Mathematical Modelling of Manufacturing Processes

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Lecture – 25
Solid State Welding-1

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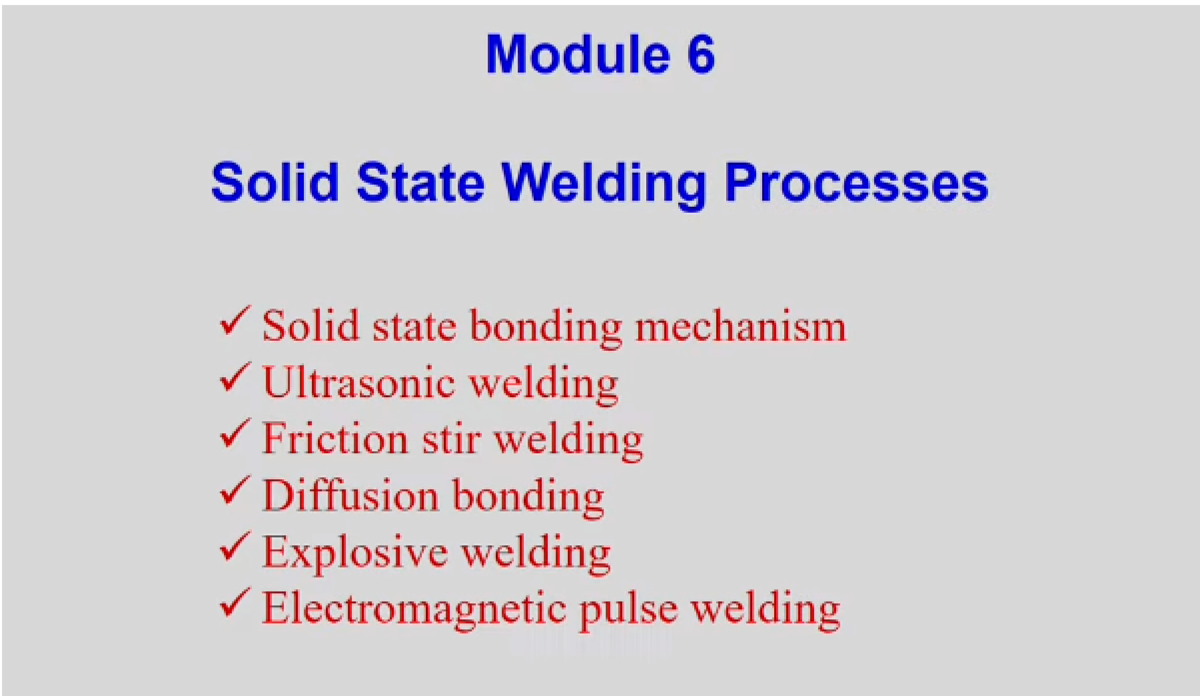

Hello everybody today I will discuss about the solid state welding process. So far we have discussed the fusion welding process advantage disadvantage and modelling up with specifically in terms of the temperature distribution. Now we will try to look into that different solid state welding processes the principle of that and how to model. Basically I will try to look into only one selective welding process.

For example, friction stir welding process here we will try to focus on that somehow to calculate the heat generation. So if we estimate the heat generation heat generation which is may be equivalent to the heat source model in fusion welding process. So once we estimate the heat generation model and keep the input to the heat conduction model with boundary conditions.

Then we will be able to solve the heat conduction equation and ultimately we will be able to find out what is the temperature distribution in specific welding process. But we here we will try to focus on the solid state bonding mechanism, ultrasonic welding process, friction stir welding process, diffusion bonding, explosive welding and finally the electromagnetic pulse welding.

But all we will discuss the basic principle of all these processes. But in general if we say that mathematical modelling of all these processes is ultimately leads to the formation of the heat generation and how the temperature distributes there that exclusively we will try to discuss on the temperature distribution for FSW process. But other processes we just only discussed the basic principle of these process.

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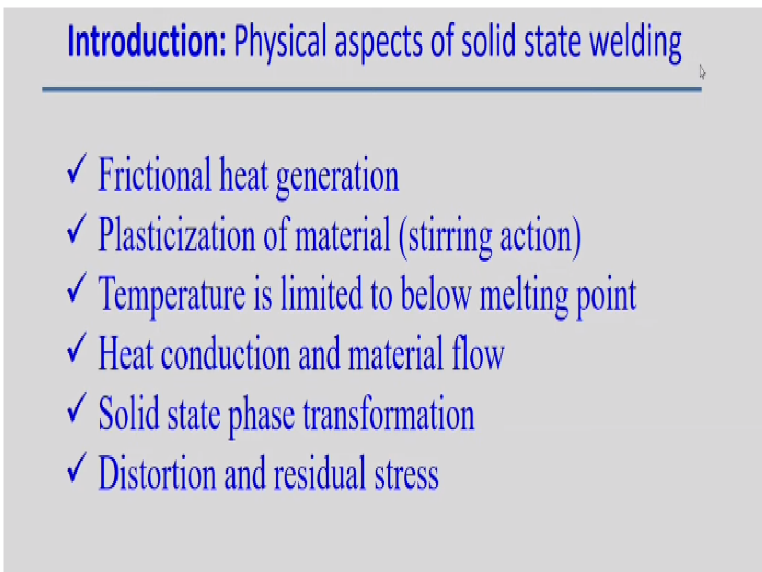

So solid-state bonding mechanism so these are the different aspects in the solid state welding processes we know that solid state welding process normally happens what generally happens the below the melting point temperature may be you can say that 70 to 80% of the melting point temperature particular material the maximum temperature can goes up to that point. Then frictional heat generation probably in this case is more involved here in the this solid state welding process.

Then plastic deformation plasticization of the material along with the plasticization there may be the stirring of the material such that it can make the violences with the two different components of the body. Temperature is limited below the melting point definitely heat conduction and material flow related to that of course in this cases the heat conduction.

We will normally follow the heat conduction equation. But if we look into that material flow in solid state welding process in that cases probably can assume the viscoelastic behaviour of the material and I could even estimate the strain rate of a particular domain so here rather than the fluid flow here the how to estimate the standard distribution and in a particular zone if we if you look into the fluid mechanics approach.

Then we can estimate this generate a particular node point in case of friction stir welding process and of course it is associated with the solid state phase transformation and finally destroys any residual stress also develop in case of solid state welding process. So let us look into that different types of the process.

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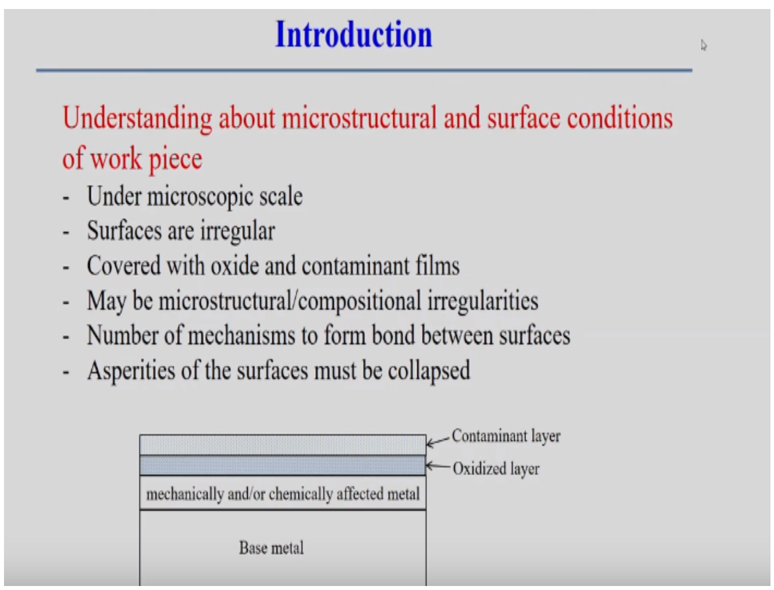

So in principle the solid state process normally look into that in ideal conditions there equivalences of the metal if they come in contact without any contaminated layer on the surface then by the application of the pressure or by the application of the force and if we keep with the added by the temperature then this can be join bonding can be done between these two components which is normally the principle of the diffusion bonding. But in actual metal surface if we look into that there may be some contaminated layer.

Then next may be oxide layer and some part will be the mechanically or chemically affected zone part and finally the base metal. So in which principle actually solid state welding process works. So if we see overall we look into that aspects two things are there one is the surface condition of the work piece and what is surface condition means that what is the surface roughness of a particular surface roughness.

If you look into the under the microscopic scale or second point is that whether it is possible to remove the all the layers that I have mentioned this three different layer contaminated oxide layer and mechanically effective chemically affected layer if it is possible to remove all the layer and then two base metals come in contact.

Then this this contact but that contact surface may be involved in the contact between the asperities of the between two surfaces and when they are not maybe continuous contact may be initial contact at the asperities and if it is possible to sharing the asperities with respect to each other than the bonding of the two solid-state components may happen. But in practical cases the metal surface is accompanied with the some kind of the contaminated layer.

So it use some kind of the heat source to just simply remove that layer so that two different components are come in contact without any oxides layer or contaminated layer then the joining can be done. So then some sort of energy application is required that energy application required because the metal base metal not in direct contact with the other metal. Because they are basically they are contact with the contaminated layer or oxide layer with respect to each other.

So that is why under the microscopic scores we just check surface and irregularities on the surface and then copper with oxygen contaminated layer we observe it may be micro structural and compositional irregulates may also happen there in the surfaces and number of mechanisms to form the bond between the surfaces. But asperities of the surfaces must be collapsed normally by the shearing action between this two components. Then it is possible to join in solid state welding process within two components.

