Finite Element modeling of Welding processes
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Module - 04
Application of FEM to model welding processes
Lecture - 20
Implementation of FEM in fusion welding processes

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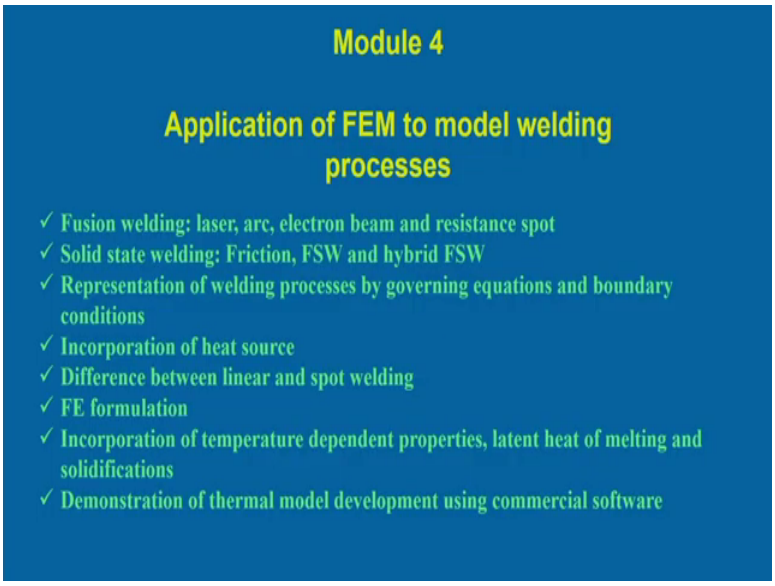

Module 4

Application of FEM to model welding processes

- ✓ Fusion welding: laser, arc, electron beam and resistance spot
- ✓ Solid state welding: Friction, FSW and hybrid FSW
- ✓ Representation of welding processes by governing equations and boundary conditions
- ✓ Incorporation of heat source
- ✓ Difference between linear and spot welding
- ✓ FE formulation
- ✓ Incorporation of temperature dependent properties, latent heat of melting and solidifications
- ✓ Demonstration of thermal model development using commercial software

Hello everybody. Now, I will start the model 4 that is application of FEM Finite Element Method to model welding processes. We have already discussed about the basics of the finite element method.

In basics of the finite element method, we have from the governing equation, along with the boundary condition, we have seen that what way we can form the one elemental contribution and by assembly these things, we can make the linear system of equation and then solving, we are getting the distribution of all; distribution of the any variable can be temperature can be distortion. So, like that.

Now, we will try to look into that what is the, what way we can develop the model of the different welding processes. May be in general, all of the welding processes may be there is application of the heat and they just substitute the melting or may be in case of the fusion welding process and then, after that solidification also happen.

And in case of the solid state welding process also, there as some frictional heat generation is there and then after that, it solidify not solidify actually after that it cool down to the ambient temperature in case of the solid state welding process. So, it means that it is associated some sort of the temperature distribution in general, looking into the any kind of the welding process.

So, from that point of view, may be all these cases we need to solve only one governing equation, maybe we can solve the heat conduction equation along with the particular boundary condition, but the boundary condition or application of this particular these governing equation can be different with the aspect to the different welding processes.

So, in this particular model, we try to look into that if a very specific adding process what way we can develop the model, but we will not discuss about the detail’s television and this elemental formation because that in general, we have already discussed parting into the particular governing equation or the heat conduct indication or fluid flow equation or in case of the stress analysis model.

So, that is not needed, but we will try to look the process what we can develop the along with the boundary condition, which governing equation we should use it and how we can model this particular welding process. So, in that aspect, first we will have to discuss the fusion welding processes.

So, fusion welding processes in general the in that particular category because laser, arc welding process is the modeling approach almost same so, we can put into one category.

Then, electronic welding process, it is also fusion welding process, but the may be to some extent, it is different up to certain aspect. So, in that case, we will make it another category or for electron beam welding processes.

And apart from that, we can put the resistance spot welding process. So, resistance spot welding process also we can put the separate category how, what we can develop the model specifically, I am talking about the thermal model in case of the resistance spot welding process.

Apart from that, the solid state welding processes also the solid state welding process in general, we will try to look into the friction welding process and hybrid picks on welding process what we can model this particular possess model means what we can do the apply the heat conduction equation and we can get the temperature distribution that will try to discuss these things.

But within this when you try to discuss one particular welding processes and there we to represent the what kind of the heat source model is required. And then, what we can represent the welding process in terms of the governing equation and boundary condition that explicitly we will focusing on one particular welding processes.

Apart from that, an incorporation of the heat source so, what we can incorporate the heat source model in a particular welding process that we will try to look into that and what are the difference between the lasers and spot welding process in terms of the modeling approach, what can be the different, what can be the how the results can be different between the spot welding process and the linear welding process.

Linear welding process means in if the welding is performed with a particular velocity that means, when heat source moves in a particular velocity in that cases, we can consider this as a linear welding process. Then, FE formulation a little bit will focus on the whenever required, we will try to look into what we can do the finite element formulation and how it is different from a spot and linear welling process that we will try to focus on that.

Apart from that, the temperature dependent property is what we can incorporate in the finite element base model and that is what I can incorporate the latent heat of melting and solidification. And apart from that, we will try to look into finally, the demonstration of the thermal model development using some sort of commercial software. So, all these aspects we will try to cover in this particular model.

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Module 4

Application of FEM to model welding processes

Arc and laser welding processes

Now, first well discuss about the arc and laser welding processes and specifically we focus on the how what we can apply the finite element method to develop the model for arc and laser welding processes.

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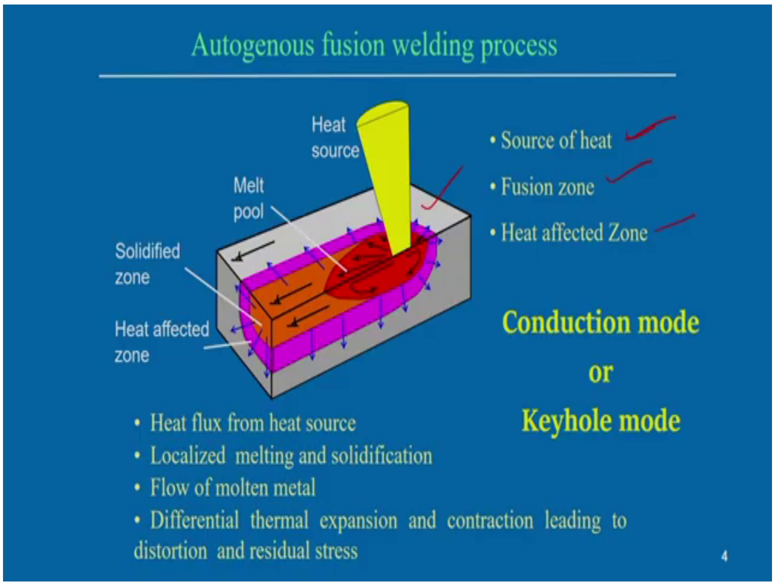

Autogenous fusion welding process

- Source of heat
- Fusion zone
- Heat affected Zone

Conduction mode

or

Keyhole mode

- Heat flux from heat source
- Localized melting and solidification
- Flow of molten metal
- Differential thermal expansion and contraction leading to distortion and residual stress

Now, first we took into this case, the autogenous fusion welding process that means, the welding process without any material addition to the domain. So, without any mental deposition. So, in that case, the we can represent the welding process is something like that, this is interaction of the heat from the heat source and then, heat source if it is a stationary welding process, spot welding process, then heats source remains stationary.

And then, we try to look into the temperature distribution as a function of time. So, in that kind of problem is called transient problem or other way also, if stationary heat source actually moves one particular direction, one particular velocity in that cases, we can consider this as a linear velocity.

But overall ones in case of linear welding process and then, with the application of the heat flux, we will get the molten pool specifically we are talking about the fusion welding process the molten pool. And once we the heat source moves from that molten from that position, then it subsequently solidify comes back to the ambient temperature. So, that is why representation of this thing.

So, we can see that typical part of a fusion welding process that melt heat sources there, second thing is the melt pool, it can form the melt pool also, but within melt pool not only the temperature distribution also there at the same time the metal flow fluid is also important in this melt pool.

Then, solidified zone. So, solidifies zone means once we move a heat source from one position to another position during that time the subsequently the well metal can solidify that means, the solidify zone mean simply which part was actually in the molten state so, above the melting point temperature that part once remove the heat source, then it solidify and that following certain kind of cooling rate and then, come back to the ambient temperature.

