Phase Transformation in Materials
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Lecture - 47
Recovery, Recrystallization and Grain Growth (cont.)

So, we have started the new topics in the last lecture that is not recovery recrystallization and grain growth. I have given you some preliminary idea that in metal working we deform the materials to get different shapes. And this deformation will produce different kinds of defects in the microstructure: dislocations, wind effects, or even voids or twinning.

So, once these defects are accumulated in a microstructure the properties of the materials get affected; mainly the mechanical and physical properties. So, because of the accumulation of these defects the strength of the material keeps on increasing, but ductility and other toughness properties gets reduced and this is a serious problem in the ductile applications that is why in most the cases we anneal the material after the plastic deformation. And these leads to what is known as recovery recrystallization gain growth depending on the temperature of annealing.

So, let us have a little bit recap and then we will go into that. So, as I said there are different kinds of metal forming processes and each of these processes leads to a huge plastic deformation.

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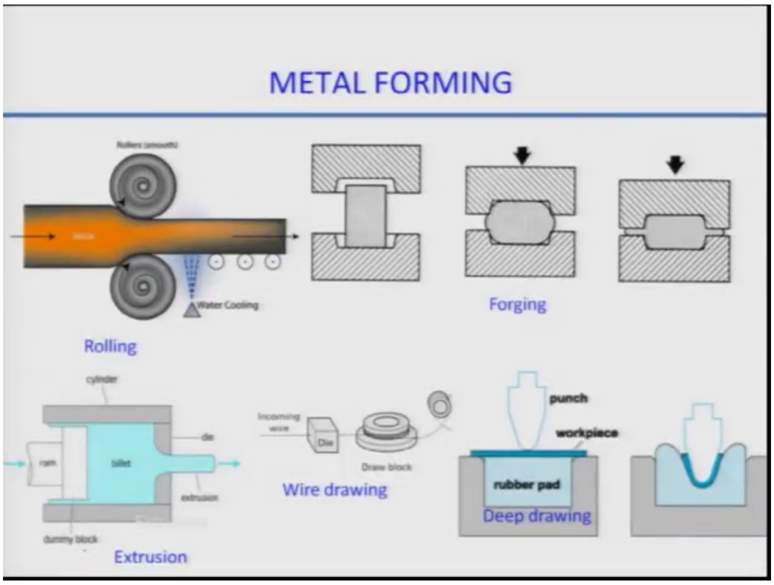

And then these can give rise to different kinds of working conditions like hot cold or warm working depending on temperatures.

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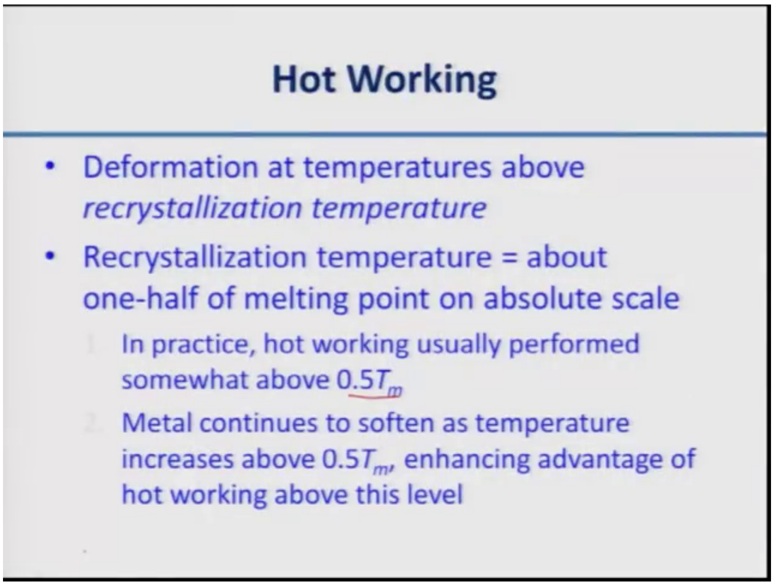

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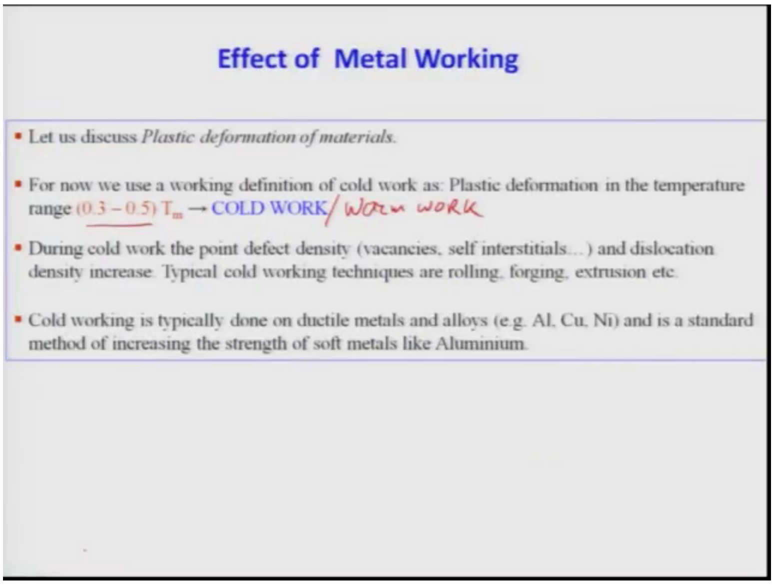

But especially in the cold working sufficient amount of strain energy is stored in the material and this cold working leads to point effects density dislocations twinning many other things which will increase. And this that is why you know cold working is typically done in ductile metals, because it is easy to deform this material said lower temperatures. But issue is that this accumulation of these defects leads to increase the yield strength, increasing tensile strength, decreasing the elongation and decreasing the ductility as well as toughness.

