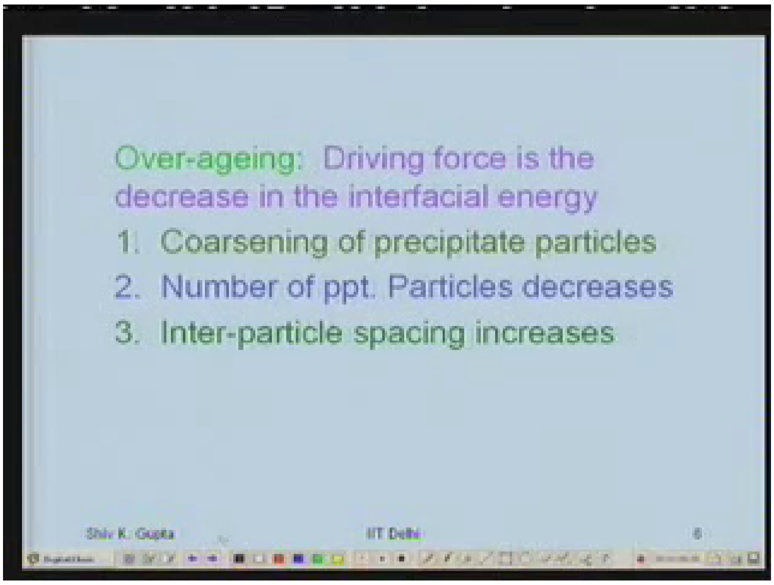

Over-ageing: Driving force is the decrease in the interfacial energy

1. Coarsening of precipitate particles
2. Number of ppt. Particles decreases
3. Inter-particle spacing increases

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So that is what we were at in the last class, over ageing occurs or the coarsening of the precipitate particles occurs driving force is a decrease in the interfamilial energy and interfacial energy is going to large if particles are small in size for the given constant volume of the precipitate. The coarsening of precipitate particles takes place in that region, once the particle coarsen the total volume of the precipitate has to remain constant which is an equilibrium as given by the Level rule so therefore number of precipitate particles decreases.

In the given volume of the specimen when the number of precipitate particles creases obviously the inter-particle spacing increases and because the inter-particle spacing increases this strength of the material, the hardness of the material decreases, that is what is happening during over ageing after you have reached the maximum what is called the optimum aging. Knowing this we have to avoid over aging process in the material which is used for the application. So therefore we know, we know how it is going to be made here, we know the time limit in which it is going to reach the optimum so therefore we put the life of the component.

If it say it begins to overage after 15 years, say I will say safely after 12 years, so we use it for 12 years, after that if it is worn out you have to replace it otherwise you can gain heat it, you can solutionize it, again quench it and then allow the precipitation to go one. However if I want good length life, good life of the component, have a longer life of the component this must be happening at the lowest temperature like that it is showed amongst the three temperature, room temperature, it takes long time. But then the good enough strength required for the machine component maybe also be achieved after many years.

Let us say optimum is reached, after about 15 – 16 years you have to wait till then is it, so what we do is we do the artificial ageing, we cut down that time, say for example I want to use the component at room temperature, so at about 50 degrees centigrade or 80 degrees centigrade where I can get the optimum aging let us say maybe in few hours or maybe in days time, I do that process but do not let it reach the optimum, allow some scope for more nucleation to go one, nucleation is still not complete.

And from there once I have reached the reasonable hardness which I can use for application then I quench it from there to the room temperature where I am going to use the component. Put it to use and with time automatically its hardness will keep on increasing and will reach the optimum value that means it shall remain at least what it is till it reaches optimum volume and that period at room temperature if it is 10 – 15 years you can decide the lifetime of the component. So that is how the artificial ageing can help us that we do not allow it to reach the optimum, we just keep it under optimum and then use the component.

In other words what I am trying to say is at this temperature I reached here, quench it that means you are somewhere here in this graph, some more nucleation will go on, right, and therefore the hardness will keep on increasing, right, so hardness will be there, this is where you are, you have not reached the optimum yet, some more nucleation has to take place, that nucleation will keep taking place and a lower temperature is a much lower process. So if it reaching the optimum in a few hours there it may take place in few years maybe, right, so that is the kind of thing which we try to exploit.

Student: (())(8:07)

Professor: Long period, yeah. It will not reach the over ageing process. Means, what I mean is the maximum is not there, the total amount of the volume which has to formed for the precipitate has not formed the process is on, till then the process is on, this process of over ageing occurs only after I have reached the optimum where the amount of the precipitate which has supposed to be formed has already formed then only the interfacial energy which is in excess is going to become the driving force for the process of coarsening.

The precipitate participles have begin to become bigger and bigger, but since the total volume doesn't have to change, some neighboring particle only then a particle can become bigger in volume, okay. So the total volume of the precipitate remains same. Once some particles have dissolved and inter-particle (())(9:11) then increases, right.

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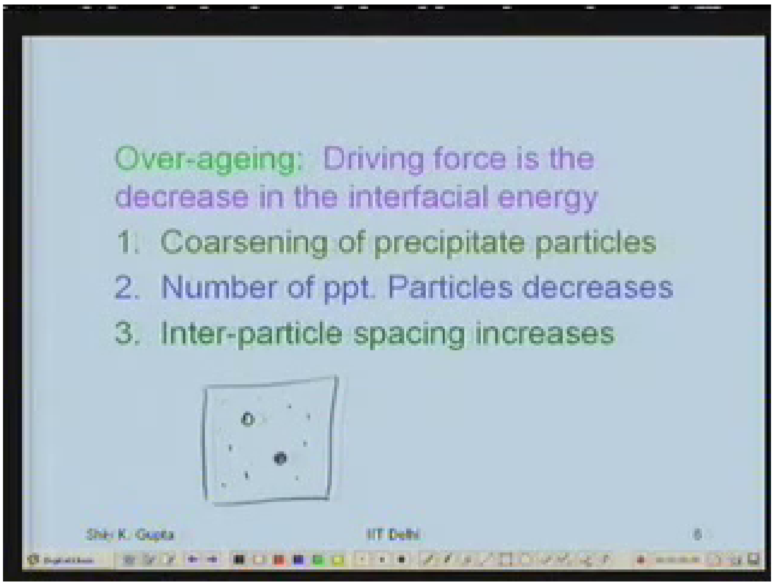

Over-ageing: Driving force is the decrease in the interfacial energy

1. Coarsening of precipitate particles
2. Number of ppt. Particles decreases
3. Inter-particle spacing increases

So for example what I am trying to say is… Let us say by the time you reach optimum you have precipitate particles placed like this. Now this particles decides to grows then this particle here, this particle here they will, this is all back, volume of these will be the volume in here, so let us say some here this begins to grow, then this particle here will have to dissolve back which I should show with the help of an eraser.

So you see the inter particle spacing has already gone up, like that if something else begins to grow it will dissolve the neighboring particles, right? So solute from these particles gets into the matrix and gets deposited overall to this particle which is growing. So this one dissolves and get deposited over here and that is what it grows in size and others dissolve that is the process of coarsening, okay.

