Advances in Welding and Joining Technologies
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Lecture - 12
Computational Welding Mechanics Part II

Good morning everybody, today I will start with the analytical solution of temperature distribution. And the last module, last time we have discussed the different (Refer Time: 00:40) model and how it can represent the different types of the welding processes, for example, arc welding process or laser welding process or resistant welding process.

So, corresponds to that there are different representation of the heat source that we can mathematically implement in any kind of the heat transfer equation for solving the temperature distribution in case of welding process.

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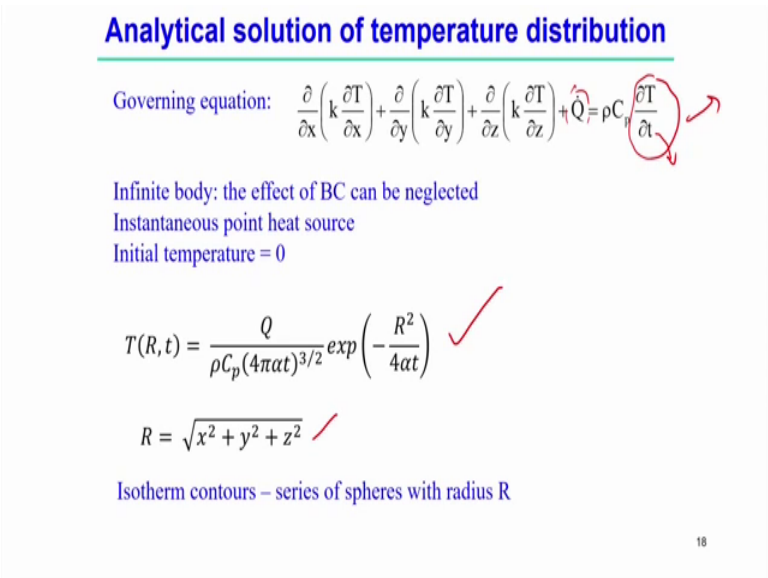

So, now will start with the analytical solution of the temperature distribution we generally observed in the welding processes. So, any the basic governing equation here is the heat conduction equation and this heat conduction equation by assuming.

So, many things and we can find out the solution of this heat conduction if you seen by analytical means. So, let us start with the very basic solution which has been developed earlier for the for to estimate the temperature distribution in case of welding process.

So, here if we see the governing equation that that case the thermal conductivity and capital T which is also temperature and Q dot is the internal heat generation and we can find out and this is the tangent variation of the temperature with respect to time t. So, this is the typical governing equation that we need to solve in a very specific to the welding process.

So, in the first case, we assume some infinite body and it is also mentioned it necessary to mention that in analytical solution we can it is limited to limited with so many assumptions. And we can get the approximate solution of this equation, because this governing equation it is not possible to exactly exact solution of this equation in analytically it is not possible. So, you need a lot of assumptions that is very specific to the welding process.

So, first case suppose the we start with the infinite body, we assume the length or dimension of the solution geometry through which we are interest to find out the temperature distribution that is infinite in size in the sense that effect of boundary condition can be neglected in this case. Then we assume the instantaneous point heat source, and we assume the initial temperature equal to 0.

So, here the instantaneous point heat source means at time t equal to 0, we just applying the amount of the heat within the domain. And then we will be getting the temperature distribution like this T as a function of a variable space R and as a function of time a small t that we can find out the solution is like that; and it is related to all the parameters that means, that Q, Q is the I thinks supply amount of the heat is applied here.

And then rho is the density of the material, C p is a specific heat, and alpha thermal diffusivity alpha. And then we can represent this in such a way that this estimated isotherm contour is a series of spheres with radius R, so a radial distance equal to R, so that means, here we are getting the temperature distribution as a three-dimensional temperature distribution with these assumptions. And these temperatures varies with respect to time also.

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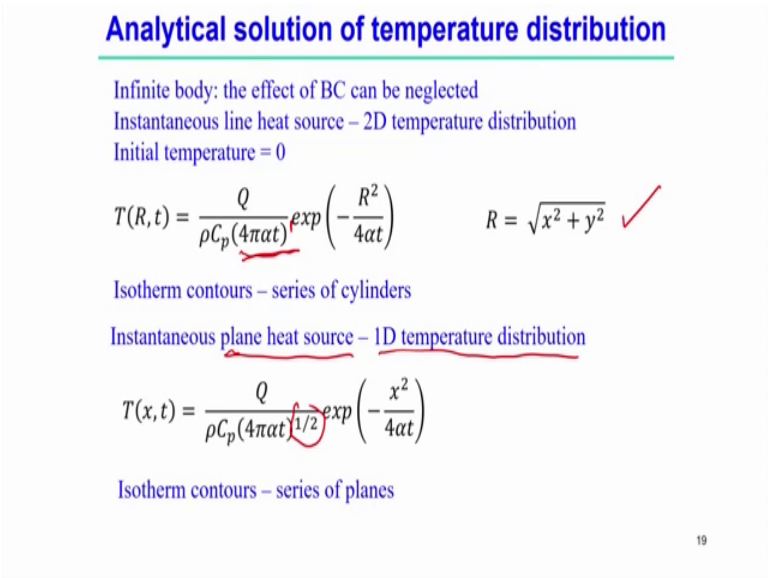

Now, if we look into other type of analytical solution, then infinite body therefore such that effect of the boundary condition can be neglected. Then next assumption since the instantaneous line heat source that means the representation of the heat source is not having a one specific point rather it is a release of the heat generally happens over a length over a finite length of the line. So, in this case, it is possible to estimate the two-dimensional temperature distribution and of course, assume the initial temperature equal to 0.

So, here we can see that isotherm contours in the this first solution and for the 2 d temperature distribution, it is also a series of cylinders and we can find out the difference the similar kind of expression. But here the power is here equal to 1 and as compared to 3 by 2 in the which was in the earlier case when we try to find out the t-dimensional temperature distribution in that case. And that q by rho c p 4 pi alpha t exponential minus R square by 4 alpha t, so that way the temperature variation will be getting on with respect to one origin point.

Now, if we assume the instantaneous plane heat source, then our solution dimensionality actually decreases. So, in this case, if we assume the plane heat source then we will be getting the 1D temperature distribution. So, if we look into that we when you try to apply the point heat source, then we will be able to find out the temperature distribution in three-dimensional. Then when we apply the line heat source in the 2D two-dimensional temperature disturbance we can estimate, but when we assume the plane heat source that mean heat source is that mean heat is released assuming that is over a plane define plane.

So, in this case, we will be able to estimate the temperature distribution in one-dimensional case. So, that temperature distribution can be estimate almost similar kind of expression, but here the x it is different at the exponential here it is one by two and remaining sense and all these cases we are we will be getting the temperature distribution with respect to space as well as with respect to time. And here we can find out that the solution represents the isotherm that means, constant temperature profile that represent the isotherm contours and it is a consists of the series of plane.

So, in this way with this all assumptions, we can we just simply find out the solution of the temperature distribution in case of welding process. But if you observe that all these three solutions that is no effect of the moving heat source that means, if heat source moves we normally we will find out in case of the linear welding process, where either laser or arc is moved with some constant velocity. So, there is in the solution there is no effect of the velocity only I will be able to find out the temperature distribution over space and time, but no effect of the velocity.

The most widely used that analytical solution of temperature distribution in case of welding process that comes is the in the in the from the Rosenthal's equations. And then in this case we assume the moving point heat source on a semi-infinite body semi-infinite one of the dimension of the dimension of the solution domain is finite and remaining becomes infinite.

So, in this case, for the semi-infinite body Rosenthal's equation for the steady-state heat flow we can find out the this is the solution.

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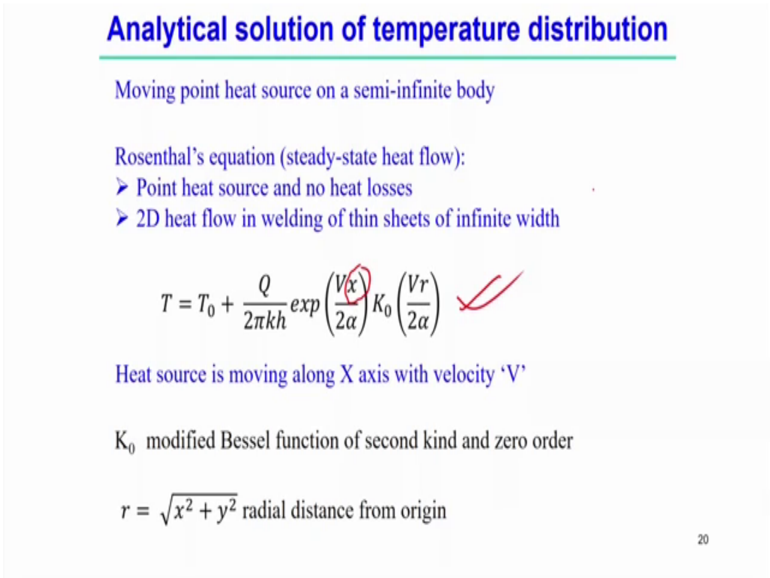

But in this case the assumption was lacked point heat source and that means we assume the applied heat source over a point and then there is no heat losses. And we will in we assume the two-dimensional heat flow in the welding of a very thin sheet of infinite width that means width of the sheet is infinite, but there is a finite dimension of the thickness of the plate.