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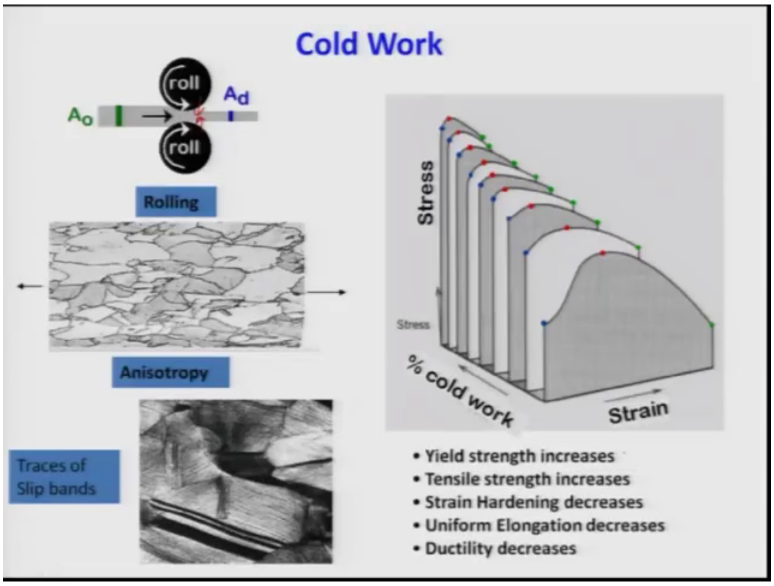

So, that is why you heat this material annealed at higher temperatures.

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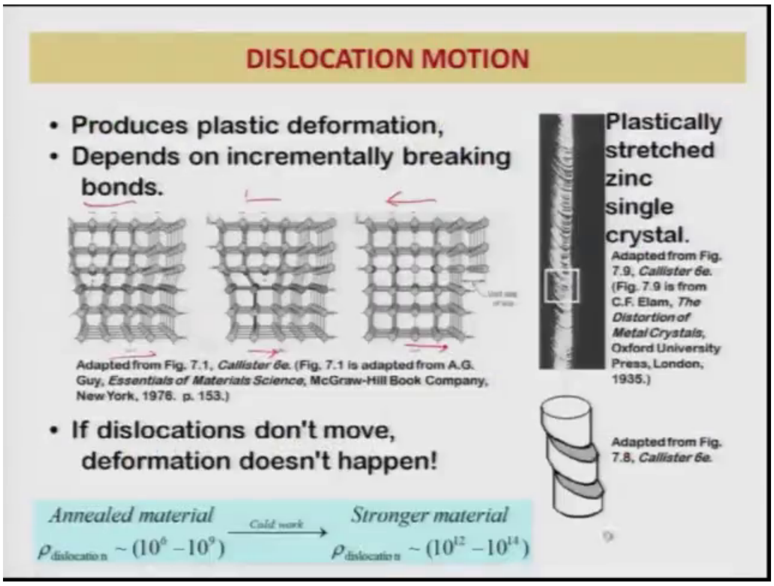

And enemy leads to recovery of the of increase of the ductility from very low value to an substantially reasonable value which can be used for applications zips Emily's strength also decreases.

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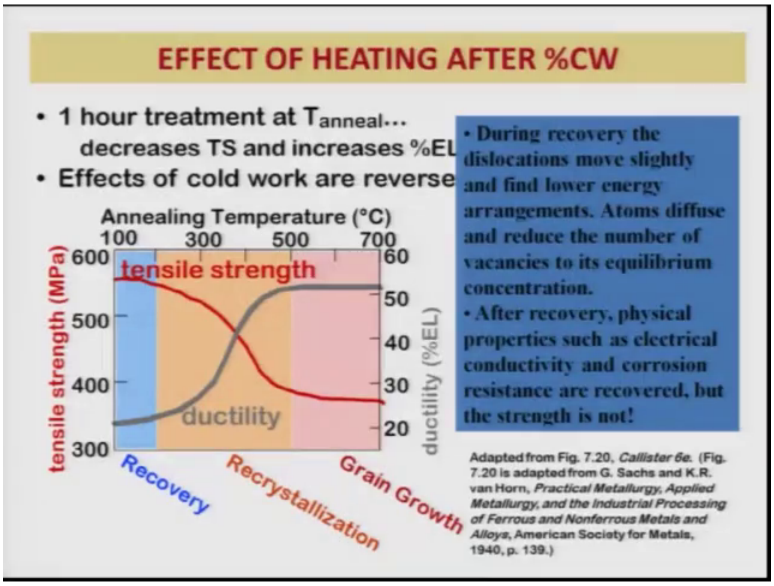

So, what actually happens during this annealing treatment? That is; what is the basic purpose of discussion on recovery crystallization?

So, what I discussed, I will go; I will now simply go back to recovery.

