Mathematical Modelling of Manufacturing Processes
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Indian Institute of Technology – Guwahati

Lecture – 20
Physics of Welding and Metal Transfer

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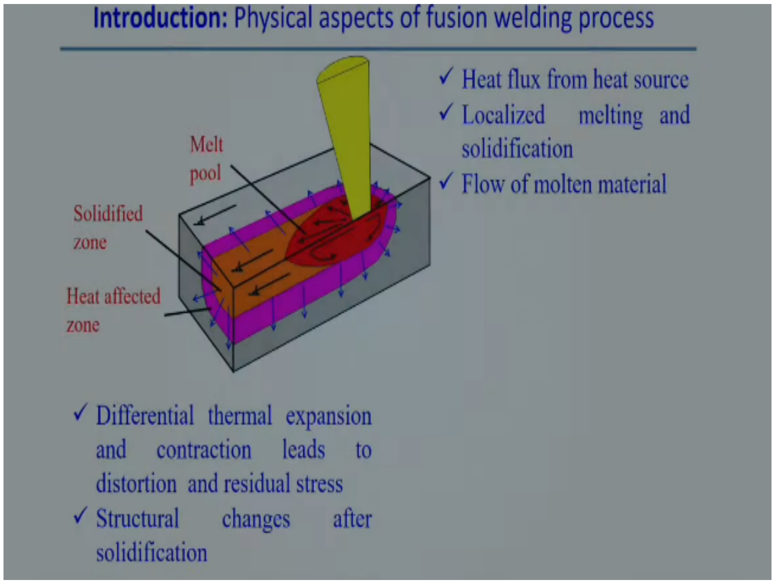

Good morning everybody, today we will start the physical aspects of the fusion welding process. So we have studied so far the different types of the fusion welding processes, advantage disadvantage and specifically application area. We say get some broad knowledge about the different types of the fusion welding processes. Now we will look into that the physical aspects involved in fusion welding process.

So physical aspects normally we can explain in terms of the how the temperature distribution material flow actually happens within the small oil pool or of course if there is a addition of the filler material then how it impact to the domain in terms of the flip in terms of the material flow and of course the at the same time the size of the solution domain. So we will look into all these aspects.

But definitely the objective is to in fusion welding process to first to in general to estimate what is the temperature distribution in the solution domain because that temperature distribution actually helps to estimate the cooling rate associated with this fusion welding process and that cooling rate can be finally integrated with the what is the type of metallurgical phenomena happens or microstructure relevant things can be explained better in terms of the rate of the cooling.

But to estimate the rate of the cooling we need to know what is the transient distribution of the temperature either in transient state or can be steady state. But before doing that what are the physics involved in the fusion welding process.

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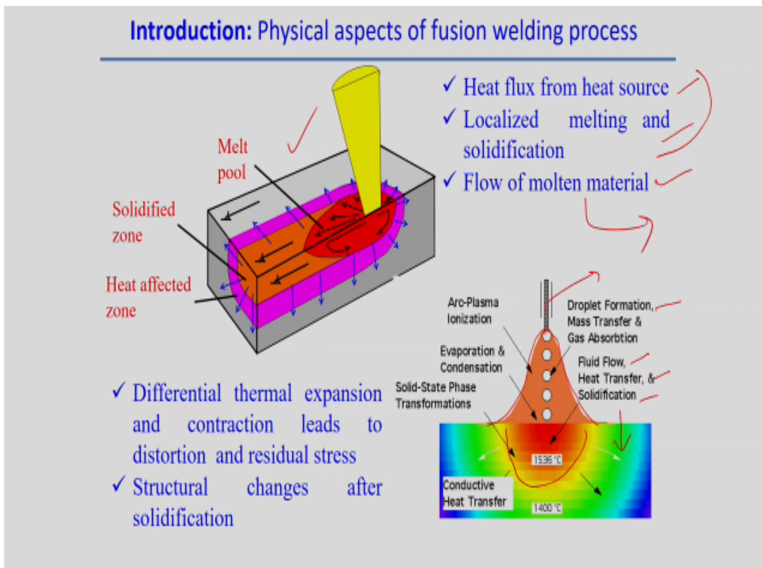

If we look into this figure, here we see there is a domain that is plate and there is a application of the heat flux so that application of the heat flux can be come from the source, it can be laser it can be arc, it can be electron beam or any other kind of the source can be used. So here see with the application of the heat flux to the domain what happens? part of this thing is melts basically it is creates some kind of molten zone and that we say it is a molten pool.

But once we move the heat source in case of linear welding process one point to another point what happens. This almost Quasi steady state situation arises and this we can get at any section is a similar size of the oil pool. But at the same time the solidification subsequent solidification of already molten material it also starts once we move the heat source from one point to the another point.

So here we see formation of the melt pool, subsequent solidification and finally there is a some heat affected zones it is creates and that heat affected zones can be identified what are the structural changes actually happen with the application of the heat flux or after the solidification. So that we normally measure what is the size of the oil pool, what is the size of the heat affected zone with the application of this.

These are the interest to know in any kind of the welding process. So first it is that part is the heat flux from the heat source then localized melting and solidification and of course within the molten pool there is a flow of the molten material. Most of the time, we normally neglect the flow of the molten material because it is needs expensive computational effort to estimate the material flow within the small oil pool.

So if we use some kind of the heat conduction equation and we will be able to explain the temperature distribution. But in that cases we assume that the molten metal is there but it is a the flow of the molten actually we neglect. So it needs to so the fluid flow phenomena which is associated with the molten melted during the welding process. This part but apart from that once the molten pool creates and then subsequently it solidify.

Then finally it creates some amount of the stress generation inside the oil pool. That states generation due to the differential thermal expansion and contraction and that actually leads to some sort of residual stress or kind of distortion in a final oil structure. So therefore apart from the only heat transfer, the analysis of the stress definitely the consequence the analysis of the ones who do the analysis of the stress the consequence effect there is a outcome in terms of the distortion as well.

So in that case we need to know that distortion analysis with the effect of the temperature distribution. So other way temperature distribution also helps to estimate the residual stress and distortion in a welded structure. So all these matters are relevant to the temperature distribution of course as well as the material flow behavior here also.

Now if we show other type of welding process. So first one it was an autogenous fusion welding process, the second one is the there is a some metal transfer. So it is may be if we use some electrode we can see what are the physical phenomena actually happens during this process. So from the electrode there is a metal transfer in the forms of the droplet and droplet actually transport to the domain and if we see that this is a domain also arc-plasma ionization.

So arc if it creates the arc, there is some domain so that domain there is a plasma formation actually happens in that zone and of course there is a possibility of the temperature is very high the maximum temperature is above the vaporization temperature. Then there may be the evaporation may also happen of the material.

So then droplet form and then mass transfer also happens to the domain and of course that molten droplet can absorb some kind of gas also and finally we can see the heat flow sorry fluid flow heat transfer and solidification within associated with these domain. But this domain is associated with the formation of the molten droplet and transferred this molten droplet to the solution domain.

Or of course in the heat affected zone there is a some solid-state phase transformation also happen. So that needs some kind of the metallurgical phenomena or metallurgical effect associated with the fusion welding process. And finally from the boundary we can see that there is a continuous heat loss by convection and radiation. So there may be the different approaches of modeling all these things.

So maybe one approach may be heat transfer, second may be the stress analysis part and third maybe some to capture the different kind of microstructural changes or metallurgical phenomena. So metallurgical model can also be done in fusion welding process and of course it becomes more complicated and it is associated some kind of material filler, filler material that forms a droplet and transfer to the domain.

