Phase Transformation in Materials
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Lecture - 54
Recrystallization

So, we are going to discuss some more aspects of recrystallization during heat treatment of the cold work samples today. As you know the recoveries of first stage of the this process in which a sample was it will be heated to the intermediate temperature, and recovery is mainly a process in which defects, mostly the point defects and the line defects they get properly arranged in the microstructure.

So, point defect classes such as voids or interstitials they get arranged, actually points will be coalising each other or maybe they will be combining with the grain boundaries. And dislocations will arrange in a low energy configuration that is the polygonization we have discuss in the last 2 lectures. Now the subsequent to recovery the important process which occurs in cold work materials is the recrystallization. Recrystallization means formation of strain free grains in the deform structure.

Now, as I said the 2 important the process which happens your recrystallization one; obviously, is nucleation and subsequent growth of these grains.

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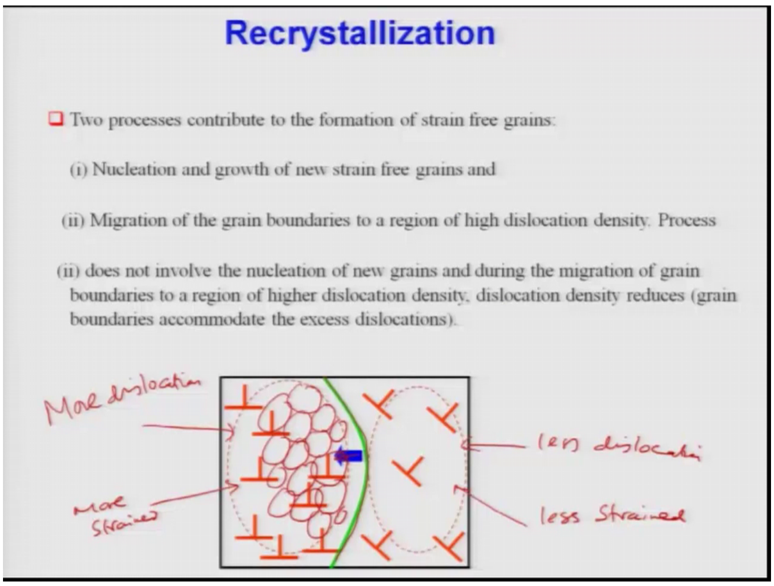

But most importantly the migration of the grain boundaries from a region of highly deformed structure to a low deform structure relatively happens. And this is the factor which contributes to the nucleation grains. One has to understand the store energy during cold work is responsible for such a kind of processes. As you have seen the free energy change which is responsible for such a kind of transformation is basically is equal to the minus of the store energy. As store energy is because of these defect structures in the material. As store energy is not usually very large, actually this is very small as you have seen in case of silver it is about point 3 3 closure per mole.

So, as this store energy is small. So therefore, nucleation is not going to happen because of thermal processes. Normally during liquid to solid transformations or even many of the solid-state transformation nucleation of the product phase when the parent phase happens because of thermal fluctuations. But here it does not happen that way, the process which governs or which basically dictate the nucleation of these strain free grains is basically the second, one the migration of sorry, migration of these grains migration of the grain boundaries actually to the regions of higher dislocation density.

This process is basically very important. You know, that inquire nuclei which are created by the formation of these phrase lattice where thermal fluctuation does not happen in this case. So, it is the things which I will show some pictures, maybe I will go little further and show you that no

See this is what is a polygonized structure in a silicon iron silicon steel actually single crystals which was deformed and annealed for above 10 minutes or thousand-degree celsius temperature.