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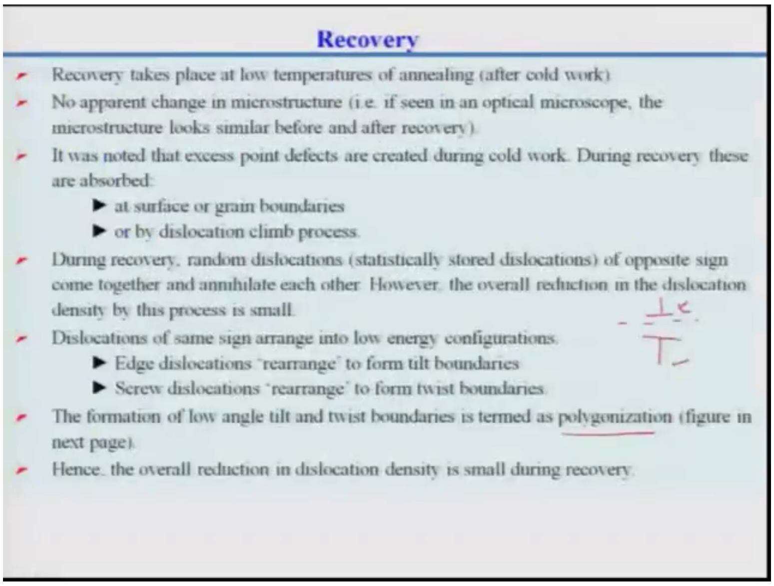

Recovery is normally takes place at a lower temperatures after just you know after end cold work we annealed and it happens at lower temperatures and it does not lead to any apparent change in the micro structures; that means, grain size the pages the distribution the grain sizes they do not change there is apparently there is no change.

So, what actually changes the thing which gets changes basically rearrangement of the defect structure in a microstructure and you know because of these access point defects are the line surface defects recovery is always associated with this kind of rearrangement of the defects. So, point defects normally can get any louder at the surface again boundaries or even dislocations kind processes not only that other defects like dislocations also gets affected.

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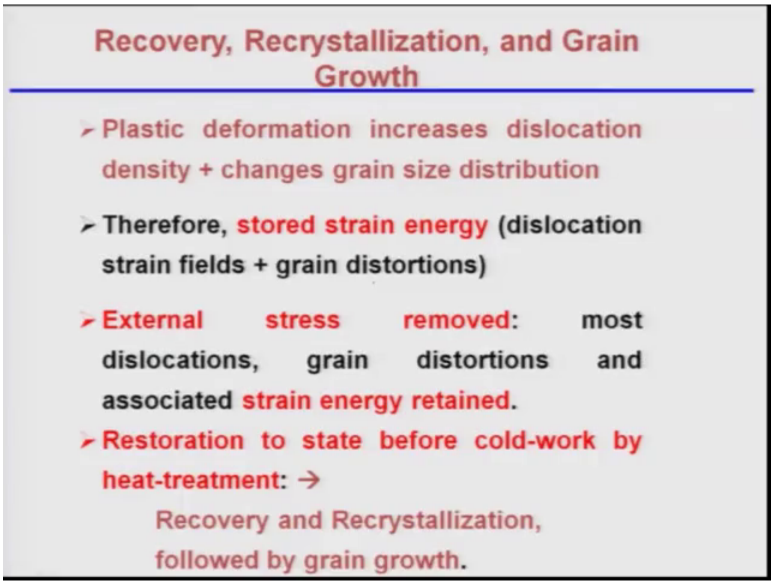

Let us now discuss one by one of these things. So, basically first thing what happens is that the stored energy which is then the material that is can relieved be because of these processes; say external stress are removed relived removed and you know and, but the stored energy which is because of the dislocation are things they gets relieved during recovery recrystallization process and finally, the grains grow in grain growth.

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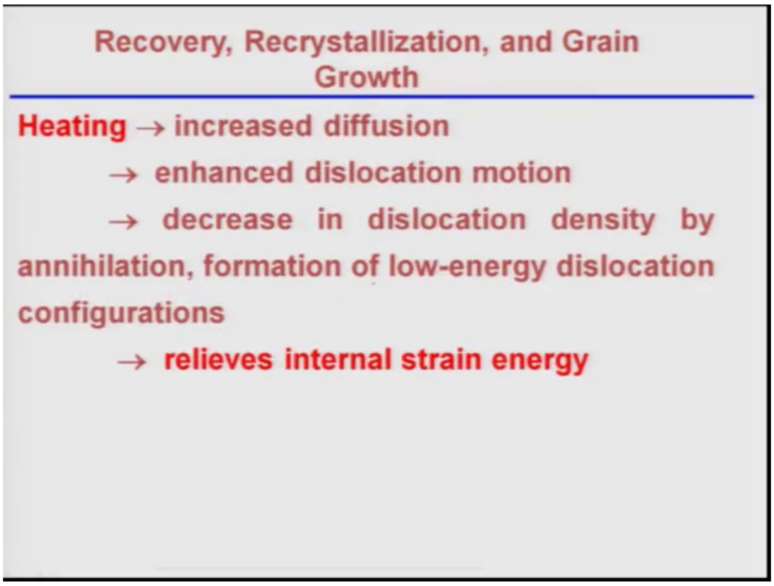

So, what actually heating does heating increases diffusion basically; obviously, because you are providing energy to the system and this diffusion leads to change in a point change of the rhythm of the point defects, they also enhance the dislocation motion dislocations can easily move because of these temperature increase and then dislocation will interact themselves they can lead to annihilations of dislocations.

So, the number density will go down or they can lead to formation of low energy configurations both of these 3 things that is point defects movements and dislocation annihilation and element in low energy configuration can relieved the internal state energy that is the basic purpose because we want to relieve the strain energy

There are many you know deformation processes in which after plus a deformations the material is given low temperature and linked treatment, just to have a recovery and this recovery will lead to deferred the arrangements recovery lead to reliefs of the internal stress or internal strain energy and then again the material can be further subsequently deformed, this is done widely in steel industry that the plastic deformation followed by annealing at low temperature again plastic deformation and this cycle actually is repeated several times in the industry.