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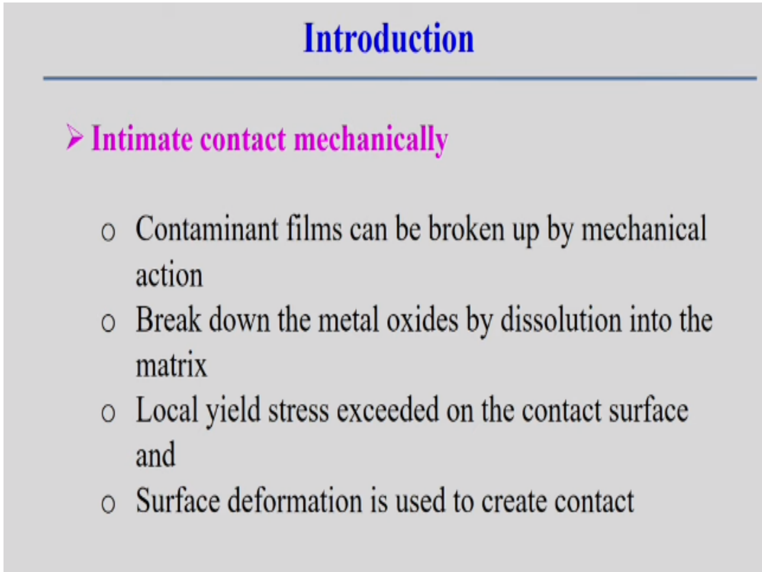

So intimate contact intimate mechanical contact is required there first the it breaks the contaminated films that can be broken up by the mechanical action and or then breakdown of the metallic oxides by dissolution into the matrix it may becomes part of the final matrix and of course local yield stress exists on the contact surface. Then only bonding mechanism may happen and surface deformation is basically used to make in contact between the two components.

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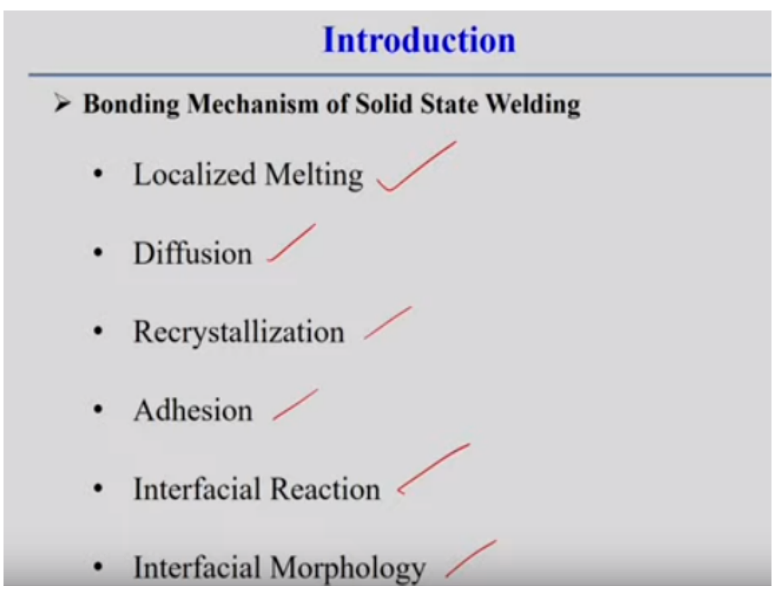

So these are the different bonding mechanism of solid state welding process we can hold on to and categorize in that way that first is the localized melting we say the localized melting it is a very small zone that it is possible that with the deformation heat generation will be there and then may very localized part there may be melting may happen but there may not be any bulk melting in that case.

Then diffusion may happen between the surface if diffusion happens between the two components and normally diffusion takes diffusion mechanism takes larger time to make diffuse with respect to and up to a certain depth of a particular material then recrystallization how actually mean by the grain boundary to migration between at the interface between the two contact surfaces.

Recrystallization mechanism may also responsible for bonding in solid state then addition means that joining violences between the two components but in these cases the surface the gap should be minimized I think maybe in the order of more than nanometre I mean contact the in addition mechanism is responsible to bonding between the components then interfacial reaction may also happen sometimes there at the interface reaction may happens and that becomes part of the both the components and solid-state bonding process may possible.

Finally, the interfacial morphology so certain specific morphology normally in case of explosive welding process we can find out the morphology is responsible to joining or bonding between the two components in the solid state process. So we will discuss and the basic principle of all these processes.

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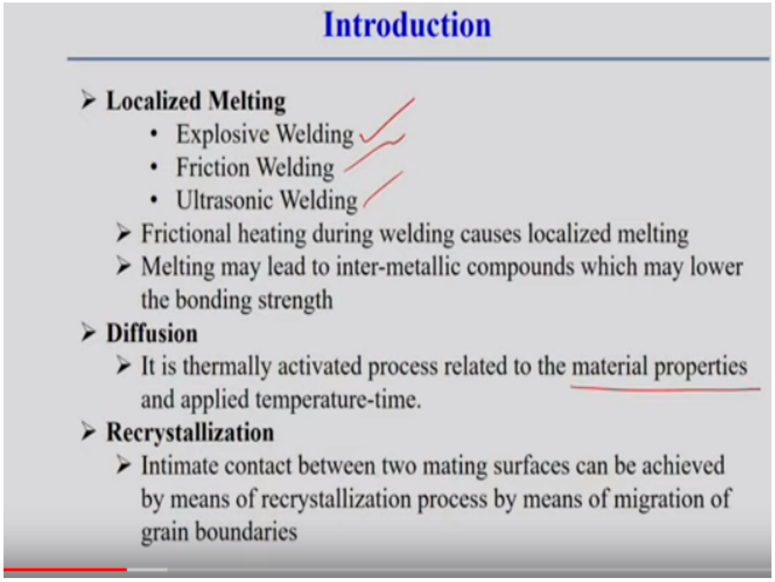

Or this mechanism is applicable what type of welding processes. First if you see the localized melting this explosive welding these are the one type of solution welding process friction welding and ultrasonic welding there may be the possibility of localized melting may happen it is a very small zone and because in this case fictional heat generation during welding process basically fictional heat generation during welding process.

That can cause the localized melting and of course this melting creates the one problem their formation of the inter metallic compounds which may be lower the bonding strength and that may be the but in this cases since in solid state welding process the melting involves specifically in case of dissimilar materials then they are try to form kind of inter metallic compounds.

Of course inter metallic compounds may also happen even if solid-state welding process is also but it is more serious problem in case of fusion welding process. Then diffusion is a normally thermally activated process but there is a need of some application of the force is required where this thermally activated process and it is the time dependent process and then when two metal are in contact it is a perfect contact between the two metals.

It is a very good surface finish then diffusion may happens between these two components of course it also related the depends on the material properties the feasibility of a particular metal to other material. So it is in that properties and accordingly integration welding process that it can decides that what is the thickness up to the diffusion may happen but normally will increase the thickness the diffusivity actually decreases but it requires very good surface preparation to successfully activate this mechanism in case of solid state bonding process.

The recrystallization it is a simply migration of the grain boundaries but the intimate contact between the two surfaces if it is possible as between the two surfaces then when they are gone this thing migration of the grain boundaries may create one the bonding between this to come between the two surfaces.

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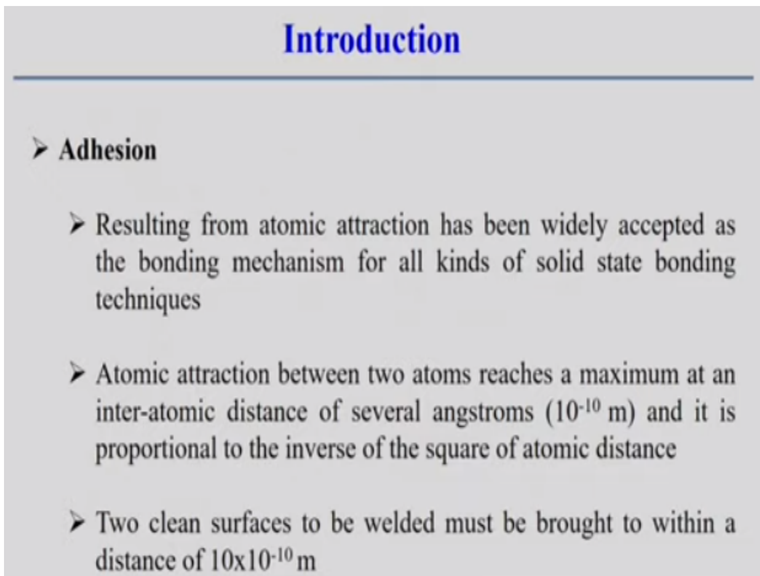

Apart from the addition in this case we see atomic attractions becomes widely accepted at bonding mechanism it is a mechanism is basically an atomic attraction but when practical it is possible to make the atomic attraction between the two at the interface basically. So at the interface it is possible to create the atomic attraction if the inter atomic distance between the several it maximum reaches a maximum at an interactive between the inter atomic distance.

It is around 10 to the power-10 meter keep in contact between this two interfaces if that kind of contact is possible with that distance then this addition mechanism is basically active joined to two different components. But of course we say it is a to specific treatment is required to clean the surfaces such that the distance can be as minimum as the order of 10 to the power-10 meter then only this addition mechanism actually works.

