**Advances in Welding and Joining Technologies**
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**Lecture - 09**
**Solid State Welding Process Part II**

Good morning everybody. Today I will discuss the one of the most significant Welding Process specifically the category of the solid state welding process that is friction state welding process.

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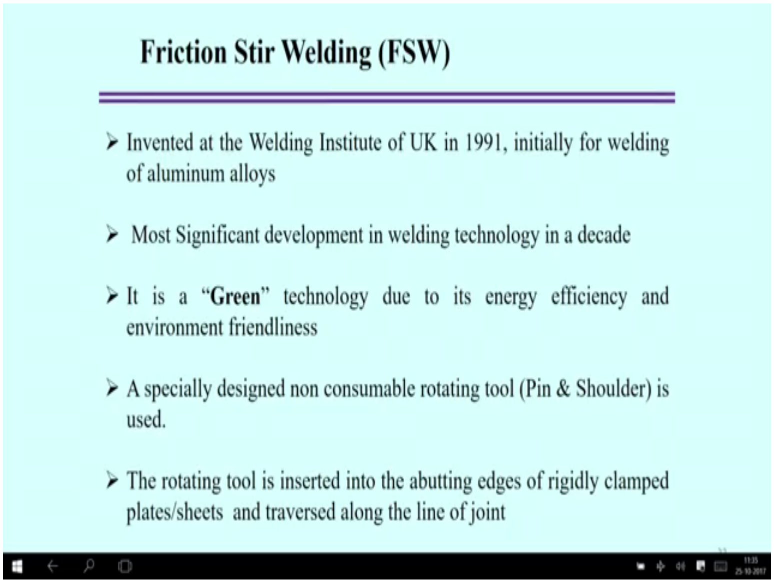


So, this process is now widely used and extensively used for different applications. So, specifically this welding process actually development started by the application of the relatively soft material like aluminium or aluminium alloy; but now a days this welding process can also be used in welding of very high melting point material very hard material. So, let us look into that the basic understanding of this friction state welding process.

So, actually it is invented in UK in the year 1991 and after that there is a lot of development still going on. And specifically it is having advantage; so many advantages as compared to the fusion welding process in terms of that specifically or dissimilar combination of the material. So, and at the same time that fusion welding also creates a lot of hazards and then some environmental issue also in case of friction fusion welding process. So, in that respect friction stir welding process is very clean process.

So, it is also called the green technology and because of this; energy efficiency and environment friendliness. Because in this case there is the machine itself consumes the electrical energy and then there is no formation of the any gas and any kind of hazardous materials during processing of this during the welding process solid state welding process. So, in that case it is called it is also called the green technology.

So, basic principle of the friction stir welding process is that that there is a some; we can use some electrode what sense we use the electrode in case of the fusion welding process here we can use that non consumable rotating tool. And that rotating tool creates the frictional heat generation between the two contact surface of course, it is also necessary to provide some relative motion between this tool and the workpiece surface.

So, that generates the heat and that heat actually better plasticize the material around a around very refine zone or very small zone. And then after plaster stirring the materials can be joined and for in any combination any combination in the sense similar kind of material as well as dissimilar kind of materials can also be joined by this process, but at the same time the maximum temperature within the system level cross the melting point temperature. So, it is a one kind of the solid state welding process.

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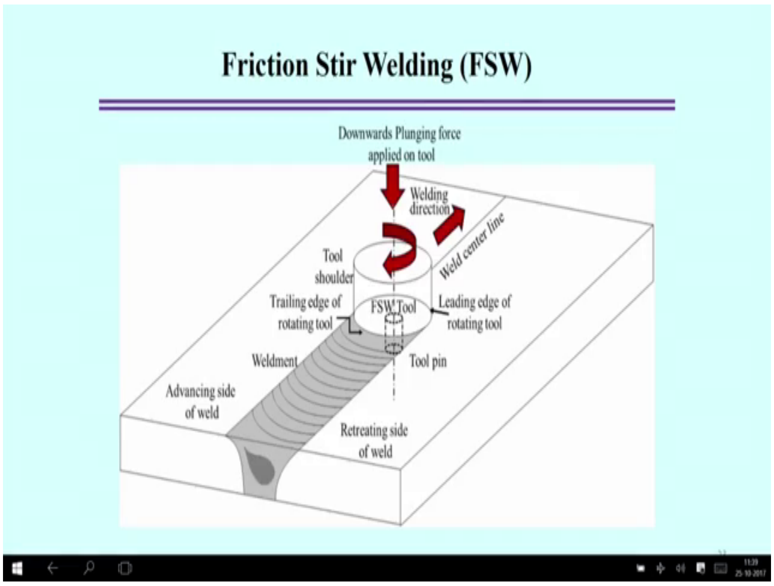

Now, if we look into details about this process schematically; if you see that two material and the different join configuration and now a days butt as well as the lap joint both configuration, the welding can also be done using the friction stir welding process. So, in this case the two materials lap or in the butt configuration we can give and at the interface of this material; we insert the tool and then start moving the tool.

So, two kind of movement of the tool one is the rotational movement of the tool that actually helps to friction frictional heat; at the same time transport that is called also the welding speed to move gradually the tool from one specific direction that also helps to make the joint between the two surfaces. So, there is a in this case the main part of this friction stir welding process is the design of the tool so, that it will be able to stirring the plastic size material and make the mixing between this two between the material and finally, make the joint.

So, this friction stir welding process mostly at the start at the very beginning it was started like that, converting the simple milling machine process to in terms of the friction stir welding process. So, in the milling process we use some rotating tool and that we can hold the; we can try to rotate the tool and that tool is inserted in the work piece and then transforms movement of this rotating tool helps to make the solid state joining of this two materials.

So, if we look into different terminology or may be specific term related to friction stir welding process, we can see that tool there is a friction stir welding tool, but there is a at the end of the tool there is a tool pin; that pin is actually in the in contact with the two workpiece. And that normally this tool pin is more or less the height of this tool pin is equivalent to the thickness of the material.

So, this there are some specific geometry direction that depends the thickness of the material or may be some limitation of the power, rotational speed or actually makes the factors to design the to define the size of the geometric tool. It can be cylindrical, it can be tapered also, but there may be some for the more flexible or more mixing of the material by plasticization; it can also provide with the some kind of a thread on the tool pin also. So, there we will see the different types of tools normally used in the friction state welding process.

But here if we see the oil central line that is that is the interface between the to workpiece or to subsequent material. And there is welding direction which direction the tool rotating tool actually moves; but normally the rotational speed is very high as compared to the welding speed of this process. There is a two things that tool shoulder we can call if we look into the figure itself that tool shoulder is actually contact on the surface of the material, but tool pin is actually inserted to the depth of the material. So, tool pin actually covers the whole depth of the material; at the same time shoulder surface actually covers the only on the top surface of the materials which is suppose to join.

So, here the leading edge that in the advancing side we can define the different terminology in the way look looking into the relative velocity or the direction of the rotational velocity and the direction of the welding speed or welding direction; based on that we can divide whether it is the advancing side or whether it is retreating side. But in the front which direction the rotation moves front side is normally called leading edge of the rotating tool and the behind side is called trailing edge of the rotating tool.