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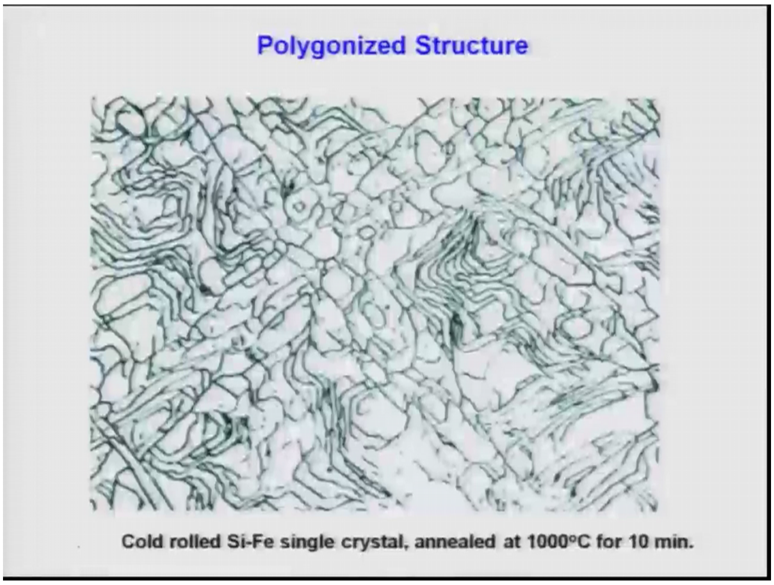

As you see here a lot of grain small angle boundaries you see here; obviously, because polygonized structure peens dislocations get arranged in a particular fashions like these. Dislocations get arrange on top of each other and this this form a low angle tilt twist boundaries. So, that is what you see here. You see lot of this small angle boundary is created in the microstructure because of annealing treatment.

And subsequent to that recrystallization will happen,

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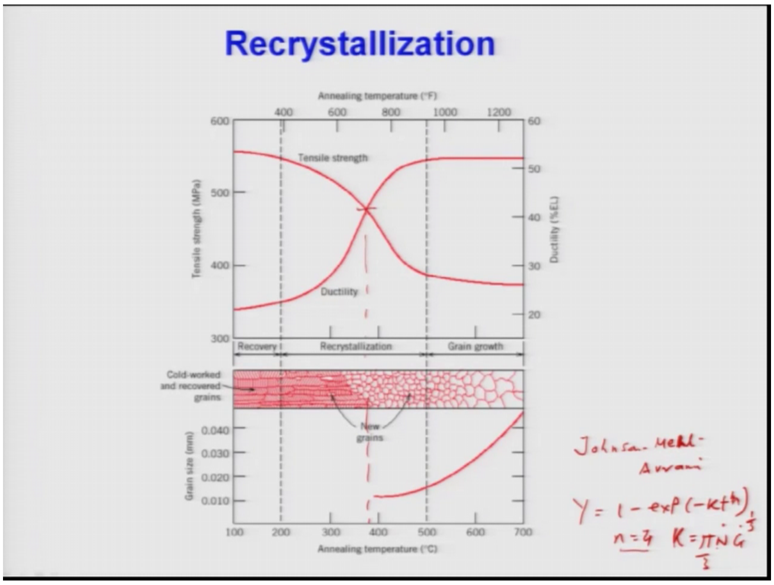

because recrystallization is after these low angle boundaries has been created; that means, dislocation has been arrange properly in the microstructure.

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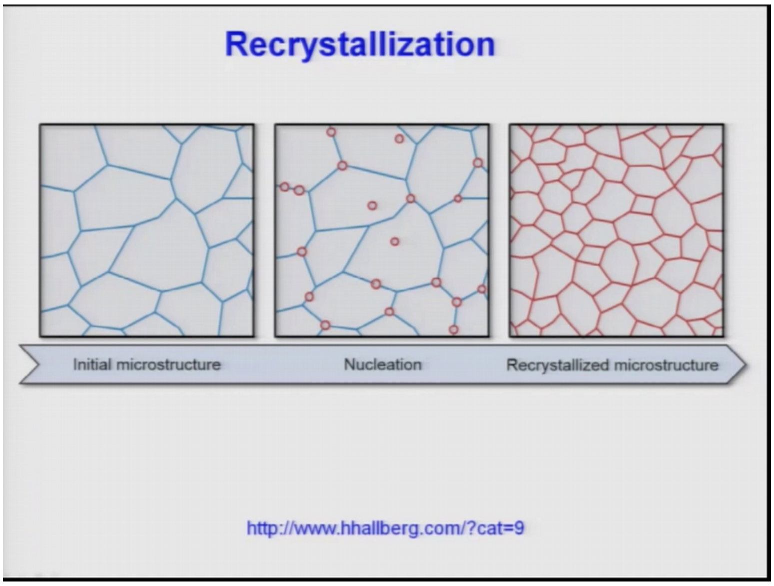

The these small grains strain free grains a nucleate either on the boundaries are inside the grains depending on the strain level, that is what is basically the start of recrystallization.

