Mathematical Modelling of Manufacturing Processes
Swarup Bag
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture – 26
Solid State Welding-2

After a friction state welding process, now I will discuss the diffusion welding process which is most one of the widely and very old process. But in principle the diffusion welding process it is also it follows the solid state welding processes. But in this case two metal surfaces are joined together by the application of the force and added by the temperature.

But in this case the application of force normally happens for a longer time and if you see the some sort of temperature added means some sort of heat generation is also possible between the two interfaces by the following the principle of the resistance heating.

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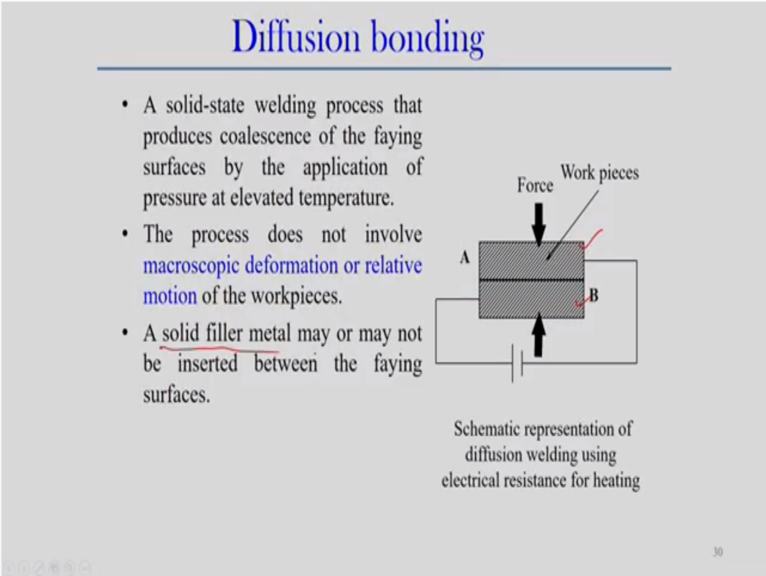

So in this figure if you see that two work pieces are there and the it is a connected to the circuit and that on the interface there is a heat generation will be there by resistive heating and then which also added by the application of the force. So this is the in principle this is the diffusion bonding between the two components. But the most important aspect is that here it is not necessary to being some kind of the relative motion between these two components, what are we doing in case of frictional heat generation.

And of course it is not involved any kind of microscopic deformations and it is not necessary but the aided by the temperature in the sense if we do some kind of resistive heating between the two surfaces then it always try to moves removes the oxides layer and then brings the contact between the two surfaces. But in principle the preparation of the surface is most important for diffusion bonding process.

So it is if it is possible to remove the contaminated oxide layers before the welding process, then it is becomes a very good alternative solid state welding processes as compared to the other processes. But of course here we can mention also that if necessary sometimes filler metal can be used at the faying surface but it is not mandatory in all ways.

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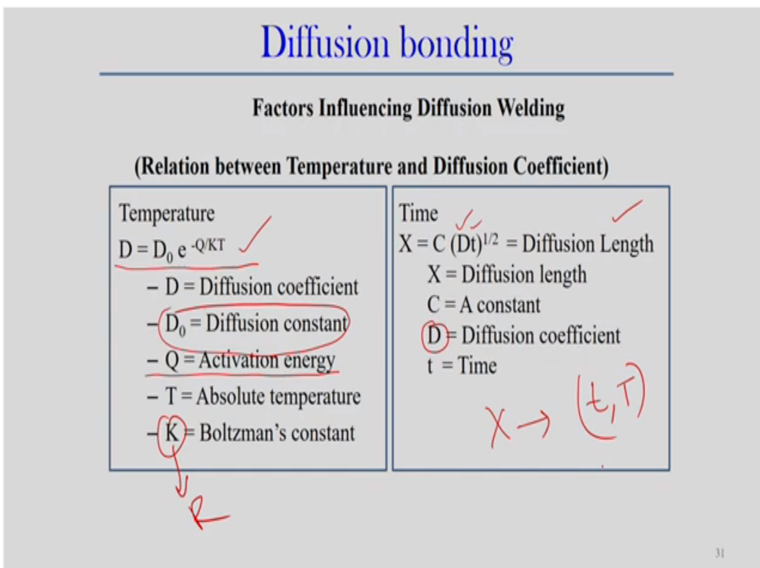

Now in this case the diffusion welding processes, diffusion bonding processes that what are the factors that actually influence the diffusion bonding welding processes that we have already discussed. And for example that surface preparation is one of the important aspect here and apart from the application of the temperature at the interface or application of the force all are the influencing factor.

