Mathematical Modeling of Manufacturing Process
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Lecture - 17
Heat Transfer and Thermomechanical Processing

Now we will discuss the same module in the separate part of this metal forming processes, the heat transfer and the deformation associated with the metal forming processes, but heat transfer and deformation itself is a very complicated process, but simplified way in general I will try to discuss about the heat generation temperature rise in a particular metal forming process.

And of course the deformation mechanism already we have discussed in terms of the different states and that becomes more complicated. Another deformation process we better explain in terms of the single component of that means effective stress value or effective strain just by avoiding the complicated three-dimensional stress-strain situation or also we can look into that simplified way what way we explained the heat transfer happens in the associated with the material deformation process.

So of course this forming processes actually define with reference to the temperature whereas the cold forming process we define in with reference to the temperature that happens near the room temperature that is called the cold forming process.

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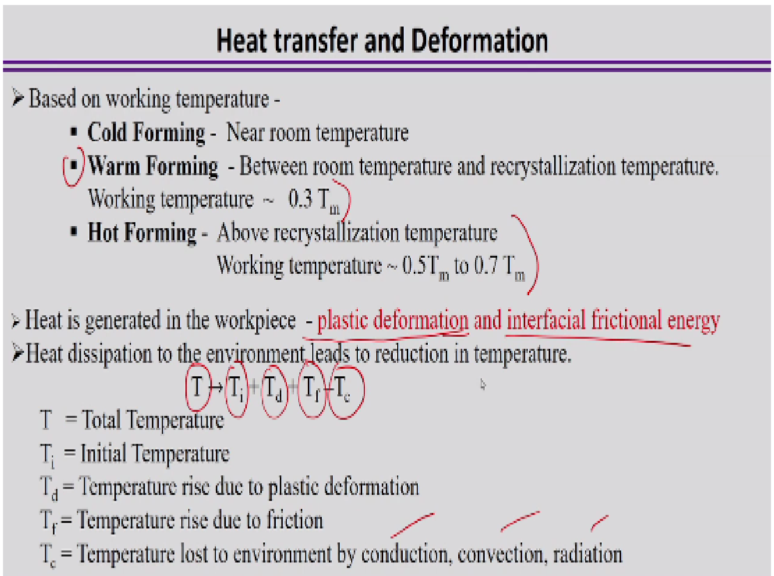

Then there is a intermediate warm forming that means it is a between the room temperature and little bit higher side of the temperature that is mostly defined in terms of the recrystallization temperature. So in between the room temperature and the recrystallization temperature that is called the warm forming process, but normally the working temperature is around 30% of the melting point temperature in case of warm forming process.

The other forming process is the hot forming process. In hot forming process they are normally above recrystallization temperature normally we can define in that way, but working temperature is around 50% to 70% of the melting point temperature in that range, but of course all this definition in terms of the temperature reference is almost relative. It is just a approximation or just kind of in general definition of categorization of with reference to the temperature for different types of the metal forming processes.

Now of course in metal forming process actually heat is generated due to the plastic deformation mainly the plastic deformation happens or maybe straining happens at different strain level or at different strain rate and of course at the same time some amount of the heat generation may be due to the friction happens between this component. We just discussed in the last module that what is the influence of the friction in metal forming process.

Of course this friction introduces some amount of the heat generation during the deformation process. So looking into this two-part plastic deformation and the interfacial friction are the main mechanism for the generation of the heat during this process, but of course once the generation of the heat, the heat dissipation actually balanced with the environment and there is a reduction of the temperature in particular component.

But there are 4 component of the temperature may be is involved here. First is if you see the total temperature which is a function of the temperature and may be temperature associated different form of the energy conversation in this process. So first total temperature associated with the initial temperature with reference to the initial temperature then temperature rise Td the temperature rise due to the plastic deformation.

What is the increment of the temperature then Tf temperature rise due to the frictional energy or due to the friction there is some temperature rise will be there and of course -Tc means in the sense that taking the negative in the sense that the loss of energy to the environment during the process and this loss of energy can be conduction, convection and radiation and that accounted in terms of the temperature Tc.

This is the overall balance of the temperature or maybe we can say that if you like the energy balance also during this material deformation process and all different energy balance we can get this is the components of the temperature corresponding to the deformation process. So now, but in these cases we will try to this is the reference temperature and this is the loss we are not count this.

But we will try to discuss this part and we try to discuss this how the temperature rise with respect to the in general due to the plastic deformation and due to the frictional energy conversation in deformation process.

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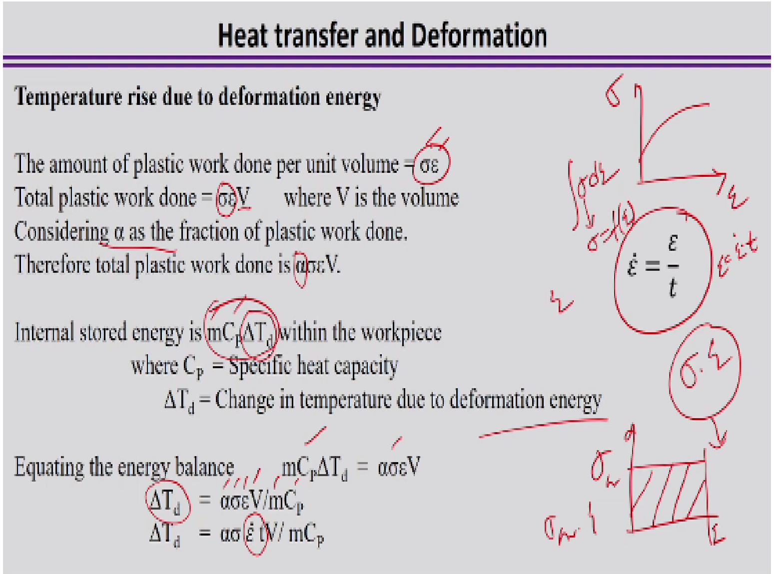

Now temperature rise due to the deformation energy. So we assume that there is a plastic deformation and we can simplify, but this simplified way we can estimate that. So the amount of plastic work done we can easily estimate per unit volume the simply stress and strain of course in this cases we are not assuming it is a simply multiplying by stress and strain, but we are assuming the average stress exist over the deformation period and over the deformation strain.

That is why this average stress and strain that actually represents the work done per unit volume, but of course practically the stress may not be average. So during the deformation may be in that case we can assume the this stress more relevant to the flow stress value and that flow stress value existence over this deformation range uniformly. So that is approximated as a average value.

If we know the stress distribution is something like that. We know in these cases the work done is basically integral form of the then we know stress as a function of strain relation between stress-strain then only we can estimate the value, but in this case it is a simply we write this expression, we are assuming the average value that means if we assume the this is the maximum amount of the strain and this is the average stress value.

And this over this thing existence of the average stress value. So this represents this area this average into strain so that it, but that amount of the work done per unit volume we can estimate. So therefore total plastic work done this into multiply by the volume, volume the deform volume during this process so either V is the volume so multiplied by this we can get the plastic work done now we assume the alpha as a fraction of the plastic wok done.

So therefore if we introduce some fraction of the energy is converted plastic work some amount of the work done is we can introduce not 100% plastic work done is useful here so you can introduce some fraction so alpha is that fraction considering that fraction. Therefore, total plastic work done we just simply introduce by other factor that is alpha you can introduce it and we can estimate this plastic work done.

Actually that if you introduce this fraction then we can easily by modifying this value of alpha we can roughly estimate during the plastic work done during the deformation process. Now what is the energy stored? So once this is the amount of the plastic work done in one point of view, but what is the energy stored within the work piece that of course can also be estimated if m is the mass of the work piece Cp is the specific heat and suppose delta Td is the temperature rise during this plastic deformation process.

So this is the other way we can make the amount of the energy store during the deformation process, but of course this mass is the mass of the work piece over the energy stored specific heat capacity changes the temperature due to the deformation energy now we just simply make this balance equating this energy balance mCp delta T and this alpha sigma strain V and from here we can easily estimate the delta Td temperature rise during the deformation energy is in terms of the other parameter alpha sigma epsilon V volume mass specific heat.

Now some cases may be in these cases we are assuming the strain, but in this particular process we measure quantity during the deformation process in terms of the strain rate. So strain rate simply we can estimate the strain rate=strain with respect to the time. So now we replace strain=strain rate* time just replace it over the time t so once the particular time what is the temperature rise if this parameter strain rate is available in this case.

So we need to introduce that this strain rate over the period of time of course over this period of the time this strain rate is actually constant then we put this value and here we can estimate the temperature rise during this deformation process. So this is the rough estimation of the temperature rise during the deformation process.

