Finite Element modeling of Welding processes

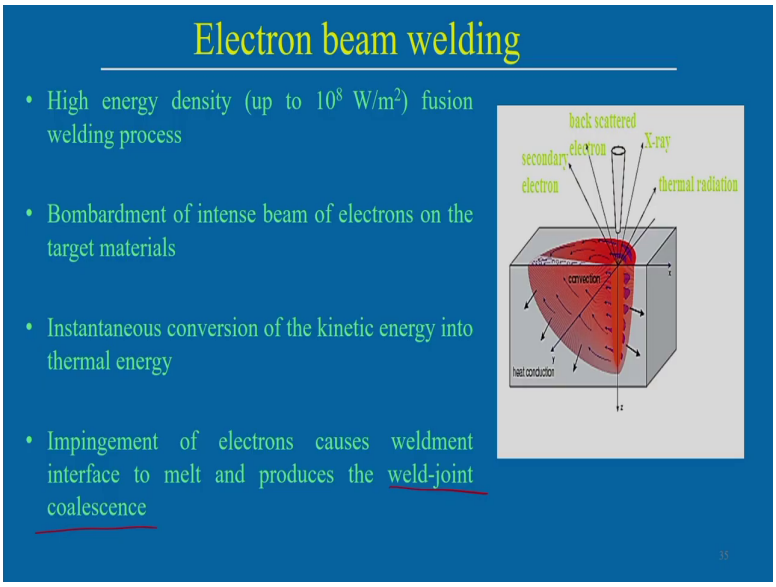
Prof. Swarup Bag
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Module - 04
Application of FEM to model welding processes
Lecture - 22
Electron beam welding process

Hello, everybody. We have already discussed the Finite Element based modeling of different fusion welding processes and what way we express the heat source model related to a particular welding process. Now we will try to look into that the how we can do the finite element modeling of Electron beam welding process.

Actually, there is a some a similarity between the keyhole mode laser welding process and electron beam welding process in terms of the modeling approach. So, almost similar kind of the approach also we can follow here even in case of the electron beam welding process, but before understanding that how this finite element model can be done for electron beam welding process we can go through some sort of the electron beam welding processes.

(Refer Slide Time: 01:34)



So, let us look into this thing overall we can see the electron beam welding process. We normally it is very high energy density fusion welding process and maybe the power density can be as much as 10 to the power 8 watt per meter square in the to that range. So, in this case what way the there is a bombardment of the intense beam of the electron basically beam of the create the beam of the electrons and that is impinge on the surface. And, then it will create some kind of high depth of penetration and at the same time it can produce some sort of a kind of keyhole.

And of course, this depth of keyhole in this case is much more than that of the laser welding process. Now, once we had the bombardment of the electron this thing electron the flow of the electron release the kinetic energy and convert it to the thermal energy on onto the with the interaction of the workpiece.

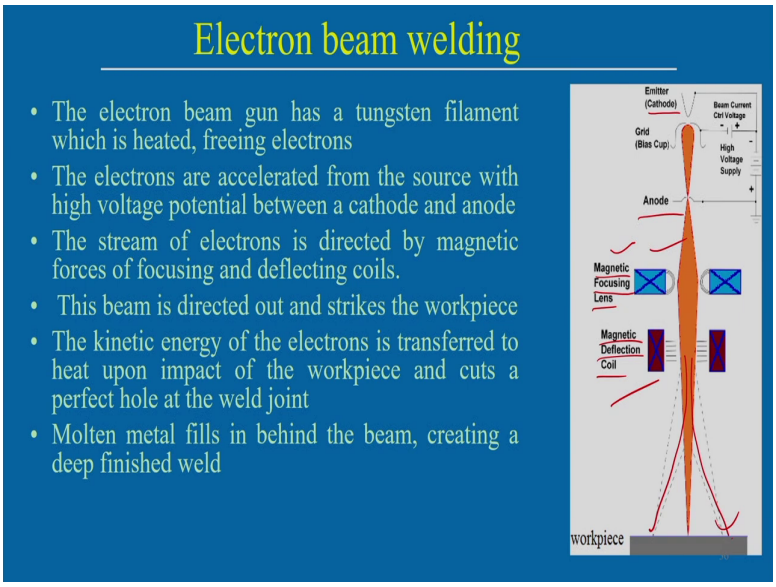
So, here you can see this figure also. So, that is a beam of the electrons comes through a from a source and then it interact with the of workpiece material and then create convert to the thermal energy from the kinetic energy of the electrons. And, but at the same time some sort of X-ray diffraction back scattered electron will we can get also even secondary electron scattered that kind of phenomena also we can observed.

But, finally, it will try to reach as very high depth of penetration and create this molten pool unless within this molten pool some convection convective flow of the molten pool or some sort of convection is there; convection means in the scene the flow of the molten metal is also there in this cases. And, remaining solid part this is heat conduction.

And, at the same way that what way we can represent the from the boundary there is a heat loss by convection and radiation. But, of course, since the electron beam welding process is normally conducted that under the vacuum so, then there is may not be any kind of a convecting mode of the heat transfer from the surface rather only the heat loss by radiation. So, that kind of the heat loss will be there.

Now, see impingement of the electrons causes the weldment interface melts and that kind of produce some sort of the weld joint coalescence. So, basically melt at the interface and relatively high depth of penetrations as to the laser welding process and then two metallic surfaces can be two metallic interfaces can be joined a by use of electron beam welding process.

(Refer Slide Time: 03:50)



But, how this electron beam welding works basically? So, in this case the electron beam gun has a normally tungsten filament we can get the that gun from the source of the electron from its tungsten filament which is heated and that freeing the electrons; so, heated it in such a temperature that will freeing the electron. So, then the electrons are once the freeing the electron so, electrons are then accelerated from the source by using some sort of the high voltage potential between the cathode and anode.

So, between you can see the between cathode and anode high potential difference we can apply so such that the this the tungsten filament emits the electron. So that electrons can be accelerated by application of the high potential difference or may be by application of the high voltage. Here we can see that from the figure also we can see that high voltages is applied.

Now, the stream of electron is created and it is directed by the magnetic forces of focusing and de-focusing coils. So, magnetic focusing lens, in these cases magnetic focusing lens because since we are handling in this case the electron beam of the electron, in these cases the focusing of the electron beam can be done by using some kind of the magnetic field.

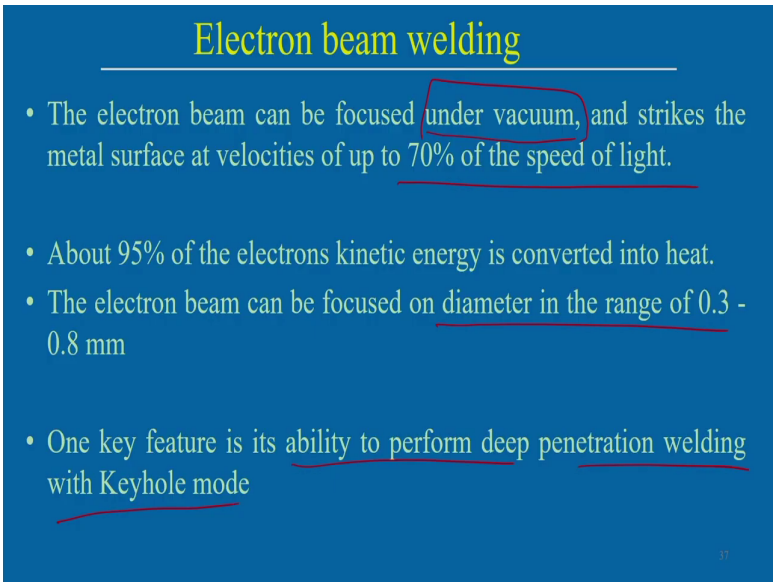
And, even also deflection of the coil at the required position that can also be done using some kind of the magnetic forces, but in case of laser welding process normally we use the lens and then laser line focusing or de-focusing or may be deflecting by using some sort of the lenses.

But, in these cases we can use the magnetic forces or magnetic field to maybe focusing the beam of the electrons on a particular position even there is a we can do the deflection, so that both focusing and deflection can be done by the magnetic field. So, then once the beam is created first the beam is created, then it is accelerated, then it is focused and after that it is deflected on particular position.