So, in that case, you will be able to find out the temperature distribution like this T equal to T 0 plus Q by twice pi K h and exponential V x by 2 alpha and K 0 V R by 2 alpha.

Here if we see that K 0 is actually modified vessels function of the second kind and zero order. So, you can further expand this or approximate this case zero value and we will be able to find out the temperature distribution. And here we can see since it is the steady-state temperature distribution, so these temperature is not a function of time component. And here you see that the there is a effect in this solution there is a effect of the velocity; that means, if we know the velocity of the welding then we will more precisely we can find out that temperature distribution analytically when in case of the linear welding process.

And here we see that we assume that this velocity is actually we have defined the velocity that means, moving the welding or in one direction that is in x-directions for when the heat source is moving in x-direction then the solution of the steady-state solution of temperature distribution is valid here. Now, if the welding direction may be y-directional maybe some other direction, so accordingly this variable should change here. And R equal to is the radial distance from the origin, and we see that it is a we will be able to find out that different contour of the two-dimensional temperature distribution on the surface or maybe normal you can find out the temperature distribution on the on the surface in this case. Or basically you can say that two-dimensional temperature distribution can be obtained from the solution.

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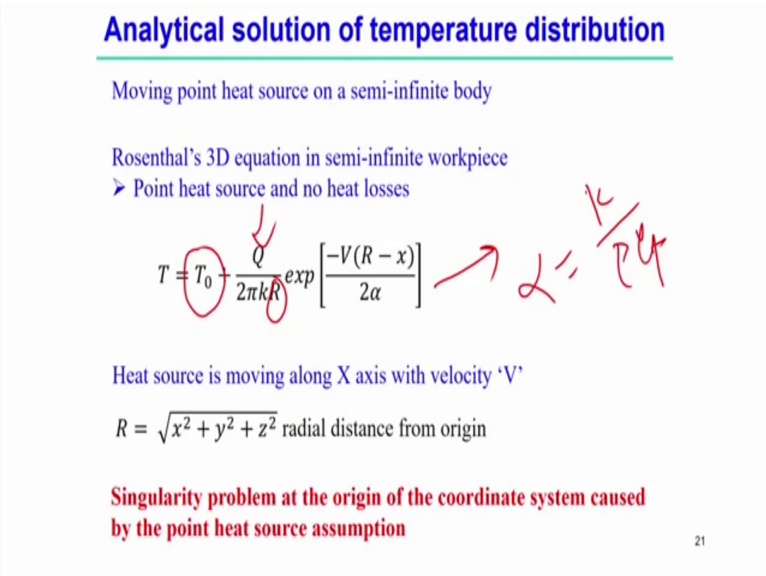

Next, Rosenthal's other solution that is a moving part heat source on a semi-infinite body, but in this case we will be able to find out the three-dimensional equation in a semi-infinite work piece. And of course, in this case also the assumption was that point heat source and no heat loss, then we will be able to find out the solution for the Rosenthal equation.

Here you can see that the solution is little bit simplified as computed earlier because earlier (Refer Time: 11:01) there is involvement of the vessels function, but here is not such. We can find out the t dimension temperature distribution, but the assumptions says that the welding heat source is moving along the x-axis with the velocity v.

For in that case, this solution is valid and T 0 was the initial temperature and the Q is the applied heat flux in this case and R is the radial distance case the thermal contraction. Alpha is the thermal diffusivity alpha is basically represented by K by rho C p means thermal conductivity wise then ratio of the thermal conductivity and multiplication of the density and a specific heat that is the alpha.

And here you can see that the solution of these Rosenthal's equation although in the in case of steady-state solution, and assuming the point heat source that will not be able to find out that solution exactly at the origin of the quadrant. Because the singularity problems also arise from this at this type of solution of steady-state equation; So, this with the with this assumptions this the analytical solution has been developed, but there are further development or so many modifications analytically by so with the assumptions and then complicated equations we can get from this analytical solution of the temperature distribution and that developed over the time.

But nowadays there is a option to find out the solution of the temperature distribution numerically. And by either this numerical solution can be obtained some readymade available software, commercial software or can be using some developed code also that more is using different a numerical methods for example, finite element, finite difference and finite volume.

The more obviously, we can getting the temperature distribution which is who is assembles the more realistic to the actual welding process. And that means, in welding process whatever physics we can find out, if we follow these things this mode is more scientifically defined the problem which is more realistic with the practical what we observe during the welding process if we follow the in numerical solution than with respect to the any kind of analytical solution.

But still analytical solution is handy in the sense the quickly we can estimate the temperature distribution and rough estimation of the cooling rate phenomena also estimation also possible using the analytical solution. So, let us see that how we can estimate the cooling rate and temperature gradient from Rosenthal's three-dimensional solution of the temperature distribution.

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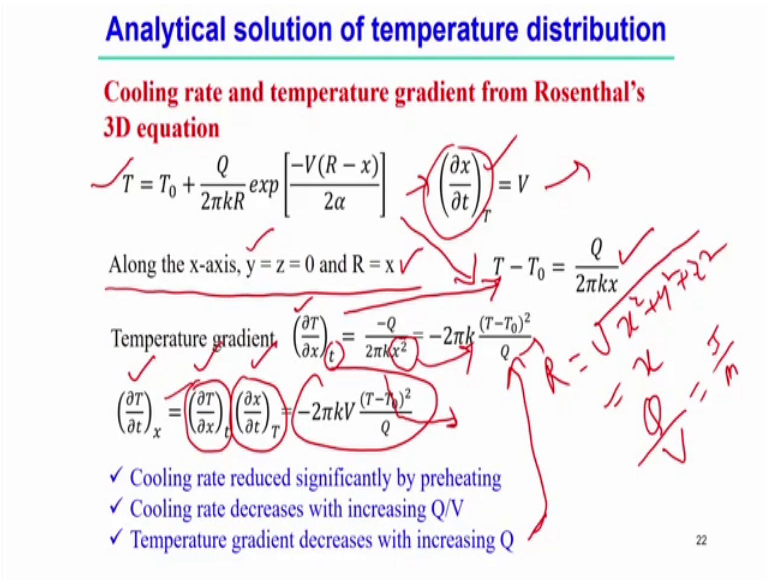

So, you know that this is the temperature distribution from the Rosenthal's equation. And from here we can simply estimate the cooling rate. So, first we assume that it is a variable is the x t v, x t, small t, capital T, temperature, time and the space are also variable quantity here.

Now, first if we see that do x the partial derivative of distance x with respect to time t that represents the velocity vector, because we assume that in this solution the heat source is moving along the x-axis. So, along that when it is moving along the x-axis, so this expression that x-axis with that change the derivative of x with respect to time component t that represents actually the velocity.

Now, if along the x-axis if we follow along the x-axis, then we can put this condition y equal to 0 and z equal to 0 that represents the heat source moving is along x-axis. So, if we put y equal to 0, z equal to 0, then R becomes x, because R was the radial distance. So, in this equation if we put y equal to 0 and z equal to 0, then R becomes x. So, in that sense R becomes x. Now, if R becomes x from this 3D solution we can find out T minus T 0 is equal to Q by twice pi K x this expression.

Next, we can find out the temperature gradient temperature gradient that means that basically slope that represents when we keeping the variable time is a constant, and this dou t by dou x that represents the temperature gradient, so that temperature gradient diagonally can be estimated from this equation that minus Q by twice pi K x square. And then if we put it replace the value of variable x this equation, we will be able to find out in terms of the temperature difference and other constant parameters, for example, thermal conductivity and the Q is the heat input.

So, now the temperature gradient a temperature sorry that cooling cooling rate, so change of temperature with respect to time that represents that two variable here the dou t by dou x first variable another is the dou x this is the partial derivative of this variable. And from the personal derivative we can express that this cooling rate is these two components.

And then if we put these values, we will be able to find out the cooling rate can be estimated like this which incorporated the effect of the velocity temperature as well as the heat input. Now, this is the straightforward to estimate the cooling rate when the heat source is moving along the x-axis so that means, the assumptions was that y equal to z equal to 0. So, in this line this is the cooling rate.