But of course depending upon the nature of the surface as well as the type of the materials the depth depends on these things. But we can estimate the depth and in the diffusion length basically up to what depth diffusion normally happens that actually dependent on the that if you see the diffusion coefficients and the time and it is proportional to the square root of diffusion coefficients and time.

We see that in these cases the depth actually dependent on the time. So normally this process is relatively slow process as compared to the other processes. But if we in other way also it is a very clean process and of course it is a and that it can avoid the other kind of distortion all this phenomena can be avoided by using this process which is usually common in case of other type of normally fusion welding processes.

Now once we estimate the diffusion length by using these parameters then we need to know what is the diffusion coefficient. Diffusion coefficient can be estimated but the diffusion coefficient itself is a function of temperature. We can see how it depends on the diffusion coefficient the diffusion this is the variation of the diffusion coefficients in this expression, D0 x exponential -Q/KT and K is the Boltzman constant or sometimes we can say that -Q/RT also.

Depending upon the dimensions given of activation energy accordingly we can use either K or either R at this point it can be R also then the characteristic gas constant. So ultimately it depends on the temperature and it is exponentially decaying with respect to temperature, D0 is a constant diffusion constant and that depends on the type of the materials and once we estimate the temperature dependent of diffusion coefficients.

And then if we put it so X is basically becomes function of time as well as temperature. That is a estimation of the diffusion length by using this simple expression.

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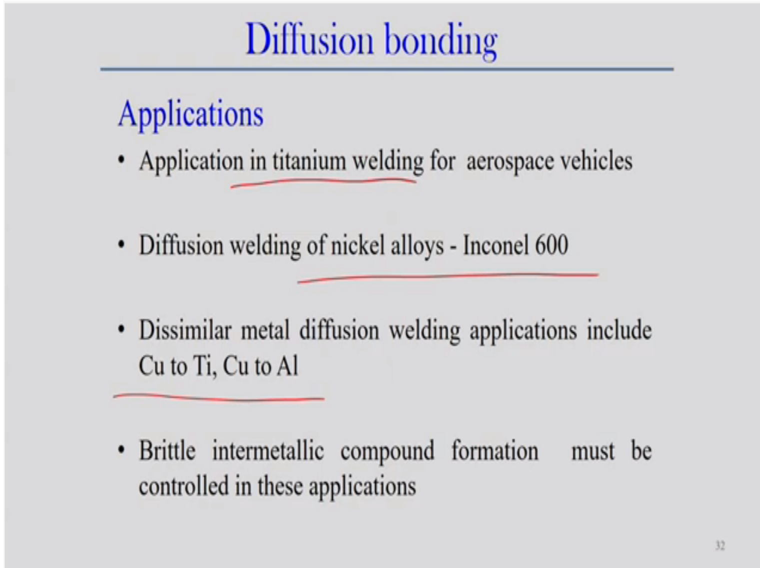

Application, the diffusion is a well-established application we can find out in the aerospace vehicles for titanium welding because fusion welding of titanium welding may be problematic formation of the oxides. And then diffusion welding of nickel based nickel alloy also it is normally Inconel 600 series we use in these applications. And of course apart from that copper to titanium, copper to aluminium that kind of the dissimilar metal welding can be joined by diffusion bonding.

But intermetallic formations normally brittle are the most serious problem for joining of the dissimilar materials. Of course it can be control better way in case of solid state welding process as compared to the diffusion welding processes.

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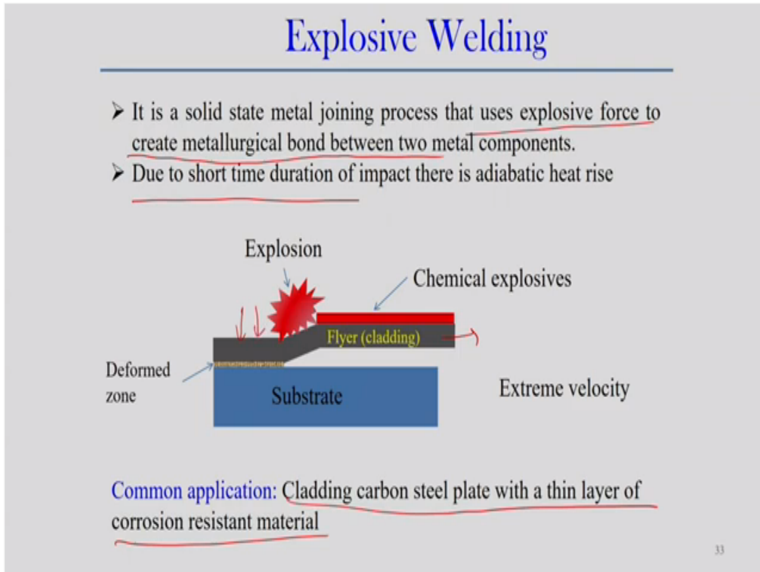

Now we come to that point explosive welding is the other type of the solid state welding process but explosive welding we normally found out the application of a normally very large structure and very thin sheet has to be deposited on substrate material for example cladding carbon steel plate with a thin layer of corrosion resistant material. Normally, the raw material having very high corrosive tendency.

