Mathematical Modelling of Manufacturing Processes
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Lecture - 08
Melting, Solidification and Additive Manufacturing

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Hello everybody today I will discuss regarding the few elements, Physics of manufacturing processes. We have discussed so far regarding the electromagnetic analysis and to some extent the heat transfer fluid flow phenomena and of course the stress analysis part, but this elements also necessary to understand the mechanism of the Physics of the manufacturing processes.

So maybe not necessarily to discuss in details about all this elemental phenomenon that normally happens maybe related to the manufacturing process but I will try to give some overall view of all this elements and which is more important when you try to analyse the physical basis of the any kind of manufacturing processes. So first we will try to look the solid state phase transformation and of course recrystallization.

And of course then the melting and solidification, I think few manufacturing process and maybe based on the melting and solidification phenomena and then of course nowadays recent trend to design manufacturing technologies that is called additive manufacturing technologies so we will try to give some brief about the additive manufacturing technologies.

And of course what are maybe the parameters and modelling approach normally happens in additive manufacturing technologies. Of course in additive manufacturing technologies we will try to look into both polymeric material as well as the metallic material. Then coupling of the different mechanism actually when you try to get some kind of modelling approach then it involves the several physical phenomena, sometimes physical phenomenon represent in terms of the governing equation.

And sometimes some constitutive relation we normally use to explain all this physical phenomena. So now if there are several physical phenomena then what way we can couple to make an efficient algorithm to explain the different mechanism for physical basis relevant to the manufacturing processes.

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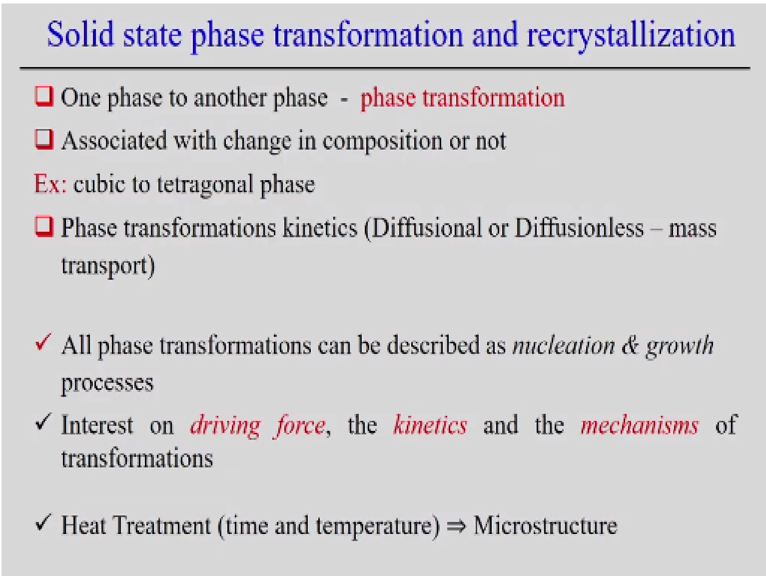

So first I look into the solid state phase transformation and recrystallization. So now of course it is more relevant the solid state phase transformation and recrystallization is one phenomena and it is related to the solid state phase transformation. So phase transformation we simply understand that transformation of the phase, one phase to another phase and of course this transformation of the phase may or may not associated with the change of the composition.

For example, if you look into that cubic and tetragonal phase. So one and like in that way we can say that even in case of iron also there maybe change of the phase from FCC iron to BCC iron that also we can consider two different phases and of course this transformation is associated with following certain kinetics that means once there is a phase transformation from one phase to another phase.

So what will be the intermediate state, how this phase transfers happens, what are the kinetics, mechanism are responsible for that, that I tried to look into that aspect. So definitely we normally use this terminology, the phase transformation kinetics. This phase transformation kinetics either can be divisional or it can be nondivisional and of course what way we can explain there is a mass transport and it is associated with that.

So therefore diffusional and diffusion less kinetics related to phase transformation that depends on the more or less it is a time aspect. Basically time phenomena is important here to explain the diffusional and nondiffusional or diffusionless transport. Now any phase transformation normally happens one phase to another phase. It is associated with some sort of nucleation and the growth processes.

So definitely whether it is solid state phase transformation that means their phase transformation happens in a solid state or during the solidification also then which from liquid phase to transforms into a solid phase, both the cases it is associated first the formation of the nucleus and then of course this nucleation formation depends on so there are so many driving parameters that actually favours to create the nucleus and phenomenon.

But that is a separate chapters, so we will try to discuss in their respective module that part and of course nucleation happens and then the perspective growth of this nucleus after the formation of the nucleation and that way it creates another new phase. So now of course whe you try to analyse the phase transformation first we need to understand what are the driving force are required in case of phase transmission.

What are the kinetics that needs further diffusion or diffusionless or what are the mechanisms of these transformation. So we can take one example, even if we look into the heat treatment process and of course the heat treatment process if we know what is the heat treatment process.

So simply we make the sample available first step is to increase the temperature of a particular temperature and keep it for a long time holder time such that we can allow the respective transformation then after that we normally follow the cooling and of course this cooling may happen at different rate of the cooling. So that simply introducing the different cooling medium we can simply vary the rate of the cooling.

For example, it may be found exclusive, it is a very controlled cooling. It is possible to produce or it may be simple normal air cooling or sample can be cooled just keeping in the water quenching that is within the water, so all this different medium so that the rate of the cooling rate are different. So that depends on them accordingly that microstructure actually develop in a particular sample.

So therefore it is also one example, of the phase transformation one phase to another phase, it forms.

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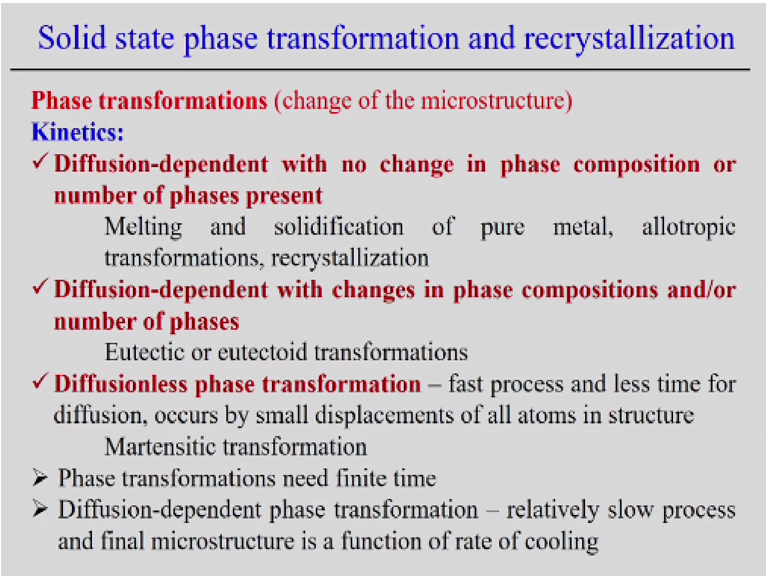

Apart from that if you look into that phase transformation is mostly associated with the change of the microstructure. So maybe initial microstructure after phase transformation the microstructure can be different. What are the kinetics, kinetics already discussed, but we can further divide the kinetics of the phase transformation in the other way also.

