Finite Element modeling of Welding processes
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Lecture - 19
Heat source model for Keyhole mode and solid state welding

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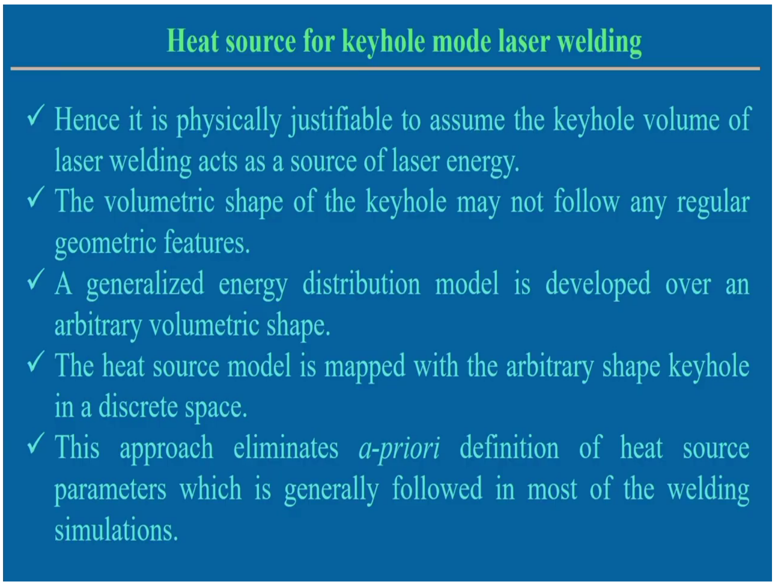

Hello everybody, and now we will discuss the last part of this heat source model associated with welding processes that is for the mainly the Keyhole mode laser welding process what way we can develop some heat source to analyze the arbitrary shape of a keyhole.

And also we will discuss about the solid state welding process, what way we can estimate the heat flux and then how we can implement the heat flux. For example, in case of friction stir welding process that part we will discuss in this particular part a particular section.

So, we assume that or we in formation of the keyhole in laser welding processes is of arbitrary shape. Arbitrary shape mean in the sense that we have already developed the heat source model assuming some regular geometric shape, for example, ellipsoidal shape, or conical shape, or something like that, or some combining these two.

But assuming the that was the assumptions was the regular geometric shapes. And with this particular shape we have developed following some kind of the distribution, probably most of the cases we have used the Gaussian distribution. And for Gaussian distribution of the flux intensity and based on that we have developed some heat source model or basically volumetric heat source.

Now, if it is of arbitrary shape, then how we can develop some kind of the heat source model that we will try to show in this particular module. So, it is just physically justifiable to use the keyhole volume laser welding acts as a source of the laser energy. Definitely, when we develop some kind of the heat source model, we have to understand that how; the heat source model means, volumetric heat, what is representation of the volumetric in a keyhole process also.

Because in keyhole mode welding the process, when there is a formation of the keyhole that is the basically the keyhole can be defined the above the boiling point temperature of particular material. So, the it can be considered as a source of energy within the size of the keyhole.

So, therefore, we will try to fit that exact volume of the keyhole, and that volume of the keyhole can be represented as volumetric heat source in case of the keyhole mode laser welding process. So, volumetric heat source of the keyhole may not follow any regular geometric shape that is true.

So, therefore, a generalized energy distribution model in this case is developed over an arbitrary volumetric shape. So, it is a more generalized form of a arbitrary volumetric shape. If we consider in generalized form and from that generalized form, we can reach some other known volumetric heat source model. For example, ellipsoidal and double ellipsoidal heat source model also.

In this case, the heat sources model is mapped with arbitrary shape keyhole assuming the in a discrete space. Basically, we discretize the space and probably it is easier to when I try to implement in case of finite element based model.

Anyway the volume can be using we need to discretize to solve the governing equation in a finite based model. So, with the same discretization, it will be easy to implement this in a discretized space the arbitrary shape of the volumetric heat source in case of the finite element based model. So, this approach eliminates the priori definition of the heat source parameters which is generally followed in most of the welding simulation. So, that we have seen the most of the welding simulation we normally predefine the geometric dimension of a heat source.

And based on that, we estimate the volumetric heat and we from that estimation of the volumetric heat then temperature calculation normals comes into the picture. So, that is the usual procedure of the definition of the volumetric heat source in most of the welding process simulation.

But, in case of arbitrary shape, if it is possible to generate the by other means or some analytical solution, we can if we predict the shape of the keyhole and then exactly once we predict the shape of the keyhole, and that shape of the keyhole is mapped over the discretized space.

And once we map the discretized space, then after that we can implement the arbitrary shape of the volumetric heat source for the analysis of the keyhole mode laser welding process.

We will see what way we can develop this keyhole mode laser welding process.

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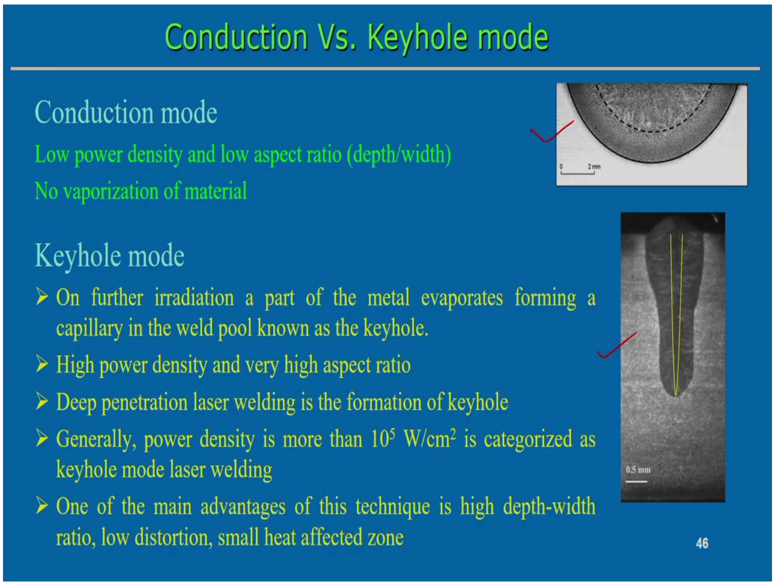

So, first we understand the what is the conduction versus keyhole mode welding process. Conduction mode, normally, this conduction mode laser welding process we understand the heat flux or power density is low as compared to the keyhole mode laser welding process.

And we assume the no vaporization of the material, so such that system of the temperature may be maximum temperature of the system in the welding laser welding system should be less than that of the vaporization temperature of a particular material. So, in that case, we assume that it is a conduction mode of welding process.

So, if you see this figure, first figure, here you can see this figure that it creates kind of profile that the aspect ratio is little bit not very high in these cases, that means, not much depth of penetration width and depth of penetration ratio can be low in these cases are near about the

1, so in this case or lower than that of 1. So that we can assume that this kind of profile normally we assume it that is the conduction mode laser welding process.

But, if we look into the second other figure keyhole mode laser welding process, in this case the depth of penetration is very high. So, it is very clear from this picture and width is comparatively low as compared to the conduction mode welding process. So, the second case we can assuming that this is normally from this observation we can say that this kind of welding mode is normally associated with the keyhole mode laser welding process.

In this keyhole mode laser welding process, so within this keyhole the maximum temperature is more than that of the vaporization temperature of this particular laser welding system. So, what way we can characterize the keyhole mode laser welding process?

That further irradiation on the this on the metal, further irradiation of the laser on the surface the metal evaporates form a capillary, forming a capillary very small capillary form in the within the weld pool and that is known as the keyhole. So, therefore, the main objective or purpose of formation of the keyhole means is that entrain the energy for a large depth of penetration such that very high thickness of material can be joined using this keyhole mode laser welding process.

Power density definitely to achieve this kind of profile power density should be much more than that of the conduction mode welding process, and very high aspect ratio it will always produce this thing. So, therefore, deep penetration laser welding is basically is the deep penetration laser welding is the formation of the is normally performed by the formation of the keyhole.

Power density is in more than that of the 10 to the power 5 Watt per centimeter square is categorized as the keyhole mode laser welding process. So, not only this geometric profile, but roughly you can estimate that just by looking into the what is the power density.

Accordingly we can say which one is the keyhole mode laser welding process, which one is conduction mode. The very thumb rule in case of the laser welding system is the critical value is the 10 to the power 5 Watt per centimeter square, so 10 to the 5 in general 10 to the power 5 Watt per centimeter square.

If the power density is less than that, we assume that we can assume that it is a conduction mode welding process. If power density is more than that, then we can assume it is a keyhole mode laser welding process. So, accordingly the particular formulation of the heat source model can be used.

One advantage of this technique is the high depth and width ratio, low distortion, small heat affected zone. In practical the keyhole mode laser welding is that efficiency that means absorption of the laser light or absorption of the energy within the work piece is much more as compared to the conduction mode welding process.