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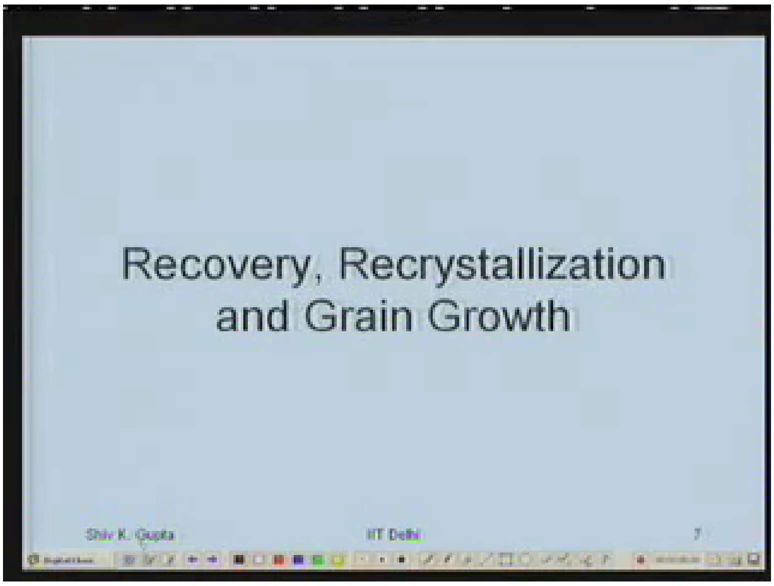

Recovery, Recrystallization and Grain Growth

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Right, we shall see the mechanism by which this hardening process occurs when I talk about this mechanical behavior. Today we will talk about another transformation, in that transformation three things are happening together, recovery, recrystallization and grain growth. One after the other in the sequence, first occurs recovery, then occurs recrystallization, and finally the grain growth. Some people do not refer to this as phase transformation; they refer to it as only structural change. There are certain differences between the classical transformation and this, we shall discuss that but first of all where this transformation occurs.

If I deform a material, let us say take a piece of copper, hammer it heavily or pass it through a dye to make a wire out of it, thin wire out of it or maybe pass through a rolling mill to make a sheet out of it or some other section, but all this process you do at room temperature which is below the recrystallization temperature of the material. We will define the recrystallization temperature in a short while. Below the temperature we do it, it is called the cold working because by that operation of deformation I am making the material stronger that is why it is called cold working or strain hardening.

Material is getting work harder, material is getting strain harder or material is cold work, all synonyms, they mean the same thing. I deform it, it becomes stronger, that is another mechanism by which we can make the material strong. Like you have heard of this reinforcement bars which are (())(12:34) steel. This steel rod at room temperature are twister because of the twisting they get deformed and work hard and become stronger.

Their strength is more than that of the normalized steel rod as it is available in the market. This is (())(12:56). So we shall we see why it is strengthen and why it is becoming stronger when I talk about the mechanical behavior but then that is what is referred to a strain harden material or cold worked material or work harden material.

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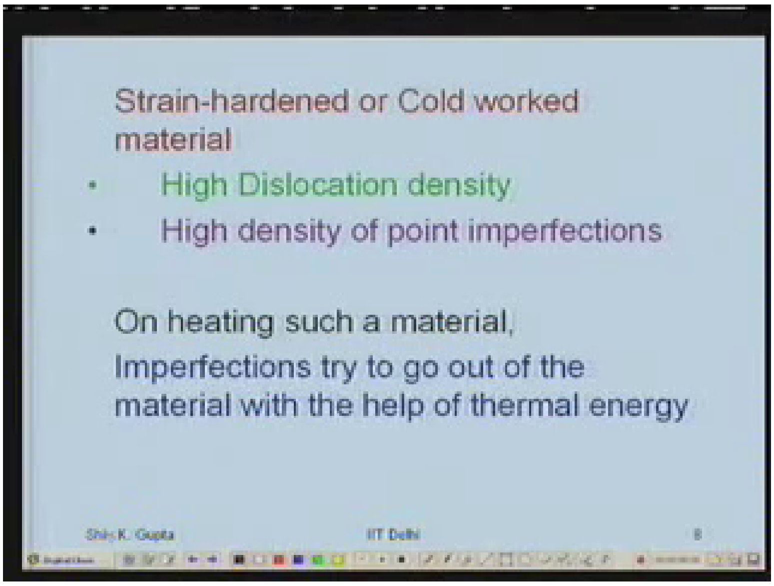

Strain-hardened or Cold worked material

- High Dislocation density
- High density of point imperfections

On heating such a material,
Imperfections try to go out of the material with the help of thermal energy

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In their I will also tell you that when this is happening the dislocation, density in the material goes up, it increases, besides point I perfection also increases in number, when I deform a material a cold worked material like this that is imperfection in the material increase, maybe the grain boundaries also increase. They may not be the grain boundary, they may be sub-gain boundary but basically they are all boundaries, internal surfaces which get created.

So that means this materials has excess imperfections and therefore has an extra free energy because having imperfection, point imperfection is in equilibrium but once they are in the excess of the equilibrium number the free energy is going to be more because we have already crossed the minimum. And similarly dislocations and the internal surface, grain boundaries etcetera they also have extra free energy, so the material has more free energy. And if the chance is given to the material it would like to get it out of this extra free energy, right?

And this happens when we heat such a material, what we call generally annealing process. Whatever is the history of the material, keep it in an elevated temperature we call it annealing, that heating of the material is what provides the extra thermal energy or required thermal energy which can help this imperfections to get out of the material and material comes to a lower free energy state.

Now this heating process can be of 2 kinds, one process is that I keep the material at a constant temperature for a great length of time, so here temperature is not changing but time is changing. I start with the 0 time and goes on increasing the time to a long value. Similarly the second kind of heating could be I continuously increase the temperature of the material. Why I am talking about these two processes in both operations these phenomena which I talked about recovery, recrystallization and grain growth are going to take place.

Initial stage whether it is a shorter time at the constant temperature or lower temperature initially is the same thing, the recovery occurs. Then once the recovery is done, finished, recrystallization takes place at second stage. When recrystallization is complete then the grain growth takes place, we shall look into that. Thermal energy is going to help the material, getting rid of these imperfections.

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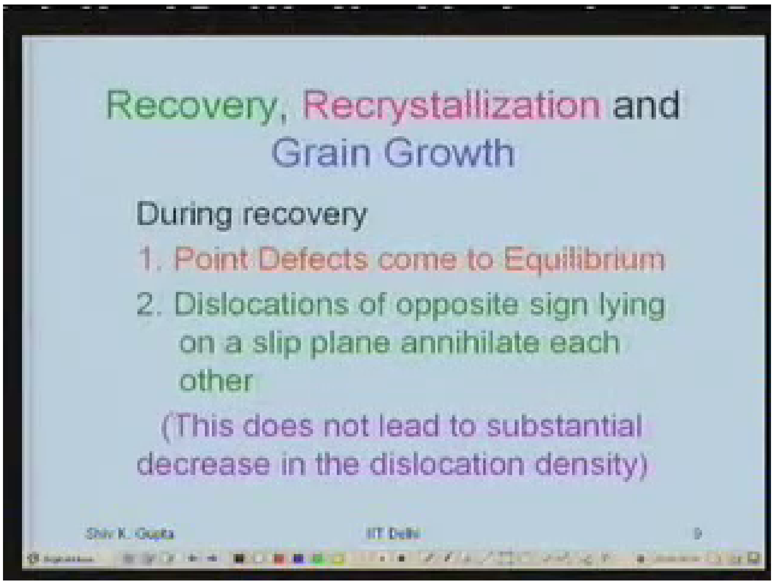

Recovery, Recrystallization and Grain Growth

During recovery

1. Point Defects come to Equilibrium
2. Dislocations of opposite sign lying on a slip plane annihilate each other

(This does not lead to substantial decrease in the dislocation density)

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Now first of all we shall talk about the recovery. The easiest thing to occur occurs first during recovery that is the initial stage is while I am holding at a constant temperature, if I am heating constantly then in the initial temperature range, round the room temperature when I increase above the room temperature the recovery phenomenon occurs. During this operation point defects come to the equilibrium first, point defects can go to the (())(16:49) location, this locations can (())(16:50) and point defects are gone.

All point defect go to the grain boundaries and get lost, or point defects can come to the surface and get lost. This we are (())(17:04) for the high temperature, the diffusion vacancy diffuse, vacancy mechanism and these points defects come to the thermal equilibrium, that is the first thing to happen. After this has happened now it is possible though the dislocations which are present in a material is a jungle of dislocation really speaking and all are convening lines. These dislocations are not necessarily straight lines, they are not straight lines, they are just zigzag and they are not necessarily lying on a single plane if you consider as slip plane, they may be lying randomly in the volume of the material.