So in that cases the modeling approach can be different when there is a metal transfer to the solution domain. But all in general we have a more simplified way to do the modeling approach using the domain, first we fixed a domain and then from the within the domain what is the interaction through the boundary happens. So interaction of the boundary happens with the application of the heat flux.

If we neglect the metal transfer phenomena, so if there is a application of the heat flux that interact through the domain boundary. But that heat flux that we can say the heat source modeling we represents there is a different mathematical form of this heat flux also exist. So that representation of heat source is the other phenomena. So we normally use some geometric shape and size and that we represents that total volumetric heat generation within the geometrics.

Let us say in general it is called the volumetric heat source model and sometimes we use the surface heat source model so in specific cases and the depth of penetration is not very high. Probably we can use the surface heat source model but that is a very simple model most of the cases we use the volumetric heat source model, so that is the one part.

So once we know the boundary interaction then what happens? then we once fixing the solution domain we solve the in general the heat conduction equation and the output as a temperature distribution. Similarly, if we use a constituent relation between stress strain and if we assuming as a thermal strain as input to the domain and output can be the distortion and residual stress in a welded structure.

So that is the we can say the stress analysis model relevant to the welding and third may be the material flow. If we consider the within the small oil pool but then molten flow is if we consider the driving force to drive the molten material maybe electromagnetic force in case of arc-welding process buoyancy force.

If there is a temperature difference from in the because of temperature difference, we can assume there is a density differences and that gives the buoyancy force. And of course the surface tension force because the arc is interact with the molten pool the two different medium when interacting at the interface there may be the surface tension force. So based on the surface tension force, buoyancy force and electromagnetic force these are the driving forces that drive some molten material flow.

So if considering all this we can it is also possible to estimate the fluid flow behavior or maybe flow pattern inside the small oil pool.

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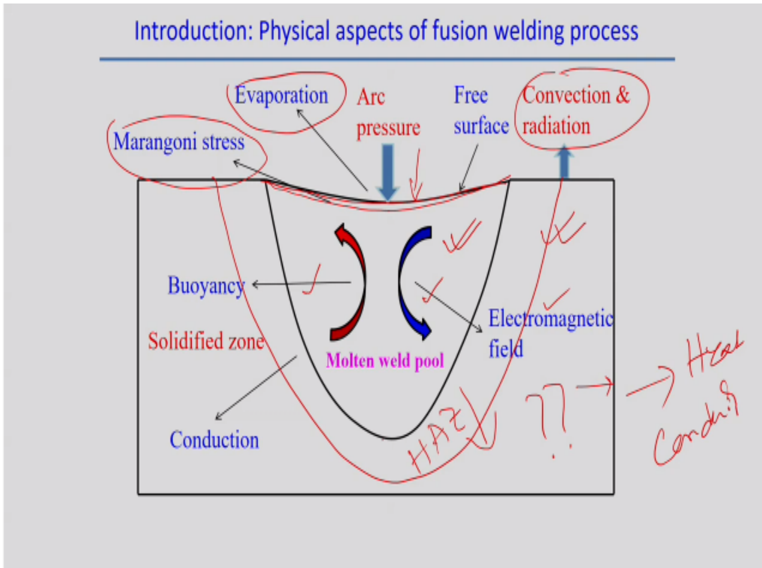

So here we can see that in physical aspects of the fission welding process what are the physical phenomena actually occurs in domain it should be more clear where it can be given or more elaborately we can say that. First suppose this is the domain which domain of interest through which we want to analyze the temperature distribution metal flow and stress analysis or maybe distortion field.

In this case first it creates at a point there is a molten pool so what within the molten pool molten material pool there is a buoyancy force. Because there is a density difference at the bottom and the top, temperature difference also there that creates the buoyancy force. Then of course electromagnetic force, so if there is a flow of the current and of course the in case of electromagnetic force is basically associated with the arc welding process.

So laser welding process there is no electromagnetic force we do not consider. But in arc welding process, there is a flow of the current it creates some electromagnetic field. Then that electromagnetic field actually influence the material flow behavior and specifically that material flow behavior is over a volume so that so we can say the volumetric force electromagnetic field that influence the material flow.

And other is the Marangoni stress that comes due to the surface tension force the interaction between the arc and the molten pool. So surface tension force act there is a several surface tension force model that we represent we say that is called is the Marangoni shear stress acting what way on the surface. So that definitely the Marangoni stress is acting only on the surface. So that surface the stress is there.

So these three are the driving force to drive through decides the flow pattern in fusion welding process. Apart from that definitely energy transport we need to know that within the molten pool and of course energy transfer is valid for this molten pool as well this thing as well as the solid part also. Here also we can get the temperature distribution. So conduction because here the conduction happens within this at this zone.

And of course we can say the solidified zone see this is the fusion zone it creates some kind of heat affected zone. So that is called the heat affected zone and the base metal unaffected zone and provide the temperature. So here heat affected zone and the base material there is a heat conduction happens. So once at the surface come to the and from the surface we can find out the convection and reduce in heat loss from the surface.

And of course evaporation may also happen specific in keyhole mode laser welding process. Because in that case the maximum temperature is above the vaporization temperature of particular material so that clears the evaporation. And at the same time there is another type of modeling brings the complexity in the modeling approach where is the arc pressure. So the arc there is a generation of the arc that actually creates the special and most of the cases the shape of the oil pool may not be exactly flat on the surface.

So that shape of this can be different. So that we can say the free surface modeling also can be done to capture the shape of the top surface profile. So these are the different phenomena is actually associated with the welding processes. But of course in general we use the heat conduction equation from here we can solve the what is the temperature distribution throughout the domain.

And that based on the temperature distribution we can predict the other kind of we can link that temperature distribution with microstructural phenomena that transformation happens during that welding process.

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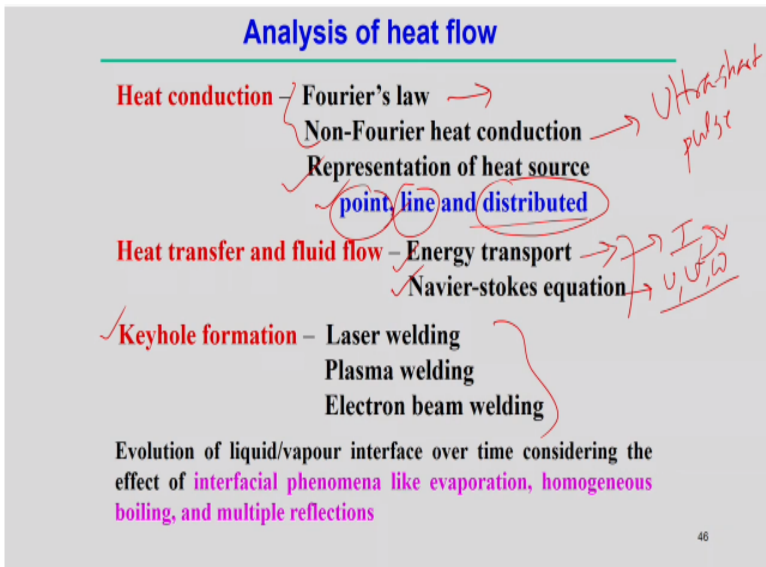

Now if we see the different how what we can analyze the heat flow, first is the heat conduction model if we assume in this case Fourier's law of heat conduction that means with the application of the heat flux that instantaneously propagated to the domain that means there may be some temperature development inside the domain. And of course there are other approach that is the non-Fourier heat conduction.

So this is in general the Fourier law we apply to estimate the temperature distribution but Fourier law is applicable in pulse welding processes also. But in this case is pulse duration is relatively large. But in other approach can be non-Fourier heat conduction. So non-Fourier heat conduction is basically applicable basically in case of ultra-short pulse welding process.

