Advances in Welding and Joining Technologies
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Lecture – 11
Computational Welding Mechanics Part I

Good morning, everybody. Today, I will try to discuss another module of advances in laser welding and joining technologies.

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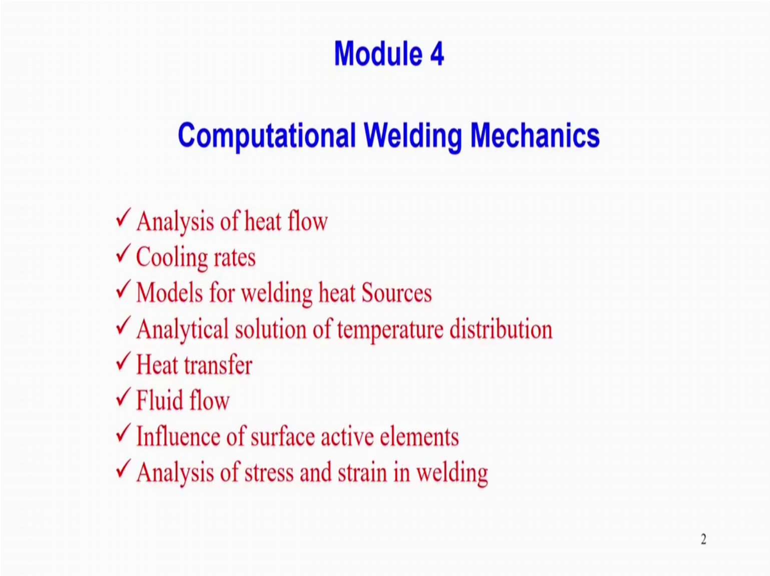

So, this module is the computational welding mechanics. Actually in this module we will try to focus on the different, but different, but very simple mathematical calculation normally follow in the welding processes. So, there are if you look into the welding mechanics that a lot of subject actually involved in this welding process. For example from heat transfer to fluid flow even at the same time we look to magnetic field also generated during the welding process. And finally, there is just some stress analysis that we residual stress is also generated during the welding process. So, there is a wide range of area actually covers this module and that is computational welding mechanics.

If you look into the subsection of this module there first we will focus on the analysis of the heat flow in the welding process. Then how to estimate the cooling rates and because we have already discussed that what is the influence of cooling rate in the micro structural changes in the welding process or maybe how cooling that affects in the solidification process of the welding that we will cover in the welding metrology section, but here we will try to focus only for the mathematical calculation or estimation of the different parameters that actually very significant in the welding process. Then we will try to look into the models of the welding heat sources because how to represent the heat sources from the different source using a welding process for example, arc, laser, electron beam, so, all these cases the presentation of representation of the heat source in the mathematical form are different. So, that we will have to focus on the how to do that kind of heat source modeling.

Then, I will try to focus on that analytical solution of the temperature distribution and then analytically how can estimate the temperature within the zone because this temperature distribution is important because we can use this tem distribution of the temperature and we can estimate the cooling rate from temperature distribution and finally, we can correlate this cooling rate and microstructure. So, in that sense we need to understand the correct estimation or distribution of the temperature and in the welding process then heat transfer mechanism. And if you try to apart from the analytical solution what are the other numerical solution can also developed in the welding process too for the solution of the temperature distribution fluid flow and that means, material flow within the weld pool and then amount of the residual stress or distortion level at the final weld structure.

So, that kind of coverage also there then will be look into that influence of the surface active elements because this phenomena is very significant theoretically that we already described what is the importance of the surface active elements in the welding process, but mathematically how we can take care of this epics of the surface active elements in the mathematical modeling of the early process that will try to discuss in this module.

And, then finally, you know what is the amount of the residual stress will be generated or what is the amount of the distortion will be generated in the final will join that is very much significant for the designing of the any component or when you try to fit in the one component with respect to the other component this distortion level analyst is just is very significant and residual stress is important to know the service life of the weld joint. So, in that respect all this phenomena is possible to estimate mathematically and that is the focus of this module.

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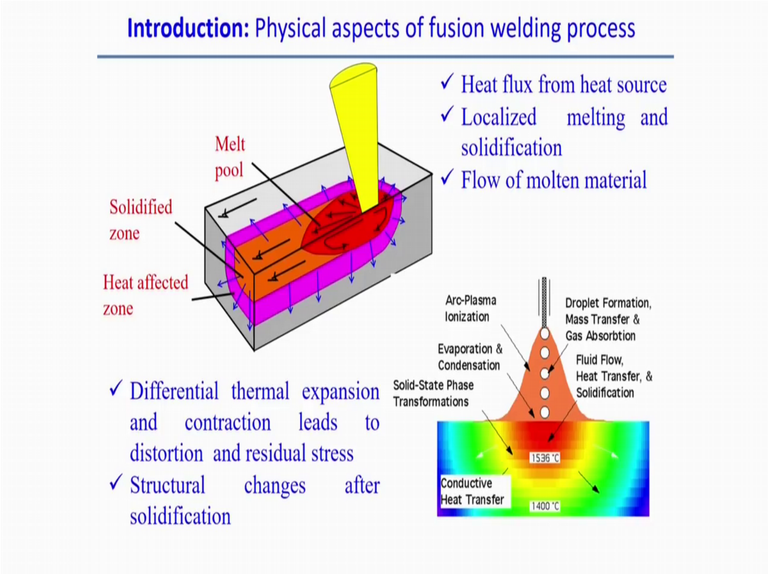

So, before doing that let us try to understand what are the physical aspects involved in the welding process. So, let us look an example here that this example shows that there is a heat source. So, that heat source comes from the laser or some electric or some electron beam or due to a resistance heating as well. So, with the application of the heat source there is a certain zone localized area the melting happens and the surrounding area also that is the heat affected zone some development temperature above the base material above the ambient temperature.

So, with the advancement of the at the same time with the advancement of the heat source the subsequently part is solidified and then apart from the solidification zone certain part is the heat affected zone. Here we can see the different zone the melt pole solidified zone and the heat affected zone from the figure itself. So, typical this is the typical characteristic. So, the if you see the physical aspect point of view here you see there is a application of the heat flux from the heat source then localized melting and solidification and within this molten pool there is a flow of the molten material. So, we often neglect the flow of the molten material, but that is that having some importance also we will discuss this one.

And, then finally, what happens there is a there is a the this variation of the temperature distributions brings some differential thermal expansion and contraction and that thermal expansion and contraction actually leads to the formation of the residual stress and distortion in the weld structure and that structural changes that due to the effect of the structural changes comes from the solidification behavior in the welded structure. So, all this phenomena actually involve in case of the this we are talking about the fusion welding process.

Now, other aspects also if we see the physical aspects of the welding process when there is involved in the metal transfer from the consumable electrode also here we can see the doublet transfer along with the droplet transport we can in the mathematical sense we can say that within the domain there is a mass transfer also happens when we using the some consumable electrode then if heat concentration is very high there is a vapor evaporation. Evaporation of the material also happens if the heat temperature is very high or maybe if the maximum temperature it is the evaporation temperature of the material. So, operation of the metal will also occur at this point of view. So, that molten droplet transfer from the some consumable electrode that actually influence on the weld pool in the sense in that molten when there is a continuous adding of the molten pool that continues adding to the mass in that domain solution domain and that actually influence the material flow within the small weld pool.