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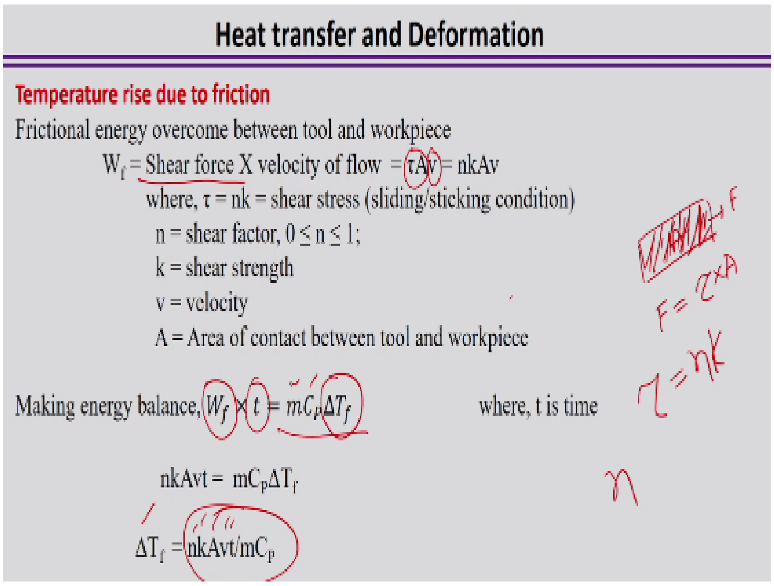

Now temperature rise due to the friction can also be estimated in the simplified way if we assume the frictional energy overcome between the tool and the workpiece. So therefore suppose this is the area (()) (09:48) friction is acting. Now that frictional energy can be estimated like that shear force because shear force and the frictional energy is basically the friction between these two surfaces.

So in these cases the cross-section area and frictional force they are actually parallel with respect to each other. So therefore here the frictional stress in terms of the shear stress we can represent and then shear force can be estimated the force estimated the shear stress into cross section area. So that stress in the cross section area that represent the shear force.

So once (()) (10:28) shear force and the velocity of the flow is specifically small v so therefore tau*A is the shear force stress* area cross section area and then v is the velocity that represents the frictional energy and of course the fictional energy per unit time, but frictional energy in this case is frictional stress basically we can say the shear stress here in this case is shear stress can be approximated that n* k and that n* k introduced n is the some kind of shear factor and k is the shear strength.

But this shear strength normally we can say the yields shear yield strength, but of course it depends on the what type of the condition exist sliding and sticking condition this frictional shear stress value can be different depending upon the sliding and sticking conditions. We have already discussed between the sliding and the sticking condition, but if we assume that it is a sliding condition exists sorry sticking condition exists then the shear strength is equivalent to the shear yield point.

But in general we can introduce the shear factor such that approximately we can assume the shear stress value by introducing this factor. Now v s the velocity A is the cross section area therefore making the energy balance this is the energy per unit we calculated the Wf that actually the frictional energy per unit time. Now if you multiply by the time t and we can in the stored energy mCp delta T that specific heat mass specific heat and delta Tf is the temperature rise due to the friction then you make it equal then we can reach this equation relation the delta Tf= nkAvt/mCp.

So there are so many parameters are involved if you know all these parameters we can roughly estimate what is the temperature rise due to the frictional energy in the material deformation process. So these are the very simplified calculation and that we simplify this calculation in such a way that without looking into the what are the sticking and sliding condition this is actually exist in during the process we just simply introduce that factor n.

And by manipulating this factor value in the particular situation we can handle, we can roughly estimate by putting the shear factor between 0 to 1. We can roughly estimate the temperature rise during the deformation process, not deformation process this is the temperature rise due to friction and in particular to the material deformation process or maybe we can say the metal forming processes.

Now to understand this process we have already discussed that what is the cold forming process and hot forming process, but intuitively in terms of the quality in mechanism there is certain difference between the cold and hot forming process.

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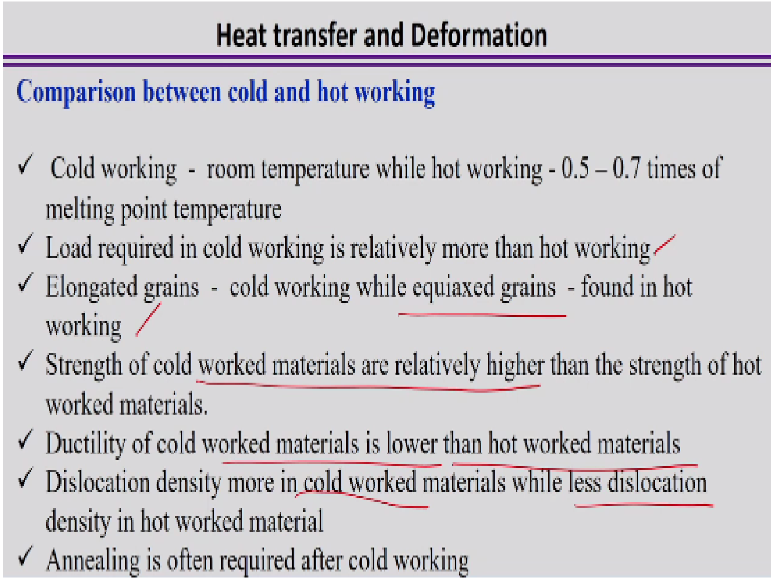

So cold forming process we know it is the room temperature process while the hot working process is relatively higher temperature normally 0.5 to 50% to 70% of the melting point temperature hot working process normally happens and of course load requirement in the cold working because in hot working process since we apply some temperature the metal becomes softer, metal become soft.

So therefore the applied load requirement in hot forming process is less as compared to the cold forming process. So this is the second significant difference and of course in the cold working process we apply the load without the application of the some external energy to raise the temperature. So in these cases the stored energy the deform when you apply some kind of the deform energy by mechanical means to the during the deformation process the energy in store in terms of the defects.

In terms of the crystal defects may be in that sense that elongated grains actually exist in the cold working process, but whereas in the hot working process once we apply the mechanical load during the deformation process and the particular temperature and strain rate conditions then normally our recrystallization happens recrystallization recovery and grain growth normally happens, but finally it produce kind of equiaxed kind of the grains in the hot deformation process.

So this is another difference between these two. Therefore strength of the cold work metal is relatively higher, strength of the cold work relatively higher because when we can do the cold working process so when you go to the plastic deformation stage the strain hardening effect is very high because all this happens at room temperature, but in case of the hot working process when there is increment of the temperature to the metal then when you try to deformation process the strain hardening effect actually decreases and as a function of temperature.

That means temperature increases and strain hardening coefficients actually decreases. So based on that strength of the hot work process, the strength of the cold work process is the more as compared to the strength of the hot work process during the metal deformation process of course ductility of the cold work metal is lower. Ductility of the cold work metal is lower because metal becomes strain hardened.

So further deformation of the process is more strain hardened. So further deformation of the process is difficult in case of the cold work metal that is why ductility level is less, but other cases the hot working process since the metal reach almost equivalent to the flow stress value. So therefore in that cases the hot working metal process and that strength level also decreases in these cases. So the deform process over the deformation can be done over a long range.

So that is why ductility of the hot working metal is actually more as compared to the cold work metal of course dislocation density more because in the cold work metal so large number of dislocation actually generates during the deformation of the process and it is particular because at the room temperature process, but while the less dislocation actually produced dislocation density is produced in the hot work process.

Because in hot work process if there is a raise of the dislocation up to lower level also then if it is a critical dislocation density then new grains can be created by recrystallization mechanism more easily as in case of the hot working process as compared to the cold working process. Of course annealing is often required after the cold working process because the deformation process distribution is of the grains are not uniform in during the cold deformation process and grains become elongated.

So once you do the annealing there is a release of the energy and that release of the energy and converted to the fine grain structure or redistribution of the grains by recrystallization mechanism that is why cold work metal is often required for the annealing process as compared to the hot deformation and hot working process.