So, then apart from that, there is some heat effective zone. So, heat effective zone is define the temperature isotherm between the solidus temperature and to some phase transformation temperature. So, that particular zone when it is subjected to a variation of the temperature during this welding process so, accordingly, we can define the range of the temperature the whether it is heat affected zone or whether it is solidified zone.

Solidified zones mean above the melting point temperature that zone we can see that is a solidified zone or between the phase transformation temperature to particular solidus temperature that particular zone is considered as heat affected zone. Now, the most important thing is that normally, we do not focus on the what is the happening to the heat source, we can assume some of the heat source, then we try to look into the temperature distribution the consider this as a solution domain so, this is as a solution domain.

So, we need this domain, we can assume that this interaction of the heat through the boundary also; so that means, heat flux can be represented as a boundary introduction or in if you look into the governing equation of the heat contesting, there is a heat source term.

So, in that cases, we can consider the if we consider the heat source term, then we can consider the heat source is represented in the form of a volumetric heat and such that it becomes a part of the governing equation and we can solve the equation accordingly. Now, apart from this thing, the heat flux from the heat source is there, then localized melting and solidification, this is the sequence, then after that flow of the molten metal is there within the melt pool.

And then because of differential thermal extension expansion and contraction that actually try to lead some sort of distortion and residual stress in your lead structure. So, now, this source of heat is very important part then how what we can represent the source of the heat.

So, in arc welding, laser welding even fixation welding process also although solid state welding process so, different cases the representation of the source of heat in a different way. So, we try to look into that what we can represent the heat source that is the source of the heats. Already, we have discussed about the modeling of the, representatives of the different heat source in the model 3 also.

Now here, we will try to see how what we can apply these things, the particular heat source model to develop this heat transfer model in case of fusion welding process. Then, fusion zone we have already defined, the heat affected zone already defined, but in case of the laser welding process exclusively try to look into whether what kind of the mode of the welding process is there, whether it is conduction mode or whether it is keyhole mode.

And there is some certain mechanism we will try to look, we have already discussed that what is a conduction mode, and what is a keyhole mode. But within the formation of the heat source model, in case of the keyhole mode can be different also as compared to the conduction base model. But in this particular topic, we will try to look into first try to look into the conduction mode of heat transport looking into that and what way we can develop the different model.

Then, other part of discussion will be related to the keyhole mode laser welding process. So, in this case, we try to represent the simple, the keyhole mode laser welding process.

The first, we try to model the keyhole mode laser welding process by some analytical means, after that we will numerically what we estimate the temperature distribution in case of the keyhole mode laser welding process, both we will discuss, and we will see what are the difference between the conduction mode and keyhole mode laser welding processes.

Of course few arc welding process, there it is possible to the heat transform may be that kind of welding can also be done in the form of a in the mode of a keyhole mode welding process, but that is very selective no, I am not focusing in this that keyhole modelling process in particular related to the arc welding process that is not the corporate only keyhole we will be considering in case of the laser welding process.

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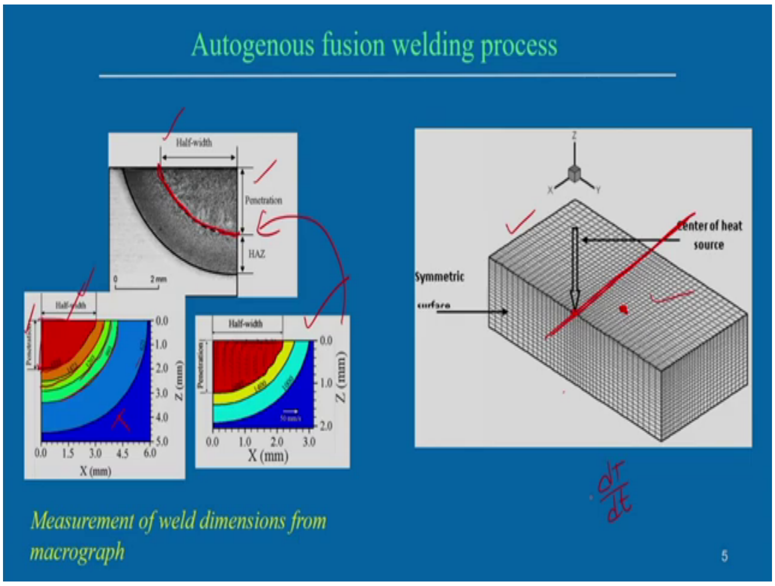

Autogenous fusion welding process

Measurement of weld dimensions from macrograph

Now, what we can model these things? So, first type of finite element model is that defining the solution geometry. We can see the sample example, this is very simple example that we define the solution domain. Here, we can see the solution domain. So, we will try to solve this governing equation within this domain alone with the boundary condition.

So, center of the heat source. So, center of the heat source, this is the heat is interacting with the solution domain. Now, we will see the interpretation of the interaction of the heat with the solution domain. There are two different ways already discussed this thing one way is that, we can simply assume the it is a boundary interaction in the form of heat flux.

So, it is interacting through the boundary or other way also, we can incorporate the some volumetric heat source model and that volumetric heat source model can be a consider; if you look into the governing equation of the heat conduction equation, there we can find out the q dot term. So, internal heat generation term.

So, volumetric heat source can be incorporated through the internal heat generation term. So, both way, the heat source or may be interaction of the heat can be done to the domain. So, once create the domain, you can see this is very finite element, if you see the meshing of this domain first, after creating the geometry some meshing is required, it is a simple brick element we have used.

But if you see the fine mash is created here about the center of the heat source such that we will be able to very if there a temperature gradient is relatively very high in the this particular in the near about the source of the heat so, that how we can consider the very fine mesh to capture all the temperature gradient or more precisely capture the temperature isotherm so that is why very fine mesh can be considered near about the heat source.

So, once we do this, this thing, then we do we solve the heat conduction problem along with the boundary condition we think, then we will be getting the temperature distribution is something in that particular profile. So, then particular profile and this profile can be from the once we get the solution of temperature distribution and of each and every node point, then using the data file.

So, data file you can plot it the data file, then we can define the different isotherm for example, this is the melting isotherm, I think that is the solidus temperature, may be this is the liquidus temperature this can be the solidus temperature and some other phase transformation isotherm, we can define in such a way so, that the different color represents the different isotherm.

So, within this the red zone, since that red zone is defined by the isotherm is that solidus temperature or liquidus temperature so, that zone indicates the fusion zone, in a fusion zone and that we can get from the solution of the heat conduction equation using the finite element method.

So, this fusion zone, but we have to understand that in the fusion zone, we can define with the width, what is the weld width and what is the depth of peneture that is most important. So, that penetration along the z direction and with along the y direction or x direction in this particular case so, we take the cross-section.

Basically, in this particular case, we take after getting the solution we take the this cross-section, we cross-section and with this particular cross-section, we can see that particular cross-section how the what is the distribution of the temperatures. Then this so, the distribution of the temperature and the temperature distribution the different zone is defined by the constant isotherm so, particular isotherm.

So, that shows the different kind of the zone. Now, once we get the isotherm, from the isotherm, we can estimate the looking in the red zone that actually define the penetration so, this is the actual value of the penetration and here, we can the half width. So, and if you multiply by the two, you can get the full width of a of this particular zone.

So, then this way we can estimate the half width and full width and here, it is showing only the temperature distribution. At the same time, if we solve the transport phenomena heat transfer and fluid flow model both this thing, then we will be getting the temperature isotherm c and there is a this vector indicated by the arrow that indicates at the velocity field.

So, that indicate the arrow indicates the velocity field also so, within the domain this fusion zone, we can get the both velocity field as well as the temperature field. So, now, similar, we can estimate the penetration and the half width. So, penetration and half width we can define just looking into the isotherm. So, that defines the penetration and half width for this particular zone.

Now, once numerically completed this thing, then now we compared with the respect to the experimental data. So, similar way, if we perform the same parameter, if we consider and if you do the experiments also and from the experiments, we can find out what is the width and what is the penetration of from the experiment also.

So, then we take the macrograph, with the follow the standard metallography process, then after that if we put the each end solution, then we will be able to see that there is changes this thing, the structural changes will be able to identify.

So, looking into the structural changes, we can find out this indicates the fusion zone this dotted line so, that indicates the fusion zone from the macrograph and then, we define what is the penetration and what is the width for this particular condition.

Now, we compare with the a numerically calculated the isotherm profile. So, that in that way, we can compare the model laser as well as a experimental laser. So, these are the way to look into the a different dimension the measurement of the weld dimension from both the macrograph as well as the measurement or dimension from the numerical model also. So, both it is possible.

We can say this is output from this model. So, apart from this temperature distribution also because from this model, we will get output as a temperature distribution each and every node point, but at the same time, it is also possible to store the data as a function of time and from that, we can estimate what is the rate of the cooling one particular, maybe we can see the we can particular fixed point.