In that type of material we can use the corrosive resistant material and just deposited on the surface. But relatively very large surface area we can do by using the explosive welding. Because in small-scale explosive welding is very difficult to control the explosive. In principle it is solid state welding process and we use the explosives to do the welding process that create the explosive creates the forces and that force finally creates the metallurgical bonding between the two components.

But how to do it is a due to a very short period of time where there is a impact of the one material on the substrate material. For example it is called the flyer which is we suppose to deposited on the substrate material it is a very thin seat and then flyer material is subjected to some kind of the explosive layer already chemical explosive is over the substrate what the flyer surface.

And once start the explosive then gradually this thin layer will deposited on the substrate material. And of course the mechanism can be different here it normally creates kind of wavy structure and that morphologies kind of wavy structure and that with this morphology, the two different flyer surface actually mixed with the substrate material. But of course this process is very subjected to it is very extreme velocity is created.

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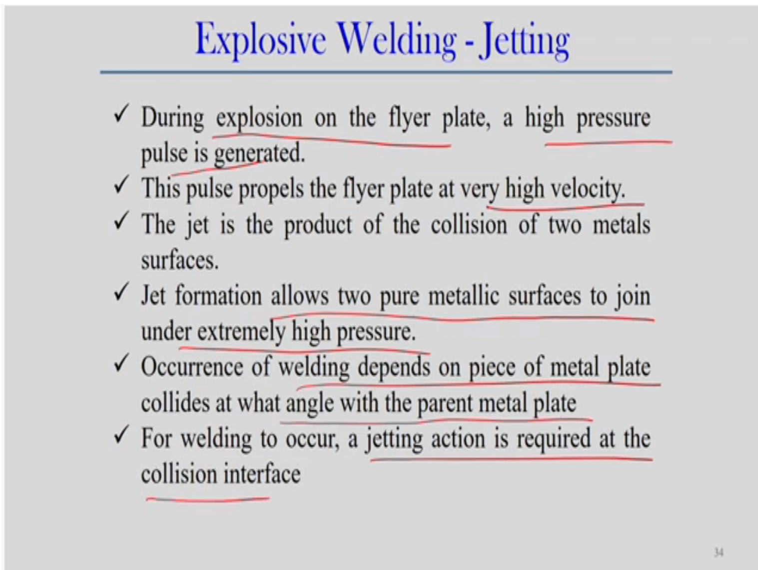

Let us look into that what is the typical range of this kind of velocities or principle of this explosive welding process we look into that. So first we start with the expression on the flyer plate high pressure creates generated and this pulse propels to the flyer plate at very high velocity on the surface, surface of the substrate material creates kind of jetting system at the interface between the two metals.

And then jet formation actually allows the pure metal surface to join under extremely high pressure so jet the because of formation of the jetting that under high pressure the one the it deform the substrate metal as well also and they can join but all this happen at extreme high velocity. So welding depends on the piece of the metal plate what it collides at the what angle with the parent metal.

So here angle is also important. So this angular shape also important and that angle is depending upon the bending properties of a particular flyer type of material. So for welding a jetting action is required at the collision surface definitely a jetting should be created jetting action must be involved here to join the two surfaces.

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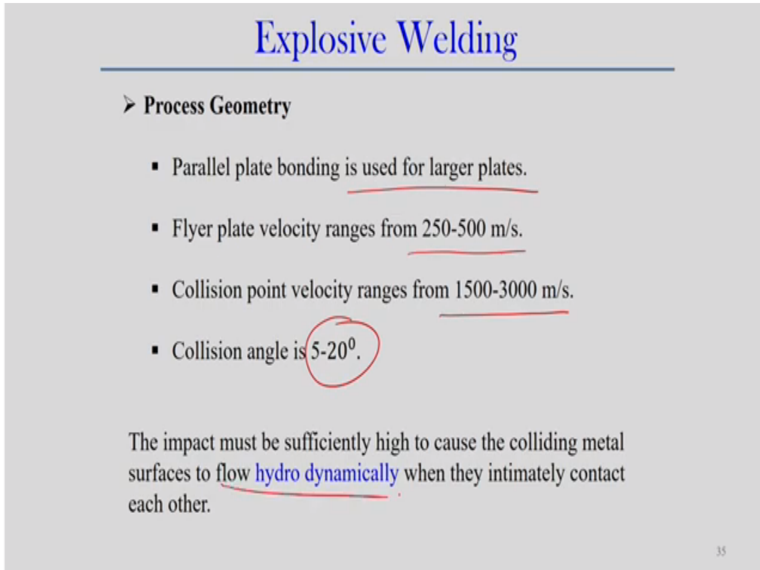

So process geometry we can see that parallel plate bonding is possible, it is a very large plate normally use the plate velocity range from 250 to 500 meter per second. And of course collision point velocity ranges from 1,500 to 300 meter per second and the angle is around 5 to 20 degree depending upon the type of the material. But impact in such that the surface to flow in hydro dynamically when they intimate contact with respect to each other.