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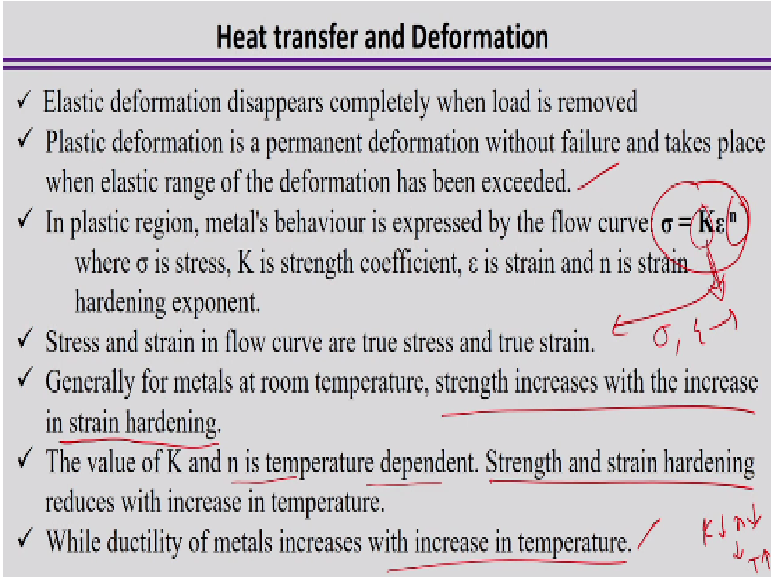

Now other prospective we can look into that deformation process also. The elastic deformation disappears completely when the load is removed definitely this is true also because metal is having the elastoplastic effect. So plastic deformation is a permanent deformation and of course without failure and takes place by elastic range of the deformation has been exceeded that means after the plastic deformation enters once you cross the elastic deformation raise.

So now of course the plastic deformation raise the metal behavior is more represented by this equation sigma= K epsilon to the power n such that n takes care of the strain hardening effect and K is the strength coefficients. This is the simple correlation between the stress and strength, but of course this correlation not applicable to the plastic deformation zone and stress and strain in the flow curve are true stress-strain curve.

Definitely when you try to represent this expression, but here sigma and strain is not engineering stress-strain, but actually sigma and strain represent in terms of the true stress-strain. Generally, for metals a room temperature strain increases with increase in the strain hardening. So at room temperature the strain hardening is more important at low temperature actually the stain hardening coefficient is more significant.

So strength increases with more strain hardening coefficient is more and in at room temperature means during the cold metal forming process. Now the value of K and (()) (19:12) is basically that this is a simple equation, but in general practically when you apply this equation K and n can be a function of temperature normally temperature so it is a temperature dependent value.

The strength and the strain hardening reduces with increase both strain hardening and strength coefficients as well as the strength coefficients both actually decreases with respect to temperature actually K decreases and n decreases when temperature increases. So that is a functional in general the functional trend of the K and n value with respect to temperature. Therefore, while ductility of the metals increases that is it is a well known fact that the deformation we can elongation we can elongate more if we perform the deformation process at some more at high temperature.

So that means in high temperature the ductility of the particular metal is more. So this is the typical information during the deformation process.

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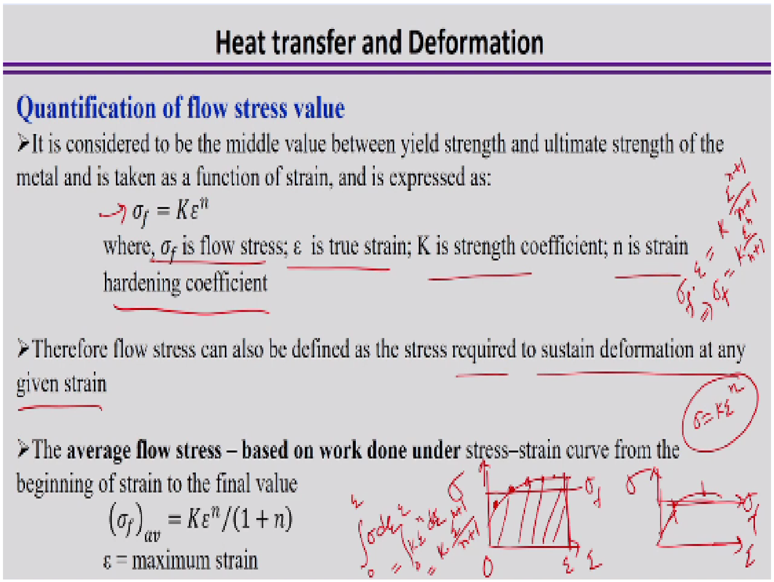

But point is that whatever we can quantify the flow stress value during the deformation process. So we can quantify the flow stress value that in between the middle value between the yield strength and the ultimate tensile strength. If you look into the stress-strain diagram is something this is the yield strength and ultimate tensile strength. So then in between the middle value we can say this is the flow stress value because since metal is having the strain hardening effect.

So strength level actually increases depending upon the strain hardening effect. So we may not get own constant value during the plastic deformation stage and that actually depends on the strain hardening coefficient. So therefore one simplified way to consider the flow stress value is taking the middle value between the yield strength and ultimate tensile strength of the metal and is taken as a function of the strength and which can be represented at this sigma f K epsilon to the power n.

So sigma f is the flow stress value in the true strain K is the strength coefficient and n is the hardening coefficients. So this way we can represent the flow stress value during this process. So therefore the flow stress value can also be defined at the stress required to sustain deformation in principle the flow stress value we can see that amount of the stress required to sustain the deformation process, but during the deformation process there is a change of the stress value due to the strain hardening effect.

But how we can takes care of this change value and which point we should consider the value of the flow stress during the deformation process so that is, but there is other way. So we can do estimate the simple average the flow stress value during the deformation process, but that averaging can be done based on the work done under the stress strain diagram from the beginning to the final strain value.

For example, if we consider this as a stress-strain diagram for example true stress-strain diagram. Now we can estimate the area and we say that sigma=K epsilon to the power suppose n. This expression consider the strain hardening coefficients here. Now sigma= K epsilon to the power n. Now what way this area represents sigma d epsilon and suppose up to the strain level=epsilon. So therefore we can say 0 to epsilon.

So then we can find out integration this thing K epsilon to the power n d epsilon 0 to epsilon. So that is the amount of the work so K *epsilon to the power n+1/n+1 that is the amount of the work done. Now over this deformation process since we can see the strain value here strain value at this point particular strain there is a changing of the strain value. So it is very difficult to actually taking the single value or flow stress.

We assume that suppose there is a some average value. Suppose this is the flow stress value averaging over this thing that means it becomes constant throughout the deformation process up to epsilon. So now we make the work done in both the cases same. For example, first if you take the average value this average value, but this average value exists over the deformation this also represents that work done that is also represented by total area.

But that total area is represented in terms of the in the rectangular form which can be equal to that other cases when there is a variable epsilon 1+1/ n+ 1 make it equal then f=K*epsilon n/n+ 1. So this is one way we can get that epsilon=maximum. So flow stress value or average value of the flow stress over this range 0 to epsilon that K we can get this relation K epsilon to the power n/ (()) (24:28) by simply taking the average value from the based on the work done principle.

So therefore we can use this estimation of the flow stress value during the deformation simply averaging this.

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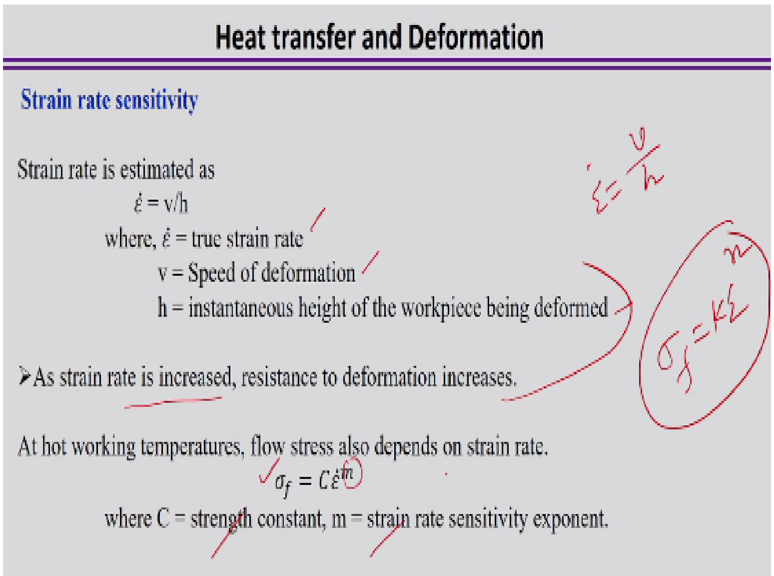

Now we will try to look into that strain rate sensitivity during the deformation process and in particular during the metal forming process, but what we can estimate the strain rate thick strain rate can be estimated that rate of change of the strain, but in actual cases the true strain rate can be estimated by the speed of deformation basically in terms of the speed of deformation and of course at a particular time what is the instantaneous height of the workpiece being deformed.

So that speed and then particular height that actually represents the measurement of the strain rate during any deformation process of course this strain having some influence on the deformation process like what we analyze the effect of the strain in the deformation process so that is strain rate increased resistant to deformation actually increase that means if we deform any particular component at a very quickly at a very high strain rate.

