Mathematical Modeling of Manufacturing Processes

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Lecture - 05
Thermofluid and Electromagnetic Analysis

Hello everybody now I will try to discuss the next module the module 2.

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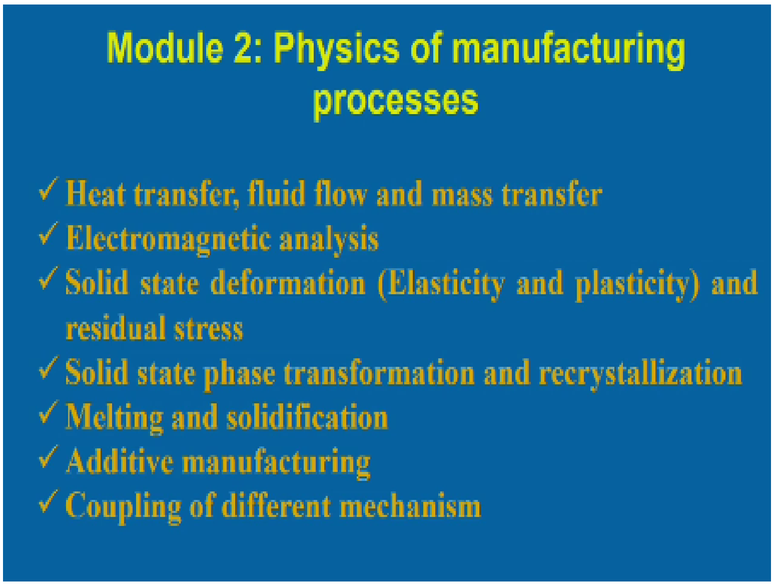

That is on physics of manufacturing processes. So in this module I will try to produce some kind of the overview of the different physical mechanism involved in different types of the manufacturing processes. So of course there is a scope to understand the manufacturing process and what mechanism is responsible, but that discussion detailed discussion we will try to look into the individual manufacturing processes.

But here I will try to give some basic concept for example the heat transfer, different mode of the heat transfer, fluid flow and of course mass transfer is associated with the different manufacturing processes and of course apart from that the electromagnetic analysis also try to look and how it is associated with the different manufacturing process and in principle whatever we can use this electromagnetic analysis or electro theory of the electromagnetic in the manufacturing processes.

Of course apart from that solid state deformation I will try to discuss the solid state deformation in the light of the elasticity and different plasticity model and whatever we can analyze develop the elastic module and plastic module because many of the manufacturing process is associated with some sort of solid state deformation process. So in that cases probably this elasticity and plasticity theory is applicable.

And of course apart from the residual stress also which is one of the most interesting component in any kind of manufacturing process and of course the objective is to how to reduce or how to mitigate the amount of the residual stress assisted with any kind of the manufacturing processes. So apart from that to some metrological site the solid state phase transformation effect.

And then how the crystallization is responsible and normally we know that crystallization is mostly associated with most of the metal forming processes. So having some relevance to analyze or to discuss (()) (02:42) crystallization, but I will try to discuss the mechanism of the crystallization. So therefore melting and solidification we know it is associated with the casting process and welding process the melting and solidification is there is associated.

But I will try to give some overview on the melting and solidification normally associated with the different manufacturing process. So apart from that recent (()) (03:03) industries also we use the additive manufacturing technologies also so that additive manufacturing, different additive manufacturing processes, but this additive manufacturing process is mostly focus on the metallic material.

And of course we know the welding process so how to bring the concept of the welding processes to develop the different additive manufacturing technologies that I will try to discuss here also. And apart from that if you know the different mechanism then in a particular manufacturing process how to couple of all this kind of the different mechanism if we try to develop some kind of the mathematical model of any kind of manufacturing process.

So that now I will start with that heat transfer first part is the module is the heat transfer fluid flow and mass transfer and apart from that we look to make analysis that I will try to cover first.

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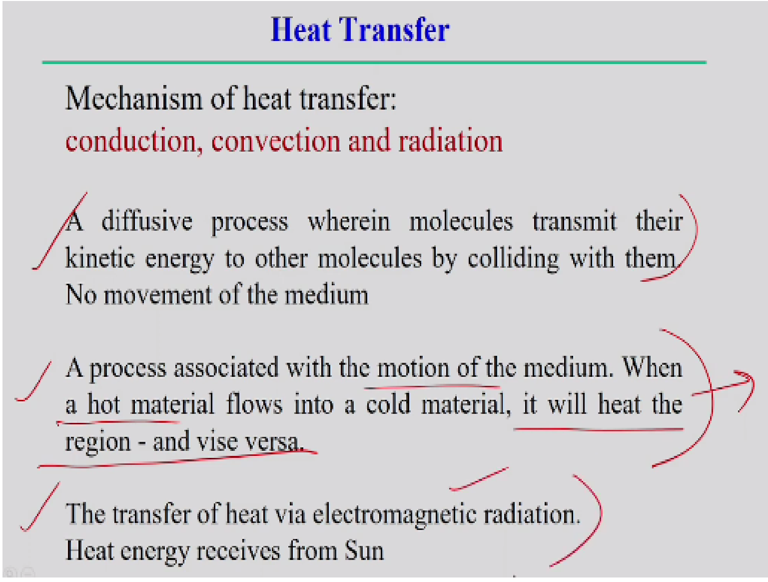

So heat transfer we know that heat transfer most of the manufacturing process it is associated with some amount of heat transfer either heat generates during this processes or maybe it coverts from the mechanical energy to the heat energy or in some manufacturing process some external heat is applied such that deformation of this particular process becomes easier. So anyway all the cases heat some sort of heat transfer is associated with most of the manufacturing processes.

We know that mechanism of heat transfer is basically 3 mechanism of heat transfer normally or 3 mode of the heat transfer exist the conduction mode, convection mode and the radiation mode this is the very basic mechanism of the heat transfer. So in conduction mode, heat transfer we can bookish definition we can say like that diffusive process definitely diffusive process within the molecule transmits, their kinetic energy from to other molecules by colliding with respect to each other.

So that is the definition of the conduction and of course when the heat conduction happens they needs a medium, but not necessary the medium will transfer from one point to another point. So no movement of the medium is necessary here if conduction mode of heat transfer is active. Apart from that convective flow or convection heat convection it is associated process associated with the motion of the medium.