First look into that diffusion dependent with no change in the phase composition or number of the phase present. So that is one kind of the kinetics and we can take example, that melting and solidification of the pure metal. If you look into that example, melting and solidification of the pure metal that also happens transformation of the one phase to another phase, liquid phase to solid phase.

But in this case there is a pure metal so there is no change in the composition of the metal and of course number of phase presents is the same. So it is a simply liquid phase. Now after transformation in becomes only the solid phase, but if you take the melting and solidification of the alloy system then there is a possibility of the even phase liquid phase to solid phase but within the solid phase there are it may mixture of the other kind of the phases may present in case of alloy.

So therefore in that cases the diffusion dependent phase changes in division dependent, kinetics part which changes in the phase composition or there is a number of phase present that is simply we can look in the iron equilibrium diagram here we can see that there is a some eutectic reaction or eutectoid transformation if you look into that equation so it may either form in the form one solid phase to decompose into two different solid phases during the cooling of a particular falling certain cooling at a particular temperature.

So that kind of eutectic or eutectoid transformation is simply example, of the, here also diffusion dependent that means diffusion happens and at the same time there may be change in the phase composition or number of phase also changes. So that is the kinetics of the phase transformation.

So of course there is another kinetic that is the diffusionless phase transformation, diffusionless phase transformation normally happens if we follow very fast cooling process and that means less time is given to the system to give sufficient time to defuse the atoms when there is a transformation of the phase, one phase to another phase. So therefore in that cases it may be most of the cases accompanied by some kind of the small displacements.

And near about the all atoms in a structure, so it is associated with that. So one example, is a martensitic transformation that is diffusionless phase transformation. Because martensitic transformation normally happens in case of steel and then when we try to follow very rapid cooling of a particular sample. Now of course what we understand that throughout the phase transformation apart from the kinetics.

Normally phase transformation need some finite-time definitely it is a time-dependent phenomena, but if you say it is diffusion dependent, diffusion normally takes a long time and if it is diffuseless, in that cases, the time requirement is very less, so that is the difference. So diffusion dependent phase transformation relatively slow process and of course in the little slow process in the sense that it takes a long time to transform one phase to other phase.

And final microstructure simply is the function of the rate of the cooling, definitely in the diffusion dependent phase transformation the different microstructure we can produce if we follow simply the different cooling rate, but of course in general diffusion dependent or diffusion dependent transformation normally takes large time as compared to the diffusionless phase transformation.

We can look into that definitely phase transformation involves change in the structure and composition and structure and composition and simply the rearrangement of the atoms.

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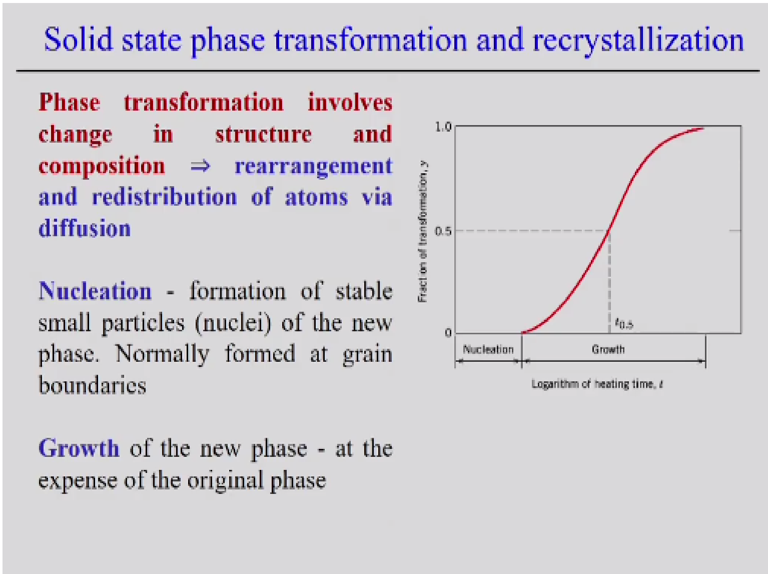

We can rearrangement as well as the redistribution of the atoms and that happens through the diffusion mechanism. So that is normally associated to the phase transformation. So now of course already discussed it is associated any kind of phase transformation. It is associated to the first the nucleation step and then the growth step.

So nucleation is simply formation of the stable small particles nuclear we can say that is of the new phase and of course this normally formed at the grain boundaries and these normal form in the grain boundaries even in case of solid state nuclear solid state phase transformation in that case the nucleation normally happens that means we can say the new phase it is a very small size.

Actually creates near about the most of the cases near about the grain boundary and then the growth phase is of the new phase when the new phase forms the new phase actually grow if he gets the favourable conditions and of course this new phase glow favourable condition and it actually consume the old grains expense of the original phase. So therefore nucleation growth is associated with the any kind of the phase transformation effects.

So graphically if we look into this transformation kinetics or maybe what we can say that the typical transformation curve we can see that it is a fraction of the transformation. So that means fraction of the transformation maybe it is transforming from one phase to another phase. So during this transformation in the very initial period normally at nucleation normally happens.

So nucleation happens at the same time at the different positions and different grain boundaries. So once nucleation over then there is a growth stage actually stars. This growth stage starts and of course this is kind of typical aged kind of curve and of course we can find out the rate of the growth in particular point.

If we look into the fraction of the transformation this is the fraction 0 so that means one phase to another initially is the very initial phase, so then change of the phase. So is consume the old phase creating this thing and following this curve and finally completely transform to the new phase that is 100% transformation happens at this point and of course it starts from this point and transformation ends at this point.

So we can say this is the more or less its total transformation time so that it transform from one phase to another new phases, but of course the nucleation happens within thing, but nucleation may also happen in between the growth stress also that happens simultaneously but rate of nucleation probably less during the growth stage. At the same time maybe at the initial phase the growth stages rate of the growth or it is may be less.

But in the later stage the growth rate is more actually and that is the typical nature of the transformation kinetics and in case of it may be either solid state or maybe in case of the solid to liquid phase transformation. Now we can look into that phase transformation and recrystallization phenomena which is relevant to the manufacturing processes what we can link and how it is helps to explain the different phenomena in the perspective of the different manufacturing process.

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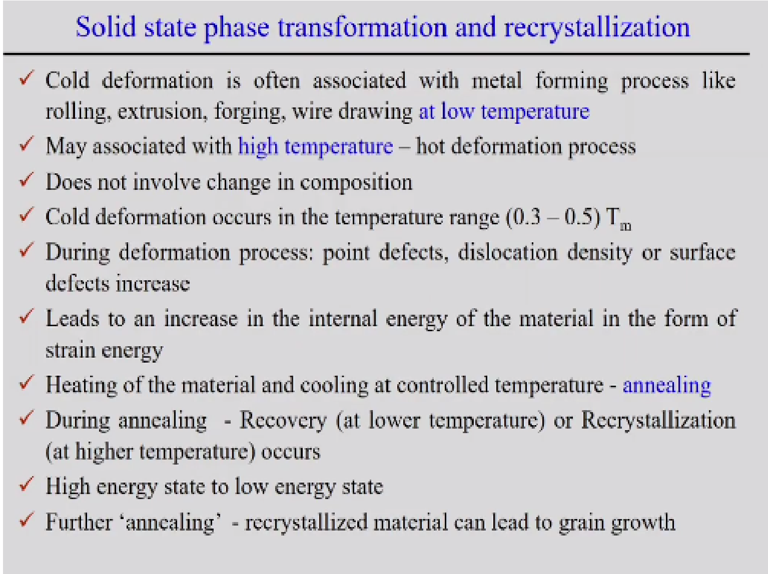

Actually recrystallization is mostly associated with the material deformation process and normally in general conventional material forming process is associated to the material deformation process, so therefore this may happens material deformation may happens in the cold process, cold process in the sense the nearly very low temperature the deformation phenomenon may happen.