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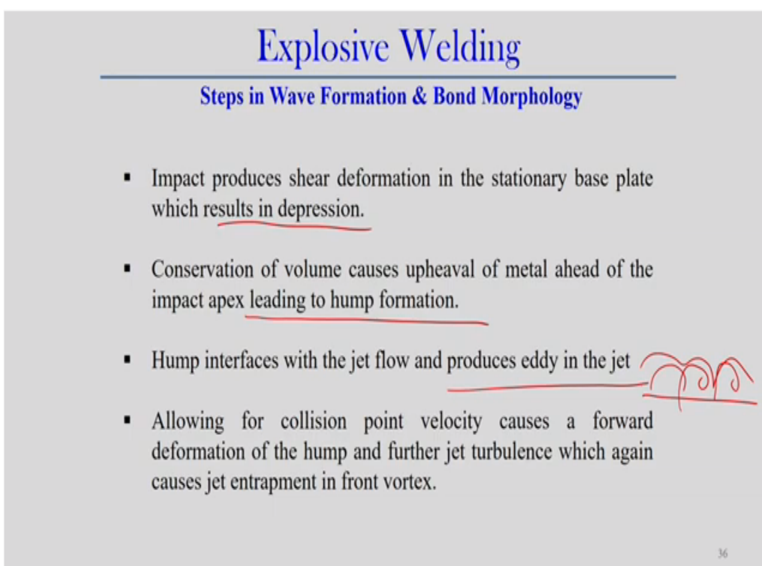

Steps in the wave formation; some wave formation is forms and the bond morphology. So when there is a impact produces some kind of the shear deformation in the stationary base plate which results in the depression in the substrate material. And of course conservation of the volume creates some kind of upheaval of the metal ahead of the impact and that creates kind of the hump formation.

And then hump formation will ultimately create some kind of wavy structure in this surface and the metals actually joined between these very thin plates may be joined with the substrate material. So hump interfaces with the jet flow and they creates interfaces with respect to each other and kind of creates the kind of eddy of the jet. So kind of turbulence may happens between these two components and normally this happens at the very high velocity.

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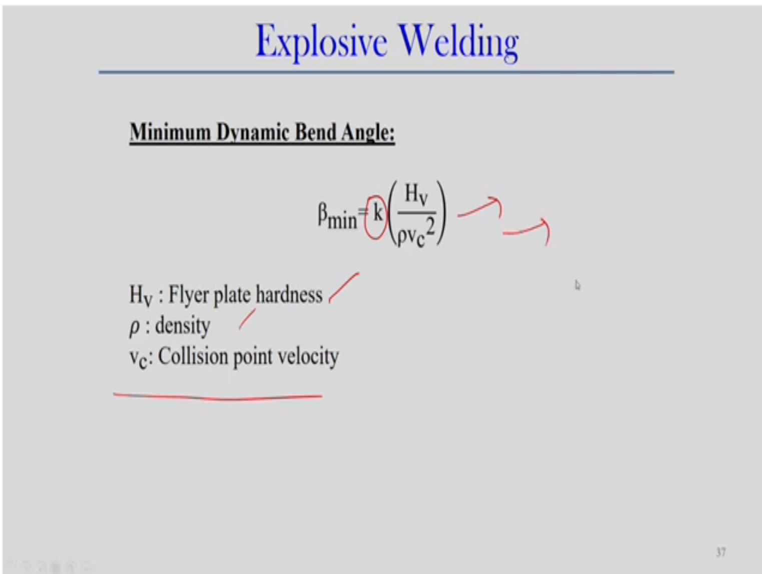

Now minimum it is depends on that angle minimum bend angle it can be estimated that actually bend angle of the flyer plate depends on the hardness of the flyer plate, density of the plate and the collision point velocity. So when there is impacting on the surface at this point what is the velocity it depends on this parameter and we can estimate the minimum bend angle as a function.

And this is the relation where you can find out it is depends the K is the constant here and the hardness divided by density and collision point velocity square. So from here we can estimate what is the minimum bend angle can be produced by particular flyer plate.