Therefore I am not referring to small number of dislocations which are of apposite sign and lie on the same slip plane. With the available thermal energy because there is an attraction between them, they can jump towards each other and can come close and relate each other. So if that happens all the dislocation on a given plane would be of the same sign, opposite signs have got lost. So some dislocation density comes down but it doesn't come down very drastically. If I start with let us say (())(18:30) 12 meters of the locations link, per cubic meter of the material it may become 0.95 into 10 to the power 12.

Student: (())(18:45)

Professor: Those which are lying on one particular slip plane and are of opposite sign they can jump towards each other, come close and annihilate, but if they are lying on different slip planes there are the same sign they will arrange one over the other to form the low angle boundary which I called the tilt boundary. This is another phenomenon which occurs during recovery. Once all dislocations let us say I am left with all the same sign then they will try to form the tilt boundaries or the twist boundaries which are the low angle boundaries.

All screw dislocation or the same sign can arrange themselves in an array and that array will form a twist boundary, at dislocation arrange themselves in an array they will form a tilt boundary, the grain is getting divided into sub grains and cellular structures can also form like this. This is the different cell walls which are provided by this dislocations, but it is only for those which are straight lines and lie opposite of one another, lie on the same plane or they are on the same sign lying on different planes, right?

So thus means all dislocations as I told you are not straight lines, so my dislocation density in his process doesn't go down, really speaking, from 10 to the power 12 it becomes 0.95 or 0.97 10 to the power is hardly decrease, that is the kind of thing that may happen at the most and that is why I make it a point to mention that this does not lead to substantial decrease in the dislocation density.

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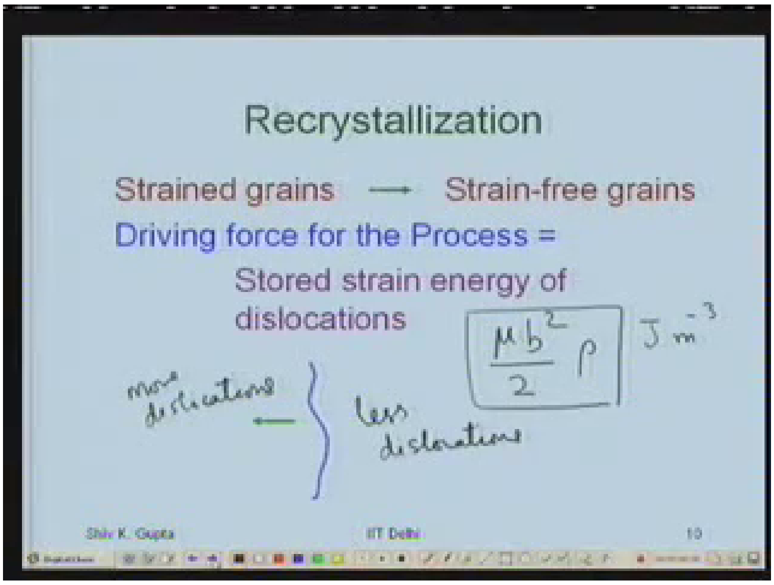

Recrystallization

Strained grains ⟶ Strain-free grains

Driving force for the Process =

Stored strain energy of dislocations

$$\boxed{\frac{\mu b^2}{2}\rho} \ J\,m^{-3}$$

more dislocations ← } less dislocations

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Once this is all done I say recovery is over and during this operation I will show you some property, those which are affected by the point defects like electrical conductivity or the electrical resistivity they get recover because they are affected by the point defects and the point defects were more that changed. Now point defects have come to the equilibrium it has again come back to the normal value. So those properties get change during recovery.

The other properties which are not affected by the point defects but affect by the dislocation they do not get recover, they do not change. Right now recrystallization is the process which occurs now next, it is basically you see the point defects have come to equilibrium what I am left with these, internal boundaries and high dislocation density. Next step is provided by the high dislocation density. Dislocation have these strains around them, if the general dislocation normally they have generalize state of strain, in case of edge dislocation mostly principal strain compressive and tensile strains, in case of screw dislocation I have shear strains.

So this strain energy is stored which I called the strained grains in the form of energy of dislocations, and these with the help of thermal energy go to become strain free grains that is dislocation free, dislocation get out, this process usually occurs by formation a small nucleus and migration of the grain boundary which is formed when nucleus is after same material, same crystal structure only thing is without dislocation and then the gain boundary jumps to make it bigger and bigger in size, so the migration of the grain boundary which is involved.

So driving force for the process as I said is the stored strain energy of dislocation and energy of the dislocations you recall stored is Mu b square by 2 into the dislocation density per unit volume of the material. Mu b square by 2 is per unit length, the density length is per unit volume of the material so therefore this is the energy stored joule per cubic meter, that is the delta g, right for the process. Now the process as I said is I have a grain boundary let us say, in here I have less dislocation density, here I have more dislocation density, so grain boundary moves in the left so more dislocations, less dislocations.

So grain boundary shall move towards that region where there are more dislocations, in other words try to consume that dislocated material into a less dislocated material or free of dislocation material so that increases in size, right. That is basic process of recrystallization. See what is the effect of this process and how it controls the process of recrystallization.

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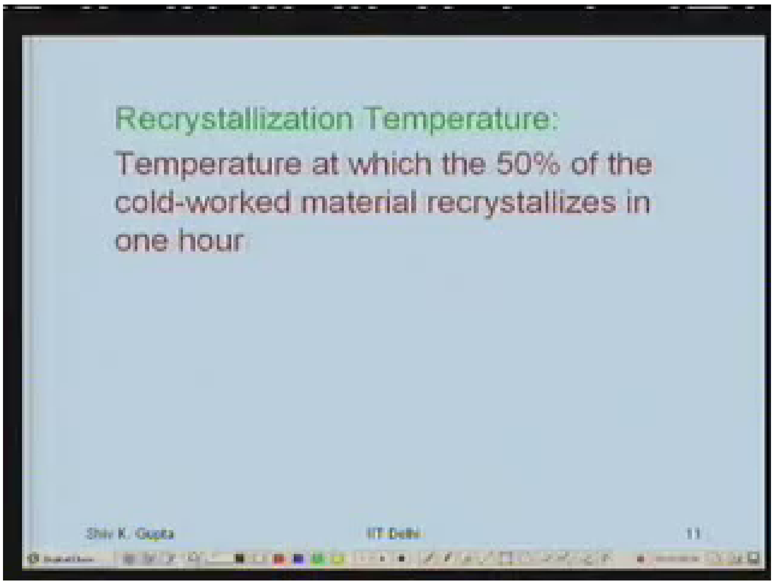

Recrystallization Temperature:

Temperature at which the 50% of the cold-worked material recrystallizes in one hour

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Before I proceed further let me ask you one thing, in the classical nucleation mechanism we talked about the free energy change delta g, and from the delta g we worked out the activation energy delta f star, same way I can worked out the activation energy for this process also but there the delta g was changing with temperature of transformation, at the equilibrium temperature it is 0, as the temperature is lower under cooling is increased, delta g increases but with a negative sign.