Then resistance actually increases, resistance to deformation actually increases with increment of the strain rate in a metal deformation process, but whatever mathematically how we can represent the similar way, we represent the flow stress value in terms of the strain rate coefficients I think k into epsilon to the power n. N was a strain hardening index, but here the similar we can represent that at working temperature a particular temperature flow stress value can be represented by this equation.

Sigma f=C* epsilon dot to the power m, but here m is the strain rate sensitivity index that means if you want to explain the effect of the strain rate during the deformation process then we can introduce the strain rate sensitivity index alike what way we explain the strain hardening effect by introducing the value of n in this relation between stress and strain. So (()) (26:35) similar the strain coefficient and m is the strain rate sensitivity exponent or strain rate sensitivity index.

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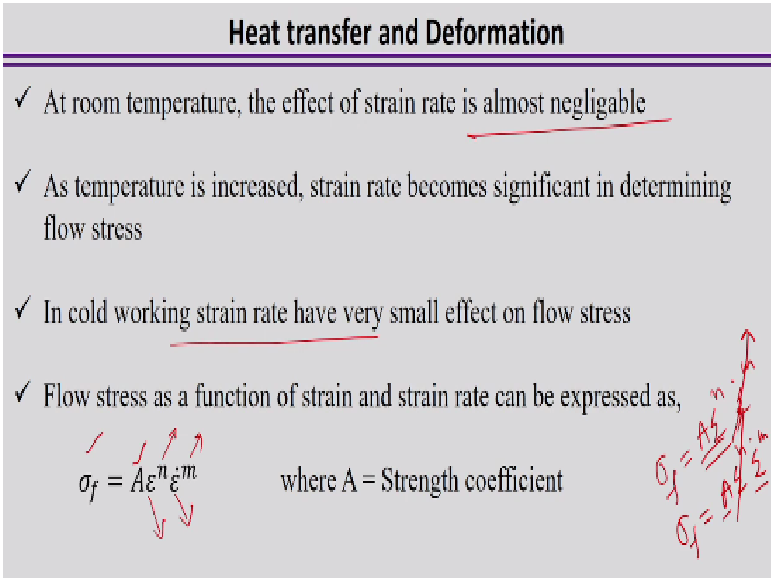

Now at room temperature we will see that what is the applicable normally at room temperature the effect of the strain rate is mostly almost negligible that means basically at cold deformation process the effect of the strain rate is negligible, but the effect of the strain hardening coefficients is more important during the cold deformation process, but once temperature increases then metals become softer.

In that cases at very high temperature if we analyze the deformation process in that case the strain rate is more significant we need to consider the effect of the strain rate particularly deformation at very high temperature and of course in that cases the flow stress behaves more uniformly and relatively very high temperature as compared to the low temperature. So then of course the cold working strain rate having the very small effect that we explained.

But we can neglect the effect of the strain rate during the cold deformation process we already mentioned that, but sometimes if we want to (()) (27:45) the deformation behavior of the metal combining the effect of the both strain rate and strain then we can use this relation sigma f= A epsilon to the power n and epsilon dot to the power m that is the strain and this is the strain rate.

And we introduced the coefficient hardening coefficients as well as the strain rate sensitivity index and A is the strength coefficient and this is the more general formula of flow stress value and A epsilon to the power n to the power m, but in case of low temperature we can use this relation only and if in case of high temperature we can use this relation A epsilon dot to the power m may be in warm forming process we can use the combined effect of the both the effect of the strain and strain rate in the metal deformation process.

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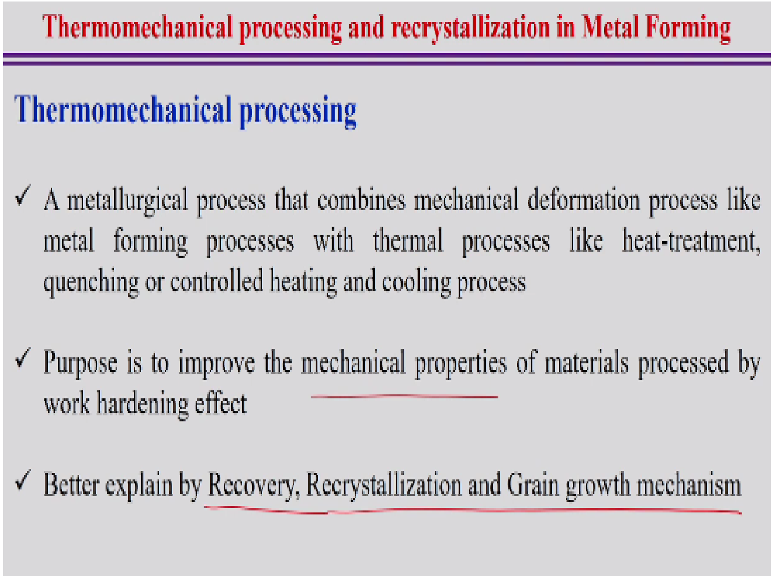

Now come to that point that during the deformation behavior and we look into that thermomechanical processing and the recrystallization behavior which is attached to the material deformation process or material forming process. So thermomechanical processing means we understand the metallurgical process that combines the mechanical process as well as the thermal process thermal process means during the metal forming.

The mechanical process means mechanical process in the sense that metal deformation like the different type of the metal forming process, but once metal deformation has been done then we intermediately or after the finishing of the metal work we can follow some kind of the thermal processing like the heat-treatment processes or quenching process or control heating and cooling rate of a particular material that has been already mechanically processed.

So that if we introduce these thermal processes also just to induce the improve the mechanical properties of the metal form product. So therefore purpose of the mechanical properties, purpose of the thermomechanical processing is to improve the properties of the material processing by the work hardening effect. So therefore this all is when you look into the metallurgical point of view to improve the properties of these things that is in material during the metal forming process.

And that is better explained by the mechanism of recovery recrystallization and grain growth actually all this phenomena most of the cases happens together that is why we normally use this terminology recovery, recrystallization and grain growth or in general we can say that recrystallization of the process and that recrystallization normally happens either during the metal forming process or after the cold work product so that we will look into all this aspect recovery, recrystallization grain growth and particularly attach with the metal forming processes.

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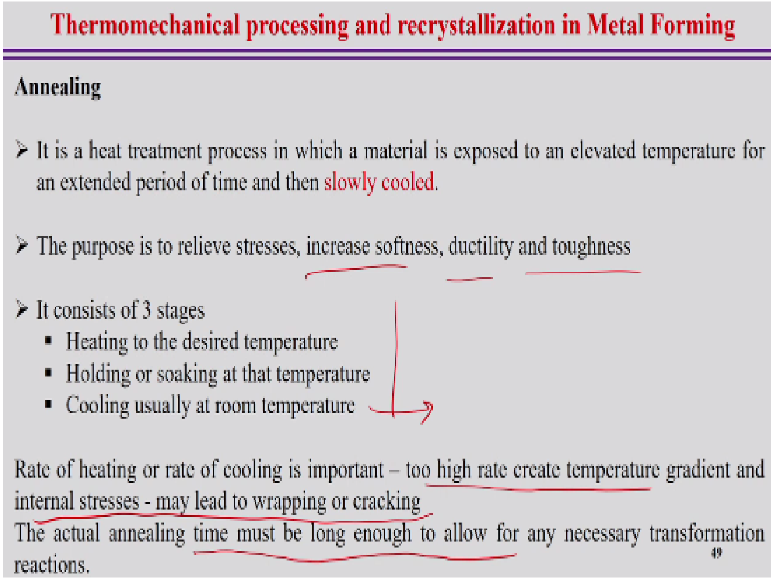

But before that what are the thermal process we normally follow that is more relevant to the metal forming processes first one is the annealing process because this is a very common process and it is a one kind of the heat treatment process that in the particular the metal is exposed at very high temperature and for a sufficient time extended period of time then you follow particular cooling rate.

Normally in annealing process we follow the cooling rate is very slow in this cases. So purpose of this kind of treatment is basically to relieve some internal stress is generated during the deformation process and of course it increases the softness and ductility improves the ductility as well as improve the toughness. So for to bring a change this kind of properties of a cold work material we normally follow this annealing process.

So in broad it is having the 3 stages. First stage is the if you keep the sample then is already worked sample at the desired temperature and keeping it or holding it for a long time and at that particular temperature and then we follow some kind of follow some kind of cooling rate and that gradually comes to the room temperature. So therefore here rate of heating or rate of cooling of the particular some place is very critical or very important to follow.