And of course, with the advancement of this consumable electrode that subsequently solidification also happen and heat lost due to the convection and radiation from the surface or inside the domain just at the solid liquid interface towards the solid domain the heat is conducted a and that finally, here when conducted a and finally, when it is come inter and on the surface there is a heat loss by the convection and radiation in that mode. So, this all this physical aspect actually involved in the welding process.

So, considering all this physical activities involved here and representation of this in some mathematical model it becomes more complex and complex. So, we can look into the one by one. So, first we will look into the thermal aspect then metal flow aspect. And finally, we look into the solidification that means residual stress or distortion aspect.

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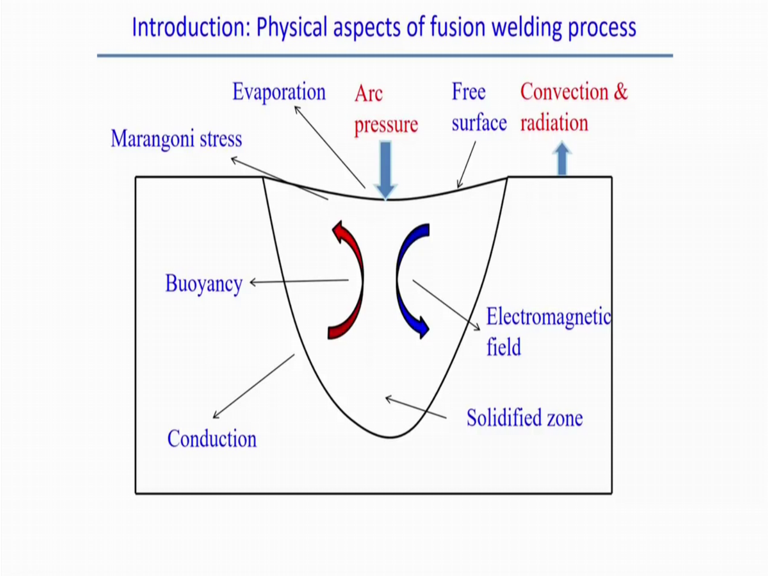

Now, if we look into that focus on the specific to the weld pool what are the different driving forces is acting because if we know of course, there is a heat conduction within the molten pool at the same time the at the outside of the solid liquid interface. But, at the same time there is a flow of the molten material and we if you see if there is an arc welding process that is not necessary the surface will be the flat which was the initial because there is a loopy arc and they say there is a acting of the arc pressure on the top surface so, that changes the free surface profile.

So, free surface can be this can be in curve having some curve having some curvature say it is not it is may not be flat. So, at the same time evaporation and on the in when there is a interaction between the arc and the molten pools, marangoni shear stress is ac actually in the on the surface; that means, surface tension force actually act when the 2 different medium come into con contact in the liquid and gaseous medium. So, at the interface definitely there some marangoni shear. So, that marangoni shear stress basically or maybe in the surface tension force actually one of the driving force that control the magnitude and the direction of the material flow within the small weld pool.

And, at the same time since in case of arc welding since there is a flow of the current involved so, that will create some electromagnetic field within the weld pool some electromagnetic field also having some influence on the material flow and of course, buoyancy forces also acts and that buoyancy force and electromagnetic force actually these two are the body force that means, these two body force is res responsible and that actually influence the material flow pattern within the weld pool what just outside the weld pool there is a conductive heat transfer also occurs and with the after sometime; that means, when the source moves from one point to other point then previous point previous zone actually solidify.

So, after solidification there is a micro structural changes also happen that is different from the base material structure. So, this microstructure changes also happens within the molten pool because the that depends on the solidification behavior of this material, but at the same time there is a micro structural changes also happens in the heat affected zone that depends that heat effected zone we can say that the solid state phase transformation also happens within the heat affected zone and then structure may be different from the solidified zone or maybe from the with respect to the base material. So, this all phenomena happens during the welding process, but there is a there is some convective convection and radiation heat loss from the outer boundary. So, this is the typical physical aspects or physical phenomena actually happens in the welding process.

Now, we will try to look into how all these aspects can be represented in to the mathematical sense.

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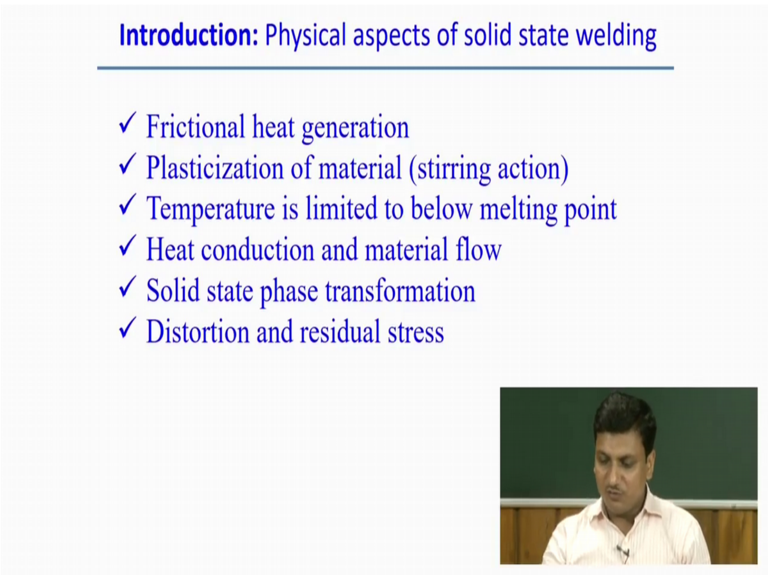

Now, before after fixed fusion welding maybe in the physical aspect of solid state welding we can see that in the solution welding process normally the heat is generated by frictional force or frictional heat generation mainly happens instead of art or laser source in case of peace and welding process. So, in solid state welding mainly a along with the frictional heat generation there is a stealing action also happens that we observe in the friction stir welding process so that plasticizer sort of materials also happens in this process then, but in this case the solution welding process the temperature is limited below the melting point temperature. So, in this case the temperature is weld below the melting point temperature. So, there is a no problem of that is related to solidification it happens in case of fusion welding process.

Then since, the maximum temperature is below the melting point temperature of this material during the solid state welding process; so here the solid state phase transformation is mainly happens and finally, the same heat conductor that we can we can we can we can see the heat transfer also happens that we normally found out through the by solving the heat conduction equation and of course, here we can model the material flow also, but in this case metal flow is a maybe we can consider a solution welding process mostly the visco plastic nature of the material and based on that we can model the material flow and most of the cases we can find out the distribution of the strain rate in case of the solid state welding process.

So, finally, like fusion early process, but there is a some residual stress generation, but distortion level in solid state welding process is normally very less as compared to the peace and relief process. Of course, these are the typical advantage of the solution welding process or difference I can say as compared to the peace and relief welding process.