So, with respect to time, how the temperature varies on this particular point and from this data, temperature versus time, there we can estimate what is the rate of temperature change. So, in that cases so, what is a change of temperature with respect to change of time that indicates the cooling rate. So, all kind of information and we can get if we solve for the temperature distribution also.

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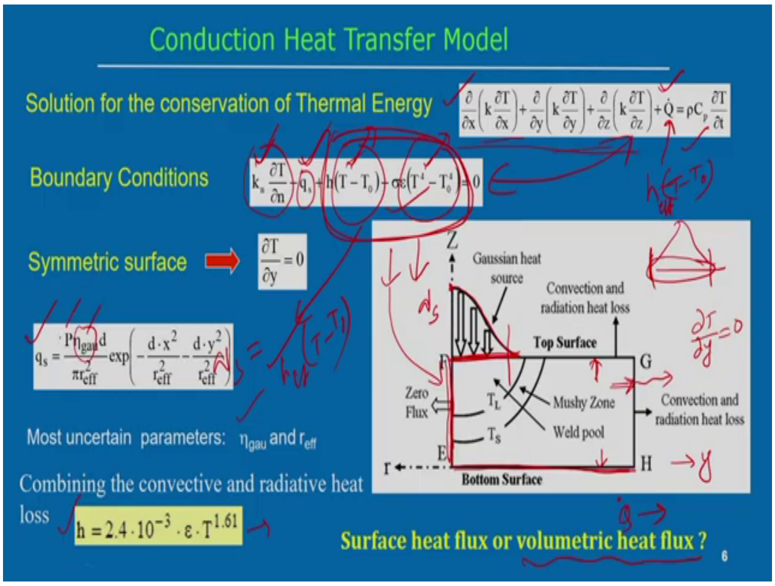

Conduction Heat Transfer Model

Solution for the conservation of Thermal Energy $\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=\rho C_p\frac{\partial T}{\partial t}$

Boundary Conditions $k_n\frac{\partial T}{\partial n}-q_s+h(T-T_0)+\sigma\varepsilon(T^4-T_0^4)=0$

$h_{eff}(T-T_0)$

Symmetric surface $\frac{\partial T}{\partial y}=0$

$q_s=\frac{P\eta_{gau}d}{\pi r_{eff}^2}\exp\left(-\frac{d\cdot x^2}{r_{eff}^2}-\frac{d\cdot y^2}{r_{eff}^2}\right)$

$q_s = h_{eff}(T-T_0)$

Most uncertain parameters: η_{gau} and r_{eff}

Combining the convective and radiative heat loss $h=2.4\cdot10^{-3}\cdot\varepsilon\cdot T^{1.61}$

Surface heat flux or volumetric heat flux ?

Now, conduction heat transfer model. So, we can say the conductive heat transform model also. In this case, we know the Fourier heat conduction model, we use this governing equation for the thermal energy.

So, del by del x k del T by del x all this and this is the Q dot term indicates the internal heat generation term and rho C p del T by del t so, it is the basically transient term, internal heat generation term and this associated with the conductivity because small case the thermal conductivity. So, that parameter.

So, basically, we need to solve this governing equation, but there is need some boundary condition also. In welding process particularly, the arc welding process or fusion welding process, we can replace the boundary condition something like that in this way also that this is the boundary condition means see this is the domain.

For example, we take a cross-section, the whole domain in three-dimensional domain and what is happening with this particular cross section? So, this E, F, G, H within this particular domain, it is necessary to solve the conservation of the thermal energies. Basically, heat conduction equation, which is necessary to solve, but boundary condition what we can see?

What is the temperature conducted to the or the boundary or may be the boundary are place basically conducted at this particular boundary what is conducted? This thing and then from here also the heat loss by convection as well as a radiation. So, then heat loss by conviction, heat loss by radiation and what is heat conducted to the boundary that is that this first term k n del T by del n in this n, n actually indicates the normal to the boundary so, we can put, we can estimate what is the heat conduction exactly at the boundary.

So, this loss and heat conducted this thing and q s, there is another term because if there is a heat input because when it is heat source is interacting with the material that can be considered as a boundary interaction. So, from through the boundary, there is a heat input that is called the heat flux q s that is a heat flux through the boundary interaction.

So, this boundary that heat is interacting with the to the surface and remaining is the heat loss by convection and radiation, but how we can count the heat loss from convectionary is? Until and unless heat is conducted to the boundary, then there will be the heat loss by convection and radiation.

So, that is why heat conducted to the boundary that term is considered, heat loss this term as well as the heat input in terms of flux that is equal to making the system as a balanced system. So, in that case that equal to 0 so, that is the boundary interaction and we have already shown that this is a governing equation and this is the boundary condition.

So, using these two, we can develop the finite element formulation of this particular problem, then we solve for this thing and final we will be getting the temperature distribution. Now, we can see that this typical pattern also because other boundary condition is 0 flux in the sense that suppose if we consider the problem is symmetric so, in kind of the symmetric problem, then not necessary to consider the analysis for the whole domain.

So, we can consider the half of this thing and the symmetric surface has to be identified such that the temperature gradient del T by del y. For example, if this is a y direction so, del T, this is symmetric surface so, 0 flux so, del T by del y should be 0 that is the boundary condition we should put the symmetric surface on this thing.

And this, it is the q flux and there is a heat flux from the surface this Gaussian heat intensity that means, when it is entering the heat source can be represent on not the intensity of the heat exactly center point will be the maximum and gradually it is at center point it is maximum gradually, it is decreased.

So, this is normally follow the Gaussian pattern of the heat flux. So, it means that at the center, it is maximum and gradually decreases towards the boundary. So, that is why there are some equation, we can follow for gaussian distribution specific equation you can follow and we have seen also in heat source model also. There are we can put the as a boundary interaction and then solving this thing using the finite element method we will be getting the temperature distribution.

But few things are very important here also sometimes the boundary bottom surface. So, bottom surface may be sometimes it is a actual in practical bottom surfaces in interacted with this some sort of a fixture and in the actual experiment. So, when it is fixture, this thing may be.

But at the center, you put some also clumping also so, intimate contact between the fixture also in that cases some contact resistance may we can consider also or other way also heat transfer, we can consider in such as that heat transfer coefficient artificially can be enhanced to account the contact resistance between this domain to the fixture also. So, between the that part has to be considered a different boundary condition, we can put for this bottom surfaces.

So, this the a typical way, but if you look into this thing, most uncertain parameters means if you look into this Gaussian distribution, then q s so, what is the this heat flux is there, but at the same time the heat flux is there, but what we calculated from the heat source?

If we calculate from the heat source also, this the total heat that follows certain Gaussian distribution, but that not all the heat is transported for the melting of this particular domain also all not from the arc or from the laser source not all the energies comes directly to the domain.

So, therefore, we can some part of the energy is basically actually transferred to the domain and then so that when you consider the not some part of the energy transport to the domain therefore, in that cases, we can introduce some sort of the efficiency term and that is we can say the Gaussian efficiency may be that term.

And second point is that it is that when you creating the arc, this thing and basically the shape of the arc or may be effective radius and over the surface, effective is when you are creating the arc also, then what is the effective area the arc is interacting that is called that we that quantitatively, we have to estimate that is a that is called high effective radius.

So, that effective radius is sometimes is very difficult to measure effective within the; within which the all energy is transport to the sub state material to the solution domain. So, that is why, we consider sometimes what is the efficiency term, what is the effective radius, it is basically, uncertain parameter.

So, roughly we can we have some idea what is the efficiency, but it is very difficult to say it can vary also different system. So, it is very difficult to say the exact value of the what is the efficiency and what is effective radius. So, these two parameters can be considered as a the uncertain parameter.

Now, combining the convective radioactive heat transfer also so, sometimes if you see the this thing it is T to the power of 4 minus T 0 so, this fourth order temperature. So, fourth order temperature discretizes in using the finite element method may be some difficulties are there.

So, in that cases, may be combining this convection heat loss by radiation term that can be sometimes we can consider the effective radius, effective heat transfer coefficient such that it considered both T minus T 0 that means, this is e effective, h effective we can say that h effective that is why effective heat transfer coefficient, that effective heat transfer effective coefficient consider the combined effect of the convection as well as the radiation term.

If you use this one the in other also, it actually eliminates the difficulty to consider the fourth order temperature term. So, that is why it is advantageous to look into this consider the combined value of the heat transfer coefficient. So, that also we can look into from the development of the model also, we can put this term instead of this thing two terms so, we can simply write h effective T minus T 0.