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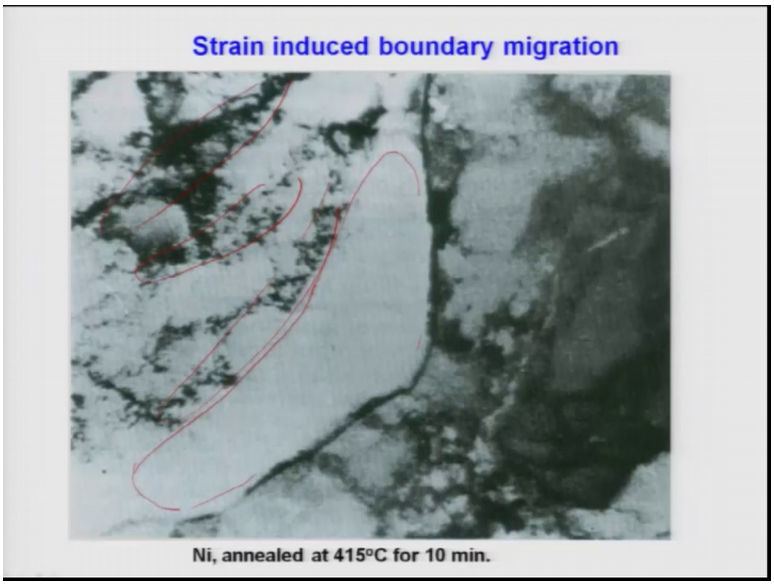

This picture is or nickel annealed at 415-degree Celsius temperature per 10 minutes after cold work, you can see the boundary which is there this boundary has moved from heavily work regions heavily dislocation regions to as little less dislocation regions. And in this process, it creates a strain free regions. You see here this is strain free region is created.And this strain free region is then becomes a phase nuclient, nucleation for the formation of the grains. That is what actually the most terminating process which governs the recrystallization, that is the movement of these boundaries. So, boundaries do gets formed initially by the process of polygonization, and this boundary switches form large number boundaries. They then start moving are basically migrating from heavily deform regions relatively high dislocation tensed regions to the let will less dislocation, this regions this migration as I said is basically because of the this concentration difference of the deformed structures.

And in this way, it creates certain kind of a strain free regions in the microstructure and this picture is very nice. It has been taken directly from the book of jena and chathurvedi. It is clearly shows that how is strain free regions can be created inside a grain simply by migrating a boundary. So, that is one of the reason you should understand the how the nucleation happens. And then once the nucleation of these grains happens they start growth. That will discuss even in subsequent lectures, but first let us discuss about that.

Now, cold work process also leads to so what is known as deformation bands; that means, sub lattice miss orientations inside the grains; that means, you have a one grain in which some regions will be heavily distorted, what is known as sub lattice distortion will happen in some part of the grains. That depends on the obviously, type of grains are they there relative orientations in the samples.

And this sharp are heavily deform regions and basically what is known as bands in this in the literature. And this band actually constrains more number of defect structures. And therefore, this probably was a band in the microstructure; you can see there are bands like this develop. And this band actually starts moving inside the grains during subsequent annealing processes, because of the availability of the thermal energy of system.

And then finally, you know this this is the boundary, which is demarcating between the 2 grains are forced to move from heavily deform region to the small deform regions. That is see main reasons for recrystallization, and I will just go back again to these slides which are discussing with you. So, you know this second aspect which is migration it does not involve a nucleation the grains, but it leads to nucleation of the phrase grains.

So, that is what is shown here you see that, this is large number of dislocations this is a one part of the grain. And this has less dislocation. And because of that the grain boundary is moving from this side to these sides. So, and that is creates a in this part of the region here same part of the grain and that that is what becomes it nucleation.

Now, once the nucleation happens the nucleation rate which is; obviously, most important aspects in dictating how many grains will be forming, as I said it depends on, but typically by these formulas. Endure the nucleation rate it depends on the number of grains a number of basically atoms and nu is the frequency of jump, and this one is the exponential term which is equal to 16 pi gamma q v square by 3 E s square plus delta gi plus KT. As you see here basically here we are going to understand one thing, as compute the classical nucleation rate equations gs is basically it is not you know it is basically converted into E s by v, and other things are not considered here.