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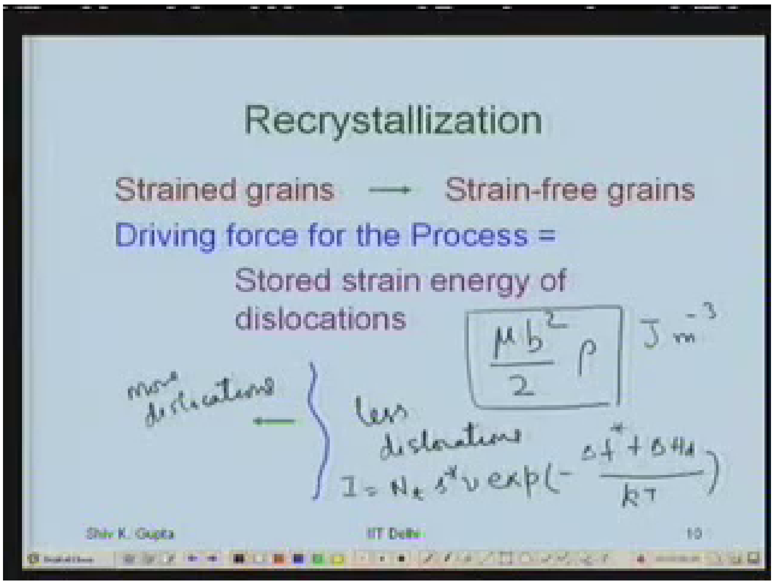

Recrystallization

Strained grains → Strain-free grains

Driving force for the Process =

Stored strain energy of dislocations

$\boxed{\frac{\mu b^2}{2} \rho}$ $J\,m^{-3}$

more dislocations ← less dislocations

$I = N_t s^* \nu \exp\left(-\frac{\Delta f^* + \Delta H_d}{kT}\right)$

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Here also it is a negative sign because the strain free grains have no energy, strained grains the dislocation energy is there, so this minus this shall become negative value h. The driving force has always taken a minus of delta g so it becomes positive, driving force is positive for a process while free energy change is negative. One is opposite of the other really speaking. In this case what would happen if I hold it at 100 degrees or I hold it at 90 degrees or I hold it at 120 degrees, would delta g change with temperature? Is delta g a function of temperature?

Look what is delta g here, where it is coming from, it is coming from the stored dislocation in the material and when did they get stored, they got stored when I deformed it, whether it passed through the dye to make it a wire or I passed it through the rolling mill to make it a thin sheet or I hammered it, during that operation dislocations came into being or the multiplied in the material.

Now this process of annealing where recovery, recrystallization and grain growth is occurring kept at an elevated temperature or constantly increase the temperature, this number of dislocation is not going to change that is the starting material I have, that is the driving force, this is not a temperature dependent energy, this is dependent on how much work I did, whether I deformed it to 50% cross section area or I reduced it to 90% cross section area, how much deformation I did, deformation is small or deformation is large, more the deformation I do more the cold working, more dislocations will get stored.

So therefore this is not a function of temperature, this is the function of the dislocation getting stored in the material. So temperature, what temperature I am talking about, not the temperature of working, temperature deformation I am not talking about, I am talking about the temperature of annealing after the deformation is done. So that number is not going to change, that number comes about at the time of deformation.

Yes, if I do the deformation at 200 degrees centigrade or I do the deformation at room temperature let us say the same extent dislocations getting stored at room temperature would be more and dislocations getting stored at 200 will be less because 200 provides more thermal energy and allow dislocations to get out. Because they are anyway their presence increase the free energy of the material. If thermal energy can help it, it will try to reduce the free energy so some of these dislocations can go out at 200 degrees centigrade while most of it will be stored at the room temperature.

So that is the temperature working but now we are referring to the temperature of annealing. So at temperature of annealing this driving force is not going to change, delta g doesn't change, what happens to delta f star, does it change it with temperature. It will not change with temperature. So if you look at the nucleation rate, what did we write for the nucleation rate. Let us say I am writing for the homogenous nucleation itself, now in this, this is not the function of temperature, delta Hd is never a function of temperature so numerator is not a function of temperature.

What does it become, numerator and the exponential term is not a function of temperature what happens, it is same as any (())(29:48) relationship. It doesn't pass through the maximum, as the temperature rises the rate of process goes on increasing, it becomes faster and faster, if you understand this then comes the next I define by the crystallization temperature. Those who have done the manufacturing process would have been told that the crystallization temperature is about 40% of the melting point.

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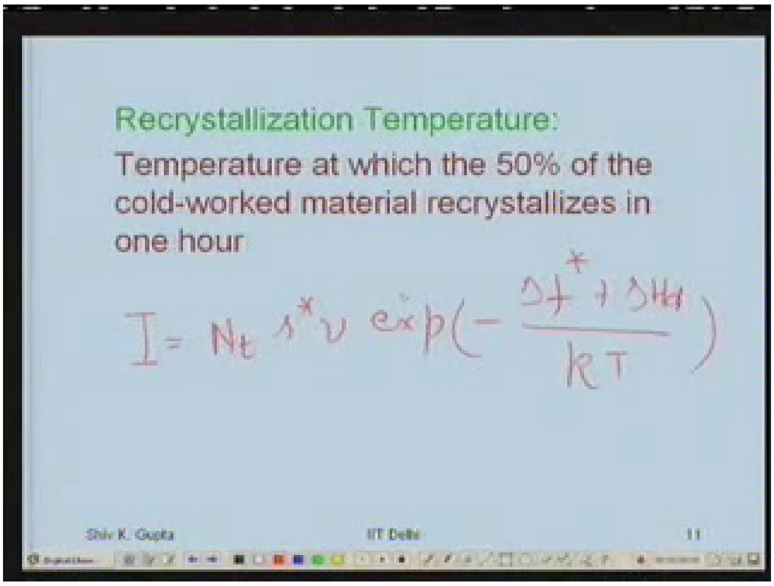

Recrystallization Temperature:

Temperature at which the 50% of the cold-worked material recrystallizes in one hour

$$I = N_t s^* \nu \exp\left(-\frac{\Delta f^* + \Delta H_d}{kT}\right)$$

That is not the correct definition, the correction definition is this, Temperature at which 50% of the cold worked material crystallizes in 1 hour, I am specifying the times and I am specifying the extent of recrystallization, that means at the left hand side where I wrote the nucleation rate, I specified, extent and time both are specified, so rate is specified. And on the right hand side I have, and I define the temperature at which this happens in 1 hour. So there must be some delta f star, some delta Hd, some this p exponential term, all these things are taken care of.

So, I have defined with the reference of the time, with the reference of the extent of recrystallization and the rate that is specified, it should occur in 1 hour, 50% recrystallization that temperature, generally it lies in the range of 0.3 to 0.5 that is why roughly we say about 40% because it lies between 0.3 and 0.5 of the melting point once expressed Kelvin. So that is the way it is, but when it is 0.3 and when it is 0.5 we shall discuss what are the factors which control these parameters, that is what we have to look at.

Now the second thing is this delta f star is not a function of a temperature, once a nucleus has formed which is free of dislocations, dislocations sent out and if particle is formed containing let us say 200 atoms or 100 atoms, will this cluster of atoms dissolve back to have the old dislocated region, can it? It is not possible for it to remember where the dislocations were, it cannot go back to that stage, so once a particle is formed it cannot dissolve back like an (()) (32:51).

These are the two basic differences why many people do not consider it a phase change. Right, that delta f star or delta g doesn't change with the temperature of transformation or recrystallization, it is the function of the cold working and same time the embryos cannot dissolve back. They can only grow in size, okay.

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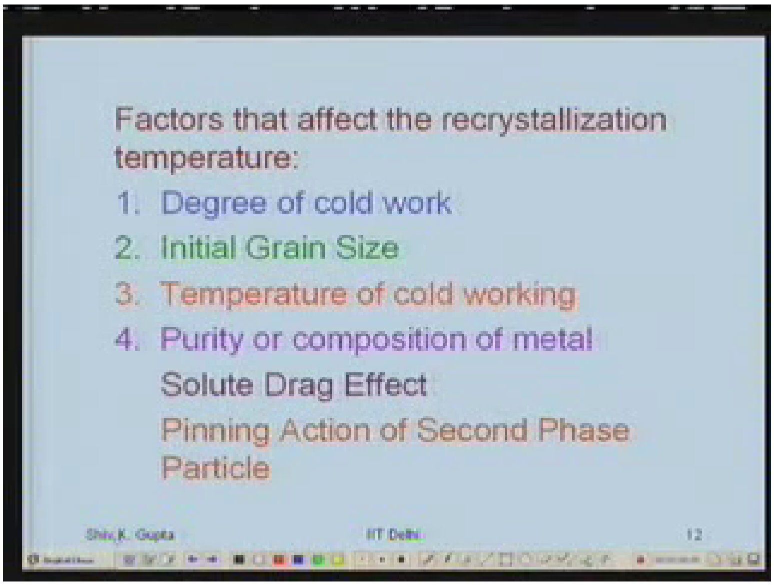

Factors that affect the recrystallization temperature:

1. Degree of cold work
2. Initial Grain Size
3. Temperature of cold working
4. Purity or composition of metal
   Solute Drag Effect
   Pinning Action of Second Phase Particle

Now let us look at the parameters which control the temperature of recrystallization. First if the degree of cold work that means more the cold working you do more dislocations is stored, the density of dislocations is higher. That means delta g is higher, delta g is higher delta f star would be smaller, delta f star is smaller nucleation rate would be faster that means recrystallization rate would be faster, but I want only 50% recrystallization in one hour, so temperature has to be lower, understand.