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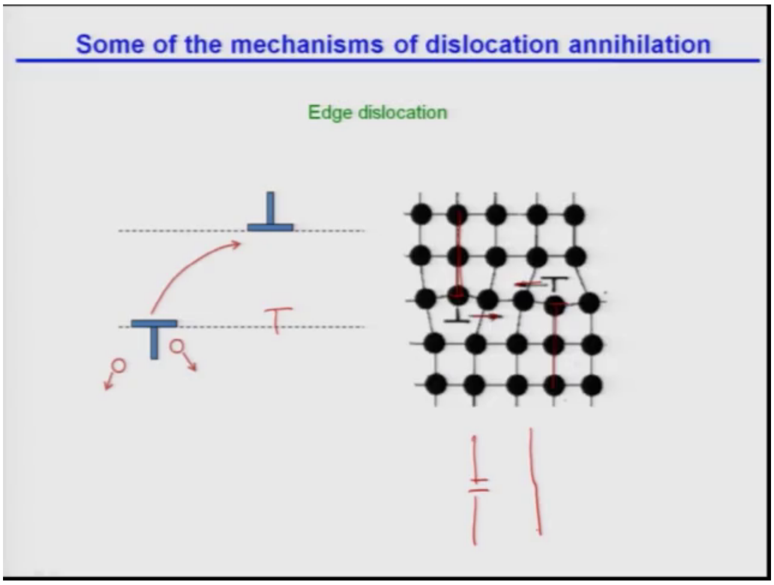

So, let us now consider edge dislocations; obviously, edge dislocations of different signs will come and they can actually an anile annihilate each other this is shown there if this dislocation moves close to this one this position, they will anneal out similarly these 2 says dislocation moves here this right direction and this one left directions. And they can join you can clearly see these 2 planes of the atom that is what I will discuss the last lecture this is an extra plane our paradigms in the left side, they are on the right side of myself. Obviously, to be opposite to you and then once they come closer to each other; these 2 can join and form a continuous plane.

So, therefore, the dislocation can annealed out not only that is and this can only happen in the divorce dislocation moving on the same plane if the both dislocation are actually moving on the same glide plane they can come each other, but come to each other and then I will have annihilate, but if they are not moving on the same plane then what will happen if they are not moving on the same plane like this one, they are not moving on the same plane it can leads to a wide formation.

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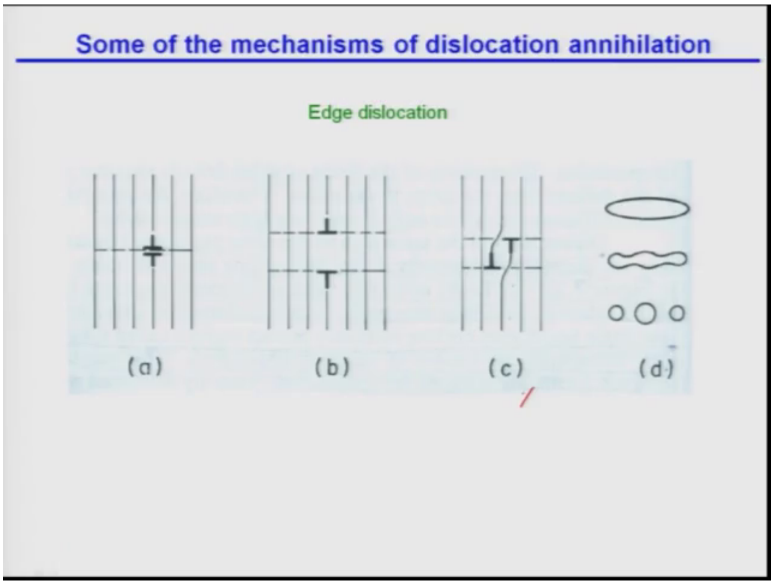

First it will lead to micro whites and then it will lead to a bigger white's formation. So, whatever it is this relieves the strain energy in the material that is most important aspect you must realize so, but what happened happens to the other dislocation screw dislocations. One of the best mechanism by which the both the edge and screw dislocation can actually really parent strain energy is by known as what is known as polygonization.

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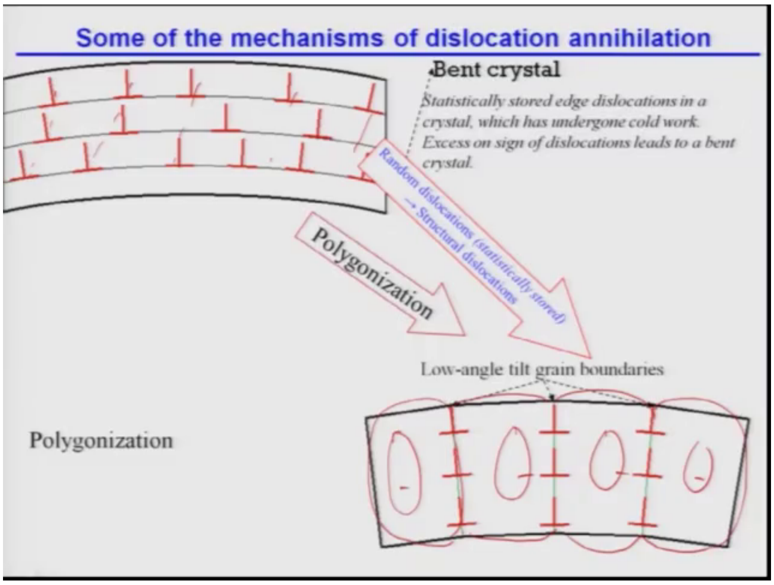

I have discussed this in last class also again giving you better perspectives; suppose you have a large number of dislocations lying on different glide plains inside the crystals and the crystal will; obviously, bent because of deformations now this will lead to huge increase of the strain energy. And this increase of strain energy can create lot of you know lot of difficulty in getting the by the ductility. So, what we can do you heat it up dislocations can align along certain directions partically. And because of that these strain energy can be reduced in the regions which is marked by this blobs physically, it can be reduced. And but by doing anneal and by arranging this way they actually create what is known as a low angle tilt boundaries if they are all edge dislocations.

