Marine Construction and Welding

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Lecture No. # 35
Friction Stir Welding

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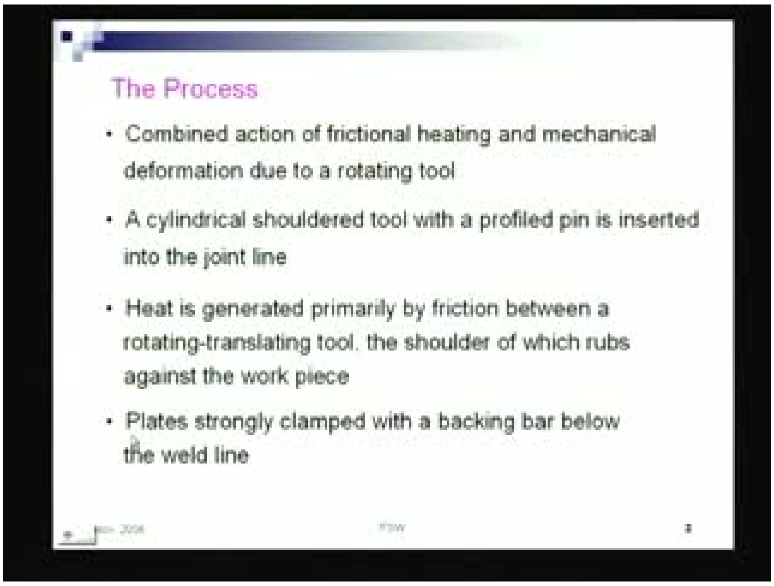

The Process

- Combined action of frictional heating and mechanical deformation due to a rotating tool
- A cylindrical shouldered tool with a profiled pin is inserted into the joint line
- Heat is generated primarily by friction between a rotating-translating tool, the shoulder of which rubs against the work piece
- Plates strongly clamped with a backing bar below the weld line

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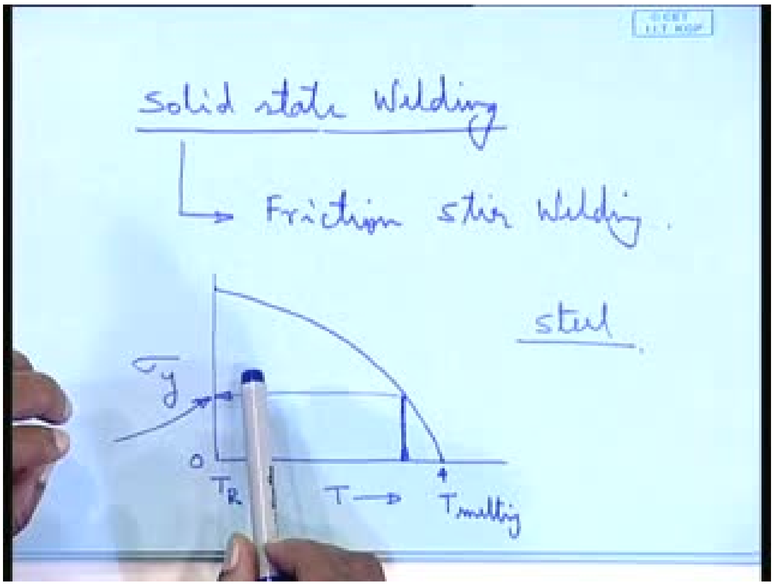

To continue with friction stir welding, here as as I was talking about that, as you can see if the temperature of of the of a metal, I mean here, obviously we are talking about steel and it is true for other metal also; so, as the temperature increases, your stress level needed to yield the metal reduces, and that is basically is the logic or the practice which is done in case of what you call - forging; if you have check the, if you have seen the operations of metal forging, what they do? They heat it up, say a steel rod, you want to give it a shape, you heated up to to where it becomes bright red, then you just slowly hammer like the blacksmith work or he slowly hammers it and brings it to the required shape. What is what is basically happening there? Because of the increase in the temperature, the stress level needed to deform it is much less, or in other words, the yield stress has reduced, right?

So, the same thing is happening here in friction stir welding through this friction stir welding tool which is ah sort of producing, which is which is giving a friction, a friction between the tool and the plate giving rise to a temperature rise, giving rise to a heat leading to a temperature rise, the metal below the tool is coming in a state which is in a plastified state; it is not liquid but, in a plastified state, which which can which can sustain mechanical deformation, right; which can sustain mechanical deformation.

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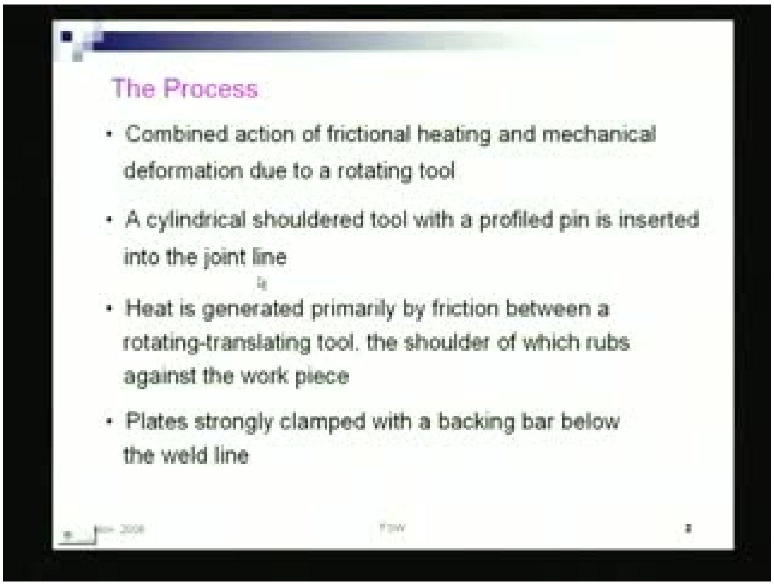

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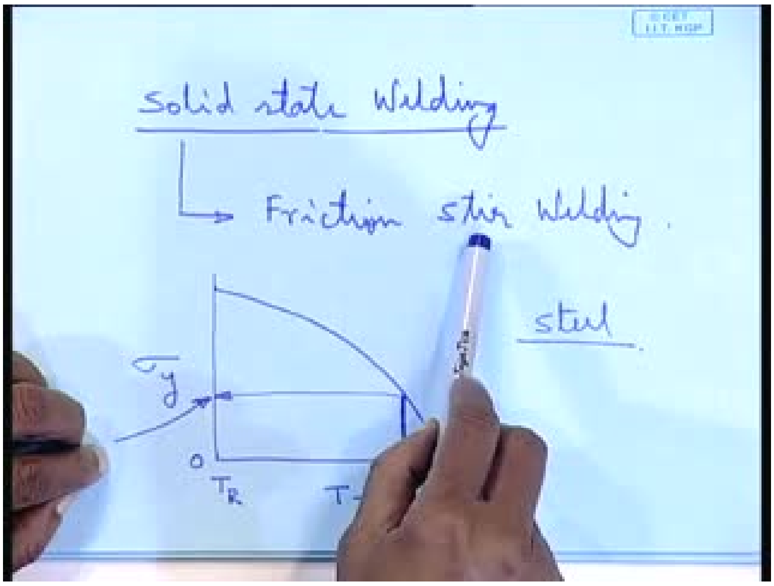

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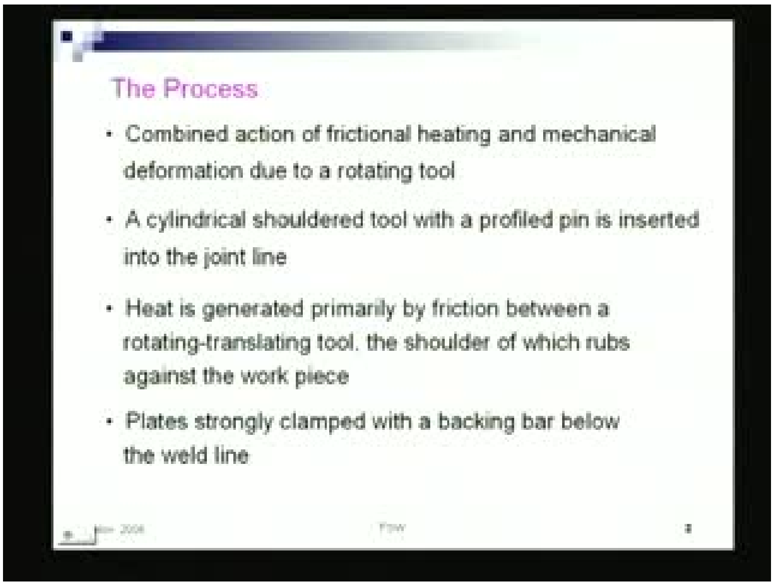

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So, that is how the name also you can see, Friction Stir Welding; through the friction, we are generating heat and then, stirring the material; the material is fluid enough to stir it. Anyway, here a cylindrical shouldered tool with a profiled pin is inserted into the joint line; we will see a schematic of that.