So medium will carry some sort of the heat it is associated with the motion so when hot material flow into a cold material. So hot material flow into a cold material mix up so heat will transfer from the hot material to the hotter side to the cold side. So therefore the heat region and the vice-versa. Therefore, hot to cold so transfer the heat to the cold metal and temperature of the cold side will increase.

And then vice versa also similar to hot the temperature of the hot side the material will reduce. So therefore in this cases movement of the medium is the necessary condition so that in this mode of the heat transfer. Third mode of the heat transfer we can say that radiation. So in radiation mode the transfer of the heat via electromagnetic radiation so therefore in this cases not necessary their existence some kind of the medium that actually is responsible to transmit the heat from the source.

We can take example also the energy receives from the sun so that is the example of the radiative heat transfer. So it is not necessary there may not be any medium in between, but mode of the heat is transferred to the Sun to the Earth and through the electromagnetic radiation so this is the 3 mode of the heat transfer process now we can start with that.

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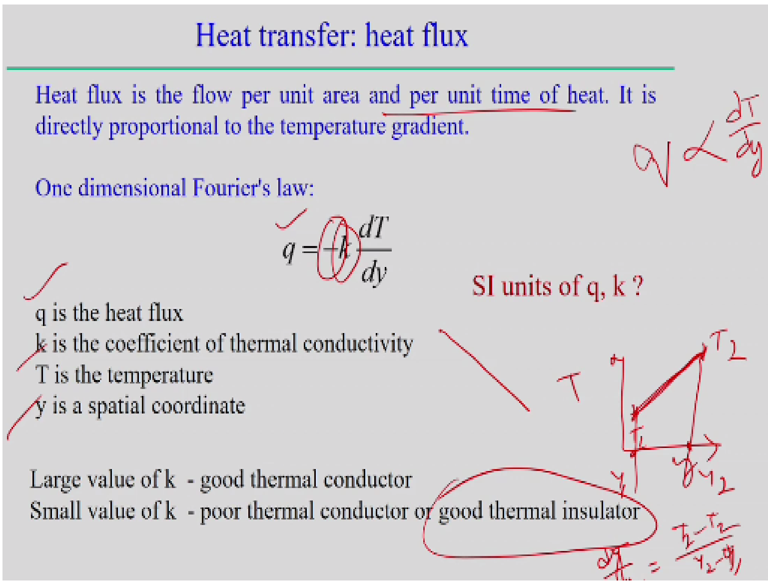

But what we try to analyze the heat transfer relevant to a particular manufacturing process then we need to define the heat flux. So if flux means we understand that either per unit volume or per unit area. So therefore also we can say that per unit time also. So it is directly proportional to the temperate gradient so that means if you say this is the heat flux here if you see that it is a per unit area so it is proportional to the temperature gradient.

Temperature gradient means over the space suppose this is the direction, this is the temperature so it indicates the constant line, this indicates the kind of the gradient. So if that gradient exist between say T1 T2 and this corresponding distance y1 y2 so that gradient basically T1-T2 and y2-y1. This is the Dt/dy this is the temperature gradient between these two points.

That means there must exist some amount o the temperature difference between these 2 points and if we assume it is a linear relation that means we assume that it is a linear curve joining between T1 and T2 and this distance between these 2 and this way we can estimate the temperature gradient. So heat flux is basically proportional to the temperature gradient, but we know the one dimensional Fourier heat conduction equation we can say.

This heat flux is proportional to this thing k is the constant of proportionality, but k is called the thermal conductivity or the coefficient of thermal conductivity. So coefficient of thermal conductivity k and q is the heat flux, T is the temperature y is the spatial coordinate. So therefore this thermal conductivity actually decides it depends on the it is a properties of the material basically.

So large value of the k maybe we can say the thermal conductivity is very high then it is a good thermal conductor. For example, the gold, maybe copper, aluminum having good thermal conductivity. So in that case the coefficient of thermal conductivity it is very high and otherwise small way of the k that means poor thermal conductivity or good thermal insulator.

So poor thermal conductivity means for example in case of stainless steel the thermal conductivity is relatively low as compared to the copper or gold or aluminum than in that case the thermal conductivity of this steel is less as compared to all this material. So some material having almost very low thermal conductivity so they can be used as an insulator. So therefore but here we can see the negative sign we have used.

When try to explain the one dimensional Fourier's law of heat conduction. This negative sign indicates that negative temperature gradient actually the heat flow from higher temperature to the lower temperature. So if it is higher temperature to the lower temperature it indicates the negative slope so because of the negative slope that – sign is used in this case. So actually the heat transfer occurs based on the Fourier's law of the heat conduction.

But if we take one element and within this element different mode of the heat transfer if we consider then we can develop the governing equation or 3 dimensional heat conduction equation.

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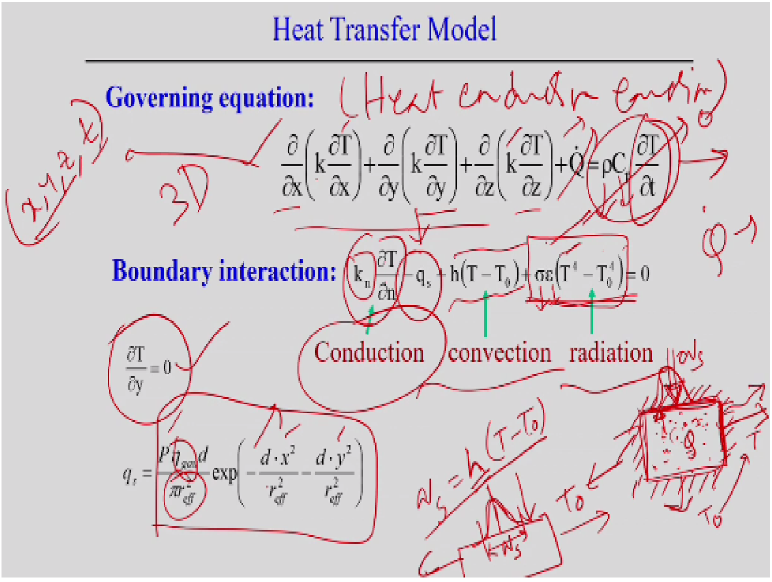

So we look into elemental analysis I am not going into much details how this equation differential equation has been developed, but it is well said that it is a government equation that means we can follow the heat conduction equation basically see this is called the heat conduction equation, conduction mode of heat transfer basically this is heat conduction equation and this conduction equation in 3 dimensional form.