This beam is directed out and strikes the workpiece surface. So, once it is directed out in particular position we can make the deflection position depending upon the magnetic deflection coil and it is a heated upon on the workpiece interface.

And, then workpiece then kinetic energy of the electron is released in the form of thermal energy and it melts the work piece surface and then coalescence of the materials can be done by using the electron. So, this is the principle; this is the electron beam welding process.

(Refer Slide Time: 06:14)



Now, electron beam can be focused under vacuum that is very important because if we see when you do the laser welding process. In the laser welding process we there is no need of kind of a vacuum all these things, you can simply use the shielding gas environment and there laser welding can be performed.

But, in cases the one difference from the laser welding is that this electron beam welding can be done under the vacuum such that it should not be this thing, the should not affect this the beam of the flow of the electron beam also and strikes the metal surface at the velocity up to 70 percent of the speed of the light.

So, since the very high velocity strike on the surface, so, then it can penetrate it is a very high depth as compared to the laser welding process. Now, about 95 percent of the electrons kinetic energy is converted into the heat and remaining 5 percent electrons may be some back

scattered electron 5 secondary electrons can emits I or reflected back or some it can put to some sort of X-ray also.

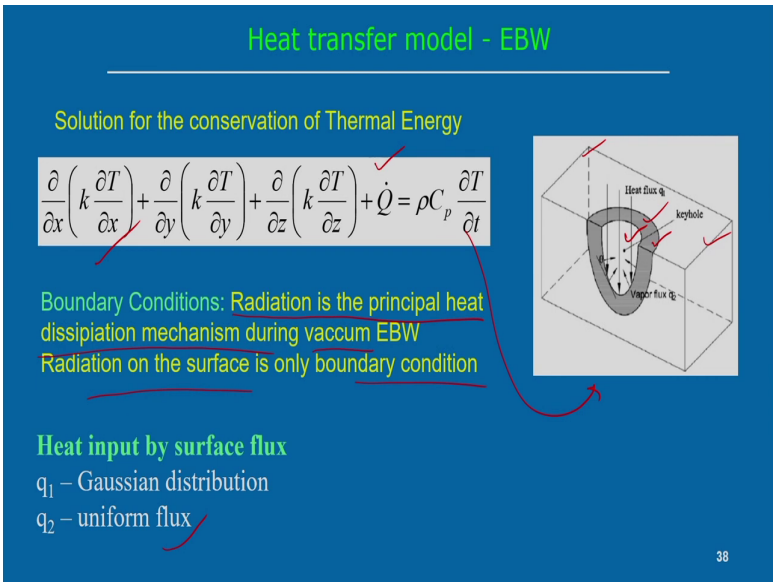
It means that most of the 95 percent of the electrons normally kinetic energy is basically converted in the form of a kinetics energy to the thermal energy. Now, electron beam can be as small as diameter on the focused range around 0.3 to 0.8 milli meter in general that is a range with an over which the electron beam is focused on this thing.

But, one key feature of the ability to perform the deep penetration welding with the keyhole mode. That is the main advantageous in case of the electron beam welding process and at the same time since it is under vacuum. So, the contamination from the atmosphere laser atmospheric environment can be eliminate in case of the electron beam welding process.

So, in that sense it is different from the laser welding process because laser welding process is perform under the shielding gas or normal open air laser welding can be performed, but electron beam is under vacuum. So, that is way these kind of advantages are always there in electron beam welding process. That is why most of the electron beam welding process is normally performed very high precision high costly material.

In that cases electron beam joining process can be done because this cost of welding is very high in case of electron beam welding process as compared to the laser and even as very much compare to the arc welding processes.

(Refer Slide Time: 08:30)



Now, what way the point is that how we can do the modeling of this part in case of finite we can say the thermal analysis or flow analysis in case of the electron beam welding process. So, here also there is a need the basic governing equation the heat conduction equation or conservation of thermal energy equation needs to be solved in the domain.

For example, this is the solution domain. This mark solution domain and on the surface there is the interaction of the electron beam. So, definitely it will penetrate and it is creates some sort of keyhole formation will be there. And, we have already explained that mechanism of the keyhole is sometime different from the conduction mode.

So, in this case if we assume that electron beam with application of the electron beam it will produce some sort of the keyhole and so, same heat governing equation we need to solve that

is the transient heat conduction equation. You can see that 3-dimensional transient heat conduction equation with the internal heat generation term.

So, this is the governing equation. Even we can see the other cases also in general if we want to do some kind of the thermal analysis or maybe temperature distribution once know in that case we can use the 3-dimensional heat conduction equation. So, depending upon the process whether it is transient or steady state we can choose the governing equation accordingly.

Now, this is the domain, solution domain 3-dimensional domain over which the heat conduction equation has to be solved. Now, what are the boundary interaction and how it is different from the other arc or laser welding process? Boundary interaction is the radiation is the primary heat dissipation mechanism during the vacuum.

Because electron beam since electron beam perform under the vacuum. So, we cannot expect some sort of the heat loss or from the surface by the convective mode. So, in that cases the heat loss only because of the radiation. So, we have to be careful to choose a boundary interaction because boundary interaction will happens only because of the radiation.

So, radiation on the surface is the only boundary condition. So, therefore, if we assume in this case this is the keyhole formation is there in the you can see in the this figure at the center, then you can assume the uniform flux within this keyhole.

So, basically first we can what way we have done in case of the keyhole, we can predict the keyhole. First we can predict the keyhole or we can assume some size of the keyhole. So, within the size of the keyhole we can assume the heat flux is uniform and we can heat flux is uniform we can assume the heat flux as the surface flux throughout this keyhole.

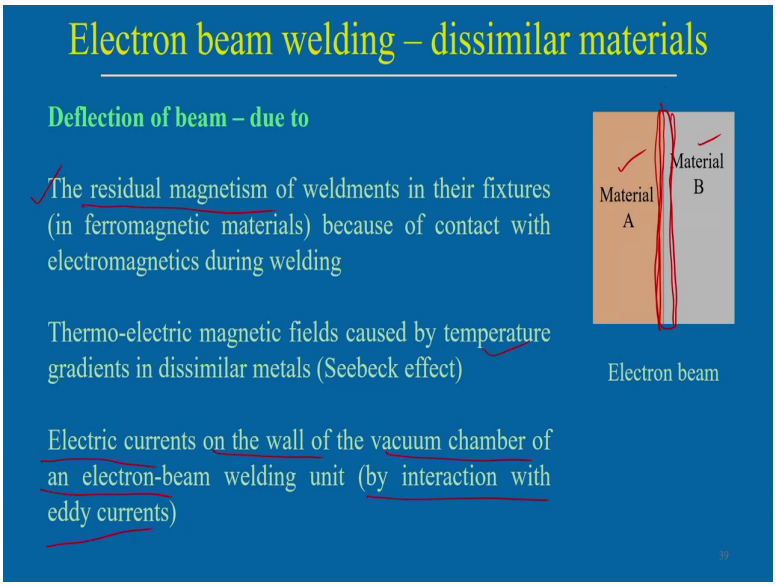
Now, remaining part so, since this part will be the keyhole and the remaining part will be the molten zone there we can assume some sort of the Gaussian distribution of the heat flux. There can it can be followed the Gaussian distribution of the heat flux and these heat flux can

be assumed some sort of the volumetric heat flux also, but this volumetric heat flux is applicable only in the this molten zone.

So, this way two heat flux to input can be divided into two parts – one is the Gaussian distribution, another is the uniform flux. So, this is the input the basically heat input to the domain. So, along with the boundary condition heat input to the domain and if we solve the governing equation, then we will be able to find out the temperature distribution in this particular electron beam welding process.

So, only challenge is that electron beam welding process what way we can represent the interaction of the electron beam with the workpiece material. So, that interaction can be represented in the form of a keyhole formation and the same kind of the treatment or similar approach can be followed what we have we did in case of the a laser welding process or specifically the keyhole mode laser welding process.

(Refer Slide Time: 11:59)



Now, one of the typical problem associated with the electron beam welding process that is the joining of the dissimilar material using the electron beam welding process. So, there are if we observe this thing in this case so, if you use some sort of the because suppose material A and material B has to be joined.

So, two different material having different properties, thermal properties are different between these two and magnetic permeability all also be different in these two cases. So, therefore, there is a chance the interaction of the this some sort of the deflection of the electron beam depending on the residual magnetism of the weldment.