And that the material properties or whatever we can say that recrystallization happens during this process mainly depends on heating rate and cooling as well as the what temperature it is (()) (32:41) and as well as the composition of the metals, but of course if heating rate is high rate we follow the high rate of heating or high rate of cooling that may create the high amount of the temperature gradient.

And that induces maybe induces the rapping or the cracking of the particular sample so we have to be very careful what type up what cooling rate or heating that we are following during this process. Now of course other important part is that this annealing time basically time we keep long enough so that means we keep it long enough in the sense that we holding after reaching certain temperature holding it for a long time.

But that long time actually helps to bring any transformation of the during this across during this process. So that gets sufficient time to get the transform from some very high deform grain to some kind of the equiaxed kind of the grains through that the recrystallization mechanism. So that is why the time is also important at what time holding time we are following in this annealing process.

So of course although it is a heat treatment process, but it is more relevant to the metal forming process and just to improve the mechanical properties of a metal forming component.

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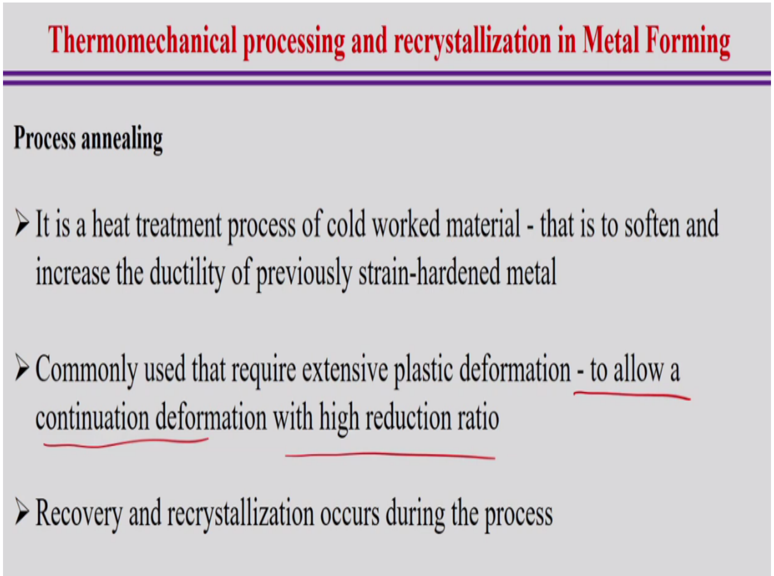

But apart from annealing we also sometimes it is called a process annealing process annealing also one kind of another type of the heat treatment process, but it is different from the other process is that when there is a necessary to reduce the particular work material and the reduction ratio is very high in this cases. For example if you want to make the follow the some (()) (34:29) process.

So in this drawing process so if we start with a very high diameter stock to very small diameter. So in this reduction from high diameter to very low diameter where if you want to try to produce through the wire drawing process it's not possible to perform these things in a single stage. So therefore the deformation is necessary to follow in the multiple stages. Now once in a particular stage though we deform particular this component.

Then there may be the metal becomes strained hardened or may be non-uniform distribution of the grains may clear some kind of the difficulty in the deformation process. So in a multi-stage process deformation process in the intermediate stage we just do the annealing, follow the annealing process such that it will be easier to deform the metal for the next stage.

Now commonly require the extensive plastic deformation so therefore if you there is a reduction extensive plastic deformation if you try to do in multiple stages then process annealing is the one of the process associated with this kind of the metal deformation process. So therefore to allow our continuation and the deformation with specifically the high reduction ratio that is the main characteristic of the to follow or adopt the process annealing.

Of course in this cases also recovery and recrystallization occurs during this process. So we will explain what is the recovery, recrystallization and grain growth normally associated with the thermomechanical processing will explain this.

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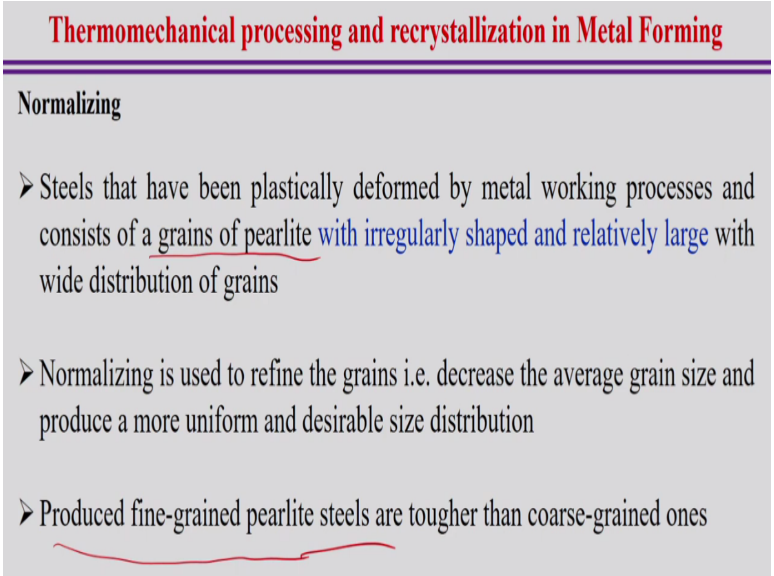

Now normalizing the another type of the treatment process, but in these cases the steels normally having plastically deformed by metal working process or any kind of metal forming processes mainly consists of the irregular grains of pearlite and which is mainly irregular shape and the relatively size of this large and the wide distribution of the grain. So variation of the grain size is very, very high in this particular situation.

So in that case normalizing kind of heat treatment we normally follow to refine the grain size basically from big grain to small grain such that average grain size can be reduced and this is the one purpose and second purpose is to that it should be uniformly distributed almost equal size of the grains. So in that cases the normalizing normally this kind of heated we normally follow in a heavily plastically deformed metal forming process of a steel.

But finally the fine grain pearlite is produced steels which is more tougher as compared to the coarse grain structure. So that is the normalizing another way to improve the grain size and distribution through the recrystallization process.

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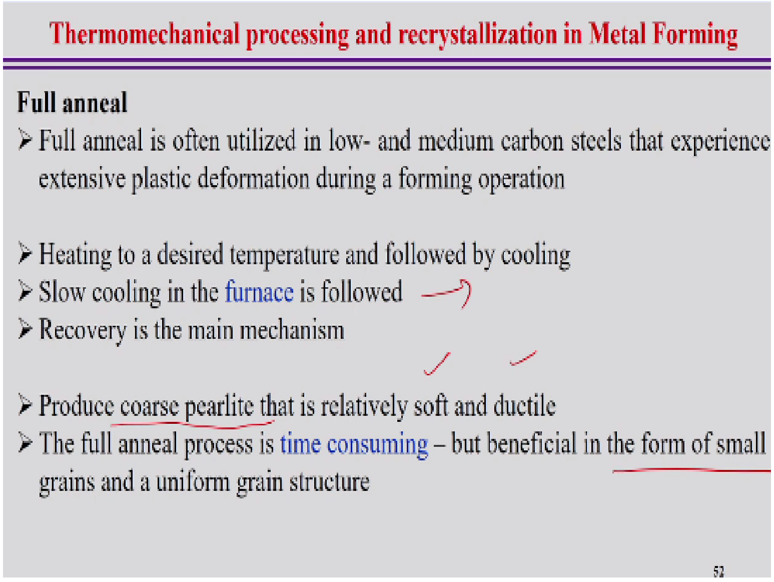

Now full annealing full annealing normally happens full annealing in the sense that when wide range of the carbon percentage exist within the steel so if you try to handle this kind of the steel through the heat treatment process we normally follow the full annealing process. So it is basically utilized for the low carbon as well as the medium carbon steel and that also experiences very high heavily plastically plastic deformation during a particular forming operation.

So in that case we can perform the full annealing process. So in this cases desired definitely desired to a particular temperature and then keep it sufficient time and then follow the cooling process, but in this case is the cooling process is important we normally follow the furnace cooling process so that means cooling rate is very low and of course since cooling rate is very low.

So the mechanism involved here the most in the recovery in the main mechanism to refine the a grain structure in a particular during the full annealing of a heavily plastically deform metal forming process. So this it produce the coarse pearlite because the cooling rate is very slow and we keep it for a long time so grain becomes coarse structures. Coarse pearlite that is relatively follow, but that coarse pearlite relatively soft and ductile.

So this kind of typical structure we normally get if we follow the full annealing process, but of course the other disadvantage is the full annealing process is very time-consuming since we follow the furnace cooling. So therefore, but at the same advantage is that is the beneficial in the form of the small grains and the uniform grain structure so more uniformity in the grain structure is as possible.