So in cold deformation process definitely most of the cases it is associated with the metal forming processes. Of course we can look into the rolling this manufacturing processes such as rolling, extrusion, forging, wire drawing these are associated with the cold deformation process and this deformation normally happens at very low temperature.

Therefore this deformation at low temperature, but deformation may happen even at high temperature also and that can be called the hot deformation processes or maybe hot forming processes we can say that may happen at relatively higher temperature. Of course these deformation process or maybe exclusively recrystallization process.

That does not involve any kind of the change in the phase transformation happens when old phase to new phase happens during this process but not necessarily it will be associated with the change in the composition most of the cases. Therefore cold deformation occurs normally this temperature range at 30% to 50% of the melting point temperature within that actually cold deformation normally happens.

But when the deformation happens in a metallic sample during deformation process if we further apply the mechanical load from outside so deformation happens, it creates lots of defects that means defects in the sense point defects in the point defects maybe substitutional interstitial point defects may also happens.

Then dislocation density or the surface defects increases. So that means during the material deformation process what way we analyse the imperfections in the crystal structure that is represented in terms of the different kind of the defects so that means it may be point defects, line defects or maybe surface defect. So that point defects, line defects and surface defects normally increases with the deformation of a, during the deformation of a particular material.

So for example, point defects increases and during the cold deformation process dislocation density also increases that means there is a combination of a large number of dislocations if we further deform the material. At the same time it may also associated to the surface defects may also increase during this deformation process.

So once there is a large number of deformation, actually defects, crystal defects creates with the application of the load or during the deformation process then each and every defects is normally associated with some amount of the strain energy and that increasing number of the defects means the strain energy stored within the material.

And the source of stain energy is basically from the, if you look into the valence of the energy what external force we are using that external force some part is converted to in terms of the defects and defects create some amount of the internal strain energy of a particular material.

So then simply we can say if there is a deformation of the process there is just storage of the strain energy in that case. So now most of the cases if you see the practically that once after doing the material deformation processing we normally try to follow some kind of the heat treatment process and normally we follow the annealing processes.

Such that that you from grain can say for their existence of kind of internal stress exist after the deformation that stress can be relieved if we do follow some kind of the heat treatment process. So therefore heating of the material, material means after performing this kind of material deformation processes for example, rolling, extrusion, forging, wire drawing, after that we try to follow some kind of the heat treatment process, normal annealing process.

So therefore annealing process is followed in controlled way so we just simply heat the sample at the particular temperature and keep it for a sufficient time and try to follow some control cooling of this process. So this is the typical features of the annealing process. So now when we try to follow the annealing process in any kind of deformed product in that cases that the phenomenon recovery normally happens at low temperature.

Or at high temperature normally the recrystallization actually happens. So it can be explained in that way that during the annealing process. So there is a increment of the dislocation density and there is increment of the point defects. So therefore when we try to recovery process that means it is annihilation of the some amount of the dislocation normally happens and the actually reduce the strain energy, internal energy which was associated with the crystal defect.

So that actually reduces, but this process is called recovery and of course recrystallization process occurs. Recrystallization means during the annealing process the strain energy accumulates in such a way that release of the strain energy normally happens by formation of the new small grains through the nucleation mechanism. So once nucleation as well as the growth of this nucleus.

So in that mechanism, so that is simply called the recrystallization process. So in general we can say the recrystallization means formation of the new grains by consuming the old grains when you try to follow the annealing process of a already hot work or cold work component. Now of course in this process we follow this annealing process there are high energy state to low energy stress normally happens.

So from higher energy level to the lower energy level normally happens and that is this energy level state with application during the annealing process. So if you do the further annealing that means if you keep for a longer time follow the annealing process then what happens? Then normally growth of the grains, already recrystallized grains normally grow and if you keep alive the further annealing process.

So therefore we can see that when you try to do the annealing process of a deform material then there is a the follow recovery, first step is the recovery then recrystallization, then grain growth happen, so that so we normally say the recovery recrystallization grain growth phenomena which is associated with the material forming processes. So therefore driving force in the free energy stored in the.

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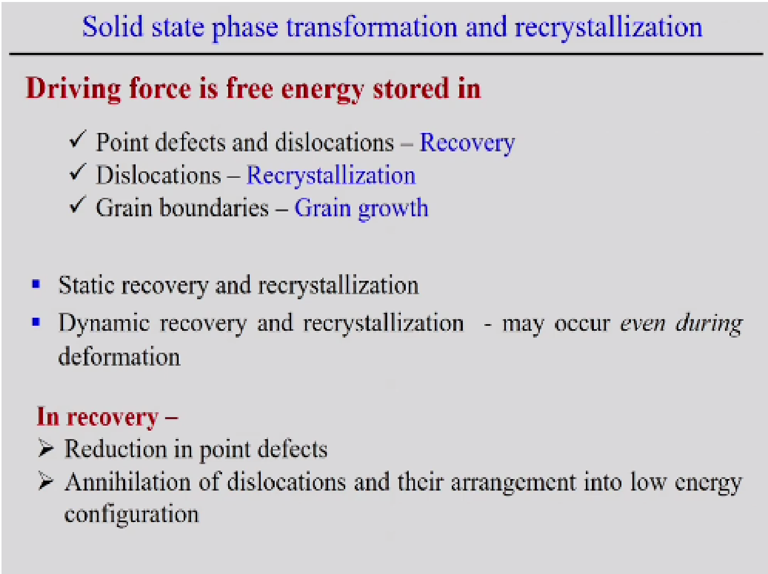

If you look into that, try to analyse the recovery process so the stored energy in the form of the point defects as well as the dislocations and that associated with the recovery process. Now if you look into the recrystallization the stored energy, driving energy actually comes only from the dislocation.

And of course if you look into the green growth phenomena actually is the driving force for the grain growth phenomena is associated with the grain boundary. So storage of the energy within the grain boundary. So that is why recovery, recrystallization, grain growth all phenomena it is associated with some kind of the crystal defects maybe in case of recovery which has discussed point and dislocation.

For recrystallization only the driving force for recrystallization only the dislocation density and of course in grain growth only the grain boundaries. So now recovery recrystallization normally happens together during the material forming process. So it can be static recovery and recrystallization, but static recovery and recrystallization normally happens after the deformation process.

And of course this process is very slow process, so sometimes we call the static recrystallization and static recovery is a very slow process and normally associated with the after the deformation process happens and of course it is normally associated maybe we can say the cold deformation process, but dynamic recovery and dynamic recrystallization it is also happen even during the deformation the same time the dynamic recovery and recrystallization normally happens during this process.

So dynamic recovery, recrystallization means even during the deformation some amount of the dislocation maybe arranged themselves such that it lowers the state of the energy and of course at the same time the formation of the new grains also through the nucleation mechanism, so that but even that dynamic recrystallization recovery normally happens even during the deformation process.