And definitely, the heat affected zone can be produce in this case is the very small, because in conduction mode laser welding process the power density is such that it is having the heat diffusion occurs through this sub material. So, in this cases, the diffusion over happen over a relatively large area or large amount of large zone in case of conduction mode welding process.

So, in case of keyhole mode welding process, the entering the energy balance in such a way that it penetrate through these things; and at the same time, the keyhole mode laser welding process can be used very high velocity. So, therefore, in these cases the heat diffusion zone can be less as compared to the conduction mode. So, in that case the keyhole mode laser welding process, we can expect the heat affected zone is less as compared to the conduction mode welding process.

But apart from that the other advantage is that a (Refer Time: 09:31) keyhole mode laser welding process you can see that total heat that this molten zone may be confined in the very small area zone or very narrow zone as compared to the keyhole mode laser welding process. So, therefore, in that cases we can expect the distortion may be associated with the keyhole mode is less as compared to the conduction mode. But this kind of conclusion we can make, it is very general sense.

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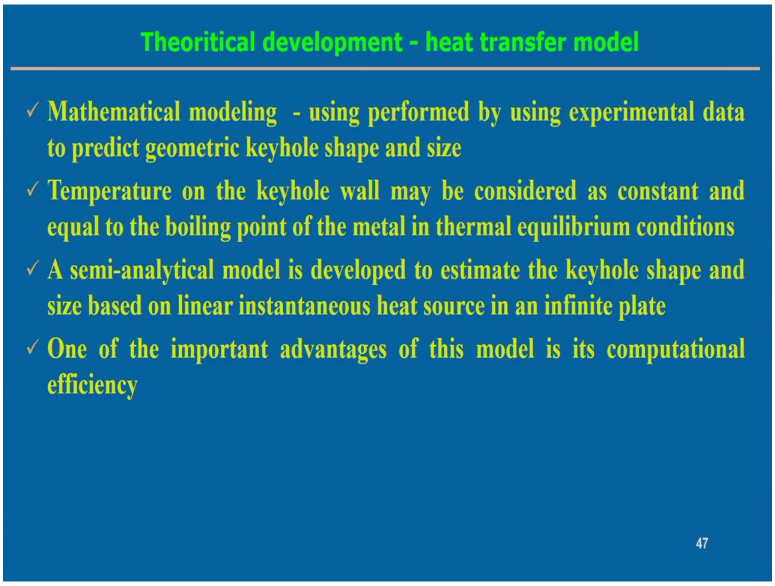

Now, we come to that point the theoretical development of the heat source model. So, once we look into the theoretical development of the heat source model, definitely there is a lots of assumptions associated with the development of the heat source model associated with the keyhole mode laser welding process, or sometimes how we can predict the geometry of the keyhole mode laser welding process.

So, definitely to do that mathematical modeling, that can be performed by using the experimental data to predict the geometry of the keyhole shape and size. So, in this case, definitely if we measure this very high speed camera, we can measure the profile and in practically and then from the data we just simply feed the data, and it is possible to predict the keyhole mode keyhole geometry keyhole profile and size.

But, actually the keyhole temperature on the keyhole wall may be considered as a constant. Definitely the temperature of the keyhole mode can assume as a constant. And it is equal to the boiling temperature of this particular material. And that boiling point of the material and specifically it we assuming that it is in thermal equilibrium condition.

The keyhole wall temperature is equivalent to the boiling temperature of this particular material. So, therefore, it is possible to develop some kind of the semi-analytical model or analytical model to estimate the keyhole shape and size and which is based on the linear instantaneous heat source in an infinite plane.

Basically, if you want to first to implement the volumetric heat source, first we have to define first we have to estimate what is the shape and size of the volume of in pertinent to the keyhole. So, to do that, it is possible to do estimate first what is the profile of the keyhole just by simply solving some analytical solution of the temperature distribution that we have already explained in this module also.

That few cases it is also possible to analytically estimate the temperature distribution with the assumptions of the point heat source, line heat source or some kind of the even then we can reach some kind of the prediction of the temperature profile associated with the keyhole mode laser welding process.

But we will implement the similar kind of the analytical solution. And from that from this analytical solution and the we can get the temperature distribution. And from the temperature distribution, we can estimate the keyhole profile. Once we estimate the keyhole profile, that means, it is associated with the shape and size we predict the keyhole profile.

Then from that profile, within that profile, we will try to fit; within that volume, we try to fit the apply the volumetric heat source associated with the keyhole mode laser welding process. So, one of the important advantage of this model is this computational efficiency.

So, definitely, if we look into the actual energy balance happening within this keyhole, the balance between the several aspect that the vaporization front and making this to computationally develop or the particular model, then it will be computationally more expensive rather it is more easier or to implement.

If we simply look into the analytical solution of the temperature distribution, and that from that temperature distribution at constant isotherm at boiling point temperature that simply predicts the keyhole profile in this case.

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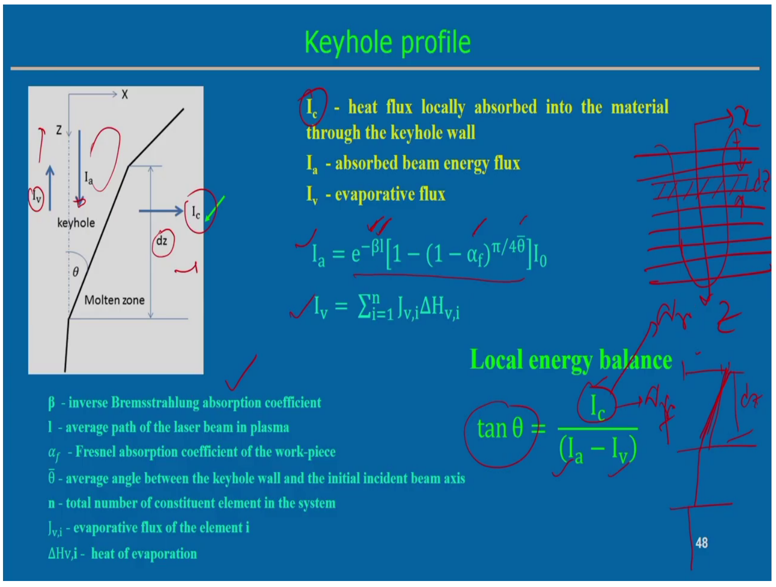

We will see the how what we can estimate this keyhole profile in case of keyhole mode laser welding process. So, let us start with this thing. So, for example, first we start the suppose in a keyhole formation, so there are some arbitrary shape of the keyhole formation. We start at layer by layer we consider the very small layer. So, having the thickness equal to dz.

So, what is happening? At this particular small part of a keyhole that we will try to look into that. So, in this particular element say the element size dz along the z-direction, so that means, depth direction dz in this case there is I a. I is the absorbed laser energy flux, so that we can assume within the local small area that small elemental thickness that I a equal to I a is the absorbed beam energy flux from the laser and the I v is the evaporative flux.

Since boiling happens inside the small zone, and then some evaporative flux will be created, and the and this evaporative flux can be a function of the elements if we consider the individual element. Boiling of the individual elements of a particular alloy system, we can estimate the evaporative flux I v.

So, we assume the I v is acting this direction and I a is acting in the downward direction. Now, I c is the heat flux locally absorbed into the material through the keyhole wall, so that means, the although this flux and this domain is filled by this particular domain within the keyhole the domain is filled by the vapor domain. We can say that vapor domain and temperature is above the boiling point temperature, and then this creates same this zone, basically the in this case is the molten zone.

So, liquid metal to vapor interface, so from the vapor to liquid metal interface the heat is conducted a that is the that flux we can say represented by I c that is the heat flux. And this is conducting in the direction x-direction in this case. So, this is the one elemental part. So, I c this is the x-direction and this is z-direction. And in three-dimensional we can consider the other y-direction.

So, with this particular element, if we look into the balance of the energy in this particular element and specifically I am talking about the very small thickness dz and then we will it will to reach some kind of the solution of the from the analytical solution, we can reach some kind the prediction of the keyhole profile. So, we will see one by one.

So, first I a; I a can be estimated, that means, absorbed beam energy flux. So, absorbed beam energy can be a function of so many parameters. So, is the absorption in absorption coefficients beta is the absorption coefficient. And alpha is the Fresnel absorption coefficient of the workpiece. Actually the alpha takes care of the when the laser light comes inside the keyhole, then say reflect in the several way it is reflected within the keyhole.

So, in that sense, it will enhance the absorptivity of the laser inside the formation of the keyhole that is why if you remember we already mentioned that things the keyhole formation the absorption of the laser energy is much more as compared to the only conduction mode, because within the small keyhole there is a reflection of the laser light occurs. So, that enhances the absorption.

So, in these cases, we can consider the two absorption of the laser two different way. One is the absorption coefficient beta inverse Bremsstrahlung absorption coefficient beta, and one is the alpha, the Fresnel absorption coefficient of the workpiece. So, beta and alpha if we consider, and theta bar is the average angle between the keyhole wall.