And, that may exist their fixture in basic specifically the ferromagnetic materials. In that cases because of the contact to the electromagnetics during the electromagnetic during the welding process. So, that is way the electron beam can be reflected by the he residual magnetism.

So, then once we try to focus the electron exactly at the interface, so that it create high depth of penetration or basically flow of the electron beam can be focused on this thing. But, practically when you focus at the interface even depth of penetration is very high in case of the electron beam welding process.

So, there is a since the properties are different between material A and B so, beam may get depleted either one side of the material. So, it may not exactly fall on the interface. So, this is one of the typical problem associated with this electron beam welding process. So, let us see how it works on what way we can explain than why that beam actually deflect one particular direction.

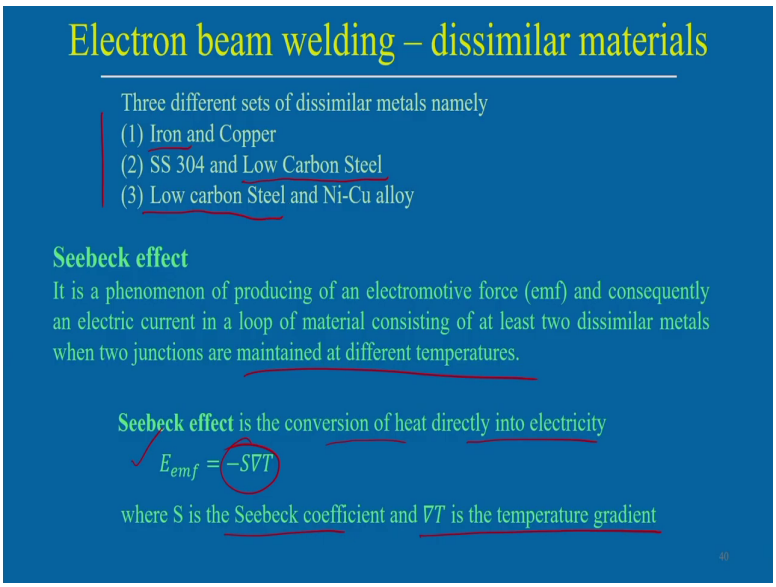
So, thermo electric magnetic field is basically created in that is caused by the temperature gradient in case of the dissimilar material. So, that is we can see the look into the Seebeck effect. So, because of the Seebeck effect so, beams may get deflected or influenced by the residual magnetism and that may causes in because of the temperature gradient between these two material.

So, electric currents on the wall of the vacuum chamber open electron beam welding unit by interaction with the eddy current. Actually the electric you can see the electric currents on the wall of the vacuum chamber. Open electron beam that may also happen.

So, there are three reason one is the residual magnetism presence with that; second was maybe Seebeck effect. Seebeck effect mainly associated with the temperature gradient between these two material and third one is the electric currents on the wall of the vacuum chamber may fold in the electric current on the vacuum chamber and that.

And electron flow of the electron get deflected because of this in the welding unit so, and by interaction with the eddy current. So, that may also influence the beam can be influenced or deflected using this during this process.

(Refer Slide Time: 14:42)



Now, it is observed it was observed that three different sets of the dissimilar materials. For example, if we want to join the iron and copper using the electron beam welding process. So, or one case 2, stainless steel SS 304 and the low carbon steel so and third one is the low carbon steel and nickel-copper alloy.

So, in that case if you see one is the; one is the carbon materials having the low certain percentage of the carbon or maybe but other material can be having almost no carbon percentage. So, in these two category material if we want to join in general and if you look

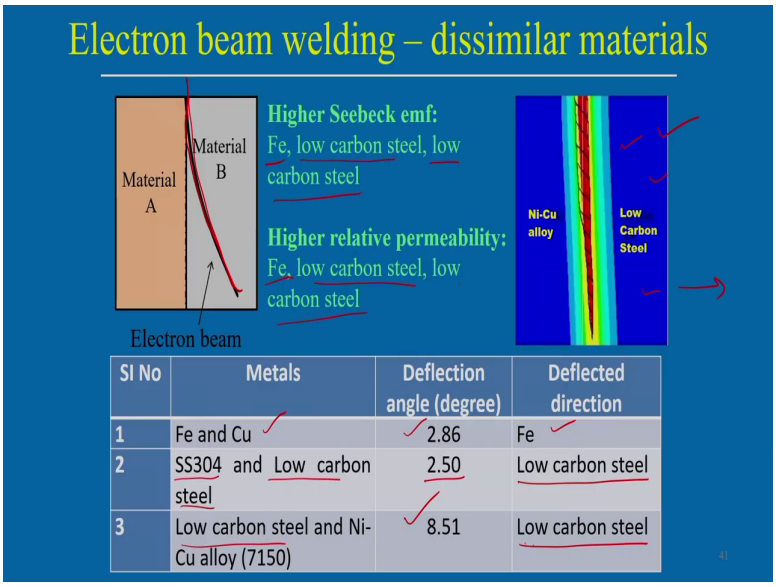
into these three sets of materials we have chosen. So, in that cases we can researchers also tested using the electron beam welding process between this combination of this material.

Then Seebeck effect comes into this picture. So, Seebeck effect can be defined something like that it is a phenomenon of producing the an electro emf it is electromotive force and consequently an electric current a loop of the material consisting of at least two dissimilar metals. So, when the two junctions are maintained at the different temperatures.

So, let us see how mathematically what way we represent these things Seebeck it is the conversation of the heat directly into the electricity. So, some electromotive force will be generated because of the passage of the electric current. Then S delta T, delta T is the temperature difference; S is the Seebeck coefficient and delta is the temperature gradient.

So, basically the electromotive force generated this Seebeck coefficient and the temperature gradient exist. So, that is the this electromotive force and the that electromotive force will try to deflect the electron beam during this process.

(Refer Slide Time: 16:22)



Now, here you can see that higher Seebeck effect we can see that Fe iron, low carbon steel and low carbon ok, low carbon steel – these three combination we can; we have seen the this combination.

So, basically iron and we can see low carbon steel and low carbon steel these three cases the Seebeck effect is more prominent in these cases. So, deflection of the beam is very obvious in this particular case. So, or we can say the beam gets deflected toward this particular material.

And, higher the Seebeck electromotive force, but higher relative permeability also this iron, low carbon steel and the low carbon steel these three combination having the these three particular materials is having the high amount of the relative permeability. So, in this case

beams get deflected depending upon the combination of the material in one side of the material.

For example, if you want to join if you actually focusing on the at the interface the electron beam, but because of the Seebeck effect the beam gets deflected either towards material A or material B. So, anyway then beam will be deflected in one sided. So, once beam get deflected in one side, then it may not melt that interface. So, that is the one kind of the difficulty in case of the dissimilar welding using the electron beam welding process.

Now, let us look into this thing even this simulation can also be done. But, in this case this that roughly analytically we can estimate the keyhole formation and then from this keyhole formation we can follow. Thus kind of the within the keyhole there is uniform flux and outside the keyhole we can follow the Gaussian distribution of the flux and that can be the input to the domain.

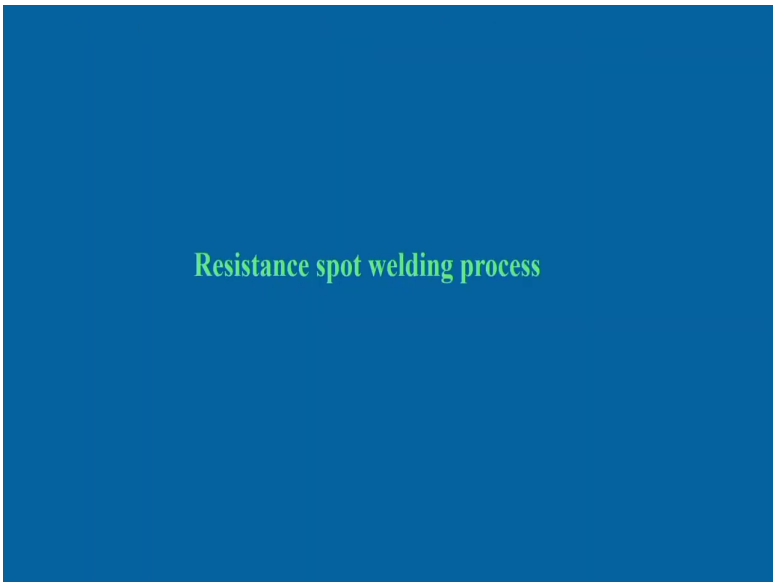
And, if we solve for temperature distribution we will be able to get this kind of the picture. See this is the simulated one we can see the low carbon steel. So, beam actually gets deflected towards the low carbon steel not exactly focusing on at the interface. So, then some part may not be able to join at the interface.