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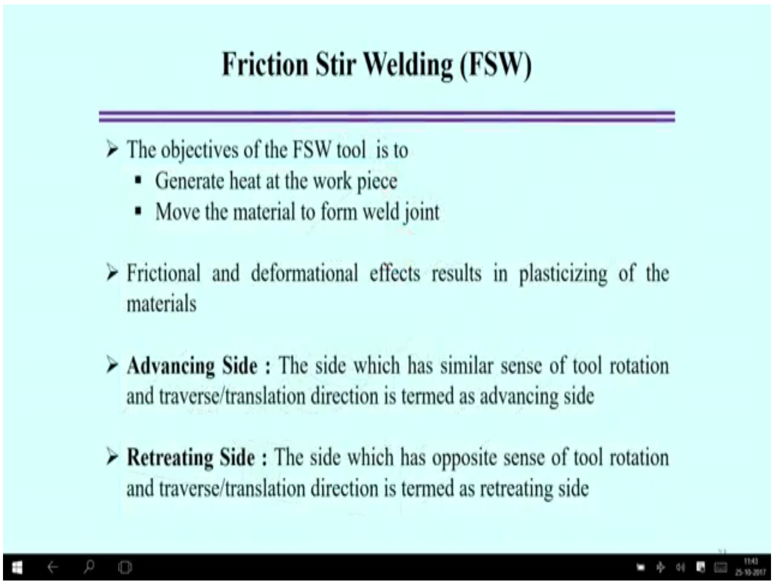


Now, the main objective of the friction stir welding is to generate heat at the workpiece surface. And other objective is to move the material such that it will be able to joint between the two materials. Therefore, frictional and deformational effects results in actually plasticization of the materials.

So, with this objective we can define the advancing side and retreating side; the advancing side is defined that with the sense that similar tool rotational speed and the traverse direction of the tool is the same side that is called advancing side. And retreating side that it is just opposite; that means, which direction tool is rotating; that means, linear velocity of a point that is tool rotational speed of and the transfer speed of the tool are in opposite direction. So, with respect to the weld central line; we can define one is the advancing side another is the retreating side depending upon the direction of the rotational speed as well as the transfer speed of the tool.

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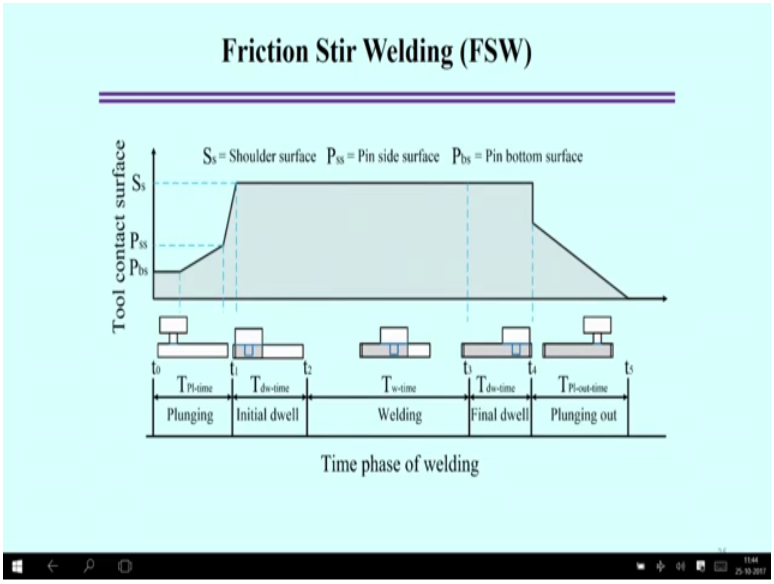


Now, in friction stir welding process; there are different stage; that means, if we look into the complete process, first is that there is a after fixing the workpiece surface or subsequent material then it is necessary to put brings the tool is in contact with the workpiece so, that initial period in the just at a fixed position or maybe at a fix axis the tool is given to the vertical motion towards the workpiece surface such that is called the plunging figure.

May be if we look into this figure first phase is the plunging phase and we divide the total time phase of the friction stir welding process. So, in the plunging force in the plunging phase the simply without any translation movement of the tool just gradually inserting the tool pin inside the workpiece. And after plunging of certain time it takes some time for the this plunging operation plunging phase.

Next is the dwell phase; so, in the, or we can say it is the initial dwell phase. So, once the plunging depth is completed then we keep the tool at the fixed position for a certain time that is called dwell time. So, once the dwell time over then we start the actual welding process so; that means, welding starts in the sense that the rotating tool just starts moving through the transverse direction or the along the welding direction.

Then gradually the during the welding directions once the it is it reaches almost at the end of the workpiece surface; then we can say assume that the welding phase or welding period completed. After that gradually we keep in the final dwell; that means, at the end position at the fixed location; that means, on the workpiece is keep for a certain time. Of course, this within this certain time the tool also keeps rotating and once this final dwell phase is over; then gradually the plunging out means gradually remove the tool from this at the end of the workpiece. And that the plunging out of course, there is a vertical movement of the tools occurs, but without any welding speed of the tool. So, these are the typical phase of the typical time phase of the friction stir welding process.

But apart from this thing time phase; we can divide the friction stir welding process also in the different metallurgical processing zone. So, this will be more clarified if we look into the actual micro structure of or micro graph of the friction stirred welded sample, we can easily identify the different (Refer Time: 12:50) what we can divide all these kind of the material processing zone.

First normally friction stir welding is in other sense is more closely related to the metal working process; that means, hot metal working process.

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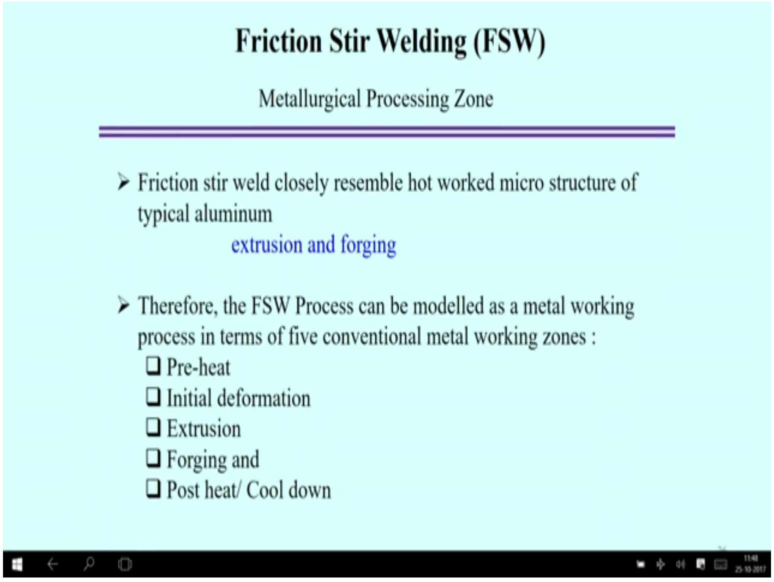


And it is resembles the mechanisms of extrusions and the forging during process. So, therefore, friction stir welding process can also be modelled as a metal working process; in consecutive I think conventional 5 phases, we can divide this different metallurgical processing zone or may be different phases here. First one zone is the that is called the pre heat zone, then initial deformation zone, extrusion zone, forging and finally, the post weld post heat or cool down zone or the cool down fear. So, this 5 metallurgical zone we will see how it looks like.