So, this is the keyhole wall. And the initial incident beam axis, so initial incident beam axis if we assume it is a vertical, so with respect to that average angle between the keyhole wall and the initial incident beam axis theta bar. So, if we put this value in particular and then I 0 is the average path, l equal to the average path.

So, beta average path of the laser beam in plasma, that means, within the keyhole formation the this strength what is the average length average path of the laser beam within the plasma that is represented by l. And beta is that inverse absorption coefficient. Based on that, we can find out some absorption of the laser beam energy.

And apart from that, due to the reflection, we can consider the Fresnel absorption coefficient. And from that this indicates the basically the what is the effective amount of the absorption in the keyhole formation. And I 0 is basically indicates the heat flux density the what is the I 0 at the focus distance, what is the intensity from the laser energy.

So, from there, we can estimate what is the actual absorb energy flux within this beam. And I v is the evaporative flux you can see the i equal to 1 to n, n represents the total number of the constituent elements in the system; and J v, i the evaporative flux of the element i and delta H i is the heat of the evaporation for the element i.

So, the summation of this thing, we can getting the evaporative that means, evaporative flux. So, once we estimate this I a and I v and from there, we can find out the looking into the local energy balance. So, tan theta equal to I c by I a minus I v. So, we are considering the heat transport, maybe heat conducted along this direction only. So, the other direction we are neglecting because keyhole profile if we observe the keyhole experimentally the keyhole profile is almost vertical.

So, in these cases, we can absorb the heat conduction in the vertical direction rather we are considering only the heat conduction at the radial direction that means, in this cases it is in along the x-axis, along x-direction. So, from there, we can estimate the tan theta value.

And in the because to estimate the tan theta value, here we can estimate the tan theta value, then we can estimate the I c, I a. And I sorry from tan theta value and from the known value I c, I a and I v. From these three, we can relate between the I c, I and I v. So, I a and I v directly we can estimate, but I c also we can estimate different way we will see.

And then from the tan theta value, we can estimate the what is the angle in the small elemental thickness that dz here. And then subsequently, we try to follow the what is the local energy balance for the next layer. So, next layer, so maybe you can say in this, so several layers exist. We can divide into this thing. So, one by one from the start from the top side, so each and every layer we can satisfy the local energy balance, we estimate the theta.

And from the estimation of the theta, we can predict the keyhole profile gradually. But this is the way to estimate the keyhole profile the one of the way to estimate the keyhole profile by simply local energy balance of a particular small thickness.

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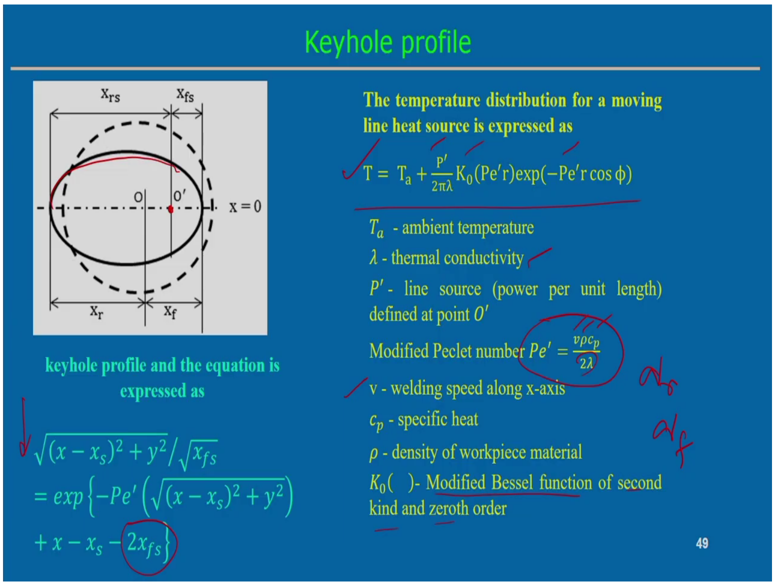

So, let us look into that keyhole profile. The temperature distribution for a moving heat source is expressed as this one. So, this is one of the analytical solution, the temperature distribution for a moving heat source. So, T a is the initial ambient temperature. P dot is the source strength, and P 2 is the line heat source.

Line source we are assuming the line heat source, the source strength, and twice pi lambda is the thermal conductivity. And K 0 is the I think modified Bessel function of the second kind and the zeroth order. So, K 0 and can be expressed in the different way also. There may be some approximation of the this Bessel's function in the form of a other spatial parameters that we can see, and then we can approximate the solution.

Like that and if we see the v is the welding speed, and P dot is basically Peclet number modified Peclet number in this case P e dot. You can see the modified Peclet number is expression of this one v rho c p by twice lambda. So, thermal conductivity it can takes care of the welding velocity, density, specific heat, and thermal conductivity. From that point, we can estimate the modified Peclet number is like that in particular to the this welding process.

So, if we know the welding velocity or speed from there we can if we assume this temperature distribution, but we need to know other parameters also that we can show this thing. So, keyhole profile it is possible it is like that if we look into this figure, the dotted line is actually representing the focus on the laser, that means, initially it was spherical it is circular on the surface that is the diameter.

But once it is moving on particular direction, but if we look into the frame of the over the solution domain that means, within the work piece, then it looks like laser beam is interacting in the what way we can consider the ellipsoidal or double ellipsoidal shape. So, in this case the temperature distribution is something like. So, o dot is basically source strength and the this indicates the this dotted line indicates the temperature distribution.

But since it is moving on particular direction, so we can assuming the it is not cannot be the symmetric in this case. So, therefore, to account this non-symmetric energy distribution in the front and rear part, this can be predicted just by simply analytical solution of the temperature by looking into the welding velocity.

In this case, the welding velocity is passes through this Peclet number. So, from that Peclet number, we can takes care of the what is the value of the welding velocity, and that shows this distribution. So, finally, we can reach this kind of the expression of the this equation in terms of the x and y. And on the surface, we can predict the temperature profile.

So, once we can predict the this temperature profile, and that means and in terms of the x and y we assume that in the particular from here. Once we x f s is the front part and rear part taking looking into this we there is a detailed solution. I am not showing here in detail solution.

But once we predict this temperature distribution from there, we can estimate what is the value of x f s, x r and then. So, this particularly at the front part what is the radial flux, and the rear part what is the radial flux q a r and q f. And the rear part front and rear part, we can estimate the radial flux. And from that, once we estimate the radial flux, then basically we are estimating the I c in this cases; the heat flux locally absorbed into the material through the keyhole wall.

So, once we estimate the I c as these things, from here we can estimate the tan theta. So, once the tan theta it is profile is something like this, based on the theta value we start with some value. Initially, we can start what is the size of the laser beam. So, from that, we can start from this size of this laser beam. And if we estimate the theta, then we d z is known, dz is known quantity, then we can estimate the tan theta, accordingly we can predict this is a profile.

Similarly, for the next layer, we can start from this point, and we can predict this profile. Next layer we can predict this profile just simply from this calculation and by tan theta by knowing this I a, I v, and I c value. So, I a, I v, and I c value, we have to estimate from the each and every layer.

Then from that, now, once we estimate this thing then we will be able to predict the keyhole profile. But keyhole profile in the front part and the rear part can be different because that should be different. So, therefore, this I c from the equivalent to front part, and I c can be equivalent to the rear part also. In the two different cases, if we estimate the separately in the front part the heat flux, what is the heat flux in the rear part.

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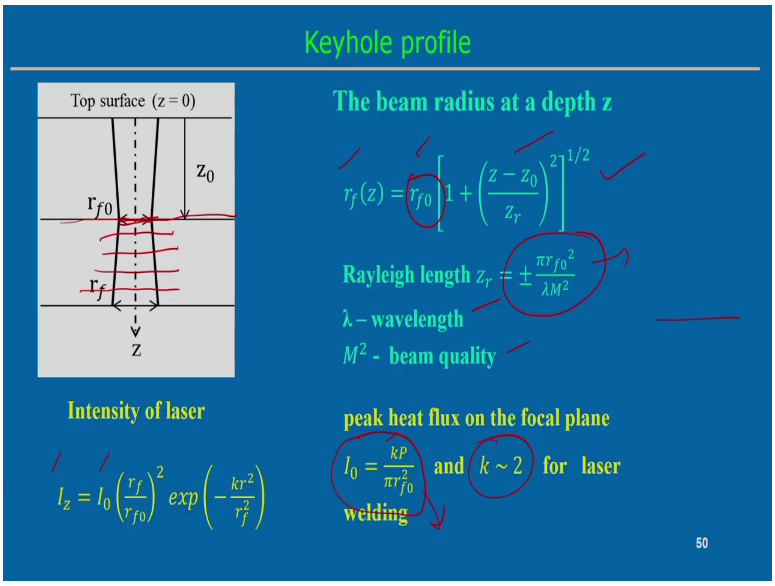

So, from that point, once we estimate the keyhole profile and of course, that is the another part that at particular distance at a particular depth, we can estimate the beam radius at particular depth that is also information is also necessary. That at a particular depth what is the beam radius the r f can z as a function of z can be like that r f 0 and 1 plus z minus z 0 by z r square to the power 1 by half that means square root that is the z r Rayleigh length and which represents the beam quality wavelength.