This is the general form of this equation, but if we use this equation we can if we solve this equation then we can get the temperature distribution of a particular domain of the analysis interest. For example, we can take suppose this is the solution domain we are interested to know what are the temperature distribution at the different points may be. So in that cases if we assume it is a continuous medium within that we need to solve the heat conduction equation then we will be able to get the temperature distribution in this.

But of course any practical problem when we try to solve the heat conduction equation or any kind of the governing equation then there is a need to define some kind of the boundary conditions if it is transient problem then we need to define the initial condition that means time dependent value some value we need so then we will be able to solve this equation, but now we can look into this nature of this equation.

So k delta T/delta x so in this case similarly y and z direction. So definitely this is 3 dimensional equation so 3 dimensional equation and k is the thermal conductivity, T is the temperature and of course q dot we can use the internal heat generation term. So rate of internal heat generation per unit volume per unit time. So that q dot is we can say it is a volumetric heat generation term.

So some practical problem is associated with the heat generation so we can in that cases we can use this term and we can solve this equation to get the temperature distribution and right hand side indicates the rho is the density of a particular material CP is the specific heat of the particular material and this is the temperature change. So here we can see that both spatial as well as temporal variables involved. So here we can see that x, y, z as well as the t.

So this spatial variable and temporal variable so time so if we use the time dependent problem then we can use this equation, but if it is a steady state problem then we can neglect this term this can become 0 such that it becomes the steady state and if we want to neglect the heat generation term if there is no heat generation then we can reduce this terminology q dot can be 0 in this particular process.

We can modify the equation depending upon the problem and we can consider the terms looking into the actual problem. Now whatever we can put the boundary interaction definitely what is the boundary condition means definitely what are the boundary interaction is happening of a particular domain that we need to define and of course if we try to some sort of heat input or heat flux to the domain can be there.

This is the (()) (13:42) heat flux to the domain then only if we solve the heat conduct based on the heat conduct heat will be conducted and we get the some temperature (()) (13:50) will be there, but at the same time from this domain from the boundary there may be loss of the heat. So that heat loss can be in terms of radiation that radiative heat loss can be estimated like this, this term but this is not the stress ter.

And that this is the emissivity and I think sigma is the Stefan–Boltzmann constant that T is the 4^{th} power temperature and T0 is the ambient temperature. So therefore if T0 is the initial temperature and with the application of the heat flux some temperature will be developed and on the surface maybe the temperature raise to T. So therefore T to the power 4- T0 to the power 4 represents and multiply this constant terms that represents the radiative heat loss.

So this integrates the radiative heat loss. Similarly, qs it represents h*T-T0 this represents that sorry this T0 is basically the outside temperature, ambient temperature and T is on the surface temperature. So therefore this T and T0 based on that difference will be the radiative heat loss and convective heat loss or convection means the convective heat transfer coefficient this h heat transfer coefficient.

And of course the temperature and the surface T and T0 is the outside ambient temperature so that T-T0 is the convective heat loss can be estimated by this. So this will be from all the surface radiative as well as the convective heat loss will be there from the surface this is the boundary interaction during the process it happens and of course this qs is the applied heat flux to the domain that is the input to the solution domain.

And this we can say the output so that looking into the sign convention and this k if we look into the balance the conduction means this conduction delT/delta n and the this is the conductivity of a particular material. So this term is actually defined on the surface actually. So thus surface means from here generation what will be the heat conduction to the surface that at the same time on the interaction on the surface the heat conducted to the surface.

And from the surface heat loss from the surface and this is the heat input from the internal source that is from the external source this is the heat input to the domain. So in actual problem or maybe some specific (()) (16:30) there may be some internal heat generation also q dot so therefore within this we can incorporate the q dot also. Now looking into the problem if you mathematically define the solution domain.

And on that domain we can see what is the input any kind of the heat flux or volumetric heat generation is there or not. Looking into that we can give accordingly we can consider the equation accordingly or we can modify the equation accordingly and then of course at the same time to the domain there must be some amount of the heat loss if there is a temperature difference from the surface this to the ambient temperature outside temperate.

If there is a difference then there must be some amount of the loss, but that loss heat loss can be represented in the 2 modes one is the radiative heat loss or another is the convective heat loss. So if we incorporate the radiative heat loss, convective heat loss from the surface and of course conduction happens within this material, but this conduction is exactly defined on the surface actually so that make a balance during the boundary interaction of the particular manufacturing process.

Now sometimes you put the symmetric boundary condition delta T/del y=0 it may be like that, that if solution domain is symmetric in nature so we can consider we can reduce the solution domain and on the symmetric surface we can simply put the flux=0 in that way we can incorporate this equation also. We can give some example also that what is the input in case of specific welding process this is the distributed heat source we can put that a surface heat flux and that surface heat flux can be like this.

It is a kind of distribution so this is the domain, boundary of the domain so it is interaction like arc is interactive with this so this is the distributed heat flux. So this heat flux is not constant it is a varying and this is the (()) (18:26) means the effective means the effective distance within this distance it is varying are effective distribution coefficients that means the distribution whether it is very stiff or very flat based on that the value can be decided.

X and y is the variable here and this is the effective radius it is the power input to the domain and of course this is the Gaussian efficiency of a particular situation in that case we can define that what is the input to the solution domain and if we solve it with this input accordingly the output and then we can get the solution of the equation in terms of the temperature distribution.

So it is very clear that according to the different manufacturing processes we can define the solution domain and solution domain simply we apply the governing equation in this cases if we stick to the analysis of the heat conduction we use that heat conduction equation then we put the appropriate boundary conditions. So along with the governing equation and boundary conditions the system of the equation we can solve it.

And this solution can be possible by analytical solution, but analytical solution lot of assumptions are required or this solution can be numerically, can be numerically done both way solution can be done and then we can get the solution output as a distribution of the temperature. So therefore heat transfer model specifically heat conduction model gives the output in terms of only the temperature distribution.

