**Finite Element modeling of Welding processes**
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**Lecture - 21**
**Implementation of FEM for fluid flow in fusion welding processes**

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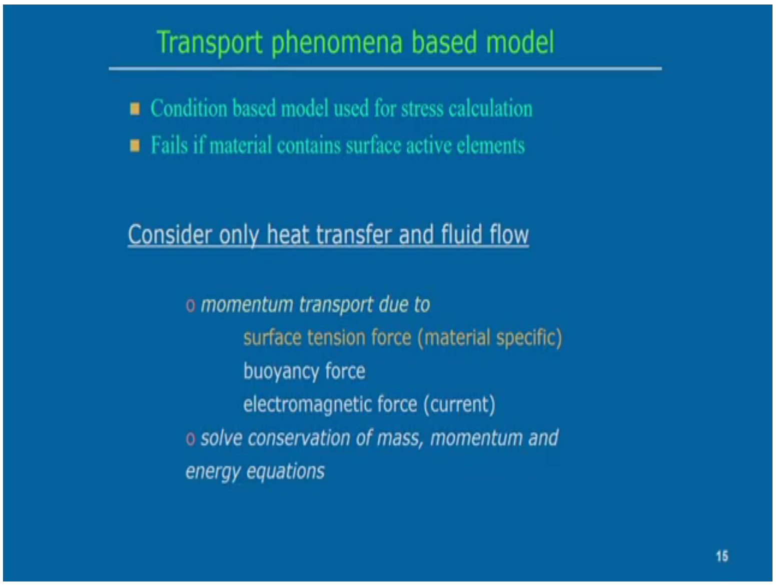


Hello everybody, now today we will discuss regarding the material flow model in case of fusion welding process. We have already seen that of course, you can get the temperature distribution if we solve only for the heat conduction equation with the appropriate boundary conditions, but in that conduction based model there is a need to define some sort of the volumetric heat source in most of the cases and specifically I am talking about the laser welding process.

So, there is a scope to develop some sort of volumetric heat source model different way also and that can be incorporated into the heat conduction model to get the temperature distribution, but in case of the heat transfer and fluid flow when you are incorporating the effect of the material flow with the actual in case of the fusion welding process.

In that particular case then you can apply only the surface flux and then accordingly surface flux and since we are taking care of the actual material flow within the small weld pool. So, therefore, in that cases not necessary to explicitly develop some sort of volumetric heat source model.

So, only the surface heat flux or surface interaction of the heat source is that is sufficient to account the heat transfer within the particular volume by incorporating the effect of the material flow. So, we have already seen that what are the driving forces for the material flow and maybe which cases the material flow analysis is significant that we have already discussed.

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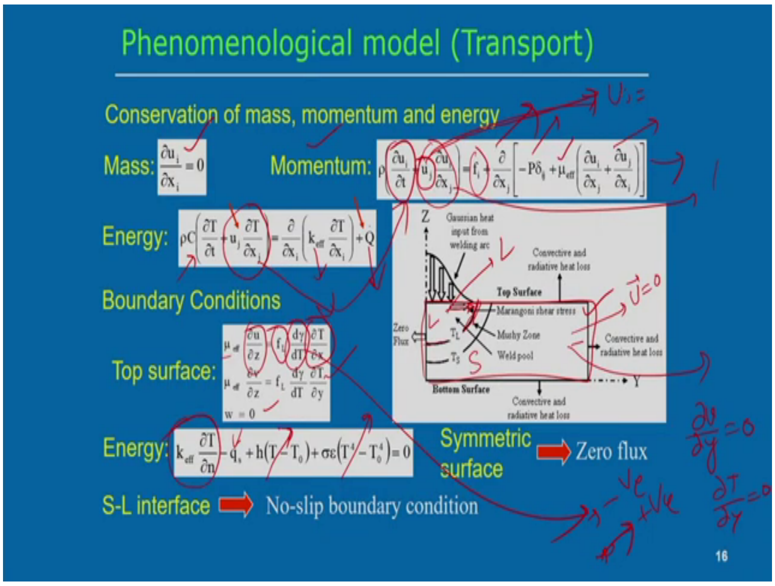

Now, we will try to look what way we can develop the model. So, that is called we can say the phenomenological model a transpose phenomena based, heat transfer and fluid flow model. In that case there is a need to solve the conservation of the mass momentum of energy in this case also, but if you see look into the governing equation as well as the boundary condition and how it is different from the conduction based heat transfer model.

So, we can see the mass conservation which basically we are looking into the continuity equation we have to consider in this particular case, then momentum equation momentum due to the material flow we can consider the momentum equation we have already seen that.

In case of momentum equation the different terminology also see there is a one thing is the this is the convective within the liquid weld pool the convective flow of the which is driven by the material flow. So, in that case this term is there and pressure term is also there and of course, apart from this is the effective viscosity we normally use this thing and this is the body force associated with the material flow.

That means, this body force is basically we can takes care of the what are the driving force which is distributed over the volume of the solution domain, that we can incorporate by this particular term. And remaining the viscosity because we assuming the viscous flow in this particular case.

So, therefore, some sort of viscosity will be there and, but in this case it is better to look into the what is the value of the effective viscosity. Because it is very difficult to define the value of the viscosity because within the small weld pool there is a strong convection current is there or sometimes it can reach to the turbulent flow.

But in the light of the laminar flow if we assume the laminar flow, but till the effect of the turbulence within this material flow is the simply way the simplified by looking into the effective values of the thermal conductivity and effective values of the viscosity. So, then in that cases although the over the we are assuming the laminar flow of the liquid, but carefully we have to estimate what is the effective value of the viscosity.

So, that is why there is a need to incorporate the effective value of the viscosity in the when you try to solve the momentum conservation equation. Now, apart from this thing there is a need to solve the along with this momentum mass momentum also you need to solve the energy equation. Then in this you can see the energy equation is also explained in this way the if we this tangent state also, then in that case we can see that this term is there and this term you can see the velocity component is involved in this case.

So, it means that when you try to solve the energy equation we need the information of the velocity field and then because that term was absent if you consider only the heat conduction equation. So, in the kind there is do not have the scope to incorporate the effect of the material velocity also.

So, in that cases we normally neglect this part. And the remaining terms are same as what way we consider the simple heat conduction equation to solve to get the temperature distribution. So, in that way, so then to get the actual energy equation then we need the velocity field and that velocity field will be coming from the solution of the momentum equation. Then we can take as input and then we can estimate the we can consider the energy equation we can solve accordingly over the finite element domain.

So, here we can see there is a effective thermal conductivity is also used and there is q dot term is used, but q dot term is normally in normal conventional what way we have discussed this thing that the arc welding processes specifically the laser welding and arc welding processes.

I am not talking about the keyhole mode welding processes, but simply conduction mode laser welding process and arc welding processes. Then there is no need to incorporate the effect of the internal heat generation term q dot term we can neglect in this case. Because accounting the heat flux through the surface is sufficient to represent the heat source in this particular problem; particular problem means when you are incorporating the effect of the material flow.

So, now once this decide the governing equation and this governing equation is solved, what is the solution domain for this governing equation? That we have to look also. Now if we look into the suppose this is the total domain and we have considered the symmetric part only and then put the symmetric surface with the zero flux.

But if we assume this is the total solution domain so, there is a some domain we can decide the liquidus temperature that domain. So, this is the domain. So, it is in the liquid state and remaining out if we assuming the one single temperature say liquidus temperature. So, that is differentiate with the liquid state and the solid domain.

So, then fluid flow is basically applicable in this liquid state. So, that means, in the in this particular domain it is a very small domain fluid flow is active and the, but in the total domain and here total domain we need to solve the energy conservation equation, but in this case in the solid domain energy conservation equation the velocity of effective is basically 0.

So, it is a simple heat conduction equation we can solve in this domain, but when within this liquid domain also, here we can solve the conservation of mass momentum and energy equation. So, therefore, in this liquid domain we wants to solve the energy equation there is a scope to incorporate the effect of the velocity field to decide correctly decide the energy distribution during this process during this fusion welding process.