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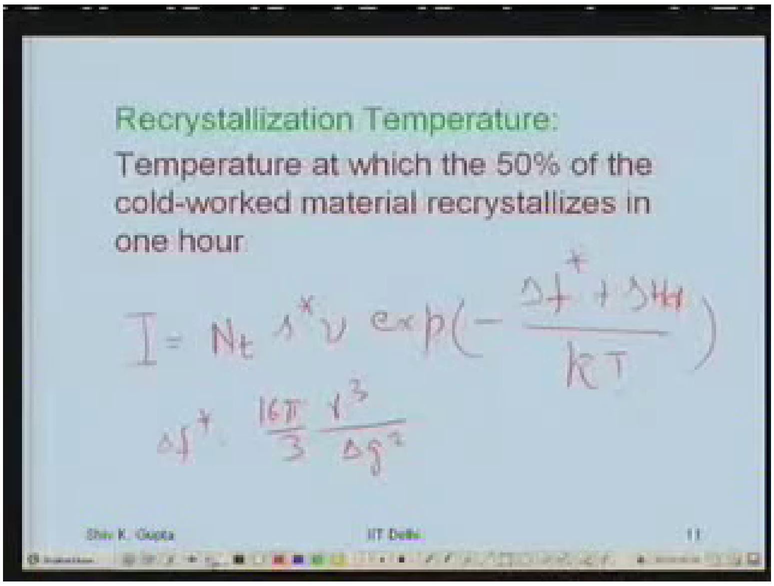

Recrystallization Temperature:

Temperature at which the 50% of the cold-worked material recrystallizes in one hour

$$I = N_t s^* \nu \exp\left(-\frac{\Delta f^* + \Delta H_d}{kT}\right)$$

$$\Delta f^* = \frac{16\pi}{3}\frac{\gamma^3}{\Delta g^2}$$

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Again just go back to this expression, see delta g is more, when you do the more cold work, so delta f star which you have written earlier, I am writing for the homogenous nucleation only. Once delta g is more delta f star would be less, if I have to keep this constant for this has become smaller this should also become smaller. So this is the temperature of recrystallization because I am maintaining it constant. So the recrystallization temperature would become lower if I do more cold working, recrystallization temperature would be higher if I do less cold working. Is it clear? Let us see all the other parameters which affect these parameters here; we will come back to this expression.

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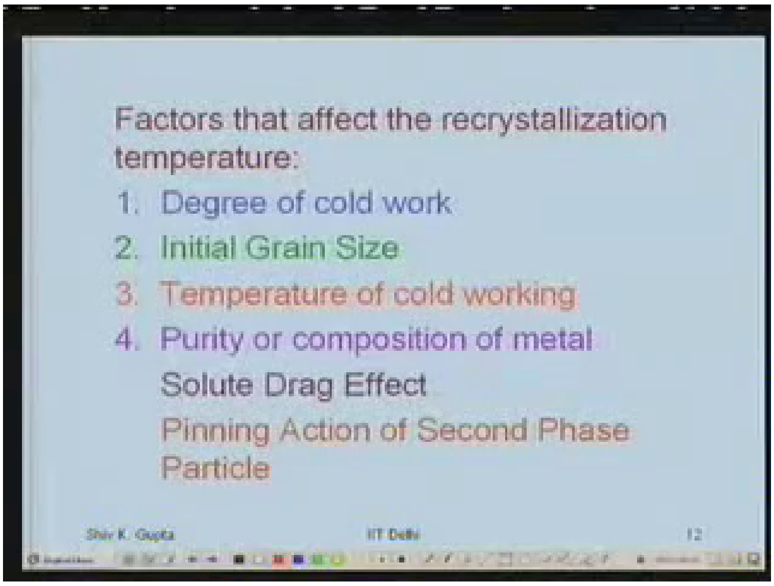

Factors that affect the recrystallization temperature:

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Next, look at the initial grain size. Initial grain size means just before you started deforming it, grain size could be a smaller grain size, grain size could be larger grain size, the process of (())(35:21) as I told occurs at the grain boundaries. Start with if it is a fine grain size you will have more nucleation sites, in the coarse grain size you will have less nucleation sites.

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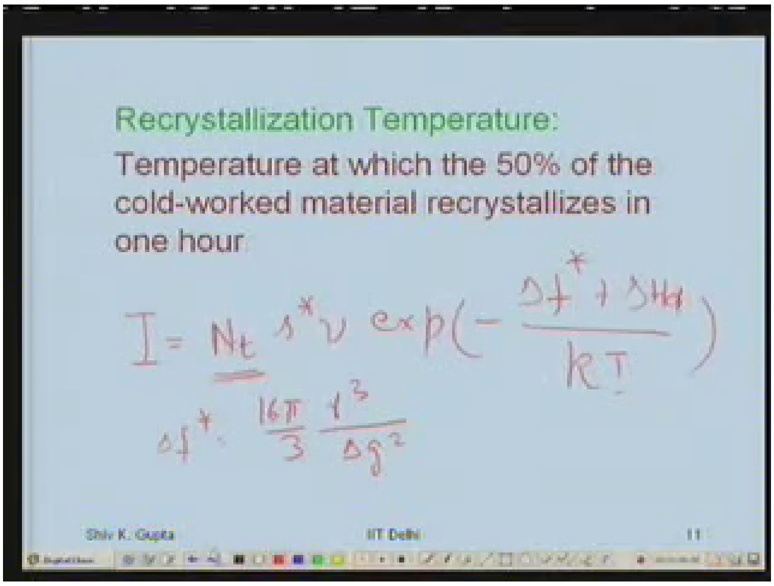

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Let us go back to that, it is affecting this, delta f star will not affected that it is a function of the degree of cold war but the grain size, initial grain size going to affect where whether this number is larger or the number is small, for fine grain material Nt is large, but this is the constant, to maintain this constant this number should go down, this number should go down meaning temperature should become lower. Okay. So fine grain material if you have deformed and try to recrstallize, it recrystallizes at a lower temperature, and a coarse grain material you deform and recrystallize at a higher temperature. Okay. That you have to see with this.

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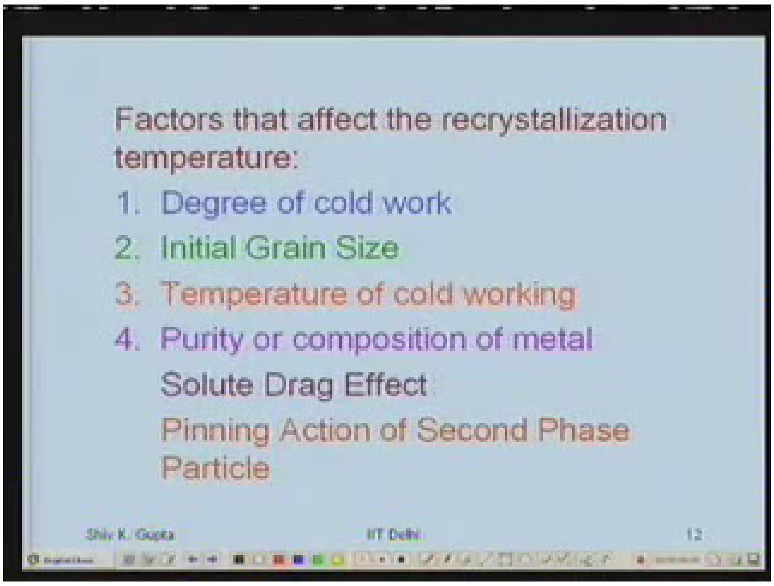

Factors that affect the recrystallization temperature:

1. Degree of cold work
2. Initial Grain Size
3. Temperature of cold working
4. Purity or composition of metal
   Solute Drag Effect
   Pinning Action of Second Phase Particle

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Then come the temperature of cold working. I just explained that if I deform the material at room temperature and deform at 200 degrees centigrade the difference is the dislocation density which gets stored at the room temperature the row is more than what is getting stored at 200 degrees centigrade for the same deformation, for same reduction in the cross sectional area. At room temperature it stores more dislocation, at 200 degrees centigrade it store less dislocation. Delta g at 200 degrees centigrade is less, delta g if it is deform at 200 degrees centigrade and if it deformed at room temperature it is more.