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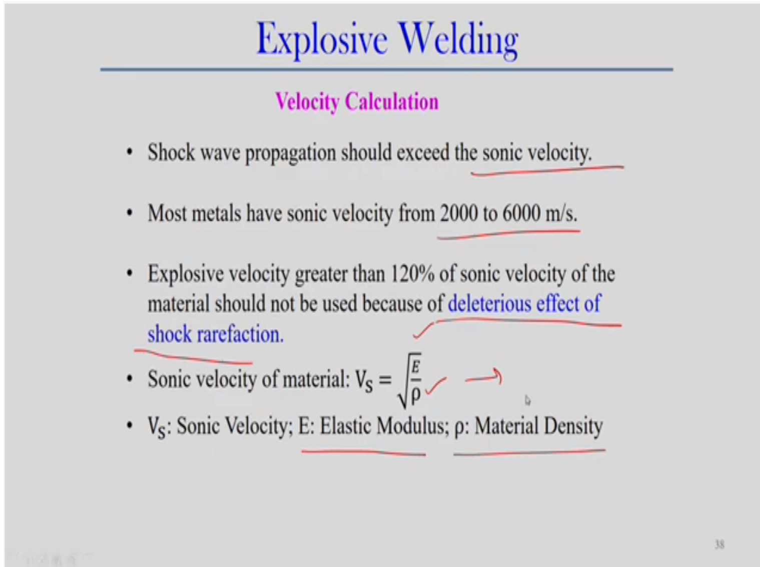

When velocity calculation we see that here definitely when there is a high impact involved in this process. So definitely that create kind of shock and shock have velocity must be exceed the sonic velocity it is a more than that of velocity of the sound in that particular medium. So normally metals having the sonic velocity is around 2,000 to 6,000 meter per second and of course if explosive velocity should not be more than that of 1.2 times of the sonic velocity of the material.

So that because if it is more than that there may be opposite effect may also deleterious effect may happens for the shock rearfaction may happen also here. So that explosive velocity should not be very high as compared to the sonic velocity. We can estimate the sonic velocity also, sonic velocity depends on the Youngs modulus and density by simple expression, root over of E/Rho, E is the Youngs modulus and Rho is the material density.

So from here we can estimate what is the sonic velocity of a particular material if we know the Youngs modulus are density of a particular metal and based on that we can decide what may be the typical range of these parameters or this kind of velocity can be.

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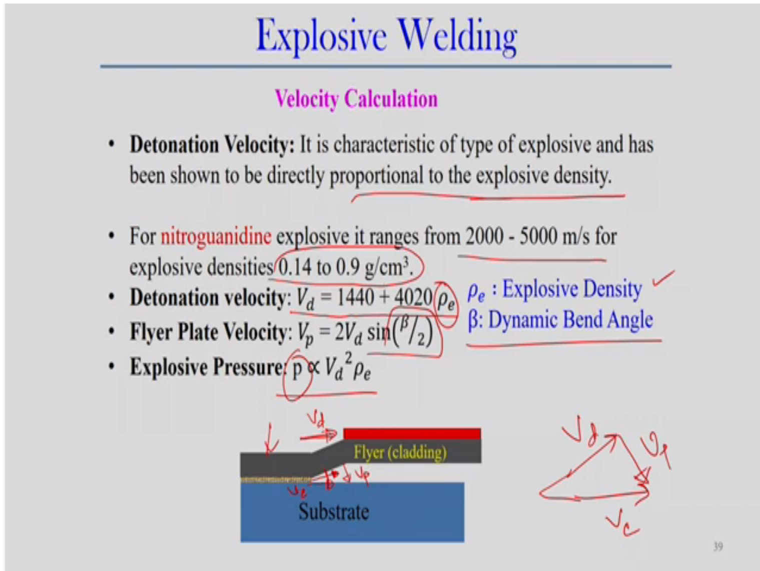

Here we can easily see that things we can estimate the velocity components also involved in the explosive welding process. So detonation velocity it basically the characteristics of the type of explosive and depends on the explosive density. So it is a directly proportional to the explosive density. Now for example a particular explosive the normally range from 2000 to 5000 meter per second for the explosive density 0.14 to 0.9 gram per centimetre.

So definitely if you want to estimate what is the explosive velocity detonation velocity then we should know what is the density of the explosives. So it is entirely depends on the density. For example one empirical illusion also given here, the detonation velocity equal to 1440+4020 x rho e where rho e is the explosive density. Of course it depends on the units also. So in flyer plate velocity we can estimate the flyer plate velocity.

So this flyer plate velocity can be presented like that. So this is called actually Vd sorry Vp flyer plate velocity and this sorry we can look into this way also. So there are two velocity components, one is this velocity actually this is the flyer plate velocity and this is the; this horizontally we can say that this detonation velocity. So that flyer plate velocity can be in terms of the detonation velocity.