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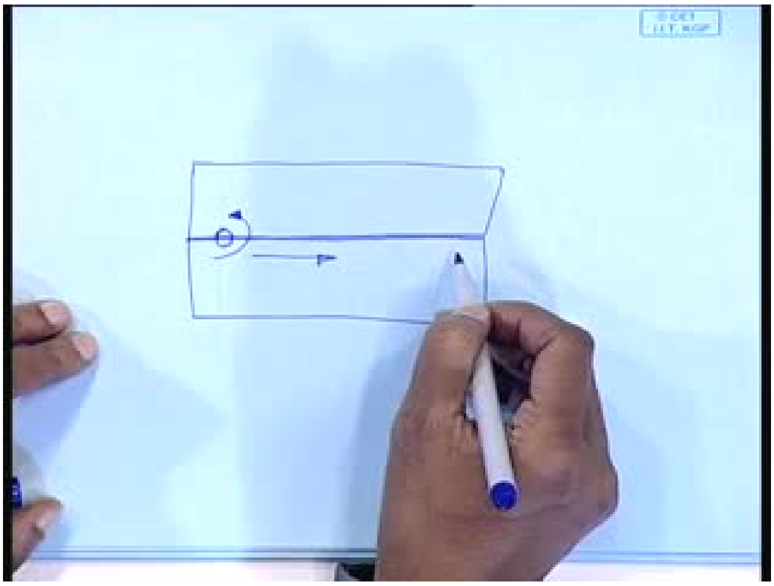

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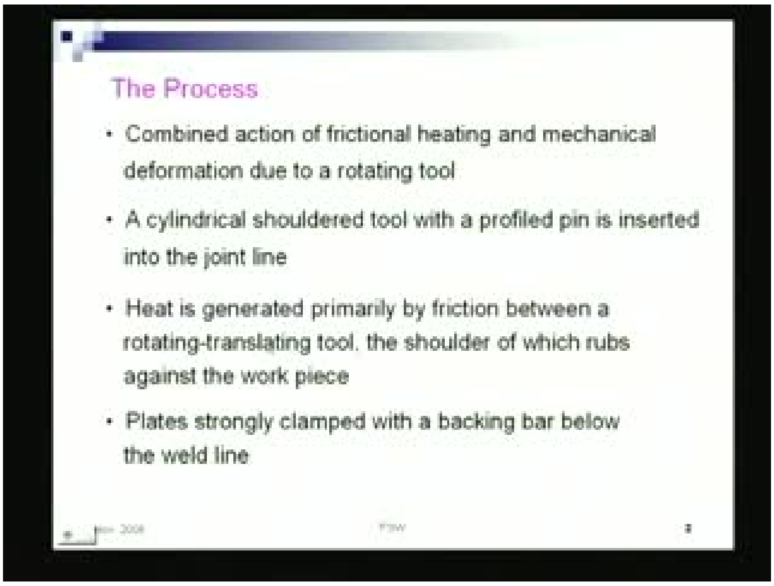

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Heat is generated primarily by friction between the rotating-translating tool, rotating as well as obviously translating; because, when you’re doing the welding means, you you you have the well, this is the plate interface, right? They are the two plates, so, you have the tool here which is rotating, right, as well as moving forward. So, in the process what is happening? It is starring the material, the pin which is plunged inside is starring the material continuously and going ahead; so, in the process as if it is throwing the metal from here to the other side and going ahead.

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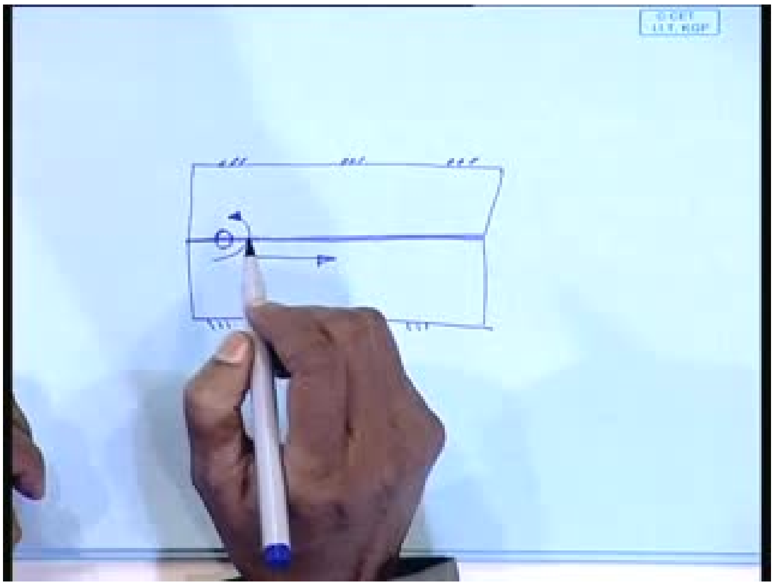

So, heat is generated primarily by the friction between the rotating-translating tool and the shoulder, the shoulder of which rubs against the work piece; plates are strongly clamped with a backing bar below the weld. So, if this has to be done, the plate needs to be clamped very strongly, because, if they are not clamped, then you’ll try to separate each other.

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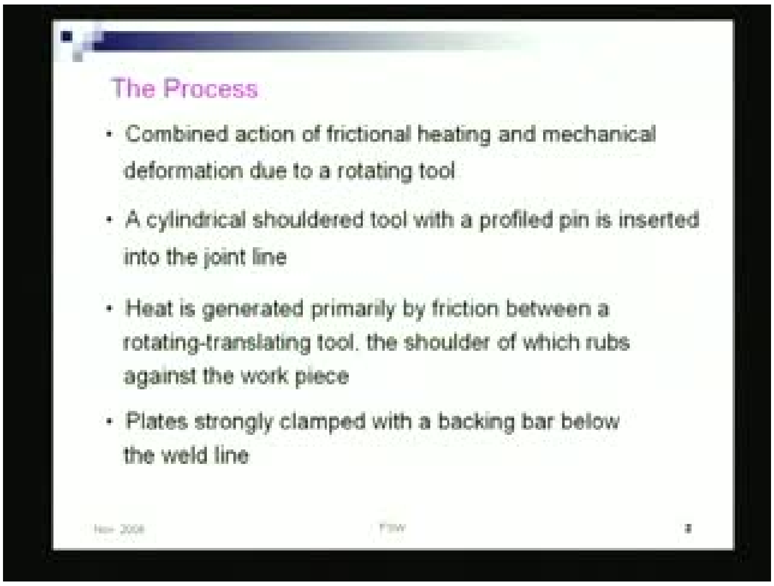

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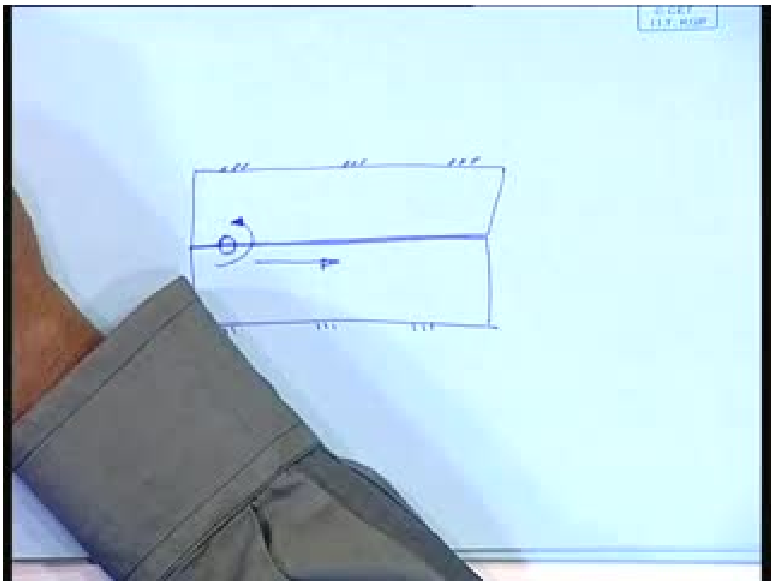
Because, what is happening? It is something equivalent to that of a drilling operation, if you have seen; you put the drill bit inside the material then, what happens? It cuts out the metal and throws off the metal. That is how the that drill, drill-bit you have, the helical kind of kind of those cutting edges, are formed such that, when it rotates, it will cut the material and throw off the material at the top, right? But here, there is no question of throwing off material; it is a blend heat which is going in under force. (Refer Slide Time: 05:09)



And, there is a shoulder on the top which is also rubbing against the plate surface; so obviously, you will have to have the plates clamped strongly, such that, they do not move apart, because the root gap has to be zero. Root gap zero means, two plates should remain in touch continuously; because, if the root gap is, there is some root gap, there is no question of filler metal here; so, welding will not be proper, right?