So, this is the typical nature of the joining of the dissimilar material using the electron welding process. So, we can look into all other combination of the materials. So, at Fe and copper so, deflection angle as much as 2.86 degree and deflected direction means it is deflected towards the F e towards the iron.

If we look into the combination of SS304 and low carbon steel in this case the deflection angle is around 2.5 but gets deflected towards the low carbon steel. Even combination of the low carbon steel and then nickel copper alloy in this case we can get the deflection angle can be around 8 degree. So, it is much more and in this case the deflection may happen. So, the beam get deflected towards the low carbon steel.

So, this way we can some idea or some sort of understanding of this seebeck effect. How it influence the joining of the dissimilar materials in case of the electron beam welding process.

(Refer Slide Time: 19:25)



Now, we will try to look into that finite element modeling of the resistance spot welding process. This is one kind of the resistance spot welding process and this resistance spot welding process is normally used in case of the automobile industry. So, the spot welding there is a huge use of the spot welding process in case of automobile industry.

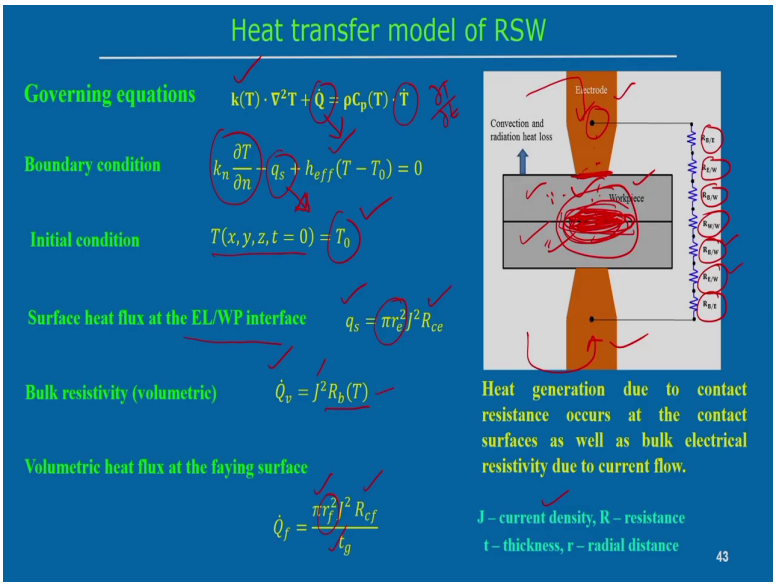
But, one of the difficulty and the resistance spot welding process is that of course, once we use the coated steel. So, then once the coated steel normally the coating is normally used in low melting point material as compared to the other advance high stand steel. In that case

once we try to do the welding or basically we are applying some sort of the heat flux on the surface then coating because coating melt fast.

So, if the low melting point temperature in that cases this it can penetrate to the gain boundary of the actual material the high strength the material. So, that will clear some sort of the a liquid metal embitterment severity and that is a which is a very common problem associated with the resistance spot welding process.

But, our focus is to what way we can do some sort of the modeling. Specifically I am talking about the thermal modeling of resistance spot welding process and we can see how the model is actually helps to predict some sort of the liquid metal embitterment severity in case of the resistance spot welding process.

(Refer Slide Time: 20:50)



Now, in principle, how it works? The resistance spot welding process we can see that this is the two workpiece, this has to be joined. So, joining means it is a maybe at the interface we can join. So, basically up to melt the interface and then this after solidification these two metals can be joined.

So, this is the in general we can say this is the kind of spot welding process. Now, to do that there are so many things are there. Because in these cases the very contact resistance is very important as well as the bulk resistivity of the particular material is also important.

Now, if we look into the actual process if we join these two slits using some sort of the electrode, we know the principle of the resistance spot welding process. Now, this is the electrode under the electrode the two workpiece is hold and then there is a flow of the current very small period of time. And after that at the some sort of the electrode force is required to hold this workpiece.

And, once there is a flow of the current at the at this point there is some the heat generation due to the resistance. So, due to the resistance the heat is generated and then some sort of the Q at the molten pool or maybe something like that Q at the molten pool and then after that joining this solidification these two metals these two slits can be joined.

Now, you can see how many resistance are there. So, one resistance is that R b e. So, then there this is the passage of the current. So, current flow is there through the electrode also, current flow is there. So, some sort of bulk resistivity will be there; bulk resistance is there for the electrode material.

Now, this is the one this is the bulk resistant which is act over the volume of the particular component. Now, there is a contact between this electrode and the workpiece. So, once there is a contact so, some sort of the contact resistance will also be there. So, that is the second one is the contact resistance.

Since the workpiece having some finite volume so, there canbe some again the some bulk resistivity will also be there which is act under the which is normally defined over the volume so, this bulk resistivity of the workpiece. Now, since there is a contact between the two workpiece. So, some sort of the contact resistant will also act that is called the contact resistant.

And remaining the same thing the symmetric part where the other it is remaining because this is also bulk resistivity of the workpiece. This is the contact resistance between the workpiece and the electrode and third one is the bulk resistance of the work piece. So, this is the typical resistant components and all this contact resistance or bulk resistivity they contribute to some sort of the heat generation.

Now, what happens in resistance spot welding process? Because this process is design may be developed in such a way that maximum heat will be released at the interface between the two workpiece. So, maybe so that means, contact resistance at this point is very important.

So, that actually responsible to generate the heat at the interface, because other cases there is no need of melting all these other point. Because finally, we want to join between these two surface at this point. So, then you choose the material combination of the material in such a way that the other contact resistance or bulk resistance can be minimized.

So, for example, some sort of contact resistance is there. So, definitely some sort of the heat generation will also be there, but that heat generation is minimized the with the intimate contact between the electrode and the workpiece. And, at the same time we can use electrode in such a way that electrode is basically high conductive material or sometimes in case of there maybe some water cooling channel within the electrode such that what maybe heat will be generated at this point.

So, quickly it will dissipate it a through the electrode because of high conductivity as well as the because of the presence of the cooling channels within electron. So, such that heat

generation will be minimized and minimized in such a way that it should not melt and they join between the electrode and the workpiece that should not happen.

So, that is the principle, but here we can maximize the heat generation at this contact interface such that the melting pool will be there and then these two components can be joined. So, this is the principle of the resistance spot welding process. Now, mathematically what way what equation we need to solve, how we can represent the different kind of the heat source or heat generation during the resistance spot welding process.

Communication we are interested to know that what is the temperature distribution in the domain. So, therefore, then heat conduction in the equation has to be solved. So, here this is the different form of the heat conduction nothing else and Q dot is the internal heat generation term and the rho C p T dot equal to basically del T by capital T by del small t. So, this is the transient heat conduction equation we need to solve.

Now, boundary condition the same kind of the boundary condition from the surface that convection and radiation heat loss. So, therefore, this is the convection and radiation heat loss with by using the effective heat transfer coefficient gives the heat flux, the surface flux applied to the domain solution domain and this is a heat conduction at the boundary.

So, then the balance of these things create some kind of the this can be represented the mathematical form of boundary condition. Now, since this is a transient problem some sort of the initial condition will be there T this thing T 0 that is the initial condition.

Now, the same governing equation boundary condition wants to define the similar way we can do this thing. But only difference as compared to the other welding process what way we can represents the heat flux or volumetric heat generation. So, here we can see the surface heat flux can be represented like this because surface heat flux is basically pi r square and J square, J is the current density and R ce is the this is the contact resistance.

So, therefore, this is the heat generation at this particular point. So, heat generation in this particular point. So, this is surface heat flux at the electrode and the workpiece electrode and

the workpiece interface between the electrode and the workpiece interface at this interface, this is the heat generation calculation. So, therefore, contact resistance has to be defined between the workpiece and the electrode material.