So, along one line the along the line which in which direction the heat source is moving; So, in that direction, we can find out the cooling rate and that cooling from this cooling rate we can say that the cooling rate is reduced significantly by preheating. Preheating means if we heat the T 0 actually the initial temperature.

So, normally initial temperature start with the ambient temperature, but if the preheater sample this initial temperature should be replaced by the preheat temperature, so that preheat temperature is very high that difference reduces, so in that sense that the cooling rate is actually reduces. So, by simply by doing that preheating process so that means, the cooling rate cooling rate can be reduced significantly by preheating by the one way to practically doing the some preheating process.

Next, if we look into that cooling rate also can be decreased with increasing Q by V, Q by V actually represents the heat input per unit length. If you see Q is the heat input and v is the velocity. So, if there that can be represented by some in SI unit joule per meter; that means, we can say it is a unit of the heat input per unit length.

So, that is the one characteristic parameter and that is in specific to the very thin state welding process. So, from here you can conclude that the cooling rate can be decreases with increasing that Q by V value ok. So, Q by V value increasing Q by V value either increasing heat input more heat input or by decreasing the value of the velocity.

So, therefore, temperature gradient another conclusion we can say the temperature gradient decreases with increasing with increasing Q.So, here we can link this equation and here you can find out if we increasing Q, then temperature gradient also a decreases. So, this kind of conclusion can be drawn simply just by estimating the cooling rate.

And from the analytical solution of the temperature distribution; And that analogy can be linked with the actual process condition or actually physically when you try to do some welding process; we can analyze just looking into these kind of parameters say whether we can increase or decrease in the rate of cooling during the welding process.

Because this cooling rate is very much significant parameter in this solidification process and final microstructure is actually influenced by the rate of cooling or whether we can say decided by the more on the rate of the cooling process. So, this cooling rate is very important parameter to analyze the welding process.

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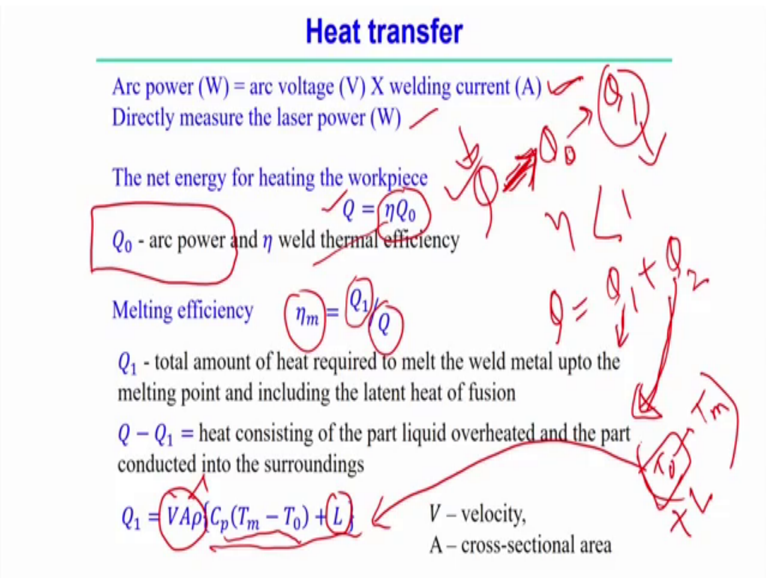

Now, some elemental calculation need to understand during the heat transfer in welding process. So, here you can see that arc power, so arc power; that means, suppose if we assume some arc welding process, so arc power can be estimated from the arc voltage from the machine direct itself which we measured the arc voltage.

And what is the welding current we supply based on that we can estimate the arc power; this is multiplication of the voltage into current.

Now, directly we can measure this is in case of arc, but in case of laser welding process directly we can measure the laser power from the machine reading itself. And so these are the input power you actually supplied in case of the welding process, but net energy which is supplied for the heating to the work is that may not be the what is the input power.

So, some then we can introduce some efficiency term also that is called the thermal weld thermal efficiency because during to the transmission of the arc or laser power to the work piece, there may be some loss of the heat to the surroundings.

So, if we look into that if you take into that account then we can say that Q is the amount of the energy actually goes to the work piece to the material. So, then we use this efficient term such that efficiency less than 1, such that less amount of energy that is the arc Q 0 is basically the arc power.

And that and when arc power multiplied by this weld thermal efficiency that is the actual amount of the energy that is actually goes into the work piece or substrate material. Then we can define our other term also that is called the melting efficiency. So, melting efficiency we define that not all the supplied power is basically utilized for the melting purpose w we can divide their total supplied heat to the work piece is the Q. So, Q may be one is the Q 1, another is the amount of the Q 2.

So, Q 1 amount of the heat is basically we can say that is utilized for the total amount of the heat required to melt the weld metal up to the melting point temperature and that also includes the phase transformation from solid to liquid phase. So, that amount of the heat latent heat also in heat accounts.

So, then if we amount if you separate out this is the amount of the total amount of the heat, you could just to melt and that Q 2 is the remaining the maybe you can say it is not necessary the supply heat which only just melt the substrate material, but it achieves some superheated condition that means, from melting point to the maximum temperature that is the superheat temperature so that means, liquid overheat temperature overheated and the part of the heat is also conducted air to the surroundings and that can be considered as a loss also.

So, the Q 2 this account that overheating; overheating means above melting point temperature plus the which amount of the heat is conducted to the surroundings that accounts that amount is accounted by this Q 2.So, therefore, based on that we can find out the melting efficiency is basically that Q 1 the in this case the to the substrate material Q 1 is actually used just melting the material and with respect to the what is supplied to the work piece Q and that ratio can be defined as a melting efficiency.

We can estimate that Q 1 also in another way that Q 1 suppose the material temperature initial temperature was T 0 and it raised to the melting temperature T m by the application of the energy from the arc or laser. So, to increase this temperature from T 0 to 2 M plus to change the phase the latent heat, so if we that amount of the heat can be estimate in this way.

So, that is this amount of the heat just to raise the from initial temperature to the melting point temperature, and this among this is this accounts the change of the phase from solid from solid phase to the liquid phase. And then this is the amount of this cross sectional area, and the over the cross sectional area and normal to the cross sectional area, V is the velocity of the welding source.

So, that account the that where V into A that may be volume flow rate. And if we multiply by the density then it becomes mass flow rate; and that mass per unit time this is the this accounts the mass and the remaining time is the heat accounts are increment of the temperature.

So, in this way we can estimate the total amount of the energy that is actually utilized to just melt the substrate material. So, in this way just simplified we can separate out the different amount of energy utilized into which purpose; and based on that we can define different efficiencies for things. For example, we can define the well thermal efficiency we can define the melting efficiency also in these two ways.

So, what are we can say that actual heat supplied that is the Q and is a arc power equal to that Q. So, arc power Q 0 and that Q from Q to Q 0, so there is some loss of the heat and that during when the there is a transmission of the arc part to the work piece and is Q 0. Then Q 0 to some out of this key one is utilized for the melting process.

So, what is the actual separate energy is Q by the from the machines itself and then to melt the substrate metal we utilization of the Q 1, so that means, definitely the this utilization will be very less as compared to the q and that it can be linked between all this Q, Q 0, Q in terms in terms of defining the different efficiency term.

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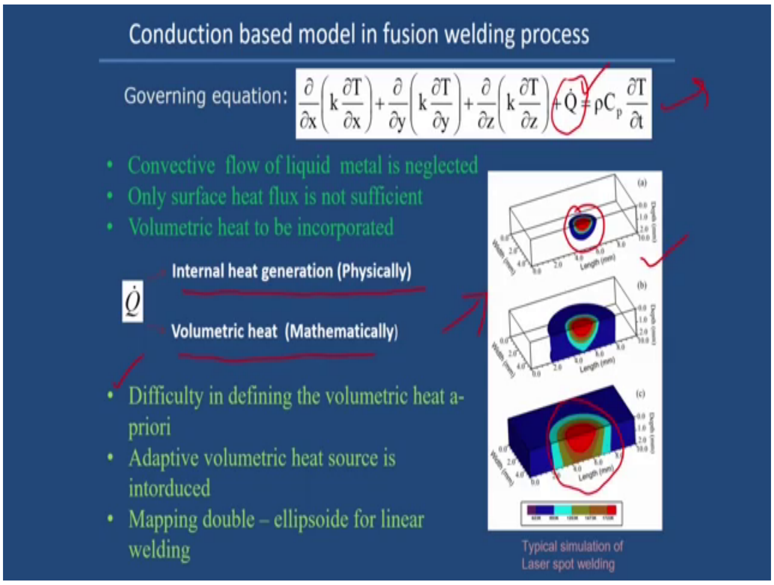

Now, apart from this analytical solution some basic elemental calculation of the heat transfer accounts the amount of the energy transfer to the substance material to this thing. So, finally, we are interested to know that what is the temperature distribution in the in the substrate metal in the work piece material.