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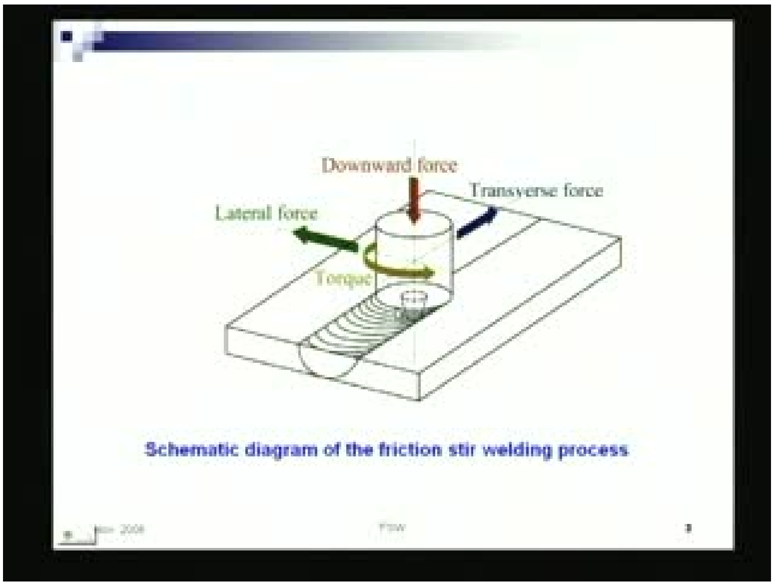

Schematic diagram of the friction stir welding process

So, this is, what is this? Schematic expression of this; as you can see, this cylindrical member is the is the tool which has a kind of a nib or a pin at the below, right? So, this intersection of the pin, and the cylinder is the shoulder; this white circular region is the shoulder of the thing and this is how the welding is being done. That means, there the two pieces of plates with zero root gap, as you can see, right? With zero root gap, they have been placed together; obviously, they are surely clamped on both the sides, such that, they do not move out; and a downward force is applied on the tool which is rotating, having a suitable amount of torque, right? And, it is the transverse force is provided, because it should move ahead, the tool should be rotating as well as going ahead.

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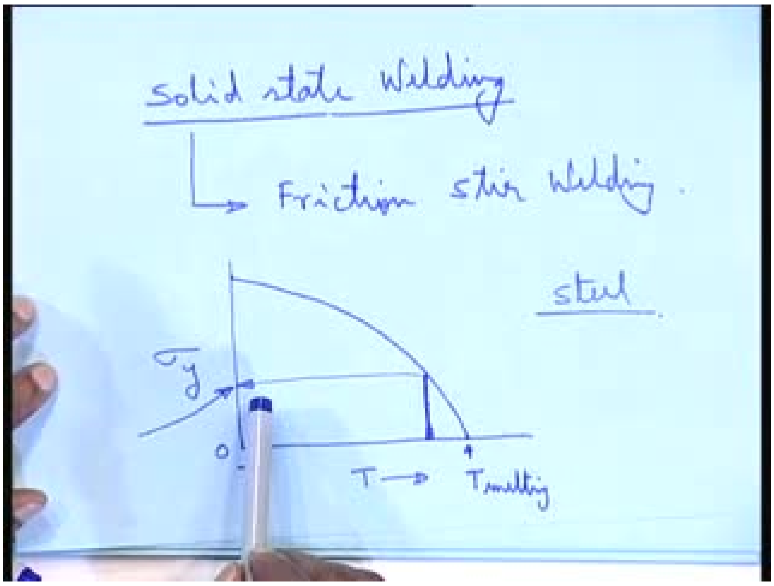

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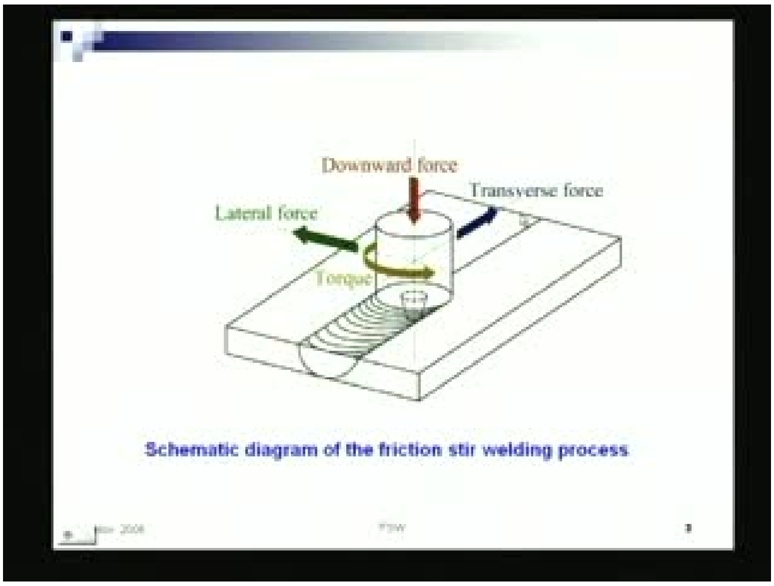

Schematic diagram of the friction stir welding process

So, while it is rotating and you will have to provide a downward force, such that the proper friction takes place, and as well as the pin can plunge through; the pin will have a sufficient blend diameter, it is not a, it is not like drill bit which cuts in and goes inside. So, here you need much higher downward force to have it plunge through, but obviously, once the friction starts, then this stress becomes less stress required. So, you do not need truly, I mean, had there been no friction. You try to plunge, put the that need plunge in the plate; you cannot, in the cold metal; simply you would not be able to do; but, once it is rotating, so it is giving friction generating heat, plastifying the material; so, you can put it inside, right?

And then, you have to provide a forward motion to the tool, that means, a transverse force is also needed which will push through the metal, but obviously, the metal is in a plastified state, so it can push through without much force. But still, that force also should be a, I mean, this nib there, the nib design depends that the force; the nib, this area etcetera and the stress etcetera; I mean, the strength of this material should be enough to withstand that force, otherwise the nib will break.

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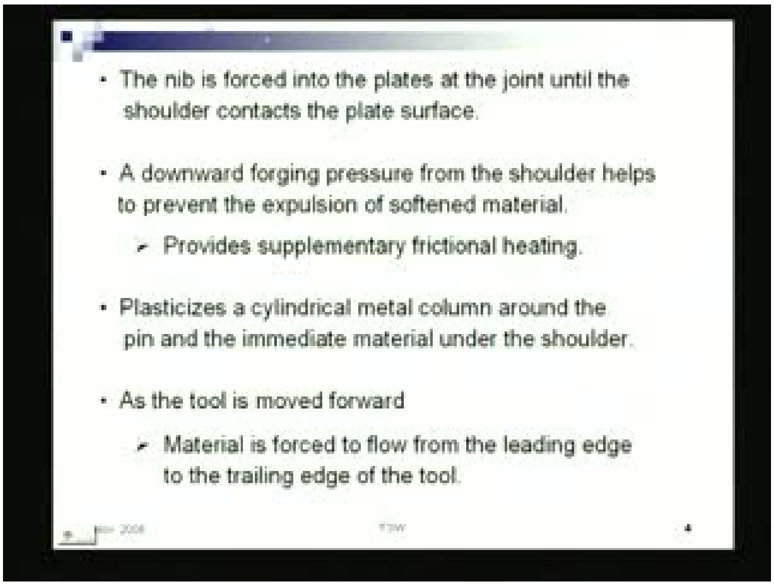

- The nib is forced into the plates at the joint until the shoulder contacts the plate surface.
- A downward forging pressure from the shoulder helps to prevent the expulsion of softened material.
  - Provides supplementary frictional heating.
- Plasticizes a cylindrical metal column around the pin and the immediate material under the shoulder.
- As the tool is moved forward
  - Material is forced to flow from the leading edge to the trailing edge of the tool.