So, that is way we can differentiate all these things, that which what is the domain, which domain there is a what kind of governing equation we should solve and other domain what kind of equation we solve. But it is actually in finite element when you try to look into the finite element based method, it is very difficult to separate out the domain, but at the specifically more difficult to incorporate the effect of the boundary condition.

So, what simple way to consider because in that cases the very simplified way to consider the whole domain, I talking about this whole domain and you can solve for the energy equation as well as the momentum conservation equation for the whole domain.

But in the solid domain simply when you try to implement the energy momentum conservation equation in the solid domain, the simple way the in the solid domain the artificially increase the viscosity term is very high.

Such that the solid domain will be showing almost the velocity will be showing the even if get the solution of the velocity field the velocity field will be showing equal to 0. So, that is the simplified way to incorporate the total domain whole domain and then you can solve the what the conservation of the momentum equation as well as the energy equation and artificially increment of the viscosity value in the solid domain and then this solid domain such that velocity will be 0 in this particular the in the solid domain.

So, this is the way to track the solution of the conservation of the mass momentum energy equation in associated with the fluid flow in case of welding problem. Now, boundary condition we can see boundary condition on the top surface though. So, we can see there are Marangoni shear stress will be acting on the top surface.

And this thing if you see depending upon the presence of the surface active elements or not this shear stress will be acting outward or inward direction or maybe I can say that rather we can there are two components are there the shear stress we can see the del u by del z and mu effective del u by del z on the top surface.

Suppose this is the shear stress component can be define f l, f L is the we can see that in particular element is totally filled by the liquid phase then we can consider f L equal to 1. But one particular element partially filled by the liquid, but partially filled by the solid domain.

In that cases we can put some value some fractional value f L and then we can account this thing, we will see the next stage also that next slide also to explain the what way we can account the partially filled element which is partially filled by the liquid phase. So, that f L can be accounting accordingly, now del T by del x the temperature gradient is the from the temperature we can temperature distribution we can easily estimate what is the temperature gradient.

Now del gamma by del T that coefficient can vary this value can vary depending upon the what is the whether there is a presence of surface active elements or no. So, in mathematically we can taking del gamma by del T this value as a this can be a strong function of the surface active element. So, it is a surface tension coefficient from there we can find out what is the surface is the as a function of the surface active elements.

We can model the surface tension force also as a function of the activity present, that means, what are the different components present in this particular material. So, that is why to account the surface tension model. So, therefore, it can be negative value or it can be positive value also.

So, it can be positive value and it can be negative value also. So, that such that depending upon the Marangoni shear stress effective will be acting in the which direction, with the inward direction or outward direction and then accordingly we will get the fluid flow free. So, this way similarly for the this is x and this is y and the z direction that means w equal to 0 means the on the top surface we put the normal to the surface the velocity component is 0.

So, whatever variation of the velocity on the top surface that is over the plane it will be distributed. So, third dimension that normal to the surface, the velocity component equal to 0. So, these are the top surface boundary condition and that is the top surface boundary condition.

And then energy equation we can see that this we have already seen in case of the conduction base model also. The heat is conducted to the boundary and this is the convection from the surface this is the radiation from the surface and q is the imposed heat flux to the surface.

So, this is the combined effect of the all the boundary interaction for the energy transport. So, we can see the energy boundary condition we can put the mathematical form we can put this equation. Now symmetric surface we can consider all the zero flux. Symmetric surface zero flux means the normal to the surface any variable gradient will be 0 for example, normal to the for example, this is the normal to the surface (Refer Time: 12:28) .

So, del v the velocity component by del y equal to should be 0 in this normal to the surface even del T by del y should be 0 because that is the zero flux normal to the surface that we can put this particular boundary condition and the solid liquid interface is basically no slip boundary condition. So, velocity component equal to 0 at the solid liquid interface.

So, these are the different types of the boundary condition we can put in case of the fluid flow problem, but one thing I like to point out here that of course, we are talking the no slip boundary condition, but it is very difficult sometimes to explicitly track the boundary also solid liquid.

So, that is why different interface or boundary tracking method we can use and we have already explained this thing in some other some sort of other module that what way we can interface, what way we can takes care of the that boundary you can define the boundary such that, in that cases there is it will be easy to implement the boundary condition.

Now, linearized final matrix equation although we have these cases, we are talking about all the momentum energy equation. We can see all the transient state transient component are there and we have already shown that from the transient state governing equation to conversation of the, this is the quasi steady state analysis, such that in the quasi steady state analysis we can eliminate the effect of the time component.

So, therefore, little modification we can do and then we can may convert into the quasi steady state condition.

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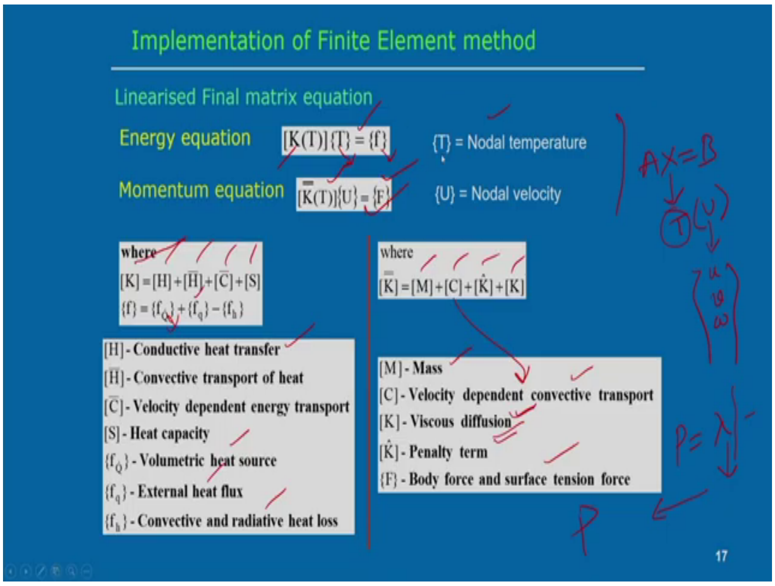


And then now we are showing in case of quasi steady state condition what are the form of the energy equation we can see that all the different form of the matrix equation. So, linearised final matrix equation in the sense the linearised term we are using because you can see that when you do this finite element formulation of this governing equation, we can assume some value U. Otherwise it will be difficult to make is the formulation of the finite element method.

So, therefore, this u j we actually defining or some sort of information we can estimate the value defining. So, its cannot be the incorporate the in the variable component for example, directly we can put the value of the velocity of a particular element, but this value the u j value and then this value del u by del j we can put the u and the shape function form.

And then in the form of a shape function there we can discretize in the domain, but we are not discretized we are not discretizing u j. So, we assuming some value of the U value directly and based on that we can linearise the finite element discretization of this particular momentum equation. So, that is why it is called the linearised term.

So, basically these velocity components can be incorporated in terms of the Reynolds number. So, we can put some sort of Reynolds number value fixed value and then we can discretize the domain then solve for this equation. So, therefore, since this velocity component u j, I think this convective flow of the u j is may not be the part of the actual discretization scheme in the finite element method.

So, that is why that we can use this term terminology the linearized final metric equation. So, then energy equation can be written like that K T and that is that K and in the this is the variable and F is the load vector. So, T is the nodal temperature we can solve in this particular way and momentum equation finally, we can linearize in this particular form.

So, all these cases is basically we are making this matrix in this particular form AX equal to B and, but anyway the A value can be different in case of the energy equation or it should be different in case of the momentum equation also. Such that an X can be in case of thermal analysis it is the temperature and in case of momentum equation you will be getting the (Refer Slide Time: 16:17) can be the velocity.

But remember this is the degrees of freedom, that means, one node point there is a defined in only one temperature, but in case of momentum conservation equation U there is the three different component of the velocity each and every node point U for example, small u v and w. So, that three component will be there corresponding to these node we can say 3 degrees of freedom associated with the each node.