Ultra-short plus means the welding process where the pulse duration is in the order of the femtosecond level or maybe less than the 10 Pico femtosecond, few femtosecond to 10 picosecond in that level. So in that cases we do not follow the behavior does not follow the kind of Fourier's law of heat conduction.

Because in that case, in case of ultra-short pulse levels what happens though with the application of the heat flux to the domain, there is some time lag is required to development of the temperature inside the body. So that lag we count and in that case of non-Fourier heat conduction model is more suitable to explain this kind of phenomena. Otherwise we can use the Fourier's law to estimate the temperature distribution.

So apart from this two different law heat conduction the next part is the representation of the heat source. So in this case we will discuss how we will represent the different type of the heat source. In general, we can say that heat source model, so definitely you start the welding process even when there was no scope to find the numerical solution. So people started with this thing using point and line heat source to find that analytically estimate the temperature distribution.

But if we look into the three diameter heat conduction requires along with the boundary condition. It is not possible to get the analytical solution to be actually real welding processes. So in that case most of the cases we follow some nowadays we follow some kind of the numerical solution. So when you look into the numerical solution then we need to consider the distributed heat source model.

It can be surface or it can be the volumetric distribution. So this we will discuss about point heat source, line heat source and how analytically we can estimate the temperature distribution and some guidelines but using the distributed heat source, what we can get the temperature distribution, what definitely will cover that distributed using the different distributed heat source model how we can estimate the most widely double ellipsoidal so ellipsoidal heat source model.

Or maybe other types of the heat source model. We will try to discuss this thing distributed heat source model in this module okay. So apart from heat conduction module, it is also possible to use the heat transfer transport phenomena, base heat transfer and fluid flow model. So in these cases there is inclusion of the fluid flow.

So in this case we need to consider the energy equation, energy transport and of course Navier-stokes equation to estimate the velocity field as well as a pressure distribution inside the domain. But in this case we need to energy transport which is little different from the heat conduction equation.

Because energy transport here we consider the flow of the molten material and that component we consider then we incorporate is the energy transport equation to find out the so energy transport equation use the output is the temperature distribution and Navier-stokes the output is the velocity distribution, velocity field the temperature.

But when we use the energy transport equation in heat transfer fluid flow model so some terminology here we need to consider the this velocity field to finding out the temperature field. So apart from the heat transfer fluid flow in general the other kind of approach may be keyhole formation that keyhole formation normally found out in the laser welding process, plasma welding process, even electron beam welding process the keyhole normally form.

So approach of the keyhole formation it depends on the how the evolution of the solid liquid interface sorry liquid vapor interface moves with respect to time and the effect of the interfacial if we know like evaporation homogeneous boiling and multiple reflection within the cavity. So that all phenomena we need to consider and we can predict, we can develop some kind of the keyhole formation.

So definitely the keyhole formation here we need to consider the vaporization of the material. So here the approach may be different but finally we will try to look into the energy balance equation and then we can predict the different keyhole model in specific to the welding process which is create some kind of the keyhole just a given example.

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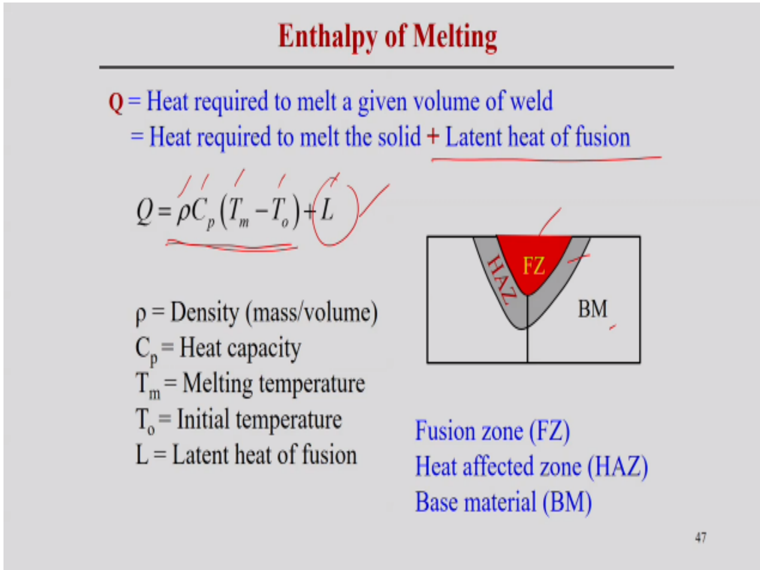

To enthalpy of melting so some basic idea suppose how to estimate the basically heat required to melt a particular oil pool volume what we can estimate of course in these cases were neglecting the material transfer material addition to the domain. So suppose a particular point this is the creation of the fusion zone, heat affected zone, and base material. So in this case what we can estimate? what is the amount of the energy heat energy is required to create that particular size of the fusion zone.

So we can estimate that for example Q. Now what is the heat transfer is required, heat required to melt the solid. So it just melt the solid, melt the solid means where there is by initial the solid is in ambient temperature. Once the application of heat flux it melts then which there is a temperature rise from ambient to the melting point temperature. Of course once the it reaches the melting point temperature there must be some kind of the phase transformation from solid phase to liquid phase.

So that we count using the latent heat of fusion. So that total energy required a particular volume of the weld metal given volume of the weld metal is the first is the heat required to raise the temperature to the melting point just to reach the melting point that we estimate the density, specific heat and that melting temperature and ambient temperature. And this is the amount of the energy required and here is the latent heat of the fusion.

And of course according to the unit available we can estimate this thing latent heat maybe in these cases per unit volume we can estimate this thing whether we can estimate per unit volume or per unit mass depending upon we use the units available and we can make the dimensional balance or not.

So this first part is the corresponds to that just to rise the temperature from melting ambient temperature to the melting point or initial temperature to the melting point and L is the latent heat. So density and then heat capacity melting point temperature, latent heat of fusion a particular material that information is needed then we can estimate what this amount of the heat energy required for a given volume.

So that means per unit volume what is the amount of the energy required to do this. So that kind of estimation is useful we can say there is an enthalpy of melting.

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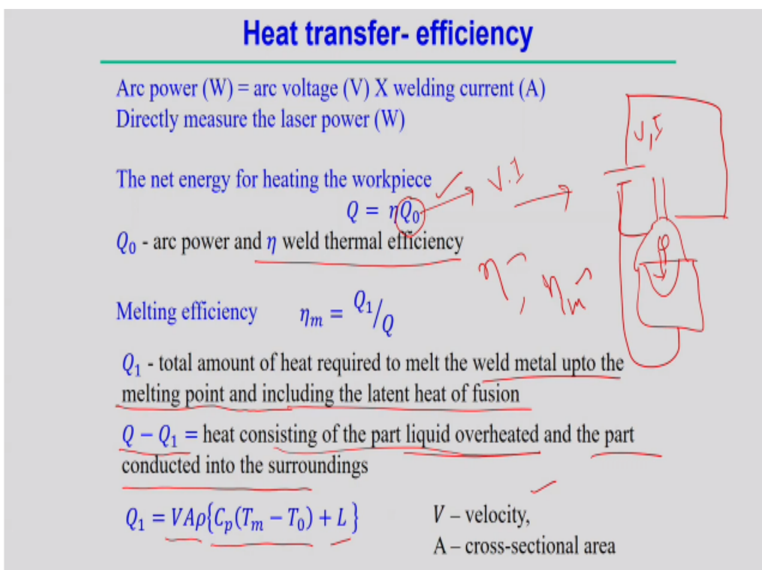

But what we can estimate the heat transfer-efficiency. So we can estimate the heat transfer-efficiency for example arc power. We can estimate the arc power, the voltage arc voltage, and arc welding current, welding current if we has the voltage and current if we measure then we can estimate the what is the power in this case. Or in case of laser directly we can estimate the laser power.