And it is mostly associated to the hot deformation process. Now in recovery, what way recovery happens? Recovery is mainly associated with the or recovery process is accomplished by reducing the point defects during the deformation and of course at the same time annihilation of the dislocations and their arrangements into the lower configuration.

Annihilation of the dislocation means for example, the orientation of dislocation one left hand screw dislocation another is a right hand screw dislocation. So they come together in such a way that they can neutralize their effect and lowers the state of the energy. So such that they rearrange themselves in such a way it lowers the energy. So that process is normally called the recovery process during the recrystallization phenomenon.

But recrystallization normally happens that already discuss the recrystallization there is not rearrangement of the dislocation rather during the deformation process it creates situation such that it overcome certain amount of the dislocation density then nucleation starts at the particular point. The favourable position of the nucleus most of the places near about the grain broundary.

So that there is accumulation of the dislocation happens during the deformation process and when this accumulation of dislocation density exceed some critical limit then at this point there may be formation of the nucleus and the nucleus further grow. So this is normally called the recrystallization mechanism, but this recrystallization happens particular temperature.

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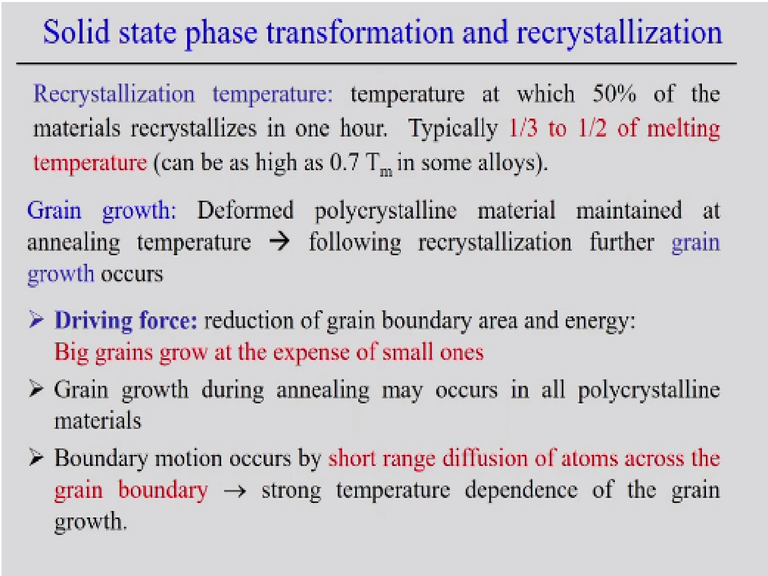

That it can be defined that the recrystallization temperature such that 50% of the metals recrystallize in 1 hour in which temperature that temperature we can see the recrystallization temperature but recrystallization temperature is not a fixed temperature it normally happens over a range of the temperature and particular material is different composition and the standard condition temperature condition also depends.

So therefore typically one third to 50% of the melting point temperature within that range we can say the recrystallization temperature and in certain cases it can go to the 70% of the melting point temperature in a particular alloy system, but of course I am not defining details about the static recrystallization and dynamic recrystallization, the mechanism of static recrystallization and dynamic recrystallization are different.

So apart from the recrystallization also there may be some grain growth phenomenon normally happened. So in this cases deform polycrystalline material maintained at annealing temperature so definitely grain growth, the grain growth normally happens after during the annealing process. So annealing temperature and this normally happens following the first recrystallization forms.

Then that after recrystallization then grain growth normally happens, grain growth occurs. Now driving forces of the grain growth is normally you can see that reduction of the grain boundary area and energy and of course the curvature of the grain boundary also influence the growth of the grain.

Of course big grains grow at the expansion of the small grains so when there is a formation of the big and just during the grain growth process it consume the near by or just attach small grains and then once it consume the smaller grains it takes a big shape. So in that way big grains grow during this process, grain growth process.

So grain growth during annealing may occur in most of the cases or in all the cases the polycrystalline materials for polycrystalline material the grain growth occurs during annealing process. Otherwise before annealing process maybe initial states of the annealing is first associated with the recovery process then recrystallization process and after recrystallization process the grain growth normally happens.

So therefore it can be explained that boundary motion occurs by the short range diffusion of the atoms across the grain boundary and of course the strong temperature depends on the grain growth. So grain growth normally it is a strongly dependent on the temperature apart from the temperature other parameters also influence during the grain growth phenomena.

Now if you look into the what maybe the modelling approach of the recrystallization and when you try to explain the recrystallization we try to look into that parameter that is called the dislocation density.

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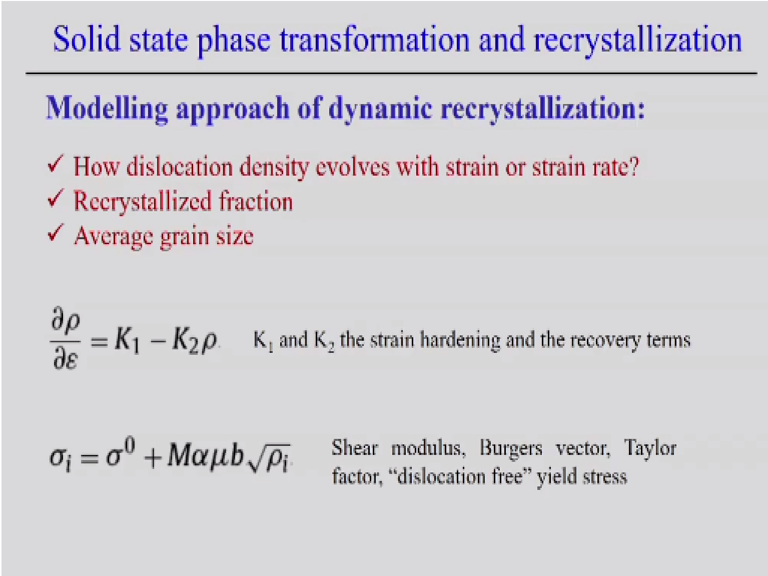

So that dislocation density is the parameter that can be linked with the mechanism of the recrystallization, recovery recrystallization even for growth also, but what we can if you know the dislocation density can be measured during the deformation process, but how this dislocation density can be linked with the recrystallization phenomenon.

Therefore we can see that dislocation density actually evolves, if we look into that if you deform simple sample there is a generation of the dislocation there, so further increase of the dislocation density so that but how dislocation density evolves that distribution density can be represented in that way.

So here rho is the basically dislocation density and that delta of rho/eplison is the strain. So that deformation process we can characterize either strain or standard and of course at a particular temperature, should assume as a constant temperature, this is the strain. K1 and K2 are the constant and this is the dislocation density. K1 and K2 are the strain hardening parameter and K1 is the strain hardening parameter and K2 is the recovery parameter.

So strain hardening parameter is the constant in this equation and with respect to that and both K2 also constant, but K2 indicates the recovery during the recrystallization process. Of course this is associated with the dynamic recrystallization. So during the dynamic recrystallization actually the nucleation and the strain hardening.

As well as the recovery all this happens simultaneously which is completely different from the static recrystallization mechanism. So in this case we can represent mathematically in terms of K1 and K2, the strain hardening effect and recovery term and thus recovery term is just simply multiplied by the dislocation density.

