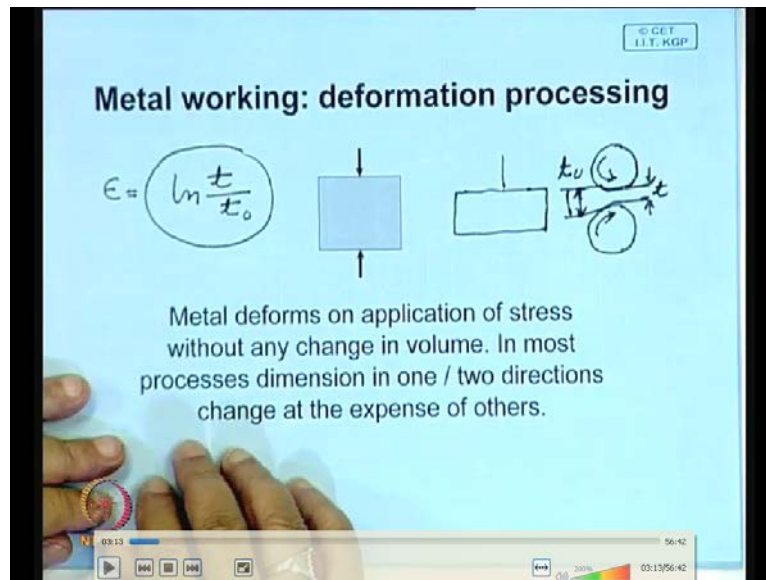


Principles of Physical Metallurgy
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Lecture No. #28
Metal Working: Deformation Processing (Contd.)

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Good morning, we have been discussing about metal working deformation processing. Last class, we primary looked at the effect of **effect of** pressure for load that you apply on a material, and the how does the resultant deformation take place. And we will see that always metal deforms with application of stress, that there is no change in volume. In most processes we will find dimension in one or two directions its change at the expense of others. For example, in this particular case, if you apply compressive stress like this; in that case its thickness will decrease, and it will increase in that particular direction. There is an increasing length along this direction there is an decrease and thickness along this direction, and we say that amount of the deformation of plastic deformation is represented as \ln , thickness t over t_0 , this is the true plastics strain. This is the thickness attending point, and this is the initial thickness.

Now, in this particular case if other side it is not in die, then in one side this side there is reduction in thickness and the on the other two side expands, but often we do this forging is done in a die where the elongation one direction is restricted in that case it is the situation of planes strain compression. And likewise, rolling is also a situation of planes strain condition, where you have two rows rotating at constant speed, and you have the job which goes through thus an the thickness this is the t_0 , and this is the final thickness. And this case, the elongation this side it that means the material the job belong it is at the expense of its thickness, but the volume remains constant.

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| | Cold work | Hot work |
|--------------|-----------------|-----------------|
| Temp | $< 0.5T_m$ °K | $> 0.5T_m$ |
| Load | High ✓ | Low ✓ |
| Structure | Elongated grain | Equiaxed grains |
| Texture | Preferred | Random |
| Strength | High | Low |
| Ductility | Poor | High |
| Conductivity | Poor | Good |

Now, let us now see that this type of processing often can be done either at room temperature or low temperature or at high temperature. If it is done at high temperature we usually call it rolling at hot working, and if it is done at low temperature we call it cold working and we looked at the some of the structural structures that the valves as a result of work, cold and hot working. We have seen that this temperature concept of temperature to decide whether it is hot or cold work is relative it is scales with the melting point this is T_m is melting point that it is degree Kelvin degree absolute.

So, if it is done below half its melting point then it is cold work if to working done above $0.5 T_m$ (refertime: 04:00) then it is hot work therefore, let if you are forming at room temperature it is hot working, but steel if you are working rolling at room temperature it is cold working and obviously, there are few other points that comes up. We know the

strength of a material decreases as you increase temperature therefore, hot working the load that you need to deform the material will be very low whereas, in case of cold working the amount of that the load sensing increases. So, the amount of deformation that you can give is very low and the load done the rolling will be very high.

So, this is what is listed here it means the rolling load will be high in deformation forging press you need the higher capacity press whereas, for hot working in low capacity press, but there is an advantage of cold work the cold work there is an no interaction with environment. Environment is more or less is not whereas, in case of a hot working you have to often depending on the material you may have to of a **of a** some kind of a protection or else there will be scaling loss. The some of metal will oxidise and it will the loss will be relatively high in case of hot working.

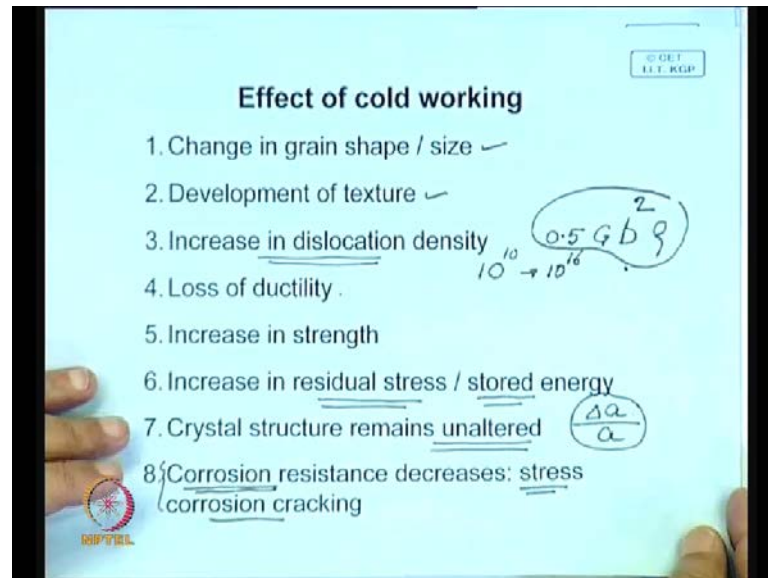
Now the cold work material you will find the grain elongated which show sign of the formation whereas, hot work something happens during the process of working the material grains deform that the grains very crystallise there are change I mean new grains are also nucleated and they grow and these grains are equiaxed whereas, here it elongated, because of this type of nature elongated grain the cold work material has the texture has the preferred crystallographic arrangement or a alignment of grains so, this next this property of a cold work material and nicer topic depends on the direction whereas, the hot work material the every chance that your property of the material will be isotropic it will be independent of the direction.

Now strength of the cold work material, because it hotence the strength will be higher whereas, strength of hot work material will be relatively low it will be something similar to normalize structure or anneal structure of the metal. Now ductility in case of a cold work material will be poor. Ductility of a hot work material will be high an other physical properties also will change like conductivity will be poor. A hot working the conductivity will be good likewise, there will several other physical properties that also will change.