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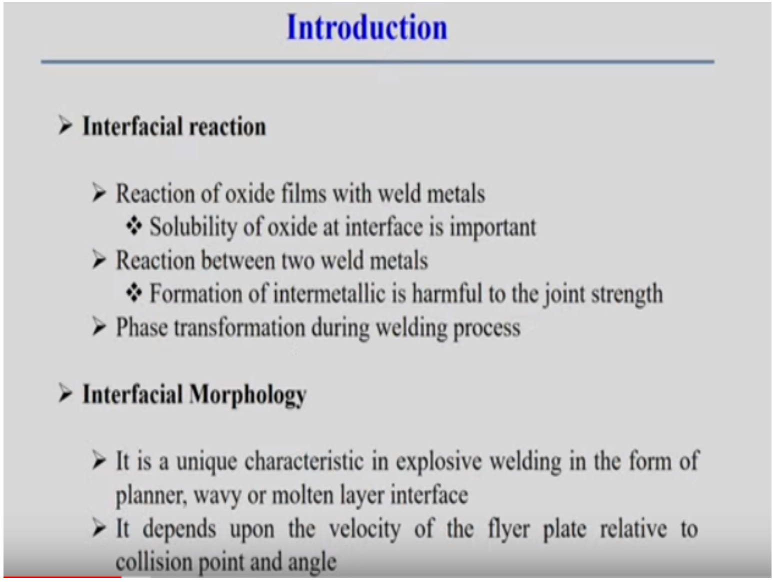

Then interfacial reaction you see that interfacial reaction, reaction of the oxide films with the weld metal may also happen and solubility the oxide at the interface they creates the joining between the two components and that is that is the important aspect we see the solubility of oxide at the interface is the main mechanism here. Reaction of course at the same time the reaction between the two metals may also happen.

So formation of the inter metallic is harmful for the joint strength but it is possible to join the dissimilar materials if there is a thin layer of the inter metallic at the interface and that creates the bonding between the two components and of course in this case the phase transformation during welding process may also happen one phase to another phase for example when there is functions of inter metalling then we can say that there is a transformation of the solid state transformation one phase to another phase.

So then interfacial reaction is sometimes responsible to joining the two different components which may also happen apart from that we can say the inter facial morphology also we observe it is a unique characteristic of the expressive welding process. So this here the wavy form of the layer may happen and that wavy form is responsible the interlocking between the two surfaces it is wavy or molten layer. But this molten layer may be limited here not like the fusion welding processes but it depends on the flyer plate velocity related to the coalition point and angle.

So we will discuss in details the explosive building process because inter facial morphology mechanism normally observed which is relevant to the explosive welding process.

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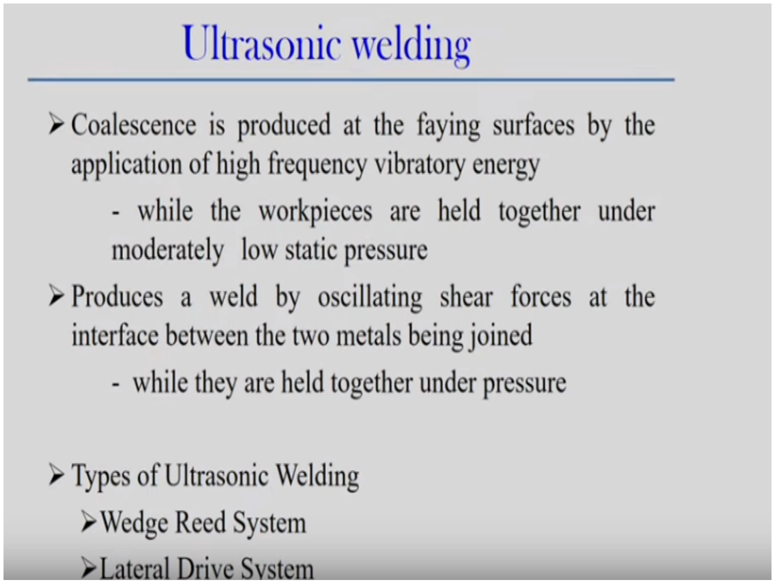

Now we will start with the basic mechanism of different or solid state welding processes. So we start with ultrasonic welding process so ultrasonic welding process if you look into the principle the Coalescence is produced at the faying surfaces. So at the faying surfaces the joining between the two components possible by the application of the high frequency vibratory energy.

So vibratory energy need to apply but in this cases when two work piece are in contact so at the interface if it is possible to create the vibratory energy high frequency then two metals can be joined. So at this there may be there is a with the according to the frequency their vibrationally there may be the shearing may happens at the interfaces and joining may happen it is a very localized area.

Probably ultrasonic welding process is more suitable if we want to join in a very small affected zone or the affected by this joining mechanism is very small in case specifically work piece. So normally ultrasonic welding is a one solid state welding process but most of the cases the ultrasonic system normally used as an assistant as in that can be used to assist with the other welding processes.

So for example in case of further development of the hybrid welding processes we can use the along with the primary welding process the secondary source can be used as a ultrasonic system. So that is why the main thing is the ultrasonic welding processes is that it applicable to when there is a need of joining it is a very small zone of it is necessary to particular small area we want to microstructure the changes we want to do probably in these cases the ultrasonic system is more suitable.

But in principle the oscillating shear stress normally happens at the interface between the two metals to be joined and then they are joined with application of the under pressure but that pressure is moderate pressure which may be comparable or less we can say as compared to the diffusion welding process. Now we see we look into that system one is the two different ultrasonic system normally observed that is Wedge Reed system and the Lateral Drive system.

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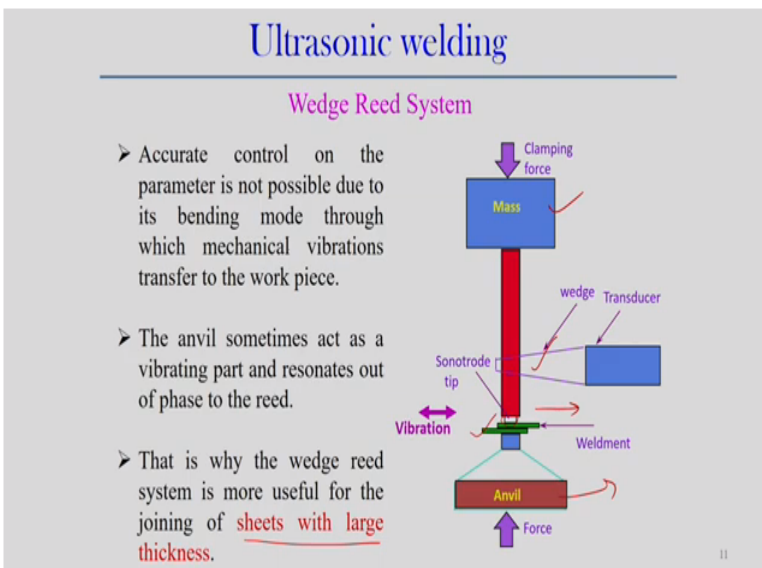

We can see the two different system here pass to the wedge reed system we see look into that mass clamping force up there and transducer are there. Transducer is basically tears the vibratory energy and then there is a sonotrode tip, tip sonotrode tip is basically nothing but the helps to transmit a vibratory energy to the workpiece. So the between the work piece this is the work piece between the work piece there is a shearing action happens between the two layers due to the application of the vibratory energy.

And that energy is transmitted mainly by the sonotrode tip. So design of the sonotrode tip is very important here that smoothly transferred the energy to the exactly at the interface between the two work pieces. So basic system is like that. Clamping system, mass is there and clamping force but it is a moderate force just to keep the moderate pressure on the work piece such that it have the flexibility to shearing between the two components according to the magnitude and direction of the vibration.

So here the amplitude may be given to this on the horizontal plane such that shearing may happen on these things but it is under very high frequency and at the interface all can be join and anvil is the simply support. But in these cases remember that pressure is not too high. Then look into this system here the accurate control on the parameter is very difficult to control due to it is bending mode through which mechanical vibrations transfer to the work piece.

That bending mode of this vibratory energy of the work piece is transmitted by the this voyage and of course these are the part of the system to where the mass is given it is a vertical pressure is given but lateral is transmits the energy in this way. But the anvil sometimes act as a vibrating part and resonance out the phase of the reed.

So sometimes if there is a resonance happens during this process so the resonance phase to reduce this resonance within sometimes anvil acts as a to phase out the resonance part during this process. But wedge reed system is more useful for the joining of the sheets of the large thickness. If thickness is large then this type of system is more suitable. Now let us look into the other system.

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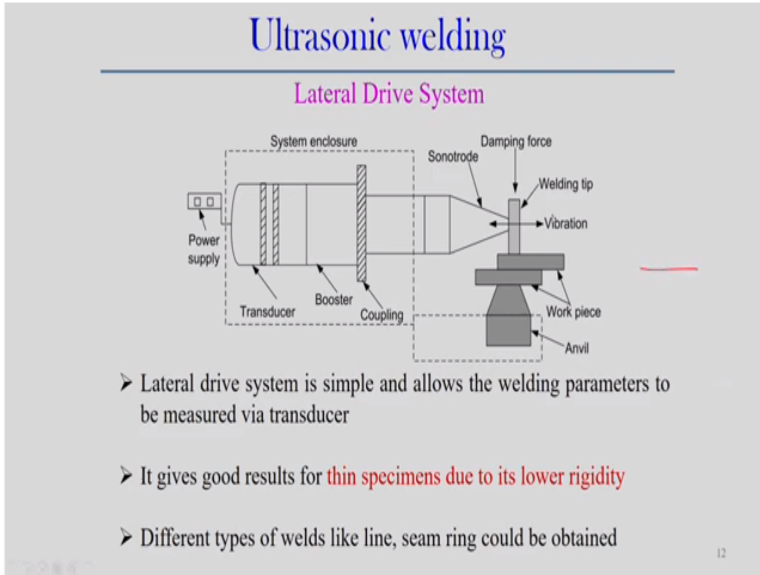

Here the lateral drive system you see that the system is other way is given the system transducer and coupling, the sonotrode is this side plate and damping force is given little here up from the per side and vibration on the horizontal plane. Vibration is given in this way and it is a welding tipped that it is a holding the geometry configuration is lateral drive system is different from the other system.