So, then solve for this energy equation and solve for the momentum equation then we will getting the total temperature distribution as well as the temperature distribution in case of the material flow field. Now in this case we can see this K it consists of this the H H bar C and this already we have discussed all this thing; whereas, a K bar can be different M C K kappa and K

So, in this case if we follow the penalty finite element based method. So, K, so all the all these terms can be defined something H equal to conductive heat transfer and then H bar is the convective transport of heat and C bar is the velocity dependent energy transport basically in this case and the S equal to heat capacity.

This terminology we can use this thing and f dot Q volumetric heat source external heat source if there is an convictive radiative heat loss this thing. But if we do not consider the volumetric heat source it will be 0 simply and if we consider the f Q also then uncertain surface flux, some values will be there in f Q.

Similarly, momentum conservation equation M is associated with the mass C is the velocity dependent convective transport if C is the velocity dependent convective term and here also in finite element discretization in this particular derivation of this velocity dependent convective heat transport there is a there is a need to linearize the particular equation.

Now, K is the viscous diffusion terms and K kappa is the penalty term and basically penalty term we have already explained this penalty term we can introduce some penalty finite element method in this particular solution of the material flow or fluid flow phenomena in case of welding cases such that this continuity equation will be linked with the pressure term.

So, it will be little bit towards the simplified this particular process finite element method and then we can get some solution, but if you apply the penalty finite element based method. So, once penalty finite element is P in terms of the lambda is the basically and then continuity equation we can link between these two.

So, that in this case the pressure term is represented link with the continuity equation and then it becomes part of the final a momentum conservation equation. So, that it is to some extent it simplify the solution methodology of the Navier Stoke equation. Then once the penalty term all this thing can evaluate these things when we can from the penalty term also we can know and accordingly we can estimate what is the pressure also.

So, then pressure distribution can also be estimated. So, anyway this viscous dependent convective diffusion term penalty term is there and body force and surface tension term is associated with the f. Accounting the body forces term is there in case of the welding process the body forces means the gravitational force, that means, and this other part of body force is the may be in case of arc welding process electromagnetic force will be there.

And surface force will be the surface tension force or maybe we can say the Marangoni shear force is acting on the surface. So, these both surface components as well as the volumetric force will be there you can account by this term. So, this way we can make the finite element model and solve for this thing.

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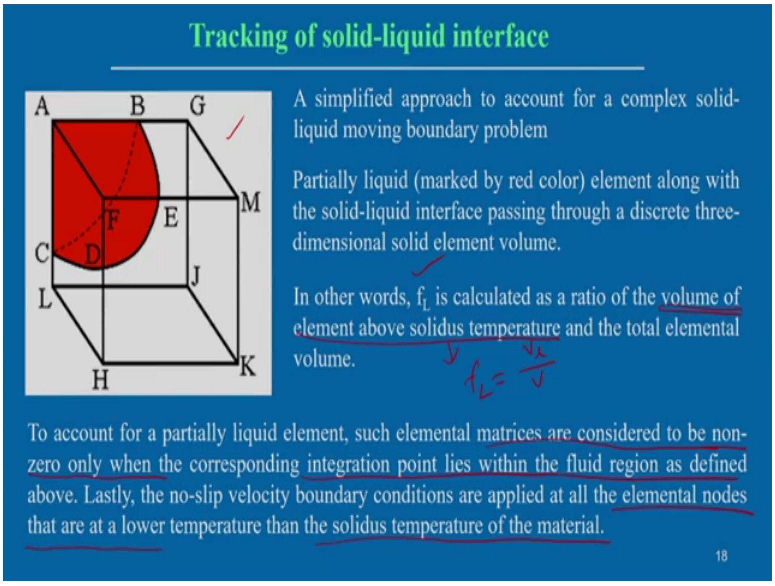

But there is one issue also then what way we can track the solid liquid interface. The here I am the very simplified approach is accounting is followed for the because accounting the it is very it is a very complex thing to track the solid liquid interface or maybe solid liquid moving boundary problem it is very difficult, but presently we are using some sort of very simplified approach.

So, we can look in that way, that partially we can focus on one particular element and we can count on this thing one particular element we can track also simply by looking into the temperature distribution. We can define that which node is above the melting point or which node is below the melting point.

So, accordingly we can see we can define for a particular element which nodes are a liquid phase and which nodes are in the solid phase. So, for example, this is the this figure you can see the this maybe this we can see that the few nodes are in the liquid phase. So, that partially it will fill by the liquid one for one particular element and remaining part is mean the solid phase.

So, partially liquid marked by the red colour element along with the solid liquid interface passing through a discrete three dimensional solid element that is always possible discrete element through which some it is passes through this thing, but we are not explicitly accounting tracking the surface profile of the solid liquid interface in a particular element.

Or in other words in this case we can see the simply estimating what is the one particular phase maybe we can estimate one particular phase which node is above the melting point accordingly we can define the fl is the fraction of liquid is calculated as the ratio of the volume of the element above solidus temperature and the total volume of the element.

So, then the basically it is difficult to find the ratio of the volume of the element above the solidus temperature for, that means, we can say above the melting point temperature other way also. So, then accordingly you can f L can be say the total volume of the element and volume of the that liquid part only. So, that approximate calculation we can do just simply counting which node point is above the melting point temperature.

So, then that way you can define the f L. Now to account for a partially liquid element and such element metrics are considered to be nonzero only. So, it will be a nonzero partially, but when we accounting this thing that when you looking into one particular element. So, contribution from the element when you are looking into this thing. So, in this particular element some part we have to consider the liquid phase is there and some part of this particular element in the solid phase.

So, in that cases the very simple approach we follow in this case that the liquid part which the elemental matrix when you try to form. So, there are so many integration points are there volumetric integration points are there within this region. So, then the volumetric integration point lines within the fluid region as defined up the above.

So, then the which is the integration point if the fluid region, we can account this thing to accounting the fluid part when you try to make the finite element formulation on a particular element and now lastly the no slip boundary conditions applied at all the elemental nodes that are lower temperature than the solidus temperature of the material.

So, in this particular element which element which node points are below the melting point temperature in this that particular node point we can apply the no slip boundary condition and apply all elemental nodes in this particular case. So, this way very simplified way or maybe I cannot say it is a very accurate way, but it is a very simplified way we can track or we can apply or this particular boundary condition.

As well as the we can track the solid liquid interface which will be more easier to implement in the finite element formulation for a partially filled liquid element. So, that is why it is very important to know also when you try to develop some sort of the finite element model.

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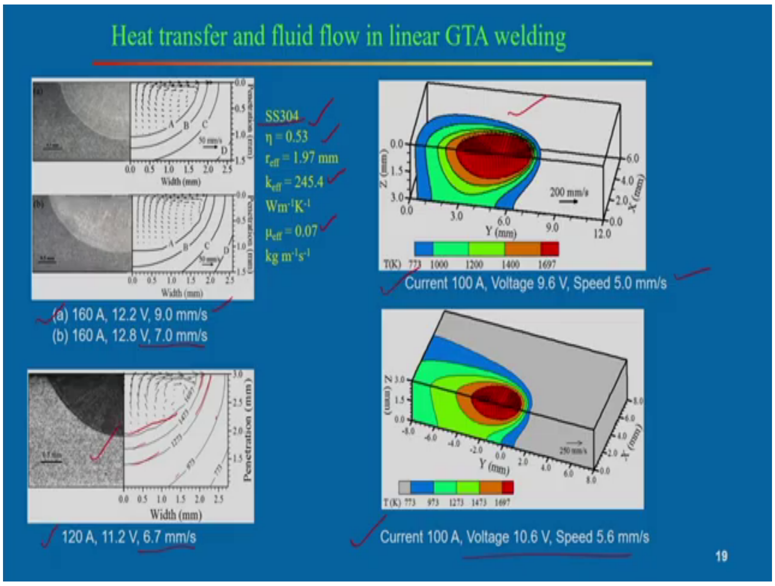


Some sort of results once we solve all the governing equation along with the boundary condition here we can see some results from the heat transfer and the fluid flow model in case of the GTA welding process gas tungsten arc welding process.