For example, density see if any deform a material as a cold working you generate lot of dislocation and we know the dislocation is made up of extra half plane and believe the plane there is an vacant lattice have an vacant plane lots of vacancies are there. One obvious things that comes up that there will be certain other changes that will take place,

because of present of the dislocation there will be lot of stored elastic energy the density of the material of a cold work material may also may be slightly less then and annealed material, because of high vacancy concentration high dislocation density.

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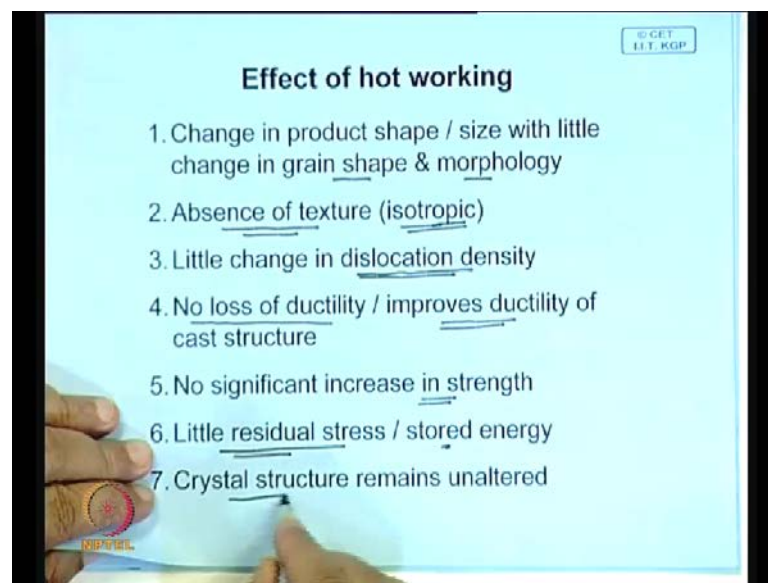


Now so, effect of a cold working which is listed here, there is a change in grain size and shape as the develop of texture and dislocation density increases. So there will be stored energy will be very significantly higher in cold work material and we know that energy of a dislocation is $0.5 G$, G is gya modulus b vector square. Now each dislocation has the this much of a elastic stored energy now imagine as result of cold working dislocation density can increase from 10 to the power may be 10 to the 10 power 16 , number of dislocation for unitary for meter square.

So, imagine how much will be if we can substitute this here so, that means multiply by dislocation density. So, this will be this stored energy in a cold work material and this will be substantially high and the material work hotence there will be the loss of ductility increase in strength and this is the increase in residual stress. So, the different area of the material may deform to different externs, it will be elastic stored energy because of the mismatch of this elastics range and there will be stored energy as the result of 5 dislocation density, but the crystal structure of the material that will remains unaltered. The crystal that may be, because of latice paramine residual stresses latice parameter may change slightly or that latice parameter change in the may be wide the latice

parameter measurement that is may be more, but the crystal structure remains unaltered and cold work material is in a relatively on stable less states therefore, it may have its reactivity may increase with the environment therefore, is corrosion resistance of cold work material usually decreases and in some material, because of the presence of the residual stress some material are acceptable use stress corrosion cracking. So, sometime therefore, the cold work material may not be use in the cold work condition in many cases and they will be given a treatment which is called a annealing treatment are we will know about it little later.

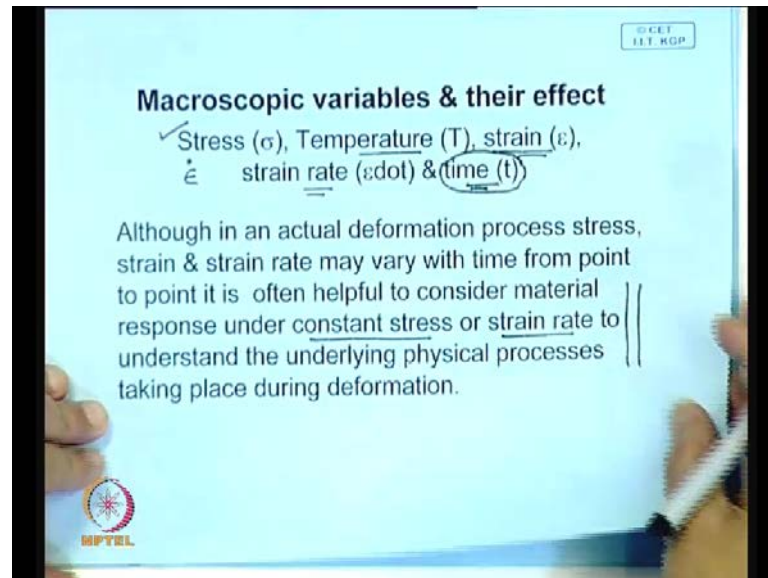
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Has against this hot work a cold working hot working also there is change in shape of the product shape and size of the product with little change in grain shape and morphology there is an absence of texture, but it also depends on paired cold work if you have a given a material heavy cold work and then if you doing hot working is the steem it may be difficult to remove some of the texture, but usually by an large effect of hot working is the **is the** does not that hot working does not lead to development of an orientation and material property in polycrystalline material is isotropic. There is little change and dislocation density, because entire operation is done at higher temperature, where dislocation an mobility is higher secondly dislocation anihilate and there is process of dislocation annihilation will know about it. So, there is an little change in dislocation density. So, there is no loss of ductility infact when you hot working a cast material it in fact improves where it removes segregation of cast work cast metal an improves its

ductility there is no significant increase in strength. Only apart from certain hot working processes we do there is amount of grain refining so there be some of amount of increases in strength, but by and large most cases there is no significant increases in strength and in the hot work material there is little residual stress of stored energy and crystal structure it will means unaltered.