So, these low angle grain boundaries will differ and subsequently create what is known as you know small angle boundaries will need to from cells or basically sub grains this is actually sub grains. So, by that way the strain energy of the majority pilot part of the grains can be reduced extensively. Similarly the screw dislocation align along patically along certain you know directions. So, then it will create a twist boundary and both the tilting twist boundary will lead deformation of the sub grains.

Therefore, these 3 important mechanisms which operate in the recovery stage leads to reduction of the store energy or strain energy in the material this is very important to for you to realize that this happens you know sometimes when you will do hot working these kind of situations keeps on happening during deformation itself like in case of steel if it is water temperature of suppose 800 to 1000 degree Celsius temperatures deformation. And this recovery will happen together and that is why actually hot working is good because it the strain can be relieved very easily during the process of deformation itself you do not need to again provide annealing treatments.

But then in cold working, if it is steel also people nowadays to cold working cold working which is done at a much lower temperature for steel 300-400 degree Celsius or even room temperature some cases depending on the ductility of the steel. So, the and the annihilation or the rearrangements of these dislocations and the point effects are only possible when we heat it at a intermediate temperature during annealing stage. So, that is the reason we annealed most of the materials after cold working now what can happen the next step.

Next step is nothing but as we increase the temperature of annealing to higher temperatures higher from the recryst completely recovery we can we will have a new kind of phenomenon known as recrystallization as a term suggest is basically crystallization again. So, normally crystallization happens from the liquid state we as you know there is a solidification course a chapter of this course, I have discussed about nucleation of different grains heterogeneously or homogeneously and that is what is known as crystallization.

So, the nucleation and growth recrystallization is what happens in a solid state during you know annealing of the deformed material.

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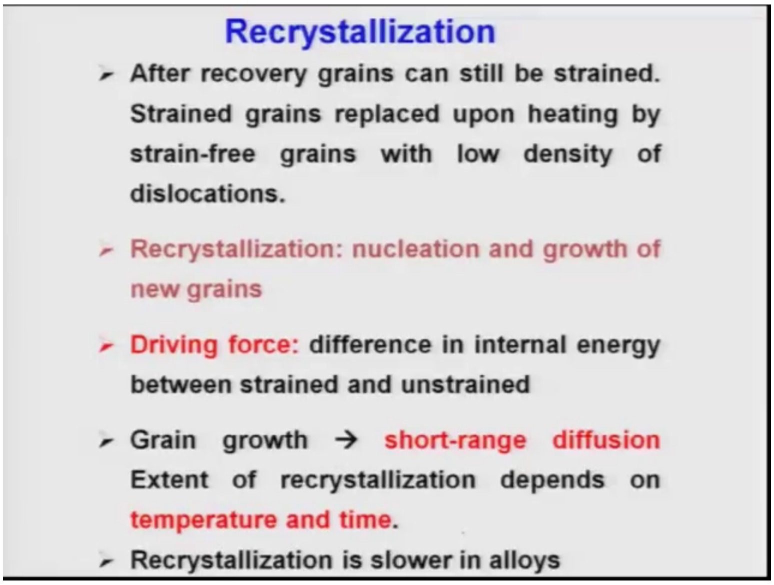

So, after recovery grains can still be restrained; obviously, recovery cannot relieve all the strained a strained regions of the grains can easily be replaced by you know by heating just heating up by the strain free grains with low density dislocation remember this texts are taken from this book by; I am just teaching this portion of these lecture from book of A K Jena and M C Chaturvedi. So, you can directly read these books and these texts are actually taken from that now recrystallization is basically nothing but nucleation and growth of the new strain free grains remember new strain free grains it is not only new grains the grains which will be forming or crystallizing or again growing strain free.

What is the driving force for that; obviously, driving force is nothing but a strain and store energy in the material difference in the internal energy of this strain and the arc strain that is what is the driving force and growth as I told you grain growth is different by the gain boundary energy.

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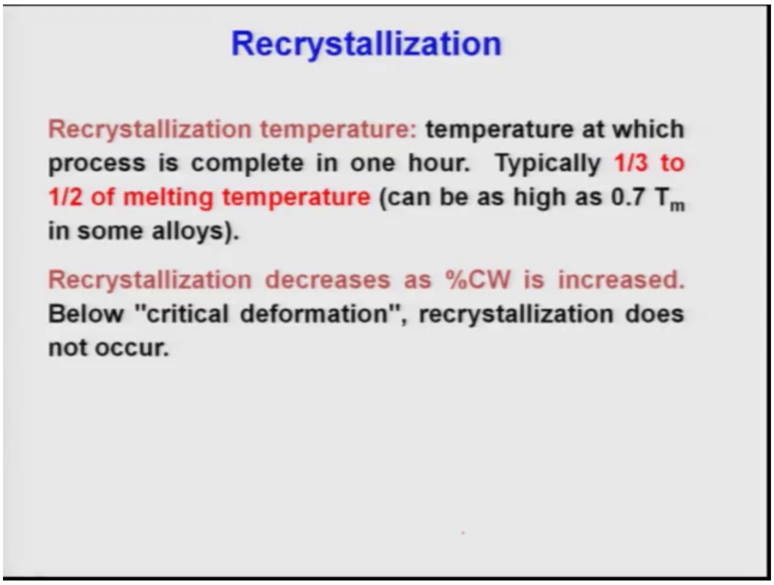

So, therefore, these depends on both temperature and time and let us first discuss the time temperature at which this happens is basically known as the recrystallization temperature; typically it is between point one point one third to one half of the melting temperature of the material. So, it can actually go even up to point seven, but very rarely normally is between point 3 one point 3 to point 5 tm basically it is more likely 0.4 to 2.5 Tm a recrystallization temperature normally decreases as a function of cold work more the cold work more higher and lower you see recrystallization temperature because you have more strain energy and the strain energy is a driving force for recrystallization.