But of course not the small grains is produced here in the relative, but there may be the possibility of the grain growth during this process. Now apart from full annealing and this simply annealing normalizing all these kind of the heat treatment process normally we follow during the metal deformation process or we can follow all these heat treatment process after the deformation.

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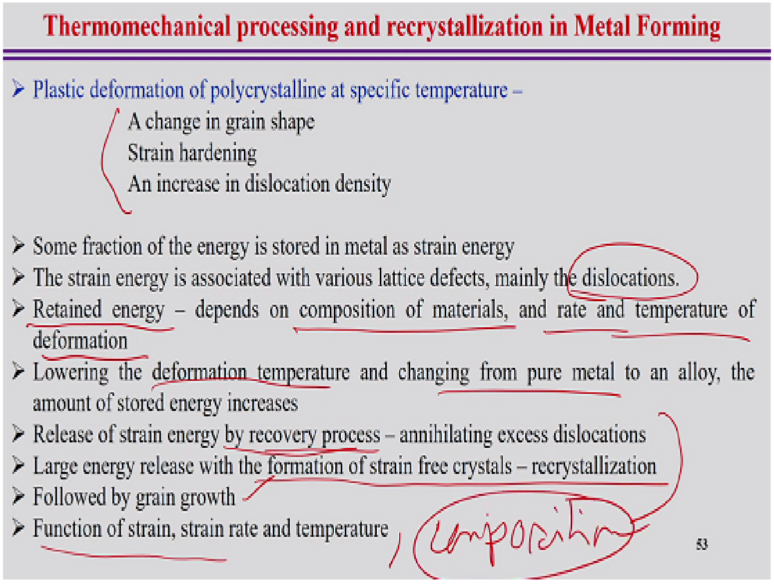

So now we come to that point of the thermomechanical processing and in general what happens during this polycrystalline deformation from the metallurgical point of view. Here plastic deformation of the polycrystalline normally happens at the particular temperature, but this induces a change in the grain shape. So in a particular component is there when you try to plastically deform there is a change of the grain it may be elongated grain or there must be some kind of the strain hardening effect that is the metal behavior also accounts during the deformation process.

And of course since we are applying some kind of the mechanical work done to the metal so there it creates a large number of dislocation and a number of dislocation actually increases and of course once the dislocation increases then dislocation density increases actually when try to deform in a sample so there exists some kind of crystal defects so it may be point surface and line defects.

But we explain all these phenomena in the sense that in case of in terms of the line defects so that means if you actually plastically try to plastically deform the metal then line defects that means dislocations actually increases a lot during the deformation process. Now point is that what way this dislocation redistribute or creates or helps to explain the phenomena of the recrystallization recovery processes that we will try to look.

Now once the deformation this existence of the defects within the sample that actually associated to the defects is some amount of the strain energy. So number of defects increases so therefore we can say the stored energy actually increases during the deformation process. So once we try to deform the metal so then energy stored through the formation of the defects within this structure.

And that defects means mainly the dislocation mainly the dislocation in this case. So therefore some fraction of the energy is stored in the metal as strain energy. So apart from what are the energy are applied during the deformation process very small fraction is stored in the form of the strain energy. Now this strain energy is associated with the different type of the lattice defects mainly the dislocation.

Of course this accounts the other kind of the point defects, but contribution of the store energy through the point defects is less as compared to the dislocation. So we count that mainly the stored energy in the form of the dislocation in a deformed structure. So now this retained energy during the deformation process it depends on what is the amount of the energy stored during the deformation it mainly depends on the composition of the materials.

And of course there must be some (()) (42:47) of the stored energy in terms if it is a case of the pure metal or if it is an alloy system. Apart from the composition of the metal the deformation rate of the deformation and at which temperature the deformation happens all are the strong function to store the strain energy during the deformation process. Now during this deformation process lowering the deformation temperature.

So at low temperature or changing from pure metal to the alloy system the amount of stored energy actually increases. So that at lower deformation temperature the amount of the stored energy is more or in case of alloy the energy of store is more as compared to the pure metal.

Now once the deformation process and the stored energy, but once the stored energy crosses some critical value.

So maybe we can say in terms of the dislocation also so once the dislocation density cross some particular critical value then the release of the strain energy in the form of the recovery process may be done during this deformation process. So therefore recovery is simply the annihilating the excess dislocation. For example, there may be right hand screw dislocation or left hand screw dislocation exist.

And this thing soon once the right hand screw dislocation and left hand screw dislocation comes closer with respect to each other then they neutralize their effect. So stored energy is annihilated during the process for this process is normally caused the recovery process. So recovery process what we understand that simply annihilating of the existing or excess dislocation in the deformation process.

Now large energy also release with the formation of the strain free crystal in terms of the recrystallization. So during the once it cross that some critical value of the dislocation during the deformation process. So large amount of the energy is converted to the formation of the new grains through the recrystallization mechanism. When it forms the recrystallized grain it is almost strain free grains.

And of course with the further deformation or further condition that particular temperature strain rate exists then once the recrystallization happens formation of the new grains the new grains may also grow and over the time. So therefore all this phenomena recovery, recrystallization and grain growth which happens during the deformation process that is a strong function of the strain rate and temperature we are following,

But of course apart from that composition of the metal is also another parameter that actually that mechanism depends on all these parameters.

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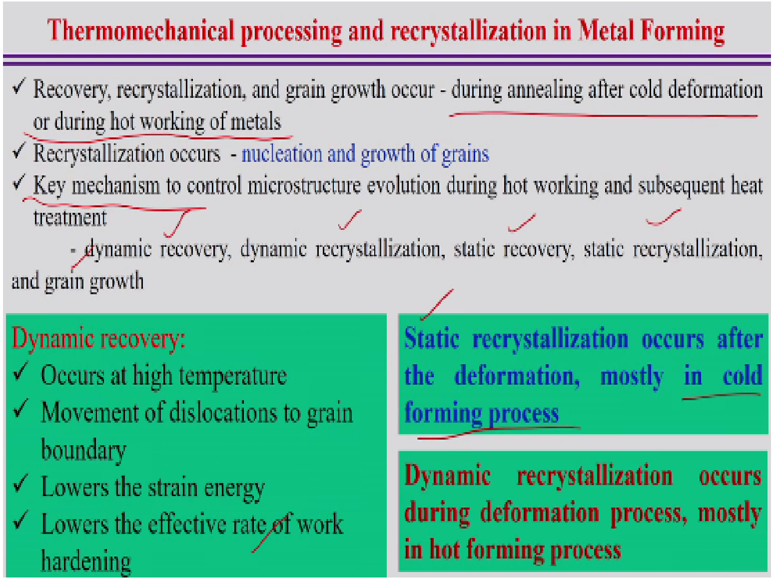

So of course recovery, recrystallization and grain growth normally happens during the annealing process. So annealing process is normally followed after the cold deformation or during the hot working of the metal. So this annealing after cold deformation or during the hot working of the metals so whether at low temperature or very high temperature all the cases it is a possibility of formation of the recovery recrystallization and grain growth during this process.

Now recrystallization it is a formation of the new strain free grains by consuming the old grain in a particular structure, but that forms in the mainly in the two steps. One is the formation of the nucleus and that formation of the nucleus normally happens during the boundary and which point the dislocation density is more. So that during the deformation normally plastically deform the metal so dislocation try to moves towards the boundary.

And at the boundary the accumulation of the dislocation normally happens and but once the dislocation density cross some critical value at the grain boundary then it forms a nucleus. So once the nucleation forms and after the formation of the nucleation and of course once it form the nucleation and it almost strain free conditions and then nucleation grow with the further grow and makes the particular a (()) (47:12) grain and that is called that is we normally called the recrystallization grains.

And then when it is in the form of the grains and that grains consume by consuming the old grain it is a formation of the new grains that is normally called the recrystallization during this process. So therefore the key mechanism to control the microstructure evolution during the hot working and the subsequent heat treatment process that is the dynamic recovery, dynamic recrystallization.

All this phenomena static recovery, static recrystallization and grain growth normally associated with this cold deform or hot deform metal. Now we look into the simple whatever way we can distinguish all this mechanism and this first is the dynamic recovery. Dynamic recovery normally happens at very high temperature and it is a simply movement of the dislocation to the grain boundary.

And once the movement of the dislocation to the grain boundary there is a lowers the strain and in that way it is lowers the strain energy and of course at the same time by annihilating the effect with respect to which dislocation and in that way also it lowers the amount of the strain energy and of course it also lowers the effective rate of the work hardening through the dynamic recovery process.

So dynamic recovery normally happens particularly in the cold deform work. Now once dynamic recovery then static recrystallization occurs and normally static recrystallization occurs after the cold deformation process when you follow some kind of the heat treatment annealing process normally so mostly in the cold deformation process. So we can say that static recrystallization is normally associated with the cold forming processes.