Because that is temperature distribution actually helps to get the idea that what are the cooling rate, we can estimate the cooling rate also from this temperature distribution. And then some kind of methodological point of view we can explain the we can predict the structure solidified structure or maybe micro structure.

So, to get this kind of knowledge we need to know or maybe other way also; that means, if we know the heat transfer temperature distribution, we can we can predict there what was the size of the molten pool, and what was the size of the heat affected zone. All kind all kind of this quantitative information is possible to know only to if we know the temperature distribution actually happens during the welding process, so that is why in this case it is necessary to solve this governing equation basically the heat conduction equation.

And then we will be able to find out the temperature isotherm based on the temperature isotherm that means, if we for a specific material if we know the solidus temperature liquidus temperature and this temperature. And we if we know the some phase transforms at temperature so that that typical temperature actually define the different zone in the weld pool mathematically.

So, let us look into this that how we can do this thing. Just before that some idea that this graph actually shows the simulation of the laser spot welding that means, laser spot welding. So, first we define the geometry, and the there is application of the laser source from and with respect to time this is a development of the weld pool or and heat affected zone. So, is a very initial time it is a fast heat time is very small then weld size is small, and gradually continuously if there is just supply of the laser energy to the work piece metal then gradually the weld pool actually develop.

So, initial we start is the very small weld pool and finally, we are getting the very big weld pool; at the same time we can estimate the heat affected zone by the different color. So, in this picture, the red color actually represents the weld pool dimension; that means, the red color represents the this is a molten state of the work piece material. And then other colors define there is a solid state phase transformation happens and that that depends on the temperature distribution. So, that kind of information from the simulation also we can find out and that actually resembles to the actual welding process.

But what are the typical difficulties or maybe issues when you try to mathematically solve this equation in case of welding process. So, governing equation straight forward, the heat conduction equations with having some internal heat generation term, so that is the very basic governing heat conduction equation in this case.

But when you try to solve the conduction based model we try to develop the conduction based model inclusion welding process, so we just simply solve the heat conduction equation.

Though assumptions was like that convective flow of the liquid metal is neglected here that means, we know that within the liquid molten pool is not the liquid molten pool may not be very still because there are several driving force, there is the arc pressure and there is a there must be some flow of the material within the weld pool, so that means, that convective flow of the liquid metal simply we are neglecting in case of conduction based model in welding process.

Then sometimes you represents the that when you discuss that the representation of the heat source we can represent the heat source in terms of the surface heat flux; that means, only on the surface the heat flux is supplied or sometimes we represent the heat flux it is a volumetric heat flux that means, heat is applied and the representation in the mathematical model that happens over a defined volume of this thing.

Now, if it is surface heat flux we can step for it in the Gaussian follow the Gaussian distribution and put through the boundary condition, we can interact the circuit we can put as a boundary condition through the surface that the surface heat flux.

But when we assume the volumetric heat flux and if we look into the actual governing equation of the heat conduction, here you can see that Q dot represents the internal heat generation. So, this internal heat generation is practically in welding process, there is no internal heat generation , but it can be utilized that to incorporate the volumetric heat through this term and that is a usual procedure to incorporate the volumetric heat through this internal heat generation term in this equation.

So, physically internal heat generation term in that Q dot represents the physically the internal heat generation , but in case of welding simulation we consider as we use this term to incorporate the volumetric heat. And if we solve and then if we solve this equation with the proper boundary condition, then finally, we will be able to get the temperature distribution that is shown in this in this figure the temperature it simply shows the temperature distribution in case of the spot welding; that means, in case of the stationary heat source.

But what are the issues that we have already discussed the representation heat source, the issues is that first this is the difficulty in defining the volumetric heat a priori that means, it is very difficult to define the volumetric heat source before the start of the simulation. So, most of the cases what we define the this heat source term is defined looking in the experimental values and the experimentally measure the length and width. And based on that we can we can map these things with the volumetric heat source term so that is the one way.

And other way also if we incorporate this volumetric heat source term in in some adaptive manner, so that basically if we can do this thing in volumetric users you know in terms of the adaptive way such that over the time or what the load step there is a mapping of the weld dimension with the volumetric heat source stuff. So, that there is a continuous change of the these dimension that means, the volumetric heat source term, there is a continuous updating of the this heat source term with respect to time and that can be linked with the actual simulation of the temperature distribution.

So, this mapping can be done in any in different types of the geometric shape, in case in can be conical it can be ellipsoidal it can be double ellipsoidal, so all this kind of geometric shape this can be mapped. So, there is a some specific mapping techniques is also required to map with this parameter that more relate to the representation of the heat source term that we have already discussed.

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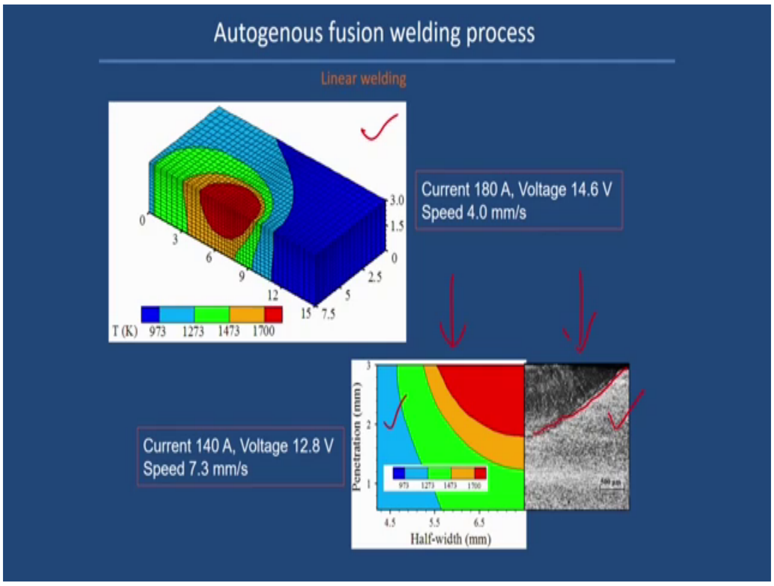

Now, we tried to look into that other simulation in case of the autogenous fusion welding process that mean without any application of the consumable electrode. So, in that case, so we generally solve the heat transfer heat conduction equation to find out the temperature distribution.

So, first figure if you see linear welding that means, for a moving heat source and in this case at any instant of time or maybe at instant of time, if he represents that at a specific point if the heat source at time t, the heat source is positioned on specific point. And that point the temperature distribution is shows in the first figure.

Here you can see that we can define the mesh that means in using the finite because this simulation has been done using the finite element method. So, by defining the mess, and at one instant of time that there is application of the heat flux and this is the typical distribution. So, red color basically represents the fusion zone, and remaining colors represents the heat affected zones.

The color body is also defined here that so that 973, 1273, we define we assume that this temperature elects to some kind of phase transformation happens and based that critical temperatures or that critical isotherm define certain heat affected zone in case of the welding process.

So, the current was 180 amps, voltage was 14.6 volt and speed then means welding piece was 4.4 millimeter per second. So, in that condition, we can find out the temperature distribution is like this. And we can predict the weld pool diamonds and that means, weld pool size at this welding condition. So, we have done the simulation without what we have done in case of practical cases. And we compare with respect the experimentally evaluated the weld pool dimension and com computationally evaluated weld dimension.

So, the red colored fusion zone and this side the original that is it is a fusion zone this represents a fusion boundary so more or less it is matching with the experimental and the numerical model data for a specific welding condition. So, this way this is the way to analyze the actual welding process what happens in practically that can be represented in terms of the some mathematical model, and do some computational calculation, we can represent the similar kind of phenomena what we generally observe during the welding process.

So that means by solving the temperature distribution only we can define that temperature distribution with respect to time or temperature distribution over the space or and that temperature control also define the different zones in the weld pool weld zone and that and same phenomena when you do the experiment after doing the welding experiment we cut the sample do the polishing and then after the after the etching solution, we will be able to find out that what was the well dimension, one specific welding process parameters, so that welding process parameters if we try to simulate will be getting the almost similar if we do the very good simulation we will be able to find the represents welding condition.

So, the compression represents that if there is a more small changes in the process parameters not necessary to always do the experiment, repeat the experiment again. Another we can rely on the simulation of this process. And using simple is a computer simulation, we can predict the weld pool size, a heat affected zone by doing the simple only the thermal simulation.