So, for example, material is considered the SS304 stainless steel and then efficiency the thermal efficiency term because which the when is considered as 0.53 also and this actually value is calculated by inverse way.

And effective radius equal to 1.97 millimetre, that means, what is the arc is focusing on the material that effective radius is considered as the 1.97 millimetre. But effective thermal conductivity and you can see the effective viscosity we consider in this case. The 245.4 although we are talking the SS304 stainless steel the thermal conductivity value is the very low in the room temperature value is around 20 to between 25 watt per metre Kelvin in case of SS304.

But actual thermal conductivity in this case we are considering the 245.4. So, this is basically high value of thermal conductivity enhance the heat transport phenomena also because actual problem in GTA w welding process or maybe some laser welding process, some sort of turbulence will be there within this small weld pool.

So, that it enhance the heat transfer effect also. So, to account this effect in the very simplified way we just try to consider, what is the effective value of the thermal conductivity; so, basically artificially increasing the value of the thermal conductivity to account the turbulence effect within the small weld pool. So, that is the one simplified approach to we can adopt for this thing.

Similar for analogy can also be applied in case of the effective viscosity. So, that is why this effective viscosity and the thermal conductivity is these values are actually estimated from the by inverse calculation. Now, this is suitable for this particular welding system for example, the current is 160 amp voltage is 12.2 volt and welding velocity is 9 millimetre per second.

So, this first case and second case is the same only there is a difference in the velocity 7 millimetre per second. So, then some sort of the difference of the temperature the velocity field distribution and we can compare with the experimental data also. And other cases also we can see it is 120 amp.

So, current is low, but velocity is also low 6.7 millimetre per second, here we can get this kind of the temperature. This is the isotherm this is the temperature distribution we can see the isotherm we can define different zones. And this is the arrow represent the velocity vector in this particular case.

So, that is why we can expect the after numerical solver you can get the weld pool also the red zone indicates the weld pool, but within the weld pool we can the arrow indicates the velocity field also. And we can see the velocity field arrow indicates that its moving from the centre to towards outer periphery.

So, it means that in this particular case there is no effect of the surface active elements in this particular material we can consider. So, that is the here you can see the different process parameter also we can get the different kind of the velocity field and different weld pool size also. And that is possible to obtain from the numerical simulation, that is very clearly seen from this particular results also.

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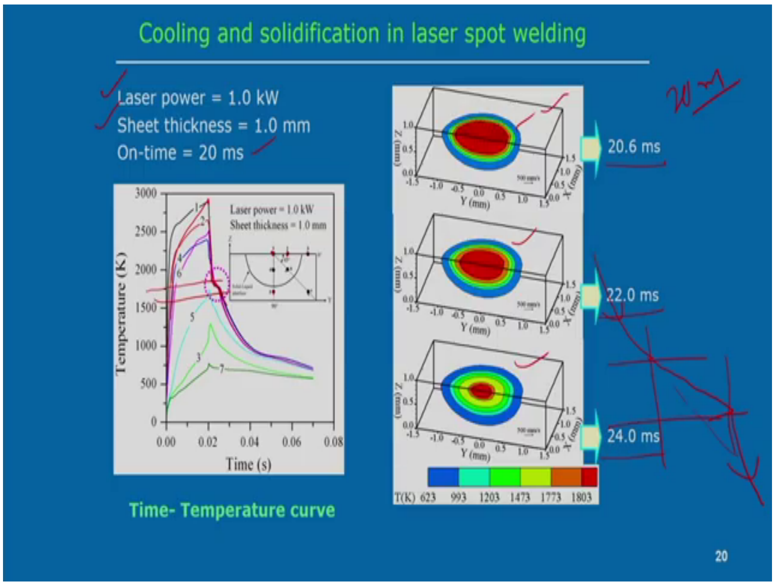


Now, apart from this thing this velocity field and temperature field further we can use this particular data. I am talking about the time temperature data, that can also be useful to get some sort of to understanding the what are the different kind of the microstructure we can develop or some sort of analysis of the solidification behaviour also during this particular process.

So, anyway it is also paramount interest to look into the what is the time temperature profile during this welding process also and that such typical process the typical time temperature profile we can see. For example, in this particular case we are considering the laser power 1 kilo watt sheet thickness is 1 millimetre and one time equal to 20 millisecond. So, that means, laser on only 20 millisecond and it is a remember this is the spot welding process.

So, spot welding process we can see the temperature versus time. So, temperature versus time at different location different location the fixed location, say the at the centre point 1 and on the outer periphery maybe along on the width direction 0.2 and 0.3 is the outside this weld pool domain.

Similarly, 0.4 in the depth direction and 0.5 also outside of the domain along with the depth direction and some with respect to the top surface we can make a 45 degree angle and then there we can put the selective points; it means that if we put the very selective points on the domain then what this particular domain we can extract the time versus temperature and that profile we can see also, the time versus temperature the 0.12 and 0.4 even 0.6, that particular all this point the temperature is above the melting point temperature.

So, initially that once the with the application of the heat the temperature will increase. So, that means, this is gradually increasing reach to the peak temperature. So, then up to that it will reach to the peak temperature until and unless up to what time a laser is on. So, once it is the peak temperature or means meaning that 20 up to 20 millisecond laser is on, then once the switch of the laser no supply of the energy to the domain. Then it will try to cool down and coming back to the ambient temperature.

So, from there reach peak temperature then it is cooling back to the try to equilibrium try to bring. So, the by heat by losing the heat to the or coming back to the ambient temperature. So, that is why here during the cooling phase we can see there is a some hump is there. So, there is a not exactly the slope the some slope is there in this particular case.

So, it indicates that there is a change of the phase from liquid phase to solid phase and then we know for alloy any kind of the alloy the melting happens or maybe the solidification happens over a range of temperature. So, that is over a range of the temperature is in between the solidus and liquidus temperature.

But in case of the pure metal there is only transition temperature from liquid phase to solid phase, that is one single point temperature. So, that is why whatever this variation the cooling is something like that, but it is not like the smooth curve in this zone. So, some sort of gradient is there.

So, that slope change of the slope is there and between the solidus and liquidus temperature because there is a change of the phase during this period. And even once from this diagram we can see this there is a change of the slope between the solidus and liquidus temperature because we can see also this is around the solidus and around the liquidus temperature of this particular material.

So, that range slope is defined it means that the latent heat for the simulation you are incorporating the effect of the latent heat then only you can expect this kind of the bump or this kind of the slope during the cooling curve of a particular welding process. So, this information was required we can see also that from there also we can estimate the cooling rate and the even it is possible to estimate the solidification parameter also from the time temperature curve.

Here we can see how what is what we have shown there is a cooling phase, during the laser spot welding process. So, 20 millisecond it reach the peak temperature, then just switched off the laser then gradually cooling back. So, you can see the 20.6 millisecond this is the profile 22 millisecond and 24 millisecond.

You can see that 24 millisecond means this liquid domain is gradually shrinking, that means, it is a cooling this thing. And then different temperature zone also, there is a variation of the different temperature zone. We can see the through the simulation also this kind of information we can get all this information you can get apart from the time temperature profile on a fixed domain.

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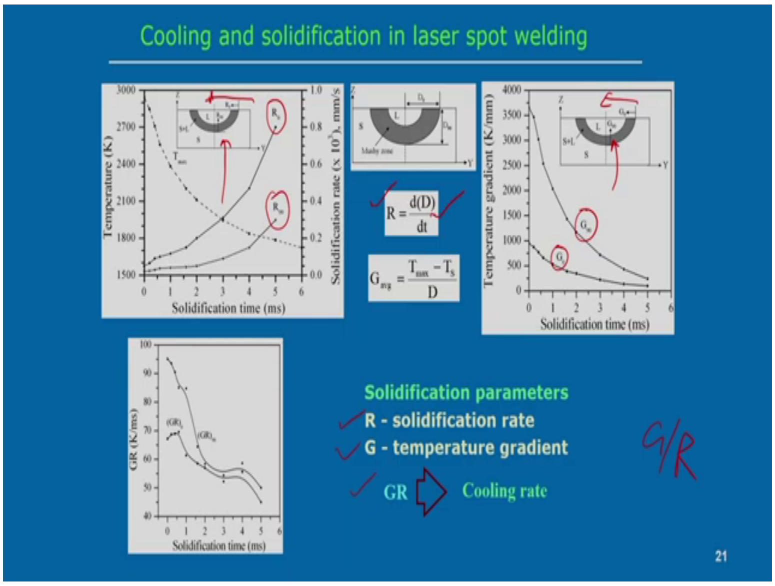


So, this kind of information may be useful for the designing of the process also and to look into this thing, may be further calculation we can do also say temperature and the solidification time. So, different cases we can see that R. Now the R is the solidification rate and G is the solidification gradient.