If you know these parameters from those things, we can estimate the z r and wavelength of a particular laser, and m square is the beam quality whether it is flat or it follow Gaussian profile accordingly m square value can be given. So, once we then from here r f 0 is the from maybe we can start with the here r f 0 is the particular this is the r f 0.

So, particular as a distance z 0, the what is the focus distance r f 0 we can start with these things. And from that, this is the reference assume this is the top surface, r f 0 is given. And we can predict the r f at any z value as a from the r f value, this is the known. Because on the when laser is focused on the top surface, what is the value of the r f 0, radius of the focused beam?

And from that using this beam other beam parameters, we can estimate the what is the r f at a particular depth direction z, because this r z as a function of z is required to calculate each and every layer what is the value of tan theta. So, or what is the value of theta, from that we will be able to predict the keyhole profile.

So, see I z the intensity of the laser, we have already mentioned the intensity of the laser as a particular depth z can be estimated like that I 0 r f by r f 0. So, I 0 is defined on the top surface, these things exponential k r square by r f square. So, this is the exponents it is varying from the center to outward periphery. If you see in this case, I 0 equal to k P by pi r f square, this is the intensity on the at the center basically intensity at the center.

And then it is a the k is the distribution coefficient, and pi r f 0 is the focal distance at this on the top surface. And it can be assumed the k can be 2, because the distribution coefficient little bit steep in case of the laser welding process. So, k can be considered as a 2 as compared to the k equal to 3 in arc welding process. So, all these parameters, if we estimate these things and based on that we can predict the keyhole profile.

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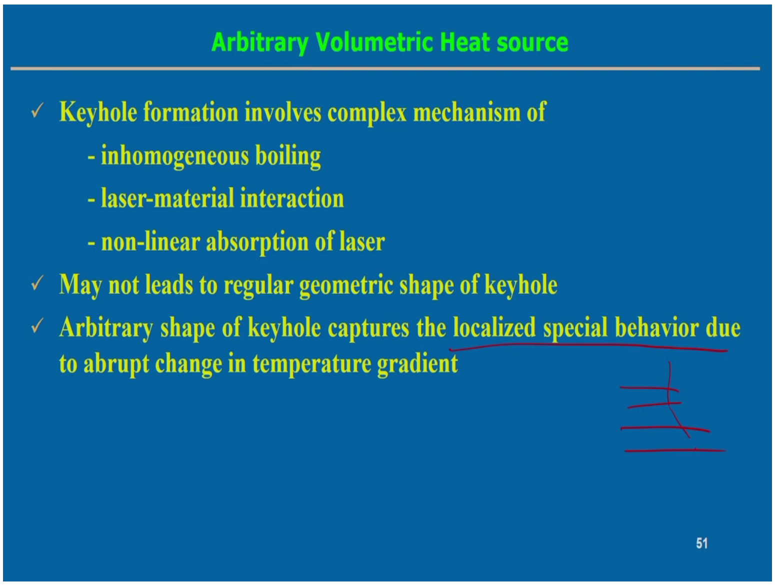

Now, arbitrary volumetric heat source is something like that keyhole formation involves definitely very complex mechanism actual formation of the keyhole, for example, inhomogeneous boiling. So, throughout the throughout this within the keyhole volume, it is not necessarily the homogeneous boiling will occur throughout this space. So, normally in homogeneous boiling occurs.

Then laser material interaction is very complex phenomena. And that we can simplified these things laser material interaction simply by formation of the volumetric heat source and non-linear absorption of the laser. The absorption throughout the keyhole may not be the linear, or may not be the same, the absorptions can be different.

So, therefore, if we look into the actual formation of the keyhole, this actually involves making considering all this complex phenomena, making a keyhole profile is a very critical task or very difficult task. So, in that sense, even it may not leads to the very regular geometric shape of the keyhole.

So, then this is quite reasonable to assume the shape of the keyhole can be arbitrary shape of the keyhole because arbitrary keyhole that it captures the most localized special behavior due to abrupt change in the temperature gradient that is true also. Because arbitrary shape, the localized special behavior.

In this case also we are trying to develop the heat source model in case of the keyhole also by simply very small thickness we are solving the we are looking into the energy balance. And from that energy balance, we are trying to solve this energy balance equation then we are predicting the keyhole profile, so that is more wise.

And, but once this very thin layer, there is a possibility to predict the (Refer Time: 28:52) shape of these things. And it depends on the what is the layer thickness we are considering in the along the z-direction. So, therefore, it is may not follow exactly the regular geometric shape what we observed in case of the other welding processes.

For example, arc welding process or even any other arc welding process. So, rather the keyhole becomes more complex. So, in that sense, the arbitrary shape assumptions of the volumetric heat source is more reliable in case of the keyhole mode laser welding process.

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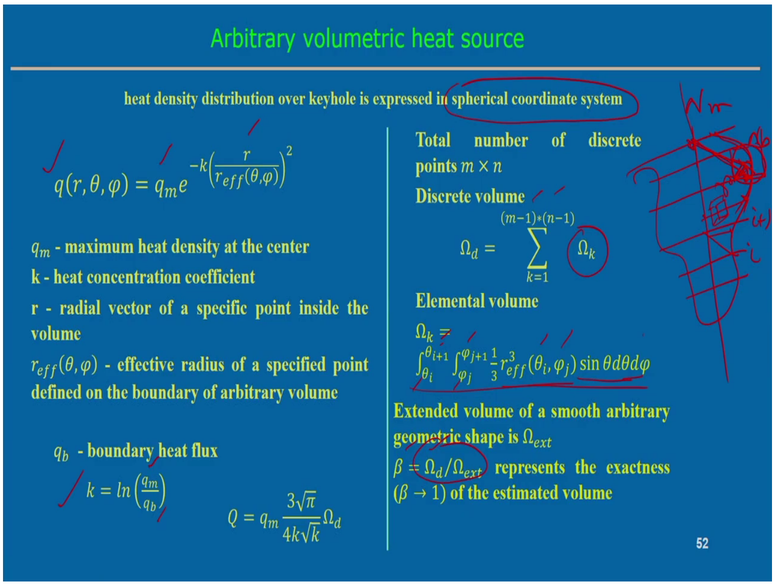

But, what way we can develop this arbitrary volumetric heat source? So, if we understand clearly that what way we can develop some any kind of the volumetric heat source that I have already explained, which first we start with the regular geometric shape.

We are assuming some this is the regular geometric shape and we are assuming some distribution. And from the boundary condition of this particular distribution, we can estimate the what is the maximum intensity, and then how it distribution happens throughout this volume. And that step by step we have already explained this thing.

Now, if we assume the heat density distribution over keyhole can be expressed in the spherical coordinate system. The same thing we are try to develop, but in the different front assuming some spherical coordinate system. And we assume the heat flux density distribution q as a function of radial distance r, theta and phi.

So, these are the three coordinates spherical coordinate system as a function of r, theta and phi can be estimated like that maximum intensity and exponentially decaying is the e to the power minus k r by r effective radius. So, r effective radius in particular it is a function of theta and phi square.

So, in this case, q m represent the maximum heat flux intensity at the center point, k is the heat concentration coefficient or distribution coefficient, r is the radial vector of a specific point inside the volume. So, basically r in case of any kind of arbitrary shape, so, we start from the center point and r is a radial distance. And within this r indicates the any point, so any volume.

So, within these volumetric shapes, r is the radial vector. And r effective the effective radius of a specified point defined on the boundary of the of arbitrary volume. So, r effective within suppose this is the boundary, and we can divide here the spherical this small layer also we can divide.

So, in the particular with respect to suppose center and we can say what is the this what is the effective radius in this particular on the surface, what is the on the surface I think it is better to in the in between.

So, suppose, this is the shape, particular shape. So, here the r effective is the effective radius. And effective versus spherical specified point defined on the arbitrary shape this thing, on the boundary of the arbitrary volume on the boundary of the r effective. And k the distribution coefficients that can be simply estimated what way we can done, the q m by q b. And this q b is the heat flux at the boundary, and q m is the heat flux at the center point

So, here you can define the q m, and boundary is defined by q b, so that a logarithm of these things can be represent as a distribution coefficient. That we have already explained because if we put the simply boundary condition that at the boundary the x portion of the maximum intensity falls on the boundary.

From that condition, we can reach what may be the distribution coefficients key that I have already explained this in case of the double ellipsoidal or ellipsoidal heat source model also.

Now, once we total number of discrete points, so it is a m into n, suppose m into n is the total number of discrete points within this structure within the shape. Basically we assume the arbitrary shape, and that arbitrary shape are divided into m into n points within this arbitrary shape that is representative volume over a particular point c g of the representative volume of this particular point.