So, this is the one surface flux, then bulk resistivity because bulk resistivity since we are counting the bulk resistivity over the volume. So, we can assume this is the volumetric heat generation because of the bulk resistivity of the particular material we can see J is the current density and R is the bulk resistivity of the component. And bulk resistivity is normally available as a function of the; this is the property can be measure or defined as a function of the temperature.

So, that is the bulk resistivity can be calculated like that. Now, volumetric heat flux at the faying surface faying surface mean between the two workpiece the we can assume some in these cases there is a some contact interface is there. So, we can assume that is a very small contact layer is there and that is contact layer assuming some finite value of the contact layer.

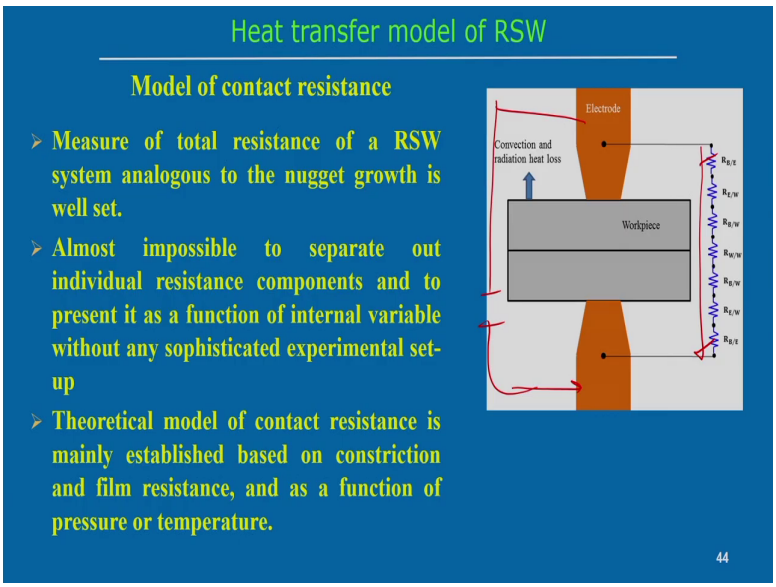
And, then we can represent the finite volume of the total heat generation at the interface is because of some kind of contact resistance, so that that heat generation can be represented in the form of a volumetric heat generation.

So, therefore, it is can be calculated like this r effective means what is the effective radius and R cf the contact resistance at this particular point. And, t g is the I think the thickness of the material or maybe I can say t g is the thickness of the layer over which the heat is released, t is a thickness.

So, that is way this both's you can see this resistance spot welding process we have we can incorporate both the volumetric heat as well as the surface heat flux to the domain. Only surface heat flux two one surface heat flux is there between these two.

Bulk volumetric heat flux will be there because at the interface plus. Because of the bulk resistivity volumetric heat flux can be incorporated in the domain. So, this is the representation of the heat source.

(Refer Slide Time: 28:27)



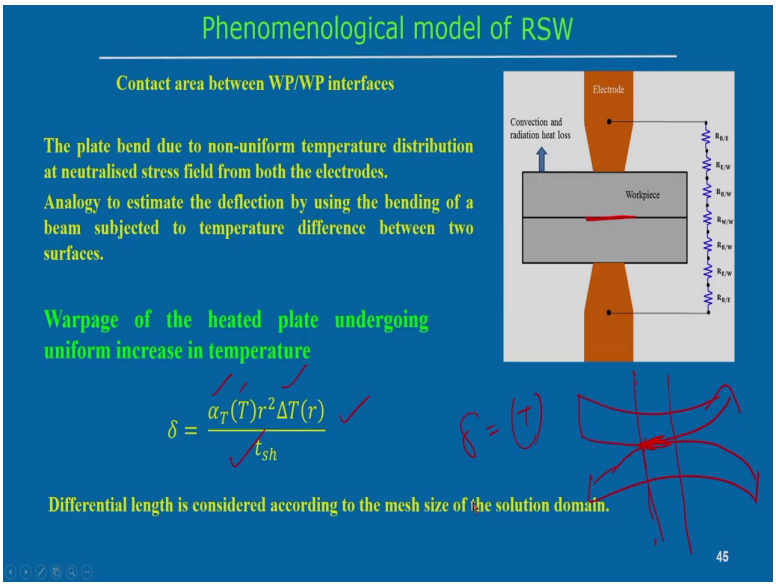
Now, how we can do that modeling of the contact basically we have seen that there are so many resistance components are there. But, how we can measure individual resistance component it is very difficult also in in case of any kind of the industrial process.

So, what normally happens this thing that it is easy to put the some kind of the sensor and sensor point these two and we can measure the resistance. It means that it when we measure this resistant between this tensor in the electrode point between these two.

Then, basically we are measuring the total resistance total all the resistance components from here to here all resistance components we can measure together. But in these cases it is very difficult to the separate out the individual resistance components. So, that can also be done.

But, we need a very sophisticated experimental setup to individually measure the resistance components which may not be applicable in the actual industrial practice or maybe in industrial process. So, therefore, some in these cases now some modeling approach, some finite element modeling approach can help into some extent to identify what is the residual stress component with some inverse approach.

(Refer Slide Time: 29:38)



So, that is we can do also here we can see first the contact area between workpiece and workpiece interface. So, contact area between the workpiece and workpiece interface between

these two this is the contact area. So, in this case it is observed that do the this thing the workpiece through workpiece contact area.

So, then when it means that over the time on the over the period of the time because during the welding process there is a application of the current that is over a certain period of time. So, during this certain period of the time beams that mean these two plates can get deflected high which is not under the electrode. So, that can be deflected.

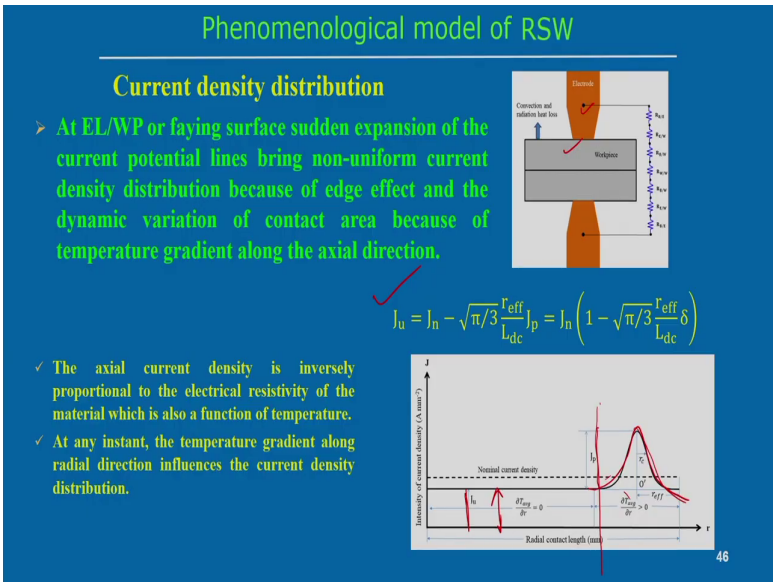
So, in that cases we can simply assuming that warpage of the heated plate undergoing the uniform increase in temperature. Some analytical means we can see then we can estimate what is the deflection delta. So, this differential length is considered according to the mesh size of the solution domain. So, delta can be considered a differential way depending upon the mesh size of the solution domain, delta can also be estimated.

So, delta can be estimated at the different mesh because see alpha is a I think expansion coefficient as a function of temperature radial distance r delta T temperature gradient also as a function of r. Because different radial distance the temperature gradient are different until is the sheet thickness.

So, all information available and all we are representing this thing we can calculating delta as a function of temperature. So, then some sort of temperature data is required to estimate the delta. So, this is simple approach we can follow what maybe the deflection of the beam because it was observed that with the application of the load and during this process also beam not beam actually the plate can also be deflected something like that.

If there is a contact normally this contact area happen the projected area of the electrode and remaining part can deflected. So, therefore, del can be estimated as a function of temperature looking into the other parameters available.

(Refer Slide Time: 31:37)



Now, current density distribution: current density distribution is normally happens we can see the current density distribution at the edge there may be variation of the current density distribution.

Here we can assume from the central point to the edge of the electrode because current density distribution were looking between the electrode and the workpiece. So, here we can see that up to this point is the uniform during the edge there may be increment and then away from this thing there is a gradual decrement of this thing.