So, then first term, second term and then effective heat transfer will be there; so, this is the one way to make the conductive heat transfer model, but point is that should I consider the surface heat flux or should I consider the volumetric heat flux? Because surface heat flux if we consider and mathematically, the Gaussian heat flux, then in case of arc welding or even for laser welding process also, then it may not predict the depth penetration well enough.

So, in that cases, it means that consideration of only the surface heat flux may not the correct representation of the heat source or may be interaction of the heat source to the domain. So, in that cases, it is more advantageous or also people have developed in such way that if we consider this heat interaction in the form of a volumetric heat source term so, that is that can be incorporated into this governing equation through this q dot term.

So, therefore, volumetric heat flux if we consider, then it is more realistic in case of and that volumetric heat source term can be incorporated into the equation, governing equation through this heat generation term. So, that is why we have developed the different heat source model.

Or most of the cases, if you remember that we consider the different volumetric heat source model to represent the actual interaction of the heat source to the substance material and it is more sensitive in case of the laser welding process because laser actually penetrate to particular depth.

Even in laser welding process, if you consider only the surface flux, then you may not get the desire result may be an temperature distribution in that cases, it is necessary to consider the volumetric heat flux. So, that means, we have to consider some heat source model and then, we have to incorporate through the internal heat generation term.

So, that is why it is necessary to do this thing and here you can see that typical expression of the q s also you can see that heat flux P, this efficiency term we have already discussed, this particular part.

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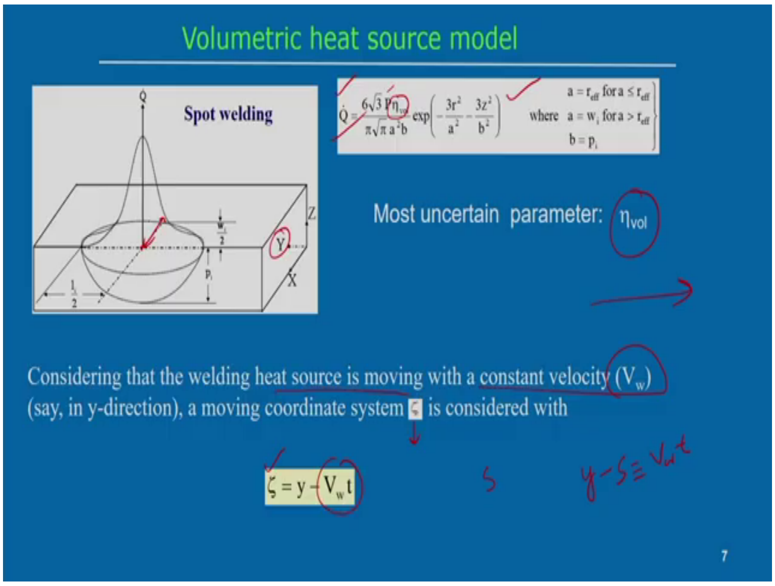

Volumetric heat source model

$$\dot{Q} = \frac{6\sqrt{3}\,P\eta_{vol}}{\pi\sqrt{\pi}\,a^2 b}\exp\left(-\frac{3r^2}{a^2} - \frac{3z^2}{b^2}\right) \quad \text{where} \quad \left\{\begin{array}{l} a = r_{eff} \text{ for } a \le r_{eff} \\ a = w_i \text{ for } a > r_{eff} \\ b = p_i \end{array}\right\}$$

Most uncertain parameter: η_{vol}

Considering that the welding heat source is moving with a constant velocity (V_w) (say, in y-direction), a moving coordinate system ζ is considered with

$$\zeta = y - V_w t$$

ς

$y - \varsigma = V_w t$

Now, if we differentiate that what we can model the, what are the difference in terms of the modeling of the spot welding and linear welding process? Linear welding process, if there is a moving heat source. So, in spot welding process, we can consider the this particular on the stationary heat source, some sort of the symmetric profile, we can consider the elliptical profile in the spot welding process, I am talking about the volumetric heat source.

So, volumetric heat source can be the typical geometric shape of an elliptical shape and then, volumetric heat source development, we have already seen that q dot may be internal heat generation term is the in terms of the volumetric heat equal to 6 root 3 P, is the volumetric efficiency and pi root pi a square b. So, a square b equal to an exponential 3r square a square and minus 3z square by b square.

So, in this case, a equal to is basically r effective. So, are r effective one, effective radius which is interacting on the surface and a equal to w i so, a equal to the w i for a greater than r effective. So, if it is a greater than r effective, then a can be considered as a w i. So, w i can see this thing the and b equal to pi the depth in this case and a equal to w i basically, this is the length of w i.

And in this case, for a equal to less than effective r, then we can consider the a equal to r effective. So, that means, up to the effective radius, we can consider a as r effective even, if it is the more than, then it can be considered w i means up to the this the width basically, the half width we have already seen the in the molten zone that is a width can be considered that a value of the a. So, this way, we can map actually the value of the a and the geometric parameters of the ellipsoid, we can directly map in the width and the depth of penetration during this process.

But by mapping, we can define the heat source, the internal heat generation term, but in this case, the uncertain parameter is the volumetric, this efficiency that is, it is very difficult to exactly to estimate what is the value of the volumetric if it is exactly to define this value, but approximately, we can define this certain value of the this volumetric efficiency term.

Now, this is the spot-welding process, once we do this kind of the volumetric heat flux and if we see this in case of the spot welding process and just by simply mapping the width and the depth of penetration, we can define the volumetric heat. And then, we solve for the governing equation, then we will be after we will be getting the temperature distribution so, this is for stationary heat source.

And stationary heat source we will be getting the temperature distribution as a function of time. So, is this kind of problem, we can see the transient problem. So, temperature vary with respect to the time. But it depends on this thing because with the respect to time, different on time keep on interacting the heat flux to the surface or the when the laser is basically interacting with the surface with a certain time.

So, that interaction time the if the interaction time is more, then it will try to create the more oil pool volume also, this particular spot welding process; but in this case, there is no role of the velocity of the moving either workpiece or moving of the laser or arc welding process.

So, in that case, the modeling approach for the moving heat source little bit different, we can simply going back to the basic governing equation. And what we can modify this governing equation such that we can develop the model in case of the moving heat source or may be what we can interpret the when there is welding velocity, in case of the linear welding process.

Now, consider the that the welding heat source is moving with a particular velocity V w say Y direction, say assuming that this is the Y direction so, assuming the Y direction, one particular velocity the welding heat source is moving. So, in that cases, a moving coordinate system is consider xi this particular variable is considered in such a way that we can consider the xi can be like that y minus V w into t.

So, this V w into T is basically is the distance s. So, y minus the distance s, the s correspond to basically, V w the welding velocity into the time particular time so that mean heat source is moving at the different time the position all will be different. So, then we can introduce the moving coordinate system and defining this thing y minus y is the actual variable in this particular same.

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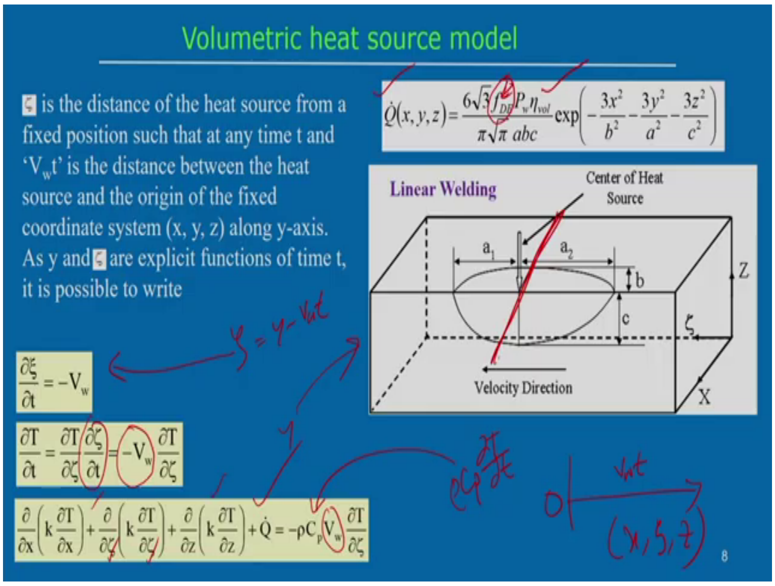

Volumetric heat source model

ζ is the distance of the heat source from a fixed position such that at any time t and '$V_w t$' is the distance between the heat source and the origin of the fixed coordinate system (x, y, z) along y-axis. As y and ζ are explicit functions of time t, it is possible to write

$$\dot{Q}(x,y,z) = \frac{6\sqrt{3} f_{DE} P_w \eta_{vol}}{\pi\sqrt{\pi}\, abc} \exp\left(-\frac{3x^2}{b^2} - \frac{3y^2}{a^2} - \frac{3z^2}{c^2}\right)$$

$$\frac{\partial \xi}{\partial t} = -V_w$$

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial \zeta}\frac{\partial \zeta}{\partial t} = -V_w \frac{\partial T}{\partial \zeta}$$

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial \zeta}\left(k\frac{\partial T}{\partial \zeta}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q} = -\rho C_p V_w \frac{\partial T}{\partial \zeta}$$

And now, zeta is the distance of the heat source from the fixed position at any time t. So, from the is that distance of the heat source from a fixed position such that at anytime t and V w t is the distance between the heat source and the origin of the fixed coordinate system along x, y, z.