Now, discrete volume can be estimated like that the k equal to 1 to m minus 1 into n minus 1. So, in this case, that this indicates that elemental volume. So, elemental volume can be estimated that theta i to theta i plus 1. So, one angle to another angle theta i to i plus 1 and the mark for example, this is i, this is i plus 1.

So, theta and i theta i to i plus 1; similarly other j or j plus 1 other dimension then such that phi j equal to phi j to phi j plus 1. And theta i to theta i plus theta i plus 1, and the in this case the finite this one by third are because this distance representing the effective radius from the center point with some reference point we can estimate the in terms of effectively.

So, this effective radius these things and sin theta d theta d phi this is that indicates the total elemental volume over the spherical coordinate system. So, it is simply like that. In principle we divide the total zone over the on the boundary. There are suppose there is a m into m, m into n points and the discrete points within this arbitrary volume.

And then within this discretized volume, we can estimate the discretized volume also total volume total discretized volume, and then that the summation of the volume of the each individual discretized space. So, then the individual discretized space can be volume can be estimated like from this equation in the spherical coordinate system.

Now, once we estimate this thing and discretized one elemental volume, and then from that point we can particular elemental volume and we sum it up, then we can get the total volume. So, basically this lambda d represents the volume of the discretized space of a particular arbitrary shape in case of the keyhole mode laser welding process.

But we can do the similar same simple calculation also beta the ratio that this ratio is represents that exactness of the estimated value that we can do simply we can assume some regular geometry and some regular geometry. We can discretize the space regular geometry. And then discretize space then we can estimate the discretized volume. And from this exact volume which is known to us.

And from that, we can finding, find out the ratio of the discretized volume on the exact volume. And from that point of view, we can estimate the beta this factor can account the what is the volume loss or maybe this thing over the discretized space. Now, that sensitivity of the discretized space can be done just simply estimating this beta value over with reference to the that can be done in case of the regular geometric shape.

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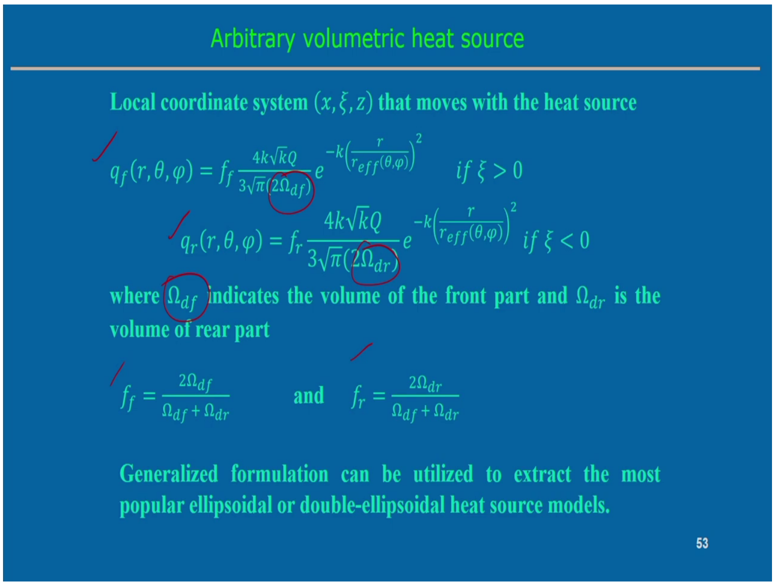

Now, once we do this discretized volume, then the if we in case of the moving problem moves with the heat source, then q f front part and a rear part, q r can be estimated the similar way what we have done in case of the ellipsoidal or double ellipsoidal cases. But in this case only thing is that this the discretized volume in the front part and discretized volume in the rear part has to be considered separately.

Then finally, we can similar way we can estimate the what is the fractional heat deposited in the front part, and fractional heat deposited in the rear part and in the terms of the discretized volume. And this is the generalized formulation can be utilized to extract the most popular ellipsoidal and double ellipsoidal heat source model.

Same thing instead of a discretized volume, if we use the regular volume also then the similar kind of the formula we have we normally do in case of the ellipsoidal or double ellipsoidal heat source model. So, in this sense that instead of the regular shape if this discretized volume is there then we can do the similar kind of calculation. And this is quite obvious and may be associated with the keyhole mode laser welding process.

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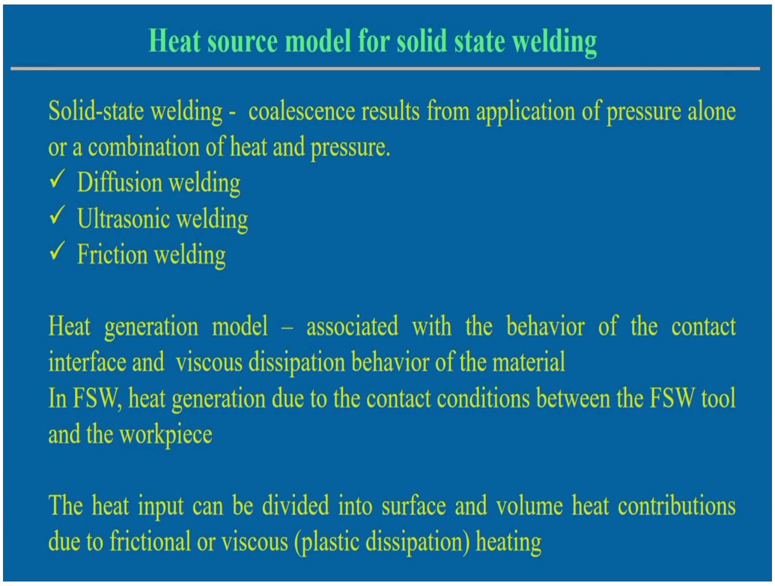

Now, we will try to look into that heat source model in case of a solid state welding process. So, you know the solid state welding processes is objective is the coalescence results from the application of the pressure alone, or a combination of the heat and pressure in principle with the application of the either application of the pressure, or application of the heat and pressure associated with the solid state welding process for the making the join of the two components.

So, in that sense, normally three different we can categorize the solid state welding process. In general, three different processes; one is the diffusion welding, ultrasonic welding and friction welding. And diffusion welding understand that in the surface preparation should be very good two different components come in contact with the application of the pressure and may be heat for a long time, then diffusion to allow between these two components. And then diffusion welding can be done.

Similarly, ultrasonic; the ultrasonic vibration is responsible, and every localized position the plastic deformation happens and the two components can be joined. But in case of friction welding the frictional heat generation is there. And that frictional heat generation with the application of the pressure the along with the frictional heat generation is responsible to join the two component.

So, therefore, heat generation model associated with the behavior of the contact condition that is more important in case of the solid state welding process. We have to understand the contact condition in case of the solid state welding process to understand the heat generation part and as well as the viscous dissipation behavior of the material.

So, viscous dissipation of the material is also there because the frictional heat generation there. And then since solid state welding process the maximum temperature is below the melting point temperature, so the material deformation can be visco plastic. So, once we assume the visco plastic, so viscous dissipation of the heat is also important. So, viscous dissipation behavior is also important to understand the heat source model.

But in this case we will try to focus on the heat source or the heat generation in case of the friction stir welding process. So, in FSW heat generation, due to the contact condition between the tool and the FSW tool and the work piece, so the interaction in case of the friction stir welding process, the interaction happens between the workpiece material and the tool.

So, definitely hardness of the tool is much more that of the workpiece material. And the tool between the tool and work piece there might be some frictional heat generation at the plasticization of the material or plastic string of the material also happens and at the same time, viscous dissipation also responsible for the generation of the heat.

But, in this case viscous generation of the heat by the viscous deformation or plastic deformation of the material can be neglected, that means, the due to the material deformation, so some sort of heat generation may be there, but that percentage is very small.

So, in these cases, normally we look into only the surface phenomena that means at the interface between the tool and the work piece, how we can model the heat source just looking into the interaction between the tool and the work piece. Therefore, the heat input can be divided into the surface and the volumetric heat contribution due to the frictional or viscous and that means, plastic dissipation heating.

But in this case the volumetric heat generation may be very less in case of friction stir welding process because the thin layer of the sheared layer in this case is the sheared layer. Sheared layer thickness is very small or may be the stirring of this molten material, the zone of the stirring of the molten material plasticized material. The thickness, the volume of the plasticized material can be less in these cases. So, therefore, heat input can be considered as only the surface heat flux.