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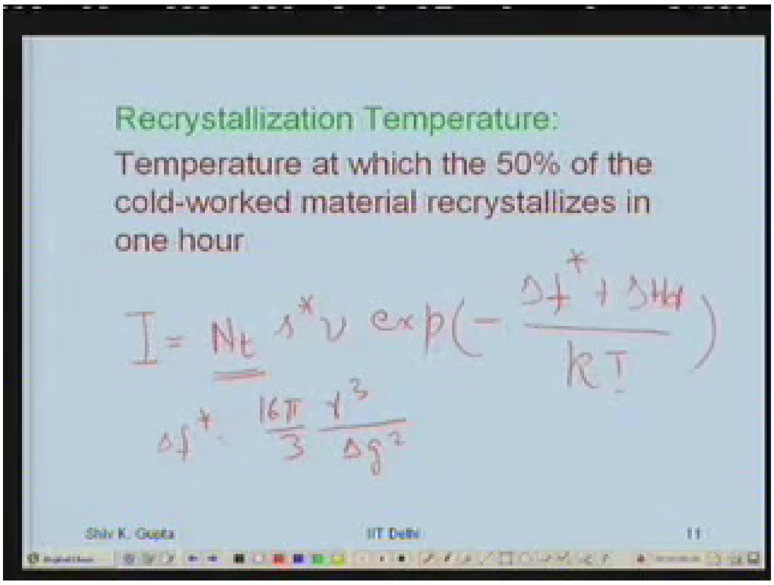

Recrystallization Temperature:

Temperature at which the 50% of the cold-worked material recrystallizes in one hour

$$I = \underline{N_t}\, s^* \nu \exp\left(-\frac{\Delta f^* + \Delta H_d}{kT}\right)$$

$$\Delta f^* = \frac{16\pi}{3}\frac{\gamma^3}{\Delta g^2}$$

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That means delta f star is more when delta g is less that is too at higher temperature of cold working. Higher temperature at cold working delta f star is more means that it will become smaller for the temperature has to rise. So if I deform it at 200 degrees centigrade at higher temperature my recrystallization temperature is also higher. If I deform it at lower temperature my decrease in temperature is low, right.

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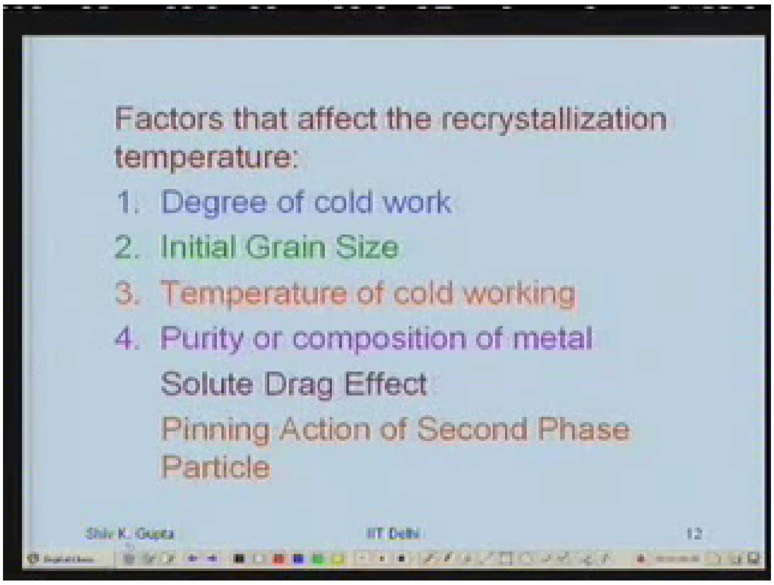

Factors that affect the recrystallization temperature:

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Then comes the very important one the purity or composition of metal. In the material impurities can be present in 2 forms, in the dissolved forms or the undisclosed forms, dissolve form it is a solute and in the undisclosed form it is a second phase particle, okay. Both the second phase particle and the solute, solute I am at the level of atom. Undissolved particle second phase, it is a particle which an ensemble of 100 or 1000 of atoms, please keep it mind there is a difference between the two, okay.

Solutes when they are present they drag the grain boundary and if undissolve particles are present they pin down the grain boundary. So what is that solute dragging effect and what is the pinning effect, let us look at that.

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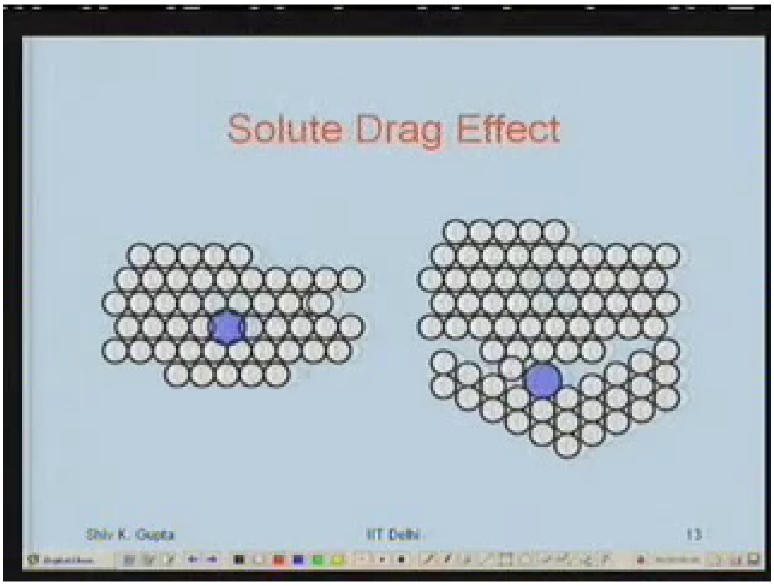

Solute Drag Effect

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This is the solute, the blue atoms in the matrix. You see the strains in the neighborhood compares it as the bigger one. Similarly if I have put a smaller it would have got the tensile strain around it, there are strange map in the matrix and there is a strain energy, extra strain energy. Let us say there is a grain boundary which is migrating upwards let us say, and the grain boundary while magneting comes here and this solute becomes the part of the grain boundary. You noticed that the strains are not as much as they were there.

This is having less energy as compared to that, stored energy here is more, stored energy here is less, that means this kind of configuration is energetically favorable. If the grain boundary migrates further this will go back to this kind of situation because this has to become the part of the grain. In the words when a grain boundary migrating comes near the solute, solute goes onto the grain boundary but the energy is lowered and that energy which is lowered goes waste as heat. It is not available for us to do any work.

But once the grain boundary tries to migrate away from it, it has to increase that energy level again and this energy has to be provided by the thermal energy, nobody is doing the work. So thermal energy will have to concentrate to provide that energy there that means process is slowed down. Activation energy for the process has gone up so the process has slowed down. Therefore migration of the grain boundary become difficult once the grain boundary reaches here, this is referred to as a solute drag effect. More the solute in the matrix, grain boundary will be facing such situation at more places.