So this is the normal we try to represents that how dislocation density evolves with respect to strength. Of course you can easily convert in terms of the, if you try to bring the time temperature phenomena and we can introduce also that standard effect also, so we can bring, we can modify this situation to incorporate the effect of the strain rate.

So therefore it is a general formula to represents the dislocation density as a function of strain or standard and that normally happens during the deformation process, but in this dislocation density evolves and what way it interact with respect to or what way the grain growth normally happens if we consider all this phenomenon, then we can develop some kind of the recrystallization model.

It can be static recrystallization model or it can be dynamic recrystallization model, but only thing we need to know the equation for what way dislocation density evolves with respect to stain or strain rate, therefore we can from here you can estimate the recrystallize fraction that recrystallization fraction means the transformation curve. Transformation from old grain to the new grain through the formation of the recrystallization.

Now that we can estimate the recrystallization fraction during the transformation process and of course it is possible to estimate the average grain size that means in an average grain size or the recrystallized part on nondecrystalize part of a particular sample that also can estimate average grain size during this process and of course it is also possible to estimate the stress also during this recrystallization process.

So that it may be associated with the sum dislocation free yield stress value sigma 0, M is the Taylor factor, alpha is some constant and mu is the shear modulus, _____ is the burgers factor and rho is the dislocation. So once from here we can estimate what is the dislocation density and once we evaluate the dislocation density from the dislocation density we can estimate what is the stress generate or variation of the stress during the deformation process just by taking the deformation of the dislocation density evolved during this process.

So that is how we can estimate even apart from that I have already explained that average grain size can also be estimate. So if you know the different mechanism, the case which recrystallization mechanism is responsible whether static or dynamic or other kind of the equation for geometric dynamic recrystallization or meta dynamic recrystallization or if you know all this different types of recrystallization mechanism.

And we can develop the model, simple model just by looking into the evolution of the dislocation density during this deformation process. Now come to that next part of this module that is the melting and solidification.

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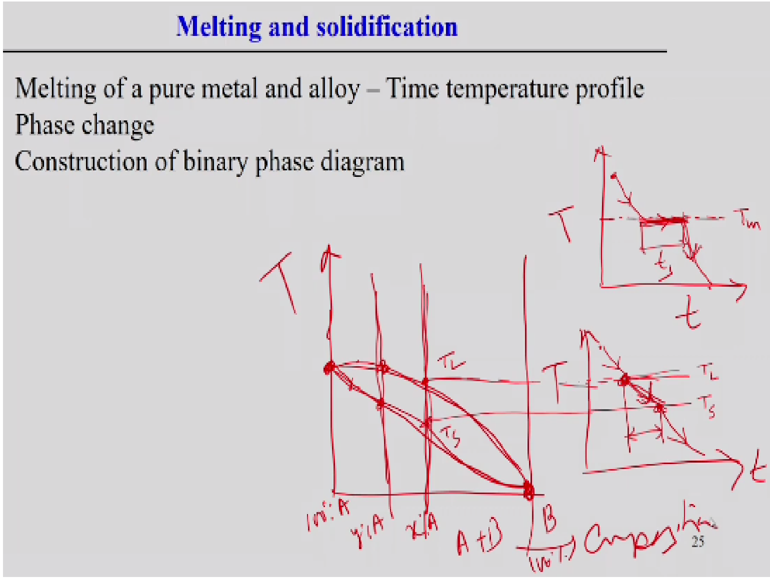

So melting and solidification we can see that melting means we just for a particular material or metal if we apply the heat and at a particular temperature there is change of the transformation of the phase from solid phase to liquid phase and then solid phase to liquid phase when it reaches then we can say it is defined by melting point temperature of a particular material.

So once sample is above the melting point temperature with application of the heat to that particular sample then we can say melting happens. Similar way if you try to allow cool of a molten material, so once it cross below the melting point temperature then we can say it is solidified. So therefore melting and solidification is normally associated with the several manufacturing processes.

And here we try to look into the basics of the melting and solidification. So actually before that we are always interested to know what is the melting of a pure metal and alloy. So if you try to represent that some time temperature phenomenon. So this is temperature and this is a time axis.

So what happens suppose this is the melting point temperature, it represents the melting point temperature particular material. We assume the particular material means we assume the pure metal such that pure metal having the single melting point temperature, so suppose this is the melting point temperature line. Now if you try to solidify this, so it comes from here at this point.

So at this point it is above the melting point temperature, so we can say it is in superheated temperature particular material, we need to come to this point, then it take the transition keep sufficient time for a constant temperature and then it comes to the gradually cool to the ambient temperature. So this is the typical time temperature curve for a pure metal, but this zone, we can say this is the.

This transformation of the phase from liquid phase to solid-phase it happens over this time span. So this time span we can say the solidification time that solidification time just simply say that phase transformation happens within that period of time, then further cool it, it comes to the ambient temperature, but why this finite time is required because in this cases there is a release of the latent heat of a particular material.

So during the release of the latent heat the typical characteristics is that during the releasing of the latent heat the sample remains for finite time at the same temperature. So because it is an impure metal, so therefore melting point temperature is single point melting temperature. So here this time the transformation normally happens from liquid phase to solid phase that will we get some solidification time during this process.

Now if it is an alloy mixture of the different composition, so in that case the melting or solidification may not happen at a particular temperature, single fixed temperature, another over a range of the temperature. So such that within that range of the temperature the mousy zone that means mixing of the solid and liquid phase normally exist within that zone and once it completely comes to solidify it, then it comes to the another temperature.

For example, you can see this is the range of the temperature. So it comes from here super heat temperature of this material. So this is one temperature, this is normal called the liquidus temperature, this is normally called the solidus temperature. So within that range it is a constant whether there is a slope.

Phase transformation happens then after the difference slope come back to this thing. So here also this is the solidification time, but here the slope was constant, here it was the parallel to the time axis, but here there is some slope, that means change of the phase happens at the same time that over a range temperature change. So that this temperature range is called the solidus temperature and liquidus temperature.

Now if you look into what the range of the temperature in a particular single composition, so this is the, so here we can see this is the and we try to explain this as a particular alloy system. Now say if you change the composition of the alloy system, then the solidus temperature and liquidus temperature can be different for a particular material. So it may be something else in this case such that here we can represent the solidus temperature.

And liquidus temperature for particular composition. If you change now it try to explain this thing suppose this is the liquidus temperature, this is the solidus temperature if you project it here and this is say x percentage is A and remaining percentage of the B metal, B composition. So in this case this is the liquidus temperature, this is the solidus temperature for a fixed composition.

Now if we change the composition the liquidus and solidus temperature can be different and must be different so in this case suppose other cases say here y percentage of A. So then in this case this is a solidus, and this is the liquidus temperature. So in that way if you plot it and if you go at this point we can say that here 100% A that means it is 100% A means it is a pure metal, if we try to mix A + B.

And here say 100% B it is also pure metal and this is for pure metal suppose this is the melting point temperature, single point temperature, here also 100%, this is the single point temperature. So now if we change the composition of the decreasing A and increasing B such that A + B always 100% then we can construct this kind of diagram, this is called the binary phase diagram.

This is temperature and this is the composition. So this type of diagram is very much useful and when we try to analyse the solidification behaviour or may be solid state even for solid state transformation associated with the alloy system and of course since we are using mixing the two components A and B that is why it is called the binary phase diagram.