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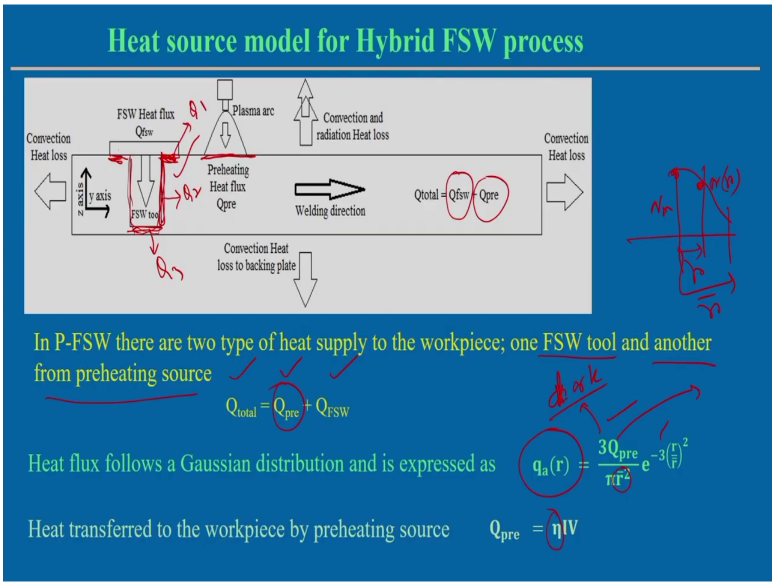

Now, what way we can develop the model? So, we start with the hybrid heat source model, because this is more general. But hybrid heat source model we can start that first is that this is the workpiece material. So, workpiece material is there and within workpiece material this tool is inserted the workpiece material FSW tool and the this is the shoulder surface.

So, shoulder surface is in contact on the workpiece surface and as well as the this tool is completely contact with the workpiece surface. So, this is the surface for heat generation this is the surface for heat generation. And this is the bottom surface of a tool is for responsible for the heat generation.

So, this is the heat generation from the FSW tool that is the one part. And the second part is that if we use some external heat hybrid FSW process, in this case, for example if we use the arc, so this arc also pre heat the sample, and it also source of the heat. And in this cases, we can assuming only on the surface flux because depth of penetration in this case is not high, and the intension is not to melt the material. But rather even if we use the plasma arc source in this case but it is for heating purpose only surface.

So, such that maximum temperature of the workpiece should be below the melting point temperature. So, then total heat input can be considered as a Q heat input from the FSW tool, due to the FSW tool or interaction between the FSW tool and the workpiece. And other part is that heat flux can goes from the some preheating source in case of the hybrid friction stir welding process. But if we use normal friction stir welding process, then there is no need of kind of add this heat source heat flux from the external source.

So, P-FSW that means, plasma FSW process, plasma assisted hybrid FSW process. Two types of the heat supply in these cases; one is the FSW tool, another is the preheating source. So, then Q total is the preheating plus FSW both are cases. So, simply we can estimate the preheating heat source means that we simply follow the Gaussian distribution.

And from the Gaussian distribution, we can assume the surface heat flux only, from the surface heat flux we can estimate the q a is these things q 3. Because 3 is the here is the distribution coefficient d or k, we use this value is the 3, and pi r effective square these things, and the e to the power exponential minus 3 the distribution group is r by, r is the variable in this case radial distance the heat flux value. So, it is like that only.

So, it is at the center, but it is maximum and at particular distance r this is the value of the heat flux intensity. And this is the value of the heat flux intensity at the center point, and this is q at a function of r. So, it is the heat flux at the boundary. So, therefore, this r is a variable bar is the effective radius in this case. And then we can simply apply the Gaussian distribution over the surface.

We can represent the heat flux in using the preheating source. But heat transfer to the work piece by the preheating source, we can simply multiply by the this thing that Q total Q pre that actually heat input, it is the effective heat input, it is the simply volt ampere into the efficiency term, thermal efficiency term in case of the arc source.

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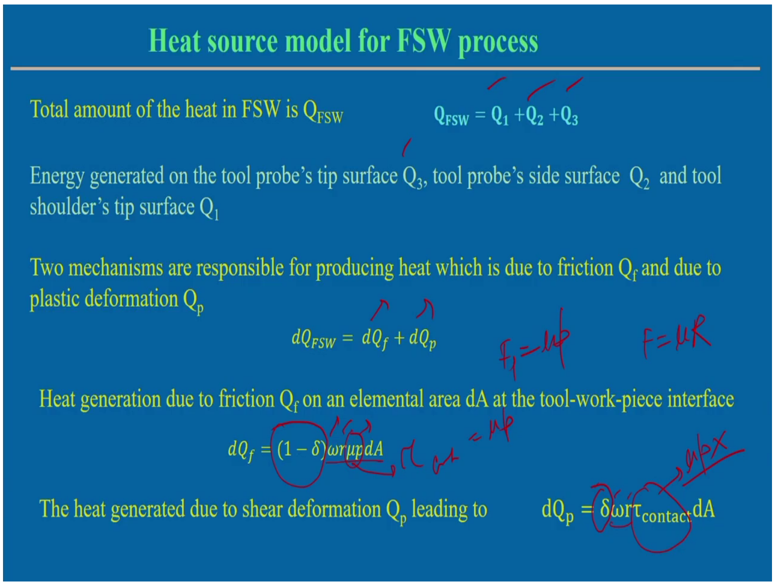

So, that way we can estimate the preheating source, but FSW part we can look into the total amount of the heat generation by the FSW tool. So, that you can divide the total amount of the heat generation by the FSW tool in the three different components Q 1, Q 2 and Q 3.

The energy generated on the tool probes tip surface is the Q 3, that means, at the bottom, and tool probes side surface is Q 2 and tool shoulder tip surface equal to Q 1. We can look into this part, this is the shoulder and this thing it is corresponding to Q 1, and this side surface Q 2, and the bottom surface we can estimate the Q 3.

So, these three different interaction the different part of the tool interacting with the workpiece material, accordingly you can estimate the surface heat generation at these three different parts, so Q 1, Q 2, and Q 3. Now, two mechanism was responsible for producing the heat which is can be due to the friction at exactly the laws of friction.

Sometimes we assuming the this thing law of friction the sliding friction, the sticking friction condition. We can put even the heat generation into part of the sliding friction and part of the sticking friction assuming this law. So, therefore, heat which is the friction Q f and the due to the plastic deformation Q p. So, in this case both this may be basically the heat flux due to the Coulombs friction law if we estimate this thing.

So, in this cases the friction can be estimated a friction force mu the coefficients of the friction and the this thing. The resultant force or other way you can say that this friction in the friction stress can be like that mu into p also, then the frictional stress also, that means, in this cases mu into p, the friction coefficient and the pressure applied to this tool, so that is the one part.

And second part is the sliding sticking friction. So, sticking frictions is basically associated with the we put some condition for in terms of the shear strength of a yield shear strength of a particular material. So, these two divide we can see the sliding part and the sticking part can be the total heat input can be composed of the two component.

Now, heat generation due to the friction of an element over an area dA and the tool workpiece interface. So, therefore, one particular we can see that we can introduce this fraction is basically 1 by delta, or here you can introduce delta term. This is simply external we can look into that what is the contribution for the sticking what part is the contribution from the sliding part.

So, basically dQ f that omega r mu p, mu p is the that frictional stress the we simply put the that this frictional stress proportional to the pressure applied pressure, and elemental area omega is the rotational speed, and r is the radial distance. So, this is the elemental heat generation for a particular element we can look in the heat generation due to the friction.

And due to the plastic deformation or shear deformation, we can estimate that delta part of this in omega into r friction this thing. And in this case, instead of taking the mu into p this is the friction, but here we can put some contact condition between these two surfaces.

So, one contact in this cases these we can use the same contact, but in this case that is the mu into p it depends on the coefficients of friction and the normal pressure. But in these cases, we can use the tau contact can be associated with the yield strength because it is a sliding it is a sticking friction condition. So, it should be associated with on the yield shear strength in this particular case.

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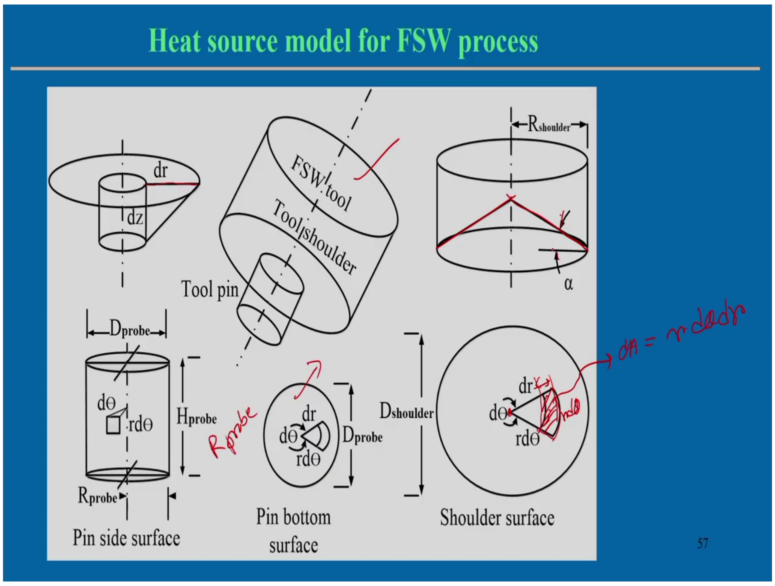

Now, in the cylindrical tool, we can see that different geometry also that elemental this is the FSW tool, this is the shoulder surface. We can take any elements on the shoulder surface between the workpiece and the shoulder at a distance r, we can consider some element we can consider dr, and this thing.