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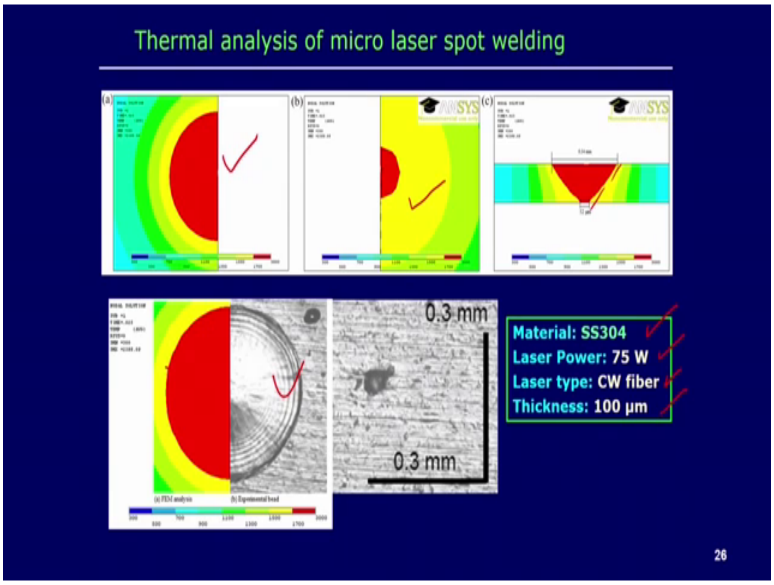

Similarly, this simulation shows that of the micro laser spot welding process that means micro laser spot welding process we can find out the metal equal to SS304 stainless steel. Laser power was used only 75 watt; laser type was the continuous fiber laser practical and experimentally. And thickness of the sample was only 100 micrometer.

So, in using the commercial software, in this case the simulation has been performed, and we can find out the from the top surface of the weld pool, weld is the this representation of these things.

And of course, here we can we have solved the symmetric problem that means, not necessary in computationally to solve the temperature distribution for the whole domain which can we can reduce the computational time depending about the symmetric nature of the problem. Only half of this half part of this can be used to do the simulation and to avoid or to reduce the computational time.

Here you can see that this is the top surface profile on the weld pool, and this is the bottom surface, so that is done from the simulation. And here the cross sectional profile is like that in case of micro laser spot welding process. And finally, if we compare these things we can see there is a comparison between the experimental value and the numerical value this is a good comparison that actually brings the reliability of the numerical model what we have we generally follow.

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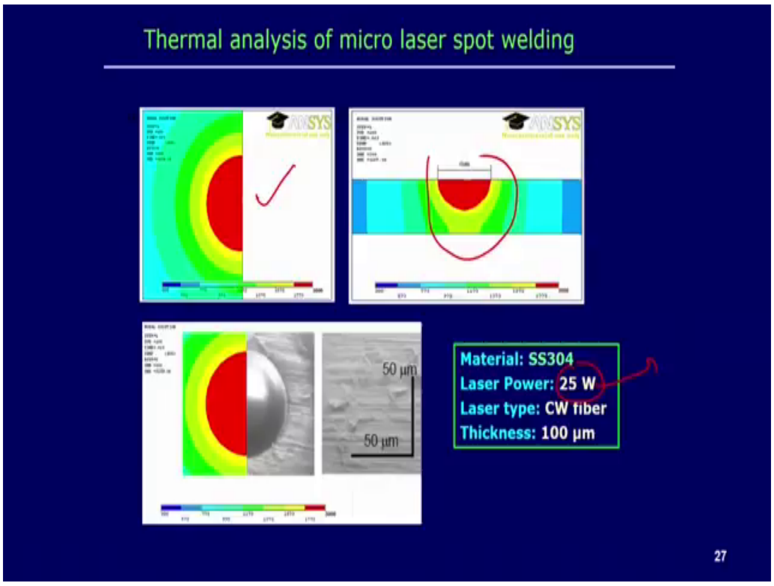

So, another simulation the thermal simulation micro laser spot welding process, but in this case I think the in initial 75, but in laser power was less even for 25 watt. So, with this laser power, so here we can see this is a top surface profile and the thermal profile that means, a red color is here indicates the fusion zone. And here you can see the cross sectional view also that it is not fully penetrated so that means, partially penetrated. So, that means, here if you use the laser 25 watt laser for only there is a partial penetration of the profile.

But if we increase the laser power, this profile will increase a with the seventy 75 watt laser power we can get this kind of profile that means, full depth full depth of penetration can be achieved. So, although without doing the analysis or maybe without doing the experimental things, so if we in this case for example, once you validate on numerical model, we can further use it for the simulation of the different process parameters. And we can predict some behavior just simply basing just simply doing is the simulation. So, here is the advantage of the computer simulation.

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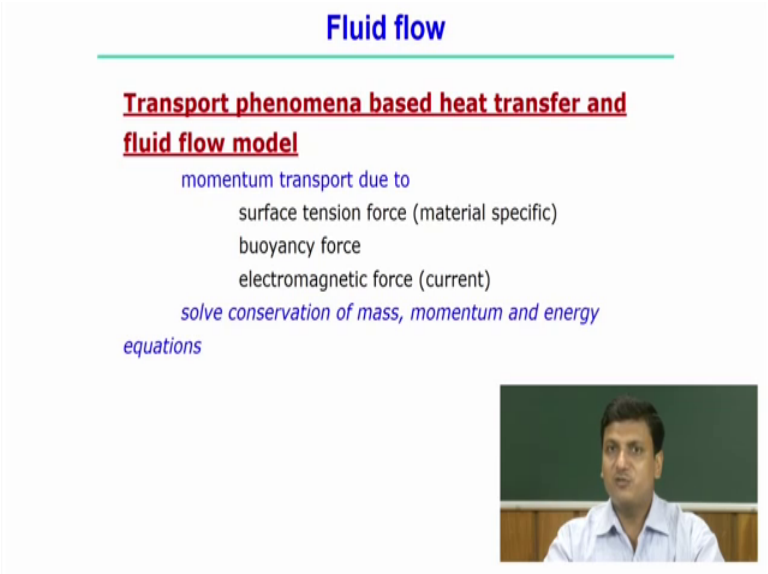

Now, since we have talked about the heat conduction equation. And from the heat conduction equation, we can incorporate the temperature distribution, and that temperature distribution can be used for the prediction of the weld pool dimensions and maybe we can estimate the cooling rate from this temperature time temperature cycle and that cooling that can be incorporated the microstructure all this phenomena.

But often to do this calculation, so we generally use most of the cases the heat conduction based model that means, within the weld pool there is a flow of the molten pool and that flow of the flow of flow velocity that means, flow field within the molten pool that actually modify the weld pool shape and size, so that thing is that velocity field within the small weld pool we often neglect it.

Because of the reason is because of that this incorporation of the metal flow within the small weld pool is tremendously increase the computational cost. But at the same time if we incorporate the material flow within the small weld pool. So, we more accurately we can predict the temperature distribution and although it is computationally expensive.

Let us see what is that why the fluid flow is also important to analyze in case of small weld pool and what is the influence of our impact of this consideration of the metal flow specifically in case of the in case of the welding simulation. So, here you can see that that in which you want to solve the fluid flow field or material flow field within the small weld pool into consider transport phenomena base heat transfer and fluid flow model you need to incorporate or we need to consider.

So, here extra fluid flow is comes from the due to the momentum transport due to the three military different driving forces. So, one is the surface tension force that surface tension put in entirely depends the material specific that type of the material whether there exist any kind of surface active elements within the within the material or not. And that actually interface between the in arc welding or maybe in the two different medium that means liquid and the gas medium in the interface, there is a acting of the surface tension force.

Next is the and but it is necessary to mention that surface tension force is mainly acting on the over the surface. And other as the buoyancy force or an electromagnet, so buoyancy force can comes into the picture due to the a temperature difference between the top and the bottom layer.

So, the presence of the temperature gradient actually brings the buoyancy force that buoyancy force is actually distributed over the volume of the molten pool, but there is another dragging force which is responsible for the material movement within the weld pool that is the electromagnetic force. But if we use a electric current especially in case of the arc welding process, this electromagnetic force is more actually impact on the metal flow or act as a driving force.

But this electromagnetic force is distributed over the volume of the molten weld pool, but if in case of laser welding normally doing we do not find out the electromagnetic force field. So, in case of laser welding it is sufficient to consider only the surface tension force and the buoyancy force as a driving force for the momentum transport within the molten pool that means that actually decides that these two type forces in case of laser welding actually decides the velocity field within the small weld pool.

So, of course, when you in case of transport phenomena based heat transfer fluid flow mold, if we want to use it then it is necessary to solve the conservation of mass momentum and energy equations which is as compared to the conduction based model.

There was only to solve the only the energy equations. And from the energy equation, we will be getting the output as a on the temperature field. But in this case we will be getting the output as a velocity field as well as the temperature field within the small weld pool as well as the heat effect regime. But it is it is also important to know that these velocity field will be able to predict in case of the welding process within the small weld pool also, but temperature field will be able to predict throughout the whole domain not only confined into the small weld pool.