So this binary phase diagram with respect to the composition and temperature we can get this kind of the diagram. Now theoretically we can see the solidification time we define during the time of the release of the latent heat.

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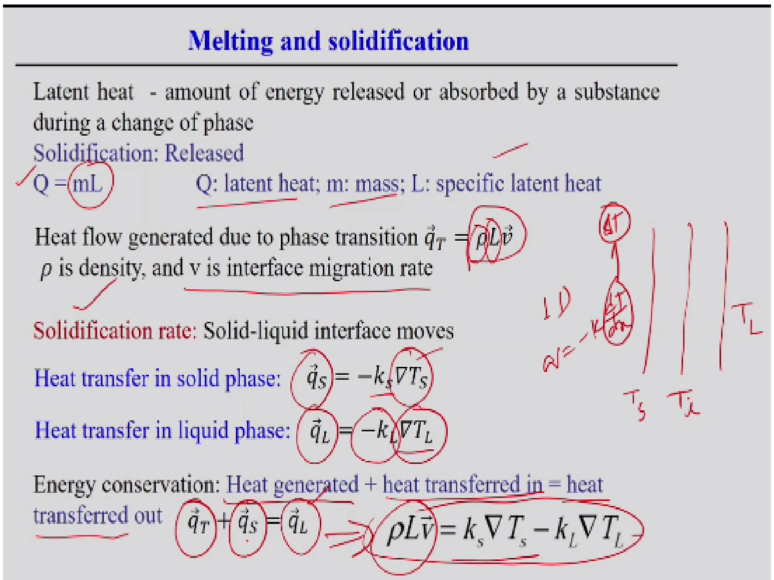

So latent heat means amount of the energy released or absorbed of a substance during the change of the phase. So when there is a change of the phase it may be liquid phase to solid phase or maybe from liquid phase to vapour phase. In that way also there may be associated with someone amount of the latent heat.

So that related to the phase change, so in case of solidification this latent heat actually released then during the melting of a material actually the latent is absorbed. So how we can measure, estimate what is amount latent heat that Q = mL, Q is the latent heat here, m is the mass and L is the specific latent heat such that we can specific means per unit mass, so this is the amount of the total latent heat we can estimate.

Now if you try to analyse what way the solidification front moves. So for example, there is a solid phase some interphase and there is a liquid phase. Now at a particular situation this is the some intermediate phase between the solid and the liquid phase. Now heat flow generated due to the phase transition, so during phase transition we can say that total heat flow during the phase transition is the, this is the density rho.

L is the latent heat and v is the actually the interface migration rate that velocity means we simply understand the what velocity the solidification front moves. So during the solidification there is a formation of the solidification front that is the boundary between the liquid and the solid phase but how this front moves that is the velocity is V here. So here we can estimate the heat flow during this phase transition is that rho L into V.

L is the latent heat here, because during the solidification the latent heat is actually released and when there is a releasing of the latent heat then what way the front moves. Therefore solid liquid solidification rate means you understand at what velocity solid liquid interphase actually move.

So suppose it is velocity V vector in the form of a vector here. Now heat transfer in the solid phase so therefore it is making the valence, the heat transfer in the solid phase we can estimate we assume the heat transfer in the solid in terms of the vector qs, the ks is the thermal conductivity of a solid phase and this indicates the gradient of a temperature.

So that means we know if you simplify apply the Fourier's law of heat conduction we have already discussed we can use that k into dt/dx is in one dimensional case, in 1D we can estimate equal = -kintodt/dx but 3-dimensional we can use this gradient term in the vector form then –ks delta Ts. So delta Ts is nothing but is the temperature gradient here dT/dx, which equivalent to one dimension ks.

Now –ks the gradient this indicates the heat transfer during the solid phase. In solid phase during this process, solidification process. Now similarly, heat transfer in the liquid phase also we can estimate that - KL into delta the gradient of TL. So that is a temperature gradient and KL is the temperature gradient with respect to the liquid phase in liquid phase and KL is the thermal conductivity for the liquid phase.

So therefore if you look into this all aspects the heat flow generated during the phase transition this is the heat flow generation of the heat flow. Now if you try to make the energy balance or energy conservation during the solidification process is simple way but what is the heat generated. So heat generated due to the phase transition that means simply this generation due to the phase transformation with what we are manipulating the latent heat during this transformation.

Now this is the heat generated term, then heat transfer in within the domain and then what is the heat transferred out that clearly indicates the energy conservation during the solidification process. Now if you put it the qT basically energy generation qs to the input and this heat transfer out, this qL such that heat transfer from the qL that indicates that making the equation like that qT = this and qS if you go other side also plus ks delta Ts – kL delta TL.

So if you have all this information, all these parameters and this temperature gradient in the solid phase or temperature gradient in the liquid phase if you keep all this information and we can do further calculation of the what way we can move the solidification part, but of course during the solidification process the what way the degree of undercooling actually exist.

That degree of undercooling is the temperature difference below the equivalent temperature of the melting that is most important to consider to explain the solidification behaviour but of course this energy balance may exist and is a particular zone and it is not necessary it is balanced overall that is very big dormant and other than it is a small very localized one if you look into this energy balance it clears the very complex solidified structure during the manufacturing process.

So therefore because the solidification is mostly associated with the costing and the welding process in general.

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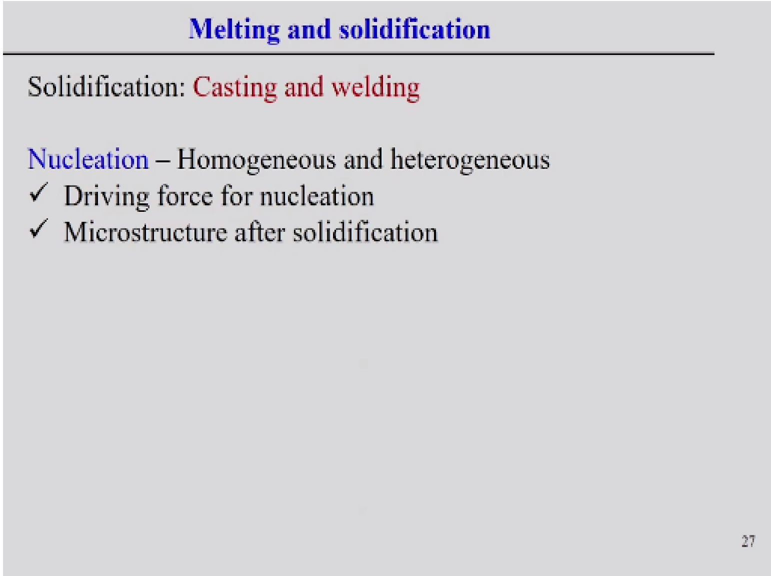

Now the solidification in terms of the heat transfer analysis would becomes more complicated if you look into the all phenomena if you try to incorporate the Kinetics of the solidification then the behaviour of the solidification or getting the simple equation is difficult and if you look into the actual kinetics of the solidification.

But of course the kinetics of the solidification also important to explain the solidification behaviour in manufacturing process specifically in casting and the welding process. Actually solidification process is associated with nucleation what we explain the solid state phase transformation there also nucleation was there even for liquid phase to solid phase.