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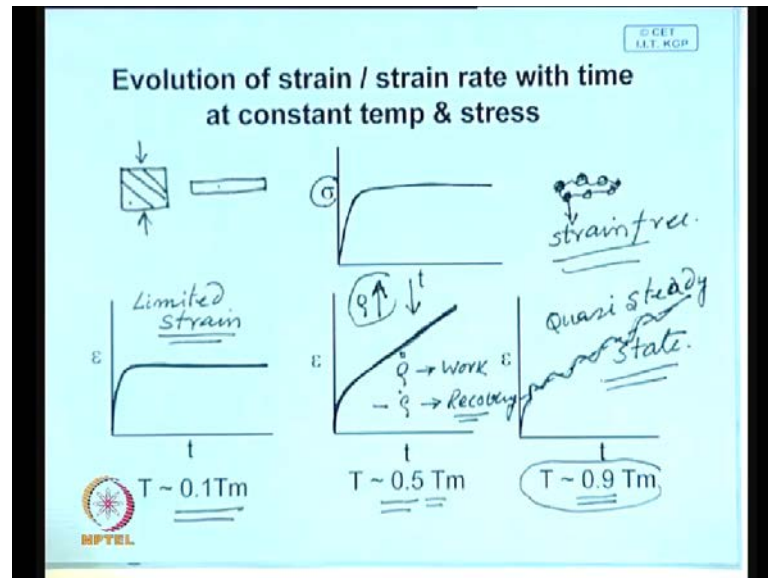


Now when you work obviously, the point that comes up what are the variable that you can control and these are listed here. So, when you applies a stress that it is stress more stress disposal you can control the stress that you apply. You can control the temperature at which your working you can control the amount of strain you want to give at every stage of deformation at every stages suppose rolling is done in several stages and in each parts how much strain you will control you can control the strain rate the rate at deformation will be given, the rate at which you apply load that can be control and obviously time is possibly you can consider this also as a variable. How much time you spend, this is time also important.

Some time you know the hot working done in stages and therefore, in two stage deformation they may be some amount of time gap between the two. There also time will play an important role and although in an actual deformation process these are variables may vary particularly stress strain, strain rate may vary with time from point to point, but it is often consider the material response to understand the material response we often

assume that deformation takes place and either constant stress or constant strain rate to understand the underline physical processes that take place during deformation. Let us see when we consider the material behavior on the this condition.

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What do we get so, when we are try to deform a material what we try change in shape. This by initial size we want to roll it down to this so, that means will every step that strain that a walls material and how does this strain or shape change evolve with time and we can visualize suppose we are during this processing by a plane stress to the material and we know the deformation takes place only major deformation takes place hold it major deformation text place throughly and some time twin also place an important role. Let us these are the slip plane when the slip takes place through the process of slip shape changes from here to here and **and** since it is a polycrystal material in you have different grains each grain will have slip system specified slip system they will be differently oriented with respect to this axis.

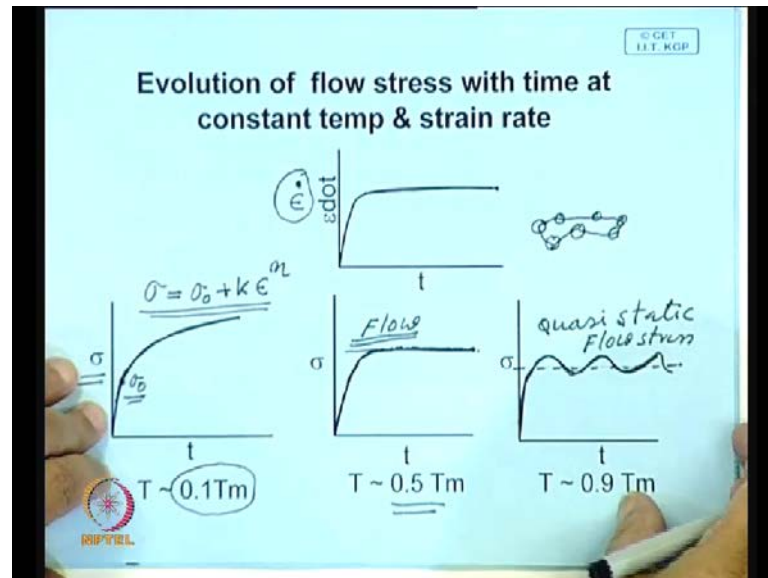
So, it is in the very complicated process, but nevertheless if we measure is stress we may find that which time this stress the material can with stand varies like this if as we are **we are** applying the stress like this to a material. Let us see what is the behavior how does this strain how mean what is the strain response to the application of stress and how does evolve it time. Thus will clearly depend on temperature, if the temperature is low say let us it is round room temperature for steel you will find initial strength will **(())**, but after

sometime it is σ strain does not increase. So, that is cold working is always there is limit how much strain that you can give there is a cold working it can give only limited strength. So, material hardens and therefore, you cannot strain it further you have to give intermediate rest to restore its initial structure bring down its strength. So, give it annealing treatment then only will be able to deform.

But, if you are deforming at higher temperature say it is something like hot working, but the temperature is still at the low end near the low end of the hot working temperature. Here you will find there is a time dependent deformation that is strain like this. And here what happens is initially there is some amount of strain hardening, but since the temperature is high as the dislocation density because of dislocation density this σ deformation dislocation density goes up, but the temperature is high dislocation have another mobility that is it can climb that dislocation can climb and annihilate also, dislocation that structure also recovers which brings down dislocation and on the whole.

During process of deformation there is a steady state. So, increases in dislocation density because of working are balance by loss of dislocation due to a process or recoveries are thermally activated movement of dislocation. And then you have a steady state and this type of behavior allows you to give large deformation to the material. Now alternatively if you are increasing the temperature you will higher you go close to $0.9 T_m$ then what happens there will be grain which can deform, but simultaneously, some of the because deformation is so as all simultaneously. Some of new grain start nucleating and these are strain free grain and this is called the process of re-crystallization. So, during working the cold work grain as a that is highly strain grain there replace by strain free grain these are strain free grain and well such grains nucleate its term comes down also an infact on the whole you may find that means you have σ that is grain evolution with time and you can this is pseudo steady state this average line you can this is quasi steady state situation. So, as again that low control process we can also visualize the strain control process

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And where I think same thing a one this axis we write strain rate and most of the cases what we control in the rolling as a where drawing we control the strain rate , that means it is material is cold at the constant strain rate.

So, this is how you are applying the strain rate to the material then what happen to this stress in the case of, **in the case of** let us say in that particular case the material state harden goes like this. An infact this strain hardening can also be written as, let us say this is stress is sigma 0 is the east stress beyond with there is the significant plastic deformation and after this the plastic strain can be written as K epsilon to the power n. So, material hardens so, unless you increase the load you would not be able to maintain same strain rate we have go and applying increase the pressure at which in increasing apply the increasing pressure to the job that you are shaping whereas, and this happens.

When you are doing the working at lower temperature room temperature, if you working in this temperature range 0.5 Tm in that case something like this happens initially this load increases, but after sometime a steady state is that end and this is where the flow stress this is called flow stress. So, the martial continues to flow atoms at a fixed flow stress on the flow stress does not change with time and this is and this is where you can give very large amount of deformations and the other case where the material behavior is search that in deform that deformed in the energy exceeds a critical energy in that case this is the deform grain.