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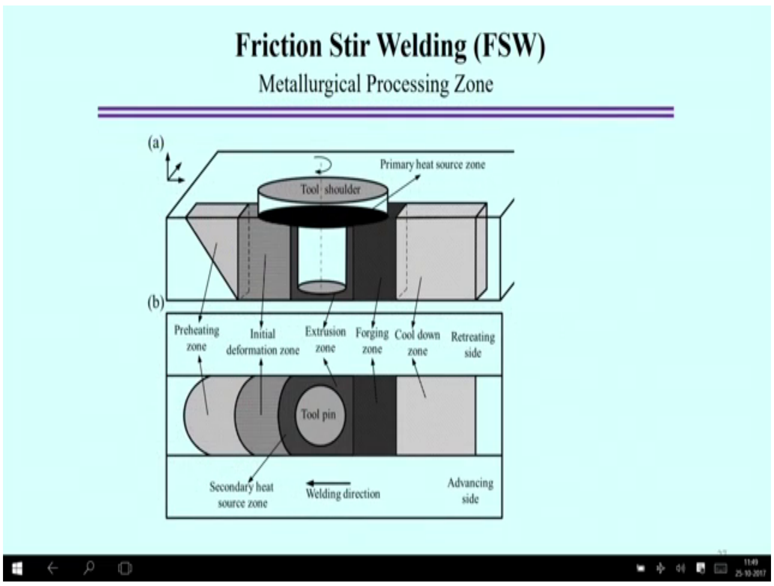

So, from the figure if you see that in this figure if you can define that rotational direction of the rotational speed I mean whether it is clockwise or anti clockwise direction. And the direction of the welding; based on that we can say that in the front side that is called the pre heating zone. And then is the initial deformation zone and then just around the tool that is extrusion zone actually exists in the around the tool. So, that extrusion mechanism prevails during the welding process around the tool and then behind this backside that is the main forging zone.

And finally, remaining part is the cool down zone because in this when you try to define different zone, we need to clearly define that the direction of the tool as well as the direction of the welding zone. So, from the figure it is very obvious that welding direction also given by this arrow; I think in one direction it is moving; that means, the welding direction is towards the preheating zone; that means, that the ahead of the friction stir welding in which direction in which direction the tool is suppose to move in the pre heating zone and initial deformation zone exist.

And then near about the tool the extrusion zone and behind the tool that is forging zone and then cool down zone. And here we can see that looking into that direction of the tool material rotational speed of the direction of the tool material; that means, clockwise and anti clock wise direction and at the same time welding direction; here we can define that the advancing side and the retreating side.

So, this mechanism actually exists to different zone.

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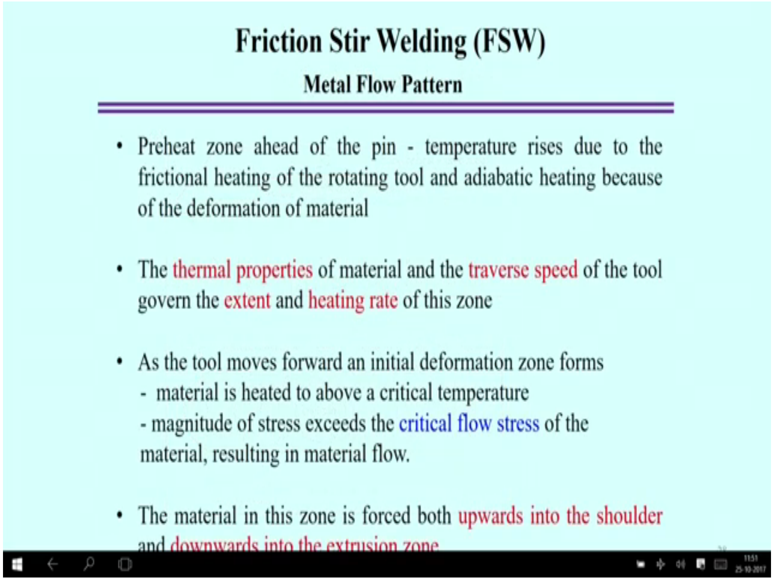


We can explain in that way that pre heat zone ahead of the tool pin is in this case basically temperature rises due to the frictional heating of the rotating tool. And at the same time there is a cause of temperature rise for the other reason that is called adiabatic heating because of the deformation of the material. So, in this case friction stir welding process there is a high deformation of the material so; that means, this mechanical energy is converted to the thermal energy without any loss.

So, therefore, that is called that is there is called adiabatic heating process also occurs due to the deformation of the material. So, both are responsible frictional and mechanical deformation; both frictional heating and mechanical deformation both are responsible to rise the temperature in the pre heat zone or in overall all the within the friction stir welding process.

Therefore, the thermal properties is definitely of the material and the transfer speed that is very sensitive parameters of the tool actually governs the extends; that means, size of the pre heated zone and it actually decides the rate of heating of this zone. So, rate of heating mold mostly influence by the transfer speed. And if we assume that thermal properties of the different types of material remains same, then transfer speed actually play the role to decide the extent and the rate of heating of the specifically pre heating zone.

After pre heating zone that the tool moves forward and initial deformation zone actually forms and in the initial deformation zone the material is actually heated above a certain critical temperature. So, deformation happens in such a way that their the temperature rise reaches above the critical temperature and of course, at the same time the maximum amount of the stress exists the flow stress value. So, once this condition reach then material starts to move there means; that means, most of the cases the materials behave like the visco plastic material. So, material flow starts at this zone. So, this material in this zone is actually forced both upward into the shoulder as well as the downward into the extrusion zone.

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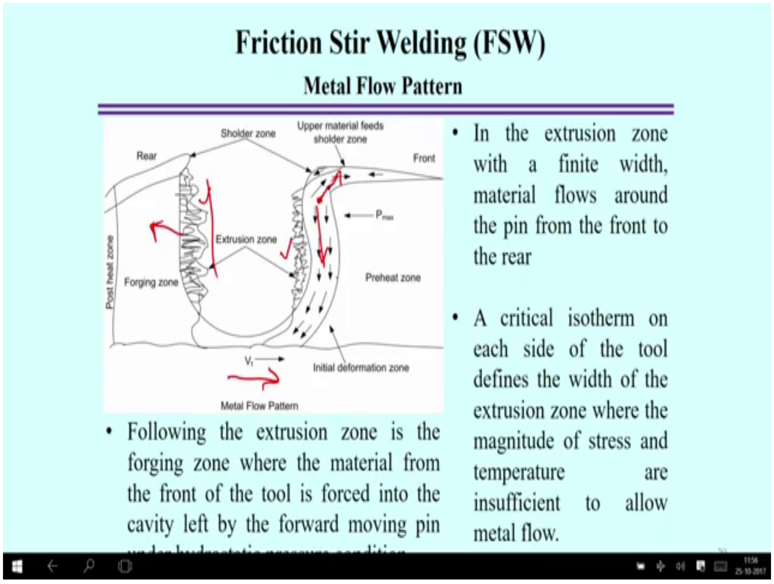


It will be very clear if we try to look into this a schematic picture here also if you define the different zones. You can see that the extrusion zone is near about; so, that extrusion zone is actually exists just surrounding the FSW tool and remember the friction stir; that means, tool is moving along this direction. So, that is the welding speed is in this direction; so, therefore, ahead of this tool there is a material flow. So, with respect to that point some materials are forced to flow upward and some materials are tried to flow the downward direction. Of course, this material flow is also restricted by the on the top surface there is a tool shoulder. So, tool shoulder actually constants the material flow also.

So, that this zone is basically initially deformation zone and that initial deformation zone actually starts creates starts creating the conditions for the start of the material flow. And in the extrusion zone if you see the in the extrusion zone also the finite width; that means, very small narrow zone; we can find out material also flows around the tool. So, even within the extrusion zone the material also flow around the tool.

Then critical isotherm on each side of the tool and actually this when you try to do some modelling approach; then we can define mathematically the critical isotherm each size of the tool defines the width of the extrusion zone. So, extrusion zone can also be mathematically defines while looking into the isotherm. And the magnitude of the stress temperature are insufficient to allow the metal flow; in the certain part there wherever we can define that certain point, whenever define the metal flow that with respect to the temperature isotherm and the condition for the material flow here or sorry condition for the magnitude of the stress by looking into that we can decide whether there is a metal flow or not.