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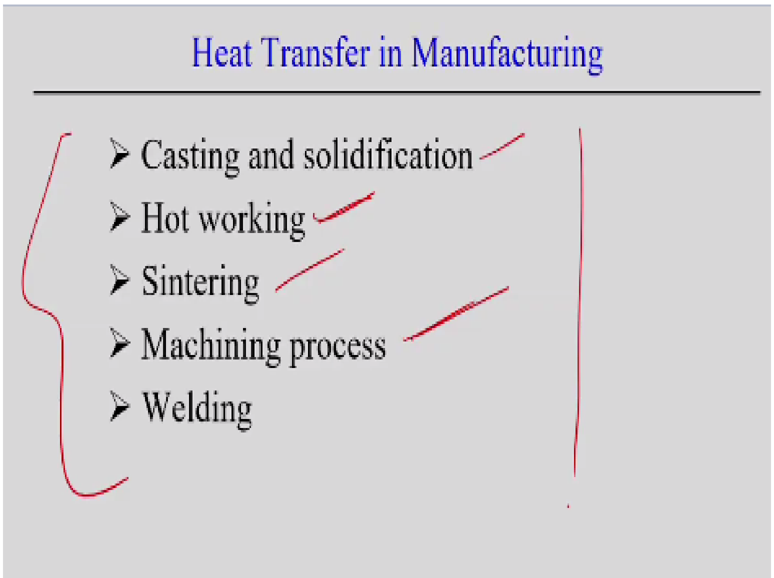

Now if we look into the heat transferring different manufacturing process we see that heat transfer is associated with the different manufacturing process for example casting and solidification, hot working process or maybe in that cases we can say the metal in general metal forming process, but cold metal forming and hot metal forming process cold metal forming process due to the cold deformation.

There may be heat generation will be there, but that amount of the heat generation is very small and of course, but in hot working process we normally apply the heat externally and anyway it is associated with some amount of the heat transfer during this manufacturing process even in sintering process also some sort of heat transfer is involved here and machining process also there.

Because in machining process it is possible to conversation of the external mechanical energy that converted to the heat energy and in terms of the temperature distribution get the output and of course. So a machining process it is associated with some amount of the heat transfer mechanism also and even welding process also. In welding process definitely in fusion welding process it is associated with heat transfer and all this cases we can solve the if you know the basic governing equation Fourier heat conduction model we can apply there.

But of course all this cases the boundary interaction may be different and maybe some cases internal heat generation may be there and some cases may not be there. So best we can define the problem accordingly and we can solve this different manufacturing process.

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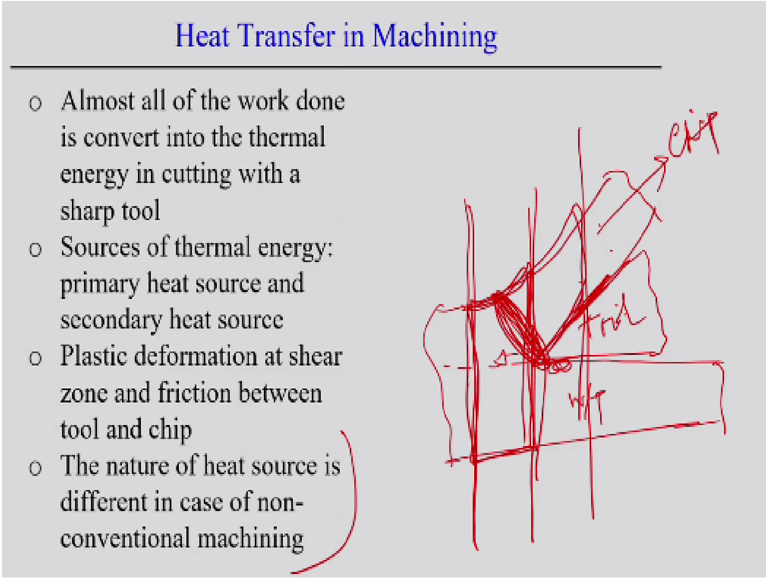

Now we look into some heat transfer in machining process some overall view on that. Almost all work done in during the metal cutting process that converted into the thermal energy and because in metal cutting process we attach the tool and we wrote the work piece material and sharp tool cut the sample. So some sort of mechanical energy are giving the input for that mechanical energy almost is converted to the heat energy.

But if we look into the typical deformation process tool this is the work piece and suppose it is moving particular velocity. So in metal cutting process when this is cutting the tool and this is the chip formation chip form, but in this cases we can see the source of the thermal energy is basically primary heat source. So this is the primary heat source the shear deformation actually happens in this shearing happen at this particular zone.

So then due to the shearing action shear deformation that is converted to the heat energy this is called the primary heat source during the machining process and of course and between the tool and the chip some kind of the frictional heat generation also there so that is called the normally called the secondary heat source. So between here also some friction happens and friction is responsible for the generation of the heat.

So between chip and tool some amount of the frictional heat generation also there. So all this mechanical energy is first primary heat zone primary zone heat source for primary deformation zone actually we can get the primary heat source this is the secondary source of course in other part the (()) (23:28) some amount of the heat is also generated. So therefore plastic deformation happens at the shear zone and friction normally happens between the tool and the chip.

So they all generate the heat during this process, but the nature of the heat source in case of the non conventional machining process in non conventional machining process the nature of the heat source are different and of course intensity of the heat development in non conventional machining process are also different as compared to the conventional machining process.

So therefore if we define the zone of interest and then we can do the heat transfer analysis just we define the first we define the solution domain for example this may be the solution domain or we just skip the tool part or maybe we can keep in this way deformation zone. So this is the solution domain, this one is the domain within this solution domain we apply the heat conduction equation.

And with the appropriate boundary condition if we solve we can get the temperature distribution of this domain of interest and which domain we are in of interest we have fixed the domain of interest then accordingly we can apply the heat conduction equation we get the solution of this equation and the solution will give the output of the temperature distribution of this particular zone.