This re-crystallization starts so, strain free grains new create the grain boundary and the keep on glowing and when this strain free grains develop their strength is low so, suddenly you get kind of oscillating behavior that flows stress keeps oscillating and this is average quasi static flow stress quasi static flow stress. Now we will see how what type of material where do you get this kind of behavior where you get this type of behavior and this type of behavior you get only in case of cold working.

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Hot working : mechanisms

Thermally activated dislocation glide,
 Recovery by annihilation & rearrangement
 of dislocations & formation of subgrains

Al & ferritic steel: high stacking fault energy
 dislocations can cross slip & recovery is easier
 & a steady state may be attained

Austenitic steel & Ni low stacking fault: cross slip
 is difficult: with strain stored energy increases
 until re-crystallization sets in & new strain free
 grains are formed. These new grains too undergo
 deformation. This gives oscillating flow stress:
 dynamic re-crystallization

Handwritten notes: SFE ↑ cross slip (circled), a graph of stress vs. time showing oscillations.

NPTEL

Now hot working is the thermally activated process and here what happens when you deform there is slip taking places and for the slip take place the dislocation movement is necessary dislocations are generated, but when this process takes place at high temperature as dislocations are generated there is also another process parallel process of dislocation annihilation. Because dislocation gets some added movement here dislocation can claim and by that rearrange themselves and try to occupy the minimum state of energy. So, this process because of this thermally activated dislocation glide.

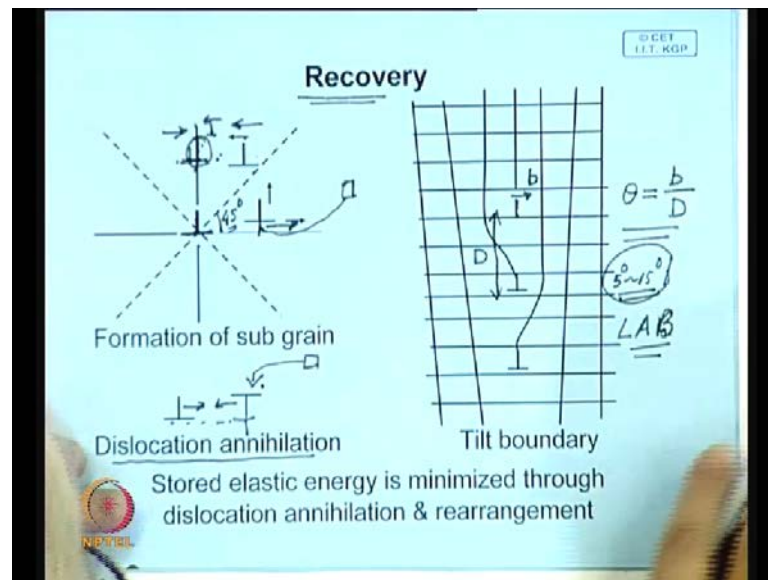
So, we can say that hot working the primary mechanism is thermally activated dislocation glide and this accompanied by there is recovery by dislocation annihilation if there is positive dislocation there is a negative dislocation somewhere here so this will claim down comes here **comes here** on the same plane and then it some moves the plane and then actually it annihilates when **to join to gether** if to join together the dislocation will disappear and rearrangement of dislocation is to the formation of the subgrains and

we have seen it earlier will again see some examples. Now this process of this dislocation glide is also affected by this stacking fault energy.

We know the material where the stacking fault energy is high the stacking fault energy material they can crossly, if gamma stacking fault energy is high stacking fault energy if this is high in that case cross slip takes place and this leads to the formation of a nice net well net dislocation network, so aluminum ferritic steel they other type of material where stacking fault energy is high. So, here dislocation crossly and this type of strains softening is easier the recovery is easier and steady state may be attained. So, here you will have here this kind of flows stress behavior **flows stress behavior** will be something like this. Whereas, **as** again this austenitic steel and nikkal.

So, these are examples of materials of low stacking fault energy an materials low stacking fault energy we will often find twins in the structure they are called in cold work an anneal structure you get twin there also sign they also of a low stacking fault energy. So, here that dislocation which split in to partial they cannot cross slip the slip planes are very specific, so it will be unable to cross slip and such type of dislocation network are formation or till a boundary formation or dislocation grain boundary formation and recovery process will be more difficult. So, here with therefore, stored energy will increase in this particular case and when the stored energy reaches the critical value when it reaches re-crystallization sets in the re-crystallization new strain free grains are formed these new grains to undergo deformation and thus process continuous and this gives oscillating flow stress and this is called dynamic re-crystallization that is re-crystallization is taking place when the deformation is being given to the material.

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Now what is a recovery process we just at that dislocation and is the process of rearrangement on dislocation, if you recollect this is the stress field of dislocation we if you recollect this top part of is subject to compressive loading the bottom half of the edge dislocation is subject to tensile loading and therefore, there is stress field around it and if there is another dislocation it also has its own stress field. Now here both this portion also is tensile this is also tensile. So, it will difficult to accumulate the to replace each other, but what happens if we claims up we have seen that this 45 degree line this is the 45 degree line if we text goes beyond this force on the dislocation instead of being one of repulsion, here it becomes one of attraction it comes here and once it reaches this particular point just about this here some just about this that is the stable configuration and here if it moves slightly this side the force act this direction if it is like this place on the side force act on this side brings it here.

So, that means if the process if the temperature if high the dislocation can climb because the vacancy from somewhere in the lattice they will diffuse to this place and this dislocation will try and once it exceed this process this particular line then it is comes because of this its stress field it moves to this position of equilibrium and in this way such an area of dislocation can form a crystal which shown here and this lattice an I think if you see on this I think use some colour here. So, here you can see on this if you can see on the screen you will see better. Now here so, this is called dislocation boundary

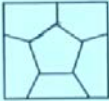
and when you have dislocation like this we have see that this is the (\odot) vector b which is the displacement.

If this is the distance between the two dislocation D then the two as if you know it is like tilting it called a tilt boundary this part of the crystal is the rotated slightly to an angle theta and this angle of tilt is given by b over D and when this angle of tilt is around say 5 to 15 degree angle. This misorientation is 5 to 15 degree so, we called is the low angle boundary low angle grain boundary total boundary. Now annihilation process something like this if you have two type of dislocation this is annihilation dislocation it is a negative dislocation if a vacancy moves from here comes this will claim down it will finally come here in this when they are both in same plane they moves towards each other and finally they will annihilate. So, this is the process of recovery some rearrangement of dislocation and dislocation annihilation the stored energy is minimize.