So, therefore, metal flow is actually metal flow is very limited to around the FSW tool and the extent is very less then next part is the if we look into that beyond that if you go beyond that zone that is the forging zone. So, in falling the extrusion zone is the forging zone for the material formed in front of the tool each force into the gravity left by the forward moving of the pin. In the extrusion zone with the finite width we can find out very small zone that is extrusion zone. And this extrusion zone is confined and even material may also occur in the extrusion zone and that is a very narrow width if the correspondence with reference to the friction stir welding tool.

So, that magnitude is very less, but if you go beyond that there is a forging zone, but of course, in the if you away from the extrusion zone that that the size of this zone is decided by the critical isotherm and basically the flow stress condition or the magnitude of the stress and temperature that actually define whether there is a metal flow occurs or not so; that means, from the above from the extrusion zone.

Next zone is the forging zone; so, in this zone forging zone the material is in front in front of the tool forced into the cavity left by the forward by the forward moving pin and that also condition exists the hydrostatic pressure condition on this zone; so, apart from this extrusion zone.

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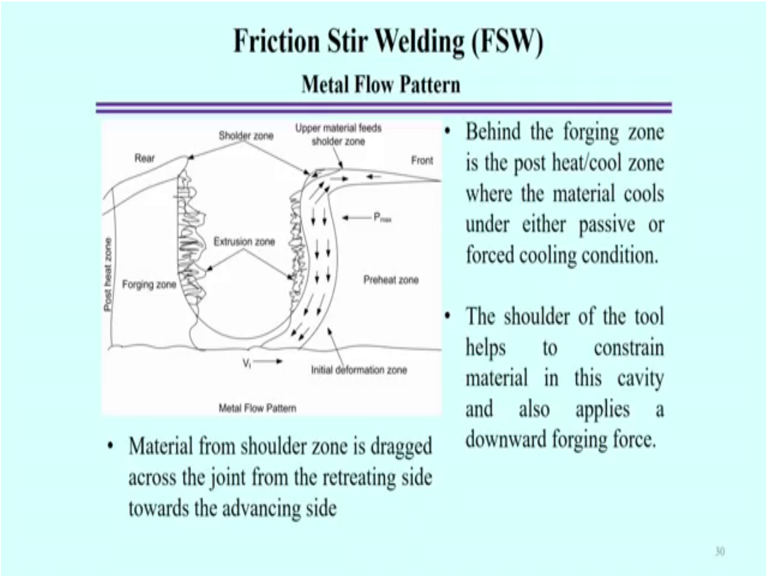


So, behind apart from this extrusion zone and this forging zone behind that there is a post weld post heat zone or may be cooled zone where the materials actually cools down under either passive or forced cooling condition. So, the shoulder, but within this if we already discussed the material flow and even for the in the initial deformation at the initial deformation zone or may be around the extrusion zone.

That metal flow having some constriction; that means, the restriction of this material flow is forced by the presence of the shoulder and that put the some constant and it changes the flow direction depending upon the size of the shoulder that is actually in contact with the workpiece material, but material flow within the shoulder also the because shoulder also create the sufficient condition; that means, the temperature and the flow stress value that the flow the material flow also occurs depending upon the pattern of the direction of the shoulder.

So, material from the shoulder zone is dragged across the joint from the retreating side towards it comes from the retreating side the and towards the advancing side. So, pattern actually depends on the rotational speed that metal flow condition and the at the same time also depends on that forward movement of the tool; that means, welding speed. So, depending upon all these parameters they create is a very complex metal flow pattern in during the friction stir welding process.

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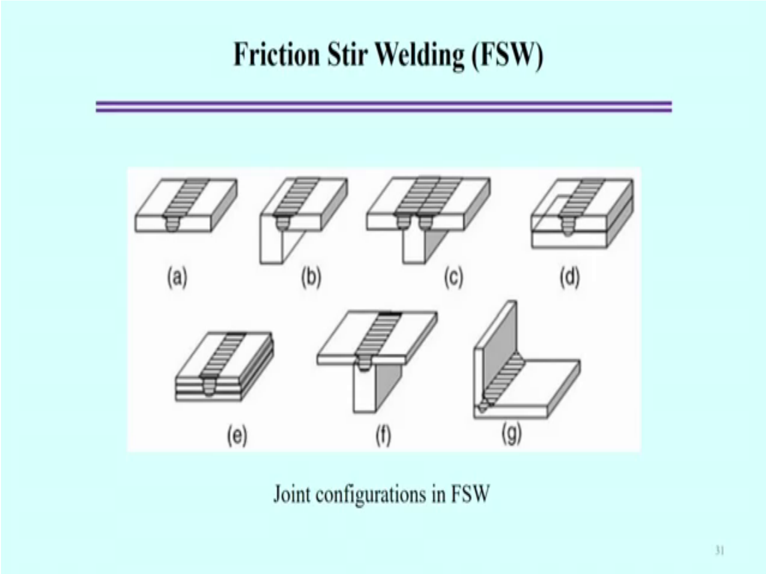


Now, if we look into that friction stir welding process having the different kind of joint configuration. So, from the figure it is very much obvious that both butt and left joint configuration can be possible using the friction stir welding process. So, if we look into that figure a; figure a actually it s a part joint configuration; that means, two materials are in contact and the interface there is a movement of the tool and that creates the certain amount of the nugget zone. And that nugget zone is nugget zone and finally, it creates the joint between these two. So, this is one type of configuration of the joint that can be done using the friction stir welding process.

If look into the b that it s looks like the L pattern the two materials are kept in such a way and then, but basically it s a part joint configuration between of the two materials can also be done in this configuration also. If we look into the c figure c that we basically there are two weld join has been created here. So, although overall structure looks like a T, but if it is necessary two different materials are two similar kind of materials or may be 3 different types of the materials, but these two weld join can also be produced using friction stir welding process; if we use the two different rotating tools two different rotating tools can also be possible using this type of weld joint configuration.

If we look into that figure d that also lap joint configuration so; that means two metallic materials can also be joined using the lap joint configuration. So, here the weld join is maximum covered on the on the top materials or the top components, but less cover in the bottom components, but of course, anyway this two metals can be joined in this way that is the ; that means, in lap joint configuration. And of course, also multiple components can also more than two components in the lap joint configuration can also be done that is very much obvious from figure e also here I think 3 materials 3 different thickness or similar kind of thickness can also be joined.

So, one advantage of this type of lap joint configuration is that the material thickness not necessary to be same. The thickness of the material can be different also at the same time they two different types of material can also be possible joining using friction stir welding process, but if you look into butt joint configuration, but with two different thickness; it s not very straight forward like joining of the similar kind of thickness material. So, little bit there may be some difficulty arising when we try to join two different thickness of material at butt joint configuration, but that may not be the in case of lap joint configuration.

Similarly, if we look into the figure also this is the one kind of t joint. So, that t joint is that one single two different materials are joined here, but that friction zone covers it is say I can say it is a one kind of lap joint configuration not the butt joint configuration. So, in this case the fusion zone dimension covers on the top surface on the top component completely and then little bit to the bottom component. And it creates the joint in that this lap joint configuration and if we look into g also here also friction stir welding process can also possible, but here if you see that is the kind of L L joint and it is joining the two materials, but here you can say it is not the straight forward like the lap joint or even it is not straight forward like the butt joint configuration.

So, with that these are the typical type of joint configuration we can make using the friction stir welding process; that means, I means the till the process is developed in such a way that this kind of the all this kind of the configuration can be possible using the friction stir welding process. Now, in friction stir welding process actually involves like other welding process; so, many process parameters.