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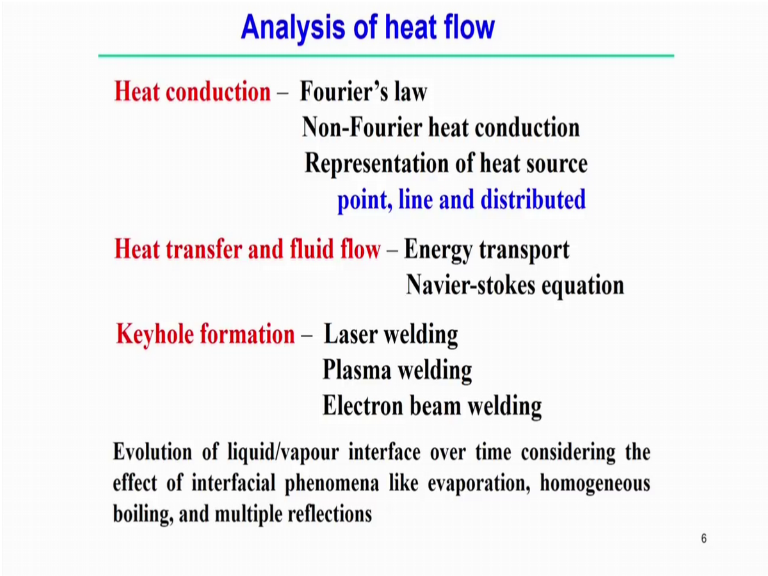

Now, analysis of the heat flow there are what way what are the governing equation or any constant equation we can use for the analysis of the heat flow or for the tempera to estimate the temperature distribution within the domain of interest. So, in case of welding process we the governing equation we consider the heat conduction equation Fourier's law conduction equation you can use it and we can we can solve for the temperature in this case of course, a non Fourier heat conduction is also important, but non Fourier heat conduction in we just apply in very specific cases.

Specifically, in case of the ultra short pulse laser welding process we in that case there is a need of solution of the non Fourier heat conduction equation we will see the difference between the Fourier heat conduction of non Fourier heat conduction in the in terms of the and the differential equation then next part is that although the governing equation heat conduction is we can solve, but how to represent is the heat source there is a definitely the representation of which says normally happens in term normally we represent in a mathematical way assuming that it is the point heat source assuming that it is can be a line heat source then means energy transport through that means, it is a string line of the source and then either it can be distributed over a certain area or distributed over a volume.

So, that is the distributed heat source. So, these are the typical division of the different nature of the heat source that we represents mathematically, but apart from the heat conduction equation it is also necessary to find out the sometimes we solve the equation of the heat transfer on the fluid flow if we more precisely estimate the temperature distribution because the material flow within the small weld pool that actually influence the heat it heat transfer or influence the temperature distribution.

For example heat conduction equation here we are. So, we generally solve only the heat conduction equation; that means, without consideration of the metal flow within the weld pool also approximately we can get some solution and that solution is acceptable, but if we try to incorporate the effect of the material flow which actually happens in the fusion welding process in that case we can improve the results at a lot or more accurately we can estimate the temperature distribution of course, at the same time the fluid flow and that means, velocity distribution within the small pool and we can explain the different phenomena associated with the fluid flow in the weld pool, but in this case we normally solve the conservation of mass movement of energy equation.

So, in this case the energy transport equation we can if we energy equation what we consider in case of the heat conduction equation, but in this case the extra term is the energy transport due to the flow field of the material. So, that term is added in this case so, then that we necessary to solve along with the heat conduction equation in this case. And, then for the metal flow analysis the you can say the mass momentum equation or mov for momentum equation we generally solve nervier stokes equation to estimate the velocity field within the small weld pool of course, as compared to the heat conduction and this heat transparent fluid flow transport equation is computationally more costly than the computational time will be more in this case as compared to the heat conduction equation.

Other another aspect is that in case of heat conduction or in case of the try to estimate the temperature distribution with the weld pool. So, in some times in case of laser welding and of course, electron beam welding and some case of plasma welding also this is a function of the key hole formation may happen. So, in this case when there is a key hole formation that key hole is a domain we within the weld pool and when practically when we use the very high concentrated laser high power density is very high that actually tried to create the keyhole formation.

So, that in the keyhole formation there is evolution of the liquid vapor interface. So, over time considering the effect of the interfacial phenomena like evaporation, homogeneous boiling and multiple depiction taking into in account and we can predict that we can develop the geometrical model of the keyhole. So, that means, we can predict the size of the keyhole in case of the laser welding process. So, otherwise apart from the keyhole if there is a conduction one laser welding process. So, only heat conduction equation or we heat transfer fluid flow equation is sufficient to predict the temperature distribution, but if when we use a very high concentrated heating specifically laser welding or electric welding condition.

In this case this is the formation of the keyhole. So, we need to consider the keyhole effect and then we can do that we can improve the simulation process than similar segments we can improve the temperature distribution processing this case. So, these are the typical aspects for the analysis of the heat flow.

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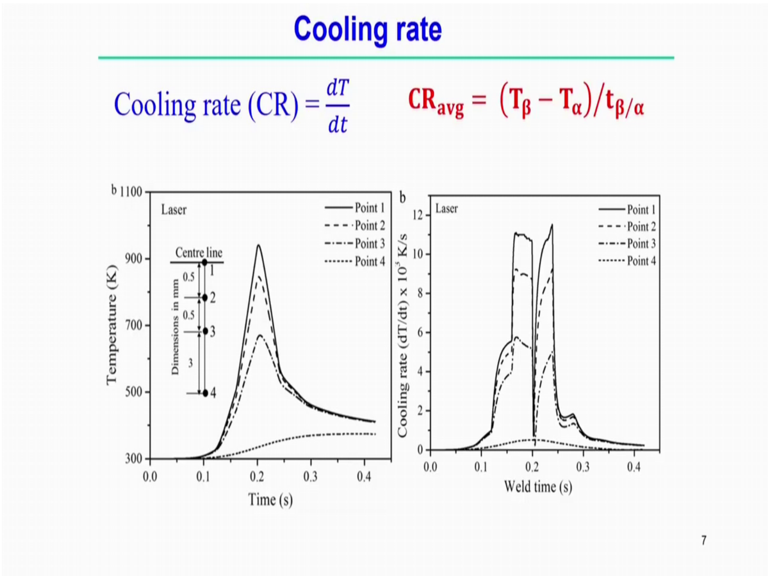

Now, we come to that point cooling rate is very significant parameter and we will see in the solidification process this cooling rate is very significant important because by looking into the cooling rate or using the information available in the phase transformation diagram for example, TTT diagram CCT diagram and continuous this type of phase transforms and diagram we can we can estimate that if with respect to the tip typical cooling rate and what should be the expected microstructure in a weld joint.

So, that is why it is necessary to estimate the cooling rate during the welding process just before cooling that means, we understand the rate of change of temperature that means, change of temperature with respect to time.

So, that is the very simplified way to represent the cooling rate, but in welding process how we can estimate in the cooling rate just let us look into these two figures. So, first figure actually represent the time versus a temperature diagram at different location in a weld zone. So, for example, if we take one specific metallic plate and we start welding from one that means, we are applying the heat source from one point and gradually the heat source is moving, but before doing that we can fix certain location into the work piece. So, that fixed location we can measure the temperature; that means, that fixed location the temperature will vary with respect to time and that depends on the at what speed the welding source is moving from one point to another point. So, that means, it is like that only so, for a fixed location this the curve represents the time versus temperatures cycle.