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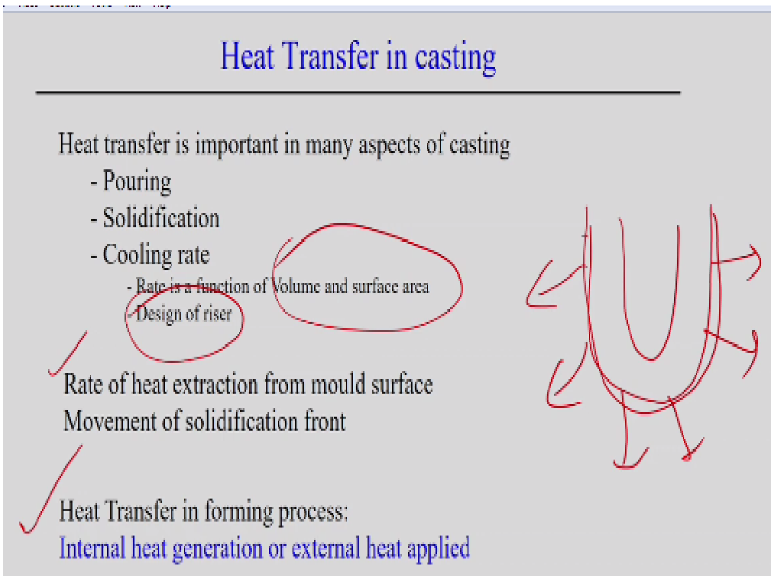

In casting also because casting process the heat transfer is most important aspect because in casting process we first melt the material then we pour the metal into the cavity and then of course after pouring the metal there maybe the solidification happens, the solidification is the most important aspect in casting process and of course apart from that rate of the cooling that is also important.

And that is more associated with the heat transfer mechanism in the casting process and this rate of the cooling is associated with the function of the volume and surface area with a cavity or filling or runner riser we are used in this cases. So based on that heat transfer heat transfer actually it is possible to design the riser because the in casting what is the filling time and what is the solidification time is more important to estimate in casting process.

And based on that we can precise the design of a casting system because in casting process we cannot directly pour the molten material to the cavity we have to go through some kind of the gating system, runner system then we have to put the riser also and apart from that the main mold cavity. So all are part of the through the molten material flow actually all this path and then finally it fill the molten cavity.

But in this case if you look into all this aspect and if we analyze the heat transfer and basically the solidification time that means time to start the solidification process so how long the metal becomes in the molten state that is also important in case of casting process. So all this calculation is possible to know or possible to do if we do the heat transfer analysis associated with this process.

So of course that is why rate of heat extraction from the mold sometimes the mold (()) (26:47) so suppose this is the cavity so the solidification depends what way it extract the heat to the mold it (()) (26:56) mold material. Therefore, this rate of heat traction is most important to calculate in the casting process and of course once solidification starts then what way the solidification front moves all these are typical features of the casting process.

We try to we may look into the modeling aspect all these things and which is associated with the heat transfer in casting processes of course apart from the casting process. So in case of forming process also it is associated some amount of the heat generation and that heat generation either external heat is applied because in metal forming processes associated with the deformation process.

That deformation can be done at very low standard or deformation can be done at very standard. So therefore when there is a high standard deformation happens so some amount of the heat generates during this deformation process that means mechanical work is converted to some amount of the heat energy apart from the plastic flow of the material. So therefore that is called the internal heat generation (()) (28:01) metal forming process.

But in case of the hot forming process it is necessary to apply the heat externally to soft the material such that flow availability of the material can be improved, but of course all can be heat applying such that it should be below the melting point temperature. So therefore in that cases hot forming process we can treat this as a external heat is applied to this process. So therefore heat transfer mechanism heat transfer also associated with this kind of the manufacturing process.

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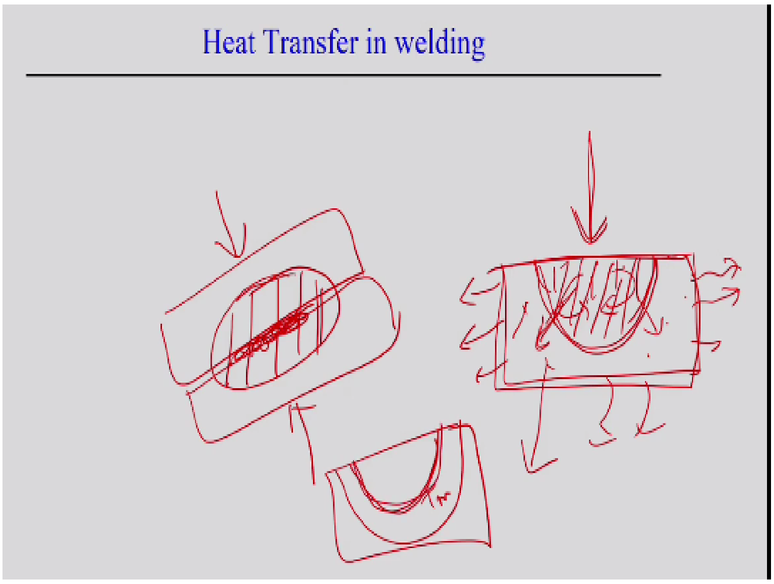

Now even heat transfer in welding also it is we can see even welding process if you see the fusion welding process. So in fusion welding process we can see that suppose this is the work piece material we apply the create the arc or laser on the surface when you put the laser arc on the surface then it melts the material and this is the molten material, but the other part become solid.

So therefore heat is once creates the molten material so heat is from molten metal to the outside we conducted away if we assume this molten material is a steel molten material so heat is conducted to this medium, but of course if it is flow of the molten material then convective mode of the heat transfer will become active then heat is conducted here and once in the surface it comes then heat loss through the convection and radiation term of course loss through conduction and radiation term.

And this molten material and this thing and of course once the heat source moves away from the particular position then that try to solidify the component. So therefore after application of the heating it solidify and after solidification some lot of structural changes normally happens metrological changes also happens during this process then after solidification we can get the solidity part of this component.

But heat transfer is associated with that some heat is supplied either in the form of the arc, laser or if it s resistance welding also. So resistive in case of resistance spot welding so in between the contact resistance is responsible here and that actually generates the this resistance actually generates the heat. So then when electric current it passes through then contact resistance generates the heat.

And it creates the molten pool between these 2 sub part of surface and these 2 component and after solidification this 2 components join. So therefore heat transfer is all these cases heat transfer is basically associated with this type of manufacturing process and of course both the cases we can solve the heat conduction equation, but heat conduction equation if we solve it this is the liquid medium, this is the solid medium.