But what is the net amount of energy actually transfer to the workpiece. So transfer Q is the arc power, if Q series is the arc power and suppose n is the weld thermal efficiency, then effective amount of the energy that transferred to the workpiece that is efficiency in the Q0 or Q0 can be estimated in to volt*current, volt*ampere. And then it is the weld thermal efficiency if we know the weld thermal efficiency we can estimate what is the amount of the energy goes to these things.

Now there is another terminology that is called melting efficiency. That melting efficiency means it is not necessary so of this actually before doing that first one so what is the voltage and amps actually supplied to the machine we can measure the display of the from any arc welding machines what is the voltage and ampere is supplied? there is the power supplied. But not necessary all the power will be transferred creating the arc, transferred to the workpiece domain.

So certain amount of the this supplied power it transferred to the workpiece zone so it can be like that. So from here what is the amount of the energy transferred to the workpiece that is corresponds to the Q. But what is the this Q how what a Q estimate? Q is the simply the thermal efficiency into what is the machine supply it. So here what is the voltage and ampere we just supplied by the machines and then we estimate this thing and after that we can estimate that arc efficiency is this quantity and then Q.

But Q will create that some kind of the material value but not necessary all heat energy which is supplied by the arc is will be utilized to melt the material volume. So some amount of the energy will be there must be some loss due to the convection and radiation from the surface. But how we can account this thing. So suppose Q1 is the total amount of the energy actually utilize to melt the weld metal up to the melting point.

So we just assumed up to the melting point Q is the total amount of the energy and of course this including the latent heat of fusion to change the phase from solid phase to liquid phase. But temperature is at the melting point temperature. Now remaining amount Q-Q1, Q is the total amount supplied so Q-Q1 that heat actually part of the consisting part of the liquid overheated that means it is not necessary that we just count that Q1 in terms of only that to just to melt the substrate metal up to the melting point.

But there must be some amount of the superheated temperature will be there. So that energy we count the other way that consisting of the part of the liquid superheated and then other part is basically the loss to the surroundings. So then the Q1 can be estimated like that V is the I think velocity, velocity means in case of linear welding process, A is the cross-sectional area and density and this is the amount just to raise the melting point temperature and erase the latent heat.

So in this way if you know the quantitatively know what is the value of Q most of the cases Q0 is quantitatively know and we define the efficiency term and of course melting efficiency term if we define then we can estimate what is the amount of the energy actually required to melt the substrate metal, what is the loss from this thing? so roughly you can estimate we using all this parameter using these two different efficiency term.

The energy actually utilized to melt the substrate metal. So this can be used for the simple calculation.

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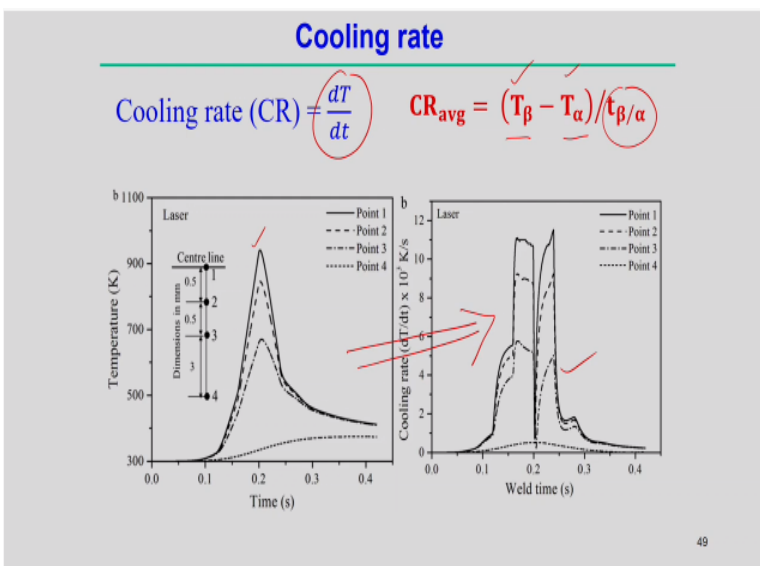

And there is another parameter which may be associated with the modeling approach that is called the cooling rate. So cooling rate is what if we know the temperature distribution for a particular point. So if you track time versus temperature diagram, so from the time versus temperature diagram, we can estimate the cooling rate at a particular point.

So that is why the time temperature distribution is very important part to capture during the welding process either experimentally or by during the numerical simulation. So for example suppose this is the typical temperature at the different position different point or maybe we can say different thermocouple points. We capture the time versus temperature, but now what we can convert this time versus temperature to a cooling rate to estimate the cooling rate.

So one approach may be this we just simply use the dT/dt. So we just tell small incremental time increment what is the temperature increment in the differential form. And we can convert in terms of the cooling rate. So this is a simple conversation of this thing the cooling rate from the time temperature diagram by using this differential time versus differential temperature.

So that if we see that cooling rate it is a there is a variation of the cooling rate at the different point and different variation of the cooling rate and of course it depends on the what is the gap we are considering the time and what gap we are considering between the temperature. So that depends on that the shape of the curve depends on that.

But most feasible way to look into this cooling rate rather not using diagonally conversation of the time temperature to cooling rate rather we can say some average cooling rate just peeking into so different transformation temperature. So normally cooling rate we normally interest in the solid state.

So what is the solid state phase transformation normally happens if we identify say suppose one is the T beta is the one time one temperature where the one kind of phase transformation normally happens and TR phase corresponds to the other phase transformation. So if we know this temperature for a particular material and then if we track what is the time required to reach from this temperature to that temperature.

What is the corresponding time required or time gap that way we can estimate what is the average cooling rate for this particular change of the phase? So this is the usual procedure to estimate the average cooling rate and that average cooling rate can be a parameter to explain the different microstructural phenomena in fusion welding process.

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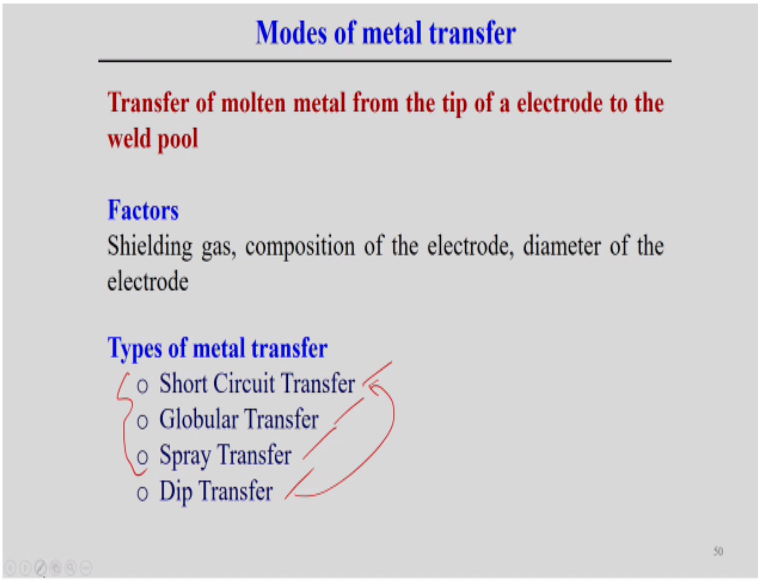

Now come to that point apart from this estimation of the elemental part and associated with the fusion welding processes we just try to look into that certain aspect relevant to the metal transfer in fusion welding process. So metal transfer is specific to the gas metal arc welding processes. So in these cases we consider transfer of the molten material from the electrode tip to the substrate material and of course normally follow in case of gas metal arc welding process.