So, if we have this information and practically this information we generally captured using the by putting some thermocouple in the work piece and then we captured the using the data logger we can measure the data time versus temperature and if you plot it getting the typical laser. So, first you can see there is increment of the temperature we can say this is the heating pace that means, one specific point there is a gradual increment of the temperature; that means, in that location if the heat source is going nearer to that point then exactly the nearest point with that point with respect to the heat source. So, at this point it will achieve the maximum temperature.

And, then if we further move the heat source then gradually there is a decrement of the temperatures because heat source is away from that fixed location. So, temperature will decrease. So, that second phase temperature will decrease we can say this is a cooling phase. So, during the decrement of the temperature so, that basically the slope here though dT by dt, that means, change of temperature with respect to time graphically represents the slope on this curve.

So, that slope actually represents the rate of cooling what if we convert the this typical time versus temperature curve in terms of the cooling rate dT by dt and with respect to welding time we can find out that there is a cooling that actually varies, so that means, slope is not constant there is a continuous variation of the cooling rate that depends what a number of points we are considering or gap of the points we have between the two points we are considering here so, but this is the typical cooling rate versus welding time that time so, there is a variable cooling rate.

Now, to this variable cooling rate it is very typical to predict the actual microstructure and to link with the cooling rate. So, to avoid this kind of situation we can represent the cooling rate in that means, we can say the average cooling rate value. So, average cooling that value if you see the expression of the average pooling that value T beta minus T alpha divided by t beta by alpha that means, here T beta and T alpha is the two different phase that in the mike in the structure microstructure different phase.

So, different phase the change of the phase have happened from one temperature to the other temperature that gap phase change temperature of the beta phase what is that temperature and corresponds to the what is the fastest change temperature correspond to the alpha phase. So, that means, over the duration of this phase stressed temperature and what is the corresponding time is required that ratio we can represents the average cooling rate.

So, in that way we can this average cooling rate estimation it is kept some information but, over duration of the time what is the duration of the time is required to change one phase to another phase and width in terms of their temperature. So, that is why if we do that then we can we can find out the average cooling rate. And then we can more precisely predict the or maybe link this average cooler with respect to the typical a microstructure will discuss further on this analysis that how we can estimate the cooling rate also.

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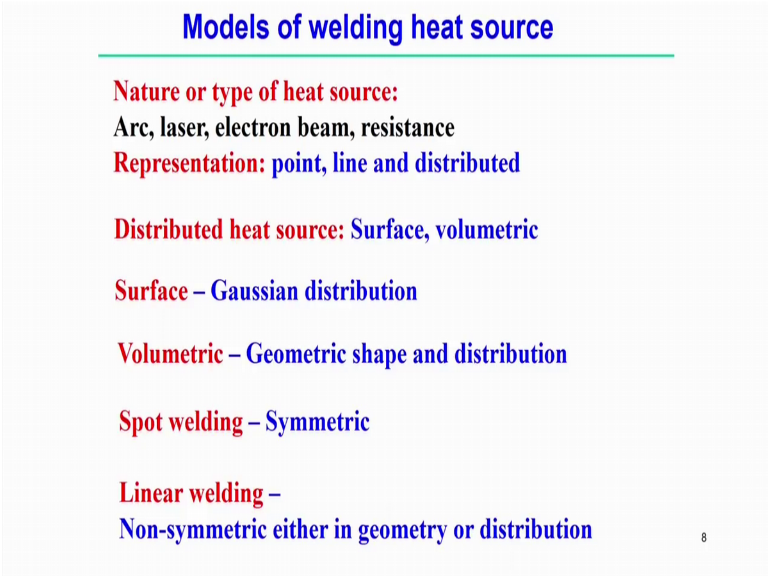

Now, I come to that point of course, there are different way to represent the heat source. So, that here I am trying to look into that models of the welding heat source that is one of the very important aspect in the computational welding mechanics. So, to understand that how to represent the heat source in here, but if you look into that nature or type of the heat source can be different; that means, it can be practically the heat source can be from the arc heat can be come from the laser also heat source can be electron beam it can be resistance. So, all the different type and nature of the heat source are different, but mathematically representation is like that we can represent the heat source starting from the point line and distribution looking into that looking into the nature of the heat source.

For example, it is a laser actually focused in the very small area. So, it is better to represents the laser as a line heat source, so that means, about the length of the line it is a string of the energy that acts as a source of the heat and that source of the heat we finally, if we apply on the work piece surface and that will generate the amount of the heat. So, that is one example for example, arc. So, it is better it is not a good idea to represents the art because arc heat source is more distributed; that means, it is not concentrated in very small zone like laser. So, arc can be represented as a distributed heat flow.

So, like that it is a representation mathematical representation from the very simple point to the very more realistic for example, point and line heat source it is not actually realistic, but realistic is the representation of heat source is more distributed and that distribution may happen over the surface or distribution can be considered over the volume also. So, that distributed heat source to nature are the surface it is source or volumetric heat source that is the more realistic heat source then volumetric real volumetric sorry surface heat source and the normally follow the distribution over a surface itself follow the Gaussian distribution, normally Gaussian distribution means at the center point if the heat intensity is maximum and it gradually decreasing to the boundary of the well defined zone.

Then, volumetric heat source, but volumetric when you try to represents the volumetric heat source we can assume the as a certain time there is a heat that certain predefined volume can be represents at the source of the energy, but when these two aspects are involved in the representation of the volumetric heat source one is the geometric shape; geometric shape; that means, what way the how what way we generally represents the volume of the volumetric source so, that normally represents in the regular geometric shape.

For example, ellipsoidal double ellipsoidal that kind of or conical that is the regular geometry shape sometimes we use these two you geo define the geometric shape of the volumetric and then second point is the distribution; that means, over this geometric shape how the energy is distributed that means, it is not necessary that throughout the volume the uniform distribution it follow. That means, throughout the volume it is better to represent the volume at the one specific sent that means, one specific center front the heat intensity will be the maximum and then gradually it can decreasing that type of nea that type that means, that Gaussian distribution most of the cases we follow. But, of course, other type of the distribution can also be followed.

Then another aspect is the two representation of heat source that whether the nature of the heat source or representation to the heat source is symmetric or non symmetric and what way we can decide whether it is symmetric or non symmetric. For example, in case of a spot welding a spot welding this heat source can be represented as a in a symmetric nature, but in case of linear welding; that means, when there is a movement of the heat source when there is a movement of the heat source with respect to certain plane the heat source is non symmetric either in that non symmetric can be represented either in geometry or can be present it in either distribution or both.

In that way we can represent the different type of the heat source. So, we will we will discuss more on that.