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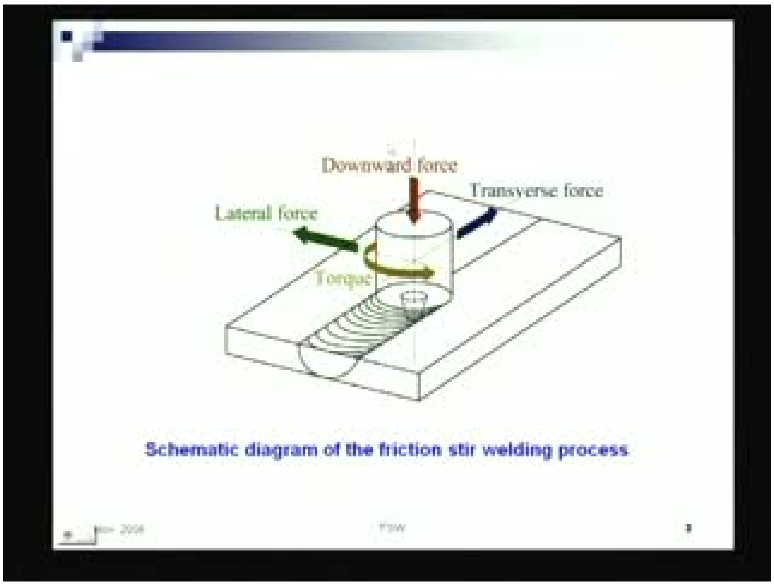

Schematic diagram of the friction stir welding process

So, that is what it is schematically... So here, what we see? The nib is forced into the plates at the joint until the shoulder contacts the plate surface; that means, as we can see, as we lower down the tool, the nib will first touch the plate surface. You further apply downward force, then the friction will start heating up the nib tip; the bottom of the nib the tip will start rubbing against the plate, generating heat; local plasitification will take place. Apply further downward force, it will plunge through; the metal will become soft enough, plunge through. Till what point it will plunge? Till, the shoulder comes and touches the surface, right?

And then, if you apply further force, what will happen? Then, this entire, this tool will try to plunge into the material, because here, you see these lines here, the metal has got heated up because of the friction. So, the metal here is soft enough; if you apply further force, this will try to plunge inside and we will expel the material from these sides.

It will sort of, cut through this along this, along these edges, so, this is how much downward force you are applying; that becomes one of the important parameter; like in in in fusion of electric arc welding, the welding parameters were the welding current; the voltage, the speed of the nozzle, speed of the electrode, right?

So here, the welding parameters are this downward force, right? At what RPM is it rotating? The RPM, what is that traverse force, right? And, well these are these are the you’re your so called welding parameters, and other parameters are like what material this tool is made up of.

Because, if it is made up of a metal having high thermal conductivity, it will have some performance; if it made up of a lower thermal conductivity, again it will have some different performance, very different performance for the simple reason. Obviously logically, this tool material should have should be of a material having much less thermal conductivity; otherwise, lot of heat will be wasted dissipated, right?

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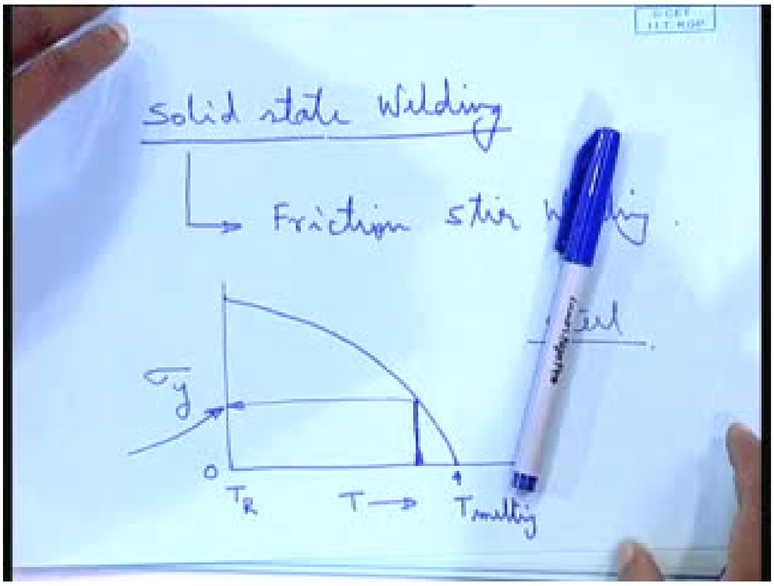

So, that is one aspect. Another aspect is the frictional coefficient should be as high as possible frictional coefficient of this material, right? Rubbing against the steel surface should be as high as possible; at the same time, this material, the tool material should be of such should have such mechanical property, that it it can sustain higher levels of temperature. Sustaining higher level of temperature means, what means, the strength of the material remains still high even if the temperature is raised; like here, we can see is strength; what what this curve means? This means the strength reduces as the temperature increases, right?

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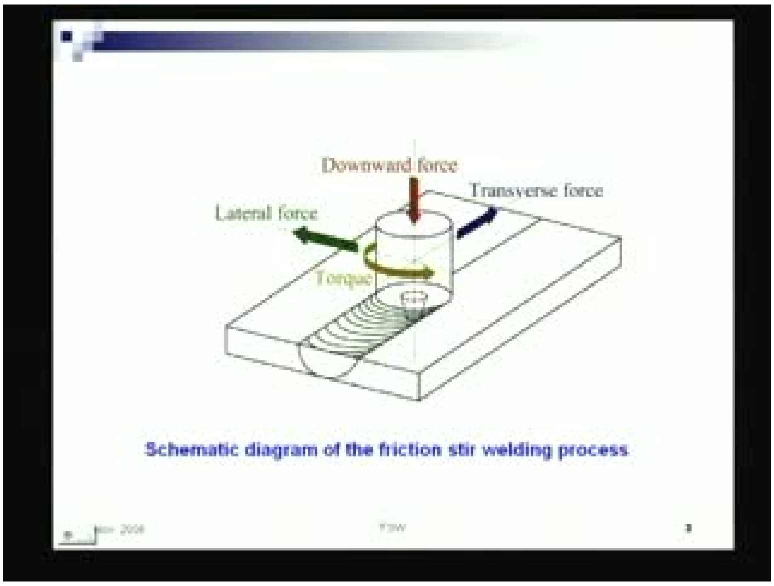

Schematic diagram of the friction stir welding process

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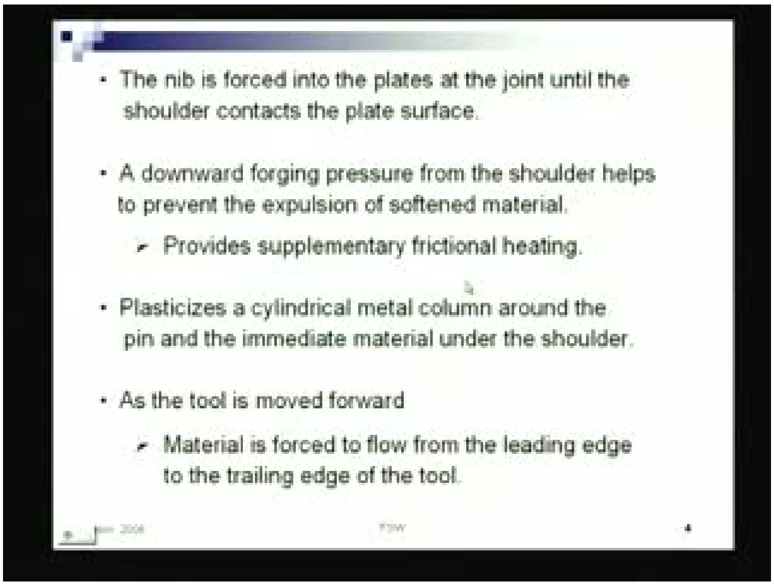

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So, this tool material should be, such that, they are the reduction in strength should obviously, once the metal is heated up, there will be some reduction in strength, but, even after reduction, it will have sufficient strength to withstand this force, transverse force. This is travelling because, will be it will be pushing through, right? Anyway, so the process is a downward forging pressure from the shoulder, helps to prevent the expulsion of softened material.