But what are the physical factors that influence the metal transfer, one is that shielding gas composition of the electrode and of course diameter of the electrode and the other parameters that mean what is the current we apply voltage, so all these matters and there is a metal transfer. So normally we can in general we can divide in the four component different modes of the metal transfer in gas metal arc welding process.

One is that short circuit metal transfer, globular transfer, spray type of transfer and dip transfer. These are the four basic types of the metal transfer. Of course I think dip transfer is more or less kind of short circuit transfer that process condition can be different little bit. So it is a interchangeable we can use short circuit transfer and dip transfer. But globular transfer and spray transfer are other three.

So basically three types of the metal transfer normally you observed in general. Now we will try to look into the or what transfer what is the in what way what is the mechanism of this type of transfer and what parameter is actually influenced the different type different modes of the metal transfer.

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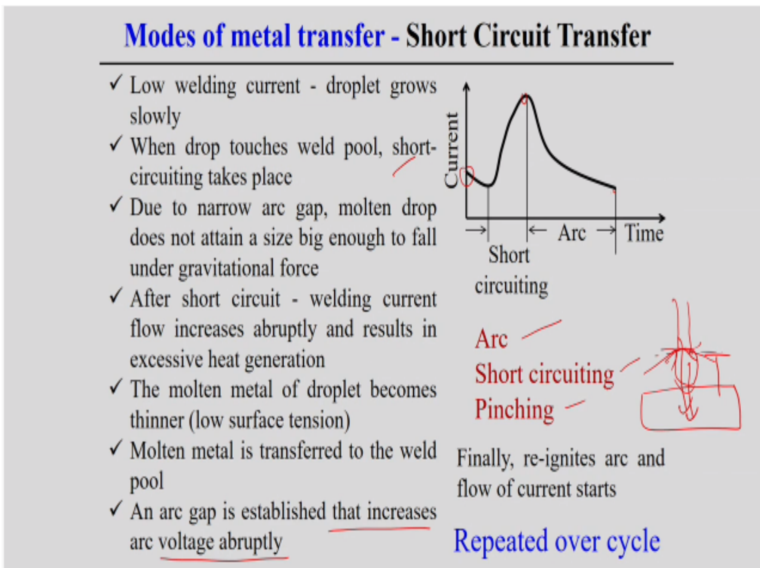

As first we look into the short circuit transfer. So if you see the short circuit transfer low welding current and droplet grows slowly because welding current is less means there is a the formation of the droplets can be slow. So once there is a formation of the droplet and actually droplet touch to the workpiece then this short circuit actually happens when it is touched to the workpiece and short circuit happens.

Then once the short circuit happens then there is a suddenly there is a current flow actually increases, flow of the current actually and the heat generation becomes excessive. So once heat generation become excessive then it actually reduces the surface tension force or we looked this surface tension force actually reduces one circuit then droplet transfer to the substrate material. Once droplet transfer to the substrate material, there is may be some small gap.

And that gap creates the arc. Once the creation of the arc that increases the voltage and that once increase of the voltage that means power requirement to the domain is actually increases and that influence again that creates the droplet at the electrode tip and that process are repeated. we can see that diagram first the condition in short circuit metal transfer, the arc gap is relatively very less.

So once see the droplet touches the weld pool short circuit once the droplet touches the weld pool suppose this is the electrode and this is the creation of the droplet and suppose this is the workpiece. So when it touch the workpiece then short circuit it creates the short circuit. So there is a flow of the current and if we see the at the end of the short circuiting occurs there is a current flow is very high.

So once current flow is very high, heat generation will be more. So then at this point the surface tension heat generation is more that actually reduces the surface tension force. Once surface tension reduces then this metal transfer to the substrate metal. So once the substrate metal actually transfers then creates the gap within the gap there is a creation of the arc and then after that it repeats the same thing.

So once arc is established that actually increases the voltage appropriately. So once there is increment of the voltage appropriately then representation of the same thing then its arc ends and what happens it creates the arc. Then voltage increases appropriately that actually again it starts creating the formation of the new droplet. So what is the typical mechanism in general creation of the arc short circuiting and then pinching.

Basically pinching is simply detach the droplet from the electrode and then repetition of this three process once again so repeated over this again. So this is the typical nature of the short circuit metal transfer.

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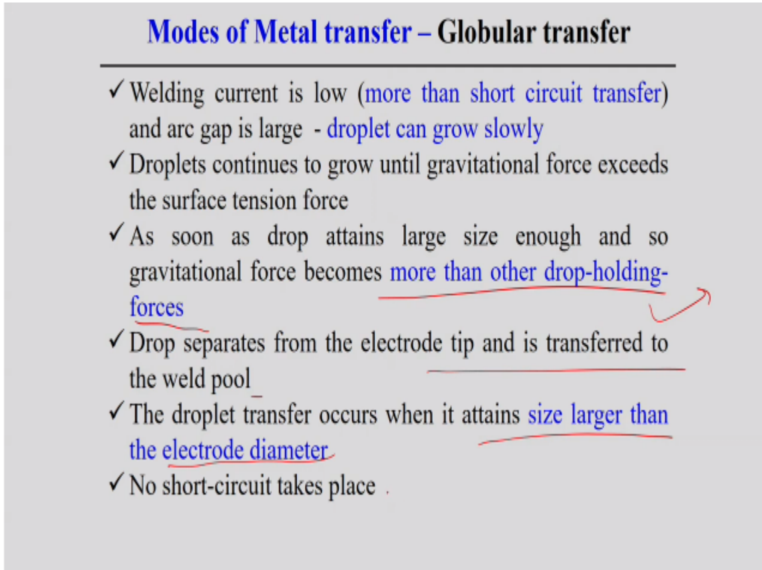

Globular type of the transfer if we see the globular transfer welding current is low but it is more than that of the short circuit metal transfer. And globular type of the metal transfer the arc gap is relatively more such that droplet can grow slowly and in general the size of the droplet is actually much bigger as compared to the diameter of the electrode even as compared to the short circuit metal transfer the droplet size is more in case of the globular type of the metal transfer.

So droplet continues to grow until the gravitational force exceeds the surface tension force. So once in typical mechanism for the transfer of the droplet in case of the globular type of the metal transfer that is a competition between the mainly the surface tension force and the gravitational force.

So when it is becomes very big so gravitational force actually increases and the ones gravitational total gravitational force increases then it exceeds the surface tension force and then detached from the electrode and transfer to this thing. So in principle the large gap is required actually globular type of the metal transfer or we can say that if current is relatively low and there is a huge gap between the electrode and the workpiece then that creates the favourable condition for the globular type of the metal transfer.

So gravitational force becomes more than that the drop-holding-forces. So drop-holding-force is mainly the surface tension force. So drop separators from the electrode tip of course we there other forces that actually acts during this process that means electromagnetic force, wind force also. So mainly that here the competition between the gravitational force and the surface tension force.

So once drop separated from the electrode tip and transferred to the weld pool. And then in this cases the droplet size is larger than that of the electrode diameter this is the typical characteristic of the globular type of the metal transfer, so no short-circuit takes place. In this cases there may not be any kind of the short-circuit.