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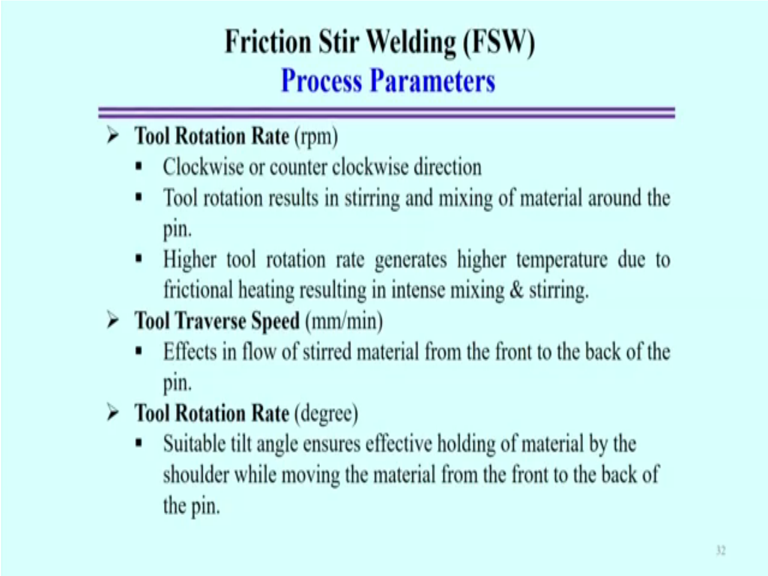


But the main process parameters involve in the friction stir welding process that is tool rotational speed that tool can be moves in the clockwise or anti clockwise direction. And this tool rotation actually results the stirring and mixing of the material around the around the tool pin. Therefore, if tool rotational speed is very high normally heat generation will be more because that when that at high rotational speed, the frictional heat generation will be more and that creates the intense mixing and stirring of the material. And second parameter that is the tool traverse speed normally this speed this that also we can say it is the welding speed.

So, this speed is also very less as compared to the tool rotational speed. So, in this the providing the tool rotational speed or welding speed that actually creates the joining of the two materials between the two metals and that depending on that the length of the weld join can be decided. Other not important always or may be important parameters, but normally we don t see that is called the tool rotation rate sometimes we use the friction stir welding process the tilt tool. So, tilt tool can also be can also be can also be used; that means, if you want to try to use the friction stir welding at the different configuration of the weld. So, it is also necessary some time to tilt the tool. So, that we can provide certain angle also and that kind of that can be that we can say it s a kind of secondary parameter is influence the basic friction stir welding process.

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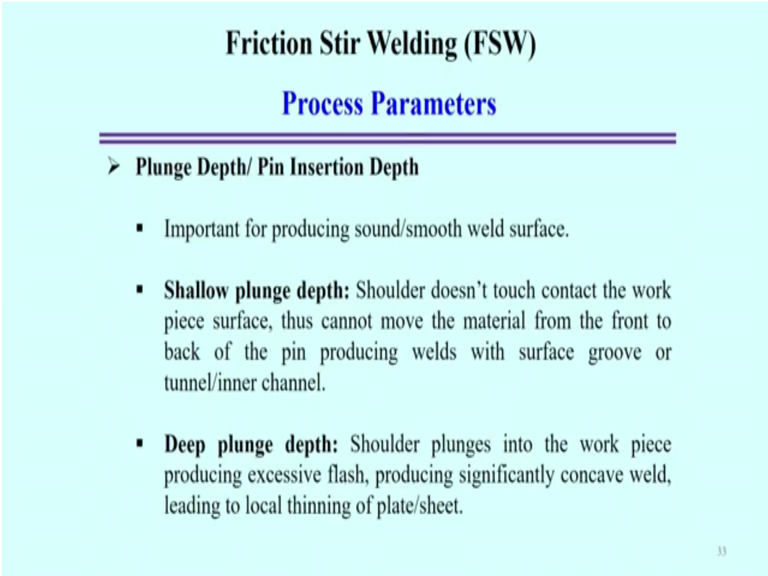


Other parameters apart from that tool rotational speed and tool transfer speed other process parameters that is the plunge depth; that means upto what depth the tool pin can be given so, that the sound weld joint can be obtained. It is a kind of this if you want to compare with respect to the friction welding process when you try to joint two different two materials may be similar or dissimilar materials the intern subjective is the cover the tool depth of penetration.

So either using laser or any other kind of different types of the; so, tool depth of penetration normally we achieve very in case of laser welding process. So, that that tool depth penetration similarly if you want to do the full depth welding in case of friction stir welding process, then it is necessary to design or define the length and the strength of the tool pin strength in the sense; that means, dimension of the tool pin the diameter and the length ratio of the tool pin that is attached with the actually friction stir welding through the shoulder.

So, therefore, tool pin size of the tool pin or we can say the plunge depth we using the actual friction stir welding process that actually decide whether it will produce the shallow weld profile or whether it is provide the deep plunge depth profile; it will produce depending upon the amount of the plunge step we can provide during the friction stir welding process.

So, if you see that for the definitely for the producing the sound and the smooth weld surface; normally we prefer the deep plunge depth because if we provide the shallow plunge depth with or shallow; that means, very small plunge depth if we decide; that means, this if this small plunge depth means the depth is very small as compared to the thickness of the material. Then most of the cases we cannot move the material from the front to back and pin actually produce with the surface of the groove a kind of tunnel or may be kind of inner channel. So, it is not advisable to use the shallow plunge depth the FSW if you try to get the successful weld joint. So, rather deep plunge depth is more suitable in case of joining of two materials by FSW.

So, here if you see that the workpiece produce excessive flash produce significantly concave well and finally, leading to the local thinning of the plate; that means, that stirring or material flow is very confined is within the small zone that is around the tool pin, but that is why if you want to achieve full depth of pane; that means, full weld joint up to the full depth of the work piece therefore, tool pin size is almost similar to this the thickness or depth of the workpiece material apart from that there are several other welding process parameters.

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For example travel speed; this in general the travel speed; that means, welding speed, spindle speed or rotational of the rotational speed of the friction stir welded tool, workpiece thickness, plunge, depth and plunge force; definitely joint offset if there is a necessary of joint offset; joint gap between the two metal when they are in contact if there is any mismatch joint mismatch and; that means, different thickness of the material and tool geometry all actually parameters are combination optimum combination of all these parameters is able to produce some successful weld join.

So, therefore, travel speed normally if we look into the individual parameter and its general effect of all these parameters it is like that travel speed it s a normally pre low; that means, we need to put that welding speed gradually very move the moment speed of the welding will be very low. It is like a; we can compare the machining process what we can give the speed motion and what we can give the cutting motion. So, it is resembles the speed motion during the machining process. So, that is why travel speed or welding speed should be followed should be followed very low.

Then spindle speed; so, spindle speed should be very high because that there is a some I think in each and every process in a material combination material and tool combination, there will be some minimum tool rotational speed to get a good weld joint. So, normally spindle speed is very high very high so that will be able to produce the frictional heat generation that heat generation basically soften the material. And finally, plasticizing that helps to plasticizing of the material; plasticizing of the material.

Third parameter is the workpiece thickness. So, if work piece thickness is very high that have it may be like that it s very difficult to plasticization of the material at exactly at the bottom of the workpiece bottom of the work piece plate. So, there is some optimum thickness of the material for a specific tool geometry, but normally we can find out that 5 4; 4 to 6 millimetre thickness of the material of aluminium alloy or aluminium alloy can be able to successfully joint using the conventionally existing tool or whatever tool geometry; it is possible to join between this two.

But if the thickness is too high then it is very difficult; that means, thickness is very high means it is necessary to provide; if you want to provide the stirring action of this material even at the bottom of the workpiece material, then it is necessary to extend the length accordingly the length or height of the pin is also required. So, if pin height is very high then there is a chances of the breakage of the pin from the actual friction stir welding tool. So, we cannot make the very sufficiently large tool pin.