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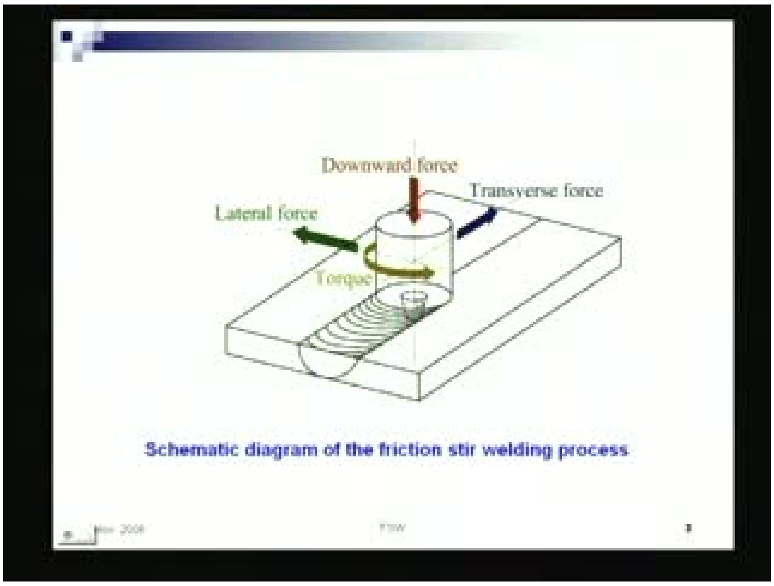

Schematic diagram of the friction stir welding process

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When you are pushing it through this nib or the profiled pin, so, this is displacing the material, so, where the material is going? It will try to, when you put it in, it will try to get expel, come out so that is what it says; that this shoulder prevents that from happening, coming out; but, you should provide a space for it, so, what is done is, the shoulder is made little concave, a little concave inside, such that, it can accommodate that expelled material; and also, that provides a supplementary frictional heating, that means, primary heating is from the nib, right? And then, additional heating from the shoulder surface.

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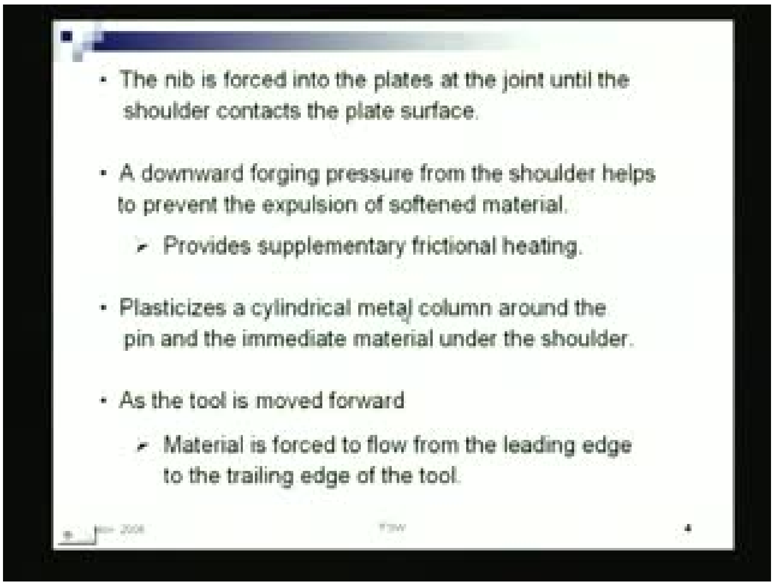

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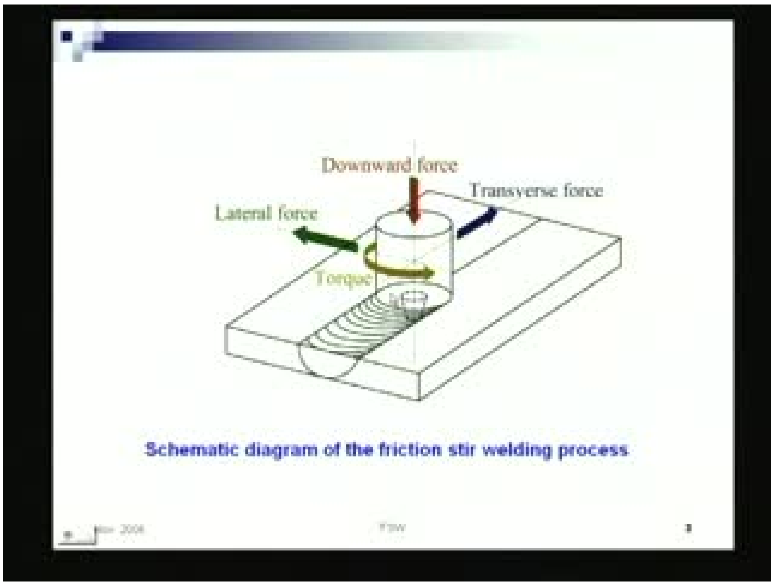

Schematic diagram of the friction stir welding process

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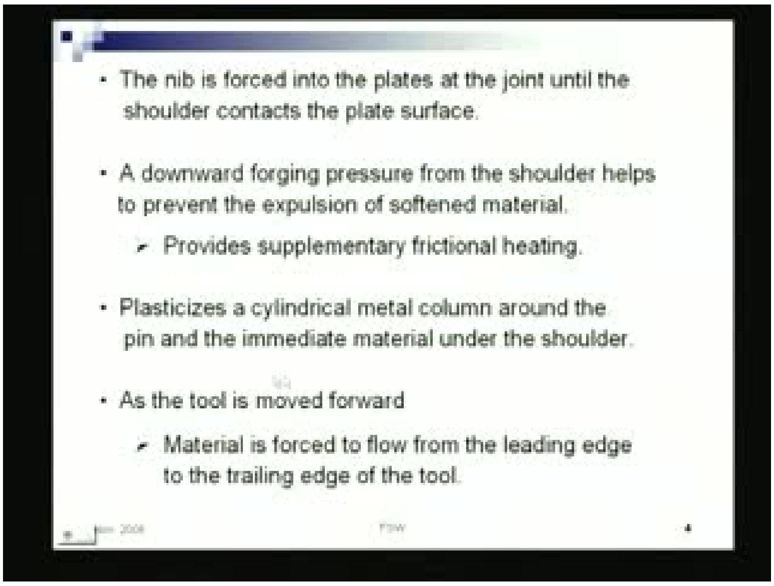

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It plasticizes a cylindrical metal column around the pin and immediate material under the shoulder; as the tool is moved forward, material is forced to flow from the leading edge to the trilling edge of the tool, leading edge to the trilling edge from one side to the other; as as as we were saying, well if it is rotating like this, so, from the leading edge, from the leading edge to the trilling edge, it will go like this, right?

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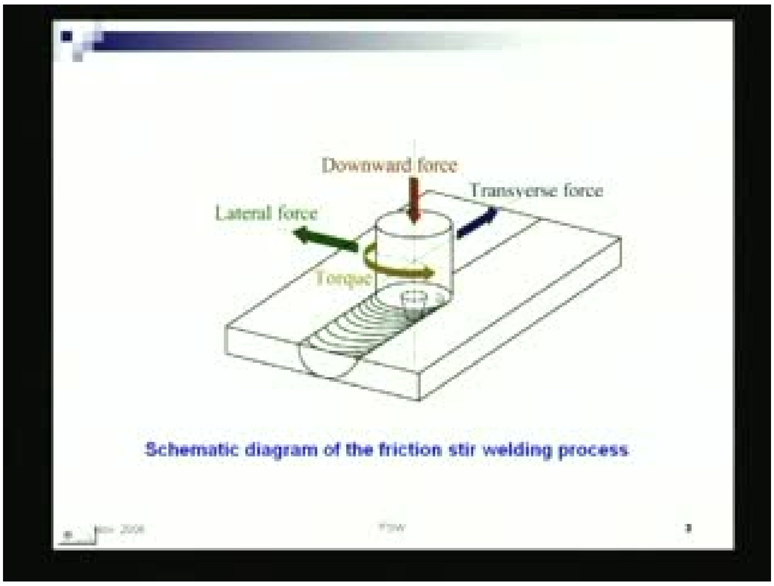