We can assume this typical nature of the current density distribution and based on then we can estimate current density distribution different parameter what is a peak value, what is the

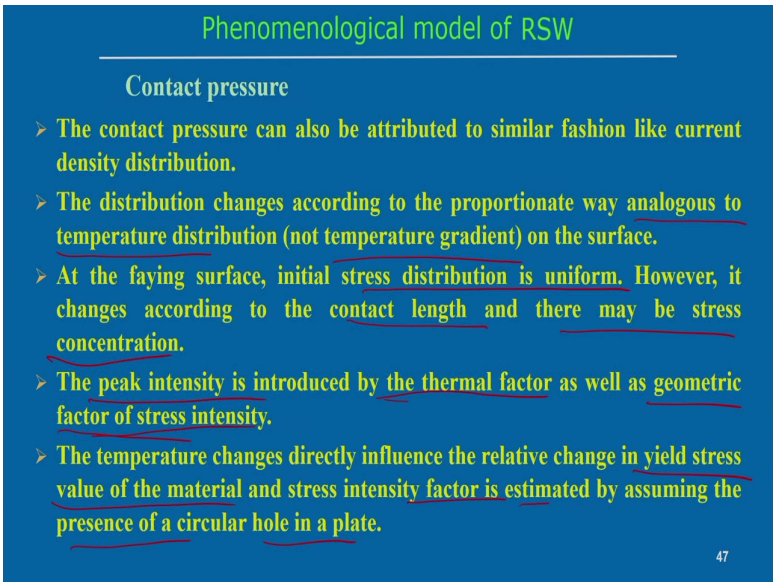
average value and then looking into the temperature gradient equal to 0 up to this point. Because this is uniform assuming the temperature up to 0.

And, remaining that temperature gradient greater than 0 and after that it is gradually temperature gradient is less than 0 and over a period of temperature gradient equal to 0. So, basically if you take the information of the temperature distribution and from the temperature distribution, we can assuming looking into the temperature gradient.

And then from the temperature gradient we can make the strategy then what may be the distribution that current density over a at the different points. So, this is the intensity of the current density distribution. So, it is the uniform and it is the variation. So, then all this kind of information we can find out if we follow this if we assume this distribution follow in this particular pattern.

So, this is simple analytical way we can estimate the current density distribution during this resistance spot welding process.

(Refer Slide Time: 33:07)



Now, contact pressure also, the contact pressure can also be attributed to the similar fashion like the current density distribution. So, same kind of similar way we can estimate what is the contact pressure, the similar pattern of following the current density distribution.

So, therefore, the distribution changes according to the properties accounts with the proportionate way analogous to the temperature distribution. So, this in these cases the changes analogous to the temperature distribution, but not the temperature gradient on the surface because temperature gradient we consider in case of the deflection. But, when you are looking into the contact pressure then we can assume it is a simply as a function of the temperature, not the temperature gradient.

At the faying surface initial stress distribution is uniform assuming the initial stress is uniform. However, it changes according to the contact length and there may be the stress

concentration may also happen that is associated with the welding process also. The initial stage distribution is uniform, but over the period of the time when there is a change in the contact length the between these two workpieces and there may be the stress concentration may happen.

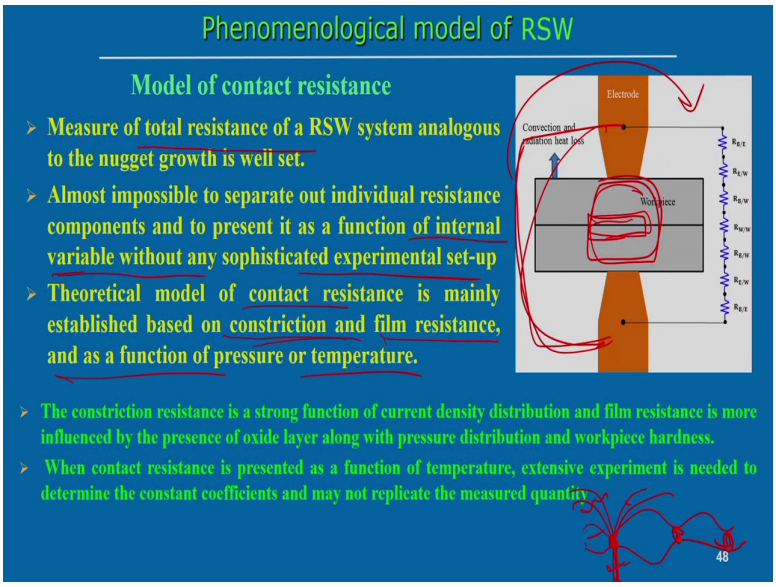
So, therefore, the peak intensity introduced by the thermal factor as well as the geometric factor of the stress intensity. So, in this case the peak intensity value can be introducing such a way by the thermal factor as well as the geometric factor of the stress intensity. We know the geometric factor of the stress intensity that simply analytical solution.

For example, if there is a hole and with the application of the load and the because of the presence of the hole in a particular plate what may be the stress concentration factor at the edge. So, that is kind of information we can take a information standard value and that standard value that can be that stress intensity factor can be a function of the temperature. So, this way you can introduce the contact pressure between this workpiece and this thing.

So, therefore, the temperature changes directly the influence the relative change in the yield stress value of the material that we know that yield stress value can be represent as a function of the temperature. And, according to the stress intensity factor also estimated by assuming the presence of a circular hole in a plate.

So, basically stress we can estimate the stress intensity factor in this when you estimate with the contact pressure in case of the resistance spot welding process.

(Refer Slide Time: 35:26)



Now, model of contact resistance so, how we can make the this because total resistance we can measure between these two point. But what is the contact resistance that can be measure also if we can contact resistance that actually the if we estimate the contact resistance at the interface that we will be able to estimate what is the actual heat generation at the interface.

So, measure of the total resistance of a resistance spot welding system analogous to the nugget growth as well. So, total resistance is normally basically total resistance is measure, but this total resistance is basically mapped with the nugget growth. Nugget growth means that how this molten basically we can say the over the under the projected area of the electrode.

How the molten zone actually created or developed during the resistance spot welding process. So, that is basically analogous to the measurement of the contact resistance.

Basically assuming the we can map the growth of the nugget as well as the total resistance during this process.

Now, it is almost impossible to separate out the individual resistance components and to present it as a function of the internal variable. It is very difficult as in terms of the internal variable means temperature, but any sophisticated experiment without any sophisticated experimental set up.

So, that is why if it is very difficult to separate out the individual component until unless there we can put the some sophisticated experimental set up and that experimental setup we will be able to find out each and every resistance components, but that is very difficult already we mentioned that thing in industrial process line.

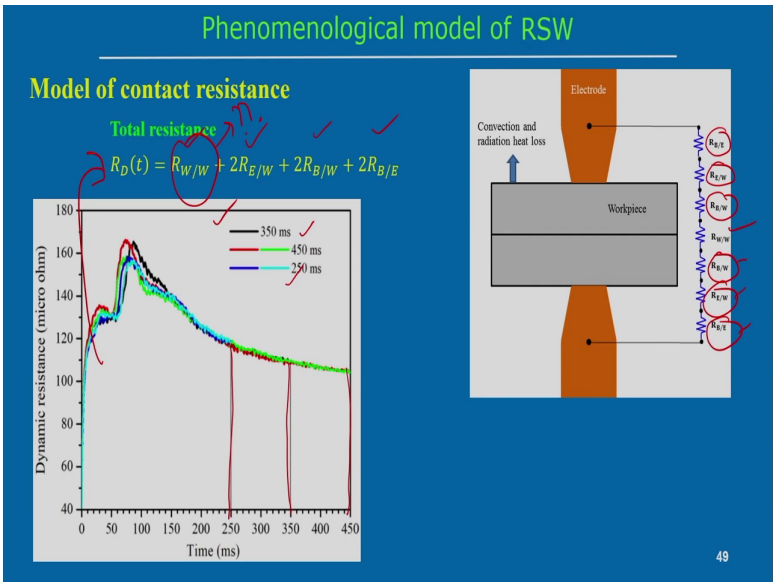
So, theoretical model of the contact resistance is merely established based on the constriction and film resistance as a function of the pressure or temperature. So, basically that will help objective is this particular case how we can estimate the contact resistance. So, this theoretical model, to some extent can help.