So, below critical deformation recrystallization never happened that is why if we deform material by lower amount lower amount of cold work then only recovery happens recrystallization is does not happen, because you do not have driving force to left to form a new crystals.

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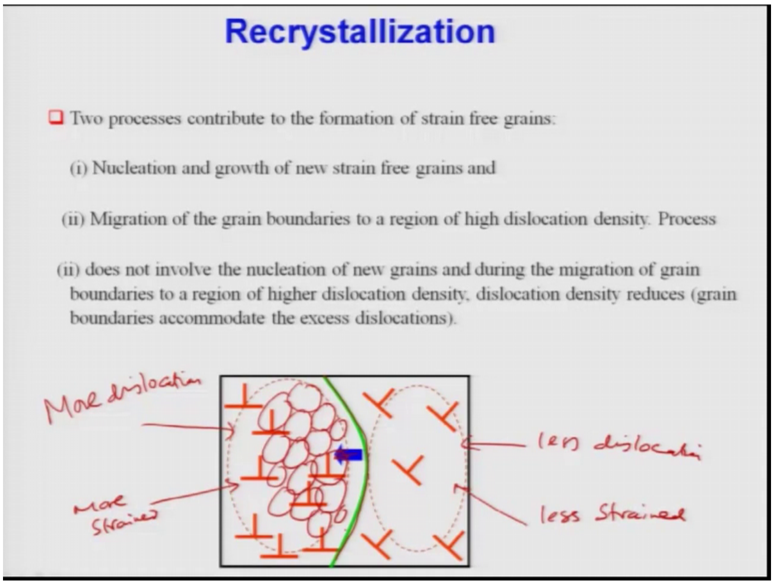

Now, let us discuss 2 important things you know there are 2 important processes very very important processes which actually leads to formation of these strain free grains first I have already discussed the nucleation and growth of the strain free grains, but that is not the only one. Remember, there will be also migration of the grain boundaries because you have already a strain grain inside the grain. There are a lot of defects and during the recovery process this defects have arrange them nicely. So, that strain energy can be reduced.

But as the new grain forms, there will be migration of these preexisting grain boundaries which are there what is that well you know this nothing this can be shown in this way; suppose, we have a strain grain which is more strain both the grain has strain one is more dislocations and other one has less dislocation this one has less dislocation.

Now, this is the arrow to which the grain boundary will move from the load lower number of distributions to learn more number of dislocations. Obviously, because of low energy dislocation this is less strained this is more strained strain energy accumulated is more if a more number of dislocations.

So, therefore, the grain boundary which is like this; this blue sorry, the green color this will move already along the arrow and given by the blue. So, that is the wakage grain boundary moves while the grain boundary will move along direction. Obviously, the reason is very simple see you have a lot of drag on the grain boundary because of these strain energies. And as soon as the as you know the cold work is more in this grain which is the more strain energy. So, the chances of formation the strain free grains are more here it is a very peril a parry widely happens. So, because of these; you know because of that the grain boundary movements the nucleation and the growth of the grains also gets affected does not involve nucleation of new grains the 2; one first 2 means of migrations and during the migration of grain boundaries to a region of high density dislocation is reduces.

Grain boundary can actually accommodate more dislocation that is why as the grain boundaries moves from lower the blower deform regions to high deform regions the dislocation density will reduce in the high deform regions because this dislocation will be then part of the grain boundary, because grain boundary can absorb the defects grain boundaries region of defective regions. Therefore, these dislocation can then actually they can they can actually part of the grain boundary. So, that is why actually grain boundary moves and reduces the strain energy. So, this is one of the way of another way of reducing the strain energy.

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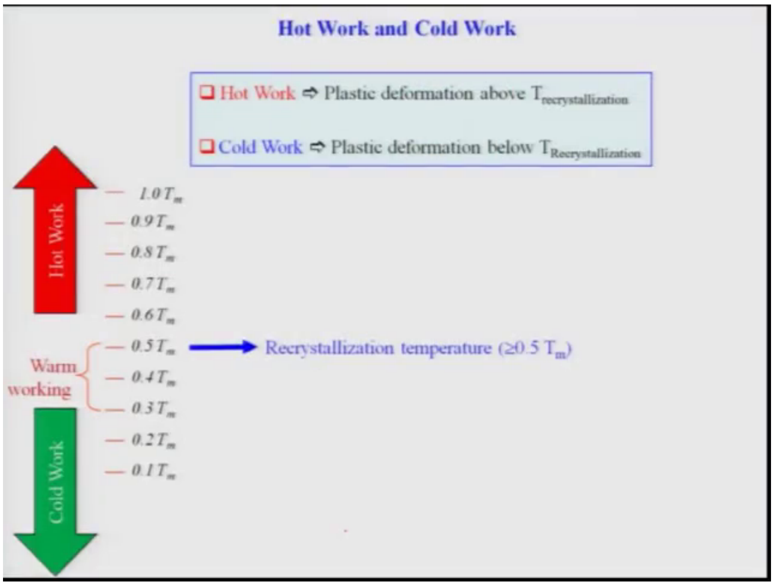

So, now question is the temperature you know actually you have seen we do normally 3 types of to metal working hot working cold working and warm working and we normally define I told you that whatever thing happens above the recrystallization temperature cold working is below recrystallization warm working is between that point 3 to 0.5 that is what is given here.