So, there may be some optimum values so; that means, it is necessary to optimise the geometry as well as that length of the pin. So, pin length having certain limitation; so, therefore, if there is a limitation on the pin length accordingly there will be some limitation of the workpiece thickness up to that point we can do the welding process we can do the welding of the two materials by FSW successfully.

Second is the plunge depth; depth means using the pin up to what extent we can we can we can give the depth of the tool; that means, it is a basically plunge depth is more or less to the size of the height of the tool pin. Plunge force; that means, dealing the plunging force there is some it is necessary to put that to shoulder in contact with the workpiece surface to hold the workpiece surface and to make the constant material movement also there is some axial load is required from tool.

So, that load is also important parameter such that during the process whatever force will be exhorted on that that will maintain the steady stir welding of the workpiece material. So, that force is can be measured also that force is very one of the significant parameter in friction stir welding process.

Then joint offset; joint offset means the offset can be done just to movement of the tool just towards either one sided of the material; that means it is not always; that means, it is not always true that this joint offset is specifically important when you try to join the dissimilar combination of the material. So, there is a dissimilar combination of the material having the huge difference in the thermo physical properties. Therefore, heat generation and the resistance to the mechanical load or flow stress value all are different in this two cases.

So, to control the mainly to control the inter compound during the friction stir welding of the dissimilar materials then tool is normally offsetted to one sided. So, normally if we try to join between copper aluminium is copper aluminium. So, one is the harder material another is the relatively softer material. So, tool pin is normally shifted towards the softer material so, that the volume mixing between the aluminium copper can also be controlled by simply offsetting the tool. So, this way it is also one another significant parameter for joining of the dissimilar materials.

Then joint gap as a parameter up to what extent we can keep the gap between the joint or it s a tight control between the joint is also necessary; that depends the type nature joint configuration also and practical limitation also. So, based on that joint parameter joint gap can be a on significant parameter for FSW process.

Then joint mismatch sometimes the two different types of the thickness of the material can also be required to join. So, that that thickness of the material are different then parameter selection of may be different as compared to the similar thickness of the material. So, that is also another important parameter.

Finally the tool geometry; tool geometry in the sense that tool geometry sometimes the tool component of the tool geometry actually which is contact during the FSW process: one is the tool shoulder that is in direct contact with the surface of the surface of the workpiece material, another is the tool pin that pin is actually in contact between the two surfaces which is supposed to join. So, there are several way to modify or to incorporate the different design of the tool as well as the surface of the shoulder.

Shoulder surface can be very flat or can be concave or convex depending upon some advantage or on that that. And at the same time pin is the responsible for the mixing of the between the two materials. So, therefore, pin surface can be very straight cylindrical tool or can provide it s a kind of chronicle chronical shape or can be different shape or different geometrical shape along with the some threaded profile on the tool pin that actually helps to mixing or plasticizing of the material. So, there is a geometry of the tool is another important parameters and that actually influence very much on the successful weld join.

But if we look into the overall advantage for this friction stir welding process we can summarize overall advantage of the friction stir welding process like that. First is the metallurgical advantages; so, metallurgical advantage is first is that it is a solid state welding process; so, it avoid any kind of the complexity in solidification that may arise in the friction stir welding process. So, all the face transformation happens in the solid state. So, in that sense it is advantageous because solid state face transformation happens in the mixing formation of the inter links or below the melting point temperature of the either of the material.

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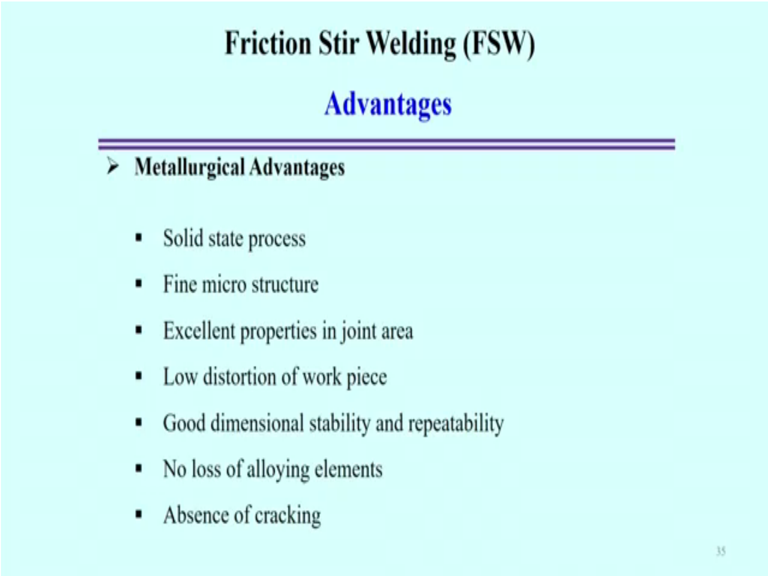


Then normally we can fine out the fine micro structure. So, this is another advantage; so, almost if we can fine micro structure we can find out in the nugget zone. And that is because of the condition, temperature and strain rate or deformation condition in friction stir welding is relatively high higher side. So, that actually produce the that the creates the mechanism of the recrystallization. So, normally in case of aluminium or aluminium alloy; we can find out the continuous dynamic crystallization. So, that due to this mechanism the this the gain refinement mechanism. So, very fine grain can be produced in the within the structure; so, fine micro structure that is the one added advantage in the FSW process as compared to the other welding process.

Excellent properties in the joint area; if the joint can be produced without any internal cracks without any defects; then the weld joint properties is very very high and almost similar to the base materials can be produces using this friction stir welding process; definitely low distance of the low distortion of the work piece; which is a severe follow in fusion welding process.

So, here distortion is very minimum then dimensional stability and repeatability is also very high in friction stir welding process as compared to the other welding process. Specifically it is very advantageous as compared to the fusion welding processes; no loss of alloying elements like in laser welding some there is a formation of the key hole and there is a may be some aluminium loss of the aluminium happens in friction welding process.

So, in that sense it is advantageous because no loss of alloying elements because temperature is limited up to the below the melting point temperature. And absence of cracking specifically the cracking in the sense the solidification cracking; we did not find in this friction welding process because the principle itself is the temperature is below melting point temperature. Therefore, the cracking normally did not do not find which is more prone to happens in the friction welding process that is not in FSW process. So, that is another big advantage of this FSW process.

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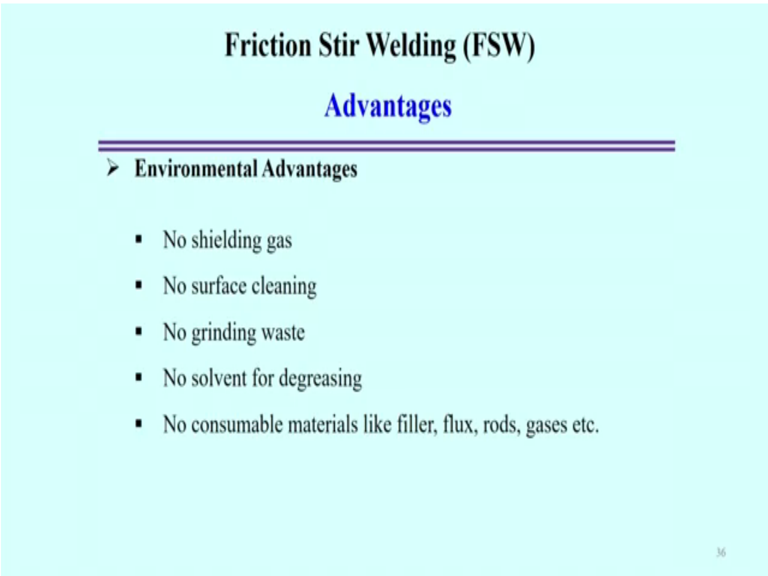


So, if we look into other environmental advantages; so, at the very beginning we pointed out that friction stir welding process is one kind of green technology. So, in that in that sense it is having very advantageous because no shielding gas is required, no surface cleaning is required, no grinding waste, no solvent for degreasing or no consumable materials like filler material flux, rod, gas etcetera required.