And this one element we can this is the for the bottom surface and the pin side surface this elemental and the shoulder surface. So, at the center, from this point, we is the particular at a distance theta and we can in the small element. So, basically the this distance is equal to is equal to r d theta, this distance will be the is equal to r d theta and this will be the dr.

So, this area is basically dA equal to r d theta dr. So, d this elemental area. So, now, once we know this elemental area, and from we integrate over then we will be able to estimate what is the frictional heat generation. Similar kind of exercise can be done on the bottom surface because bottom surface is the cylindrical shape this can be the exercise can be done.

But on the side surface pin side surface this is the height and the this interaction at the at a distance r in this case is the at a radial distance r probe; at a r probe the radial distance is interacting with the element.

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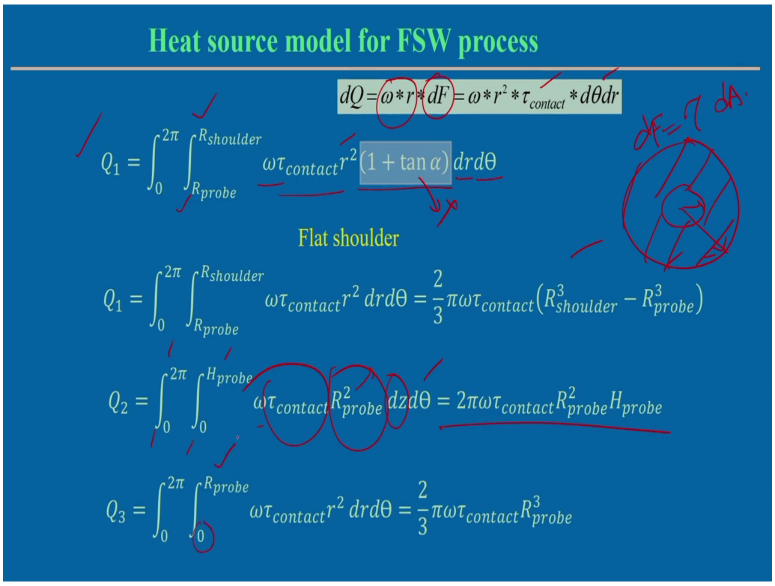

So, from this element, we can estimate that what is the energy generation, energy generation the energy is the omega into r. It is a linear velocity p c v equal to r omega. So, omega in to r into dF, the elemental force in this case. So, force into velocity that indicates the total heat generation.

So, therefore, this omega into r and dF can be estimated in this cases dF can be r theta. So, dF equal to that area the elemental area and the shear stress and the contact stress at this point, so that contact stress in the elemental area represents the dF. So, finally, omega r square tau contact into d theta. So, that indicate d theta into dr. So, that indicates the heat energy heat generation particular point.

Now, if we do the integration over this point, then we will be getting this kind of the expression. For example, first we are estimating the Q 1; Q 1 means, the between the workpiece and the cylindrical surface, so workpiece and cylindrical surface. So, in the elemental area though this thing that omega tau contact into r square that we have already shown and the d theta.

But we have introduced the 1 plus tan alpha this term can be incorporated here. For example, if the interaction between the tool shoulder and the surface may not be exactly flat, maybe tool shoulder something like that having some kind of this kind of the profile having some angle alpha.

So, in that cases, then the, but that is interacting with the workpiece, but in this cases we can modify this expression 1 by tan alpha will comes into the picture if the shoulder surface is not exactly flat. Then this can be express these things and element 0 to 2 pi. So, the theta is varying in the radial direction 0 to 2 pi.

And the radius in this cases the in the shoulder surface interacting with this in the probe, that means, pin radius from that point to the shoulder radius between this area. So, it is like that only, the interaction happens over this radial distance to this radial distance. So, therefore, this area the interaction happen.

So, therefore, R probe to R shoulder the should be the range in this case. To do this integration in case of the flat surface, that means, this effect can be neglected. Then Q 1 can be estimated to omega tau contact r square dr d theta 2 by 3 pi omega tau contact R 3 shoulder cube. This expression we can easily reach.

Now, in case of the flat the vertical surface of the pin side surface. So, in this case, there is a elemental area over the z, and z, and then other case it can be like that only. So, in this case tau contact, but R is constant here, because R exactly at the end of the probe. So, therefore, R should be R probe square. So, no variation along the radial direction in this case.

And d theta 0 to 2 pi, so d theta 0 to 2 pi, and dz 0 to H probe, so no vary, it is not varying. And, but tau contact the shear stress at the contact surface can be define the contacts the condition at this point can be represented by the in terms of the stress contact stress omega tau this thing. So, we can integrate we will getting this expression.

Similarly, in the bottom surface same and the surface but in the bottom surface the range from 0 to R probe in that range, because all the pin bottom surface is interacting with the workpiece material. So, we can reach this kind of the expression.

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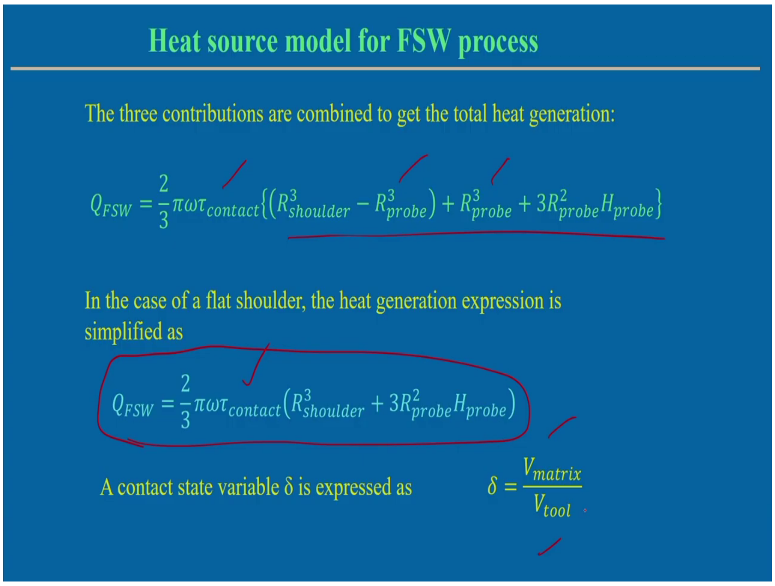

Now, three contribution are combined to get the total heat generation can be simply Q FSW, Q 1, Q 2 and Q 3 irrespective of the contact condition. So, that we can reach this expression tau contact and this we can add this one. And finally, this and this will be balance. So, we can reach this expression; Q FSW total heat generation.

But in these cases, we are not considering any kind of the, we are just simply assume this is the contact condition. Now, contact state variable can be introduced such that delta equal to V matrix by V tool, that means, the volume velocity relative velocity between the tool and the matrix material.

So, tool is rotating, but at the same time the when material is in contact with the tool, the material is also following some velocity. So, therefore, that ratio can be considered as a state variable, so that means, contact state variable delta t.

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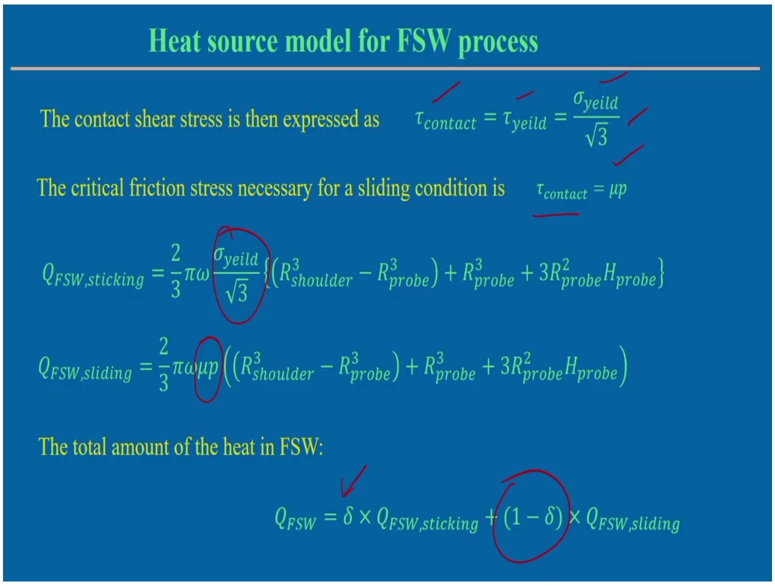

So, that ratio can be. So, from there, we can define what is the value of the delta. So, tau now we look into the contact shear stress the contact stress value can be like that only. The, this is a sticking condition there is sticking material is stick with the workpiece material.

So, at this point, it should be tau contact should be exactly should be to be equal to the yield shear stress in this particular, shear yield stress value of this particular material. So, shear yield stress value is equal to sigma the normal stress value by root 3. So, same we can use the shearing stress value. So, that can be one contact what is the.