So in this case this system is actually more suitable if sheet thickness is very small because in the rigidity specimen due to this lower rigidity this kind of system is more suitable. So different types of weldings like seam weldings, ring could be obtained using this process.

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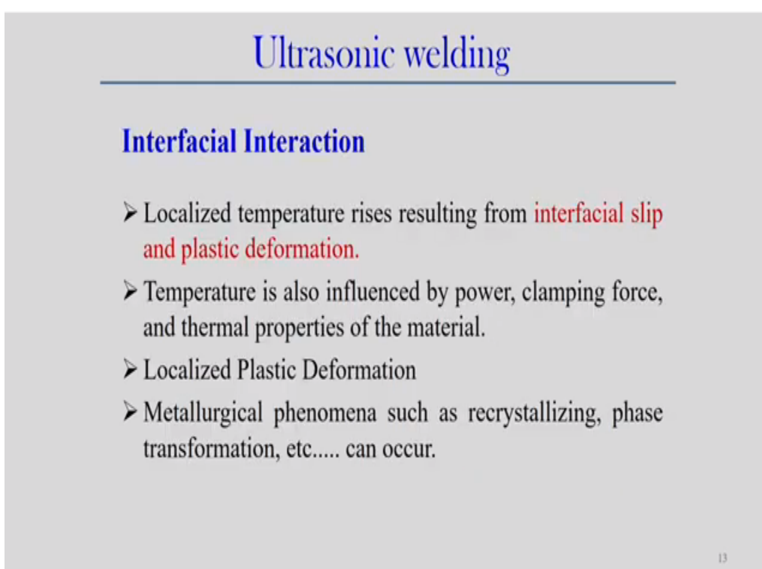

Now what interfacial reaction happens during the process are the actions normally we observe during this process. So localized temperature rise happening due to the resulting of the interfacial slip and the plastic deformation and there is a continuous vibration with a certain amplitude vibrating at the interface. So that creates some kind of the temperature rise due to the slip and plastic deformation mechanism.

But in this cases temperature rise is relatively less as compared to the other processes. So temperature also influence of course it depends on the other power given clamping force and thermal properties of the material. So definitely with the power according to the thermal properties of the material the temperature generated depends on that but it is influenced by the power and coupling force and optimum power and coupling forces is need to be determined to get a successful ultrasonic welded joint.

Localized plastic deformation may happen definitely at the interface localized plastic deformation may happen but other metallurgical phenomena since the plastic deformation so we can observe the recrystallization also happen. Phase transformation may also happen but that is in solid state crystal formation happen at the joint interface.

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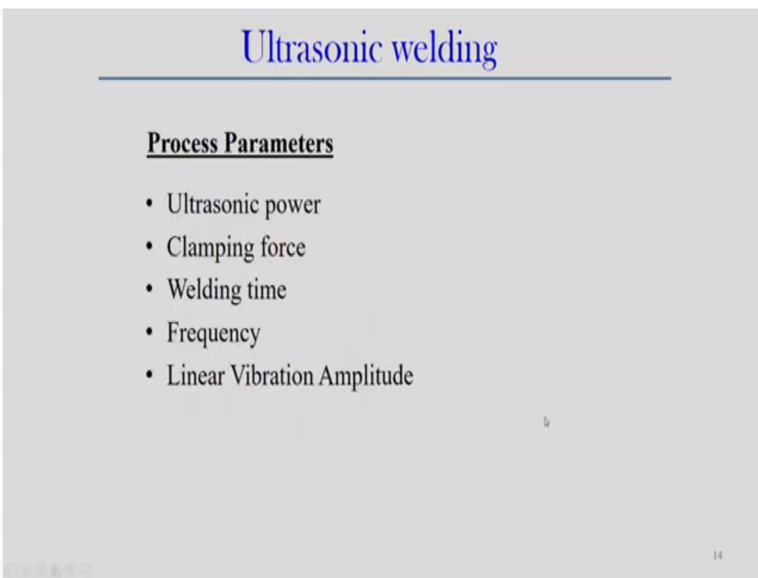

But of course in this case if we look into that process parameter there is a optimum process parameter is needed. So one is the ultrasonic power, clamping force, welding time, frequency and the amplitude of the vibration all are important parameters which govern the process. But main thing in this case is the most important thing is that we you see the transducer and then we create the vibration in certain part and then it is next important part how this vibratory energy actually transmits smoothly to the weld interface?

Which weld interface so which part we are supposed to join so that is the main important so that depends on the what are the pressure clamping force were using here. So that is why there needs to be optimized the clamping force so as that it actually smoothly transfers the energy to the at the interface.

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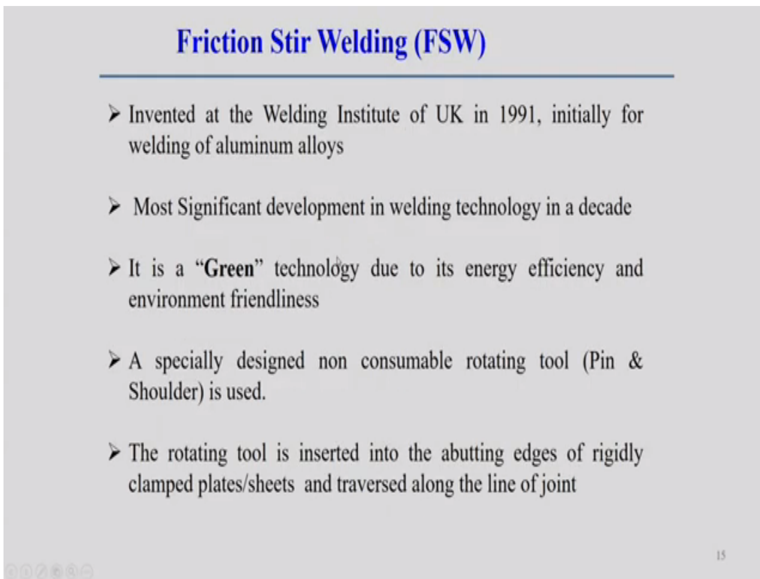

Now we come to that point friction stir welding process. So we know nowadays friction stir welding process has been widely used and you say well established welding process specifically for the software material for example aluminium, aluminium alloy, magnesium, magnesium alloy. But of course it is not very well established in case of high temperature high melting point material specifically for example steels or different graded of steels is not well established.

But of course with added or by hybridization of this conventional friction welding process it is possible to join or weld in the solid state even for the different kinds of the steels. Now we look into the basics of the FSW process. So it started with the aluminium alloy but nowadays it is expanding to other high melting point material as well as high strength alloy also and of course it is a called as a green technology.

Because we know that like fusion welding process here it is not involvement of any kind of fume generation during the process or that actually impacts on the environment that kind of things are actually absent in case of FSW process. If we see that we use FSW process we use some electrical energy it is a FSW process we can say that from the milling machines will be the conventional milling machines or we can convert that into the FSW welding machines.

But only need to attachment of the different force measurement system and picture according to you need to design then we can directly use the milling machine as a FSW process. But FSW is a called green technology because of energy efficiency that means energy efficiency is very high in that sense that we use the rotational tool maximum energy heat generation is transmitted to the work piece.

And of course it is a energy efficiency in that sense as compared to the fusion welding process because creation of the arc transmitting of the energy actually energy supplied and what is the amount of the energy to the workpiece. There is a loss of heat energy by radiation in case of fusion welding process specifically arc welding process. So in that respect maximum amount of the energy is transmitted to the workpiece for the heat generation and during the process.

So that is why energy efficiency at the same time it is a environment friendliness. Because of that it is called the green technology. So in principle we use a non-consumable rotating tool rotating tool but tool must have two parts one is the pin another is the shoulder. So that along with the pin and shoulder it is a complete tool but this can be made of the different types the material. So in terms of rotating tool inserted.

But we need to maintain the rigidity of this particular tool and hardness of the tools should be more than that of the material which are supposed to join. For example if we want to join aluminium or aluminium alloy it is sufficient enough to use the tool material as a stainless steel.

So both material is easily available and because there is a huge difference in the hardness between the stainless steel and aluminium.

So that is why like that different type of material combination what type of metal are you want to join accordingly we can select the properties of the tool material and or in effect what is the tool material we should choose.

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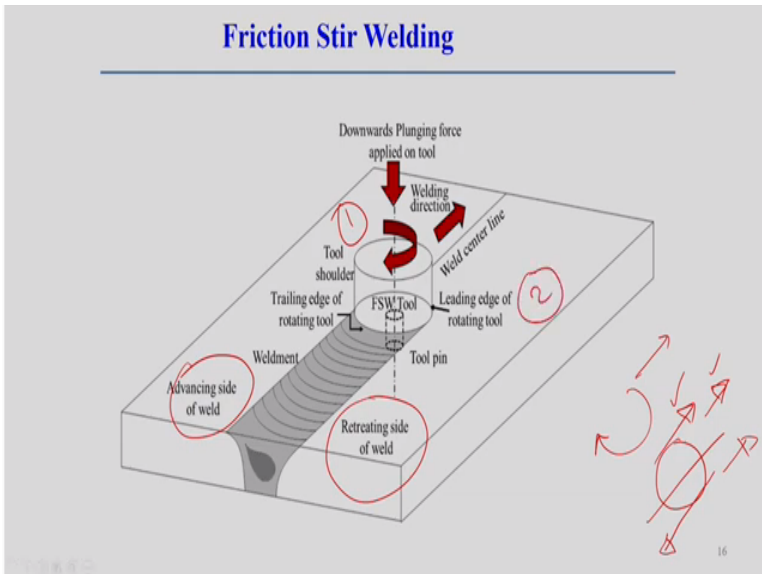

So the FSW process how it works see there is a rotating tool continues rotating tool and suppose we want to join the two plate in **bart** joint configuration so we keep on as close fitting between the two plates and at the interface we insert the tool pin but through rotation and then due to the rotation of the tool it will generate the heat and at the same time when it generate the heat it plasticize the material and then coalition from one material point of view one from one material come to the one side to another side.