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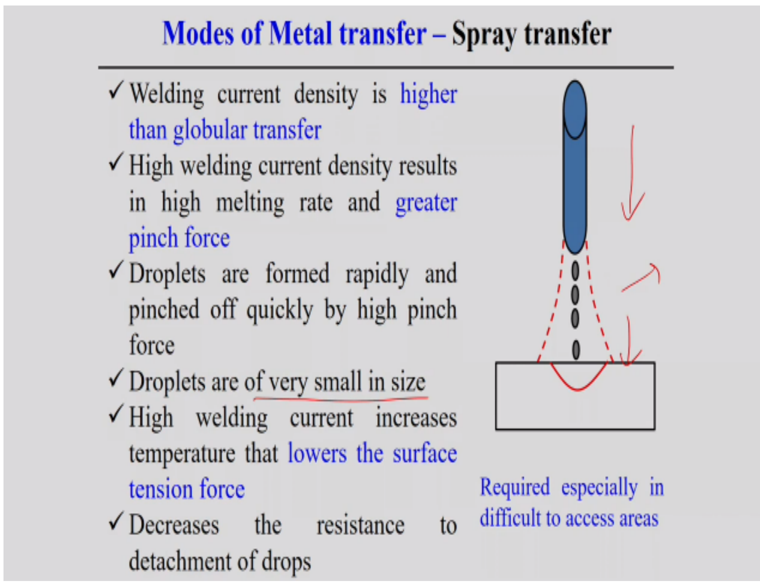

So apart from that we can say the most of the metal transfer other types of the spray type of the transfer. Spray type of the transfer normally happens the we can say, we can see from the figure itself, the lots of small small drops can be created and transferred to the workpiece droplet. So definitely in this case the current density should be very high. Such that it creates the metal transfer it enhance the metal transfer rate and high heat generation actually happens.

There is high melting rate heat generation as well as the melting rate and of course when using the current density increases that actually increases the pinch force that is correspondingly electromagnetic force actually increases. So that electromagnetic force helps to create some small droplets and transfer to the metal. So in this case the typical conditions for spray type of the metal transfer the normally current density becomes very high.

And of course droplets is very small and if we say the mechanism if current density becomes high, current density becomes high that means melting rate increases. So pinch force actually increases that means it also try to help to detach the droplet and once current density heat generation very high that actually reduces the surface tension force that means it reduces the drop holding forces.

So both are favourable to creates the high rate of the metal creation of the droplet and transferred the droplet to the workpiece. But here there is no sufficient conditions to grow the molten, molten as the bigger size like in case of globular type of metal transfer that type of phenomena does not happen in these cases.

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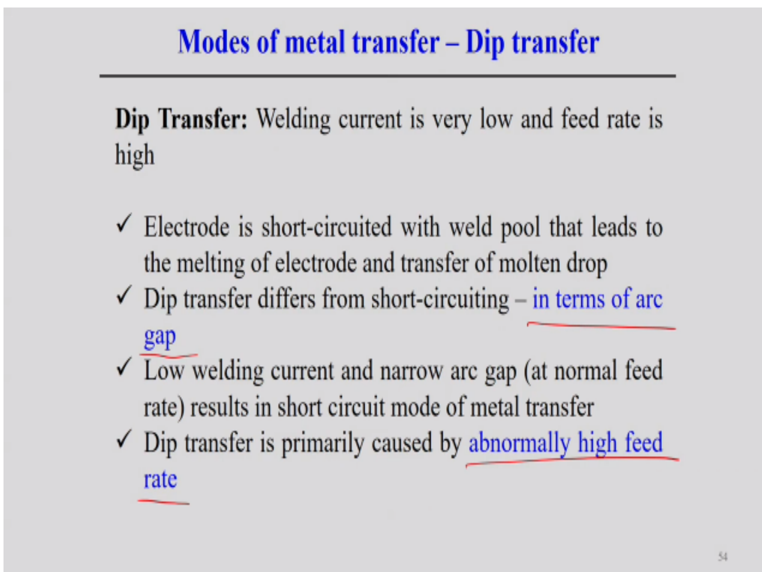

There is another type of the metal transfer that is dip transfer. But in this case welding current is a very low and feed rate is high so what as compared to the short-circuit metal transfer, there also welding current is low or gap is low. And of course but in that case feed rate was feed rate means was low in that case but here in the feed rate is high so in these cases electrode is short circuited with the weld pool that uses the melting of the electrode and transfer of the molten droplet.

Similar principle so dip transfer differs from the short circuit in terms of the arc gap or in this case there is another difference abnormally high feed rate. We normally follow in case of the dip type of the metal transfers. So in general we can say dip type metal transfer is more relevant to the so we can equal to the equivalent to the short circuit of metal transfer.

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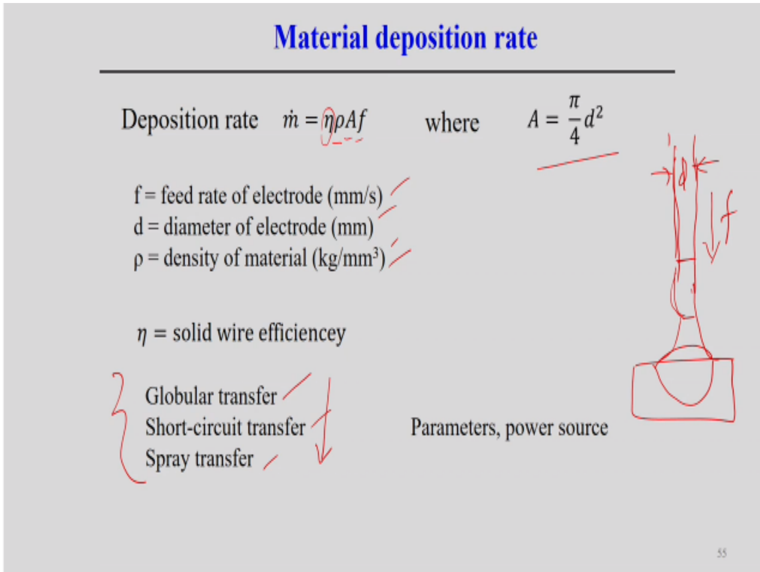

Now how to estimate the metal deposition rate in case of gas metal arc welding process. So we assume that metal deposition rate if suppose the electrode is a continuous this is the workpiece material so this is a continuous consumption of electrode normally at steady state situation the rate feed rate remains constant and that means the constant metal deposition. So in the workpiece material so what is that deposited material sometimes we are interested to know deposition rate by using the consumable electrode.

So suppose this is the feed rate and we assume the diameter of the electrode solid diameter of the electrode at the solid part is d. So we can estimate the deposition rate m dot equal to some efficiency term we can come to that point solid where efficiency and the density we can say density we represent the row is the density, material and A is the cross-sectional area. So A is the cross section area so cross section area equal to pi/4 d square is the diameter of the electrode.

And f is the feed force. So here we assuming the feed force is acting normal to the cross sectional area. So that estimate this basically if we multiply this density cross section area of the solid wire and the feed rate of the solid wire feed of the electrode basically we can see the dimensional it also we can estimate the deposition rate, mass per I think mass per unit time. So something we can say that kg per second that may be the rate of the deposition.

But here we can introduce the one efficiency term that is the solid wire efficiency. Actually the solid wire efficiency it is a in most of the cases is almost around 90% 0.9 but it depends on the what are the type of the metal transfer if we want to the if we consider the type of the metal transfer actually happen during the process accordingly we can decide the solid wire efficiency. But in general it is more or less almost around 90%.

But of course there is a difference in the globular type of the metal transfers, short-circuit metal transfer, spray type of the metal transfer, these efficiency term can be different. But of course in this cases normally if we see the difference it is actually increasing order. The efficiency for the spray type of metal transfer may be more. Of course it is not only that it depends on the parameters what type of the power sources basically we were using.

Based on that we can estimate the what is a solid efficiency for a particular type of the material mode of the metal transfer. So this way we can estimate the metal deposition which may be useful in case of welding process where we need to consider the consumable how do you use the consumable electrode.