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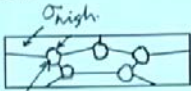
Re-crystallization



Original structure



Deformed structure



Nucleation of strain free grain

σ_{Low} σ_{High}

$\Delta G = \frac{4\pi\gamma^3}{3}\Delta G_v + 4\pi r^2\gamma$ $\frac{\partial \Delta G}{\partial r} = 0$

$\Delta G_v < 0$: it increases with cold work but $\sigma > 0$

NITEL

Let us see the process of re-crystallization we have just seen that a result of deformation this is the original structure this are the different grain if you reformat grain shape changes and when this grain changes you know each of these boundary they have some energy. So, it is the grain boundary energy also has increase there is lot of dislocation density in the material and bulk of dislocation density will be corrects here and then therefore, the material in a highly on stable state. If there is if there is a heat the material are it some amount of the thermal activation this work grains they are replace by strain


free grain sub strain free grain nuclear a like what shown here. This is the strain free grain the nucleate and these grains have a much low strength. So, this cold work grain this is high strength that is that is light strain is close stresses low.

Now during the process of working the plastic work that you do the 90 percent of the work is dissipated as may be some amount of adiabatic heating the job make heated up and, but only 10 percent of this energy is stored in the form of either increase dislocation density or increase grain boundary energy. So, there is elastic it is stored some form of stored energy in the material and this cold work structure is thermodynamically unstable and in fact what you can see here if it is possible that when this is strain free this cold work grain replace by this strain free grain. So, these are the strain free grain the new surface is be created this has also some energy and we have seen that this energy is the say suppose.

We assume these are the spherical its energy will be $4\pi r^2$ and its surface energy if say is γ . So, this is positive this much of energy has to be supplied and this is provided by the elastic stored energy that is ΔG_v this is elastic stored energy per unit volume and if you multiply this by the volume you get the total energy. Now you can also you can differentiate it this is the function of if you can differentiate ΔG with r of equated to 0 you can find out a critical size of the nucleus and also you can find out what is the maximum that is that activation (ΔG^*) which exceed so, that the process continuous.

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Critical nucleus size & activation energy

$$\Delta G = \frac{4\pi}{3}r^3\Delta G_v + 4\pi r^2\sigma$$
$$\frac{\partial \Delta G}{\partial r} = 4\pi r^2\Delta G_v + 8\pi r\sigma = 0$$
$$r^* = -\frac{2\sigma}{\Delta G_v} \quad \Delta G^* = \frac{16\pi\sigma^3}{3(\Delta G_v)^2}$$


$\Delta G_v \propto$ stored energy

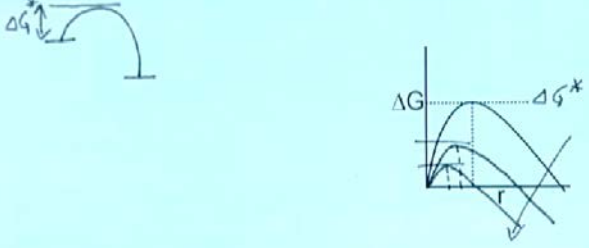
As cold work increases activation hill decreases. Lower thermal activation is required for re-crystallization. Grain size is finer.

NPTEL

This is shown in this figure over here so, the critical nucleus size and the activation energy and this is total energy and differentiate it equate it here [here](#) I think sigma represents is an surface energy and this is the critical nucleus size. So, in fact this negative therefore, this will be positive critical nucleus size is positive and this is the activation hill which is shown in this diagram this is the delta G plotted against r. This is the activation hill and this is the critical nucleus size. Now as cold work increases what happens as cold work increases that activation hill what will happen to the activation hill.

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Critical nucleus size & activation energy



$\Delta G_v \propto$ stored energy

As cold work increases activation hill decreases. Lower thermal activation is required for re-crystallization. Grain size is finer.

NPTEL

Obviously, if you increase the cold work you can imagine like this you have a cold work material you have somewhere here annihilate material its more stable material that state is here from here although, there is a driving force therefore, it does not process does not continue always itself it has go to have to provide a thermal activation and this is the thermal activation. This is the delta G star so, this is the delta G star. Now if you have more cold work what happens you can see from this diagram is the previous expression is activation will decreases that means more cold work then the activation hill decreases also the critical nucleus size also decreases. So, that means if you have increased cold work so, this will be like this.

You increase cold work further so, that will this is the critical nuclear size. So, you increase cold work the activation hill comes down the critical nucleus size comes down. So, therefore, if you want to get the final structure you have to give higher amount of cold work and if you want to have very close grain structure then you have to give very little cold work to the material.

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Re-crystallization

Nucleation & growth

$$N \propto \exp\left(-\frac{\Delta G_v}{RT}\right) \propto \exp\left(-\frac{\Delta H}{RT}\right)$$

$$G = H - TS$$

f

t

$$f = 1 - \exp(-kt^n)$$

The slide contains a graph of fraction f versus time t showing a sigmoidal curve. To the right is a diagram of a nucleus represented as a rectangular box containing several dots. At the bottom, there is a video player interface with a progress bar and a timestamp of 38:50/56:42.

Now the process of this is energetics of you can say we have just consider the energetics of re-crystallization process that is thermodynamic of the re-crystallization process. If you look at this slide here apart from this we has just consider what is called the thermodynamic instability and once the stable nucleus develop they will grow also and this process of growth also **also** important and this nucleation rate we can know that the

rate of nucleation will depend on that activation hill. If the activation hill is low nucleation rate will be very high that will faster nucleation higher cold work higher is the nucleation rate and in fact the **the** and, this is activation energy.