So, we can estimate the solidification rate and solid temperature gradient both this parameter is possible to estimate also. These two parameters are normally called the solidification parameters. And finally, when you multiply G into R and G by R is basically the mode of decides the mode of solidification and G into R is basically indicates the cooling rate.

So, the whether rate of the cooling indicates the fine structure or core structure in a particular welding process that kind of information we can see from the microstructural analysis. But that can be correlated with this all this information from the simulation data also. Now, what we can estimate the R, R means we can track say D on particular direction D means along the depth direction along the width direction.

So, how D evolves? So, from that a D evolves means during the solid phase we are already seen that liquid metal is shrinking, but we can capture this data also, how it shrink with respect to time. Then that ratio dD by d small t that indicates what is the value of R. So, here we can see that different the R0 means the particular define in this particular direction the surface the R0 and R 90 means towards the bottom direction.

So, at this R0 and R 90, how it evolves with respect to the time this information we can get from this simulated model also. And this zone is the mushy zone is the between the solidus and liquidus the black zone indicates the solidus and liquidus temperature also.

Now, even we can estimate the temperature gradient also by the different direction G 0 and G90 also. G0 is this direction and G90 is basically depth direction. So, G0 and G90 how it evolves that also you can see this is the G0 curve and this is the G 90.

So, different plane or different position or different direction depth and direction with direction the values of the R solidification parameters are different. Now, once we get this R and G value, then we can find out what is the value of GR. GR is basically the indicates the solidification time.

So, solidification time we can estimate also with respect to the solidification time what is the value of GR. So, how GR evolved this thing that information we can get even also similar way we can estimate the G by R ratio.

So, some sort of understanding or the sort of the solidification all kind of information it is possible to get, even from this thermal analysis or maybe we can say that if we track the data during the cooling phase all information it is possible to evaluate during this particular calculation.

So, that is why once we get all these G by R we some sort of understanding of the solidification behaviour can be linked also. So, in that sense this simulation may be helpful to understanding the microstructural behaviour or expected microstructure in a fusion welding process.

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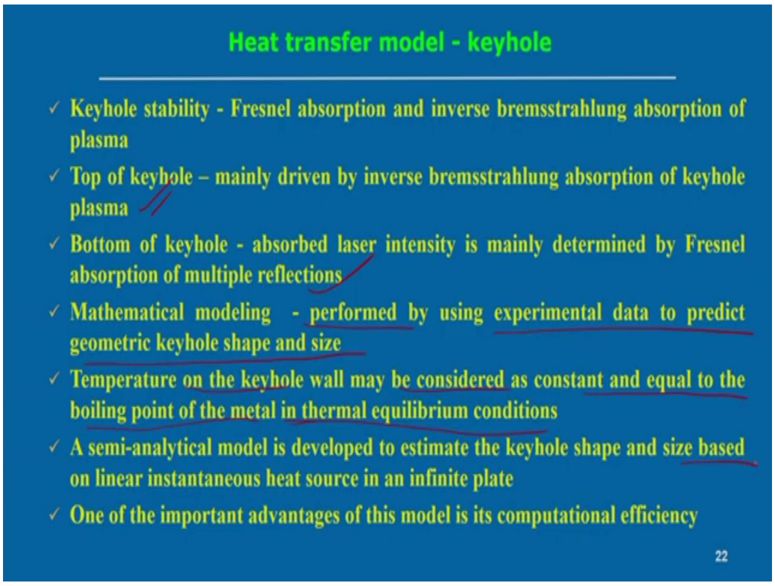


Now, we try to look into the heat transfer model in case of the keyhole mode welding process. We know that keyhole mode welding process we have already shown that in the how we can develop that volumetric heat source model in specific to the keyhole. Basically what way we can predict the keyhole also here also we will try to repeat the few things also to see the how we can make the heat transfer model in case of the keyhole mode welding process.

Of course, it is the similar fashion what way we can do the heat conduction equation here also we need to solve, but in the different way how to incorporate the effect of the volumetric heat can be different as compared to the other conduction weight heat transfer model.

So, now keyhole is the this thing keyhole stability is very important because keyhole we can we know it is form the some Fresnel absorption and inverse, then solving absorption of the plasma.

That means, different absorption coefficient when you try to produce some sort of the keyhole formation, in case of the keyhole mode laser welding process, but top of the keyhole mainly driven by the inverse bremsstrahlung absorption of the keyhole plasma in the top surface. A bottom surface is basically mainly determined the Fresnel absorption of the multiple reflections.

So, basically this is very difficult to looking into the different nature of the absorption and make the keyhole model also is extensively difficult. So, in that cases some sort of analytical estimation can be done also. So, most of the mathematical modelling is normally performed by using the experimental data to predict the geometric keyhole shape and size.

So, most of the cases what happens? They collect the experimental return feed the experimental data to define the keyhole profile, but in this cases there is a need of lots of experimental data to actually define to predict the keyhole size.

Other way also that we can look into the mechanism of the keyhole and based on that we can very simplified way we can analytically develop some sort of the keyhole profile also and that is the, that I am trying to explain here also.

So, temperature on the keyhole wall may be considered as the constant and equal to the boiling point of the metal in the thermal equilibrium condition. It means that once we look into the keyhole process and keyhole wall is basically the it is a boiling point temperature of the keyhole and maybe inside it can be above the boiling point temperature within this keyhole.

So, by these assumptions we can develop the semi analytical model of the keyhole shape and size. Based on the instantaneous linear instantaneous heat source of an in an infinite plane so it is points that, we have some we have shown the some sort of the temperature distribution that in case of the welding process, but that is the analytical distribution of the temperature.

So, we can adopt some sort of the solution of this analytical temperature distribution and we implement in keyhole mode laser welding process to show to estimate the roughly estimate the keyhole profile.

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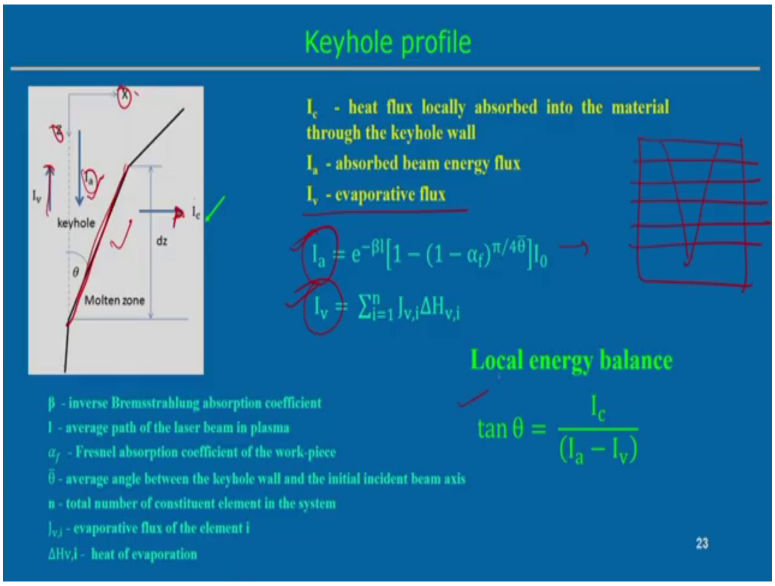


So, let us look into this how it can be done. It is like that suppose we can take this is the total domain and maybe in the particular domain, the keyhole can be something like that see in these cases first we can make a small small layer very small layer. And we are looking into one particular layer and then what are the interaction of the different kind of the heat absorbed?