Now, recrystallization temperature is somewhat close to point 5 normal it is more than 0.5 or close to 0.5, but as I said it can be between point four 2 point 5 also. So, that is 3 temperature of recrystallization and this is true always so; that means, its scales with the melting temperature for pure metal alloy is skilled to the multi temperature that is what you should do and this is you know understandable well, it will be clear to you very soon.

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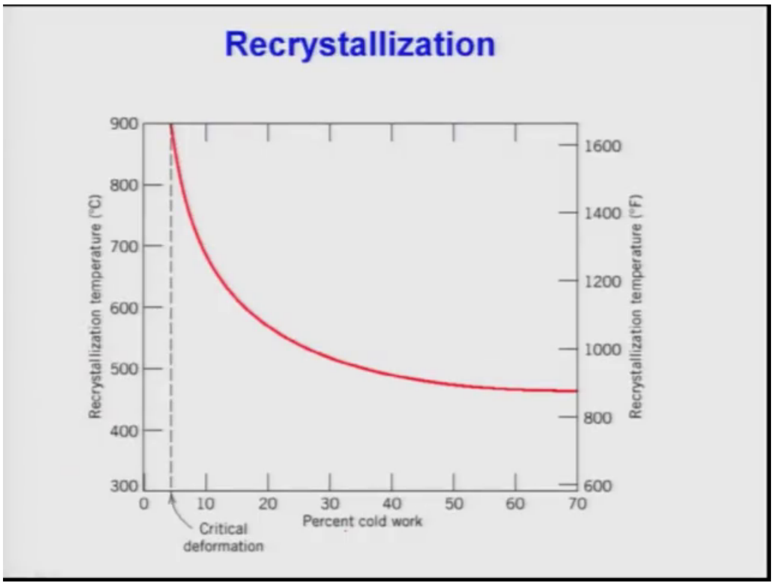

You know this is a plot of recrystallization temperature versus cold work and this is again taken from Callister’s book on materials engineering as you see here recrystallization temperature strongly depends on depends on the cold work it also depends on strain rate it also depends on strain rate let me tell you and also mode of deformation if you are deforming by you know by torsional by normal uni-axial loading things will change, but obviously percentage cold work does affect recrystallization temperature strongly. As you see here you have a critical deformation required and remember this is for steel. So, inverts have a recrystallization need about 5 percent strain below that there will be no recrystallization.

And as you increase the plastic work from 5 to above 65 to above I think 30 percentage the temperature can go down from 900 to above 500 degree Celsius temperature. So, that is what you said it varies 1.1 third to one half off actually of the melting temperature depending on the percentage cold work and after that the temperature recrystallization temperature does not change much, this is for a particular steel. So, there are a lot of steel which can recrystallize a temperature of 500 to 550 degree Celsius temperature and so; obviously, once a huge amount of strain is built up in a material that itself acts as a driving force for the recrystallization. Therefore, the recrystallization temperature becomes independent of the cold work beyond certain values of the cold work.

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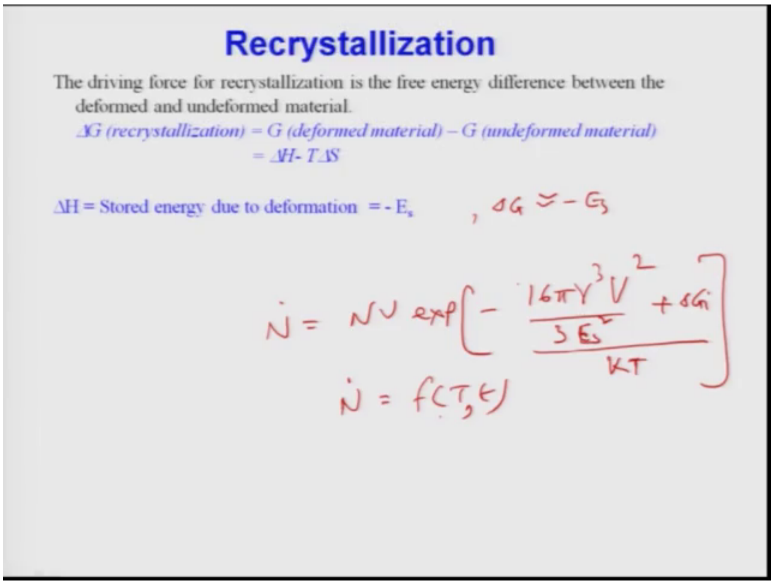

Second important thing is that you know recrystallization as I told you is the driving force is basically free energy difference between deform and undeform crystal material and this is given by delta H minus tilt T delta is obviously now delta H is what this is stored energy due to deformation that is always can be defined as a minus Es. And this value is it has been found to be Ex in a much much higher than the T delta S.

So, therefore, we can actually know the T delta s part and we can actually write down delta G is almost equal to Es and to give you an value which is given in this book you know the value of Es basically. So, for I think is for by material yes value of Es for there are silver gold alloys silver a seventy percent gold and 38 percent silver it has got 0.3 D kilo joule per gram atom. So, that is C value available. Now, this is the important aspects. So, Es actually depends on you know, it depends on percentage cold work it depends on the deformation process strain rate and also the temperature at which the deformations done.