So, these are the typical requirement of all these shielding gas surface cleaning and all these things; that means, consumable that actually is related to the fusion welding process. So, in that sense it is more environment friendly process and that is why it is called the one kind of the green technology.

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Now, if you look into that we have discussed that friction stir welding process. Now, we look into that friction stir welding tool normally used for this things. From the figure if you see that different types of tools can be used during the processing; we can just have a look that differences types of if you see. The first on is the straight cylindrical tool pin and straight cylindrical tool pin just pin which pin just pin is extended from the tool shoulder surface.

So, tool shoulder is here is the tool shoulder surface is flat and then the apart from that part the pin is basically formed and that pin is in the size of the pin is very very small as compared to the shoulder diameter. So, diameter of this very less in this case that is that also following in friction welding process. And it is the geometry is like that it is called a straight cylindrical tool pin with the flat cylindrical shoulder surface. If you look into figure b also here you can see the straight cylindrical parts square threaded tool pin.

So, it is also tool pin geometry is the cylindrical, but with square threaded tool pin and if you see the figure c also straight cylindrical, but V threaded pin tool. So, all if you put in the different kinds of the threads on the tool pin that actually directly influence the material flow pattern in during the FSW process.

Fourth one is that taper cylindrical tool pin. So, straight taper sorry taper cylindrical tool pin without any thread and if you use other tool profile is that taper cylindrical square threaded tool pin and taper cylindrical V threaded pin tool these are the normally apart from that we can create the different geometry of the tool pin, but all these cases different types of tool pins is definitely having some influence on the metal flow pattern and finally, the heat actually influence the weld join properties as well.

Because this profile; that means, thread profile changes the flow pattern of the material during the stirring action of the two different types of material and that finally, influence the weld joint properties. And of course, not only the not only the flow pattern also at the same time the frictional heat generation are different because although it is a pin height is same, but the pin surface which actually in contact with the workpiece material the surface area different in all these cases.

So, therefore, since surface area difference; so, heat generation during the frictional action will be different in all these cases; that means, it finally, affects the temperature distribution as well as the material flow behaviour within the material. So, although the this type of a tool profile we can use it, but when you choosing the tool material; that means, what should be the material of the tool this would have some kind of basic properties or suit follow. First is that the tool material should have high compressive yield strength at elevated temperature because most of the because this tool is basically subjected to highly compressive stress.

So, therefore, compressive stress is very high even at very high temperature then there is one desirable properties of the tool material. Next is the dimensional stability and creep resistance; so, dimensional stability that; that means, even it is at very high temperature condition the it can returns it hardness. And at the same time creep resistance properties should be very high that is the; another desirable properties of the tool material frictional stir tool material. And thermal fatigue strength will be very high because this tool material is always is in repeated heating and cooling cycles this subjected to that.

So, that repeated heating and cooling cycles can create some kind of thermal fatigue. So, would have good thermal fatigue resistance, good fracture resistance and of course, low coefficiency of thermal expansion all of these desirable properties of a tool material. So, based on that the typical tool materials are used in the high speed steel, nickel alloy metal carbides ceramics these are the common materials we used. And all these tool metals actually we can recall that what we use for the metal cutting process what are the typical types of the tool which is used in metal cutting process.

So, almost similar categories of the tools material has been developed that are actually used in the friction stir welding process, but high speed steel we use it, but at the same time we can use for example, that that difference of the tool metals is not actually is difference between the this mechanical properties of the workpiece material and the tool material. For example, if that in general the tool material should have some hardness difference with respect to the workpiece material which is suppose to do supposed to join by the FSW process.

For example, in case of aluminium simple aluminium pure aluminium that can be joined just by simply sterile steel sterile steel; SS 304 or SS 3016 can be used as a tool material for joining of the simple aluminium pure aluminium. So, therefore, like that even when you try to join some harder material. So, tool material should be more hardness as compared to the substrate material that is general principle of the choosing the any material.

So, apart from that the material should have this kind of desirable properties just we have mentioned. So, all these desirable properties exist then we can use the tool material, but there is a separate analysis of the tool material. Because here also other side of the tool material or tool which is used for FSW is that tool where and cost of the tool to produce the any kind of weld join that is also different aspects of the analysis that is in this case that is beyond the scope to analysing the effect of the tool and the cost of the tool in FSW process.

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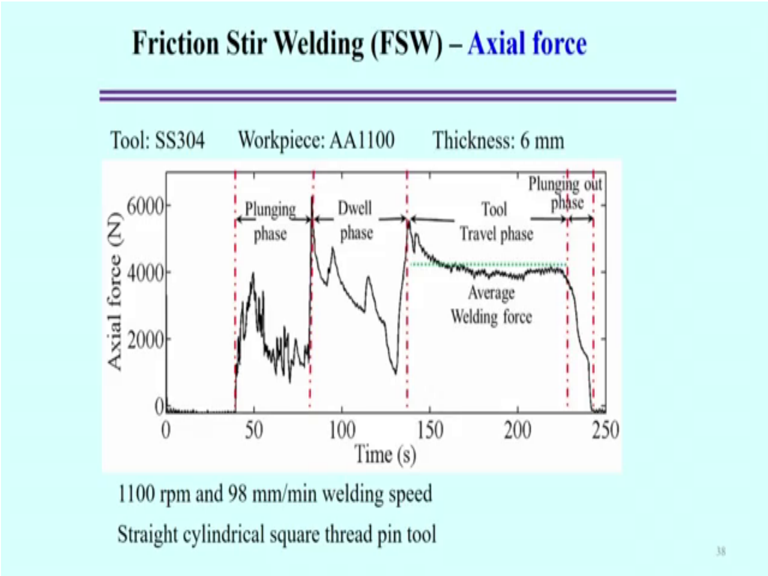


Now, we just simply try to look into that other aspects in the friction stir welding process; as we have mentioned that welding machine is normally used as a friction stir welding process. Since that there is a rotating tool and that rotating tool is we put into the plunge depth certain depth and we just give you hold the tool and the rotating condition. Therefore, certain amount of the axial force at the same time some torch is required to maintain the welding process during the welding during the welding.

So, we look the typical variation of the axial force; if we measure it and using the using some dynamic meter we measure it that force. So, if we look into that different phases of the friction stir welding process and the typical profile of the axial force that is that was acting during the during the FSW process. So, here if we use the tool material as SS 304 workpiece material AA1100 is almost aluminium, thickness of the workpiece material was 6 millimetre. And corresponding welding condition rotational speed was 1100 rpm and transport speed or welding speed was 98 millimetre per minute.

And in this case we have used the straight cylindrical square threaded pin tool. So, shoulder surface was very straight geometry of the tool pin was the cylindrical, but along with the square threaded. And here if you see the plunging phase if you see the plunging phase means gradually inserting the tool inside the workpiece material without any transverse moment of the tool. So, in this case when you try to just insert the tool; there is a gradual increment of the force because more and more the tool is more and more the rotating tool is interacting with the workpiece surface.

So, throughout the whole plunging phase; the complete insertion of the tool inside the workpiece and that is gradual increment of the force. Next is the dwell phase; in dwell phase if you see that once it reaches the maximum value of the force during the plunging at the end of the plunging phase and when we start the dwell phase we just keeping the we just simply rotating the workpiece at this desired position.