So that is why it is mixing of the material but plasticizing the material and weld below the melting point temperature. So in that way it creates the coalitions of between two workpiece components. Now what are the different terminologies associated in FSW process. First if you see that from figure that this is rotation one rotational speed of the tool at the same time is transverse speed along a particular direction what way we define the we say that other way in fusion welding.

Normally we say there is a welding velocity. So particular direction rotational speed as we will as the linear velocity in a particular direction. Now if you see the rotational speed in one direction and linear speed in directions. So with suppose this is the interface so due to the rotational speed this is the direction of the rotational speed in one side, this is the direction of the original speed in other side.

Now at the same time tool also moves with a linear velocity. So if this linear velocity at any point and the welding velocity both are in the same direction then that side we say that advancing side of the weld okay. And in this cases the welding speed and the rotational speed if we convert into linear speed but in different direction so that is called the retreating side of the weld.

And here see that it creates the mixing of the on the top surface and basically the material is in contact with the tool shoulder surface as well as the tool pin surface and both are responsible for the generation of the heat but the maximum amount of the heat generation normally happens when the shoulder is in contact with the work piece material. So this is with one work piece part and two.

So similar kind of materials can be joined or dissimilar materials can be joined between this using this FSW process.

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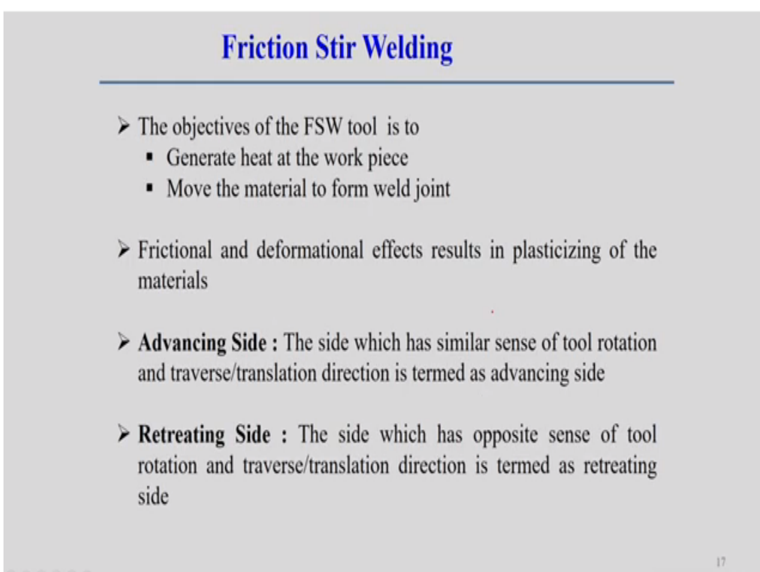

Now if we look into the tool aspects, so what is the role of the tool FSW tool. First role is the generate heat at the work piece such that it helps to makes soften the material and makes easy to plasticization of the material. So heat generation is one part and second role of the FSW tool also movement of the material. So it since is rotates the particular direction so metal moves from one point to the another other point.

So one side of the metal to other side of the metal it moves because of the rotational movement of the tool. So mixing of the material as well as the heat generation both are the roles of the FSW tool. So frictional but if we look into the heat generation mechanism here one is the frictional heat generation also there friction is also responsible there for the generation of the heat.

But at the same time deformation effects also plastic deformation of the material that actually account for the some amount of the heat generation. But in these cases in FSW process the heat generation due to the deformation plastic deformation of the material accounts very small part as compared to the frictional heat generation.

Now advancing sides we already defined that similar sense of the tool rotation and the tool transfers or welding speed direction is same that is called advancing side. Retreating side opposite sense of the tool rotation and translation direction then that is called the retreating sides.

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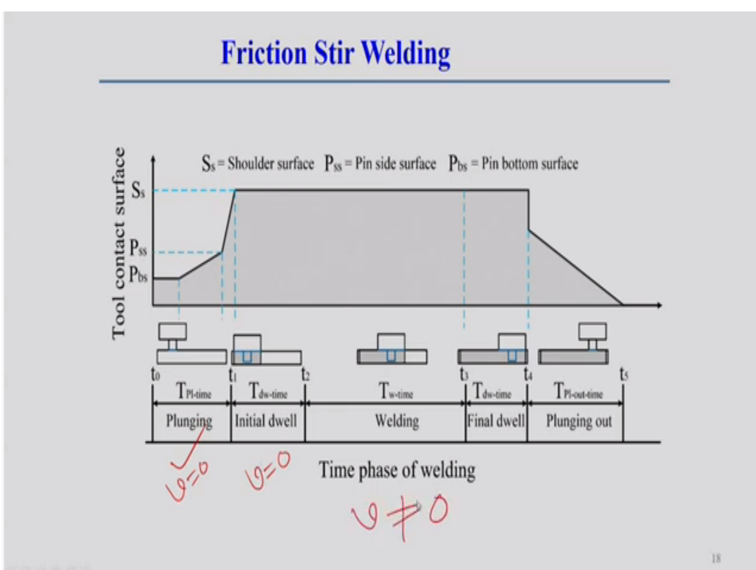

Now what are the different phases of the friction stir welding process. How it happens so these phases with respect to time. So first we start with that plunging phase so you say that plunging phase so at plunging phase making tool pin is merely the keep in contact make contact with the work piece but without any movement of the tool in transverse direction that means weld velocity equal to 0 at the plunging stage.

It starts from the top surface starts with and gradually moves in the downward directions such that tool pin in contact with the work piece. Then initial well once plunging done that means total immersion of the tool pin is over and then work piece is in contact with the tool shoulder material tool shoulder. Then we keep in contact some allow some dwell period without movement of the tool in the transverse direction.

Even here also welding velocity we can say the transverse direction equal to 0, here also welding velocity 0. But keep rotating the tool at this point. Rotational speed is always there both the cases. So once dwelling initial dwell phase is over then we start the actual welding period. Then we start moving not equal to 0 velocity we give certain velocity and there is welding period overs then once done that means at the interface total length of the interface is covered then after that give the final dwell.

Final dwell means it is just plunging out of the tool outside from the work piece sorry final dwell means we just keep on holding the tool at the same position with velocity equal to 0 but with the rotational speed and once it is done. Then we just plunge out of the tool from that position we just keep on downward direction we just move the tool from the work piece that is a plunge out phase.

So it is a repetition that so we can see that mainly three phase plunging phase, dwelling phase and welding phase in case of FSW process.

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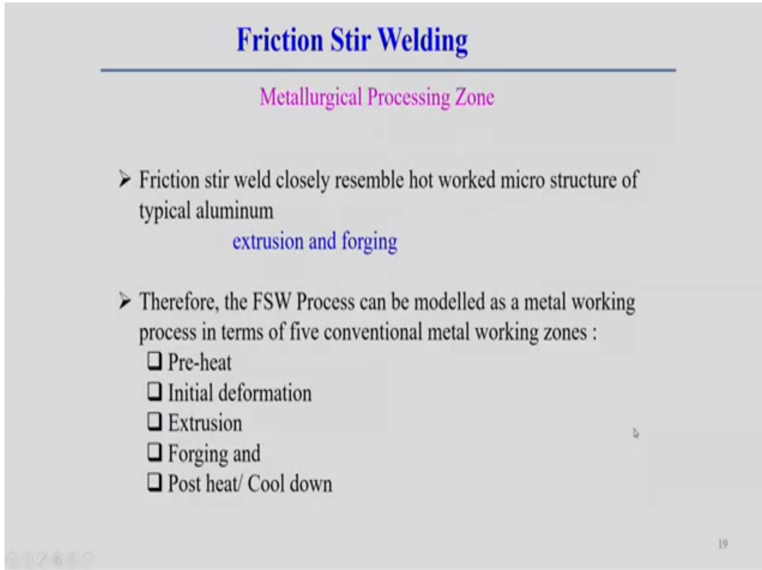

Now apart from that if we look into the metallurgical processing zone we can divide the FSW process and the different parts that micro structure of the typical aluminum we sense look into that actually the FSW process to some extent kind of metal deformation process but it is some part is follow is the resembles to the extrusion and forging process we will see that processes. But there are the five conventional metal working process involves during this FSW process.

One is the pre-heat part we can divide different zone of this initial deformation zone, extrusion zone, forging zone and post heat treatment or cool down zone we can see in this process.