But also it depends on the bend angle beta; beta is the dynamic band angle. And of course here in between it creates some kind of jet directions and here the collision point velocity can be represents as Vc. So here basically three components are there velocity and the; this the flyer plate velocity and there can say that this is the detonation velocity. And of course this angle is the minimum bend angle.

So what this is already deposited substrate. So initially there is a gap between the flyer and the substrate material. So once it creates by using the explosive it creates it in the gap has been filled by this flyer material and then it creates this kind of joint. So at any particular instant this creates this kind of velocity diagram and we can estimate and explosive pressure also we can estimate it is which is proportional to the flyer plate velocity and density of the explosive.

So, all these matters and all these parameters are significant in specific to the explosive welding process.

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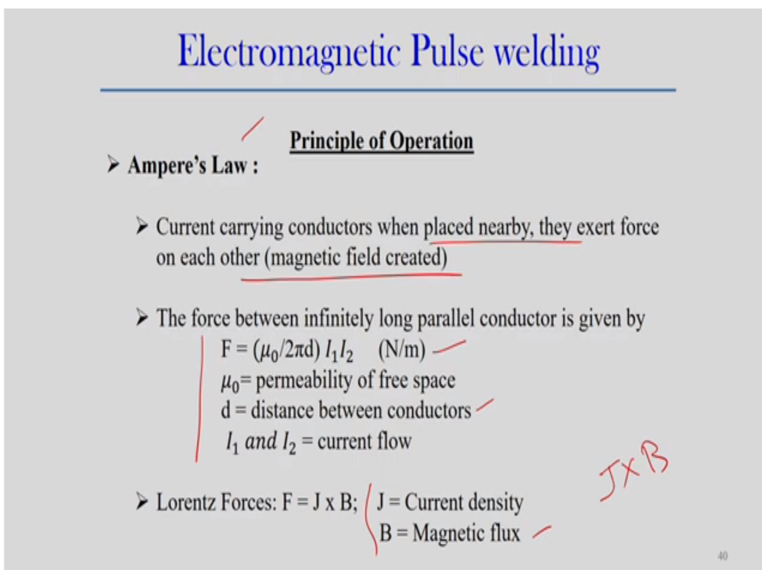

Now we come to that point electromagnetic pulse welding, which is another advanced welding processes. So we know that principle of operation is follow Amperes law first current carrying conductors that if there is a flow of the current during the welding processes it will try to create some kind of the magnetic field.

But by this electromagnetic pulse welding, we can wisely use this magnetic field to join up the two components mainly the tubular kind of components we can join by using the electromagnetic pulse welding. We can find out that current carrying conductors when they are placed nearby they exact one kind of force with respect to each other and because they create the magnetic field.

Now we can estimate the force between the infinitely long parallel conductor which can be estimated by F=this expression, mu0 is the permeability of the free space, distance between the conductors, I1,I2 the basically current flow during this process. Now of course in this case also Lorentz force is estimated that which depends on the current density because if the process is involved the flowing of the current and magnetic flux the cross product of the magnetic flux.

So Lorentz force is basically the direction our normal to this this thing current density field vector and magnetic flux vector. So this is a in principle we use the Lorentz force and ampere law for to explain the electromagnetic pulse welding process.

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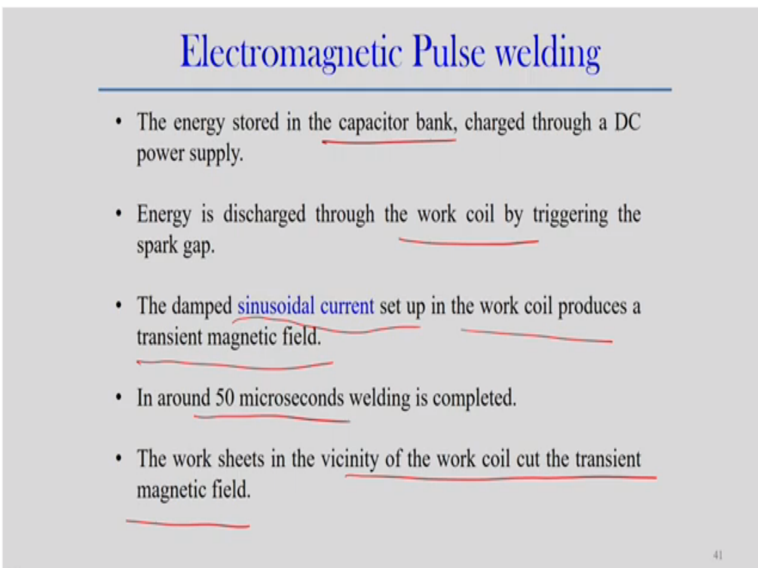

But how this process happens or what we can explain this process. Energy stored basically in a capacitor bank by DC supply DC power supply and then when the energy is discharged through the work coil we use some kind of the work coil and which is work coil we just switch on to pass the energy from the capacitor bank to the work coil and that is a function of time and that time is very small basically.