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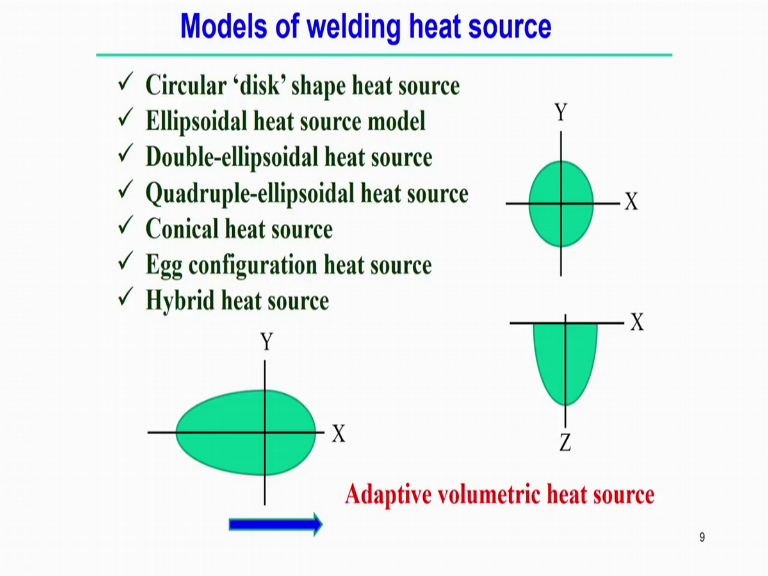

Here models of the heat source or in welding terminology or maybe in the in case of welding process we can find out the different type of the heat source model developed so far until is developing and the other type of heat source models in case of welding process. First is that circular disk shape heat source model, then ellipsoidal heat source model, double ellipsoidal heat source model, quadruple ellipsoidal heat source model, conical heat source model, egg configuration heat source model, hybrid heat source model. So, these are the typical names that we using in case of the welding simulation that depend up with the heat source model, of course, there is much more, but here I am trying to make you understand that what way we can represent the heat source. So, let us look into this first figure.

So, here on the X, Y plane we have we considered the simply one circle. So, that means, on this circle so, this type of, that means, we assume that there is a surface heat flux so that means, heat in terms of the flux it is intensity or is the one specific point at the center point at the origin point the intensity is the maximum and then it is distributed throughout this area surface area. So, at the center point it is the maximum intensity is maximum and then gradually if you go towards the periphery of the circle. So, gradually it is or boundary the gradually it is decreasing.

So, these are the this way will represent the Gaussian distribution of the heat source and over the surface and that this type of heat source normally you use in case of the spot welding that means, when there is a no movement of the heat source. So, that means, for the stationary heat source typical we use the surface heat source, but this surface heat source is limited when the sheet thickness is small or maybe heat intensity is very small. So, surface heat flux or surface heat source model is more representative, but if the intensity is very high intensity sphere then means in that case we consider generally the not surface heat source model that we can say volumetric heat source in that case we represent the volumetric heat source that means, the heat is distributed over the volume.

For example, if on the top surface it is on the circular shape then it can be like that on the along the Z axis and the on the X, Z plane it we can represent this as a is a kind of ellipse part of the ellipse. So, that means, over the surface the circular, but at the depth direction if you in the X, Z plane it can be like ellipse. So, therefore, if you represent the incase of spot welding, but a spot only, but if heat intensity is very high, then we can use the ellipsoidal heat source model. This is one kind of the volumetric heat source model. So, that ellipsoidal heat source model in the first and second figure that represents the ellipsoid a heat source model, but there is a other things that is the case for the spot welding.

But, if the heat source moves then what way we can represent the heat source; that means, in this in this case the since the heat source is moving in or may be in practical arc or laser is moving on specific direction. So, in that case it is not necessary with respect to the one plane it looks like exactly the symmetric nature. So, here the brings the non symmetric nature of the heat distribution as well as the geometric shape of the weld pole which since, there is just some finite amount of the velocity one specific direction. So, in that case then that means, in that case it is called generally linear welding.

So, in case of the linear welding then normally we use the double ellipsoidal heat source model of course, we can use the volumetric heat source model, but the volumetric source model just merging the part of the two ellipsoidal heat source model. So, then it becomes the double ellipsoidal model here you can see that third figure. So, with respect to the Y axis with respect to the Y the Y axis the front side is the one ellipsoidal and the back side we can with another ellipsoidal, but such that exactly the one parameter is the same in this case and we can consider that merging the two ellipsoidal and we can create the double ellipsoidal heat source model that is a better representation of the moving itself for the high intense high intensity laser or electron beam or some of the high intensity arc also. So, within that case this is a representation of the heats volumetric heat source by a double unit by merging the two ellipsoidal. So, that is called double ellipsoidal heat source model, then comes into the picture the quadruple ellipsoidal heat source model.

So, quadruple ellipsoidal heat source model you say is simply nothing, but instead of the two ellipsoidal here we can use the four ellipsoidal heat source and we can merge it this geometry shape take into account the two non-linear non symmetric nature one non symmetry in nature is that due to the welding movement in one direction other is will be the due to the two different material when you try to join two different material. So, two different materials the energy absorption or that will be different because of their thermo physical properties are also different.

So, in that case so, two to account all this non symmetric nature and the energy distribution for the material A and material B at the same time due to the linear movement in one direction we can merge the four ellipsoidal together and we can create this quadruple ellipsoidal heat source model. Of course, sometimes people use the conical heat source model because conical heat source model is the in this case when the temperature gradient is very high along the depth direction maybe specifically for laser welding process. So, because heat intensity is very high so, in that case we can use the represents the geometric shape of the heat source as a conical and we can follow the other distribution also.

And, recently there is a development of the a configuration heat source which we will discuss that the looking into the distribution simply modifying that ellipsoidal heat source model we can convert we can develop the a configuration heat source model and sometimes people use the hybrid heat source model; that means, by combining the conical and the ellipsoidal certain part will be ellipsoidal source and certain part will be the conical heat source to present the complex nature of the welding process or may be in hybrid welding process the representation of heat source people normally use the hybrid heat source model by combining the two different regular geometric shape and then develop the heat source model for in that case.

But, one point is that there is a one another type of the heat source model that is called the adaptive volumetric heat source model. So, adaptive volumetric heat source model this is introduced in the sense that there is a this all these heat source model when you try to apply in the in simulation of the welding process we need to pre define all the parameters for example, geometric parameters of the ellipsoidal source or maybe geometric ellipsoidal or geometric parameters for the conical geometric parameters for the double ellipsoidal.

So, to avoid these things if we continuously adapt the with respect to the analysis time step or with respect to the load step if you continue continuously adapt the shape and size from the estimation of the temperature from profile; that means, estimation of the weld pool profile and that directly map continuously with can with the geometric shape and in that way we it is possible to develop the adaptive nature of the heat source. So, in that case it is not necessary to predefined all the geometric parameters in this case. We will discuss in details the adaptive volumetric heat source.