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Critical nucleus size & activation energy

$$\Delta G = \Delta H - T \Delta S$$

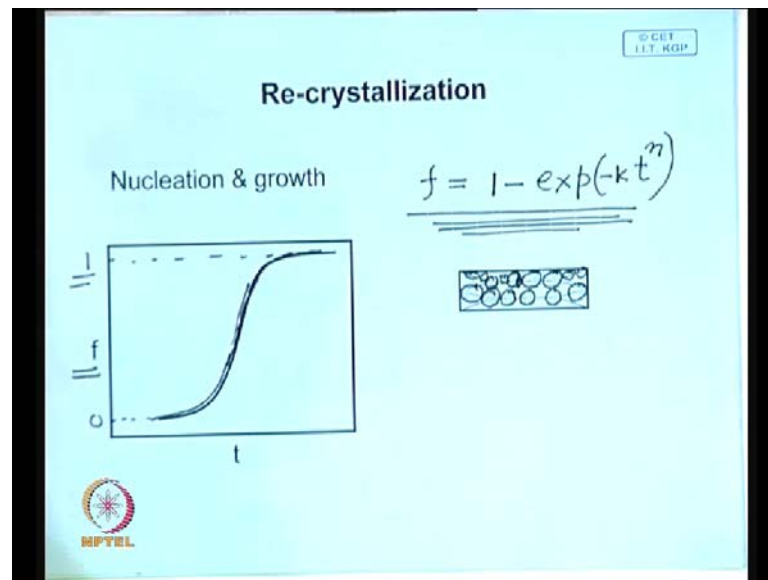
$$\therefore \frac{\Delta G}{RT} = \left(\frac{\Delta H}{RT} \right) - \left(\frac{\Delta S}{R} \right)$$

$\Delta G_v \propto$ stored energy

cold work increases activation hill decreases. Lower thermal activation is required for re-crystallization.
Grain size is finer.

So, basically when you look at this delta G any thermal any free energy it has to component one is the enthalpy part and this is the entropy part. When you split the two in that there is the pre exponent term this is delta G by RT this becomes delta H by RT minus delta S by R. So, this does not depend on temperature only this part this is temperature dependent and this is called the activation energy of re-crystallization. So, this is what is shown over here now apart from this there will be a growth process also and which is pictorially shown here when this number of nuclear the form they will be grow also and when the grow there will be the factor called impeachment factor.

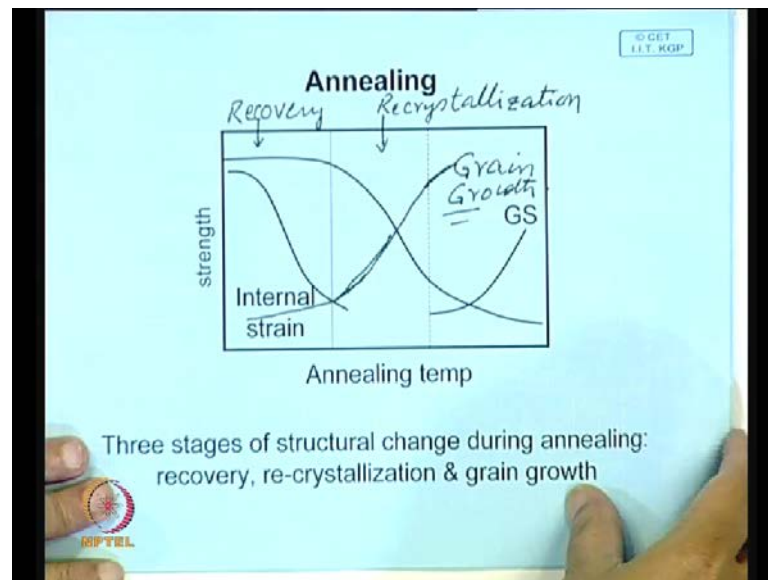
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Which is shown here if this grows **if this grow** finally a stage will come when they will touch each other and when the touch the growth will decrease. When this **(0)** lies mean the touch each other because of the impeachment factor the rate of growth will slow down. So, therefore, the process of re-crystallization if you can say that f case the fraction re-crystallize. So, here it is 0 and here it is 1 then we say the fraction re-crystallize if follows something a plot something like this **this** is 1 minus exponential minus some constant time to the power n and nature of this is like this is plot.

So, somewhere in between you have the maximum rate of transformation where growth nucleation and both favourable they add up and you have maximum and later on that growth actually again become slow and nucleation also will become more difficult because most of the sides where the nucleation could take place the grains up nucleated therefore, again the rate decreases and this is most of the types of the solid state transformation they follows this kind of kinetics and we will referring to this type of equation again and again.

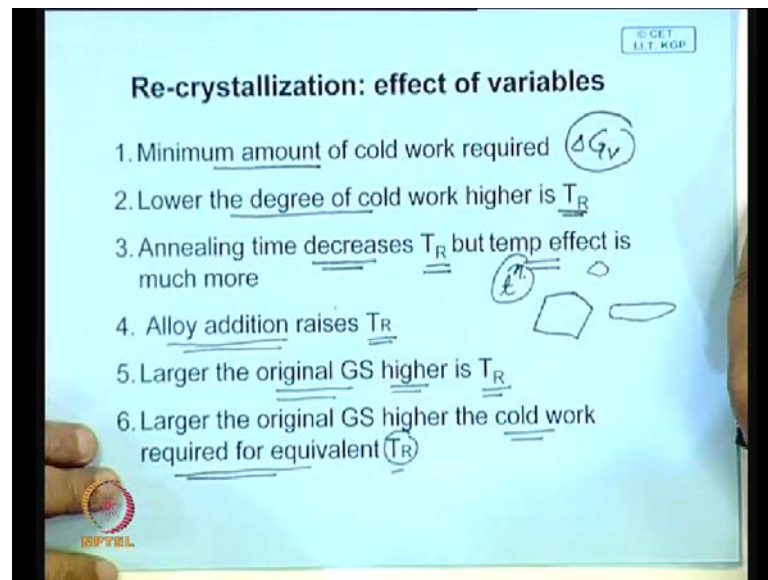
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Now what happens to some of the properties which is shown over here. Now with annealing see this is a plot that represents strength, so strength initially with annealing temperature it does not decrease much in marginal decreases and **and** this is the stage where it is the maximum decrease and then later on also this rate of decrease goes down. Whereas, internal strain or internal stored energy this decreases significantly in this part in this region the temperature zone. And whereas the grain size you will find over here you have very fine grains, but if you still raise this annealing temperature you will find when you raise beyond a temperature this grains keep growing and they become they can even become very large.

So, what it means that annealing you have to divide the process of annealing into three distinct stages and which are shown here and this diagram is called these stages called the recovery zone or recovery stage this is the re-crystallization stage **re-crystallization stage** and this is the grain growth range. Accordingly all several other physical properties also will change, say suppose ductility **ductility** here will be low the ductility here there will be marginal change, but here the ductility will increase and again ductility will decrease the grain becomes coarser then the material becomes less then time something like this.