So once we set the sinusoidal current setup in the work coil then that actually produce the transient magnetic field that transient magnetic field over a very short period of time. We can say that around 50 microseconds the verification of the transient magnet field and then at the same time work sheets, the vicinity if the work coil cut the tangent magnetic field. So this capacitor bank is normally used to supply the energy creates the magnetic field it is a very short period of the time and at that period of the time to metallic components can be joined.

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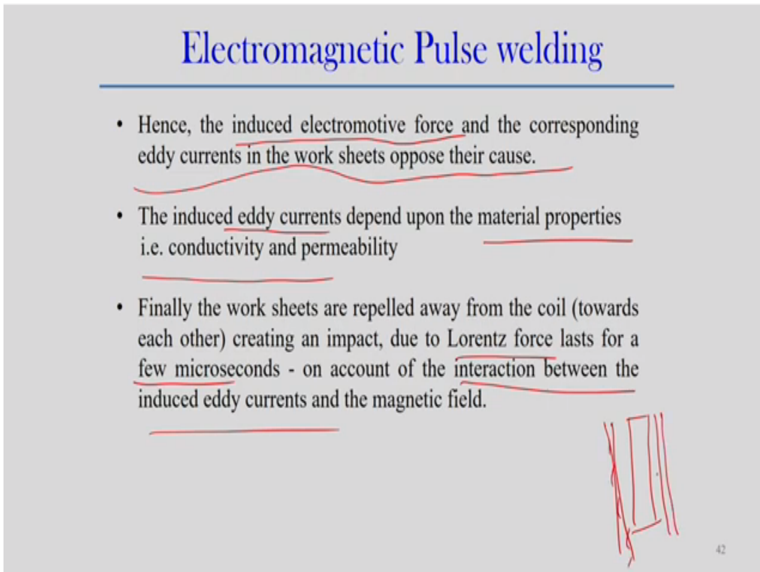

So hence induced electromotive force will be created because of the passage of the current at the same time the corresponding eddy currents also create in the walk sheet. And that induced magnetic field and the eddy current they actually create oppose with respect to each other. Now of course the current eddy current depends on the material property mainly the conductivity and permeability of a particular material.

So finally work sheets are repelled away from the coil and the work coil create the electromagnetic field EMF is generated towards this and causing an impact and due to the Lorentz force which lasts for a few microsecond on account of the interaction between the induced eddy current and the magnetic field. So magnetic field and induced eddy currents they creates they oppose with respect to each other.

And then one two tubes can be joined, so say one is the inside the solid and so it is creates this kind of force such that surfaces will be intact with respect to each other because of the opposing effect of the electromagnetic force and induced eddy current.

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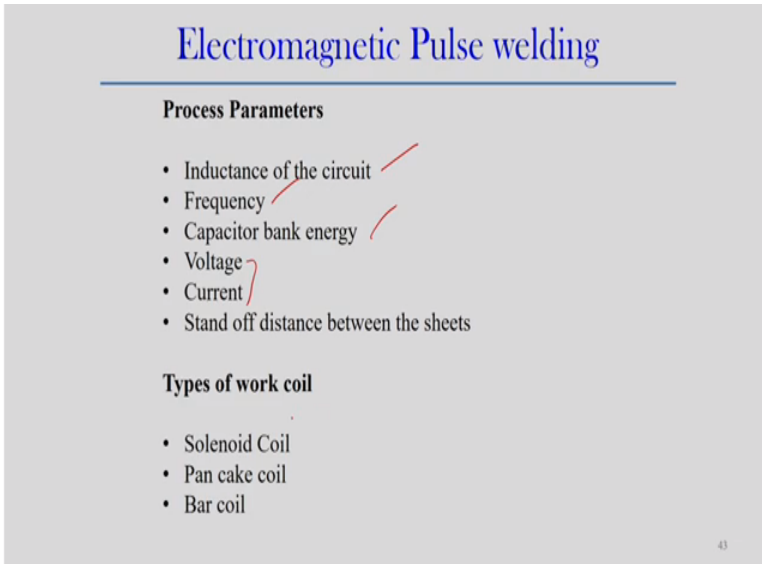

So process parameters the inductance of the circuit basically frequency capacitor bank what is the capacity of the energy that capacitor can sustain during the process, what is the voltage current they applied and stand-off distance between the sheets and these are the different types of the coils that can be used in normally used in case electromagnetic pulse welding process.