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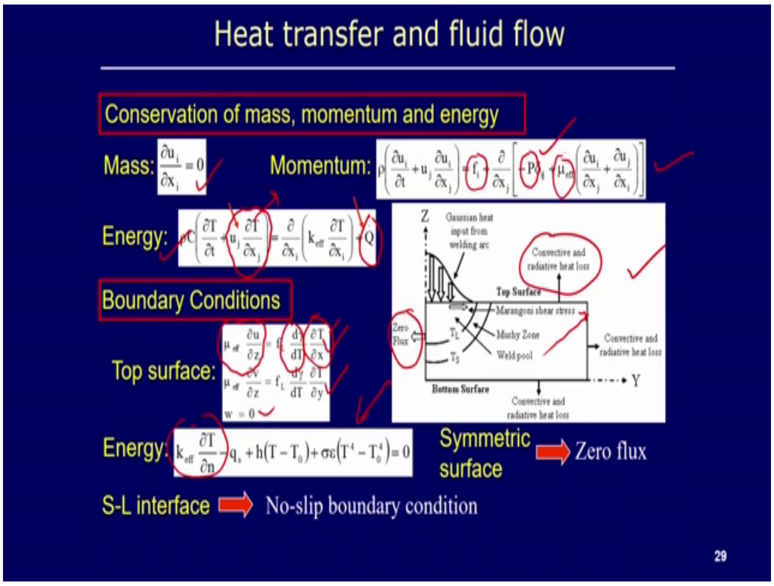

Now, to solve this heat transfer and fluid flow problem in specific the welding process of course, if we try to there is a limited solution available for the analytically, so it is more easy convenient to do the numerical solution of this problem to get the actual effect of this kind of physical phenomena in case of the welding process, so that is why I am directly shifting to the numerical solution of this problem.

So, by avoiding the and any kind of analytical solution in case to find out the fluid flow field in case of welding process.

So, definitely first we need to solve the conservation of the mass momentum and energy in case of the heat transfer and fluid flow model. So, mass conservation we can represent this equation.

And here we are showing the momentum conservation, we can use this equation that here the small u is actually represent the velocity field. And x the coordinates, x is the coordinate, and t is the time component, capital small t is the time component and P capital P is actually represent the pressure, and mu is the effective is the viscosity. So, that parameter is also necessary to define when you try to solve the fluid flow in case of the welding process. And f i represents the body force through the f i term we can incorporate any kind of the body forces here. So, this is the governing equations for the momentum transfer in case of the material flow.

Then we need to solve the energy equation also. So, energy equation as compared to the heat conduction equation the this term is extra in this case because this energy equation or maybe temperature field is modified by incorporation of the liquid molten metal, so that is a convective flow of material we can consider here in the by this term. And we can modify the solution of the temperature distribution in case of the energy equation. So, absence of this term is just simply using of the heat conduction equation.

So, here this is a Q dot is the internal heat generation term normally when you try to do the actual phenomena that means, fluid flow phenomena in case of the fusion welding process not necessary to consider the Q dot term in case of the arc welding process. So, only surface heat flux is sufficient that can be incorporated through the boundary condition and that that is that we will be able to find out the actual solution of the temperature distribution as well as the velocity distribution in case of the welding simulation.

Now, if you look into the boundary condition, the boundary interaction how we can represent here. So, on that surface top surface basically if you look into this picture, the top surface there is a in the heat flux is applied, it can be either laser, it can be either arc welding process. So, that because a simply Gaussian distributed heat input from the welding arc and then on the top surface there is a interface between the welding arc or may be along with the gas, this is shielding gas as well, and the liquid molten pool. So, that interface on the top surface, the gas medium and the liquid molten pool so on that surface there is acting of the surface tension force. So, that surface tension force can be represented in this way.

So, normally we incorporate the surface tension force is the temperature coefficients of the surface tension. This term and f l represent the liquid fraction here and to by delta x that represents the temperature gradient with respect to one direction x-axis. And this is the represent the shear stress basically this term so that we estimate on the surface, the shear stress value two components along the x-axis and along the y-axis in this way.

And to on this x-axis, y-axis we can consider the shear stress value and that shear stress value in terms of the surface tension coefficients, temperature surface temperature dependence sorry the surface tension coefficient, a temperature coefficient of the surface tensions and the temperature gradient in terms of that. And then along the z-axis that means, normal to the z-axis there is no such that w equal to 0 means ah; that means, the displacement on velocity field normal to the surface equal to 0 that means, we assume the it is a flat surface, and that is why we getting this kind of boundary conditions.

And the energy equation mathematically we can see that energy equation; that means, what is the heat conducted a on the surface and from the surface heat is convey heat convection or radiation also happens that means, convective and radiative heat loss from the surface that can be mathematically represented by this equation. So, that can act as a boundary condition here.

And the symmetric surface since it is a symmetric problem. So, on the symmetric surface, we can assume the heat flux equal to 0. And at the solid liquid interface with no slip boundary condition, we apply these are the typical boundary conditions for the momentum transfer for the solution of the momentum and energy equation; So, with this solution of this with the boundary condition, these governing equations and along with the energy equation.

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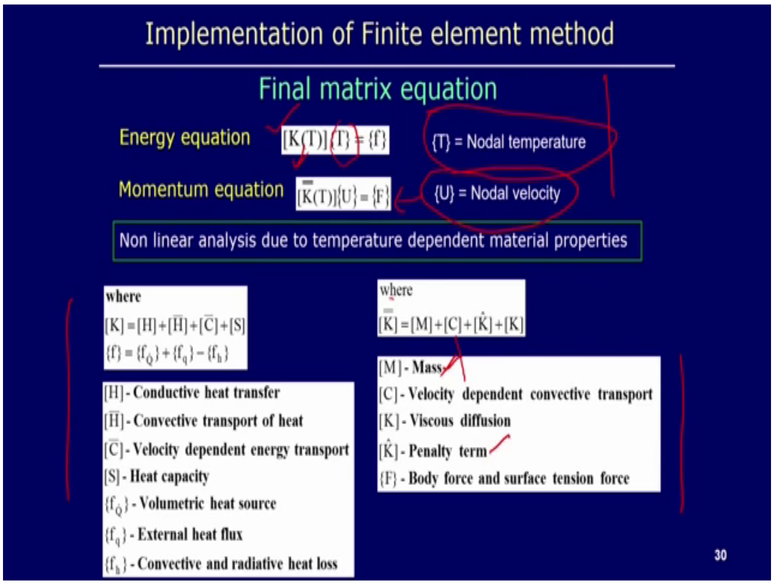

If we solve these things we can find out, we can implement in finite element method like this that final matrix is basically from the energy equation it is a kind of A x equal to B, but in that form. So, a f is equal to the right column vector right side and we are finding the solution for T temperature distribution, but this K form this matrix is a also a function of temperature when you try incorporate the temperature dependent material properties.

And finally, getting the nodal temperature as the out that each and every node point will be getting the value of the temperature each and every node point that means, distributed value of the temperature in node point; But when you from the momentum equation we can find out the solution of the nodal velocity in the similar fashion and that finally we are making the matrix in the form of A x equal to B.

So, they will be getting the velocity field each and every node point if it is the three-dimensional problem will be getting the three component of the velocity in the in each and every node point. And that each and every node part we can we can that distributed value if we get it then we can predict that over the solution domain what is the velocity field each and every node point.

So, these are the typical methodology in case of finite element method, we can solve this equation and we will be able to find out the temperature distribution as well as the velocity field each and every node point in using the finite element method.

So, here all the different terms are also defined here also and we can find out all the different term also define that which represents of what. So, we each and every is every component that means, K, K matrix and the both the cases the K matrix consists of the several other matrix component and each and having the physically represent the some physical behavior for example, and in the momentum that M is the capital M is the mass from the mass conservation from taking the amount of the mass, and then velocity dependent convective term is taken care of by matrix C, viscous diffusion term is taken care of by K.

And the penalty because in this case we use the penalty finite element method for the solution of the momentum equation, so in this case the penalty term is in corporal bar other K K matrix. And b that F sorry f that actually represents the body force and the surface accounts the body force and the surface tension force in this in this form of this equation.

So, when they solve the linear system of the equation using some solver, we will we can find out the temperature and distribution. Of course, there are so many strategies to follow how to solve all this equation that is beyond the scope this analysis. So, just to get some overall idea how I can solve the temperature this temperature then energy equation and momentum equation to get the solution of the temperature and the velocity field.