The lesser solute it will be facing at less places. So solute present in the matrix dissolve impurity would like to drag the grain boundary and increase the recrystallization temperature, right. So if the solute is present in the matrix the recrystallization temperature would be higher and if solute is not present it will be lower. Like say for example for pure aluminum recrystallization temperature without any impurities could be around 75 degrees centigrade but commercially pure aluminum it would be around 175 degrees centigrade. It goes up.

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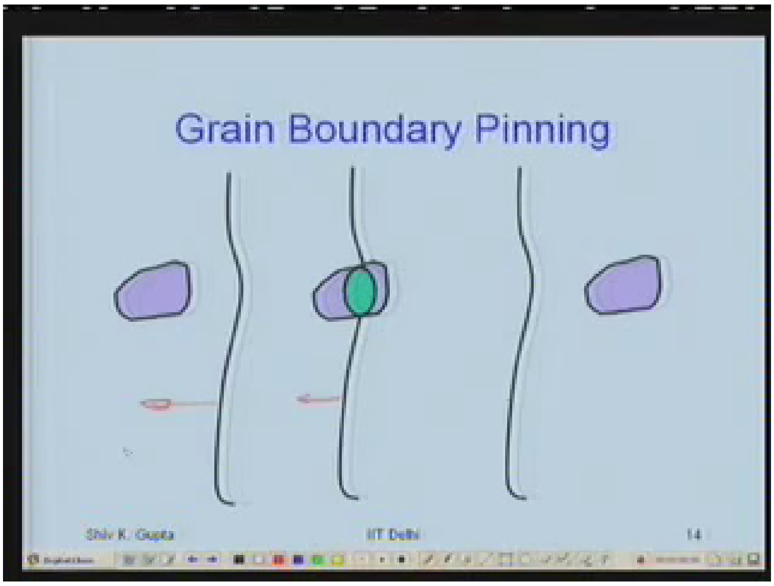

Grain Boundary Pinning

Let us look at the grain boundaries which are pinned down the second phase particle. Here is the second phase particle which is lying in this grain and this is the grain boundary which is trying to migrate, it is trying to migrate in this direction. I have certain grain boundary energies stored in the material and I also have certain interfacial energy stored in the material. Now when this grain boundary migrates comes near the second phase particle this is the cross section, the particle with the grain boundary, this green one. In that area I don't have any grain boundary, but interfacial area is still the same.

But in that cross sectional area I don't have a grain boundary. So such particles are present in the matrix, grain boundary faces them and wherever it comes in contact that cross sectional area is no more the grain boundary. There was a grain boundary area and the material decreases. Was the grain boundary area decreases the grain boundary energy store decrease; it is a lower energy configuration as compared to this. The two energies out of which one has not changed, but the other one has reduced. Once that happens the energy which is lost goes waste as heat again.

But when this migration goes one grain boundary has to come out, a particle has to be left behind another grain, that energy is the same as this, the entire grain boundary plus this interfacial area. So now this is again high energy configuration that area has come back and that extra energy has to be provided by the thermal energy only. So process becomes difficult and slows down. We say the grain boundary has been pinned by the particle. This is the particle containing maybe 100 of atoms or 1000 of atoms, it is not a single atom like this solute which I showed you earlier, don't ever confuse with those things.

Atom is one single atom, this is group of atoms here as a particle, it could be a crystalline material, could be glassy phase. Alright. So this is how the second phase if it is present in the matrix it can pin down the grain boundaries and slower down the process. So whether I have any impurity which is dissolved or I have an impurity which is not dissolved insoluble, both way the process of migration of grain boundaries is slowed down and thereby recrystallization temperature goes up. So impure materials or the alloys would normally find higher recrystallization temperature than pure metals.

So recrystallization temperature is a function of purity that way. And for pure material it is low towards 0.3, for impure material depending upon the impurity content towards 0.5 that is why normally you are told as above 40% of the melting point but I would say it would be between 30 – 50%, because recrystallization temperature between 30% and 50%. Right. Was the recrystallization is over, means all over the volume strain free grains have formed all over, all the strained grains are lost, the whole volume is filled, I say recrystallization is complete. So far I define only recrystallization temperature as that where only 50% occurs process will go to completion when 100% volume is filled with recrystallized grains.

Once that has happened I am left with in a material let say dislocate and it comes down very low and no dislocation energy but I am left with fine grain structure in the material that means a lot of grain boundary area. Once I have a lot of grain boundary area that also increases the free energy of the material because the grain boundary is also not in thermodynamic equilibrium. So it increases the free energy of the material that is driving force now. These grain boundaries would like to go out, after recrystallization is over what takes place is a grain growth.

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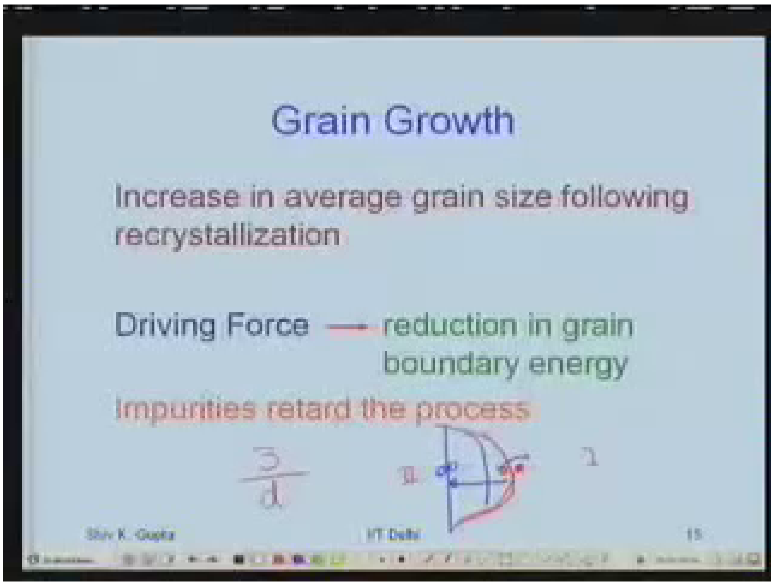

Grain Growth

Increase in average grain size following recrystallization

Driving Force → reduction in grain boundary energy

Impurities retard the process

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Increase in the available grain size following the recrystallization. So driving force here is the reduction of the grain boundary energy because you have fine grains, we did one problem we will recall, the grain boundary area stored per unit volume of the material is 3 divided by the grain diameter. Smaller the diameter more is the grain boundary stored per unit volume of the material. Larger the diameter smaller is the grain boundary stored, that means grain boundary energy stored.

So tendency now is to have this recrystallized which are fine size, they become bigger, they become coarser and thereby reduce the grain boundary energy. And gain here if basically a process of grain boundary migration. And grain boundary migration is affected by the impurities, so grain growth is obstructed by the solutes which are dissolved impurities which are affected the second phase particles, thew ay it affects the recrystallization and grain growth would be slower with the impurities present.

That is grain boundaries would be dragged by the solutes, grain boundaries will be pinned down by the second phase particles and the grain growth would be a slower process. Right. The driving force is to get it off the grain boundary energy stored in the material, that has to get out of the material. Okay! So that is the process of grain growth. Well you should be able to assume that when the grain growth occurs ultimately you should be able to remove all the grain boundaries and you will get a single crystal.

Some attempts have been made by deforming the materials like that to get the single crystal but not always. There should be only one nucleus to grow that will give you the single crystal. What happens in the grain process is to be seen very carefully. Alright, let us make it here itself. Let us say this is grain 1 and this is grain 2, I will look an atom which is here, and an atom which is here, I am looking into the atom in the grain which belongs to the lower free energy side and which belongs to higher free energy side.

In the volume available around this which has more neighbors and which has less neighbors, because a neighbor means the bond form, a bond form means energy is lower, which has more neighbor and which has less neighbor, let me ask this.

Student: 1.

Professor: 1, 1 has more number of neighbors there for low energy, 2 has less neighbors and it has more energy. So this atom from the higher energy side would like to jump to the other side where it would have more neighbors. What would be happening is that this would be trying to jump out of this side, when that happens what happens to the grain boundary so their grain boundary is moving this direction and this is the direction of the center of curvature of this grain. Grain boundary is moving towards its center.