But sliding condition can be where the contact is the mu into pressure coefficients of friction and the pressure applied to this at the surface. Now, looking into this thing if we look into the sticking condition then is the replace the contact should be this value. And if it is the sliding condition, then the contact could be the mu p value.

But what amount of the sticking part and what amount of the sliding part that can be introduced this thing simply the contact state variable delta. So, here multiply this delta and this should be 1 minus delta. Such that if we consider both sticking and the sliding condition, and we can estimate this value. So, from there, total amount of the heat generation FSW can be estimated like this.

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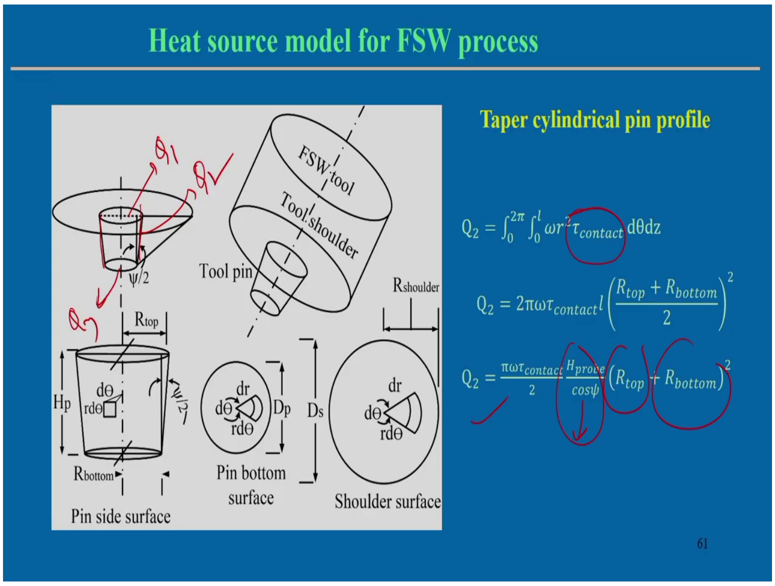

So, similarly if we consider the taper cylindrical tool profile instead of the cylindrical tool profile, if the this profile is a taper, then the heat flux on the Q 1 will be the same, and bottom surface Q 3 will be the same, but Q 2 will be the different in this case. So, Q 2 will be can be estimated like that 0 to 2 pi 0 to l is a length is a height of the pin in this cases, and tau contact similar way d theta d z because the variation happens over the z direction.

So, that can be estimated this thing z direction in the psi value. So, if we look this cos psi, that can be estimated in terms of the top value of the tool and the bottom value of the tool. It is basically truncated cone what is the value of the top and the bottom from that dimension or parameters we can estimate the cos psi value and it is a function of H and of course, R top and R bottom.

So, this simply we can modify the Q 2 value in this case in case of the taper cylindrical pin profile. And then Q 1, Q 3 will be the similar estimation, so that is way we can also estimate the in case of the taper cylindrical tool profile in case of the FSW process.

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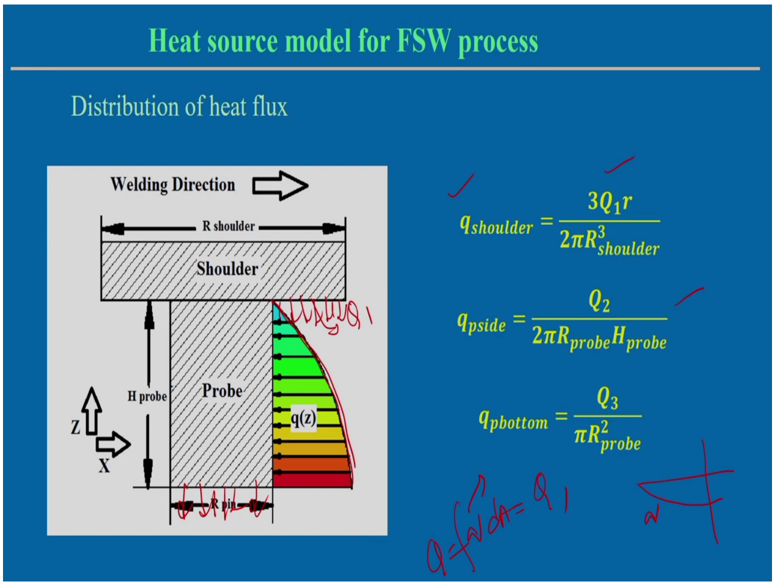

Now, once we estimate the that we are showing the how what way we can estimate the total heat generation in FSW process. But once we implement as a distributed heat flux in a case of FSW process that will help to the get the actual temperature distribution.

Because this we are estimating the from the surface the total heat generation Q 1, but distribution can fall in the different way also. So, it is quite reasonable to assume that distribution can follow the uniform distribution at the this surface.

So, heat flux density can be uniformly distributed on the over the surface. So, once we look into estimate the Q 1, and then Q shoulder can be estimated like that only uniform distribution or we can follow some other distribution. It is parabolic. So, for example, in these cases it can follow this kind of distribution. But we have to define what kind of the distribution it is following and based on that we can find out the heat flux also.

For example, in these cases, heat flux Q shoulder, this Q 1 into R twice 2 twice pi R cube into shoulder. So, this is the shoulder. But, in these cases, we are not assuming the uniform distribution. We can assume the other kind of the distribution and we can reach it. It is a simply that if we follow some distribution, the you define the distribution equation something like that or some other distribution equation.

So, for example, q, so q into d area should be over this area, and then this flux per unit area, the total heat equal to this integration Q and that should be equal to Q 1. So, from that, we can estimate what is the distribution or distribution parameter also. Similarly, side surface can be considered as the uniform distribution.

So, even in the bottom surface also, we can assume some kind of the uniform distribution. So, it can be uniform distribution, side surface can be uniform distribution or parabolic distribution depending upon the problem. But we have to know what is the distribution equation. And from the distribution equation, make the energy balance total make it equal and from that, we will be able to finding out what is the distribution parameter, that means, this flux distribution equation.

So, that is why; this is the next step of the FSW process. First we estimate the total heat generation and from that, we can estimate the heat flux its acting on the surface at the because we are distributed heat flux and that will be the input to the any kind of the finite element model to get the temperature distribution in case of the FSW process.

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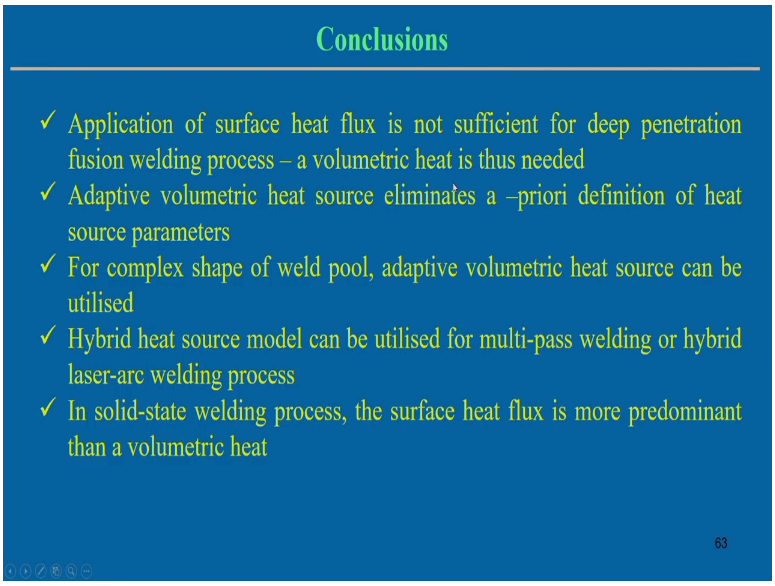

So, in conclusion, we can say that we have seen the different heat source model, but see application of the surface heat flux is basically not sufficient in case of the deep penetration welding process even arc welding process or laser welding process both. So, in that cases, it is necessary to define some kind of the volumetric heat source.

And we have seen that adaptive volumetric heat source it is a certain advantage, because its eliminates the defining the heat source parameters before start of the simulation process. For complex weld pool shape, if the weld pool shape is very complex which exactly not fitting the regular geometric shape, in that cases adaptive volumetric heat source can be utilized or even arbitrary shape is more useful in case of the complex shape of the weld pool.

Or sometimes the hybrid heat source can also be used by combining the in case of the hybrid welding process. Mostly the hybrid welding process we use the arc and laser hybrid welding process, or this hybrid heat source model can also be used in case of the multi-pass welding process.

In solid state welding process, the surface heat flux is more predominant as compared to the volumetric heat. So, therefore, surface we can estimate the total heat input to the substrate material, and from that we can estimate the distribution heat flux distribution in case of the solid state welding process.

So, in general we can see that there is a several flexibility to develop certain kind of the heat source model. But in basics we understand that to develop of the heat source model, first we need to know what are the typical geometric shape we should follow, and second pointing is the what may be the distribution. So, whole heat source model development lie on this two different phenomena.

So, thank you very much for your kind attention.