So, E s is basically strain energy stored. V is the volume gamma is the interfusion energy which is there, and KT k is the Boltzmann constant temperature delta gi is basically coming from the aspects of as I discuss is basically coming from let me see, this is a energy which is derive from the what is that? Just a minute, let me check. So, delta gi basically I is basically activation energy for the grain boundary diffusion yes, that is what we have been discussing. This is the activation energy for the grain boundary diffusion. So, grain boundaries which are moving because of these difference of the dislocations on the both sides of the grain boundary are that is what comes into picture.

So, as you see here this is a negative term is a positive term. So, if you want to have a higher amount of nucleation density. So, you need to have a large value of the grain boundary migration, why? Because this negative part will be reduced further as you go along. Remember that E s is independent of temperature, E s is the store energy store energy store did you concern a cold work basically depends on the strain rate depends on the cold work depends on the type of material depends on the event type of deformation processes you are adopting but it does not depend much on the temperature.

So, that for that means, nt n dot is a basically strong function of the temperature. It depends in just like nucleation rate in case of classical solidification. If you plot nucleation rate versus under cooling, after some point time it suits of increases rapidly. And that is exactly same thing happens here. Because it is a exponential minus 1 by t terms therefore, at a certain value of the you know value of the temperature it will increase rapidly. Although we cannot talk about exactly under cooling here because this is solid state deform structure, but we can always plot make this plot as a function of temperature. And if you do that it will have a similar kind of things it will rapidly increase.

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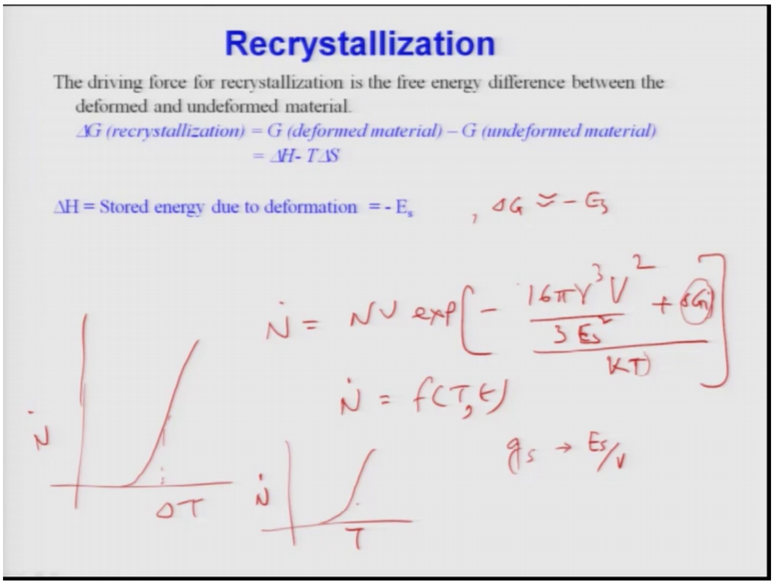

So therefore, there will be bust of nucleation happens in this case also, recrystallization also. And this is mostly dominated by these migrations of the boundaries. That is one important aspect which is which is to be must be remember always. So, once the new grains forms subsequent process is nothing but growth the kinetics by which this whole thing depends on is known as the Johnson, mehl, avrami, type of equation, as I told you Johnson, mehl, avrami. These 3 scientists they develop a model and this model dictates you how the grain actually grow.

So, will discuss in subsequent follow lecture what is this equation is as I tell the equation tells you the rate of the growth of are basically rate of the process. Basically, both nucleation and a growth is given by 1 minus exponential minus KT to the power n. And where n is nothing but n is equal to 4, normally it is basically exponent growth exponent.

And k is a constant and k is basically given by pi n dot g dot one third, and is pi by 3. Where n dot is the nucleation rate and g dot is the growth rate.