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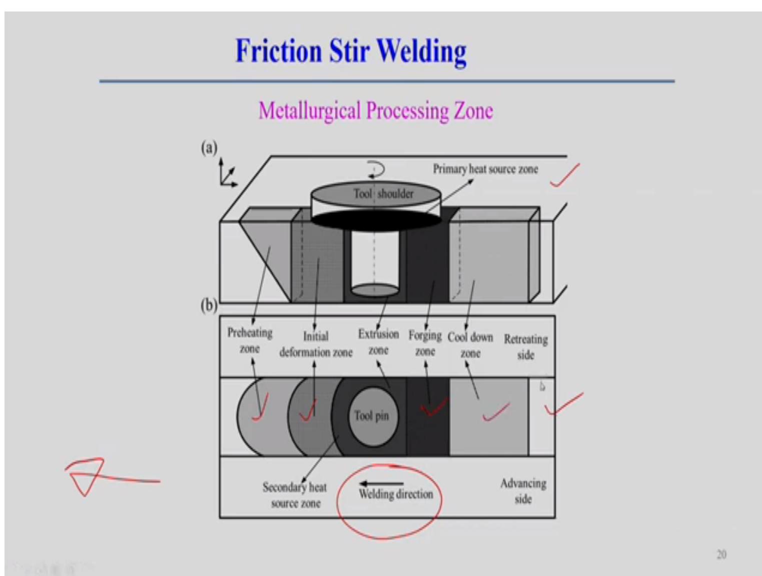

So if we look into this figure and suppose the weld this is the welding direction it moves along this direction suppose tool is move along this direction transfers movement along this direction then what happened. At the near about the tool zone if it is this one is the if we see this is the side view and if we see from the top view also then near about the tool the some part it is say extrusion zone which is very much attachment with the near about the tool pin that is called extrusion zone.

And beforehand the this part is called the initial deformation zone and before that zone is the primary heating zone but apart from backside it is a forging zone and we can say that is a cool down zone. So this is the different types of the zone actually creates during the process and these are the called metallurgical processing zone in FSW process. But how we explain all these things.

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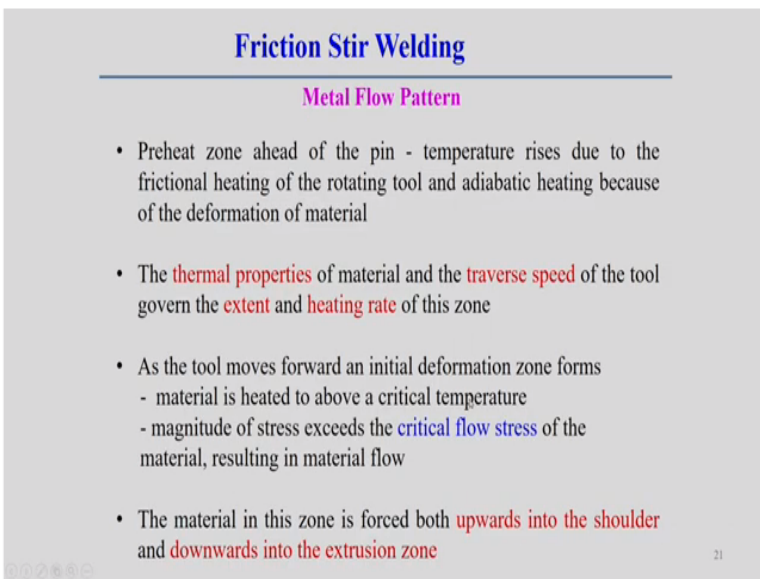

Preheat zone ahead of the tool pin if we see that preheat zone ahead of the exactly ahead of the tool pin is the preheat zone. So in this case what we can define the preheat zone, temperature rises due to the frictional heating definitely frictional heating is always there up there due to the rotational tool and of course at the spot adiabatic heat occurs because of the deformation of the material.

So that preheat zone there is a temperature rises because of the frictional heating and that actually follow kind of adiabatic heating process that means there may not be at this part temperature gradient actually 0 at this part so because of the deformation of the material. So that heat generation is mainly deformation of the material. Then thermal properties of the material and transverse definitely depends upon the thermal mainly the thermal conductivity of the material.

And the transverse speed means welding speed of the tool governs the extent and the heating rate of this zone. So it depends that zone is decided by the mainly the material properties. So due to heat conduct heat conductivity of the particular material and what is the transverse speed of the welding. These are the main governing parameter who decides the preheat zone ahead of the tool pin.

But once tools moves forward and initial deformation zone forms. So at the initial deformation zone before we can see that this is the preheat zone and next zone is the initial deformation zone. So initial deformation zone what happens? at the initial deformation zone material is actually heated above some certain critical temperature and of course the magnitude of the stress basically in that part exists the critical flow stress value of the material and resulting in the material flow.

So that initial deformation zone the deformation happens in this cases once it is exists the pro stress value of a particular material but when it exists the flow stress value the academic flow stress will reduce as a function of temperature. So that decided by this critical time such that it should exist the flow stress value and then initial deformation starts at this part. The material in this zone force upward into the shoulder and downwards into the extrusion zone.

So in this zone the material is try to keep upward but that movement of the metal is restricted by the shoulder and downward for the extrusion zone.

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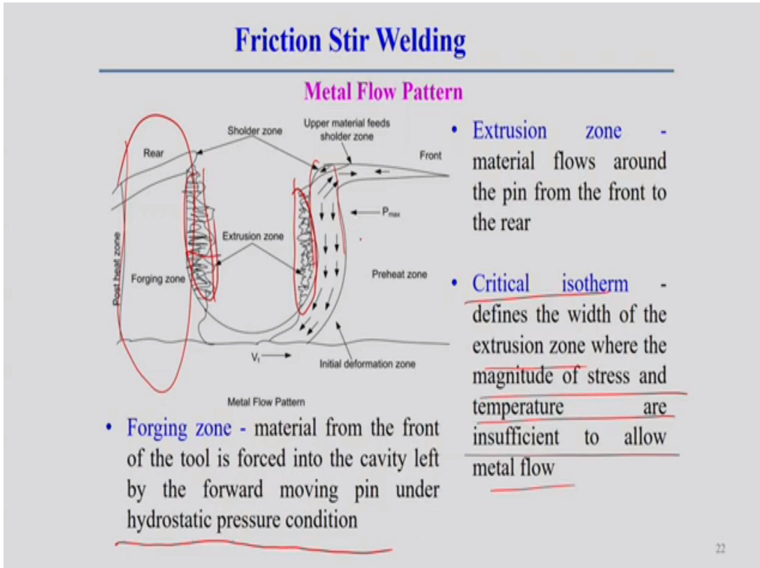

Here will be more clear that extrusion zone we see that near about the tool there is a small part is a extrusion zone what happens in the extrusion zone, materials flow around the pin there is a flow of the material. Normally viscoplastic flow of the material normally happens around the pin mean about the very small zone tool pin that is the extrusion zone. But that extrusion zone is decided by the critical isotherm is important here.

Because temperature generation also there that all this zone is better described by the different step of the isotherm. Critical isotherm so it defines the width of the extrusion zone, the magnitude of the stress and temperature are insufficient to allow the material flow. So it extend up to what extent the deformation will happens such that temperature and material magnitude of the it decided by the temperature and magnitude of the stress up to insufficient of the up to that actually flow of the extrusion zone is normally happens up to certain extent.

And that extent can be defined by the temperature condition isotherm and corresponding flow stress value which when it is find that insufficient to material flow that stop there up to that extent the extrusion zone can be defined. Then forcing zone also we can see the material flow from the front of the tool force into the cavity left by the forward moving pin under the hydrostatic pressure condition.

So some part it is a material is allowed to flow from one part to another part and then certain part will be leaks that it is a sorry ahead of this these will getting the forging zone and that zone is in the forging zone normally the it happens the hydrostatic pressure condition prevails in that part. So that is characterized by the forging zone and if you see the initial deformation zone which is the initial deformation the material is try to flow from upper side which is restricted by the shoulder and some part either it can go to the downward side.

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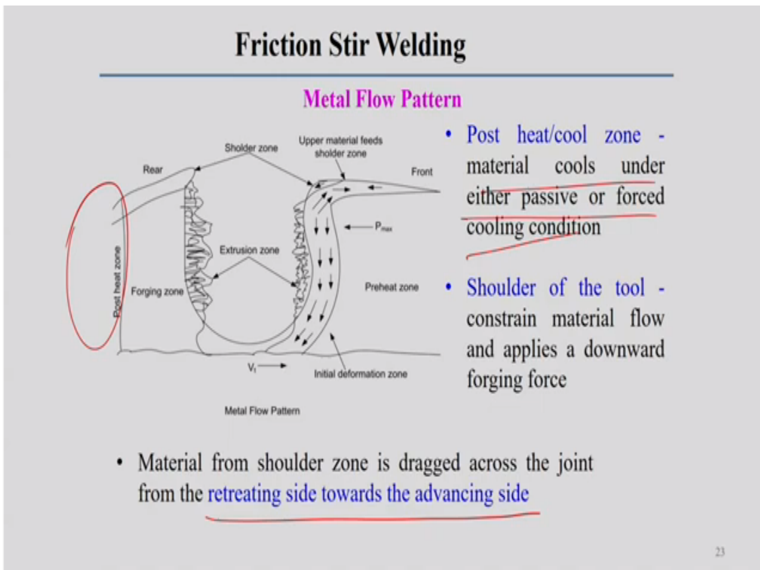

So here post cool zone or post heat or cooling down zone is basically the application of the passive or forced cooling condition that creates the kind of the heat forced heat zone or post cooling zone at this part and of course the role of the shoulder is to make the material flow and keep in the downward force and of course to constrain brings the constrain in the material flow. Such that metal flow may not give upwards okay.

And material from the shoulder zone is dragged across the joint and retreating sides to advancing side. So metal is try to flow from one side to retreating side to advancing side if there is a flow of the material. So that case it is defined as the material flow pattern depending upon the type of the tool. So this all are the mechanism.