Schematic diagram of the friction stir welding process

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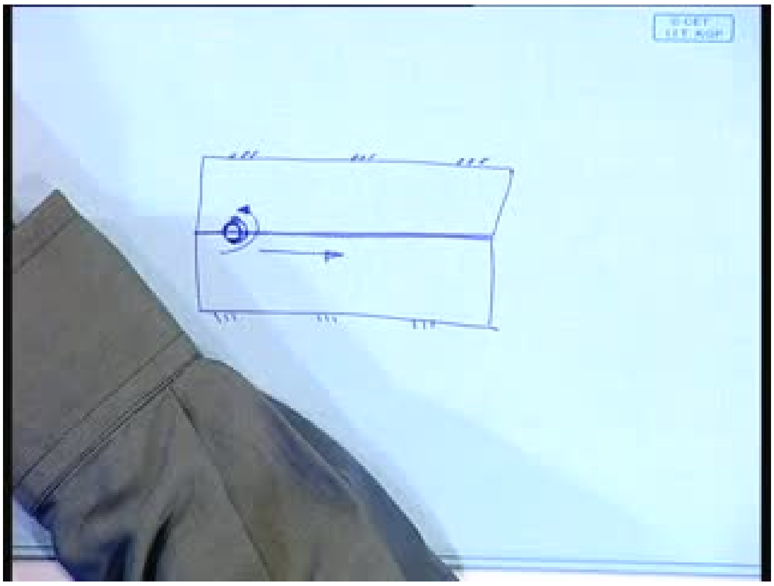

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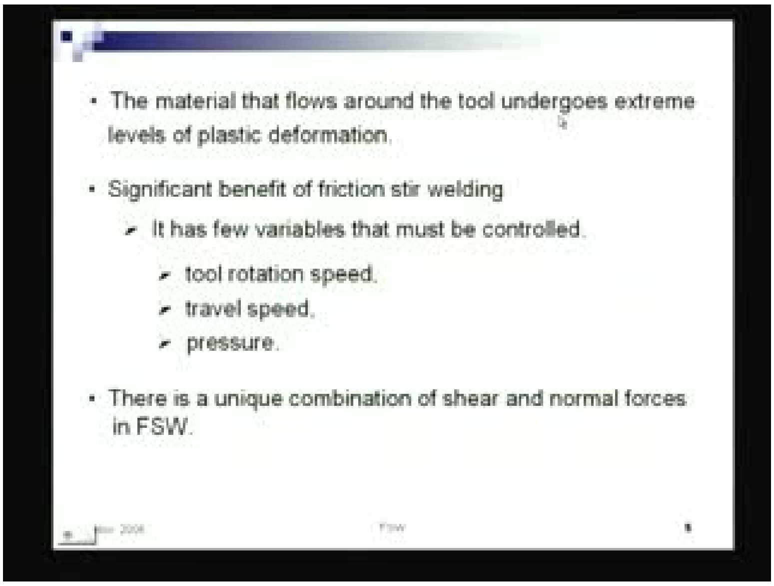

- The material that flows around the tool undergoes extreme levels of plastic deformation.
- Significant benefit of friction stir welding
  - It has few variables that must be controlled.
    - tool rotation speed.
    - travel speed.
    - pressure.
- There is a unique combination of shear and normal forces in FSW.

The material that flows around the tool, that material movement is taking place; so, whatever material is flowing around the tool, it undergoes extreme level of plastic deformation because, till now, by plastic deformation, we knew that bending of a plate, elongation of a rod, right? But here, it is a total dislocation of the material is taking place; the entire metal is getting it, is because the ultimate sort of plastic deformation is when the metal becomes liquid; it it just flows right, extreme displacement then, right? But here, it is just before the liquid state, it is not liquid; but, so called soft enough, like, for example, you may have seen those putty kind of thing plasticine, the kids they play; you can make any shape, right? It has, it is not liquid, but it is fluid enough, soften up to give it any shape, and it holds there, right?

Similarly, the metal has become has become to that state of a plasticine, you can move the metal as you wish at that temperature; of course, the movement temperature is removed; it solidifies, it becomes hard solid, so, that is the principle being used here. So, the material flows around that is why the term ‘flow’ is being used; though it is not liquid, it is not a liquid flow, but, it is equivalent to that. So, the dynamics of this material movement can be modeled using the principles of fully dynamics, right?

So, the material that flows around the tool undergoes extreme level of plastic deformation, significant benefit of this process. Why should we do this, what are the benefits? As I have mentioned in the beginning, that apart from, since here no melting is taking place, so all the defects related to melting are automatically eliminated; they are not there.

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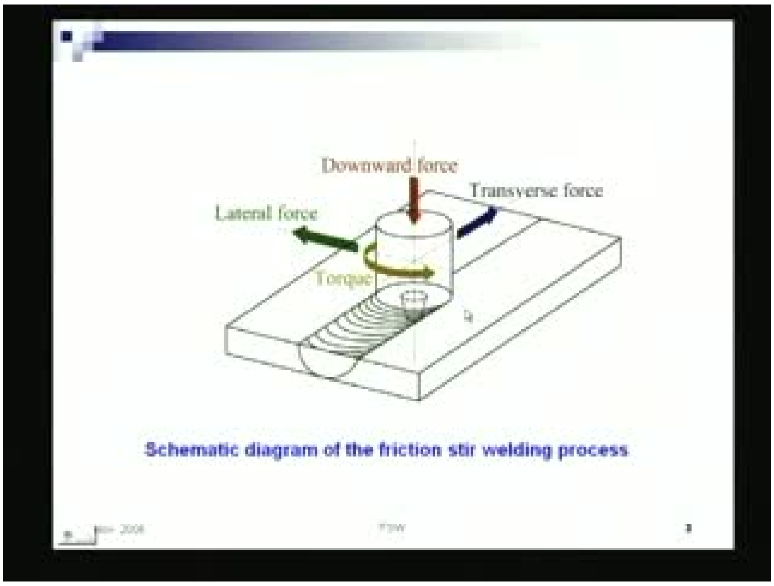

Schematic diagram of the friction stir welding process

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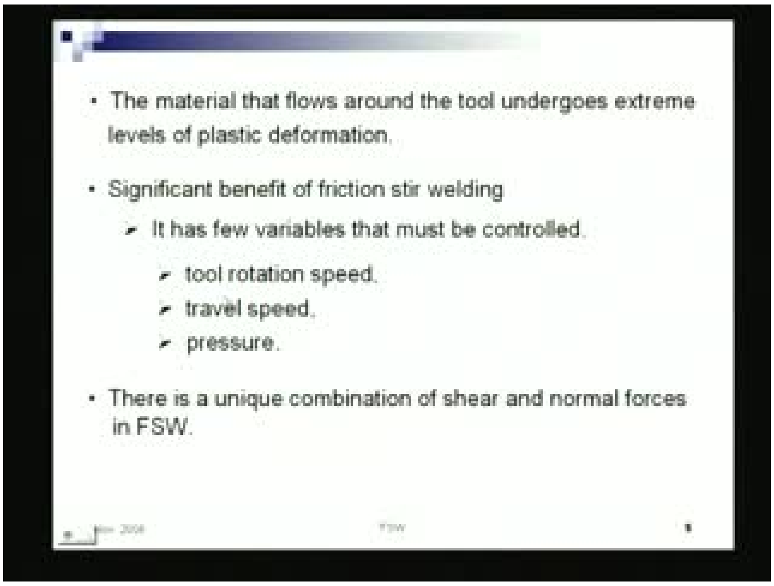

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Other additional advantages are here, we have very few variables that must be controlled. As I said, that in this the few basic operators, basic parameters are the downward force and the RPM; these are the two most important parameter tool rotation, speed and obviously, travel speed, travel speed and the pressure. Pressure is nothing but the downward force, how much you are applying, at what speed you want to move that, and what is the RPM? These are the three primary primary variables which need to be controlled; whereas, if we compare with fusion welding, again the primary variables were current, voltage, speed, and then you had electrode diameter, then you had root gap, then you had length of stick out, right?

Then, you had the orientation of the electrode, you had polarity of electrode; all these were affecting the weld deposit. You change any one of them, the weld deposit will change, so, you will have to have a total control or a total sort of an optimum selection of all these around 8 parameters and also, there are shielding gas. What type of shielding medium may be using? So, all these 8 to 9 such parameters are to be controlled properly, such that, you get the proper weld bead, proper joint quality.