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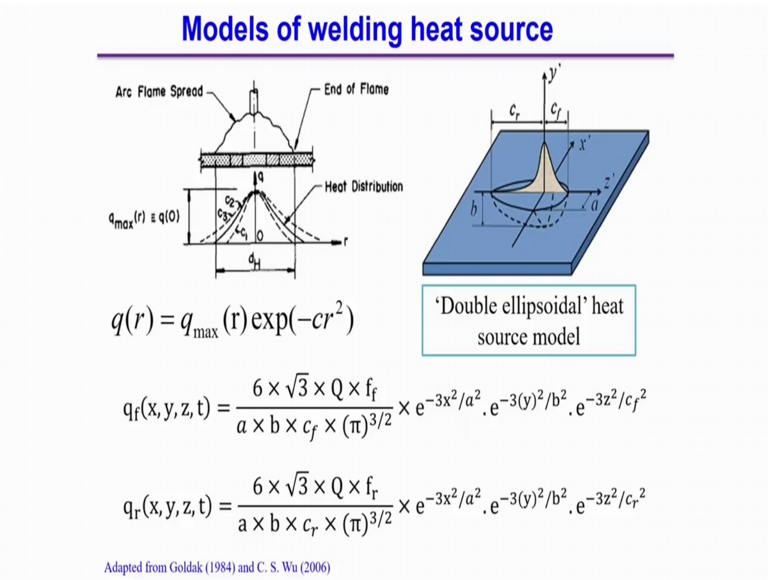

Now, we start from the models of the heat source were just look into that dicks type of heat source here you can see that top figure it is a representation of the art normally we can see the end of the flame happens over a certain boundary that with respect to the center and this is this follows generally typical Gaussian distribution. Now, this heat distribution in mathematical representatives of the heat distribution we can use this equation the q r that is means q the heat intensity at a radial distance r equal to q max; q max means at r equal to 0 what is the maximum intensity and how it is vary with respect to the maximum value it starts from the maximum value and gradually dec decreasing with the exponential way.

So, e x p exponential way and that minus c into r square; c is the distribution coefficients, actually the c by varying the value of the c we can represents the distribution whether it is very stiff or whether it is very flat that actually decided by these parameter distribution coefficient c. So, this is the typical representation of the surface heat flux that we can follow we can see in the welding process.

Now, there is another representation that is the double ellipsoidal heat source model. So, here also if we see the figure that at the there is a dis two parameter geometric parameter of the double ellipsoidal is like that c f and c r that brings the distribution of the because temperature gradient or maybe energy deposit in the font and the backside of the will may be different because of the velocity in one direction and then a may be another dimension of the ellipsoidal and depth represented by the b, so a, b, c f and c r all geometric parameters of the double ellipsoidal of heat source.

And, then if we know the geometric parameters or if you can define the geometric parameters we can represent the distribution or heat flux that, but that heat flux distribution of the heat flux over the volume can be represented by the first these two equation first equation and second equation, but different of these two equation is that we can not even distribution of the energy in the front part of the ellipsoid and the back side back part of the ellipsoidal can be taken care of by these two factor f f and f r these two fraction actually brings the difference in the non of energy distribution in the front and the back side of the ellipsoidal double ellipsoidal the heat source model.

So, here if we see that q f as a function of x, y, z and time t we can represent this thing and here q capital q represents the actual amount of the heat is applied to this is. So, the this q can be estimated that what is the effective amount of the energy is transferred to the work piece from the laser either from the laser or from the arc. So, we will see how to estimate this key.

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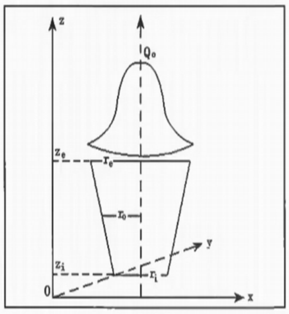
Models of welding heat source



‘Conical’ heat source model

$$q_v(r,z) = \frac{9 \times P \times \eta \times e^3}{\pi \times (e^3 - 1)} \times \frac{1}{(z_e - z_i) \times (r_e^2)} \times \exp\left(-\frac{3 \times r^2}{r_o^2}\right)$$

Adapted from Goldak (1984) and C. S. Wu (2006)

Here how to represent the heat source is that this is the one typical conical heat source model here you can see the conic we can consider the truncated cone geometric shape and on the top surface is the distribution can follow the Gaussian distribution; that means, at the center it is a maximum (Refer Time: 41:16) and gradually decreasing and then typical estimation that flux density distribution and can be formed in this way of the P basically is the laser power efficiency and all geometric parameters e radial distance r, z, e and z i geometric parameters of the cone with respect to the certain coordinate system.

And, then if we define all these parameters we can easily define the conical heat source model also.

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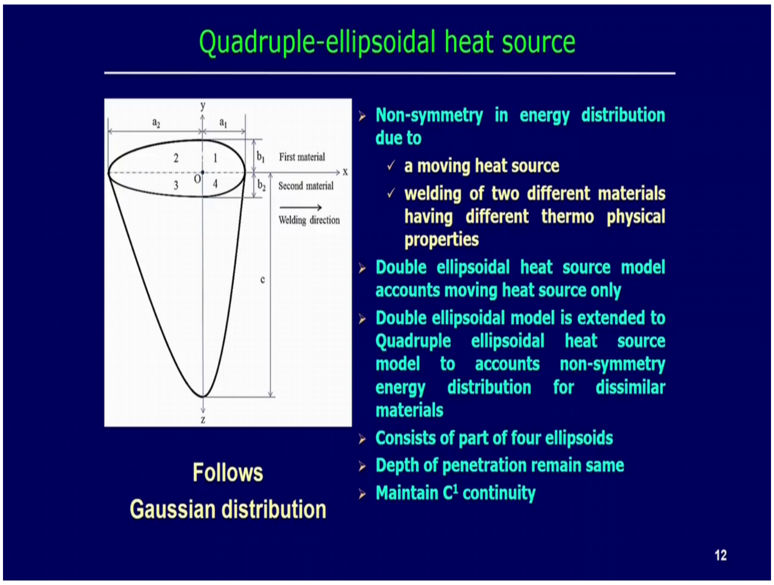

Here you can see the quadruple ellipsoidal heat source model and so, here if you look into that figure there is the march of the four ellipsoidal here we can see that 1, 2, 3, 4. So, with respect to the x axis the if you consider the x axis upper side is the that first material with one material and the other side is another material, second material. So, that since the two materials having variation in the thermo physical properties so, therefore, not symmetry energy distribution will occur between these two metals, but in term what since the non symmetry energy distribution then this is the one way to represents the heat source or to bring the difference in the heat source model. So, that is why this dimension of the ellipsoidal the parameters in the first material one material and the other material will be different in this case.

So, non symmetry energy distribution due to one reason is that two different materials and another reason is that is this is another moving heat source. So, when you want to take care of the moving heat source then we can consider the non symmetry with respect to the y axis. So, non symmetry with respect to the y axis as well as non symmetry with respect with respect to the x axis for the two different materials. So, then we merge the 4 ellipsoidal part of the ellipsoid here 1, 2, 3, 4 and we can make this ellipsoidal heat source quadruples ellipsoidal heat source.

So, of course, because here you can see the double ellipsoidal heat source model only accounts the non symmetry in terms of the moving heat source only double heat source model is here the double heat source model we can simply extend in terms of the quadruple ellipsoidal heat source model two accounts the non symmetry energy distribution and simply contents of the four parts of the ellipsoidal ellipsoids and then, but this one thing we have followed here that depth of penetration and that means, depth of penetration even the same and of course, maintain the C 1 continuity, that means, when you merging this thing the four ellipsoids in this case and that the slope at this point is a there is a the continuous slope at this point. So, there is no mismatch in the slope as well as continuity is also there.