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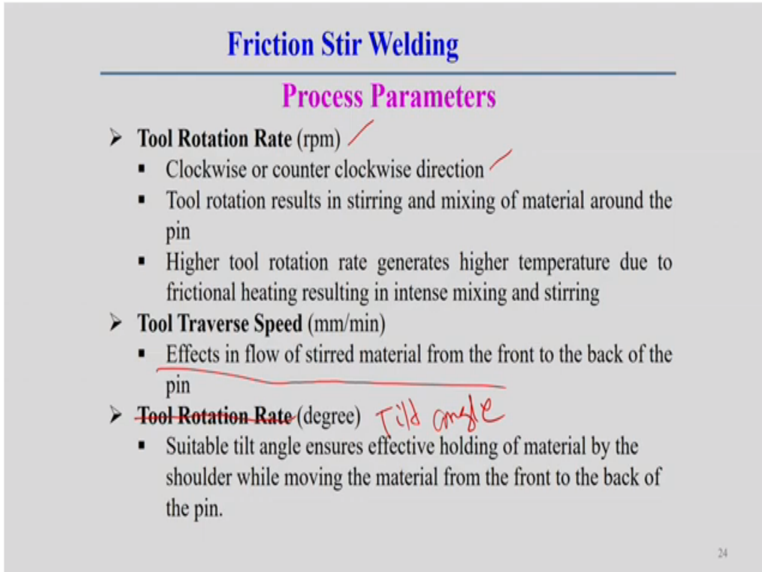

But process parameter near FSW process if we look into first is the tool rotation rpm, tool rotational rate and then it can be clockwise or anti-clockwise direction and this tool rotation is basically frictional heat generation and stirring of the mixing material and high if rotational speed is very high definitely high heat generation will be more, rise of the temperature will be more and that promotes the mixing of the material.

So the tool travel speed is the effects it is linear transfer speed or that speed actually influence the flow of the state material from front to the back. If the tool transverse speed is too high then it creates the insufficient flow of the material that means insufficient mixing may create or it can creates that actually promotes the formation of the defects. So moderately low tool transverse speed in this case.

Then tool rotation rate so I think this is not tool rotational rate it should be tilt angle. The tilt angle is basically we use some not exactly necessary to keep the straight the cylindrical tool sometimes we bring some kind of the tilt angle to ensure effectively holding the material by the shoulder. Shoulder can hold the material and of course some angular form is given to that shoulder.

That means shoulder surface may not flat always so intentionally it can be this kind of profile can also be given such that it can retain the material moving material from the front to the back of the pin.

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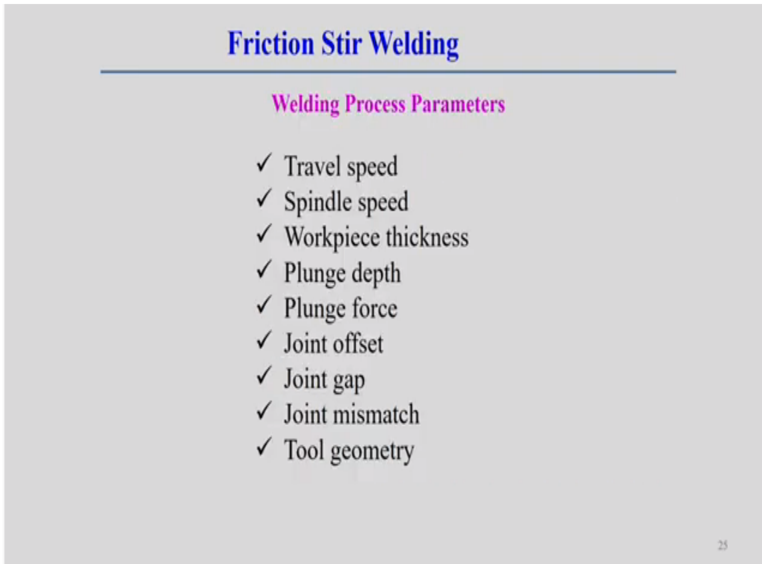

Apart from the welding parameters in FSW process at the travel speed, spindle speed, workpiece thickness, plunge depth. So plunge depth should be decided in such way that shoulder surface will be in contact with the workpiece at the same time pin should not touch the workpiece from the bottom side. So accordingly we can give the plunge depth and plunge force also is important the vertical force is given.

And given to the tool then joint offset that means we are exactly passing the centre of the tool through the interface of the two components or we can given some offset. This offset is helped in some other way also. Gap of the joint we cannot keep much gap between these two contact surface between the two workpiece surface in plunge joint configuration. Of course joint mismatch may be thickness of the material two different thickness of the material can also be joint in using these pins.

But it is more suitable if joint thickness that means thickness of the workpiece material both are same. Then of course it also tool geometry is another parameter or the tool geometry can be of different cylindrical type of so depending upon the type of material and of course if there is a threaded it actually enhance the mixing of the plastic mixing of the material.

So depending upon the process conditions and then a design of the tool geometry all actually influence the weld joint morphology as well as the weld joint strength in friction stir welding process. So when we look into friction stir welding process we need look into all these parameters and proper selection of the parameters to get a successful weld joint.

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In general if we see the advantages and disadvantages of FSW processes, that first FSW process we can see that solid state welding process fine micro structure is possible because with the normally the recrystallization happens it may be most of the cases and you can find out the dynamic acceleration or geometric dynamic crystallization may also happen in this during this process.

So finally it creates in the earliest structure with the fine micro structure fine grain size it is creates. Excellent properties in the joint area, low distortion normally low distortion in the work piece it is very much compatible with respect to the fusion welding processes, dimensional stability and repeatability is possible using this process, no loss of alloying elements because like laser welding there may be some loss of the alloying elements.

Because the temperature becomes very high even above the evaporation temperature. So in this case it is melting since it happens all below the melting point temperature. So there is a alloying elements loss of the alloying elements may not be there. So it is absence of cracking normally since this mixing of in solid states happens so dilution of the materials is minimum in this cases. So whatever transformation everything happens in solid state that is why the chances of the cracking is very less in this cases as compared to the fusion welding processes.

And of course no shielding gas is required, no surface cleaning is required, no grinding waste it produced and no solvent for degreasing is not required, no consumable we do not necessary to use any kind of the consumable like filler metal until or unless very specific cases. So filler material cannot be not necessary to be used in this cases like in arc welding processes. So all this kind of advantage we normally observe in case of FSW process.

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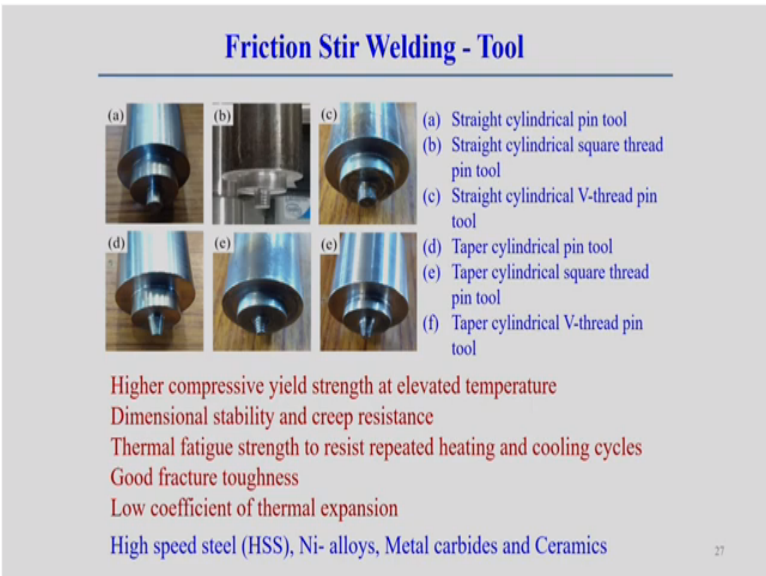

Now FSW tool if we see that different types of the tool here we can see from the figure the straight cylindrical tool we can find out that state cylindrical square threaded tool pin also straight cylindrical V-threaded tool pin and of course taper, taper cylindrical square threaded pin, taper cylindrical V-threaded pin tool.

All different set type of tools can be generated and all individual this geometry having some individual influence of the heat generation or plasticization of the metal during the FSW process.

But in general if we look into the perspective of the tool that tool should have this kind of properties that it should be high compressive yield strength even at very high temperature elevated temperature. It can retain its dimensional stability also and could have very good creep resistant properties.

Then should be if we look into the thermal fatigue strength able to resist because repeated heating and cooling cycle is to be associated with different heating and cooling cycle and of course there is a asymmetric heat generation on the both advancing side and the retreating side may also happen.

So temperature distribution may not be symmetric in this cases. So that is what thermal fluctuation may be there so because of that it should have good thermal fatigue strength properties and fracture toughness properties should be good enough so it can absorb even for the dynamic load condition it can absorb that kind of loading and such that because of that it is having should have good toughness properties.

And then finally the low coefficients of the thermal expansion. So that creates the dimensional accuracy of the weld joint. So this material what it should be such that coefficients of that. Basic so looking into all these basic properties we can choose the different types of the tool material which is suitable for the FSW process. So common materials are the high speed steel, nickel alloy, metal carbides and ceramics is the very.

But all these case it is the very costly material as a tool material. For example if we look simple aluminum welding process we can use simple stainless steel, stainless steel as a tool material we can use it but of course the tool material all this is FSW process all relevant to the life of the tool that is another concern. Most of the cases we found the tool where is the major concern in FSW process.

So that means tool life is a one of the limitation of FSW process of this solid state welding process.