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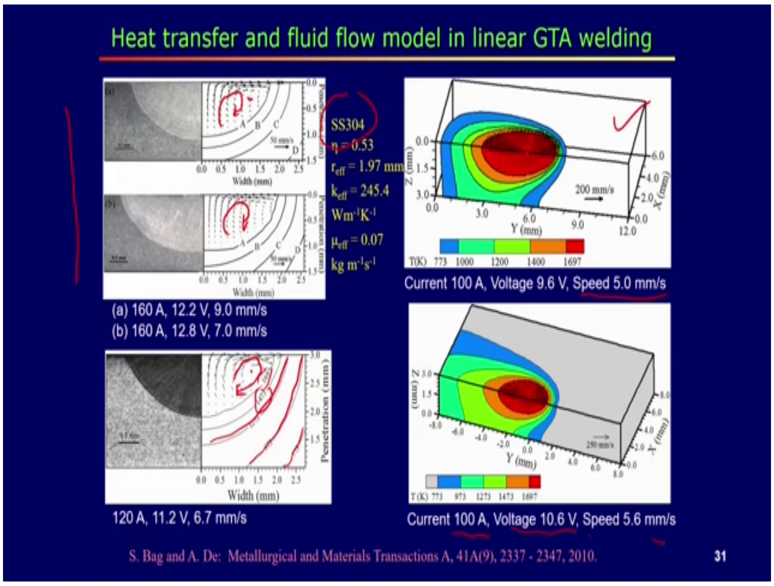

Here you can see some results also by the solution of conservation of mass movement of energy in case of the linear GTA welding process. So, linear GTA welding process if we look into the right hand side figure first here we can see that within the small weld pool that is red color represents the fusion zone. So; that means, there is the liquid velocity field in the vector form it is represented. We can see that one centre point is there. So, from centre point to outward direction, the liquid metal is try to flow from center to the outer directions. And on the surface on the phase that that clears are some circulation loop also.

So, in two different cases we have shown that the temperature distribution, but at the same time we the same figure we can see the also velocity field the temperature distribution as well as the velocity field can also be obtained for the other cases also. Here you can see the current equal to 100 amps voltage; that means, in these two cases the parameters are different. For two different parameters we can find out from the simulation that we are getting the a different temperature distribution that means, different size of the weld pool as well as the velocity vector also.

So, if we look into the here in details that comparison between the experimental measurement graph and the computationally evaluated, the velocity field also as well as the temperature field we can find out for stainless steel 304, we can see that there is a velocity vector is moves one we look into the it is the clockwise direction. Here also we can see the velocity vector is in such a way the clockwise direction so that means, metal flow we observe with respect to the one centre point, there is a the metal flows in the clockwise direction. Similar, we can see here also, so metal flow in this way and other temperature also that other these this represents that this line represent the constant temperature contour.

So, here we can see that it is possible to solution of the conservation of the mass momentum upon energy, we can predict the temperature in velocity field and we can compare with the experimental data. We can see that in case of stainless steel the normally the temperature that flow field is happening flow field is following this is in this case all these cases it is the in clockwise direction.

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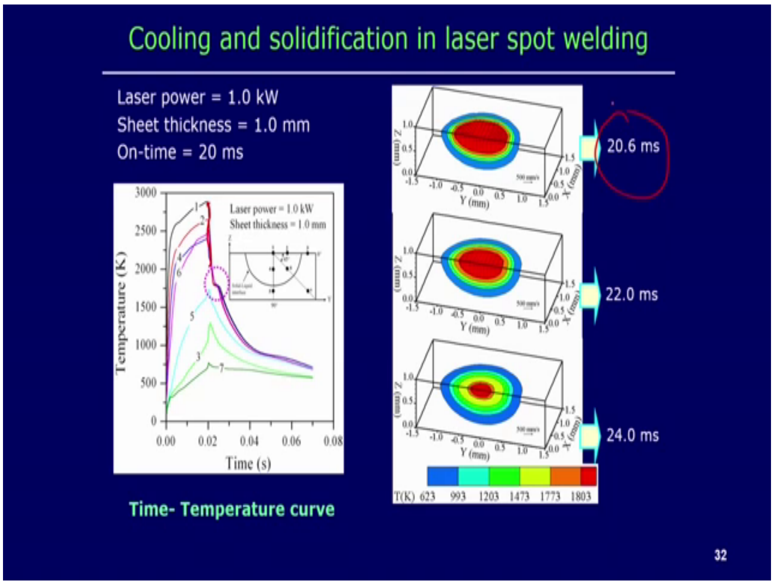

Similarly we can from this temperature simulation we can find out the cooling and solidification behavior in case of the laser spot welding. Here we can see that in case of the laser power 1 kilowatt laser power, sheet thickness is 1 millimeter and one time equal to 20 millisecond that means for 20 millisecond laser was found; then we can find out the time versus temperature graph is like that at the different fixed basis.

So, we have defined that different species 1, 2, 3 along the along the surface and the along the depth direction the 4, 5 this some characteristic points has been defined and on that point we can find out the temperature versus time. So, it defined the point in such a way having some importance to do the further calculation.

So, here you can see that in case of laser welding process there is a initially there is an increment of the temperature is the peak temperature. We can say that is the heating pace and then gradually when the we can switch up the laser. Then after reaching the peak temperature there is a gradually decrement of the temperature.

Here you can see reaching the peak temperature and gradually decreasing and the marked space here you can see that there is a kind of hump is there that actually in this part actually represents the if you see the temperature then there is a phase transformation; that means, from the liquid phase to the solid phase happens and that happens over a narrow range of the temperature in case of alloy.

So, here ; that means, in case of alloy the this phase transfer from liquid phase to the solid phase happens will between the solidus and liquidus temperature. So, that we are getting this kind of harm here. So, that actually indication that phase transformation happens in this during this process, so that also actually signify that in this numerical model also we can incorporate the effect of the phase transformation.

Now, right hand side figure shows that the temperature and the velocity field distribution after the switch of the laser sort that means, there is a decrement of the weld pool size. And that first cases it was 20.6 mill second there will up to the 20 millisecond we have applied the heat flux; that means, laser source then we switch up the laser source. And then gradually the size of the molten pool actually decreases during the cooling phase.

So, the cooling phase we see 20.6 millisecond then 20 millisecond, and then 24 millisecond also, there is a decrement of the weld pool size. But at the same time the velocity field also decreases gradually during the cooling phase. So, all this kind of phenomenological behavior that we generally observe that actually observe in the actual welding processes can be represented through some mathematical model as well.

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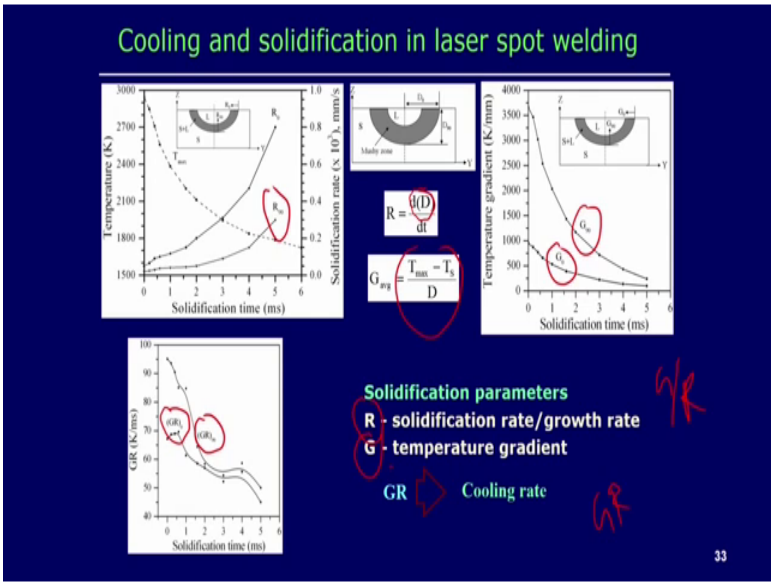

So, we can see some estimation of the cooling in the solidification in case of the laser welding process. I have already mentioned that temperature distribution is and the basically we can use the temperature distribution in case of the welding process. And this temperature distribution can be used to estimate the different cooling and the solidification behavior possible to predict or cooling rate all these parameters can we predict that can be closely linked with the micro structural phenomena in case of the welding process.

So, let us see how we can estimate the cooling different solidification parameter. So, two different solidification parameters can be defined here one is the R. R is the solidification rate or growth rate that this R parameter will be will be more explain the actual kinetics the solidification in the in the chapter that the welding metrology in that module we will be explaining this phenomenon. But mathematically this can be calculated here are the solidification rate and G is the temperature gradient. These two parameters can be considered as the solidification parameter we can do further calculation using these two parameters.

So, either here you can see G, G by R one is the solidification parameter and GR is the another parameter. So, G R is basically represents the cooling rate, but how can estimate the G and R. So, here you can see the R a change of the dimension with respect to time so that means it represented some rate that means that is called the solidification rate. And another is the G is the temperature gradient.