Now dynamic recrystallization is normally associated or the hot deformation process, but the dynamic recrystallization is more characterized in terms of at a relatively highest rate of the strength and relatively at high temperatures in that temperature and that strain rate normally we can found out there is a formation of the dynamic recrystallization.

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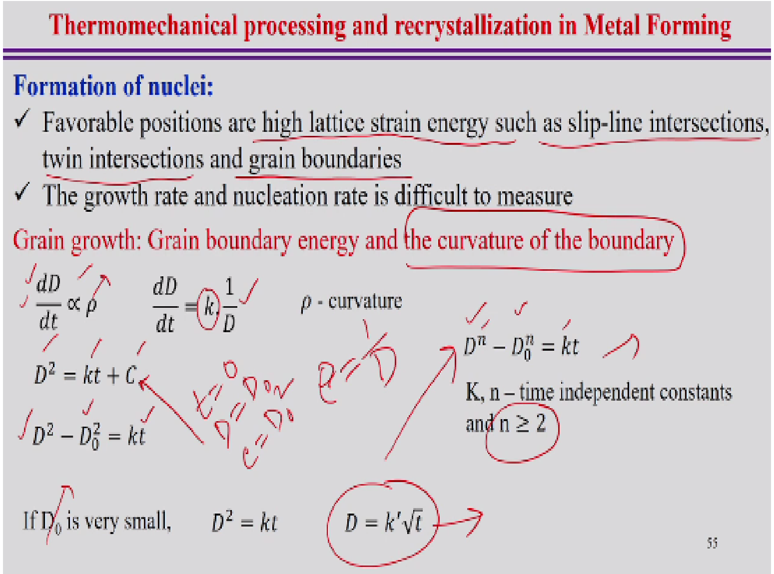

Now this recrystallization or grain growth we try to explain in the very simple mathematical relation and we can found out to a correlation it is possible that of course the recrystallization is associated to the formation of the nucleus, but favorable position of the formation of the nucleus at the high lattice strain energy such as slip line intersections the slip line intersection, twin boundaries and grain boundaries twin intersection basically not grain boundary twin intersections and the grain boundaries.

All are the favorable points where we can found out the formation of the nucleus during the recrystallization process, but once the nucleus forms then it try to grow and that growth rate and try to grow and of course, but what is a growth rate and what is the rate of the nucleation in a particular recrystallization is a very difficult to measure experimentally, but we can use some kind of the theoretical model to explain this mechanism of the grain growth also.

Therefore, grain growth theoretically it depends on the grain boundary and associated with grain boundary energy and of course the grain boundaries basically associate with what is the throughout the grain boundary what is the dislocation density that is the another important parameter that influences the grain growth also and of course the curvature of the boundary grain boundary.

So based on the curvature of the grain boundary then we can say the change of the grain size or here d is the grain diameter. So change of the grain size with respect to time that is actually proportional to the curvature here rho is the curvature not the dislocation density. So it is this ratio the rate of change of the size of the grains that actually proportional depends on the curvature.

So if we assume that this change is only depends on the curvature then we can get this kind of relation proportional to that now if we improve remove the constant of proportionality by introducing k that= k and rho is the curvature is represented by 1/D D is the diameter of a particular time then we can represent this equation k* 1/d. Then we can get this kind of expression D square=kt+ C, C is the constant term. Now if we assume t= 0 the initial grain size D= D0 and put this condition here we can find out that C=basically D0 square.

So now this is the equation the relation at a particular time what is the size of the grain and that depends only on the time t and what was the initial grain size. Now of course this kind of the grain growth is we are assuming that the grain growth basically rate of change of the grain size only depends on the curvature and based on that we can get this kind of relation.

Now if D0 is very small negligible then simply D square=kt or D= k root over t. So this is the simple as a function of time this is the size of the grain during this growth mechanism in a during recrystallization process, but of course this is not very convincing relation with respect to time because it depends on so many factors or grain growth because the grain growth also should be affected what is their surrounding grains or availability of the surrounding grains.

And of course we are not considering here influence of the dislocation density the formation of the that actually influence the grain boundary movement. So all this we are not considering, but in general little better expression can also be done in simply taking the D to the power n and D0 to the power n= kt that is the more convincing experience, but K and n= time independent constants. So define the k and this exponent n is not dependent on time of course this depends on the particular alloy system.

And it become complex function of the other parameters and of course in these cases n> or=2 so that is the more convenient way to represent the relation the grain growth during this deformation process of course it is a very simple, but by introducing this parameter k and n term parameter.

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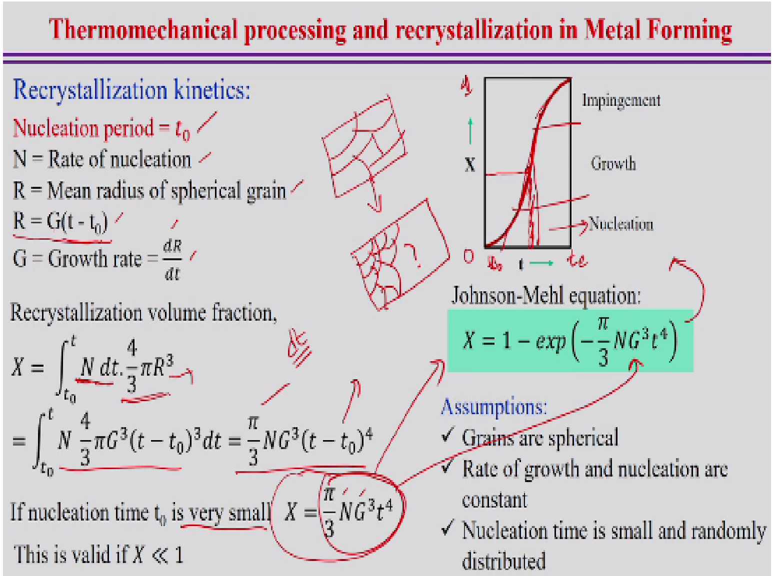

Now apart from the grain growth we try to look into the recrystallization kinetics and whatever way we can estimate roughly the recrystallization fraction. So the crystallization fraction can be estimated like that suppose this is the first we tried to look into the what is the recrystallized fraction. So suppose we have the sample and this sample having the old grain strain grain.

Now once through the recrystallization mechanism it creates a very fine grain structure. So through this recrystallization mechanism, but this kinetics can be represent by (()) (54:47). So once all this all this old grain will consumed by the new grains then we can say the recrystallization fraction is 100% recrystallization happens or we can say recrystallization fraction= say 0 to 1 for example and over this 0 to 1 and in reach the 100% recrystallization of a particular time say for example te 0 to t within that time 50%.

So now if we say it is a particular point this is the recrystallization fraction say is a 40% or 60% recrystallization happens and it is with respect to time. So in there is a 40% then with 40% space within the sample is occupied by the new grains remaining 60% the old grain. So in that case we say that the recrystallization fraction=40% or we can say 0.4. Now whatever way explain the recrystallization kinetic and we estimate them mathematically the recrystallized fraction in this case.

Now we first the assume the nucleation period= t 0 and N is the rate of nucleation here we can see the all this terminology nucleation period, the nucleation happens over the very initial period of time t0 and N=rate of nucleation we assume and then we can say the R=mean radius of the spherical grain of course we are assuming the grain size as in the form of the as a spherical grain and R= mean radius of this spherical grain.

Now R= G* t-t0 so at a particular time T G is the growth rate here so G=growth rate so mean radius of a particular as a function of time so in terms of G is the rate* multiply by the time. So time=t- t0 here. For example, we are assuming the growth rate after the formation of the nucleation. So we assume up to a particular time normally it is particular time t 0 we assume there is a only nucleation happen.

Then with this particular time nucleation happens then growth starts grain growth starts. So that is why at a t- t 0 we have considered as a time here. So G growth rate is simply the dR/ dt and that R=mean radius of a spherical grain at a particular time then now recrystallization volume fraction we can find at a particular time T we can find out that X=for a particular element time dt.

So element elemental time dt what is the recrystallized fraction we can estimate at the particular time dt N is the rate of nucleation and that rate of nucleation in we assume as a constant. So rate of nucleation N * dt we can say the number of nucleus normally happens over the time element dt. Now size of its nucleus is 4/3 pi R cube. So at this particular time dt the mean radius of the spherical grain is=R.

So therefore 4/3 pi R cube is the volume of a sphere. So this is the volume single and this is the total number. So then that indicates that at time dt, dt is the total volume of the recrystallization grain. Now if we integrate over the time t 0 to t because we are assuming the recrystalization, we can assuming the fraction we are accounting the fraction over the after the time t 0 so then it is t 0 to t if you put it.