During solidification process it is also associated with the nucleation process, but the nucleation may happen homogenously or nucleation may happens the heterogeneous both the way homogenous nucleus or heterogeneous nucleation and of course in this cases what are the driving force for the nucleation is most important.

Because in case of the homogenous nucleation process the driving force maybe the undercooling that exist and this mostly associated with the pure metals. Now in heterogeneous nucleation process the driving force may lead some kinds of enucleating agent or some kind of the particle just actually introduce the nucleation process there or maybe that interphase.

Presence of the interphase there actually helps for the heterogeneous nucleation process, anyway we will try to discuss all this homogenous, heterogeneous nucleation process in details calculation in the respective module, but here try to give some overview of this things and of course most of the cases the important aspect is the microstructure of the solidification which is mostly driven by the solidification kinetics.

Rather than only we cannot predict the microstructure just simply looking into the heat transfer phenomena in a solidification process. So therefore it is very important to know the different nature of the nucleation process and what are the driving process and how this driving forces normally is influenced by the different kind of the solidification process.

For example, the driving process for casting and welding may be different and different situation can be created that means homogeneous or heterogeneous nucleation process in solidification depending upon the nature or type of the manufacturing processes.

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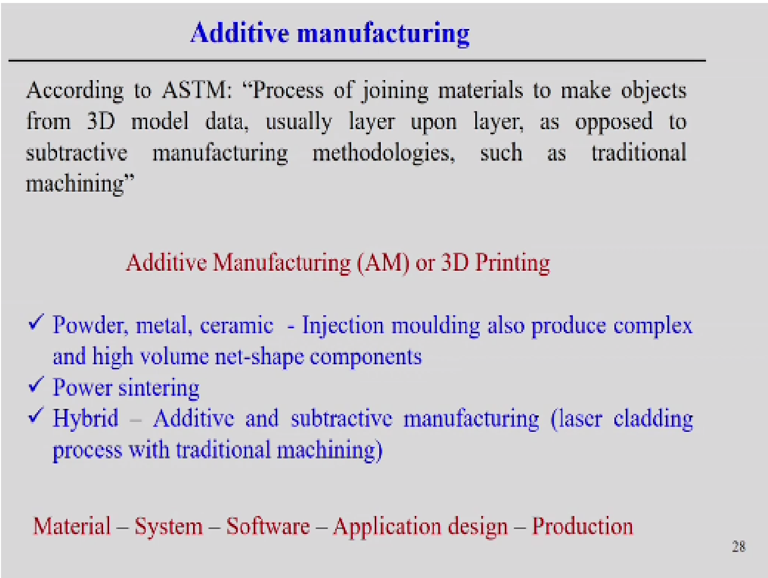

Now apart from that there is additive manufacturing. So in additive manufacturing is nowadays it is one attractive technology and now it is gradually more rapidly developing, this additive manufacturing technology, but additive manufacturing simply we understand that apart from the subtract we fall in machining process, we can create any kind of the complex shape just by layer by layer deposition of particular material.

So according to the American Society for testing and materials the additive manufacturing is defined like that process of joining materials to make objects from a 3D model data usually layer-by-layer as opposed to the subtractive manufacturing methodologies suggest additional machining process. So it is complete opposite different from the approach methodology we use in case of machining process.

But of course objects can be created from the 3D model, suppose we have to create any model, any geometry, but we have to predefine that geometry and that geometry simply created the deposition process following the layer by layer. So therefore there is a loss of the material what we generally observe in case of the machining process by just removing of the material.

It is absent in case of additive manufacturing technologies, but there may be other difficulties, other complexity exist associated with the manufacturing technology, additive manufacturing technology. So this additive manufacturing synonyms to the 3D printing process also and sometimes we can say that 3D painting process of course.

Apart from this additive manufacturing process the allied processes that people works are already developed processes or relevant more close to the additive manufacturing process that is called the injection moulding. It can be powder based, metal based, ceramic based, injection moulding processes, that also produce the complex and very high volume almost net-shape components.

What thing we can get from the additive manufacturing technologies also, even power sintering process which is more relevant associate the concept is more relevant to the additive manufacturing technology apart from that hybrid that means additive and subtractive manufacturing also develop one example, of the laser cladding process with the traditional machining process.

So in this cases laser cladding process we can produce a product but unwanted things we just simply remove by following the traditional machining processes. So it is a approach, it is called the hybrid process, deposition also there at the same time we are following the machining process, but in this cases we try to bring the machining process to get a good surface finish for the product.

So that is the more relevant or more related to the additive manufacturing process, but of course additive manufacturing process or technologies completely different from all this three processes. In general it is associated with the first material so material mostly used in the form of the powder or wire.

Then what type of the system we are following, development of the technology in additive manufacturing technology whether directly we are using the wire or we can using the power whether we are sintering the powder or whether we are melting the powder that is the system is the next important part in additive manufacturing.

Then software is required to create the CAD model and maybe after creating CAD model you need to create the geometric feature of a particular component which component we try to produce by following that given manufacturing technologies. Then design, application design that means if you try to achieve layer by layer deposition what strategy we need to follow, which layer should be deposited first.

And which may be deposited layer on and what maybe the time gap between the deposition of the first layer to the second layer because if it is associated with melting some time is required to solidify the material. So all this matter, so that is called the designing of the process or may be application just by looking into the application we need to design the process.

And finally the production means once looking into all these aspect we develop the machines or machines are available then using this machines we can look into the what way we can increase the rate of the production. So all these 5 elements are associated with the additive manufacturing technologies.

Now we generally if you look what are the developed additive manufacturing processes overleaf we look into that.

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Additive manufacturing

Application in
- Polymeric materials
- Metallic materials

Processes developed based on
- Liquid binder and curing
- Melting and solidification
- Sintering

Materials in the form of: Powder, wire or sheet

Welding to metal printing

The application is either in the polymeric material, the 2 basic parts, either in the polymeric material or metallic material or it is also possible to create some kind of the functionally graded materials so that is combining the 2 different material depending upon the applications. Now apart from the application area process the additive manufacturing process is developed based on the looking into the liquid binder and the curing process.

So this process is a very old process actually in additive manufacturing. So we use the liquid binder, we just fill using the liquid binder and then once we fill the liquid binder certain dimension then or maybe layer of the liquid binder is existence we just focus on the some laser or ultraviolet ray to cure only that particular part of this component.

So that particular part of this component once is cured and if you follow this way then we can create one kind of the object that is the in principle the liquid binder and curing process. Then apart from that melting and the solidification also we just in additive manufacturing process we use the metallic powder, but in metallic powder if we focus the laser beam or electron beam fuse it and melting and then after that is solidified.

But the quality of the product or maybe surface accuracy depends on the particle size and then of course there are so many parameters to control to look to get the good surface finish product. So it is associated with either solidification or melting or in certain cases we follow the sintering process and the sintering process means we just melt, not melt actually, we just put the temperature below the melting point temperature.

And similar strategy follow what we can do the powder metallurgy techniques. So therefore sintering can be another option. So these are the 3 basic mechanism based on the different additive manufacturing processes has been developed, but of course materials is used in the form of either in the form of powder or direct where we can use it we can use the wire and then we simply heat the wire and that wire has been deposited according to the desired shape.

Of course this deposition can be for some predefined path and of course the additive manufacturing which has also been developed using the seat also by stacking of the seats the techniques can be developed also and of course apart from this directly using this things there is a development of the conventional welding process converted to the additive manufacturing or we can say the metal printing processes.