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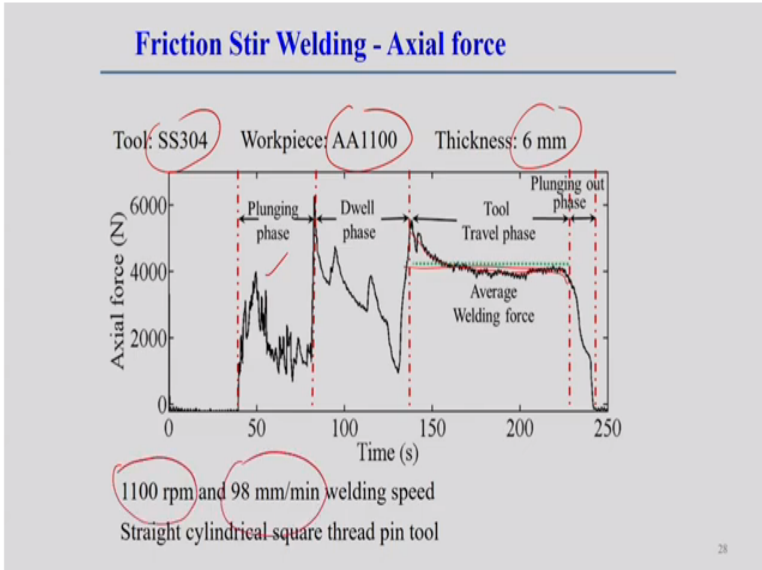

Here we can see that we can measure also the vertical tool axial forces during the welding process if we see that plunging phase the welding process is very relatively low and there is a variation of the low. Because in this phases tool pin is just simply inserting to the workpiece material.

Then dwell phase the welding force is moderate and if we see there is a variation of the dwell phase because purpose of the dwell phase is that keeping the rotational speed such that before start of the welding process the heat generation could be stable at this point. Then axial welding process this is a variation of the tool force but average force is along that we can say that 4000 newton or 4 kilo newton for a particular for the workpiece material is this.

Tool material is SS304 and thickness is 6 millimetre plate thickness. These are the typical amount of the axial force we can use during this process. And speed we can get some idea that rpm we have used 1100 and the linear welding speed 98 millimetre per minute and in this case straight cylindrical square threaded pin profile has been used to get to for this welding process.

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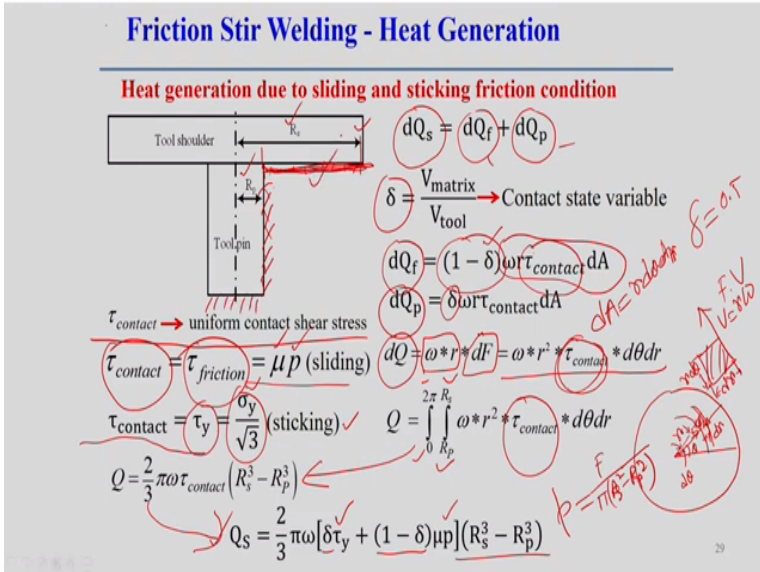

Now we look into that what is the that heat generation how we can estimate the heat generation in FSW process. So we understand that if we look into the this is the tool shoulder that shoulder surface in contact with the work piece and pin also are in contact with the work piece. So first we will try to find out what is the heat generation at this interface between the work piece and the tool shoulder, tool shoulder and the workpiece.

Now the dimensions also given, shoulder radius is given Rs and the tool pin is also given Rp. These are the two radius. Now this heat generation can be estimated by assuming the sliding and sticking conditions of frictional heat. So if we assume the frictional heat generation by this by assuming the sliding and sticking condition then at an element if we consider a particular element here.

See for example this is the centre point and on the workpiece surface we can use at an angle theta we can use at a distance radial distance r and suppose this element radial distance is delta r dr and of course this corresponds to 1d theta angle the elemental angle is d theta. So here if we look into this elemental area what is the heat generation and if we integrate over this particular in this domain then we can find out this total heat we can estimate the heat generation.

So we assume that this elemental area the elemental heat total heat and the shoulder and the between workpiece and the shoulder at that interaction at that area interactive area. So here it is consists of the 2 part one is the we can due to the sliding friction another is the sticking friction this dQf maybe we can assume that heat generation due to the sliding friction and dQp we assume that heat generation due to the sticking friction.

So it is consist of a two elemental heat generation so this part and this one. But in proportionate way we can it is very difficult to up to what extent the sticking condition exist and then sliding condition exist it is very difficult to define. So to separate out what is the sticking condition and sliding conditions at the interface we can introduce the one is the that is called the contact state variable.

Delta is say ratio of the V matrix/V tool that means linear velocity at this particular point what is the linear velocity at a particular point? the tool if tool velocity and a matrix velocity. So tool and that tool is interacting with the material so then velocity of the tool as well as the material is same, then delta=1. Then we can say the material is moving along with the tool velocity along with the tool with tool velocity.

So in that cases we can say that completely sticking conditions exists. But if delta=0 that means matrix velocity=0 only tool velocity is there. So in that case delta=0 for example so in that case we can say tool is moving in certain velocity but matrix is not moving. So in that cases we can say there is a pure sliding condition exists. So that means we assume by varying the delta for example if you say the delta=0.5 that means there is a 50% sliding condition and there is a 50% sticking condition exist like that.

If delta=0 we can say the completely sliding condition exist, if delta=1 we can say completely sticking condition exists. So like that by varying the introducing this delta parameter we can differentiate what is the sticking role of part of the sticking and part of the sliding conditions exist. So let us look into first that what is and how can estimate the elemental heat at this particular area contact at this contact surface.

Frictional heat generation we can estimate we assume first we introduce that 1-delta say for example 1 delta is basically that part is the basically indicates the part of the sliding conditions exists there and such that we can if it is 1-delta and other cases we can introduce only delta. So to estimate the other part of the heat generation will give. But that we just proportionately we can divide this part.

Now what is the heat generation, heat generation how we can estimate the heat generation. Of course here normally we assume there is a heat generation with the sliding happenings between these two surfaces. So then what is the force the energy heat energy generation at this part equal to that I think pressure say contact pressure for example tau contact is the stress basically at this part and that we can say that more or less it is a shear stress.

So that shear stress into that elemental area dA that shear stress into elemental area stress into this elemental area that represent the force and the force into velocity, velocity=radial distance into omega, omega is the rotational speed. So that indicates the total FxV the amount of the energy is generated at this part. And of course here we contacting the energy generation per unit time here.

So if we estimate this, this is the elemental heat energy per unit time generation at the contact surface. But tau contact we have to decides this value and here you can see that very clearly the dQ omega x r it is a linear velocity and dF it is the elemental force which is corresponds to the dF is basically dA and dA into the stress. So dA here we can say the rd theta x dr. This is the elemental area what we mentioned this thing.

So this part is equal to dr and this part equal to we can say r d theta. So in this case we can estimate rd theta and dr then we can estimate dA. So then one multiply this we are getting this condition along with we say this is a shear stress conditions at this contact, contact stress basically we can say that. Then we can estimate Q directly by d theta 0 to 2pi so it is vary from 0 to 2 pi and but dr radial distance it is starts from the Rp this part to this part.

Rp to Rs so here we put the Rp to Rs and 0 to 2pi that limit of the integrant and we can find out put this and we can estimate this part. Once we estimate this we perform the integration along with these things then we can find out this expression. But before that how to put this contact stress conditions here. So accordingly the sliding and sticking conditions friction condition we can modify this contact.

For example uniform shear stress contact shear stress tau contact is defined like that. Now if we assume there is a existence of the sliding friction conditions then tau contact can be is the tau friction (57:07) law of friction if you follow. Then it is corresponds to the mu x p, p is the applied pressure here. So p is the normal pressure basically on the surface we estimate the frictional force we count that what is the normal force acting on the surface based on that we can estimate.

So coefficient of the friction instead of normal force we use the normal pressure here. So that satisfy the sliding condition. Similarly when there is a sticking conditions so when there is a sticking condition means it is flow with these things so metal is basically shear deform. So that deformation condition we can that shear yield strength. Shear yield strength is corresponds to the normally strength divided by root 3.

So that is equal to the shear yield strength or directly we can write the shear yield strength there in this formula. So that the tau contact equal to tau shear yield strength because the material is actually flowing with the tool material. So that is in that cases we can use this kind of condition. Now if you combine the role or from sliding and roll from the sticking conditions.

Then we can find out that the expression after integration we can get this expression and from here by accumulating accounting both the sticking and the sliding condition we can find out these are the expression. So delta tau y is the shear yield strength value and 1-delta we can use but it is correspond to the pressure and then if we integrate Rs cube-Rp cube. But pressure can be estimated from the axial force divided by the cross sectional area.

Cross sectional area I think pi x Rs square-Rp square that is why we can estimate what is the cross sectional area in this case and if we know the axial force then we can estimate what is the pressure and if we put all this value and we can estimate what is the frictional heat generation assuming the sliding and sticking friction condition exist in this cases. So this estimation of the heat generation is corresponds to the at this surfaces.

So between the that which surface in contact with the shoulder. Similarly, we can account the similar kind of exercise in case of the interaction of the tool pin surface at the same time bottom surface also. But maximum heat generation accounts at the shoulder surface. Here heat generation is pin surface is little bit less even more less in case of at the bottom surfaces. But this calculation only shows that at the tool between at the shoulder surface what is the heat generation we can estimate.