So, change of the temperature with respect to the distance, so that represents the temperature gradient. So, in this case, so here you can define that the weld typical weld pool is like that only the liquidus and solidus temperature and the (Refer Time: 61:41) is there between the liquidus and solidus temperature.

And the distance with respect to the center point D 0 ; that means, at angle zero or D 90 along the depth direction that we define is the distance D 90 and on the surface horizontally you can define as the D 0. So, this distance parameter can be evaluated and that actually changes with respect to time. So, here if you see to track the changes, so D 0 and D 90 or R 0 or R 90 having the similar dimension here you can see that R 0 and R 90 how it is changes. So, here R 0 changes is more as compared to the R 90.

That means the solidification rate is more in this case the solidification rate yes solidification rate is more one cases is in the with respect to the solidification time along the on the surface as compared to the depth (Refer Time: 62:45). So, on 90 value is less , but if you look to the other cases that here you can see the G, G is the temperature gradient. So, temperature gradient is actually is more along the depth direction in 90s, G 90 is more as compared to the G 0.

So, variation of the G 90, from the very high value to the low value that happens in case of laser spot welding along the depth direction as compared to the width direction; So, here if you if we if we estimate the cooling rate, so here you can see that cooling at a 90 degree at cooling rate 0 degree; that means, the 90 degree means along the depth direction the variation of the cooling rate is more as compared to the variation of the along the width direction in case of the laser welding spotting.

So, this kind of mathematical calculation of the different solidification parameter that means, temperature solidification rate and the temperature gradient as well as the cooling rate can also be estimated just to know about the time temperature profile in case of the welding process.

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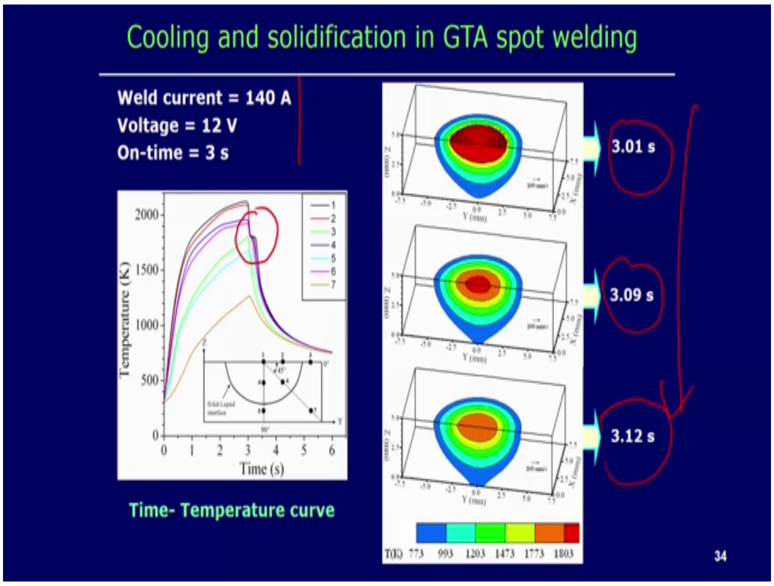

So, here further the cooling and the solidification in GTA spot welding process here you can see that welding current 140 amps voltage 12 volt and on-time equal to 3 second. So, here you can see that different a similar kind of the different characteristic point on the along the width direction or along the depth direction, we can find out the temperature distribution.

This hump also represents that the solid phase to liquid phase transformation happens over between the solidus and liquidus temperature and that can be clearly captured just simply looking into the time temperature simulation.

Here also we can see in GTA spot welding process the three second; that means, on-time was 3 second means after 3 second just switch up the heat source. Then we can follow the nature of the weld pool at the cooling phase. So, at 3.01 second, 3.09 second and 3.12 seconds at 3.12 seconds there is a disappearance of the weld molten pool.

So, these kind of mathematical calculation can also you have to analyze the physical viewer what is happening within the weld pool bottom and this kind of physical phenomena it is not always possible to capture just simply doing the experiment. So, in that way it is advantageous to analysis these thing.

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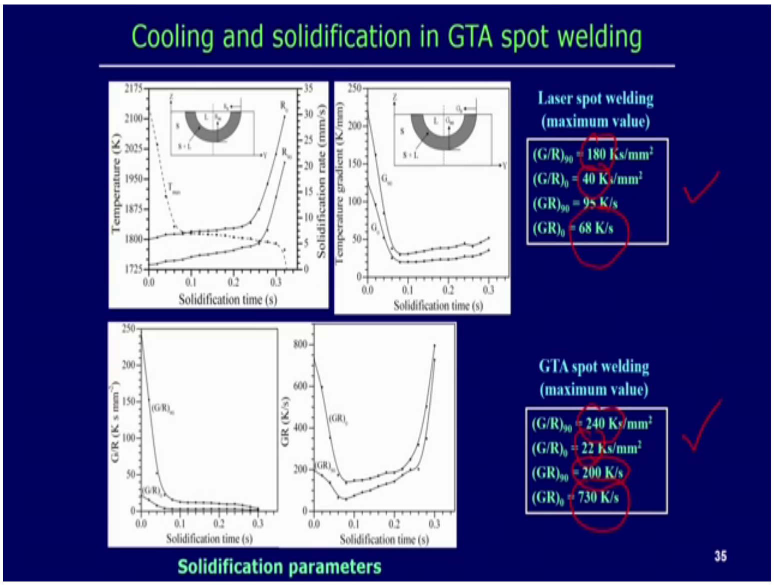

So, similar kind of calculation cooling and solidification GTA spot welding can also be done. But if we look into this comparison that G by R that one solidification parameters, and G R and if we look into that, so GTA spot welding process that G by R is very high in case of GTAs as possibly it is high as compared to the laser spot welding process. G by R that means, G by R is also other cases than at 0 degree in case of laser it is 40, but in case of GTA spot it is less.

But cooling rate is in laser which is significantly higher as compared to the GTA spot welding process. And if we see that at 0 degree that means, we found out as a 730 Kelvin as compared to the, but zero degree 730 Kelvin in case of GTA welding, but in case of laser it is less. So, what we understand that cooling rate is basically along the width direction cooling it is more in case of the GTA spot welding as compared to the less, but along the depth direction the cooling rate is more in case of the laser spot welding as case of an as compared to the GTA spot welding process.

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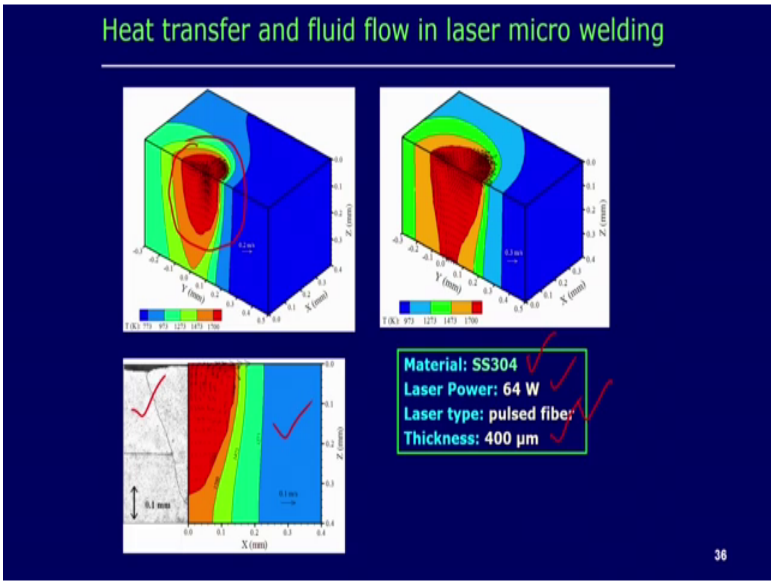

So, now we can see the further heat transfer and the fluid flow in laser micro welding processes here you can see the one cases is that in case of SS304 that only laser power was 64 what pulse fiber laser has been used. Thickness was the 400 micrometer. And we can see that the temperature distribution in the within the molten pool as well as the velocity distribution. And we can everywhere we can see the velocity distribution it starts from the center point to the outwards periphery in that direction actually we can observe the flow of the liquid molten metal happens during the welding process.

And if we see the comparison between the experimental and the numerical results and we can see that the there is a the there is some circular loop in this case that means, clockwise circulation loop or observed in case of the micro laser welding process.

And because these are this loop actually depends on the which direction the surface tension force is acting. So, if there is change of the surface direction of the surface tension force, and then the fluid that this pattern can also be change. So, we will see later on that how what is the possible way to change the this direction or pattern of the velocity field.

Thank you very much for your kind attention. The next class will try to discuss the surface active elements or then fluid flow how the surface active areas actually increases the material flow.