So, if we look in one particular layer for example, this is the x direction this is z direction and I a is the absorbed beam energy flux. So, it is the absorbed beam energy flux and I v is the evaporative flux some evaporation will happen because vaporization may happens and I c is the flux locally absorbed into the material through the keyhole wall.

So, this is the keyhole wall and this is the Ic is transported that amount of the flux which is goes to the locally absorbed by the keyhole wall. Now, this basically molten zone and this is keyhole we can say the keyhole means the vapor zone basically vapor domain and this is the interface and this is the effective absorption I c is the amount of the flux which is basically transferred to the molten zone.

And making the balance of all these three flux I c is there in the this direction I a is the input that means, absorbed beam energy flux and of course, this is the effective value of the absorbed beam energy flux. Because we have seen the different absorption coefficient within the multiple reflection also within the keyhole; so, this is the effective value of this thing and I v is the evaporative flux which is actually working in the outward direction.

So, then we can estimate the I a basically different way the I v also some sort of looking into this different assumption. So, that I a and the all the parameters are defined in such a way the absorption coefficient, different terms of the absorption coefficient, what is the average angle between the keyhole wall and the initial incident beam theta bar and the evaporative flux for element I.

So, particular there are one particular alloy. There are so many elements we can know we have the data of the evaporative flux particular element and there we can estimate what is the value of I v. So, once we estimate the I a depending upon the different absorption coefficient.

And then why the different upon the different elements present in this particular alloy you can estimate the I v. Then from the local energy balance we can relate between these two say for example, tan theta equal to in terms of the I c, I a and I v see three different flux and this is happening on the particular layer.

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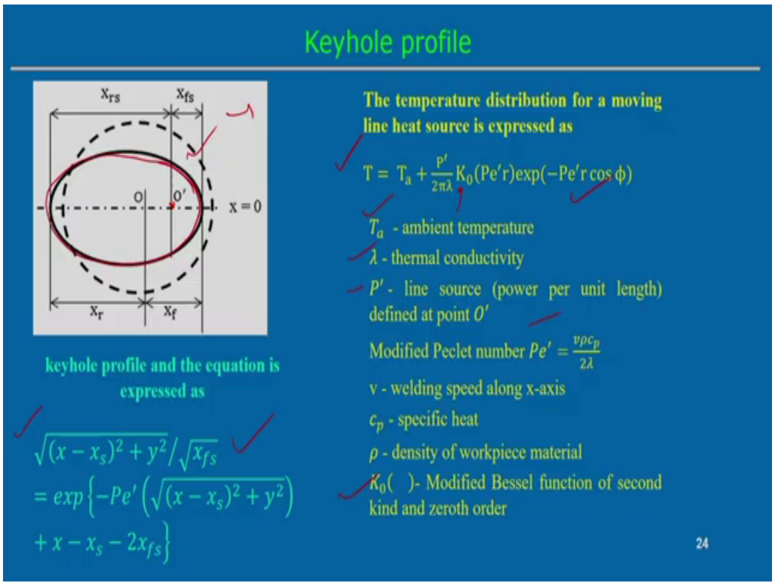


So, once we do that do we can assume some temperature distribution or we can pick up some solution of the temperature distribution for a linear line heat source model. So, suppose this is the temperature distribution of the line heat source model we pick particular solution analytical solution.

So, let us look what are the parameters involved in this particular solution ambient temperature lambda equal to thermal conductivity that is known P dot is line heat source. So, this is the is power per unit length defined at the point O dot. So, in this particular point O dot. And the it is a modified peclet number it actually modified peclet number introducing this particular solution because in this case we will be able to take care of the welding velocity or laser scanning velocity.

Specific heat density of the workpiece material and some sort of modified vessel function of second kind in the zeroth order will come into the solution also you can see the K0. So, if you use some we assume this analytical solution of a particular temperature distribution. Now, we try to implement this solution actual keyhole mode profile, to predict the keyhole mode profile.

So, here since it is moving on particular direction keyhole profile and equation can be expressed something like that how the keyhole profile is we have heat source model. We have already explained this thing, but just in this cases x it is moving x and this is the actual keyhole profile in this point O dot and making this is the laser from the laser source this is the profile of the laser source.

But while laser is interacting with the workpiece and then what will be the profile on the workpiece, because on the work when a laser is interacting on the workpiece it is moving one particular direction. So, that is why it can provide something some sort of this can moving non symmetric kind of profile we can expect.

And accordingly we can decide the O dot is the centre of the heat and we can get the solution for the we look into different geometric parameter and can give the solution and x into fx this is the keyhole profile equation is finally, expressed in this particular we get the solution and then we solve this equation. Then which is the particular domain indicates the T temperature distribution is equal to the boiling point temperature that actually defined the keyhole wall.

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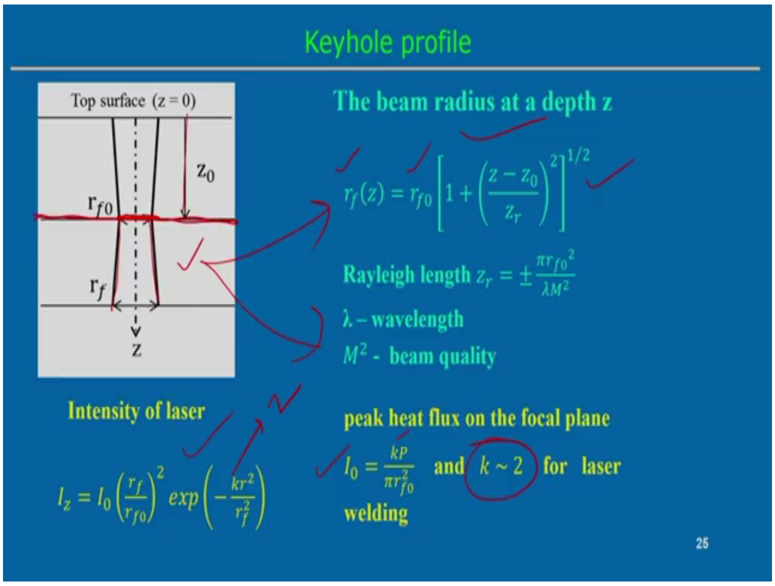


So, that is way we can estimate the keyhole profile and then beam radius at a particular depth because finally, the how is interacting with the beam. So, beam is basically interact on the z direction at the laser beam focus on this particular point. And this finally, it is a some sort of diverging will be there within when we interacting in the workpiece domain.

Now, this expression can be represented this thing beam radius in terms of the other parameters Rayleigh length also wavelength beam quality all will come to the picture with this particular expression. And finally, the intensity peak heat flux intensity on the focal plane it can be represented like this kP is the k is the distribution coefficient and it is normally laser welding process k can be equal to 2 distribution coefficients for laser welding can be considered in this case.

Similarly, intensity of the laser can be represented this thing, if you see the it follows that the Gaussian distribution, but in this case is the distribution coefficient is 2, but in case of the GTA welding process we normally use the distribution coefficient equal to 3. So, that is the difference.

So, k simply represented by 2 this thing such that we can use the same kind of the Gaussian distribution and if we look at the track the what is the laser profile where which forecast and again is to some extent diverse in the laser beam. Based on that we can get all this kind of profile and which is represented by this particular equation. So, that means, radius of the laser is the effective radius is varying with respect to the c rf and rf 0 at this point the focus basically laser is focused on the work piece surface.

So, there is the radius is rf 0. Now it is diverging that we can taking by this particular equation and this particular equation very important because if you see all this point of laser parameters also takes care of this particular expression. So, wavelength, beam quality all these particular parameters are there to predict the keyhole profile.