So now question is that we must know how this equation is basically obtained. You know this equation has many interesting aspects, because this equation integrates nucleation and growth together. So, as you know here k is the most important factor, and the n is the important factor is a depends on the time. It is a kinetics that which must be dependent time. So, it is basically 1 minus exponential minus KT to the power n are n, n is time exponent which is equal to normally 4 it can be equal to 3 also depending the process, but here now a recrystallization is taken as a 4. And k is a constant it is not exactly constant it also depends on the temperature. It will basically equal to pi by 3 n dot g dot to the power one third, or n dot is the nucleation rate and g dot is the growth rate.

So, how do we get this equation? Well, this equation is obtained in a very nice manner, which I will do that in that, and tell let me just do it; so that you can understand. Now question is this as I said let us consider a transformation simple transformation.

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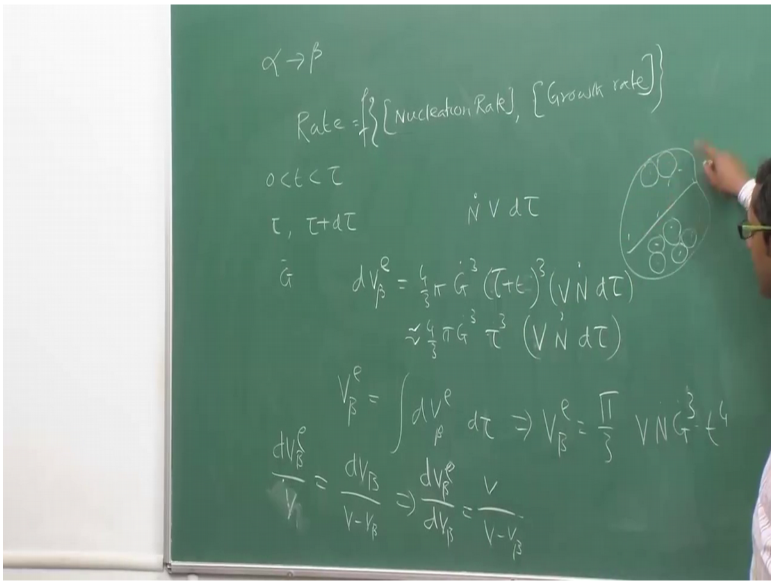

Alpha going to beta, same as like any crystallization. The deform grains transform to a on a strain free grains, and as you know rate of this process is depends on; obviously, is a function of nucleation rate as well as the growth rate right. Both as I said the growth of these strain free grains is basically dictated by the grain boundaries, energy small grains will be larger grain boundary area. So, you have to reduce that grains actually start coalescing and groove.

So, finally, rate of the whole process depends on basically nucleation rate and the growth rate. So, let us consider a very short time scale experiments in the time region of 0 to tau. Tau is basically very time small time scale. And now as you know form as you increase the time from tau to tau plus d tau, the nucleation are the total number of nucleation nuclei basically will be equal to nucleation rate multiplied volume multiplied by the time increase obviously, ok.

So, this is the time increase from tau to tau plus d tau, and d tau is the actually it is been small increase of time. Because of time increase total number of nuclei will be equal to nucleation rate multiplied by time multiplied by the volume, because nucleation is per unit volume normally. And this is total other nuclei which inform at a at a time when you provide sufficient driving force for the nucleation.

So now let us assume that this you know growth is also dependent will happen subsequently. Normally the major important thing which we discuss is that a suppose if you consider a big grain these are the nuclei which is formed. As an nuclei growths they will impinge on each other then they will stop growing that is what happens. All the nuclei will start growing around it and when the impinge on each other these phrase, and then they stop growing that is what is the end process.

So, normally the nucleation and growth will happen together, in this 2 cases. They will not be happening one after another. Because nucleation is the start process once it starts then these another inputs is available for each to group for the recrystallization process also. So now, question is that if I have a growth rate given by jd dot of these grains. And if I want to calculate what is the volume change. Suppose this is the volume which beta is forming, suppose this is the volume change?

So, that is obviously, will be equal to 4 third pi r cube. Because that is that is the volume of a sphere. And obviously, growth rate is g gq that is why multiplied by the time suppose which you spent after tau; obviously, tau was the time individually things have started. So, sorry tau plus t will be a time which will be specifically spent on the growth although this will happen together.