And, assuming that the contact resistance or the because of the there is two parts of this resistance – one is the constriction resistance another is the film resistance; film resistance means the presence of the oxide films and the constriction means when there is a contact between these two maybe if you look into the microscope.

So, this contact at the contact interface something like this. So, contact may be something like that middle point. So, that means, whatever the current will be try to flow between this.

So, it is basically that is a large area the current maybe pass through a very small area, so that means, there is a constriction of the flow of the current. So, because of that some sort of the resistance will be there. So, that resistance components we can count and film resistance components we can count and both can be a function of the pressure or temperature and, then accordingly we can estimate the contact resistance.

(Refer Slide Time: 38:09)



Here we can see the model of the contact resistance, we can estimate this thing. So, total resistance this is the measure of the dynamic resistance that is the total resistance the on time is a 350 milli second for example, 450 milli second and 250 milli second. We can see that is 350 milli second 250. So let us look into the 250 milli second up to this point 250 milli second.

So, nature of the contact total resistance is same even it is extend to 350 reduces and it is 450 also reduces, but the typical nature of the pattern is the same if we look into the if we measure the total resistant during the resistance spot welding process.

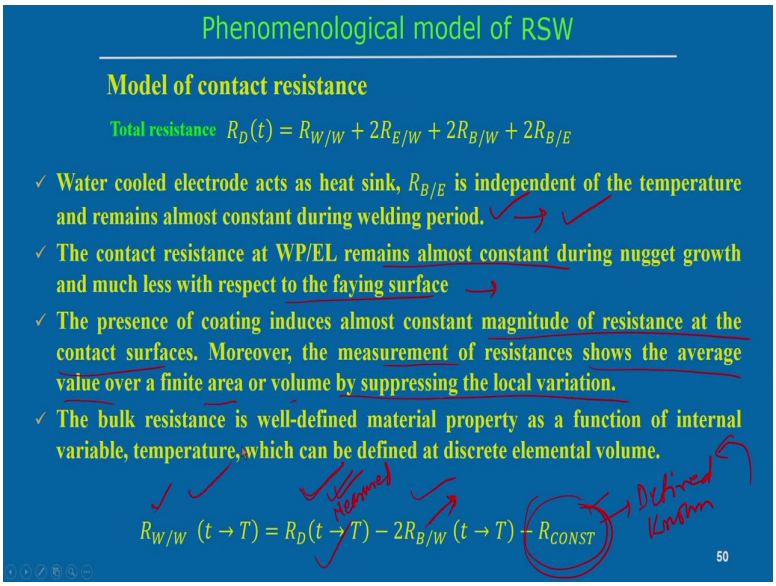
Now, assuming the total resistance is consist of this part the resistant between the workpiece to workpiece, resistance between the electrode to workpiece and resistance between the this

bulk resistant between the workpiece and bulk resistance of the electrode. We can sum of all these thing there are 1, 2, 3, 4 components are there.

Now, this is the four components means there this same both side and E W also same both side and B E also some both side. So, that are 1, 2, 3 and this is the fourth one. So, total four resistance components and this is the measure of the total resistance. Now, this total resistance we can measure also experimentally during the process.

This is the total resistance this total resistance is represented by this now our interest to know what is the value of this contact resistance between the two workpieces so that we can estimate the heat generation at the interface.

(Refer Slide Time: 39:44)



Now, total resistance this is the formula. Now, water cooled electrode acts as a heat sink. Basically the electrode is a very high conductive material as well as the cooling channel is there. So, that, we can consider that as a work as a heat sink. Therefore, this bulk resistivity of the electrode is independent of the temperature and remain almost constant during the welding process.

So, from we can make some assumption in this way, first thing. Second thing is the contact resistance between the work piece and the electrode it remains almost constant during the nugget growth and much less with respect to the faying surface. So, with respect to the faying surface means that are between the workpiece and the workpiece, with respect to that the contact resistance between the workpiece and electrode remains almost constant.

So, some sort of value we can define. Here also we can define some value because bulk resistivity also defined in as a function of the temperature for a particular material. That is well defined in the in terms of the material property. Now, presence of coating induce almost constant magnitude of the resistance at the contact surface.

So, therefore, measurement of the resistance shows the average value over the finite area or volume by suppressing the local variation. That we can see because although we are talking about the dynamic value of the contact resistance, but we can see even there is a different on time we can get the similar kind of the total resistance graph.

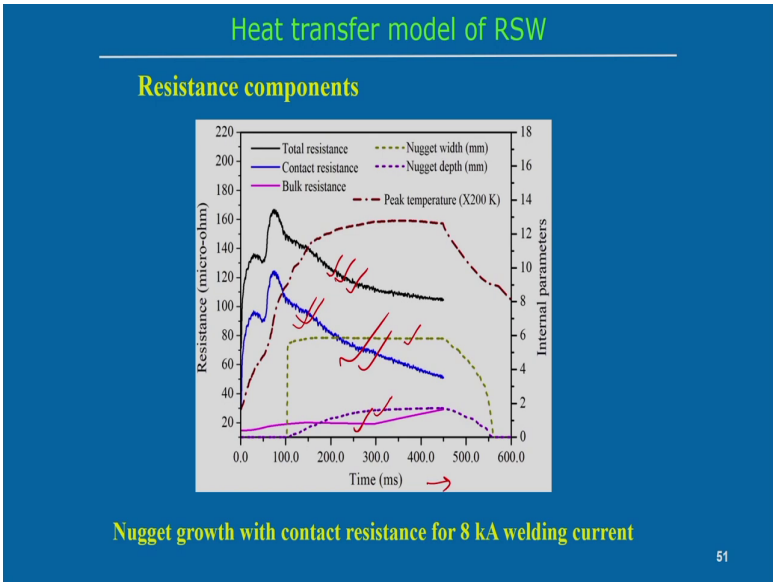
So, therefore, coating induced almost constant values of the magnitude of the resistance. So, therefore, now once we this thing R W W that is we want to know this is a total minus of the other components this value and R constant may be depending upon this thing. So, but this is the bulk resistivity of the workpiece and remaining remains constant bulk resistivity of the electrode and then contact resistance between the electrode and the workpiece remains as a constant.

So, therefore, this is well known, this is defined, or this is measured basically this is defined for a combination of material these values is known defined or known value. And, only thing

is that if we know what is the bulk resistance of a workpiece material then we can say the value of the contact resistance the between the two workpieces.

And, but in this case the bulk resistance is normally available as a function of temperature. But since we are looking into we are measuring the growth or basically contact resistance we are measuring as a function of time. So, therefore, we can mapping in this thing this time as a function of temperature because converting the temperature to as a function of time, then we can say the what is the value of the a contact resistance as a function of temperature.

(Refer Slide Time: 42:26)



Here we can see this figure also. Now, here total resistance is measured is this value, this is the total resistance value this curve; total resistance that is measured through the experiment. Now, this is the nugget width and nugget depth we can see this is the nugget width and this is

the nugget depth that is the measure and we can see that we are plotting this time; time versus resistance.

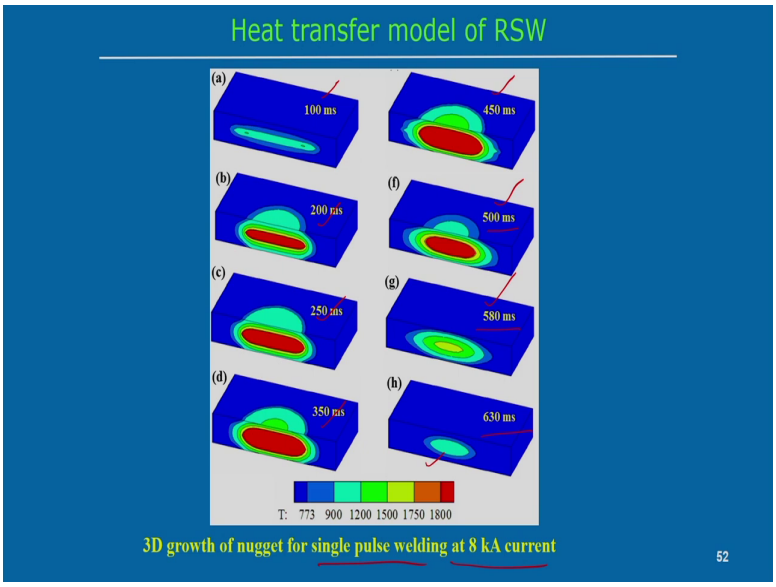
So, although the bulk resistivity values are available as a function of temperature, now we can map with the what is happening with respect to time because spot welding the duration is more very less time maybe 200, 300, 400 milli second only. So, now this is the value this thing and we can see this is the this indicates the bulk resistant. This bulk resistant is basically defined bulk resistance of a particular material is very well defined. So, bulk resistance this is the total resistance, this is the bulk resistance.