So, that is why we are maintaining here the c one continue to develop this heat source model.

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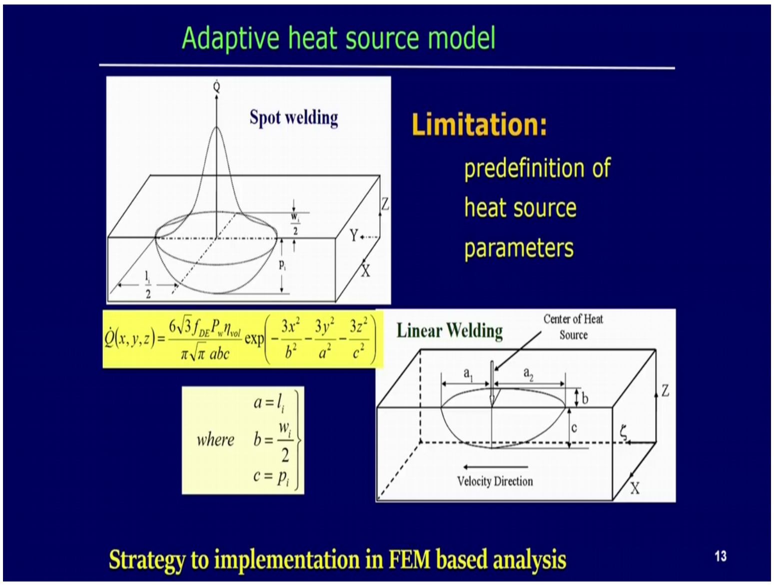

Now, adaptive I have tried to represent the adaptive heat source model we use in the welding process. So, one if we see the in case of spot welding process there is a definition of the that means, volumetric heat source can be represented by defining the by assuming the equation of the or assuming the geometric sub of the ellipsoid. So, here that ellipsoid the once we define the ellipsoid, but that parameters geometric parameters of the ellipsoidal can be vary with respect to time what can be vary with respect to the load step.

And, we have already mention that we are doing the adapting heat source model because the all other heat source model here it is necessary to predefine the heat source parameter. So, before start of the simulation for the temperature distribution we need to define all the geometric parameters of the heat source and then we can use these volumetric heat source for the for the temperature simulation, but in adaptive it is not necessary to predefine, so, in that sense it is advantageous or maybe one a development happens in case of the simulation of the welding process.

So, in adaptive welding process we can use the same distribution equation what we consider in the ellipsoidal or double ellipsoidal heat source model, but only thing is that there is a continuous changing of this geometric parameters with respect to time if we use the transient analysis or with respect to the load step if we do some steady state analysis. So, definitely this adaptive volumetric heat source is should follow some strategy for the implementation of the any finite element base analysis.

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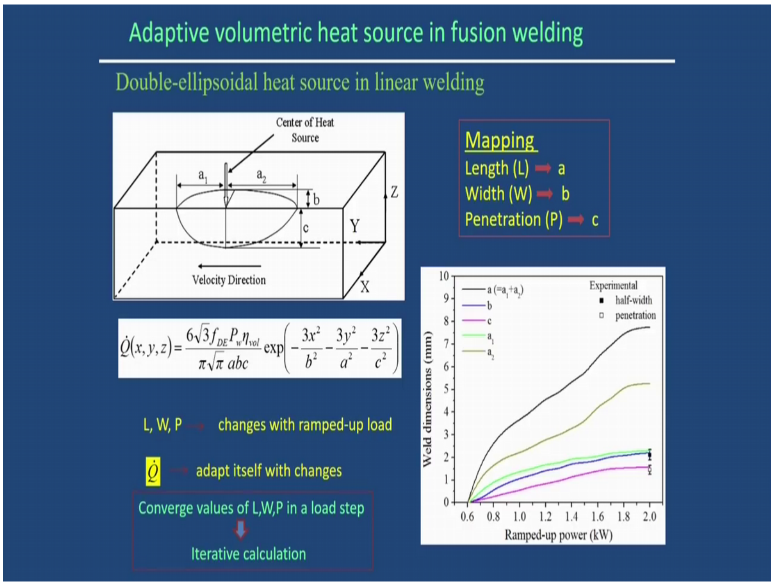

In case of adaptive volumetric heat source in case of infusion early here you can see specifically when you try to apply in case of steady state analysis because steady state analysis the development of temperature in one specific point we can observe, but it is not a function of time; so then how to adopt how to change these parameters; that means, how to change this heat source parameters. So, here you can see that the distribution equation source is say the heat source changes; that means, the distribution is over the space this is no time function here and we see that double heat source with geometric parameters; that means, length width and penetration a, b, c the length these things we are simply mapping a length on this with the geometric size of the volumetric heat source.

Now, if you look into that figure this is a continuous development of the; that means, operation of the weld the different parameter. So, we see the double ellipsoidal heat source model a, b, c and then these are the three parameter or a is basically a 1 plus a 2; that means, due to the linear movement a 1 and a 2 and other 2 parameters b and c. So, all these parameters evolve with respect to the ramped up power, that means, normally we do the steady state analysis in the during numerical simulation not directly putting the whole power in a single step rather total power we can divide into number of steps, that means, we can divide in that is called the load step.

So, each and every load step we can update the value of thus geometric parameters of the double ellipsoidal heat source and then and then once updating then there is a gradual changing of the volumetric heat. So, that means, with this that updating is happens with respect to the ramped up power here, as compared to the transient analysis because in transient analysis this mapping or changes of these geometric parameters actually happens with respect to time, that is the difference. So, in this way we can implement the adaptive volumetric heat source.

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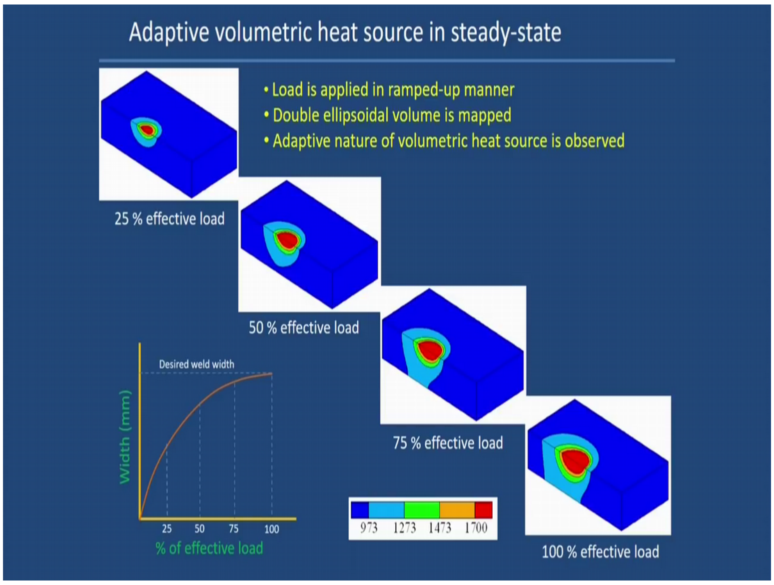

We can show some simulation also that adaptive volumetric heat source in steady state situation here you can see the in the first figure actually we actually apply the 25 percent of the effective load that means, we can say suppose our total power in the steady state welding process is 1 kilowatt. So, therefore, after application of the 20 to 50 watt power this is the typical size of the weld pool here you can find out the weld pool; that means, red color is mainly represents the molten pool zone and remaining other colors actually represented depending upon the phase that heat affected zone just looking into the different phase transfers and temperature here. So, then when the 100 percent effective load is happening then that means, we completely application of the 1 kilo watt power then there is a this is this represents the that shape or size of the weld pool so, which is different from the first figure.