So, along x, y, z, we can see that at particular distance it is a V w t it will travel with respect to seems of this origin for and that is with respect to the original cartesian coordinate system x, y, z system. Now, as y and zeta are explicitly function of the time in such a so, it is possible to write this thing already I have seen zeta equal to basically, y minus V w t.

So, if we define this thing now, we transfer this coordinate the, if you this thing with respect to this thing do the derivative also with respect to time, then it becomes the velocity minus V w. Now, minus V w, other terms we can consider that del T by del t that means, if you see the heat conduction remember, the heat conduction equation also so, here we can see there is one term is there, the basic governing rho C p by del T by del t that is transient heat conduction equation.

Now, rho C p del T by del t so, with respect of time t. So, now, del T by del small t, we can see in terms of del T by del xi similar del xi by del t, here you can see that del xi by del t is basically the minus V w del t by del xi. So, now, this governing equation, the transient governing equation, transient (Refer Time: 32:00) governing equation we can see, modify this way also.

This term is there and of course, this is k, the now it is with respect to the moving coordinate system. Now, the coordinate system basically, x y z as zeta and z. So, with respect to that to that coordinate system, then y in terms of y is replaced by this particular this coordinate system there moving coordinate system and z components will be there plus q dot into the heat generation term equal to rho C p del T by del t converted to minus rho C p V w del t by del xi.

Now, if you look into this governing equation is just to takes care of the moving heats source problem that we respect to the moving coordinate system in that case, we can find out this governing equation, there is no time component is not there actually, explicitly there is no time component in this particular equation.

So, this kind of equation, we can say that it is a kind of quasi-steady state problem. So, quasi-steady state problem and here, we can solve the independent of the time also, time component. So, quasi-steady state problem, if we solve it, then we can get the temperature distribution in a particular domain that we will see that what the temperature distribution can vary also in the quasi-steady state analysis, but this is the difference with respect to the only the transient analysis.

Because transient analysis we got, there is a temperature term is there and we can discretize both in the this particular domain also, we can discretize in the event there is necessary to spatial domain as well as the temporal domain, both it was required in case of the transient problem. But once if transient problem converted to the quasi-steady state problem, then the discretization over the spatial domain is sufficient to get the solution of this particular equation.

Now, at the same time, there may be some change in the representation of the volumetric heats heat source term also. Now, the volumetric heat source term, now it is no longer interpreted in the form of the elliptical model.

So, in that cases, the most mostly that is a double ellipsoidal kind of this thing. It means that seems the heat source moves one particular direction so, with the respect to this particular axis if you see the front and rear part will be not may not be the symmetric, it should be some kind of the non-symmetric.

So, that cases, we represent the heat flux, internal heat generation term in this particular equation 6 root 3 some fractional part is there and remaining pi root pi by abc, abc is basically mapping the geometric parameter of an ellipsoid and maybe we can consider double ellipsoidal model, the front part is a one part of the ellipsoid and the rear part is the another part of the ellipsoid.

So, then that combining these two, we can get the double ellipsoidal heat source model. So, in that case is the all the geometric parameters a, b, c are the geometric parameter associated with the ellipsoidal or double ellipsoidal model. But once we consider the front part of the ellipsoidal, then we consider this fractional part. Now, we can consider the geometric related to the front ellipsoidal.

Then, if we consider the rear part also, then in that cases, the it is different also you can consider the all geometric parameter associated with the rear ellipsoidal and in that cases also, we need to that this front f DE that means, this fraction can be different when it is if we consider the rear part.

So, accordingly, once we consider front part or rear part these two part accordingly, we use the geometric parameters can we change and then, this represent the internal heat generation and we can form the elemental form can be done or we can say the internal heat generation term can be incorporated in that particular way.

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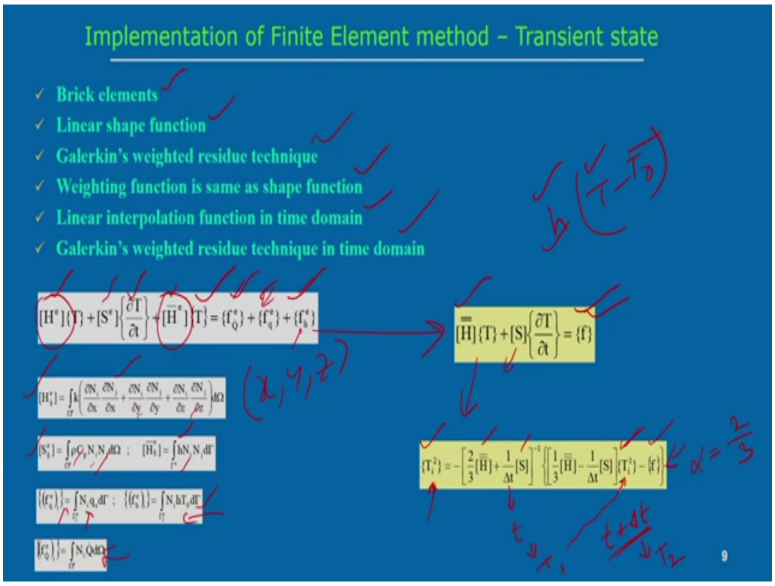
Implementation of Finite Element method – Transient state

- ✓ Brick elements
- ✓ Linear shape function
- ✓ Galerkin's weighted residue technique
- ✓ Weighting function is same as shape function
- ✓ Linear interpolation function in time domain
- ✓ Galerkin's weighted residue technique in time domain

$$[H^e]\{T\}+[S^e]\left\{\frac{\partial T}{\partial t}\right\}+[\overline{H}^e]\{T\}=\{f_Q^e\}+\{f_q^e\}+\{f_h^e\}$$

$$[\overline{\overline{H}}]\{T\}+[S]\left\{\frac{\partial T}{\partial t}\right\}=\{f\}$$

$$[H_{ij}^e]=\int_{\Omega^e} k\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}+\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right)d\Omega$$

$$[S_{ij}^e]=\int_{\Omega^e}\rho C_p N_i N_j\, d\Omega \;;\quad [\overline{H}_{ij}^e]=\int_{\Gamma^e} h N_i N_j\, d\Gamma$$

$$\{(f_q^e)_i\}=\int_{\Gamma_q^e} N_i q_s\, d\Gamma \;;\quad \{(f_h^e)_i\}=\int_{\Gamma_h^e} N_i h T_0\, d\Gamma$$

$$\{(f_Q^e)_i\}=\int_{\Omega^e} N_i \dot{Q}\, d\Omega$$

$$\{T_i^2\}=-\left[\frac{2}{3}[\overline{\overline{H}}]+\frac{1}{\Delta t}[S]\right]^{-1}\left\{\left[\frac{1}{3}[\overline{\overline{H}}]-\frac{1}{\Delta t}[S]\right]\{T_i^1\}-\{f\}\right\}$$

Now, implementation of the finite element method. If you look into the transient state so, if you discretize the governing equation along with the boundary condition so, final form of the equation can be like that. But in this case, if we can follow the brick elements, the very simple we can consider the brick elements, it is very easy to keep accounting in a finite element base model, if you consider the brick element.

Then, linear shape function was used, then Galerkin weighted residue technique was used in these cases and weighting function consider is the same as the shape function that is already there. Then linear interpolation function in the time domain also same, linear interpolation function we can consider the time domain also and discretize in the time domain and Galerkin weighted residue technique even considering in case of the time domain discretization.

Now, we have already seen the how what we can discretize the governing equation and what is the typical form finite element base equation also. There in this particular case may be transient problem, we are getting this particular form this H term is there, we have defined the H term also that all this in terms of a thermal conductivity del N by del x, y, z so, it is a it is here the coordinate system x, y, z because it is a stationary problem. So, heat source is applying at a fixed position. So, we can consider then x, y, z.

Then, S term is there, we can see define S term in terms of the rho C p N i N j over the elemental volume also, then H bar, the heat transport coefficient here conviction part is gear in this case, but we are not considering there is no radiation term is not there because we have considered the combined heat transfer coefficient that is that considered both the convection as well as the radiation. So, that is why H is accordingly defined that combined heat transport coefficient.