On the other side I have a bigger grain, right? So we normally, we are talking about that during the grain growth bigger grains consumes the smaller ones, they eat up this smaller grains and the reason is this. But I want to make another point here, let us say I am doing so, I reached a region where it becomes a flat boundary like this. In some microstructure did you see boundaries like that?

Student: Annealed copper.

Professor: Annealed copper, very good! So when I have an atom here now and an atom on this side what is the difference in the energy of the two?

Student: No.

Professor: No. So such a boundary has no tendency to migrate. So grain growth does not go on indefinitely, we would like it to become a single cyrstal but this was stopped somewhere here, when it becomes flat boundaries and copper I showed you the boundaries have become flat. That is the grain growth we have done it in some 800 degrees centigrade that specimen has been kept for a good length of time so that the grain boundaries try to migrate to make the grains grow bigger and bigger and grain growth has taken place that is where it stops once it becomes flat. The competition of the atom to jump from left to right and right to left is the same, it is when boundaries are unable to migrate.

Here it is migrating because this atom when goes to the other side lowers it free energy but the boundary by that time comes to left. So that is how the boundary is moving towards the center of curvature of grain when the grain growth occurs and you would notice that this was happened other way round in recrystallization.

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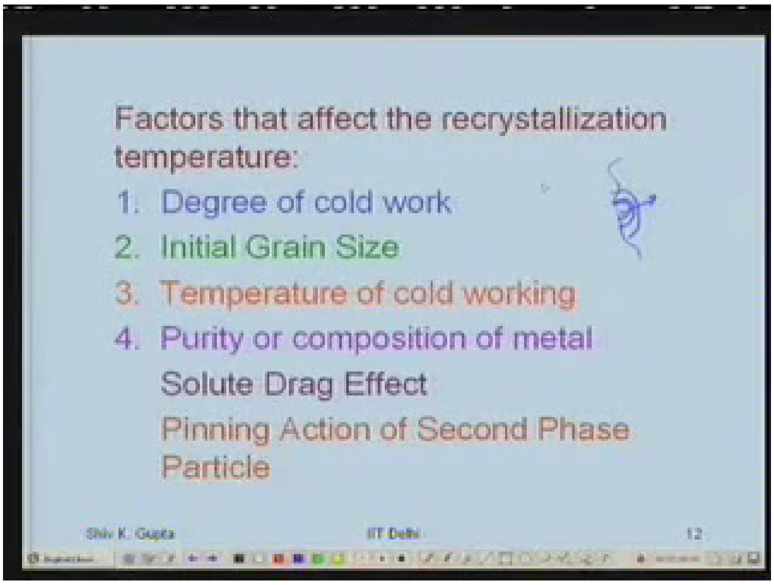

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In recrystallization let us say you have one grain, this is the other grain, the particle nucleating and the grain boundaries is then moving, jut moving away from the benter of curvature but when the grain growth occurs the body beings to move towards the center of curvature and that we say why the smaller grains are eaten up by the bigger grains.

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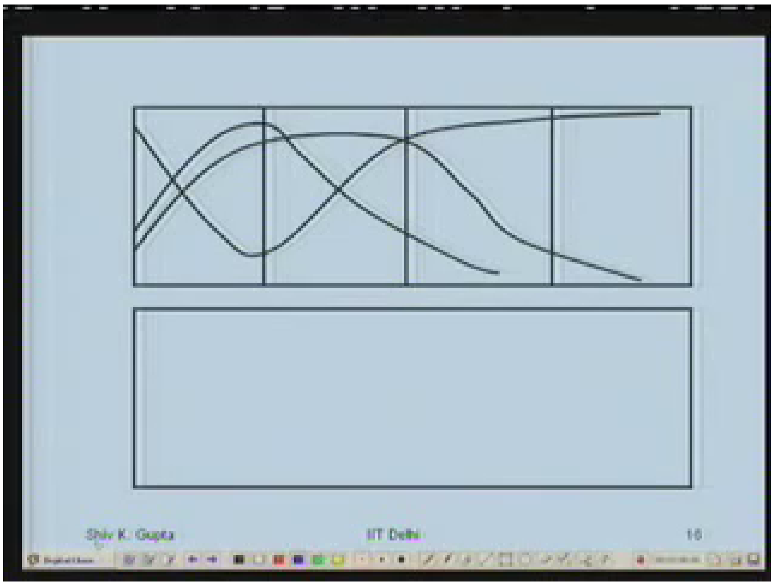

Alright! Let me now show you what happens to the properties, or structure and then the properties. Here is the configuration access, on this configuration access let us say this is equal working. This is the region of recovery, region of recrystallization and this is the region of grain growth.

Student: (())(54:29)

Professor: I deformed it grain growth had taken place but it has reached a certain level where if you keep it now for a longer time, not much, you may not see much growth because boundaries have become flat plane, there is no competition for the atoms to jump either from the left to right or right to left or it is the same.

Student: (())(54:59)

Professor: I am not saying that, what I am saying is it all depends on the amount of cold working you have done that is going to say where I shall have 1 nucleus for recrystallization or I shall have many nuclei for recrystallization. If I have more nucleation events taking place I have more nuclei and more grains and they all have to grown, some will be consumed in the process and others will start competition them when they get the flat boundary in the between. That is when even if I keep it for a longer time I may not get much increase in the growth as much increase in the grain diameter.

That means what I was trying to make a point was it is not the way I can get single crystal, because of this competition I cannot get the single crystal, for getting the single crystal there is a critical amount of cold working which has to be done so that there is only on grain which begins to recrystallize and that is the grain only grows. It has been done, it has been attempted, it is a very low degree of cold work is required for that. Alright. So what happens initially you have a material, let us say you start to… I will show you the microstructure which what has happened.

To start with I have equiaxed grains whatever the grain size is of the material. When I deform this they start elongating in the direction of rolling. In the direction of deformation they begin to elongate and when the elongate in the direction of rolling they also get crushed. They more and more degree of cold work, they get crushed and become thin long grains, right. We start with equiaxed grains when I deform they become elongated and they become quashed, right. That is the process of cold working.

Now when recovery begins this structure of the grain remains more or less as the same because grain boundaries are not migrating there, that doesn't change and this goes on till the recovery is there. Only thing what has happened is the point defects have come to the thermo dynamic equilibrium and then number is reduced, that remains. Grain structure is not changed. Now once the recrystallization begins to take place, well I have more or less that elongated grains which are there but somewhere I start to form round equiaxed grains.

And as the recrystallization goes on I get more and more recrystallized grains, some are still elongated but when the recrystallization is complete I get all equiaxed grains of fine size, very fine grain size I get, means the grain diameter is small and then when the grain growth occurs they begin to grow, they become coarse as the grain growth occurs. Start with the fine grain it becomes slowly bigger, bigger and still bigger and that is how the structure is changing.

Now here I will show you certain properties which change, firs of all the property which is affected by point defects very strongly is, let us say decreases like this when the cold working is done, during recovery it is recovered back, right? That is electrical conductivity. Similar is the effect on ductility, okay. Then there is a strength of the material what I call it as tensile strength, it increases during cold working but is not affected by the point defects so it remains constant during the recovery it remains the same.

But during recrystallization when the dislocation is becoming less and less strength comes down and strength comes down further when the grains gown in size. I told you that fine grain materials are better mechanical properties. Strength comes down when I increase the grain size, remove the dislocation strength comes down, when I deform the strength goes up because I have increased the dislocation, I have also crushed the grains, I have increased more internal boundaries so therefore it goes up but the strength remains constant during recovery because it is not affected by the point defects.

And that is I think the another property which should be, resistivity should go up with the cold working, opposite of electrical conductivity I think one must prefer ductility, so that goes up and with the recovery it recovers and during recrystallization it goes down further. For some properties which are affected by the point defects, they get recovered during recovery itself. Some properties which are affected by the dislocation, they get affected during recrystallization. By recovery means we are recovering some of these properties which are strongly dependent on the point defect, right.