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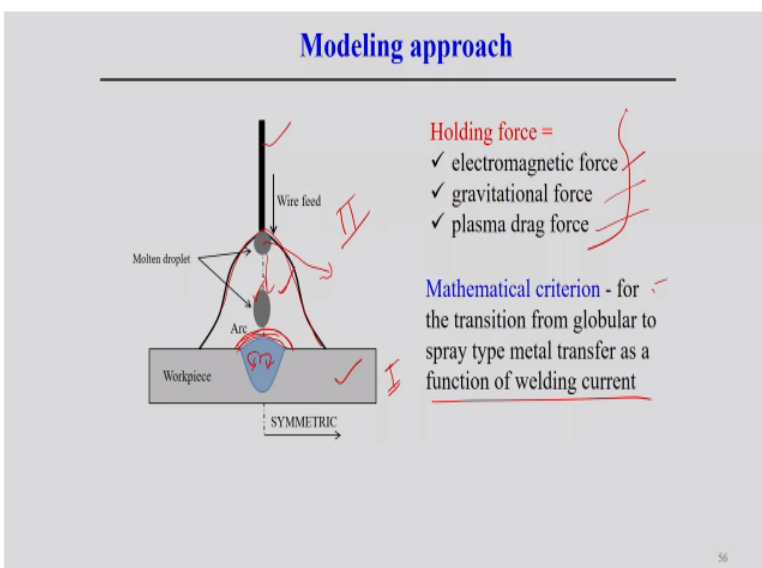

So apart from that we will try to look into that what are the different modeling approach in gas metal arc welding process definitely we will be discussing the heat transfer phenomena of these things in autogenous fusion welding process. But here I am try to discuss what are the modeling approach in gas metal arc welding process.

So if we try to capture all the phenomena what happens during welding process it will become very complicated things to model these things because there are so many things are there in here. First is that two things are there first is the we can create that this is the domain one for example and this is the domain two we can divide.

Domain one is completely strict with the workpiece what is happening within the workpiece that means what is the temperature distribution material flow actually happening within the workpiece this is the one domain. Other domain can be the how metal transfer happening and what are the criteria we can apply such that different modes of metal transfer can be decided.

So in general we see there is a solid wire electrode there is a wire feed is there and at the creation of the arc and then there is a formation of the molten droplet at the electrode tip and that droplet actually transfer to the domain solution domain. So then domain one can be interest may be we can find out this is the one solution domain other is a domain two that consists of the droplet mechanism droplet formation mechanism and the part of the arc.

Because this medium of this arc is different from the atmosphere surrounding atmosphere. So here also and that medium of arc there is a flow the arc as well as the there is a shielding gas that actually influence the shape size of the molten droplet and as well as the formation of the droplet. So what output we can get from this numerically. So what kind of output we may interest to know these things if we want to know how the changes of the shape of the droplet actually forms.

Then this droplet is subjected to that we need to know what is the temperature distribution beside the droplet or at the same time what is the fluid flow basically happenings within the molten droplet. Then we will be able to see the different shape of the melting but all this happening this is interacting with the second other medium, that medium is surrounded by the arc as well as the shielding gas.

So then here two mediums are there this liquid droplet and the other medium so how interaction happens between these two that can be one of the modelling approach and within the arc. And second part is that once it transfer to this domain so in this the first domain here we are interested to know what is the temperature distribution in this domain at the same time what is the metal flow within the domain.

But this domain is continuously updating with the application of the mass with the application of the molten mass that supplied from the wire feed. Of course the transient phenomena will be relatively difficult because every time there is a change of the front this profile weld bead profile actually changes with the since there is addition of the mass from the electrode.

So then we need to consider that how with this transient change of this profile transient profile is changing with respect to time and accordingly we can get the there is updating of the solution domain and what is the temperature distribution and metal flow within the domain or there may be the another approach that can be if we assume in case of quasi-steady-state situation that means if we know or we can predict roughly the what is the weld bead profile beforehand.

Weld bead profile then in that cases only we can analyze the temperature distribution as well as the metal flow analysis but by keeping the solution domain as a fixed. So this is can be the another approach to get the temperature distribution and material flow in case of gas metal arc welding process. So if we see when we try to look into the metal transfer here we can see that the holding force.

So that means holding force means how the detachment of the molten droplet from the wire can be done. But we need to consider the electromagnetic force, gravitational force and plasma drag force all actually influence the formation of the droplet and holding force maybe this two force the surface tensional force can be the holding force and the electromagnetic force, gravitational force, plasma force is plasma drag force actually influence to detachment of the droplet.

So making the balance between these two forces decides the type criteria for the molten droplet formation. And of course if we see the other these three forces more than the holding forces definitely the droplet will detached from the electrode. But mathematical criteria can be said for the transition from the globular type of the spray type that depend of the metal transfer metal transfer.

Which can be function of the welding current that can be the another criteria to set mathematical criteria to set to decide that there is a transformation of the different types of the modes of the metal transfer. But this can be done analytically and by looking into the what are the parameters actually influencing here. We look into that quantitative value of this parameter then we can predict some we can select some criteria we can decide some criteria or the type of the metal transfer.

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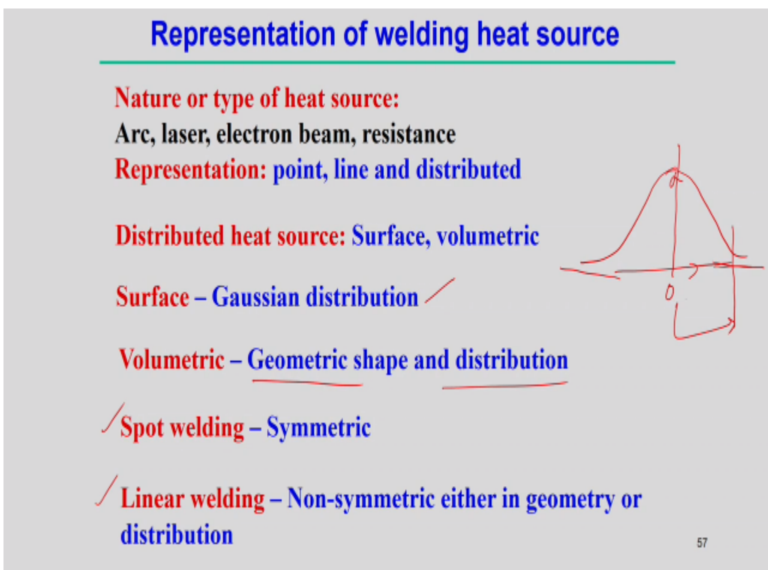

Now these are the modeling approach from gas metal arc welding **force**. Now I will come back to that point that in general what we represents the different heat source model. So nature and type of the heat source if we see that actual cases we use the arc welding process laser, electron resistant welding process but what we represent the that source of the heat. Representation can be done by the point, line and or distributed heat source.

But point, line is very simplified things and but more realistic thing is the distributed heat sources model. But distributed heat source model can be the surface that means over the surface or can be over the volume particular volume. Normally on the distribution of the arc welding process we assume or maybe other welding process we assume even for laser process or laser welding process surface distribution follows the Gaussian distribution of the flux.

So Gaussian distribution kind of so that it can be like that representation of the heat source that is intensity at the centre point is very high but is the gradually move at the boundary arc this thing with just arc suppose this is the effective radius of the arc. So at the boundary there may be very small it is about to asymptotically converge to the boundary. So this using the Gaussian distribution is the ideal representation of kind of resource.

Because in this cases this radius and the intensity can be adjustable. Now volumetric heat source of course the volumetric heat source the two things are what is the distribution of the heat flux. So that means distribution of the heat flux is one part in parameter and second point is that what is the geometric shape the volume basically how represents the volume by using usual geometric shape.