Now, in other cases, f is the internal heat columnar T f Q, it is a general expression that q s term is there, f q that means, f q is this one sorry this one and f capital Q dot is the internal heat generation term and f is the there is a reference because of the reference temperature because one cases we can see the T minus T 0 h so, one term is come because of this two and another term is coming h and T 0. So, that this term is the because of the h and T 0.

So, right-hand side is basically represent the columnar column vector and left-hand side represent all in the metrics form, the some sort of square metrics represent all this thing. Now, we see discretization is the special domain, but there is a one we have not discretize in the temporal domain also del T by del small t then, once you form this equation a spatial domain, then we have to discretize in the time domain also.

So, time domain if we discretize this thing and we can see this is a simple from we can use equation in H bar, H bar consist of all this, this H e and H bar basically, is H double bar indicate the consist of this two n, S is related to the transient component that means, this thing and right-side represent because similar kind of all other column vector, we can combine this thing we make a single column. So, these are the equation after considering in the discretization over the spatial domain.

Now, this time dissertation domain, we have already shown in that even it is possible to discretize the thing in case of the time domain also. So, once we do the discretizes in the time domain, then we will be able to get this time temperature equal to T 2 on one particular time step.

At the end of this time step, this is a particular temperature which consists of this term and see delta t is the increment of the time, one particular step and T is the temperature of the initial step and then, f is the load vector. So, this way we can get the temperature distribution. So, that is the typical formulation associated with the transient problem also.

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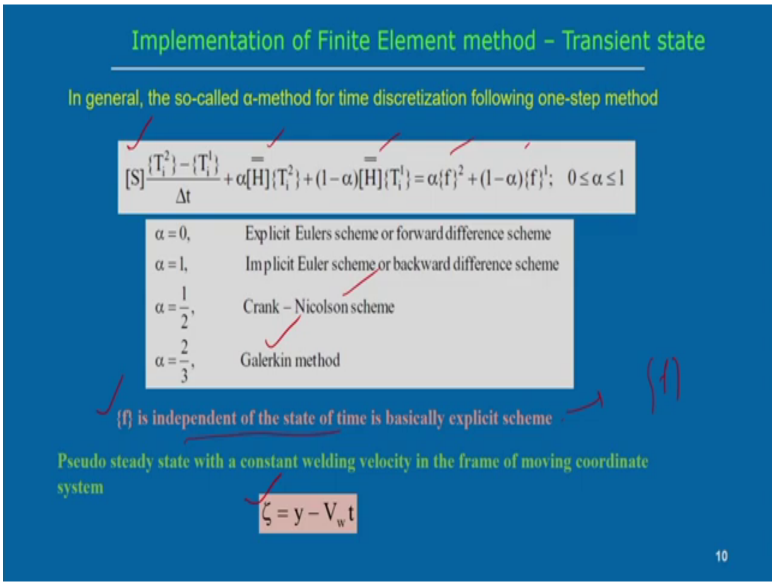

Implementation of Finite Element method – Transient state

In general, the so-called α-method for time discretization following one-step method

$$[S]\frac{\{T_i^2\}-\{T_i^1\}}{\Delta t}+\alpha[\overset{=}{H}]\{T_i^2\}+(1-\alpha)[\overset{=}{H}]\{T_i^1\}=\alpha\{f\}^2+(1-\alpha)\{f\}^1;\quad 0\le\alpha\le 1$$

$\alpha = 0,$	Explicit Eulers scheme or forward difference scheme
$\alpha = 1,$	Implicit Euler scheme or backward difference scheme
$\alpha = \frac{1}{2},$	Crank – Nicolson scheme
$\alpha = \frac{2}{3},$	Galerkin method

{f} is independent of the state of time is basically explicit scheme

$\{f\}$

Pseudo steady state with a constant welding velocity in the frame of moving coordinate system

$$\zeta = y - V_w t$$

Now, in general also so called alpha method for time discretization following the one-step method can be used in general way, we can this thing time discretization we can see this way also, we can interpreting in the time domain also, then we can in general form this equation can be written like that. So, but here, alpha is a constant so, in different scheme, the alpha value can be different.

So, alpha equal to 0, explicit Euler's scheme or forward different scheme. Alpha equal to 1, implicit Euler scheme or backwards different scheme. An alpha equal to half, Crank-Nicolson scheme and alpha equal to 2 by 3, Galerkin method. If we use the alpha equal to 2 by 3 in general, then we are getting actually this particular expression.

So, here actually, we have used alpha equal 2 by 3 and from there, we are getting this temperature distribution of the at the end of the time t plus del t. So, t plus delta t at the end. So, you can see this is the, this we can say the we are getting t plus delta t, the temperature as a T 2 and at the time t, we are getting the temperature this as the T 1. So, T 1 that information is required to estimate the temperature after one-time step.

So, this way and we have already shown that f is possibly in this discretization scheme, f is independent of the state of the this time so, state of this time. It means we consider f this matrix the right-hand side, it is independent of the step of the time that means, we are assuming the what was the f value at time t is the same as the at time t plus delta t. So, that is the assumption in this particular scheme.

Now, if you look in the Pseudo steady state analysis, the for a constant welding speed already frame, we consider the moving coordinate system, we have already defined, we have already explained in case moving coordinate system, we can use it for the discretization of the domain.

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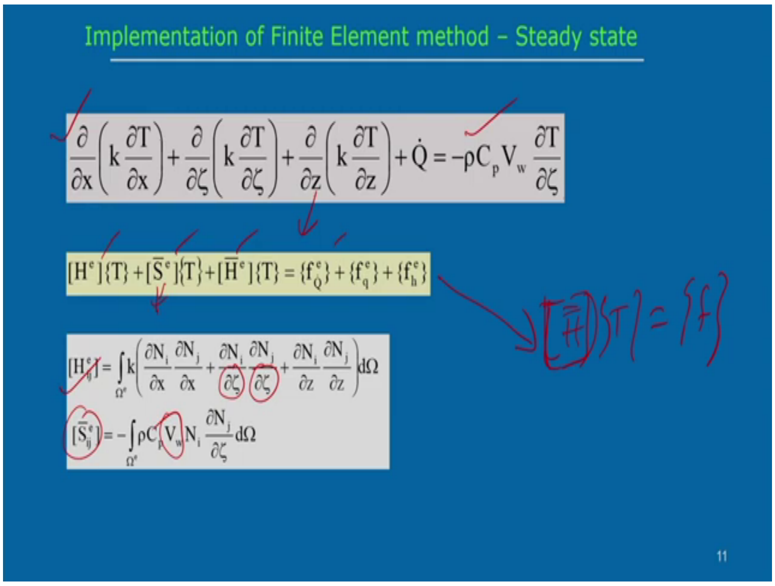

Implementation of Finite Element method – Steady state

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial \zeta}\left(k\frac{\partial T}{\partial \zeta}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=-\rho C_p V_w \frac{\partial T}{\partial \zeta}$$

$$[H^e]\{T\}+[\bar{S}^e]\{T\}+[\bar{H}^e]\{T\}=\{f_Q^e\}+\{f_q^e\}+\{f_h^e\}$$

$$\boxed{\bar{\bar{H}}}\{T\}=\{f\}$$

$$[H_{ij}^e]=\int_{\Omega^e} k\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial \zeta}\frac{\partial N_j}{\partial \zeta}+\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right)d\Omega$$

$$[\bar{S}_{ij}^e]=-\int_{\Omega^e}\rho C_p V_w N_i \frac{\partial N_j}{\partial \zeta}d\Omega$$

And we are getting, we are already seen that the governing equation can be from transient equation to we can they in the form of a quasi-steady state so, such that the governing equation we can see that it is the there is no time component. So, in these cases, only the special discretization is sufficient to form the final matrix form or the discretized form of the equation.

Now, if we do discretize along with the similar kind of the boundary conditions because if you look the boundary condition, we define in such way that is boundary condition is independent of the time component. So, same kind of the boundary condition, we can use even for the quasi-steady state analysis.

Now, it is a step forward guide discretizing the spatial domain, we will be getting this expression like this and such that final you will be H T equal to f, this kind of expression will be getting here, from here to here so, similar, but there is no need to discretize the domain in a time domain it is not required.

Now, only two terms are different here, this is H equal to in terms of this thing that this is a moving coordinate system and S, the this term also S bar that is the if we see minus rho C p V.

So, here, this when you discretize in this domain, then are the velocity actually the we can incorporate the effect of the velocity for this particular term, S term. Now, take the form in this particular take the equation in this particular form, we solve for it and we will be getting the temperature distribution using the quasi-steady state problem.