So, you understand that the Es is the critical parameter and remember Es, it does not depend on temperature Es actually depends what I mean by is a weak function of temperature normally is independent of temperature; so, because it is a store energy. So, that mostly depends on the percentage cold work strain rate deformation processor.

let me also tell you 3 important facts; facts about the recrystallization temperature; obviously, as I told you as higher the temperature working metal working a lower the strain energy stored; obviously, because recovery will happen subsequently a strain energy will be relieved and this will lead to higher recrystallization temperature you know.

Second important aspects the rate of recrystallization you know rate of crystallization is given by this formula as you have seen N is given N dot is given by N nu exponential you know that this is all exponential function minus 16 pi 16 pi this is pi and cube pi gamma cube sorry, this is gamma; gamma is the surface energy interpretational energy rather. So, sorry in interpretational energy is sorry this is v square not e square v capital v is the volume divided by 3 Es square plus delta G i divided by KT; let me define all these terms I have already defined your Es this is the volume.

Obviously, the atom volume the atom volume per atom Es is the stored energy and v nu is the frequency N is the number of atoms presents and gamma is a surface energy K is boltzmann constant T is the temperature and what is delta Gi delta Gi is the activation energy for the grain boundary diffusion why it comes into picture because grain boundary moves during this process that is why. So, that is why and this is N plus term remember grain boundary migration requires energy and this energy is positive term. Therefore, higher is the grain boundary kinetic deformation energy lower will be the available energy for the systems and its term.

Now, as you know normally Es predominantly Es is independent of temperature it is not always the case, but most of the cases and because Es independent temperature N dot the nucleation rate is also independent of temperature it is not dependent temperature so, but it depends on time why it depends on time well let me explain that, but you know so; that means Es. As that means, the N dot is basically is or not only function of temperature here you see a temperature is there KT, but it also function of time. And we will see later on maybe in the next subsequent lectures. Once you know the growth we can actually define these whole kinetics using Johnson milligram type of equations and that is the classical way of representing the nucleation and the grain growth theory recrystallization and grain process.

So, a question is this picture I always show you again and again because this particular slide is for you very important to keep, it in your mind always as you know this is the picture.

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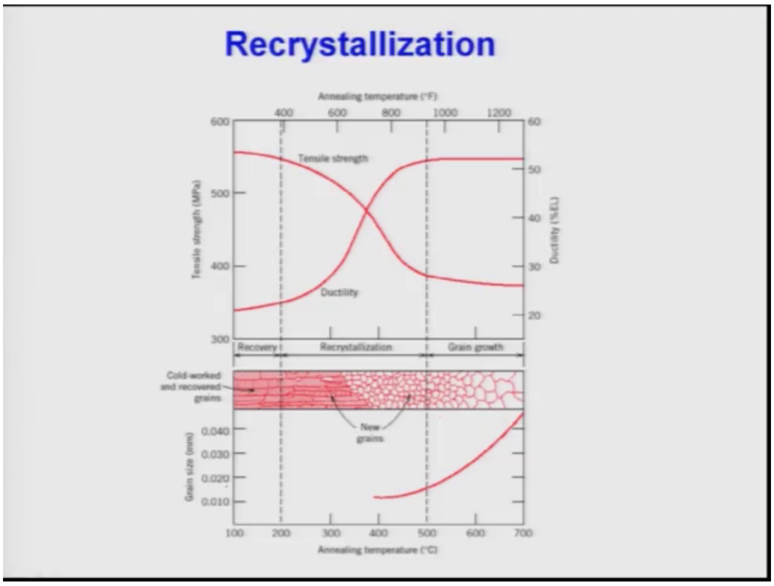

As you see here the let us look at the bottom picture which is tells you the things my easily what you see here you see here that at a temperature annealing temperature versus grain size and this is this microstructure given schematically. So, at lower temperatures you have cold work grains lot of dislocations and point defects and other defects represents and then as the lower temperature annealing needs to recovery of these defects.

So, defects means dislocations mostly point defects they can get anneal out of the grain boundaries or dislocations can also anneal out or they can actually forms voids or they can actually arrange by polygonizations and then higher temperatures if what if basically leads is basically nucleation on the strain free grains what is known as the recrystallization process starting and then if you increase the temperature further be on pointed the grain starts point because that is the way they can hang and reduce their grain boundary energies.

And this whole process drastically effects or their effects the mechanical properties ductility improves subsequently see ductility improvement is not very large to recovery stage, but at later stage when recovery here the recrystallization happens together the ductility improve substantially. So, one can actually stop here at this temperature because you have a critical value of both strain and ductility stained is about 470 and ductilitys about you know something like about 40 percent can be achieved and any subsequent increase of temperature leads to drop of the tensile strength further and ductility increases, but ductility does not increase much much means subs are increase happens only during recrystallization process that is why the strains can be relieved extensively.

So, at a lower at the higher temperature when the grain grows much; obviously, the strength decreases very very heavily that the grain becomes bigger the whole page mechanism starts operating and the grain size increase will lead to decreases in this tensile strength substantially similarly the ductility will improve, so but this is at the cost of huge decrease in this strength. Therefore, in the actual industrial practices this temperature of annealing temperature should be chosen perfectly properly, rather I will say in order to have a bright combination with strength and ductility during these deformation and annealing processes subsequently.

So, that is the most important message I like to tell you in the next lecture: we are going to discuss about the some of the aspects of recrystallization which are remained and then can growth. And finally, we will talk about Johnson milligram types of kinetics of the recrystallization process.