So, once we try to establish the keep on increasing the dwell phase means there is a more heat is generated and softening the material. So, therefore, mechanical force excel force is required is less so; that means, in during the dual phase; there is a gradual decrement of the force axial force and once after that once we just start moving the rotating tool in the welding direction along with the welding speed; then at the start of the fits then again gradually increases the amount; that means, magnitude of the force requirement will be high increases linearly.

And then once the welding phase done; that means, continuous movements of this things it creates some almost steady state condition; that means, constant force movement and once that is obvious from the figure also. So, once the welding phase is over; then is the plunge out of the tool during the plunging of the tool; that means, disengagement of the tool with the from the workpiece. So, gradually the force will be reduced to the 0 at the end of the welding process. So, these this is the typical picture of the axial force at the different welding phase.

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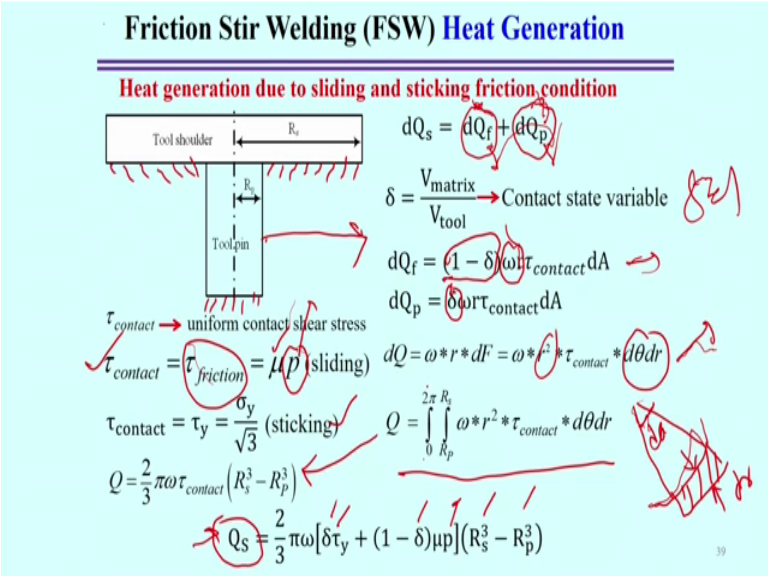


Now, we can do related to the friction stir welding process [vocalized nose], we can do some simple mathematical calculation that is the how to estimate the heat generation assuming the simple cylindrical tool with the straight cylindrical pin profile and of course, stack shoulders surface.

So, to do before doing this calculation; we assume from the figure that is a tool shoulder the tool bottom of the tool shoulder is in contact with the workpiece material and also tool pin is in contact with the workpiece material and shoulder radius is R s with respect to the axis and pin radius is R p. Now if we assume the theory that heat generation is due to the sliding and the sticking friction condition. Actually we can divide the heat generation is due to friction in general due to components; one is the sliding friction another is the sticking friction condition.

So, sliding friction is generally follow the (Refer Time: 59:30) law friction based on that you can find out if we assume that friction law and then we can estimate the amount of the heat generation. And sticking friction means at the certain part the metal is in stick with the workpiece material, but not necessary the all contact surface are in the either sticking or sliding condition; may be certain part is in the I think very initial part is in the sliding mode and the remaining part in the with the sticking with the workpiece material. So, based on this sliding and the sticking friction condition; we can divide the elemental heat generation dQ s into these two components. So, one is the this friction condition ds, dQf and this is the this is the sliding condition and this is the sticking condition.

So, this two components of the total heat generation it should divide into two components. But it is a very much difficult to find out the up to what extent there is a sticking and up to what extent there is a sliding condition (Refer Time: 60:39) the friction stir welding process. So, in that sense here we can define one is the contact state variable that is the V matrix by V tool that related that is the ratio of the velocity between the matrix material type and the velocity of the tool is the tool side; that means, if delta equal to 1; that means, V matrix equal to delta equal to 1 is equal to V matrix is equal to V tool; it indicates that metal is moving along with the same velocity of the tool; so, that condition prevails.

If delta equal to 0; that means, V matrix equal to 0; that means, there is no material flow at all. So, that is the two extreme condition; so, that we can divide this things up to certain part it s a sticking and may be not 100 percent sticking or not in certain parts sticking and certain parts in sliding condition prevails here. Then that it is better explained with the with the state variable delta, we assume that first is the del dQf so; that means, I think sliding component.

That means, frictional heat generation due to the sliding components it is 1 minus delta; that means, some part is the is the is the due to the sliding condition. And then velocity equal to omega into r and then taw contact means contact shear stress value; that means, at the contact surface what is the sheer stress value and then dA is the area.

So, that shear stress into elemental area that actually represents the basically shear force. So, that force into velocity actually force into velocity that actually defines the amount of the frictional energy. And for that we this energy we divide into these two components one is the 1 minus delta another is the only delta. So, only delta; that means, it s a sticking condition we can say only delta omega r taw contact into dA.

But point is that what way we can divide what we can decide the contact shear stress value in this cases. If you know the contact shear stress value then it will it will be possible to find out the actual heat generation, but if you look into the expression for that dQ the simple velocity into elemental force in this shear force omega r into df and for the cylindrical component then df can also be represented by the elemental area. So, d theta into dr; so, if there is a circular component this is if suppose this is d theta and this is dr. So, that actually represents the this area.

So, then r d theta into dr actually represents that elemental area. So, from here we can find out r square d theta dr omega into taw contact and if we look into that defines is the defines the range of the diameter or radius of the shoulder then we can find out this thing. So, here we can actually we are trying to find out what is the heat generation when the metal is contact on this surface actually on the shoulder surface.

So, then Q can be integrating over 0 to 2 phi; that means, theta varies from 0 to 2 phi and radial distance from this radial to this. So, that is the r from R p with respect to R p to R s that is the range of that and if you do we can find out that Q equal to that two third of y omega the contact shear stress value and the R s cube minus R p cube. So, this estimates the amount of the heat generation on the shoulder surface which in contact with the workpiece and the shoulder surface, but excluding the part of the pin component.

Now, it is necessary to define the uniform contact shear stress value at the contact surface. So, there is a two we have define in the two different condition that contact surface is one is the sliding and the sticking condition of the friction. So, then it is better represented that the contact due to the sliding friction condition; taw friction equal to mu into p co efficient of the friction at p is the pressure on that; pressure means that pressure can be calculated from the axial force and that axial force is here if you know the axial force and divided by the cross sectional area which ever it is distributed and that cross sectional force divided by this cross sectional area that actually define the pressure.

So, that this defines the sliding friction condition. So, taw contact should be replaced by this from this sliding condition and if and which part the sticking conditions prevails; in that case since we are assume the sticking condition. So, here it is reasonable to assume the shear stress value is equal to the yield shear stress value. So, yield shear stress value better represents by the sticking condition.

So, if we put the corresponding value of this two at the two different conditions and the sliding and the sticking component, then we can find out the Qs which defines the amount of the heat generation at the on the tool shoulder surface in case of friction stir welding process and if you see that here it accounts the shear stress value of the material.

And of course, it accounts the extend of the sliding and sticking by incorporing the contact state variable delta. And it should know the pressure that comes from the axial force and then what was the diameter of the tool pin and diameter of the shoulder all actually the simplified way we can find out the amount of the heat generation.

So, the similar calculation can also be done if tool pin bottom surface profile is in contact is with the workpiece. So, what is that tool pin bottom surface creates the, generates the amount of the frictional energy or heat generation we can find out also in the similar way. But here the range of the surface it should be from 0 to 0 to R p that will be the range of the radius in this calculation.