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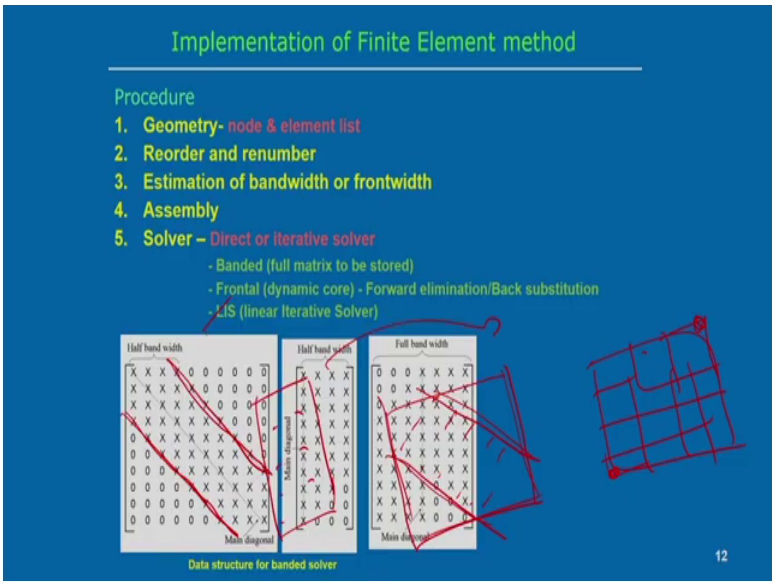

Implementation of Finite Element method

Procedure

1. Geometry- node & element list
2. Reorder and renumber
3. Estimation of bandwidth or frontwidth
4. Assembly
5. Solver – Direct or iterative solver
   - Banded (full matrix to be stored)
   - Frontal (dynamic core) - Forward elimination/Back substitution
   - LIS (linear Iterative Solver)

Data structure for banded solver

Now, implement is the final element in general procedure is the first geometry. You have to clear geometry node and element list also because that is required. Once you clear the geometry, then discretize the geometry, then what are the list of the node and what is the list of the element, how they are connectivity of the element with a particular node and each and node and element having some global numbering system, all information actually required.

Then, reorder and renumber is also required because we have to arrange this particular node number in such a way that contribution so that it can so, the connectivity can be represent with the minimum bandwidth and one node to another node.

It means that for example, if particular problem, we discretize the domain the this way also so, it is not necessary, this information is may not for this particular node point that connectivity may not be required when you try to solve in the final matrix form.

So, in that case, we can reader in such a numbering way such that the contribution from all the node going to the matrix form it can be accumulate in the small band. Then, if you accumulate within the small band, then it will easy to solve, it is possible to develop some solver such that this solver can quickly get the competition time can be reduced. So, that is the purpose.

So, that is why some sort of reorder and some sort of renumbering of the element or node point, it may be required. Then, finally, estimate the bandwidth or frontwidth means what is the this width in a in the particular matrix. So, once we get this thing, perform of these matrices, then we simply pick up these bandwidth matrices, then we solve find out the solution strategy for the we can use the some banded solver.

Then finally, solver we have discussed the direct solver, iterative solver we can use it. But in very simple problem, if it start with these things, then it is try to look into the in the banded form, the store the matrix in the banded form and then, banded form the after assemble, then we can solve for the if simple using the Gaussian elements method, we can solve this particular set of the equation to get the temperature distribution.

But if the big problem also that means, the matrix, number of nodes, elements is very high, may be it is possible to use the frontal solver, this is also direct solver frontal solver, but this is direct solver, but in this case, it is not necessary to assembling for the contribution all the matrix together, then you solve for this thing that may not be required.

But some sort of dynamic code is required to develop such that after forward elimination, one contribution from the one element is done, then it perform the forward elimination in the stored in a matrix. This once all forward elimination for individual matrix are done, then you start from the back substitution or if some iterative solver can be used the linear iterative solver to solve this problem ok.

So, here we can see the structure of this particular data structure for the banded solver also. So, this is the if you assemble this thing, contribution from all the node and it will be coming like that also such that if we see this is the non-zero element, will be the may be scatter within the certain band, but it depends on so, how effective you are reordering and renumbering scheme are there. Basically, reordering scheme is there.

So, if you follow certain very good reordering scheme, then this non-zero elements can be accumulated with this small bandwidth. So, that is why, then once we look into this thing we can store all in this part, accounting this thing in the basically half within the if it is symmetric matrix only you can show the half bandwidth, then you solve for the half bandwidth.

If it is non-symmetric problem, you can solve the a full bandwidth also, then we solve for that, then we will getting the solution of this (Refer Time: 46:12). Then, that is why the some sort of accounting will be easier if you follow this particular steps that if we follow some kind of the reordering and then, it is possible to develop the solver and that is competition time can be reduced follow this particular solver also.

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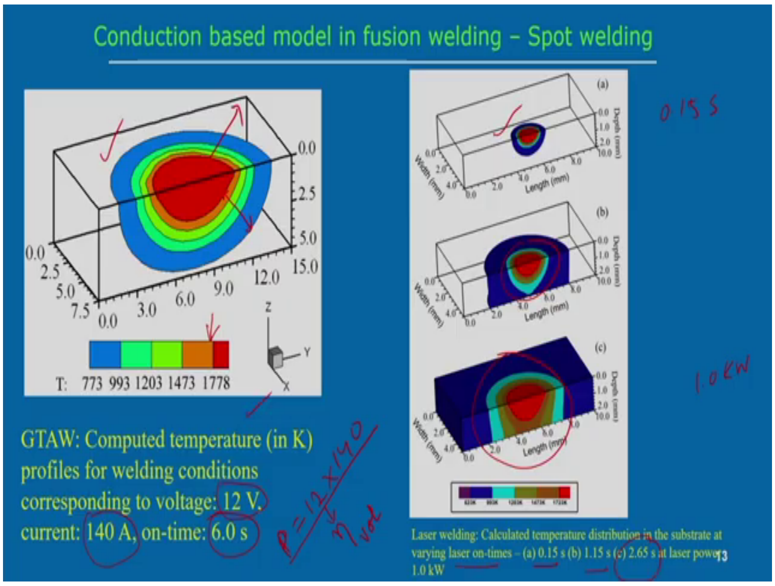

Conduction based model in fusion welding – Spot welding

GTAW: Computed temperature (in K) profiles for welding conditions corresponding to voltage: 12 V, current: 140 A, on-time: 6.0 s

Laser welding: Calculated temperature distribution in the substrate at varying laser on-times – (a) 0.15 s (b) 1.15 s (c) 2.65 s at laser power 1.0 kW

Some sort of results also we can see that conduction base modeling fusion welding process so, a spot-welding process. Here we can see that Gas tungsten arc welding process, the it is a computed temperature distribution in Kelvin, the corresponding to voltage is equal to 12 volt and current equal to 140 amps and on-time equal to 6 second. So, this is the spot welding in case of the spot arc welding process.

So, here, if we can see the current is equal to say 12 volt and current sorry volt is equal to 12 and current equal to 140 so, then power equal to this one, this is the power, but we can if you this is a total power with the supply power for this particular welding process, but when a actual energy goes to the domain, then in that case, we can use some efficiency term.

So, definitely, it should be less than 1 so, efficiency term that is the actual effective power goes to the substrate material. So, that is why, this kind of information is required. So, then we are getting once we solve for the spot-welding process, then we will be getting the temperature distribution something like that, we can see also that 778 so, this is the solidus temperature for a particular 778 Kelvin. So, above that domain, this basically, red domain we can see this is the fusion zone.

And we can see the temperature isotherm between the 778 to I think 12 or 99 or 773; 773 means in case of steel, it is very important some sort of a critical temperature also. So, then from this temperature to this temperature, this particular zone, we can say that is a heat effective zone for this particular problem.

It means that from the mathematical model, once we get the temperature distribution from node point, then you can define that particular temperature range isotherm and that we can correlate with there is any phase transformation or some sort of some critical temperature associate with this particular material or not. So, that kind of information will be getting from the mathematical model or from this finite element model.

Here also we can see the laser spot welding also that calculated temperature distribution substrate at the laser on time, when is laser on time is 0.15 second, it means that the keep switch on of the laser apply a supplying the power only 0.15 second, after that 0.15 second is simply switch of the switch of the power source, then it will create this kind of the weld pool.

Now, if it is 1.15 second, it will a little bigger weld pool can be created. Now, if it is 2.6 percent keep laser as on, then it will relatively bigger profile it will create. So, that is way, this kind of information from the simulation as we can get from the finite element model that if you keep on all this thing laser and this in this case, in particular laser power equal to 1.0 kilowatt.