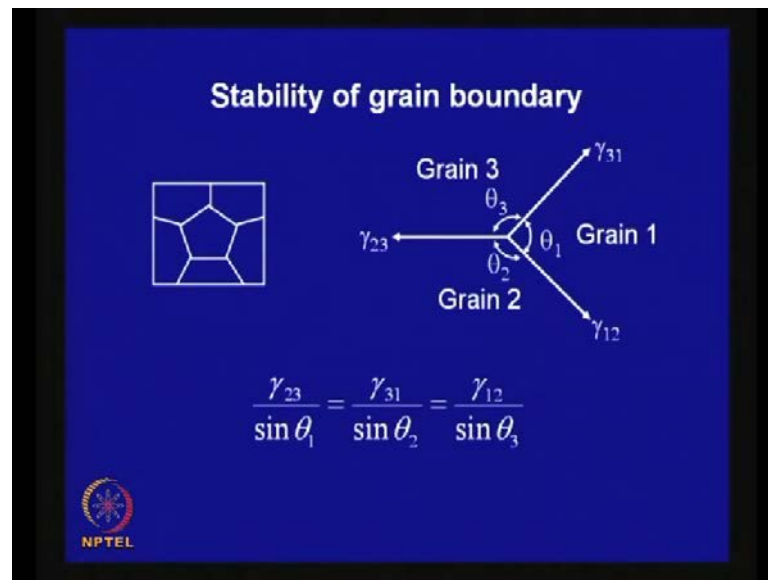
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So, if you sum up the process of re-crystallization we have seen that some amount of cold work is necessary for a crystallization to take place. The lower the degree of cold work, higher is the re-crystallization temperature that means low cold work you have to give more amount of thermal activation. Because delta less cold work this **this** is low delta G_v is low there is activation hill is high then annealing time also decreases **decreases** re-crystallization temperature if you **if you** hold time increases then also re-crystallization temperature decreases.

But, temperature effect much more temperature if it exponential whereas, time effect you can see that time effect is much less than the temperature effect then temperature effect temperature is exponential whereas time effect you have seen that is T to power n is the fraction it is a very small compare to the temperature effect. Alloy addition if you add alloy addition then material will stronger its re-crystallization temperature goes up then larger original grain size the grain size very large then whenever cold work the grain boundary of course increases, but if you have a final grain **grain** boundary area increase will be much more. So, here therefore, if original grain size is higher than the re-crystallization temperature is also high and larger original grain size then higher cold work required to get re-crystallization at the same temperature re-crystallization temperature.


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Now let us look at why does grains grow? Now grain boundary they have certain energy and next of the cases will find the grain boundaries are like this. So, this angle in 2 d it will something like 120 degree. So, this if you resolve this grain boundary they have certain energy they like tension and if there are same you can show that if they are at 120 degree. The total force and show there point will be 0 and they will be stable and which is shown over here this are three grains these are grain boundary energy. Now if you assume that all are same r all equal to gamma then you can easily show as over here this type of force balance is possible and in that case all three angle, if they are equal then all theta 1 theta 2 theta 3 will be equal. So, therefore, three lines can meet with equal angle and that angle is 120 obviously, 120 degree.

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Estimation of GB energy


$$2\gamma_{sv} \cos \frac{\theta}{2} = \gamma_{ss}$$

Origin of surface energy lies in the number of free bonds / atom

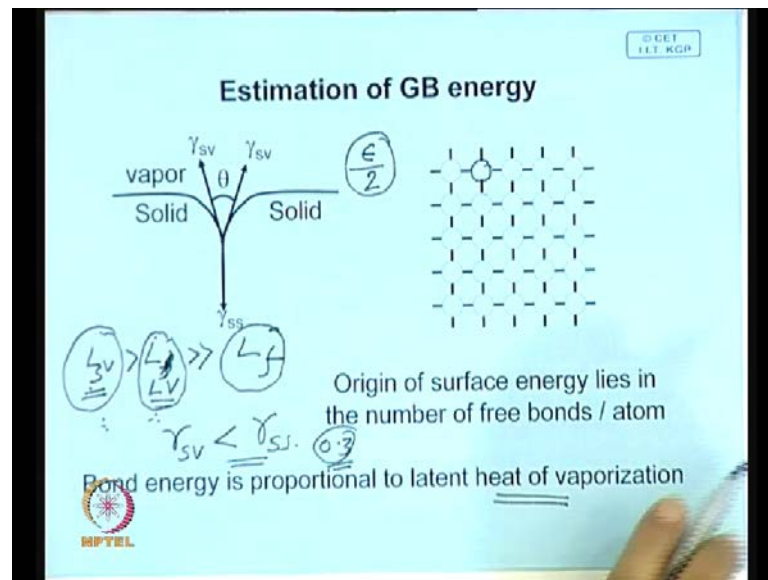
Bond energy is proportional to latent heat of vaporization

NPTEL

Now what happens how to estimate the grain boundary has energy, but is it possible to estimate the grain boundary energy. Yes it is one of the simplest way, if you take a polish material it says its polish has be taken it is mirror finish if it heat it in vaccum, then what happens this grain boundary they get (()) and when you look on the microscope and there are profilometer you can follow the profile you will find the grain boundary area there is depth something like this and here you can take a section and draw line and measure this angle of that angle between the two grain or else in a profilometer reading also it is possible to measure this angle and if you do this so, this is the surface energy between solid and vapor.

You can say this is the any solid there will be some amount of vapor we can thermodynamically. How so, far less maybe the vapor pressure there may be some amount of vapor and then environment surrounding it and there is a stable equilibrium. So, therefore, what you can see here equating the force you can resolve it in this here the vertical component will be gamma s the cos theta by 2 there be two of this. So, the upward force twice gamma s the cos theta by 2 and this will equal to this surface energy along this direction. An inreality what you it is possible to calculate this also it is possible to calculate this from a simple concept that on the free surface some of these bonds are missing. So, here what you can say this atom?

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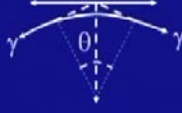




So, every atom has four bonds. So, this atom near this surface one bond is missing, that means if you say that bond energy is epsilon then the missing energy for atom is epsilon by 2 so, and this epsilon it is possible to calculate where from the latent heat of vaporization and this latent heat of vaporization it is possible to calculate and this is how the grain boundary energies have been calculated and it is found that always this grain boundary latent heat of vaporization is greater than latent heat of fusion and it is much greater than.

This **this** is solid to vapor this is much greater than less of theta fusion and this from liquid to vapor latent heat of vaporization liquid to vapor this is latent heat of sublimation from solid to vapor and always this is highest next is latent heat of vaporization difference between this two not much, but the both of these significantly larger than latent heat of fusion. So, even though that means what it will be because that the grain boundary energy will definitely be much smaller than this **this this** energy that means this is gamma sv will be much smaller than this grain boundary energy. So, may be 0.3 times or even less, but it has a definite value.