But total domain we solve the heat conduction equation with the appropriate boundary condition just we have discussed along with the boundary condition if we solve this we can get the temperature distribution and that temperature distribution gives that if we solve it heat conduction equation it gives a temperature disturbance and isocontour in this profile and that this is the melting profile.

For example, this is the melting temperature and this is some heat phase some lower solid state phase transformation temperature so that constant isotherm, isocontour that actually define the weld full shape and size from the mathematical model.

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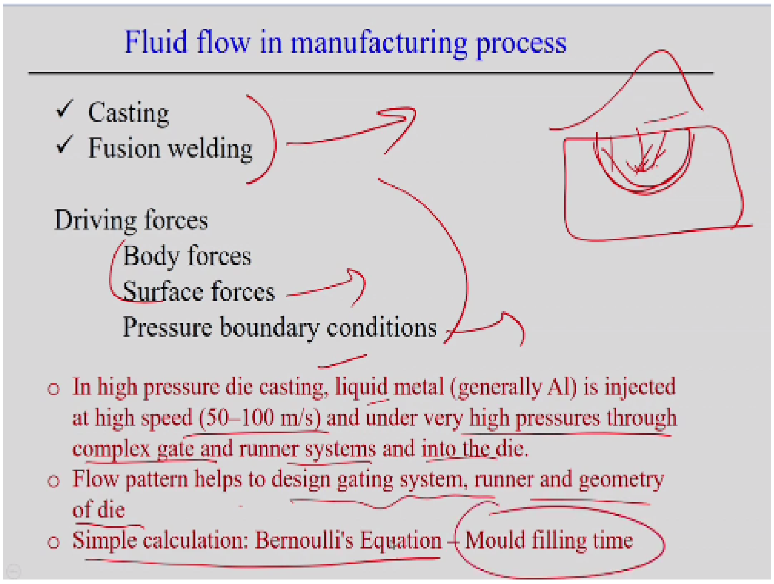

Now apart from the heat transfer we can look into the fluid flowing manufacturing process also In fluid flowing manufacturing process we can see casting and fusion welding is mostly associated with the material flow, but the material flow, flow of the molten material is basically not most of the manufacturing processes not only the pure fluid flow happens rather we can say the heat transfer and fluid flow happens together.

So in casting process also there is a continuous flow of the material at the different domain at that flow potential line by the streamline we can define the flow potential of a particular during the flow potential of liquid metal. Even in fusion welding process it is associated with the fluid flow also, but of course the material flow even if we look into the fluid flow also this small weld pool this liquid metal creates, but it flow in particular driven by the driving forces.

So this driving forces can be body forces that means forces for example Bauschinger sorry this is this body force (()) (33:00) approximation we can see that this is the body force is normally acting and here and apart from that body force surface force also drive the material for example surface tension is mostly responsible to drive the liquid material in a particular directions.

And of course in casting process also apart from that some inlet and outlet pressure, condition pressure distribution also act as a boundary interaction that also we can say the pressure boundary condition if we put it then we can which is applicable in case of the casting process. So the governing equation solve and we can get the field velocity field basically, but if we solve the combine heat conduction and heat transfer as well the fluid flow phenomena if we look into it in that cases the output is the velocity field as well as temperature field.

But the driving force is associated with a particular manufacturing processes for example in case of welding process the driving forces are the electro in case of arc welding it is a electromagnetic force and that acts as a body force. Surface active elements that actually treated is the surface forces we can say that surface acting element is represented in terms of the shear force acting on the surface between these 2 medium liquid and liquid medium.

And in case of gas that means the model can be represent interest of the surface tension force that is acting and of course casting is mostly associated with the spatial boundary condition to get the material flow field. Now if we look into the high pressure die casting process liquid metal mostly aluminum is injected that is a very high speed and of course under high pressure through the complex gate and the runner system into the die.

So therefore in this cases this pressure conditions can be represented in terms of the special boundary condition we can get the velocity field by solving the governing equation. Apart from that flow pattern helps actually design the gating system runner and geometry of the die actually why you are interested to solve this flow field in case of the casting process because that actually helps to design the gating system, size, shape of the runner and shape of the die also.

That is that so we need to know what are the different flow field exist in case of the casting process and sometimes if we want to know what is the filling time simply we can solve the Bernoulli equation, MAG equation and that helps to estimate the mould filling time in case of the casting process.

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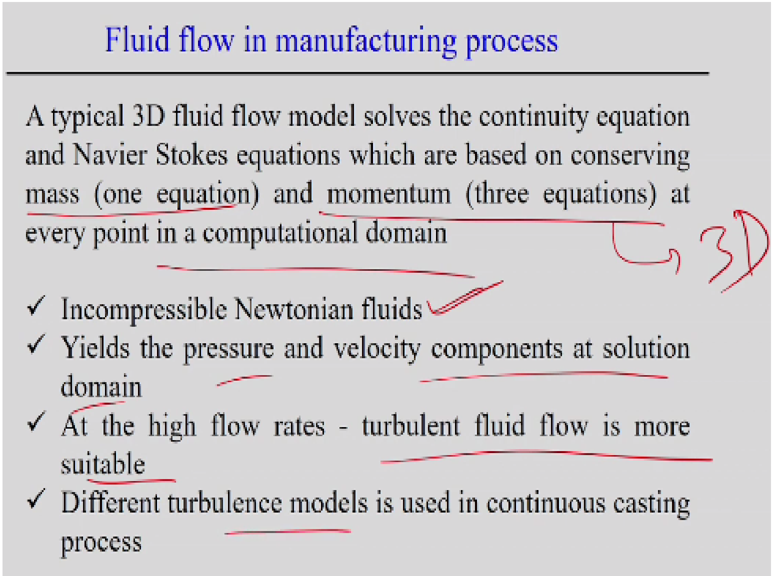

Now typical 3D fluid flow model if you try to develop it actually solve the Navier's stokes equation and which is based on the conservation of the mass and momentum equation. So mass one mass equation and basically 3 momentum equation because it is 3 dimensional so momentum in x, y and z directions we can solve it and we can get the fill all this things and within the computational domain.

But to solve apply of this equation definitely we need to know whether behavior of the liquid metal incompressible Newtonian fluid can be assumed then we can solve this equation then of course yields the pressure and the velocity component at the solution domain output as the pressure field as well as the velocity field that gives output if we try to solve the Navier's stoke equation.