Basically, 1 kilowatt laser power particular 1 time we can expect that this kind of profile or this kind of the weld pool dimension, we can easily estimate from the finite thermal analysis of the finite element model. So, that is output from the model, numerical model.

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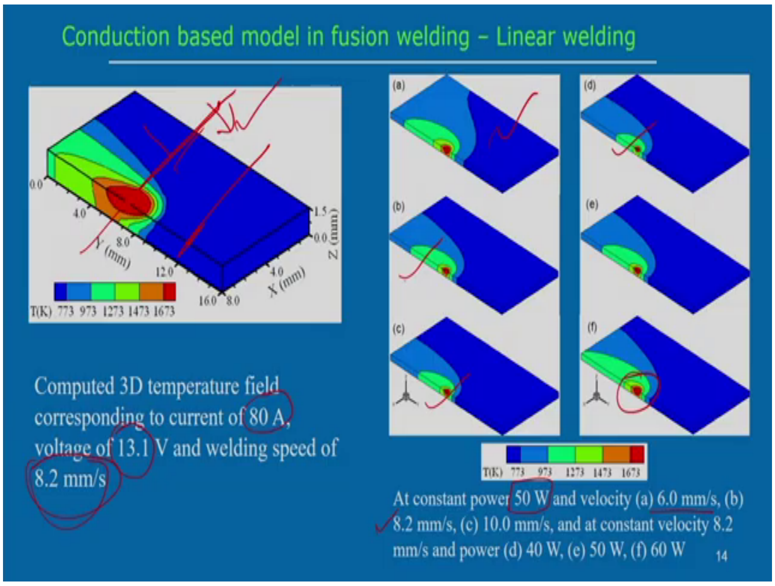

Conduction based model in fusion welding – Linear welding

Computed 3D temperature field corresponding to current of 80 A, voltage of 13.1 V and welding speed of 8.2 mm/s

At constant power 50 W and velocity (a) 6.0 mm/s, (b) 8.2 mm/s, (c) 10.0 mm/s, and at constant velocity 8.2 mm/s and power (d) 40 W, (e) 50 W, (f) 60 W

Similarly, if you look into the conduction base model in case of the linear welding process. So, in that cases, the heat source moves one particular direction. So, here we can see the kind of non-symmetric profile we can expect this thing and it is for in case of the arc welding process, the computed 3D temperature field corresponding to the current of 80 amp ampere, voltage is 13.1 volt, and the welding speed is 8.2 millimeter per second.

So, here also, we can estimate power with this particular velocity if you see, this kind of the non-symmetric propylene is mostly associated with the velocity, velocity is very high, large a sort of a nonsymmetric profile we can expect. But in this case, we have done the quasi-steady state analysis.

Quasi-steady state analysis means we are assuming this particular point the heat source is applying that is a center and then, non-symmetric heat source term we have used in this case, it means that front and rear part can be different, then we solved for the temperature distribution, then we will be getting this kind of the temperature profile.

But in this case, a quasi-steady state means the it is not the temperature distribution, it is not as a function of time explicitly. Here also use the stationary heat source, but in this case, this quasi-steady station mean if we put heat source, we are getting this kind of profile even if we put the heat source also here, we will be getting the similar kind of the profile.

So, at any section theoretically, if we place the heat source in this particular position, we can expect the similar kind of the profile. It means that there we are following the quasi-steady state heat transfer analysis for this particular case. So, if we look the similar kind of non-symmetric profile in case of the laser welding process also, in this case 50 volt and velocity is 6 millimeter per second. In this case, 6 millimeter per second, b, 8.2 millimeter per second.

So, if we see that 8.2 millimeter per second, the profile is little bit different and c, 10 millimeter, higher velocity profile is different and at constant velocity, 8.2 all these cases, the power are different so, power different means in this cases the weld pool dimension is bigger as compared to the first one.

So, that is why that kind of the variation if we change the parameters also, the simulation as we can see that the variation of the temperature profile different with respect to velocity and with respect to the on time. So, that is the way we can expect the different results after following the finite element base method.

So, now, we understand that what is the difference of the temperature profile in case of the spot-welding process. We can see the spot-welding process with the respect to particular plane, it is symmetric, and we can see it is symmetric in the sense suppose with respect to this plane, it is symmetry, the profile is the same both the side. So, that is the characteristics of the this plane, the this spot welding process.

But linear welding process, it is not symmetric with respect to this particular plane. So, here, we can get the non-symmetric profile. It means that in these cases, we are because of the there is a one welding velocity is there, heat source moving in particular direction, particular velocity so, definitely some sort of non-symmetric profile we can get.

So, it means that both transient problem as well as the steady state problem can be developed and using from the same governing equation and we can understand that how this quasi-steady state model that mean the there is a moving heat source model, what way we can modify the this governing equation to takes care of the welding velocity in the particular governing equation and remaining interpretation of the heat source model all this thing is the same both for the spot welding process as well as the linear welding process.

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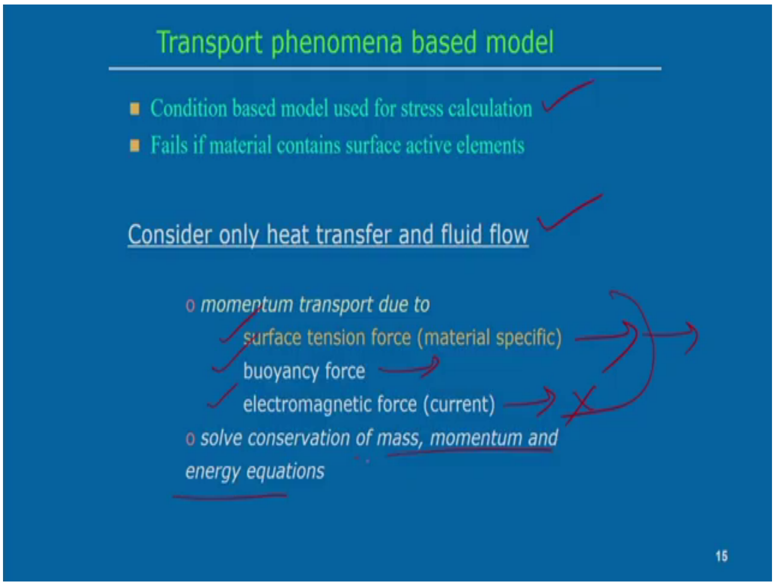

Transport phenomena based model

- Condition based model used for stress calculation
- Fails if material contains surface active elements

Consider only heat transfer and fluid flow

- momentum transport due to
  - surface tension force (material specific)
  - buoyancy force
  - electromagnetic force (current)
- solve conservation of mass, momentum and energy equations

Now, we can look into that once we look into the conduction mode heat transport model also, there we can see the transport phenomena-based model. So, that means, if we consider the velocity field also we can the transport phenomenal model we will getting the other apart from the temperature field, we will be getting the velocity field.

Conduction model is normally used in case of the stress calculation that means, if you want to know the distortion residual stress, most of the cases we use the conduction-based heat transport model. Because combining the conduction based heat transfer model along with the stress analysis model can be as the associate with the each computational several time or other cases also, if material having some kind of the surface active elements.

Then the conduction based model is fails also not able to predict the correct profile of a weld pool. So, in that cases, there is a need to consider the metal flow phenomena in case of the welding process. Now, in that cases, consider only the heat transfer and the fluid flow, both heat transfer and fluid flow you should consider in the particular case.

But when you consider the a fluid flow problem also, in that cases momentum transport will be there because of the several driving forces. One particular diving process is the surface tension force another cases is the buoyancy force, another cases is the electromagnetic force, these are the all driving force which I should drive the molten material.

And surface tension forces also material specific so, that is why if we want to incorporate the effect of the surface-active elements, then there is a need to develop some sort of the surface tension model also for a particular material so, in that cases, because that is a driving force for the material flow.

Then, buoyancy force will be there due to the density differences from the buoyancy force is there and electromagnetic force is there, but electromagnetic force, we consider in case of the arc welding process because the flow of the current, they will induce some sort of the electromagnetic field and that actually influence the material flow fluid also. So, in that case, we consider the electromagnetic force also.

But in case of the laser welding process, we neglect this electromagnetic force. In that cases, the driving force for the fluid flow is only for the surface tension force as well as the buoyancy force also. But apart from all these three forces, then more specific the which is more influencing on the metal flow pattern that is the surface tension force as compared to the buoyancy force and electromagnetic force.

And other important point is that surface tension force it is actually considered only on the surface, but buoyancy force and electromagnetic force means it is actually that is a; that is distributed over the volume. Now, in this case, the solve for conservation of the mass, momentum and energy, all these three equation has to be solved in this case, then we will be able to get the combined the temperature distribution as well as flow fluid.