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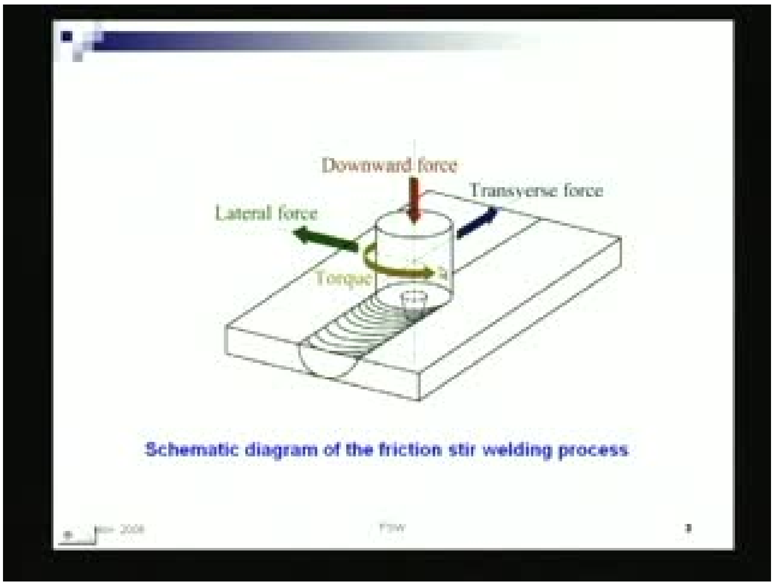

Schematic diagram of the friction stir welding process

In compression to that, here we have as such only, these three are to be controlled; but here, what we are assuming is that, we are assuming these three for a given type of tool geometry. For a given type of tool geometry tool geometry means, this tool here, it is schematically shown a simple tool with a tapered pin here, as it has been shown in the diagram; it is a tapered cylindrical pin, but, this tapered cylindrical pin can be of different types, it can have a helical shape, it can be trapezoidal kind of thing, not necessary cylindrical, it can have threads in it.

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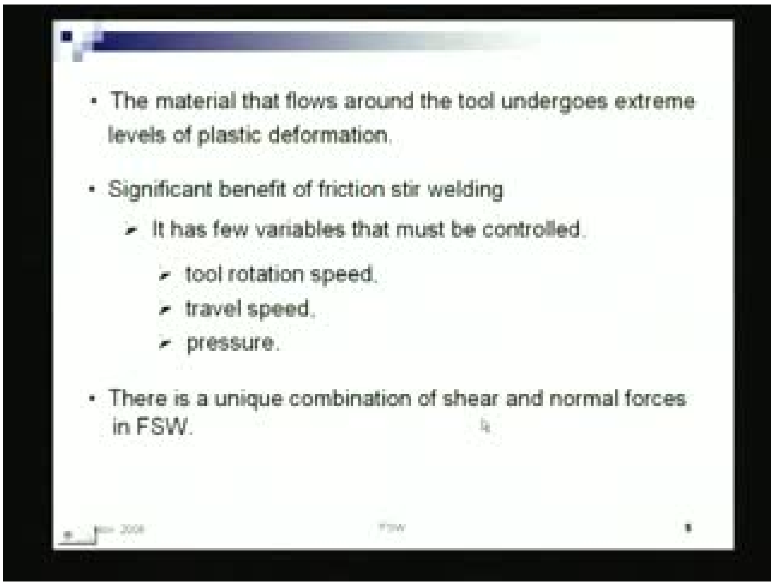

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- There is a unique combination of shear and normal forces in FSW.

Different types of people have tried; so, for a given tool, these are the only three parameters which need to be controlled. So, there is a unique combination of shear and normal. Well, so in FSW, what basically happens is, it is essentially a combination of a normal force and the shearing forces; these are the two kind of forces that...

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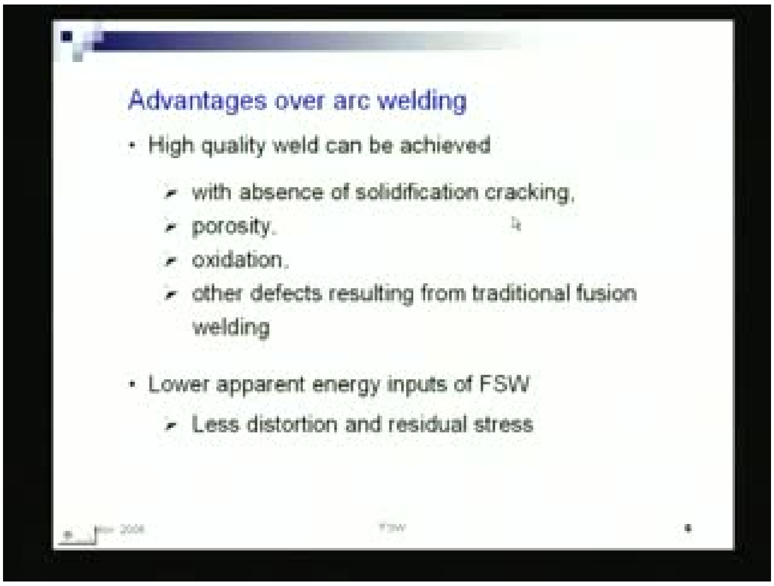

Advantages over arc welding

- High quality weld can be achieved
  - with absence of solidification cracking,
  - porosity,
  - oxidation,
  - other defects resulting from traditional fusion welding
- Lower apparent energy inputs of FSW
  - Less distortion and residual stress

So here, well, explicitly talking about what are the advantages here, the high quality weld can be achieved; what is that high qualities? With the absence of solidification cracking, there is no question of cracking. If you want to see what solidification cracking means, you can come to the work shop in our lab, in our department; we have just done some welding where you can see a very nice solidification.

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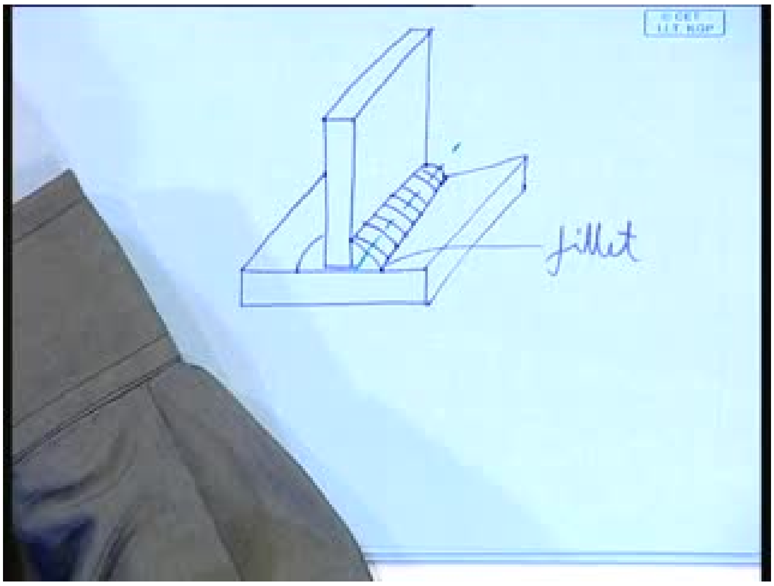

I mean, a case of solidification cracking; what has happened is, a simple fillets joint was made; a T was welded like this, that means, two members, this is called a T t section, T configuration, and this welding is referred to as fillet welding. So, both sides welding was done after it it was it still hot, right?

They were holding as just over and immediately, you see a crack through; and through the crack forming at the middle, all along the length all along the length. So, that is what is referred to as hot crack that means, well, still the metal is hot, it is cracking; and also, referred to as solidification cracking means, it is getting solidified and the cracking is taking place. The metal is getting solidified, right? This this is your deposition; this is the fillet deposition, right? And, along the green line, you find a crack developed all along; that is what is referred to as solidification cracking.