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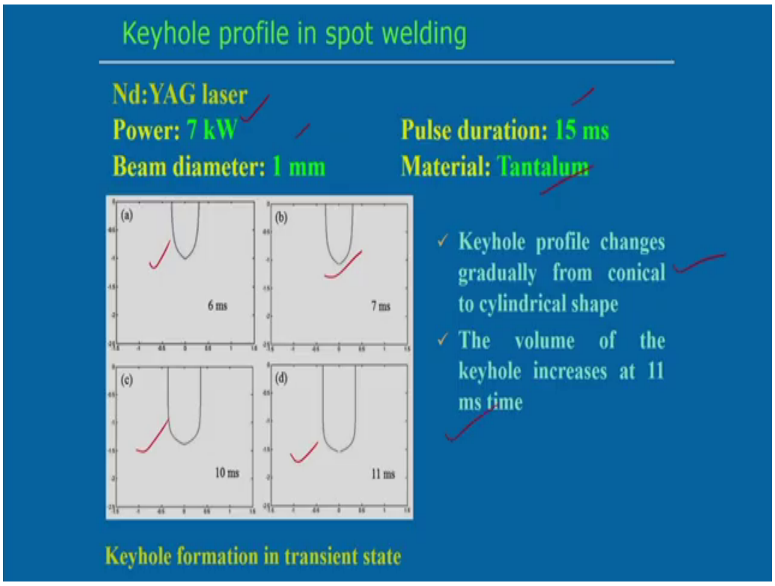


So, this is the some results of the keyhole profile in the spot welding process. We can see the Nd:YAG laser power is the 7 kilo watt beam diameter equal to 1 millimetre. Pulse duration is 50 millisecond material is a tantalum. We can see at 6 millisecond this is the typical profile of the keyhole

So, this profile you can get by analytical solution of the temperature distribution. So, 7 millisecond it is increasing 10 millisecond it is increasing and more or less it is basically increasing and the this 11 millisecond we can getting this kind of the keyhole profile in the that for this particular process.

So, keyhole profile changes gradually if you see from conical to towards more of the cylindrical cell. So, therefore, the volume of the keyhole increase at the 11 millisecond time that also we can see also, that gradually with the if you interaction time is more the keyhole profile is gradually evolving.

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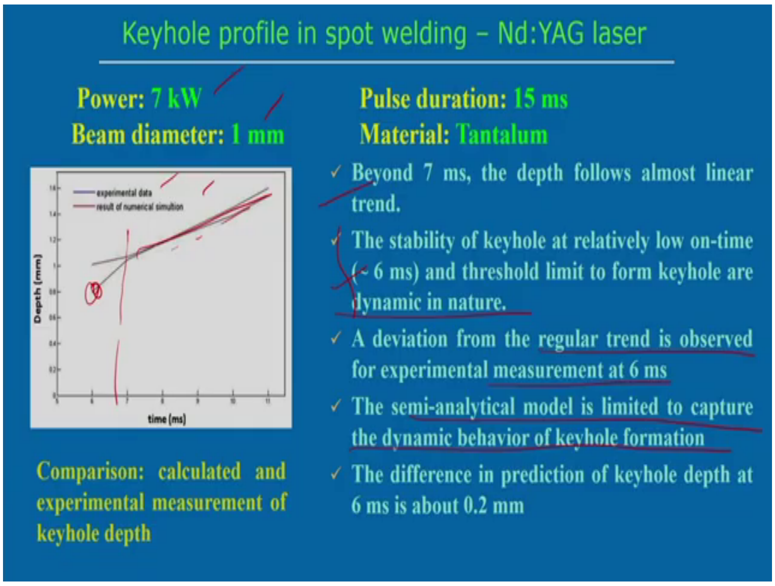


Now, over all if we look into compare with the keyhole profile in the laser spot welding process using the indirect laser we can see the same power and the beam diameter this cases we can see the depth the keyhole depth. As well as the experimental simulation we can see the initially it is not matching because there is some deviation and, but that after this second 6, I think 5.5 millisecond this is the more or less it is close to the value of the experimental value.

So, it means that initial phase it is not matching in the sense that some threshold values is not able to predict by this particular analytical solution. Of course, this is the particular limitation of this analytical solution, but if we follow the to predict the keyhole profile by using some analytical solution also. Then to some extent we can get some sort of calculation.

So, once we look into this thing this particular point that beyond 7 second depth of almost linearly trend we can see almost linearly trend stimulator relatively low on time is and the threshold limit to form the keyhole are not dynamic in nature definitely the initial phase, it is not basically following the trend.

So, that trend is not able to capture or anyway stability of the keyhole not able to explain by this analytical solution of the keyhole profile. So, deviation of the regular trend is observed and measurement at 6 millisecond that we have already mentioned. So, therefore, semi analytical model is limited to capture the dynamic behaviour of the formation.

That is very limited because similar analytical solution of the keyhole in that cases we have to estimate the different way also some sort of numerical calculation is required to overcome this kind of deviation due to the dynamic nature of the keyhole profile.

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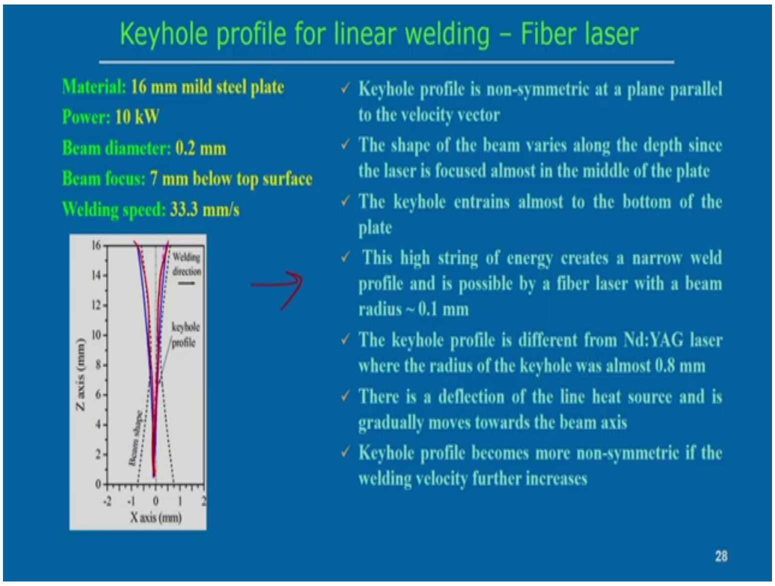


Now, we can see that keyhole profile for the linear welding the fiber laser also that it is a initially that was the spot welding process. Now if it is the linear welding process fiber laser. We can see that its moving on particular direction, we can see this is the typical profile the blue colour indicates the typical profile of the keyhole profile.

When there is a the same analytical solution we can incorporate also, when you try to look into the keyhole profile in a moving laser source. So, this way we can it means that it is possible to predict from the analytical solution to the size of the keyhole.

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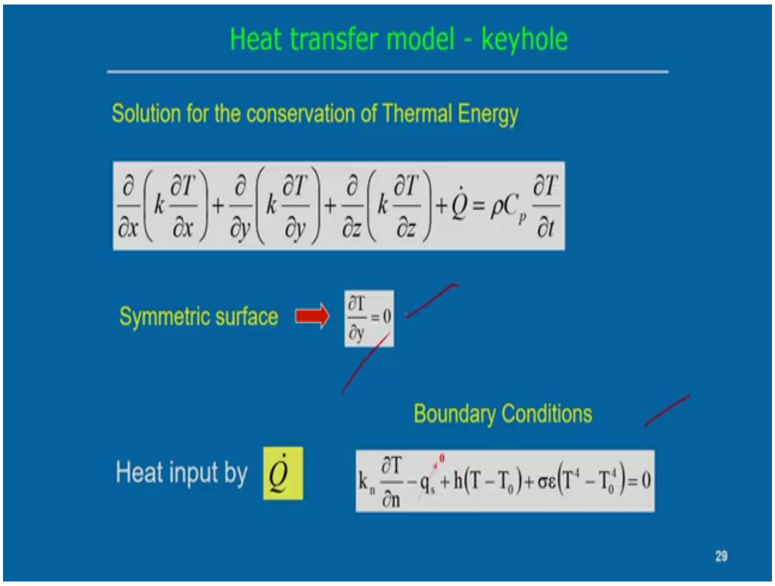


But what will be the next look into the what we will do with the size of the keyhole the same kind of analysis. Now, once we get the size of the keyhole then if we follow some kind of the simple solution of the heat conservation equation of the thermal energy and then with the proper boundary condition the same way we what we can do the heat transfer analysis in other welding processes also. So, same approach we can follow to get the temperature distribution even in keyhole mode laser welding process.