So, it does not matter whether if you use this equation like this, tau cube does not matter it will be similar, because tau is a very small-time scale. So that means, this is the sphere which is with the or the change of volume, and which will happen multiplied by v dot this one. So, it should write it v n dot d tau this is the nucleation rate nucleation total number nuclei and the growth ok.

So, it is it assumes all of these guys all of these things going like a sphere, which is not always true. In fact, if you have seen the grain boundaries they are not always looking like a spherical. That is the major assumptions which is made here. Second assumption is made that you see basically you know we always assume that this nuclei are growing in the only in the untransformed regions.

So, you have a suppose the grain which is not yet fully transformed and this grain which is already been transformed. So, likelihood chance that the nuclei which will be sitting here they will be growing much faster, than a nuclei which is sitting there. Because you already lot of strain energy he has been reduced because of deformation of these nuclei. So therefore, chances of growing these nuclei are much higher than these ones. And that is why the one of the assumption on this model is that the untransformed regions has I know more propensity to from upon for the nuclei to grow, than the regions which are which are already transformed and some parties remain to be transformed.

So, in such situations this equation tells you that the volume which is being the change of this transform volume, because of the transformation is basically is nothing but they apparent volume is not exactly the volume which has got complete transformed, because unless until all these wholes spaces are actually getting transformed you cannot really talk about what is the actual volume of transform.

So now if I integrate that if I integrate that what I will get simply I get transform v that is equal to nothing but dv beta e dt right, d tau tau other is it will be mathematically not sound. So now, if you do that and that is you can do it from 0 to t timescale. So, what will get you will get v beta e is equal to and this is q. So, one third it will become pi that is what you have seen, and that is equal to v n dot g dot one third g dot one third g dot q. Sorry g dot q and t to the power 4. And this is exactly I wrote.

Therefore, in expression which you have seen, now what how do I do that? Normally this is the total task form regions. And we have to consider fraction transform y was 1 minus exponential minus k t to the power 10 right.

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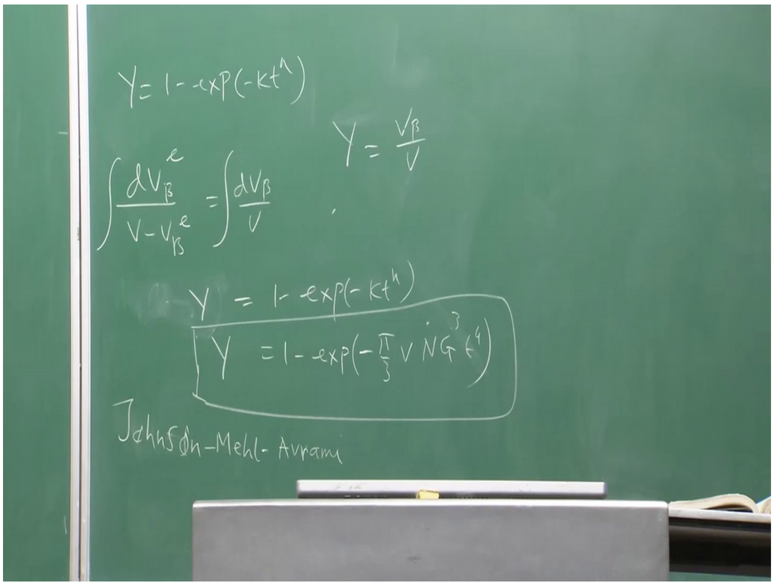

This y is the faction transform this is the total volume of v created.

So, fraction transform we can always write down dvbe by vb e. Oh sorry, dv v is the transform this is divided by v is equal to always write down basically equal to it is better write down like this. So that means, if this is the apparent volume, and this is the volume which is actually transformed this must be equal to v divided by v minus vb this v is basically the volume which is present in the material this whole volume the grain, and b beta is what is being transformed.

So, the remaining volume v minus vb is what is and transform. So, this region as I said you as more purposely transformed has to be accommodated someone. So therefore, that the apparent volume divided by the actual volume transformed will be equal to the volume which as totally occupied divided by the volume which is left over. That is understandable volume which is been left over will be more propionate to transform ok.

So, that is why if you increase this this you know this one and v minus vb more; that means, when vb is very small then this ratio will be equal to 1 then whole area is equal purposely transformed, but as the vb is increasing. So that means, sorry vb is increasing as the vb is increasing the chances of transforming these regions is lower than the regions which has got transformed ok.