Of course if the flow rate is very high then we need to incorporate the turbulent flow model. So when we look into the turbulent fluid flow model is more suitable, but in this cases we need to incorporate the extra, we need to solve the extra equation turbulence equation we need to solve to get predict the turbulent flow of the liquid metal during this fluid flow analysis of different turbulent models actually exist in case of continuous casting process.

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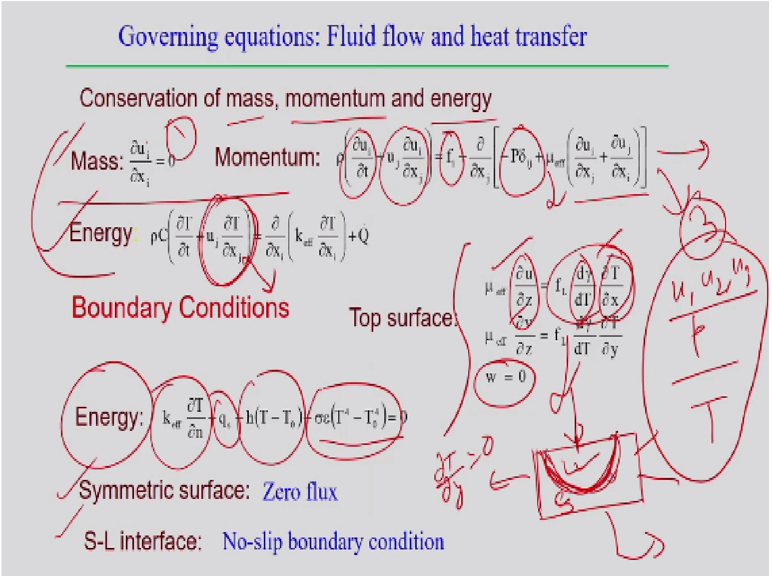

Now look into the governing equation we can see the conservation of the mass, momentum, energy most of the equation we normally combine fluid flow and the heat transfer model if we try to develop then we need to solve conservation of the mass, momentum and energy equation. So this is the mass conservation equation, velocity gradient delta ui/delxi=0 and this is the momentum equation, this is the convective term.

And this is the velocity with respect to time, this is the body force terminology we can incorporate here, this is the pressure term here and thus it is the effective viscosity and this is the velocity gradient and of course this is the typical nature of the well known Navier's stoke equation. So if we solve this equation of course here you can see that this momentum equation we have 3 equations and one equation and 4 equations we have.

But here we have the variable 3 variable, u1, u2, u3 and pressure that means 4 variables actually 3 velocity component and 1 pressure. So of course 4 equations are there and 4 variables are there we can easily solve this equation, but difficulty is that this pressure term is not associated with the mass conservation equation. So therefore I would say not straight forwardly we can solve this equation and getting all this variable.

So some specific strategy are developed and some numerical techniques also developed to get the both the velocity fill as well as the pressure fill from the Navier stoke equation. This equation we can say the governing equation if we try to combine the heat transfer fluid flow analysis, but this is the energy equation. So this energy equation is actually different from the heat conduction equation only this term are different from the heat conduction equation.

Because this term actually comes from the velocity components convective the heat transport by the flow of the liquid metal. So therefore this term we can incorporate in the energy equation and of course this is important when you would analyze the fluid flow analysis then only we can incorporate this terminology energy equation otherwise if you do only the if there is no fluid flow analysis if you do the only heat transfer analysis.

Then you do not consider this terminology because we do not have this velocity field here, but apart from that we can this energy equation conservation we can get the complete velocity field as well as the temperature field we can get the output, but of course the boundary condition is also important in all this cases. So boundary condition is important in the sense that in the top surface.

If we assume this is the flat surface for example in case of welding process it is liquid molten metal. So within this domain we can solve the conservation of the mass and momentum, energy all this equation, but outside this domain we can use the only heat conduction equation to get the temperature distribution, but within this domain we can solve this energy equation, incorporate the effect of the metal flow field.

So therefore here transfer is effected by the molten material flow field. So that is incorporated using this term here. Now if this is the case so how we can incorporate the boundary conditions. So first is on the top surface there is interaction of the shielding gas and the liquid (()) (40:32) 2 different medium. So therefore they must act some amount of the surface tension force, but surface tension force if you assume it is a flat surface.

Then velocity component normal to the surface=0 so whatever velocity component will be in the x and y component not in a normal component, but this is balanced the velocity gradient if you see it is balanced with the it is a basically surface tension model from the surface tension coefficient temperature gradient and it is the shear force basically this particular 2 direction this is the shear force.

They match the shear force from the surface tension force on this thing make the balance this act as a boundary condition on the top surface. Of course energy equation we have already discussed the energy equation this is the radiation loss from the surface, radiation due to radiation and convection and this is the heat input to the domain and this is the heat conduction exactly defined on the surface only.

See if there is any symmetric surface we simply put the zero flux that means gradient normal to the particular gradient along this direction=0. For example, if you see the symmetric with respect to y so then we can say delT/del y=0. And of course at the solid liquid interface so this is the liquid component and this is the solid part and this is the liquid part. So at this interface we can put the mostly boundary condition it is a simply velocity component becomes 0 this surface.

So these are the typical interpretation of the governing equation when you try to do some kind of the fluid flow and heat transfer analysis and their corresponding boundary condition need to be defined that we can analyze or in general we can analyze a boundary conditions and modification of the governing equation can be done according to the problem we are interested.