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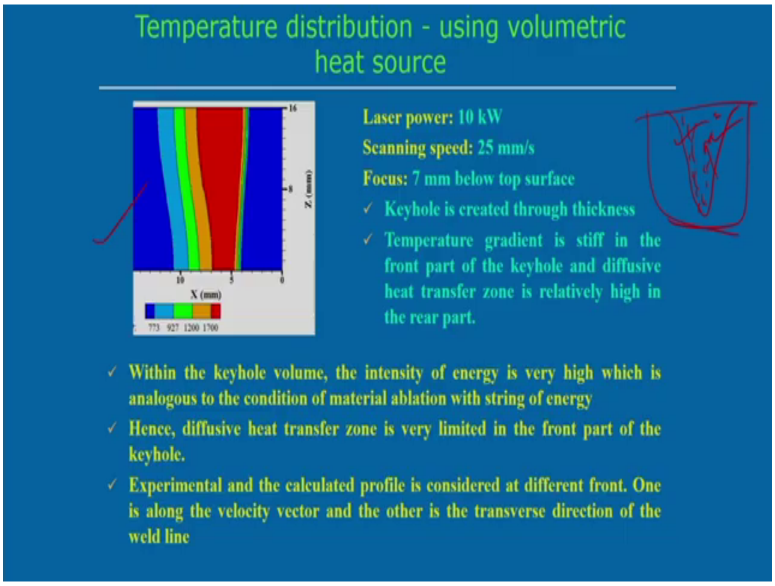


So, some sort of this thing we can see the same kind of the heat conduction equation boundary conditions we are using, but only thing is that within this suppose this is the domain.

First we have defined the keyhole profile within this keyhole profile. So, it is a vapour state also then we can use some sort of uniform flux also and then we can develop the model and using this because in once we try to apply the volumetric heat source in case of the keyhole mode laser welding process, then first step is to you have to define the keyhole size.

So, once we define the keyhole size within the keyhole size we apply the volumetric heat source model and to get the temperature distribution. So, pattern or maybe the methodology is the same as the conduction.

Even conduction mode heat transfer model, but only thing is the in case of keyhole mode only difference is the there is a need to define the keyhole profile first, then we apply the volumetric heat flux within this different zone to get the temperature distribution in the similar way in case of the keyhole mode laser welding process.

Here you can see some results also you can see this is the result laser power particular scanning speed and then we can get this kind of the profile also even for a moving.

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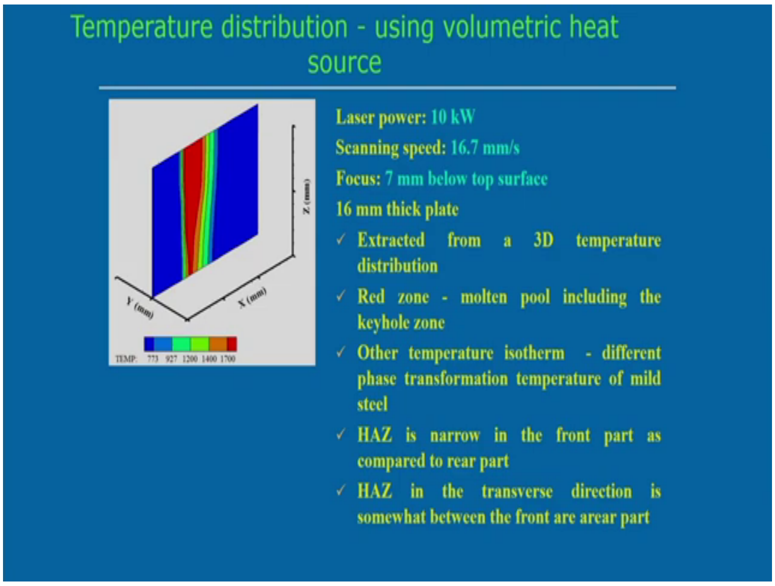


So, same kind of profile also we can get the laser power in particular velocity and focus is seven millimetre below the top surface. So, therefore, it is necessary to look into the what are the focus distance and then 16 millimetre thick plate we can get this kind of the profile also temperature profile even is the even. Although in these cases first we define the keyhole volume, then we solve the conduction mode heat transfer analysis.

So, in that frame if you follow this thing, but it is better to define the keyhole profile once you keyhole profile. And if you remember in keyhole profile we have when we estimating the keyhole profile in the slicing in the particular z direction and then we looking for the each element in the z direction, we estimate we get some data.

So, once we get this kind of element then it keyhole volume may not be the regular geometric shape. So, in that cases we can assume some arbitrary shape of the volumetric heat and then we may apply the arbitrary volumetric heat source model in this particular in keyhole mode laser welding process to estimate the temperature distribution.

We have already explained the what is the arbitrary volumetric heat source model. So, implication implementation is different or approach is little bit different as compared to the simple gas transients or maybe other conduction mode laser welding process.

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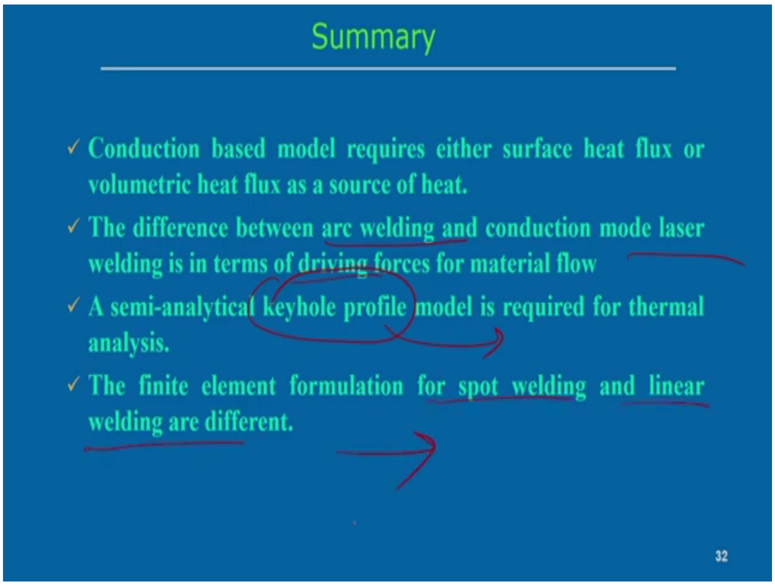


In summary we can say that conduction based model requires the either surface heat flux or the volumetric heat flux as a source of the heat, that is definitely required. But the difference between the arc welding and the conduction mode laser welding process in terms of the driving forces for the material flow. So, it means that the arc welding process and the laser welding process once we look into the fluid flow phenomena.

In that cases the only difference between the laser and arc welding process in terms of the driving forces because the electromagnetic force driving process is available in case of arc welding process, but that is absent in case of the laser welding process. Semi analytical keyhole profile model is required also estimation of the profile is required to for the thermal analysis and we can see once the keyhole profile we can estimate and from there we assume the that is particular volume of the keyhole.

And accordingly we can apply the volumetric heat source model to estimate the temperature distribution in case of the keyhole mode laser welding process. Now, finite element formulation for the spot welding and linear welding are different you can remember that first we try to develop the finite element formulation in case of the spot welding process there is a transient term is there.

And we know it is a moving frame moving coordinate heat source model also, if we shift the moving frame there we can eliminate the time component and we can develop the quasi steady state heat transfer model also. So, that formulation is little bit different in these two cases in the spot welding as well and the quasi steady state or steady state heat transfer problem. Same thing also applicable in case of fluid flow problem as well, so.

Thank you very much for your kind attention.