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Grain growth

$$F = 2\gamma \sin \frac{\theta}{2} \approx \gamma\theta = \frac{\gamma l}{r}$$

$F=0$ if r approaches infinity


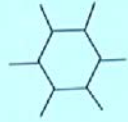
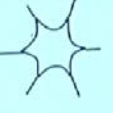
$$\dot{\bar{D}} \propto \frac{\gamma}{\bar{D}}$$

$$\bar{D}^2 = D_0^2 - Kt$$


So, what it means if you have such a tension surface tension of grain boundary energy existing then it is possible to show easily there will be instability of the card grains will be instable there will be force acting this side. Any curve grain will try to state in out and the force you can easily show this that this force acting on this grain boundary will be equal to proportional to grain boundary surface tension gamma l over r. So, only when r is flat that will something like this force acting on it is 0 otherwise there will be some force. So, therefore, where ever you have curve

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
Grain growth

$F=0$ if r approaches infinity

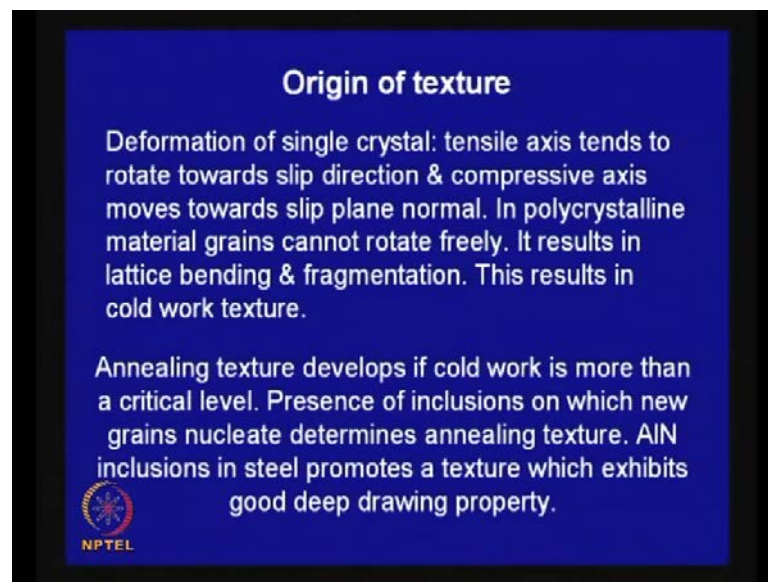
$n = 0.5$
 $0.2 - 0.3$

$$D - D_0 = kt$$

$$\frac{1}{D^m} - \frac{1}{D_0^m} = \frac{K}{m} t$$



boundary like this. So, they will try to state and **an** in fact this will move towards this and finally, this state grain will form and this grain will get eliminated similarly, here also that means any curve boundary will be unstable and they will try to straighten up and it is possible to show that rate at which this therefore, the grain will grow will be determine by this surface energy and this is γ over r , r you can say it is half the grain size. So, that means this is D by 2 so, in a way you can say the rate at which the grain growth takes place is inversely proportional to the grain size then can easily show that a grain growth kinetics will be something like this. $D^2 - D_0^2 = Kt$ in general it has been found that this exponent this is written as $1/n$. So, instate to get $2/n$ has to be 0.5, but some of material this may be round 0.2, 2.3. It is not exactly 0.5.


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Origin of texture

Deformation of single crystal: tensile axis tends to rotate towards slip direction & compressive axis moves towards slip plane normal. In polycrystalline material grains cannot rotate freely. It results in lattice bending & fragmentation. This results in cold work texture.

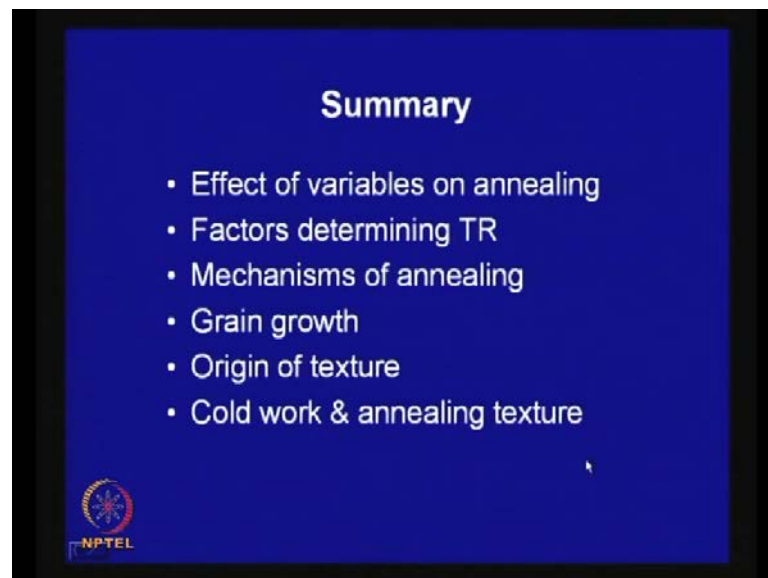
Annealing texture develops if cold work is more than a critical level. Presence of inclusions on which new grains nucleate determines annealing texture. AlN inclusions in steel promotes a texture which exhibits good deep drawing property.

 NPTEL

Now deformation as we have seen deformation energy I try to recollect that the tensile axis tends to rotate towards the slip direction then compressive axis also moves. So, that means sliply normal tends to moves the compressive axis. So, therefore, in polycrystalline materials the single crystal this is possible polycrystalline there is lot of restrictions the grains cannot rotate and move freely they will get disstarted fragmented, but nevertheless there will be some effect of rotation and you get a texture. This is a cold work structure and which will be so, therefore, there will be prefer orientation which is called cold work structure likewise.

You can also annealing texture if cold work amount is extremely high is a greater than a critical value then even if you anneal there will be some amount of texture and this texture also depends on type of second phase particle that are present in the material. Like a steel if you have aluminium nitrite this favours this gives the texture which is quit favourable for deep drawing kind of steel. So, if you a deep drawing you want prefer orientation that means in case of deep drawing through thickness you want very high so, you on such a structure so, that the thickness does not reduce, but on the planer it should reduce very easily. So, that types of texture it is possible to develop by controlling cold work an annealing and by presents of certain inclusions like aluminium nitrite and steel.

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So, with this we finish this topic, and what we have looked at we look at the process of annealing, the variable that control annealing. We looked at that that re-crystallization temperature factors that determines re-crystallization temperature. We looked at mechanisms of annealing grain growth origin of texture. Thank you very much.