And then we can in we can put the R because R=G * t - t 0 if we put this expression here R=G*t-*t0 we can get this expression and if we do the integration we are getting this. So this is the estimation of the recrystallized fraction, but with lots of assumption and here and first assumption is nucleation happens over the time t 0, but in that case or through this time we are not accounting this as a to formation of the new grains.

So once formation of the new grain starts after time t 0. So this is the expression for the recrystallized fraction. Now if we assume the nucleation time is very small t0 is very small then X can be approximated as pi/3 and NG cube t 4. So that means the recrystallization fraction we can say is a function of time, but at the order of fourth order and it depends on the rate of the nucleation is one parameter and of course growth rate also.

So growth rate, rate of nucleation and the time all these parameters that decides effects on nucleation, but this expression one once we check with the experimental data we can found out that this is valid expression but it is a very small value of recrystallized fraction that means very initial value of the recrystallized fraction this expression is valid, but this expression are not valid in the other condition.

Therefore, this equation can be modified that is called Johnson Mehl equation and this expression can be modified as the recrystallization fraction at a particular time=1-exponential –pi/3 we use this expression here and change here, but - exponential 1-exponential of this term- of this term and that is the actual more relevant expression to estimate the recrystallization fraction during the recrystallization process.

But why it is like that because first thing is that we assume in the very initial period the nucleation happens. Then growth rate is more actually at this at this middle point. So growth rate is more at this point, but at the same time the impingement of the already recrystallized grain. So therefore at the later stage it becomes more competitive of the growth of a particular recrystallized grains because it is there are surrounding grains and each grains try to grow during this process so therefore it becomes more competitive.

So then the rate actually decreases at the end of the recrystallization process that means when it is towards the full recrystallization then at this point that it becomes more competitive because of the impingement of the grains or already from the grains during this process. So therefore to account all these factors then this equation is modified, but at the same time but practically we assume the nucleation process growth and impingement all actually happen simultaneously or it may happen at the same time also.

This is very difficult to separate or maybe it is impossible to separate out the effect of the individual in the form of the time component. So therefore all happens simultaneously or all happen together at all this mechanism. So in that sense we use this exponential form this is the more practical expression to estimate the recrystallization fraction during this process, but the assumptions all this calculation is that we assume the grains are spherical in nature.

And rate of the growth and a nucleation we consider as a constant and of course nucleation time is very small and nucleation happens randomly distributed. So it is not as in the random places nucleation we are having the nucleation happens during this process. So with this assumptions we can reach this expression John Mehl which is more practically usable to estimate the recrystallization fraction during this process.

So now to look in to summarize the recrystallization process in the metal forming process we can get the significant comments on the recrystallization.

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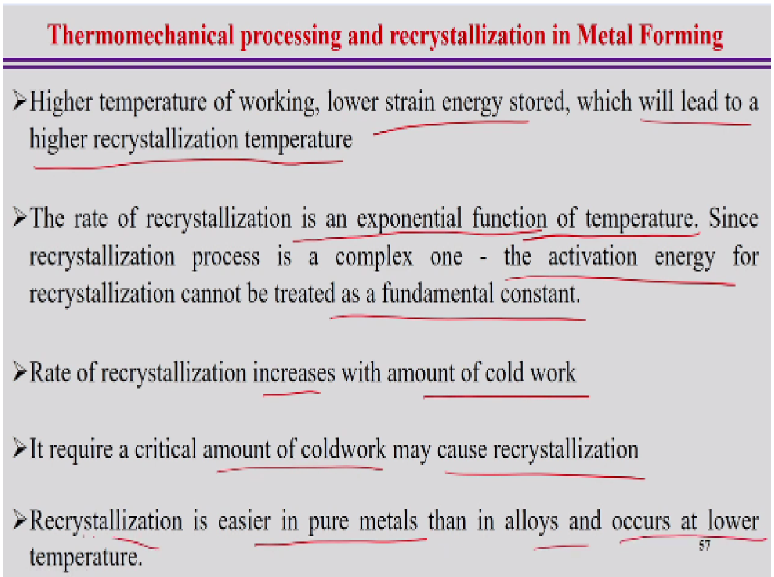

First is that at higher working temperature a lower strain energy stored basically if we deform at very high temperature then store energy will be the less and of course which will lead to the high recrystallization temperature. Therefore, recrystallization happens it is very high temperature of course rate up recrystallization also we can say normally we use the in exponential function of the temperature.

So it depends on the temperature, but the varying the rate of the recrystallization is exponentially wearing with this temperature and of course recrystallization process is very complex and there are so many factors is involved during this process. So therefore to start the recrystallization process though that means the activation energy of recrystallization process may not constant or may be cannot be estimated from the fundamental constant.

Because it depends on the metal parameter as well this recrystallization mechanism. So this that is why it is different from the other driving mechanism and of course rate of recrystallization increases. So rate of recrystallization increases with the amount of the cold work. If amount of the cold work is more then rate of recrystallization will be more during the process.

So we say the dynamic recrystallization in the rate is more as compared to the static recrystallization process the rate of recrystallization is less in case of static recrystallization or rate of recrystallization more in case of dynamic crystallization it require it required a crystal critical amount of the cold work may cause the recrystallization. So recrystallization actually happens once is some critical value of the we can say the critical value of the dislocation.

If we assume the dislocation density is a parameter during this metal deformation process so once it is the critical value, then only recrystallization starts or maybe below that another critical value up to that critical value there may be the possibility of the recovery process may active during this deformation process. So recrystallization definitely we all explain that easier for pure metals than alloy and of course occurs at lower temperature. In case of pure metal recrystallization normally happens at the more and lower temperature.

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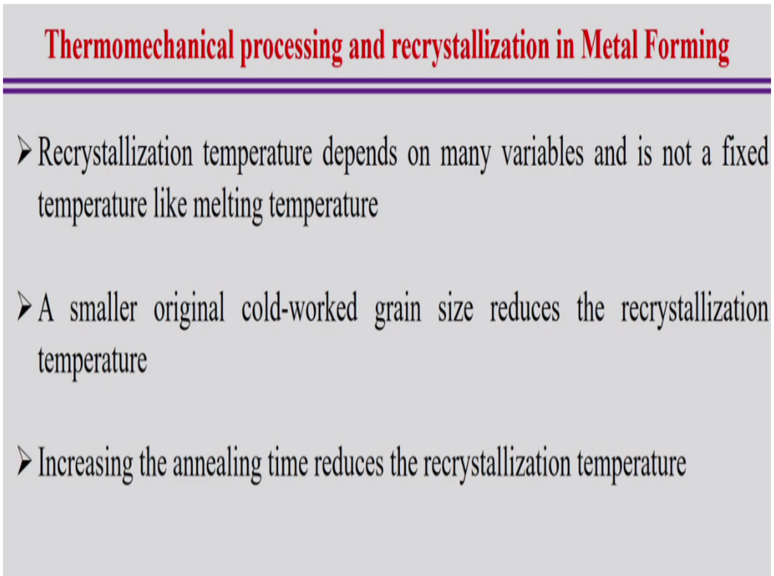

Apart from that recrystallization temperature depends on so many variables. So therefore it is we cannot fix the recrystallization temperature like what we fixed the melting point of a particular metal because we know this is any if you know the metal we know this is the particular melting point, but in that way we cannot define we cannot fix the recrystallization temperature. Smaller original cold work grain size reduces the recrystallization temperature.

So therefore if we start the recrystallization process with the smaller grain size and cold work grain than the recrystallization temperature is less in that cases original cold work and small grain size increasing the annealing time and if we keep for the deform metal for a long time that actually reduces the recrystallization temperature. So once the annealing time increases for a long time the recrystallization temperature actually reduces.

So here we can see that there is a depending upon the other conditions or practical dependent annealing process or heat treatment process we follow the recrystallization temperature actually varies. So basically recrystallization happens at the different temperature. So it is not possible to fix a particular temperature it corresponds to the static recrystallization process or dynamic recrystallization process.

But in general the static recrystallization process relatively at the lower temperature, but dynamic recrystallization process normally happens at the higher temperature. So we have discussed on this material deformation process or different metal forming process and the prospective of that different mathematical calculation and we can follow during the material deformation process and whatever way can estimate the temperature raised during this different type of the metal deformation process.

Apart from that we try to link the metal deformation process with the recrystallization because recrystallization process is more relevant to the material deformation process and it also having some practical importance to understand the recrystallization mechanism which is associated to the material deformation process. So thank you very much for your attention.