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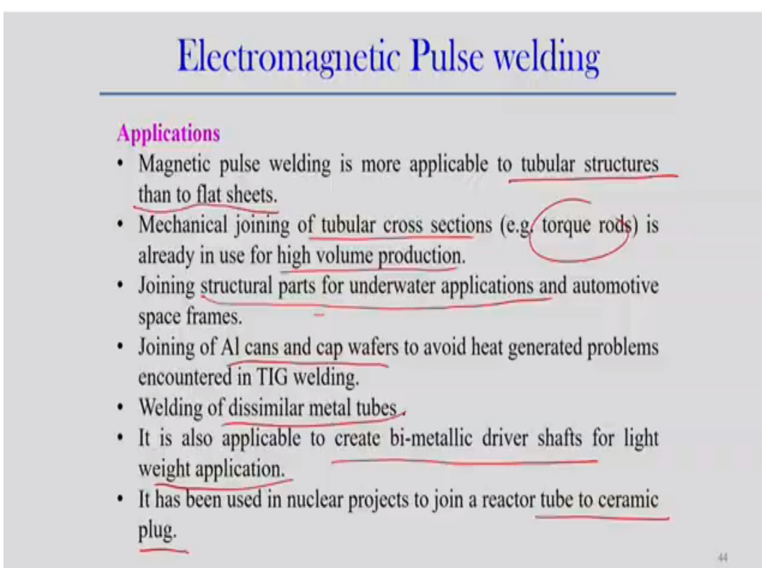

Application we can see a lot different areas we can find out the application of the electromagnetic pulse welding, we can see normally the tubular kind of structures can be there tubular structure to flat sheet. Basically welding is more applicable to tubular structure with respect to the flat kind of workpiece, then joining of the tubular cross section maybe torque rod already in use of the high volume production.

So normally already use in and parts structural parts in underwater applications and automotive frame spaces. Of course joining of aluminium cans is to creates the probably using the fusion welding process magnetic volume pulse that can be replaced by this kind of electromagnetic pulse welding process. Joining of dissimilar metallic tubes can also be joined. It is also applicable to bi-metallic driver components; diverse shafts to the lightweight application can also be used.

And of course it can be nuclear projects we use the tube to ceramic plug can also be joined using this electromagnetic pulses. So we can find out that there is a lot of application in electromagnetic pulse welding process and this process can be used as an alternate with respect to other fusion welding processes.

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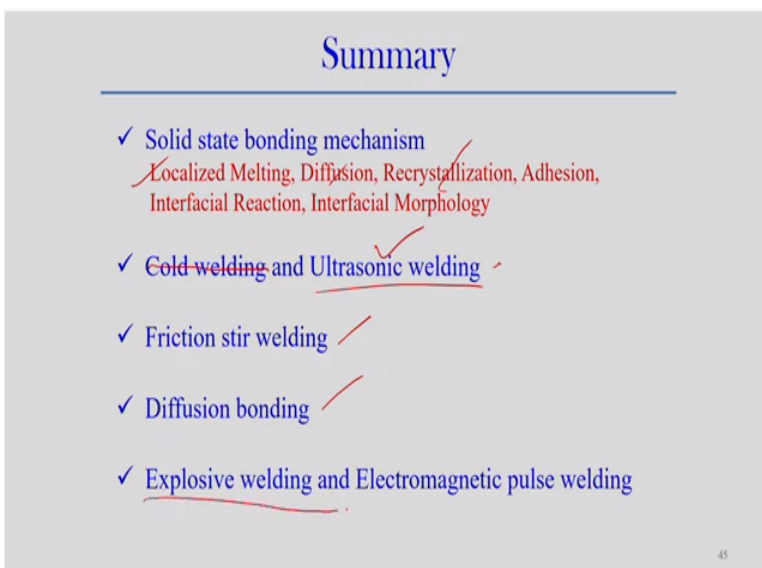

In summary we can say that solid state bonding mechanism is we explain localized melting, diffusion, of course recrystallizing may also happen, adhesion, also interfacial reaction these are the mechanism normally involves when we try to explain the different solid state welding processes. Of course we explain the cold welding we have not explained but ultrasonic welding we have explained during this process.

Which ultrasonic welding process mainly applicable where you can find out the application a small scale application want to modify certain changes then we can use the ultrasonic welding process and normally this ultrasonic system normally used to create kind of the hybrid processes. Then we explain details about the friction stir welding process and in friction stir welding process how we can estimate the heat generation also.

Then we can use the diffusion bonding mechanism of the diffusion bonding and we explain the overall idea about the explosive welding and as well as the electromagnet pulse welding. So this is all about the solid state welding processes. Thank you very much for your kind attention.