So the welding process is associated to the metal deposition. For example, simple example, gas metal arc welding process. So it is associated with the metal deposition process. So what way we do the multiples welding processes, so deposition in the several layer, but of course it is a very controlled way and that control way and that can be used to develop the different type of the 3D metal printing process or additive manufacturing of metallic materials.

Now coupling of the different mechanism now the last part of this component we can look little bit that if you look into manufacturing problems we can see that.

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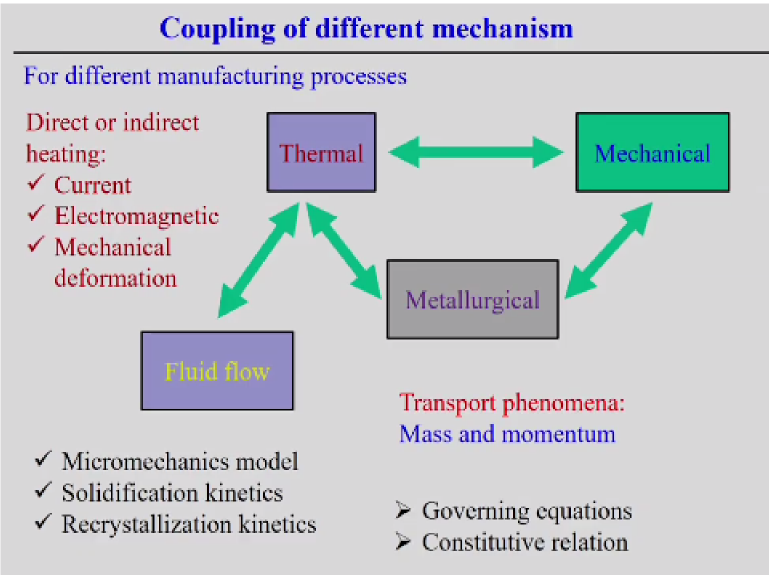

For different manufacturing processes if we analyse that there is a need of the direct or indirect heat generation, either heat generation or this heat generation can be done in the different way also we can directly use the in case of welding process we can use directly arc quickly at the electric arc, but passage of the current is required electric arc.

Or we use the electric current electrical in such a way there maybe some resistance. So that resistance follow some joule heating fundamental such that heat generation may also happen at the interphase, but at the same time electromagnetic energy created and then electromagnetic but in this cases electromagnetic get in such a way that it creates the high impact of the solidification deformation process.

What we have seen the electromagnetic forming processes so there also we can use the electromagnetic force, but at the same time electromagnetic analysis process can also be used to create the induction heating phenomenon so induction heating we just create the situation such that Eddy current will be responsible to generate the heat. So that way also we can create the heat also.

Apart from that direct mechanical energy we can used in the solar state deformation process of manufacturing process of these are the different way we apply the direct or indirect way different heat sources required to generate the heat and then we can develop the different type of the manufacturing, different manufacturing technologies.

But of course when we analyse all this manufacturing processes in general it is associated with the thermal process. So that means temperature distribution is associated with thermal process once there is a heat generation definitely some kind of temperature generation will be there and that we use a temperature analysis can be done some following the different thermal model.

Then once it is isothermal model if there is a temperature difference between 2 consecutive points it is maybe associated some kind of the thermal strain or if there may be associated with some kind of the concentrated load or external load that clears the kind of states generation or deformation of a particular metal that is normally called the mechanical analysis.

So thermal analysis, mechanical analysis, but this mechanical analysis when or thermal analysis when it is associated some kind of the microstructural transformation may also happen that way we explain that there may be phase transformation, that phase transformation that may associated some amount of the strain, but it is a very localized position or if we look into very small scale.

Then we will be able to realize this kind of the transformation so that transformation called the metallurgical transformation so the metallurgical transformation actually influence the stress generation or residual stress during the manufacturing processes. So that actually thermal model influence the mechanical and the mechanical model is influenzed by the mechanical model is more.

But of course this metallurgical transformation maybe associated some kind of small even it is very small, some kind of the heat generation it may be associated with. So but link is very weak between thermal and metallurgical model, but link is more strong between the metallurgical and mechanical model. So that it is a some algorithm is required actually to coupling all this thermal mechanical metallurgical model if you try to develop it is a very good model which is associated with any kind of the manufacturing processes.

But apart from the thermal model if we take even for fusion welding processes it is also associated with some amount of the fluid flow. So therefore if there is a material flow in that cases we need to develop the fluid flow model and what the fluid flow model and thermal model they are associated with that because fluid flow model will give the velocity field actually.

But if we look into that already discussed in the transport equation energy conservation equation the energy conservation equation we can see that transport of the energy also important there. So that transport of the energy is basically this velocity field actually influence the transport of the energy and it finally influence the temperature distribution.

So therefore it is having strong relation between the thermal and the fluid flow model and if you analyse the fluid flow model then of course we need some kind of the information which are temperature dependent when you try to look into temperature-dependent properties also then we need to know or should know, do thermal analysis.

So therefore or having some relation or some link in certain way between the different kind of the analysis per schedule but main important part is that we are trying to it is a complex model situation then the important part is that what we are coupling all this phenomenon. So that is why this model is called the coupling of the different mechanism.

But of course when you look into the definite metallurgical transformation during this process deformation process also that associated with this create some kind of the micromechanics model and then incorporation of the micromechanics model enhance the quality of the simulation process also and once it is a kind of when it is application of the heat and then thermal analysis if you do thermal analysis also then increases during the solidification process it is relevant to the thermal analysis or heat transfer analysis.

But of course if you understand the solidification process more clearly, if you try to develop the model of this process, the kinetics of the model is more important and that kinetics is very much relevant to the metallurgical field which is related to the different types of the materials handling for what we are applying the heat to the particular manufacturing process.

So then similarly, in solid state deformation process also and then mechanical reformation process the recrystallization kinetics also important, so when we try to do some mechanical analysis even for metal forming processes if we develop some model we need to know what are the recrystallization kinetics and what type of recrystallization mechanism actually prevails.

Such that this information if we pass the mechanical model it improve the quality of the simulation of a particular manufacturing process associated with the mechanical defamation. Of course if you look in to the transport phenomena here also associated with the mass transport to the system then it becomes more complicated and of course separately when you try to the fluid flow fill that the fluid flow fill normally we get from the momentum equations.

So overall if you look all this phenomenon or if you know what we can coupling all this but finally we need to look into that to represent all this phenomenon what are the governing equation we need to use. For example, if you look into thermal analysis, we need to go for the heat conduction equation to solution of the heat conduct that is the governing equation of this process.

Or of course if you look into mechanical analysis then we use the constitutive relation for example, what way the stress is related to strength and what way we can relate between the deformation and the strength, so that follow some linear or nonlinear relationship and that actually in plastic deformation it becomes definitely it is a nonlinear relation between the stress and strain and all this cases.

So that creates kind of the constitutive relation or constitutive relation can be developed if you know between the 2 parameters. So it is open use the constitutive relation when you try to develop the different kind of the model and in manufacturing process. So thank you very much for your kind attention. I hope you are able to understand the overall idea of the physical mechanism associated with the manufacturing processes. So next module we would try to discuss about the different types of the manufacturing processes. Thank you very much.