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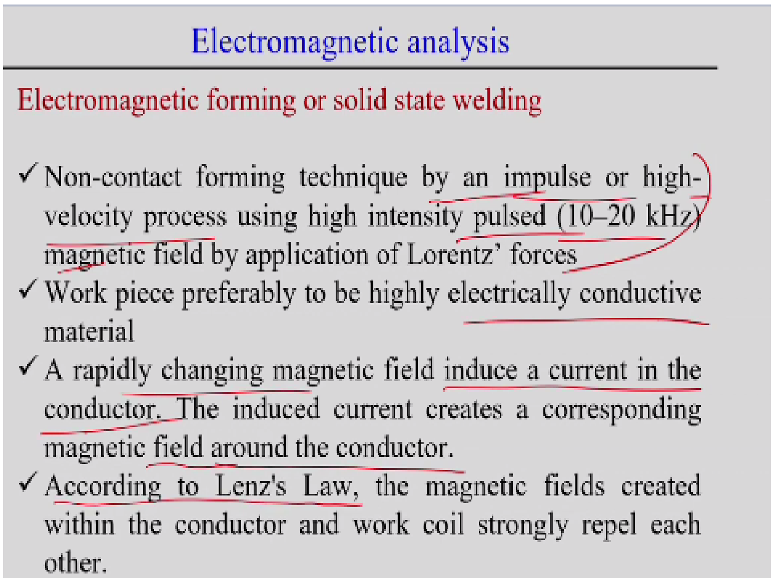

Now we look into that electromagnetic analysis also so electromagnetic analysis in the manufacturing point in most of the cases either we can use most of the process develop using the electromagnetic analysis that is the electromagnetic forming and that is a pulse mode we can say the pulse electromagnetic forming or this can be forming can be extended to the solid state welding processes or other mode is the induction heating.

So induction heating also we can use for the different types of the manufacturing process or can be some allied manufacturing processes or to modify the manufacturing processes. So first into the electromagnetic forming or solid state welding process. So electromagnetic forming is basically non contact process is the one advantage or by an impulse or high velocity process.

So basically it is a forming process, but it is a very impulse it creates the very high impulse or high velocity process impact using the high intensity pulse magnetic field. So that pulse maybe 10 to 20 kilohertz pulse magnetic field we can use and with the application of Lorentz forces in principle and this follows to develop the electromagnetic forming process. So therefore definitely in this process the work piece must be preferably very high.

It should be electrically conductive material, but of course if it is not electrically conductive material there maybe the process can be modify different way, but in principle it should be electrically conducted to apply this process. In principle the rapidly changing the magnetic field with the application because we use a very high pulse, high frequency pulse magnetic field here that actually induce some amount of current in the conductor.

So when you apply the high frequency magnetic pulse it creates the current in the conductor, but at the same time the induced current also creates corresponding magnetic field around the conductor. So therefore this according to the Lenz's Law this magnetic field actually create some kind of the within the conductor and the work coil from which we create the magnetic field.

That work coil and conductor that creates the strongly ripple force and they can be deform in a particular shape or by tactfully you can use this repel force in such way that 2 components can be joined in the solid state deformation process. So that is the basic philosophy of a electromagnetic forming or we can say the solid state welding process.

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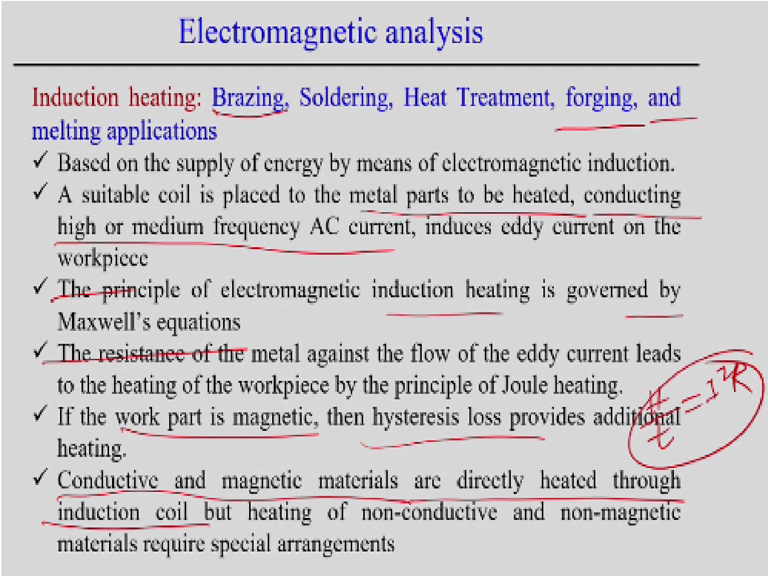

Similarly, electromagnetic analysis can also be used other way that is the called the induction heating. In induction heating we can find out so many manufacturing process even brazing process, soldering process also different heat treatment process we can use the induction heating also, forging process we can use the induction heating even for the melting application.

That means by application of the induction heating we can melt the work piece material and in a manufacturing process so that in that process the induction welding process has been developed. So therefore the principle based on the supply of the energy by means of the electromagnetic in principle supply of the energy is basically use the electromagnetic induction principle here.

So definitely first step should be use on coil that is placed on the metal parts the metal parts which part we supposed to heat and of course conducting high or medium frequency AC current. So we pass the high and medium frequency AC current and that AC current induce some amount of the eddy current on the workpiece material. So that eddy current those are the principle of the electromagnetic induction heating is governed by the Maxwell equation.

So their formation of the eddy current that follow the principle of the Maxwell equation. So once there is a formation of the eddy current and that resistance of the workpiece material against the eddy current generate some amount of the heat and that follow the principle of the joule heating. So this similar principle what we can observe in case of the resistance welding process also.

So there also some passes through the electrical current and that creates some kind of resistance at the contact surface and the resistance generates the heat in the principle of the joule heating. So therefore here also principle of the joule heating is responsible to induce and by the application of the magnetic pulse sorry magnetic medium frequency AC current that creates the electromagnetic induction.

And that electromagnetic induction actually creates the eddy current and that resistance of the eddy current generates the amount of the heat by following the principle of the joule heating of course if the work part is also magnetic then some kind of the hysteresis loss provides additional heating to the workpiece material. So therefore conductive and magnetic material are normally used for this processes.

But are directly heated through the induction coil, but heating of the non magnetic and non conductive material some kind of the special technique or special arrangement also needed to apply the principle of the electromagnetic induction to develop any kind of the manufacturing process. So actually induction heating is the most kind of heat source available and by controlling the design of the coil.

And of course this other parameter for example AC current frequency we can control the depth of heating in a particular manufacturing process. So in this module I just try to look into the different aspects of the heat transfer and the fluid flow and how, what we can apply in the manufacturing process and apart from that what is the importance of the electromagnetic that also actually helps to develop the different manufacturing process.

Just I discuss in principle words I have tried to produce some kind of the overview view of all this different mechanism and that normally used or in the perspective of the different manufacturing processes. So thank you very much for your kind attention.