So now if you do the maths properly; that means, this one if you do properly. So, that is nothing but I can write down from that dv e minus v vBe is equal to dvB by B and that tells you log of 1 minus y and where y is basically define as vB by v, v is the original volume. And vB is the task from volume that is the fraction. So, that is equal to 1 minus exponential minus Kt n and it is easy, easy to understand that if I put this one. So, this becomes exponential minus pi by 3 v n dot g dot cube t to the power 4. And this sorry, this is 1 minus y long has come there, because we are integrating these things.

So, why becomes this y will be this. And this particular expression which is derive basically is nothing but from the 6 equation is known as Johnson, mehl, avrami equation. I will write it here because it is cannot be cannot be see properly. So, y is minus 1 minus exponential minus pi by 3 v n dot g dot cube t to the power 4 remember this is a fraction. Because this exponential minus term and n dot is always very small number is n to the power minus 30 minus forty and g dot is also very small number g dot actually.

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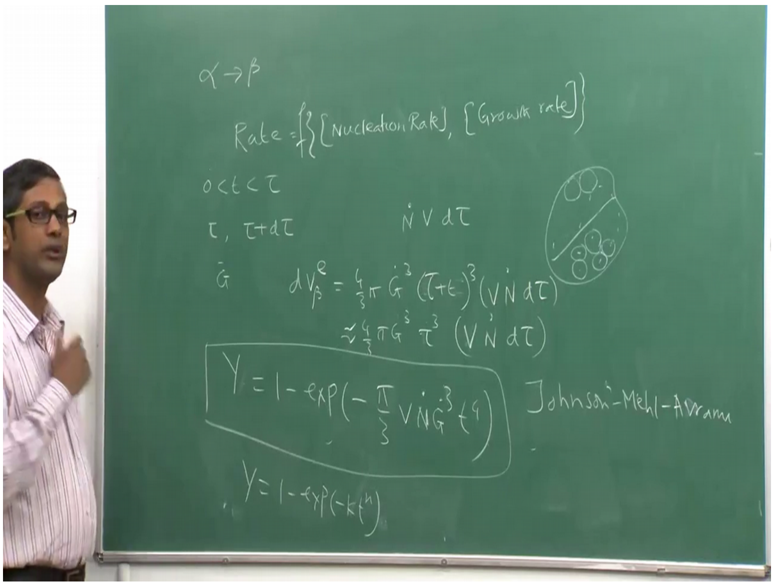

So therefore, depending on the type of process you can modify these expressions. Nucleation rate can be easily obtained from heterogeneous or homogeneous type, but growth rate will depend upon what kind of process going on. So, we see in our recrystallization grain growth the G will be depending on something else. G is not same for all the processes. So, in a paralytic growth diffusion control growth g has a different kind of expression than in martensitic growth or in case of a recrystallization growth.

So, depending on the type of process these factors g and n dot will change G dot and n dot and remember these exponents on the time, it can change also. Because some process is actually time is it is a based some function of time it can be order 4 or 5. And some process will be the exponent will rather 2 or 3, but this is the classical expression so many cases people write it in this way also 1 minus exponents minus k t to the power n that is generalize expression. And this is what is generalized Johnson, mehl, avrami expression. What does it provide us? It provides us very important things once you know k and n we know the whole things what is happening we know what kind of time dependent exponents it has we know also the coin kind of nucleation and growth process going on in this in this in the particular phase transformation.

So, this is a very important expression thing. Now we I derive is basically looking at diffusional transformations from alpha to beta, but it can be derived using other kind of transformation also in the book it has been done be this way, that is why I have done; so that you can understand very clearly. So, what I will do is next or next lecture after now that I have discussed with you how the recrystallization happens, and what is the kinetics on which it depends on our next targets will be to discuss how these grains actually grow. The strain free grains which form inside these deform crystals how they actually grow.

So, this will discuss in next lecture the growth of these grains. And subsequently we will talk about little bit about how we can actually use these equation to explain both these all the transformation whole transformation process. And we can show how plots can be made from different deform materials to obtain the interesting parameters of such kind of kinetics.