So, this way we can see there is a continuous development of the weld pool, but during this continuous development of the weld pool with respect to the ramped up power here each and every step there is an updating of the volumetric heats geometric parameters of the volumetric heat source. We can see from the figure also that width and the effective load step there is a gradual increment of the effective load and there is a variation of the width. So, that means, from the very beginning the 25 percent effective load there is a small width and gradually increasing and almost up the certain time on 100 percent load it reached the steady state situation and that is actually implemented using the adaptive volumetric heat source.

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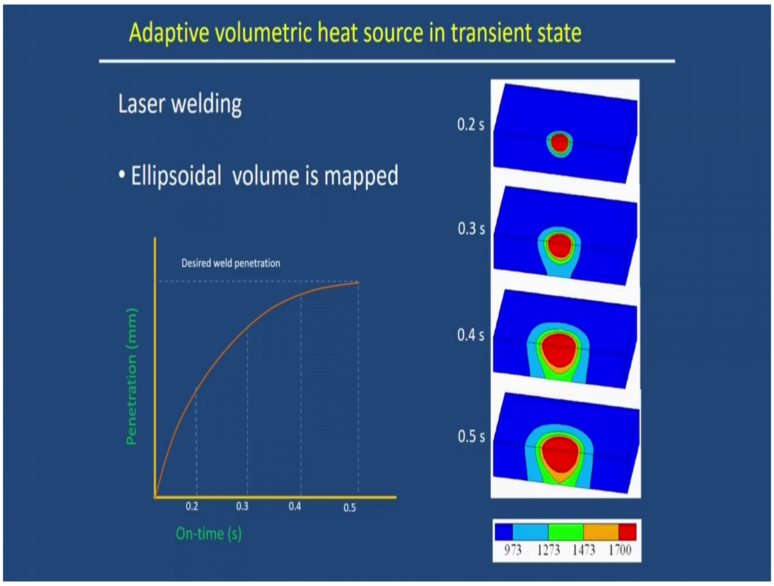

And, but one point like to mention that this adaptive nature of the heat source is independent of the geometric shape and size this can be implemented by assuming the any other geometric shape and size of the volumetric heat source for example, not only limited to only the ellipsoidal double ellipsoidal heat source we can assume the any other geometric shape of the volumetric heat source and the similar fashion we can apply the concept of the adaptive volumetric heat source for the simulation of the welding process.

So, here we can see the adaptive volumetric heat source in the transient state. So, transient state also in case of specific welding process and we assume the ellipsoidal volumetric heat. So, the geometry except the volumetric is as assume as a ellipsoidal. So, here you see 0.2 second there is a development some weld pool developed or gradually it is increasing and when it reach to the 0.5 second that will pull size is bigger. So, throughout this step time step the different times to are maybe you can say that at different time there is a updating of the geometric parameters and we can see that from the figure that penetration and the on time that means, laser on time continuously we give putting the laser on time there is a gradual development of the weld penetration; that means, 0.2 there is a less amount of the penetration, but when you reach that point second the penetration becomes very weak.

So, there is a continuous development of the weld pool and we are doing the simulation just simply this growth development of the weld pool that means, we measure at any step at any point of time what is the size of the weld pool and that size is simply mapping with the size of the volumetric heat source.

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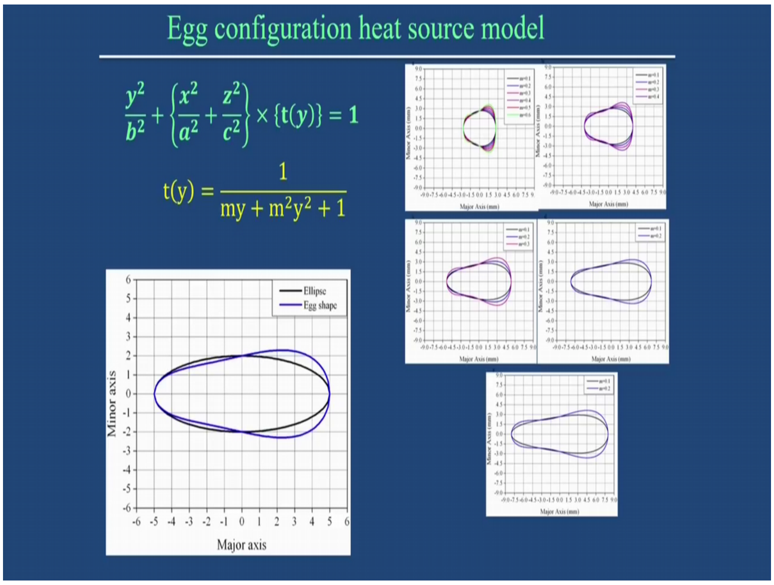

There is another type of the heat source that is called development happens that is called egg configuration heat source model. Here you can see the equation is basically we use the ellipsoidal when you try to develop the illustrator heat responded we use this equation, but if we use just multiplying the factor t y any functional form we can modify the equation a different way.

So, egg configuration heat source model just simply modifying the ellipsoidal equation and by introducing some functional form the in this way; that means, x square and z square that is modified by the t y, that means, this function alpha as a function of y here, then we can develop the different shape we can generate the different shape of the different geometric shape. So, that is called typically called the egg configuration heat source model. So, looks like an oval shape or maybe you can say the egg shape.

So, if you see this figure that if we change this parameter because t y 1 by we consider the one that this functional form is the 1 by m y plus m square y square plus 1. So, here by simply changing the value of m we can generate the different shape. Let us see that here different shape can be generated or we need to optimize the what may be typical value of the m such that we can use this geometric safe for the whirlpool simulation. So, in this case if t y equal to 1; that means, t y equal to 1 it is the simply representation of the equation of an ellipse. So, that means, that is equal if t y equal to 1 that it becomes equivalent to the ellipsoidal heat source model.

So, here you can see the difference between the ellipse and the egg shape. So, in certain ellipse is the is a very symmetric with respect to this thing and most of the cases is we merge the two ellipse ellipsoid and we generally generate a double ellipsoidal heat source model to merging the two ellipsoid. So, in this case double ellipsoidal heat source model actually the number of parameters are more, but we can reduce this parameter by simply looking into this concept by checking the geometric shape that looks like an oval shape or looks like in the egg shape simply the modifier you modifying the equation of the open ellipsoid.

So, this can be incorporated in the weld for modeling of this thing that is the one of the modeling approach, how you can apply that egg configuration heat source model.