So that is the two things we need to look the geometric shape and the what we distribute, distribution can follow the Gaussian distribution or other kind of the distribution, a geometric shape can be kind of depending type of the welding processes it can be conical can be ellipsoidal kind of things. And of course if we look into the spot welding process all the parameter normally we assume the is a symmetric kind of the heat source particular plane.

But in case of the linear welding process with respect to the velocity vector it can be with this relation it can be symmetric but normal to the velocity vector that plane it can be the non-symmetric distribution. So here we will try to look into how what we represents all these different kind of the heat sources.

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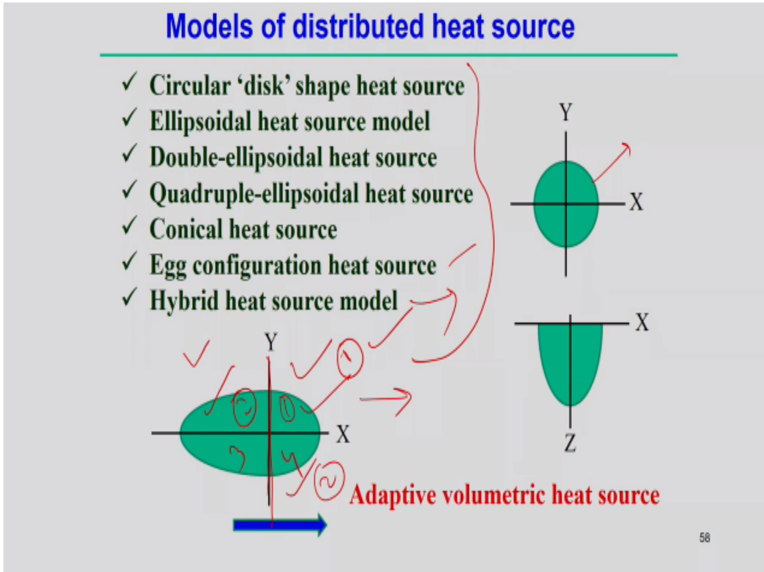

Now models of the distributed heat sources we can start with these things one distributed heats we look into the distributed heat source first was the circular shape of the disk. This is a simplest circular shape of the distributed heat source. We assume over this circle there is a application of the arc and within this circle and then we can assume the uniform distribution we can model or we can assume the some Gaussian distribution kind of these things.

Then ellipsoidal heat source model, so ellipsoidal heat source model means the geometric shape we assume as a ellipsoid. But ellipsoidal heat source model is practically applicable in case of spot welding process. Double-ellipsoidal heat source model we can say the double-ellipsoidal heat source model also the geometric you say simply double-ellipsoidal heat source model is the merging of the two ellipse.

If suppose with respect to this is the part of the one ellipse, this is the part of the another ellipse merge it. So that it represents the heat source for a moving heat source that means suppose one arc is moving in particular direction. Suppose in this case it is moving in X direction though temperature gradient or energy distribution to be in the front and rear part can be different.

So to accommodate that things we use we can normally use the double-ellipsoidal heat source model but just by simply merging the two ellipse source. And of course we will see the mathematical formulation of the double-ellipsoidal model and then quadruple-ellipsoidal heat source model.

So quadruple means instead of two double-ellipsoidal is taken as 1,2,3,4 ellipsoidal can be merged together such that non-symmetry phenomena can be accounted based on the moving heat source that means in case of similar kind of material if we want to join. So if we moves particularly this direction, so this part and this part can be non-symmetric one. But if material one and material two, two different materials are used in the both the sides.

So in this cases the other two sides will be the also be non, so this side and this side can also be non-symmetric. So to accommodate these things we need to consider the four ellipsoid merging together then we can say the quadruple-ellipsoidal model. So that dissimilar materials for a moving heat source problem we can use the quadruple-ellipsoidal heat source.

Then conical heat source model can be used so when there is a deep penetration is required. So using the laser welding process or keyhole mode laser welding, plasma welding processes, in this case we can assume the shape is a kind of truncated cone and that kind of conical heat source can be develop.

Of course apart from this thing A configuration heat source model in this cases so distribution it is not necessary the distribution can be always the Gaussian distribution rather than just by simply modifying the ellipsoidal equation we can use the oval shape equation. So this which oval shape can be some realistic phenomena that looks like oil pool in specific welding processes. So then A configures an heat source can we develop defining the different kind of geometric shape or different kind of the distribution.

And of course combining two different type of the heat source distribution and geometrics or two different type of the heat source can be combined to create the hybrid heat source model and it's specific to different type of the welding process. But apart from that one of the limitation of this kind of the heat source model that when you try to do the simulation we need to define the heat source parameters beforehand that mean heat source parameters.

Normally we define mapped with the weld pool shape and size. But weld pool shape and size can be decided once if you have the experimental data what is the width and depth of penetration for a particular oil zone. And if we map directly this weld using that weld zone dimension we can define the heat source parameters all these cases.

So to overcome this heat source may be it is not necessary to define before start of the simulation. In that cases probably we can use the adaptive volumetric heat source. So in these cases we start application of the heat flux of the substrate material then it creates certain weld dimension and ENB and that weld dimension continuously mapping with respect to time. So not necessary to the feed the predefined or premeasure heat source parameters.

So in that cases it is advantageous so here it overcomes that limitation of the all these kind of the heat source model.

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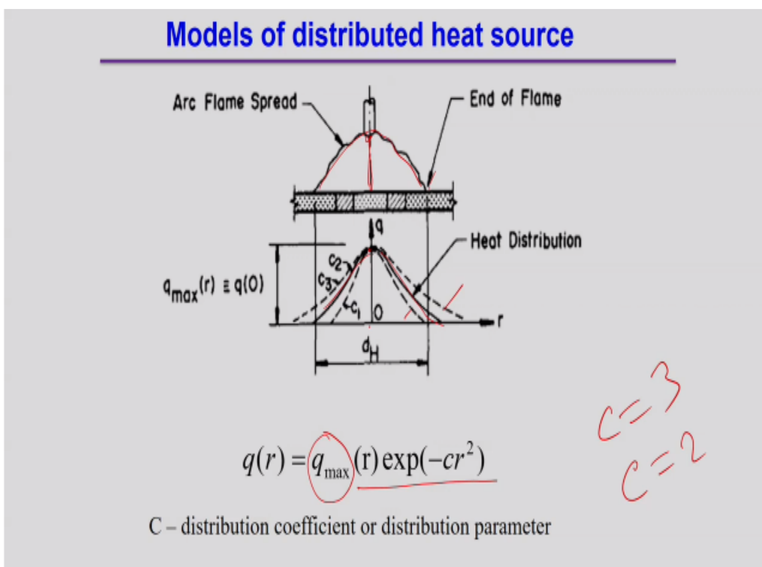

And here we can see that how to represent the heat source model the Gaussian distribution we start with the suppose this is the arc and end of the flame and the arc of the flame and the intensity is more at the arc. So that means at the centre at the intensity will be more. So that intensity want to represent this is the centre point, this is the maximum intensity and gradually decreasing.

So that can be better represented by the q max, q max exactly the intensity at the centre point and then exponentially varying -c x r square, r is the radial distance, c is the distribution coefficients or distribution parameters. So r is the radial distance. So these distribution parameters are coefficients actually if we change the distribution parameters then we can see that accordingly you can decide the heat source distribution will be very flat or will be very steep that can be accommodated by simply changing the distribution coefficient distribution parameter.

For example, in case of arc welding process c=3 can be used. In case of laser link process, the it is the distribution becomes more steep we can use the 2 or less than 2. So it depends on the type of the heat source and accordingly you can adjust the distribution parameters to decides whether it be very flat or it can be very steep. So in that we can accommodate in Gaussian distribution the intensity of the heat flux.