Now, by with the help of the numerical model because with the from the numerical model that will help to converting the as a function of temperature to time that mapping. Then we can see from total resistance minus of the other component of the resistant, then we can represent the blue color this is the contact resistant and that contact resistance. We can define as a function of time not as a function of temperature as a function of time we can represent this is the contact resistance.

So, once we separate out this contact resistance value, then that value can be used again in the numerical model the as a source of the heat to calculate the heat generation part this is these values is important. So, that can take the input. So, this actually this value of the contact resistance components is normally done it is a there is a need to integration of the numerical model.

Basically there is a we need to help from the numerical models simply converting to temperature dependent to the represent in the time scale. So, that using the help of this particular numerical model we can get this kind of calculation contact resistance we can more precisely estimate the contribution. We can be considered as input to the domain and then we can do the further analysis.

(Refer Slide Time: 44:38)

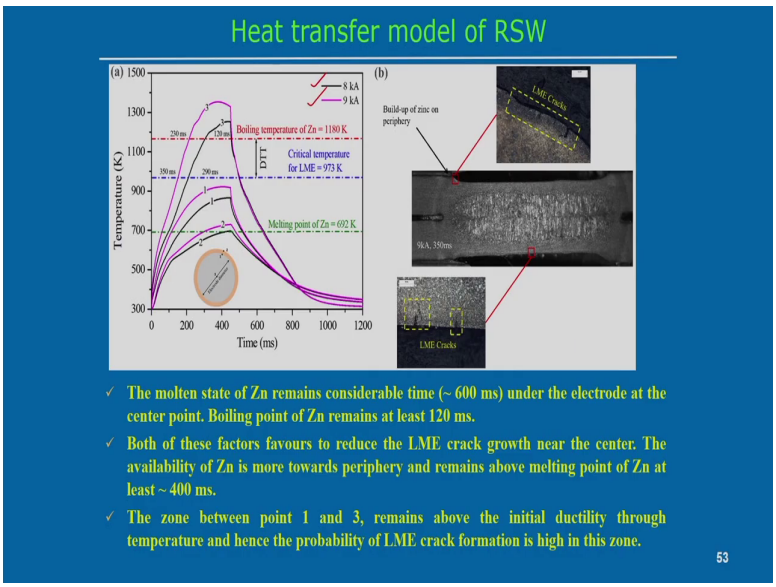


So, now output from this thermal model in resistance spot welding process we can see that is the 3-dimensional growth of the nugget for the single pulse welding process at 8 kilo amp current. We can see the 100 millisecond the growth the development of the weld pool, red color actually defined the weld pool in this case.

251 we can say the nugget growth of the nugget 350 milli second. So, up to 350 milli second we can see this is the red zone reach in this particular position and that is the that define the weld pool and this is also 450 millisecond. Now, above 450 milli second after that the switch of the application of the current.

So, there is no heat input to the solution domain, then gradually the molten pool will disappear we can see 500 milli second, 580 milli second and 630 milli second we can see, very quickly it come back to this a very low temperature less than 7 900 900 Kelvin.

(Refer Slide Time: 45:36)



So, that is kind of information we can get from the thermal simulation, we can utilize this information to predict the this thing. LME phenomenon associated with the resistance spot welding process. We can see that temperature 8 kilo amps, 9 kilo amp ampere you can see this is a typical temperature distribution at the different position 1, 2, 3 different different position we can estimate that which cases at which point it is above the boiling temperature of the coated material.

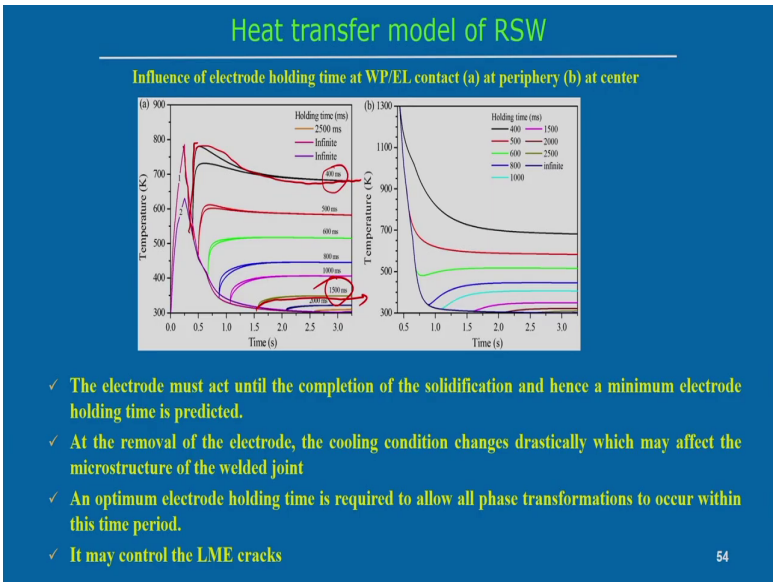
So, in these cases coated material can be zinc also and then we can estimate the critical temperature for the liquid metal embrittlement; that means, these kind of information we can

get the ductility through temperature range what is the ductility through temperature range. We can see the some part may be associated goes through the ductility through temperature and some part the temperature is below the ductility through the temperature.

So, therefore, this zone 1 and 2 may not be any kind of the some sort of the liquid material embrittlement may not be there or even it is there also that maybe it is a point and the it can be in very small quantity. But, other point that this thing the LME phenomena can be much more. Because this all these information whether LME phenomena or liquid material will happen or not.

That kind of information we can get simply from the time temperature distribution associated with the resistance spot welding process. So, accordingly we can predict that this location we can expect some sort of the LME liquid metal embrittlement track a particular in the particular position. With that information we will be able to find out from the temperature distribution.

(Refer Slide Time: 47:08)



Now, here also influence of the electrode holding time because electrode holding time means one of the resistance spot welding process there is a need to hold the workpiece by the electrode. But after passage of the current we can keep some minimum time such that solidification to occur and after that we can release the electrode.

So, but if we release the electrode what is the effect of this thing we can see the temperature versus time. So, if we very quickly we can release the electrode for example, after this particular position even it is milli after 400 milli second if we remove the electrode.

That means, it is a very just finishing the welding process, then immediately we can the electrode then what will happen and then maybe which time we are allowing this thing some sort of cooling process.

Then once we remove the electrode, then again temperature will increase and then gradually decrease or try to equilibrate some position or it will take much more time to come back to the ambient temperature. So, this kind of the typical temperature we were will be able to link with the microstructure formation one kind of the structural formation can be link with this thing.

Particular material also even electrode holding time it is for visible 1500 milli second that means, we can allow to cool down up to 1500 milli second then you remove the electrode, then it will follow this particular temperature. So, it will near about the ambient temperature. So, that so, from here we can estimate the what is the minimum time or we can modulate this thing electrode holding time also just from the information from the numerical simulation.

So, that is why we have discussed this different resistance spot welding process in these cases an electron beam welding process. And, I hope this will helpful to understand the first what are the physical aspect associated with the this particular welding processes and then second thing is that what way we can develop the finite element based model.

Basically the I am talking about the thermal model or temperature distribution, but now once we develop the thermal model. Then what way we can utilize this temperature distribution to explain the different physical phenomenon associated with the welding process.

Even most of the cases we can link with the we can estimate the cooling rate from the time temperature diagram or from the time temperature information. And, that cooling rate will help to link what kind of the microstructure we can expect in a particular welding process.

So, that is why there is a need to go through some sort of the modeling calculation or to develop of the particular model or analysis of the model. That will help in design of the experiments or some sort of the other kind of information can be extracted from the modeling approach.

So, thank you very much for your kind attention. So, next time I will be discussing I mean focusing on the thermal analysis or thermal model in case of the solid state welding process.

Thank you.