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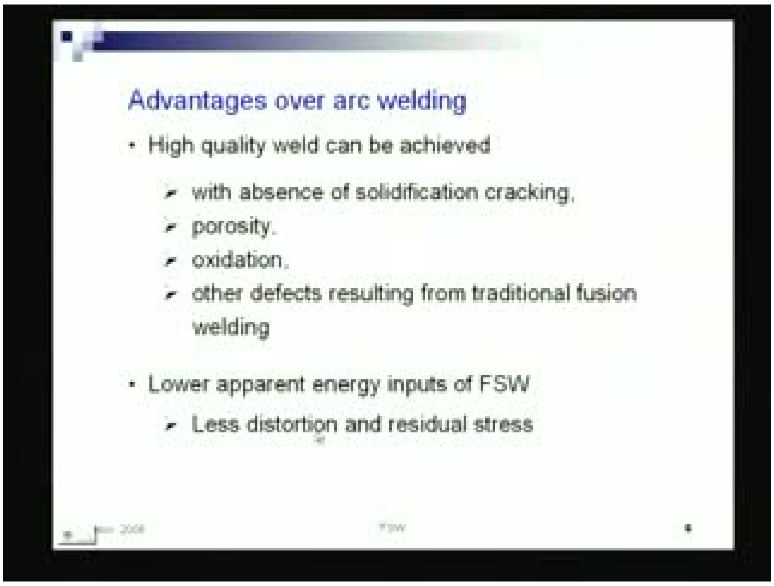

Advantages over arc welding

- High quality weld can be achieved
  - with absence of solidification cracking,
  - porosity,
  - oxidation,
  - other defects resulting from traditional fusion welding
- Lower apparent energy inputs of FSW
  - Less distortion and residual stress

So, if there is no melting, this possibility of cracking will not be there; anyway, similarly, no porosity, right? Porosity means, it caused by because of gas interruption; no oxidation, because there is a here there is no no necessity of shielding. Because, the temperature rise is such that, there is not much of oxidation is taking place additionally, right? So, requirement of shielding is also not there; all other defects resulting from traditional welding fusion welding is also not there.

Basically, all which are involved with fusion, they are eliminated; and, another aspect here, what we see is, apparently lower energy is needed, a lower energy input is there; the rate of heat input is less so, it leads to less distortion and residual stresses. Because, since the metal is not melting, means, obviously, I am putting in, lesser amount of heat, lesser amount of heat. When I am doing fusion welding, the amount of heat going in is mode, but of course, this is not always true; because, in fusion welding, there can be situation where heat going in is mode, but the rate at which it is going in is less. If I can say electron beam welding or or say, plasma arc welding or laser welding, where you have a very intense heat source, but, because of the intense heat source, I can instantaneously melt the necessary material which is being welded; I can instantaneously melt the required amount of electrode so, I can, as well, have a higher speed of movement.

So, the rate at which heat is going in is less; what is important is the rate of heat input, not the absolute heat input. The rate of heat input, at what rate, that means, how many joule per meter is being deposited? So, in FSW, what happens? The overall absolute heat generated is less, but at the same time, the speed of welding is very less here; in fusion welding, one can achieve a higher, much higher speed of welding, so, even if the overall absolute heat is more, since the speed of welding is higher; so, rate of heat input can be less, can be less whereas, in friction stir welding. The absolute heat generated is less, but speed is also less, so, rate of heat input can be higher; but, depending on cases, it it will have a lesser rate of heat input and thereby, less distortion and residual stress.

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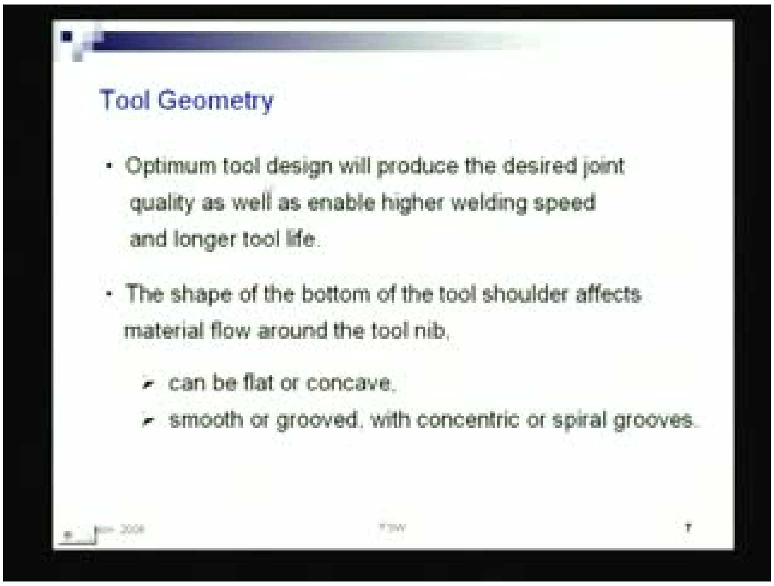

Tool Geometry

- Optimum tool design will produce the desired joint quality as well as enable higher welding speed and longer tool life.
- The shape of the bottom of the tool shoulder affects material flow around the tool nib.
  - can be flat or concave.
  - smooth or grooved, with concentric or spiral grooves.

Well, now let us come to little more in detail about the tool geometry, because the tool is the heart of this process. In electric arc welding, it was essentially the electrical power, right? It was essentially the electrical power which worked towards the generation of heat, the fusion process, and thereby, the welding.

Now here, the most important aspect is the tool the friction stir welding tool, so, optimum tool design will produce the desired joint quality as well as enable higher welding speed and longer tool life. So, these are the aspects you not only you need a good weld quality, you need good speed as well as good tool life. Because here, like in welding, we had well the welding torch that has a very high life; the torch does not get damaged.

The welding torch through which the electrode comes out, say, in a gas metal arc welding or the nozzle, in case of a submerged arc welding, they have a very long life; they do not get damaged. Electrode goes in it, melts it, gets deposited, but here, the tool it gets damaged; you will have to replace the tool possibly, I mean, depending on its life.

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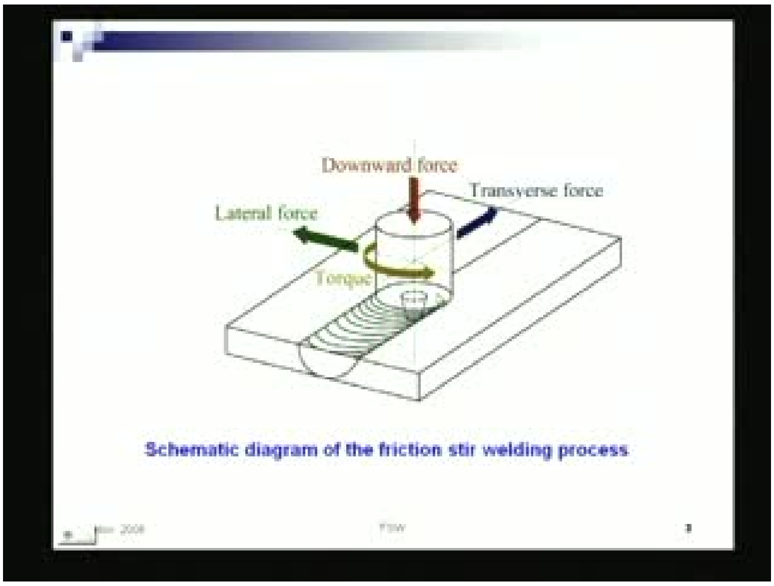

Schematic diagram of the friction stir welding process

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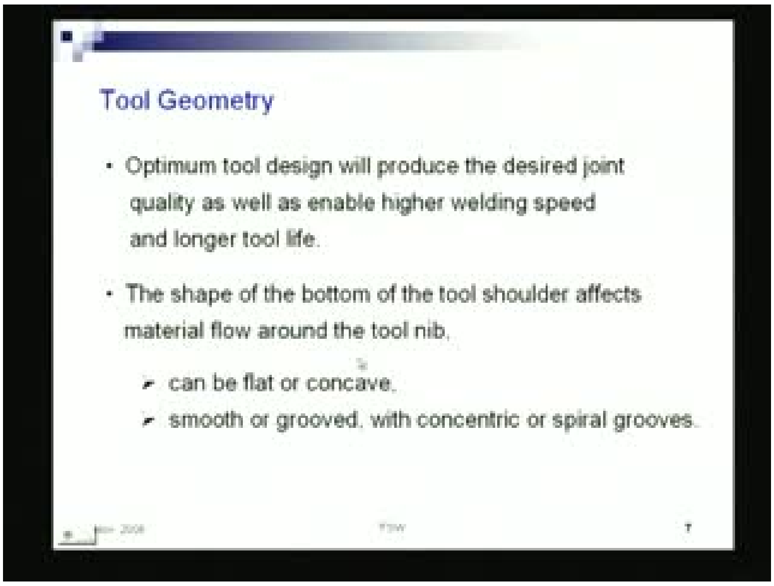

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So, that is, so, these all aspects, they depend on the geometry, also the shape of the bottom of the tool shoulder affects the material flow around the tool nib, how the bottom of the shoulder will be, right? That also will again depend; it can be flat or it can be concave; that means, this shoulder part it can be flat; there is no harm, one can keep it flat or it can be concave, so, this small change can cause a sufficient change in the in the entire operation in the in the in the weld quality, in the entire operation speed; so, as I say, it can be flat or concave, it can be smooth or grooved with concentric or spiral grooves, right?

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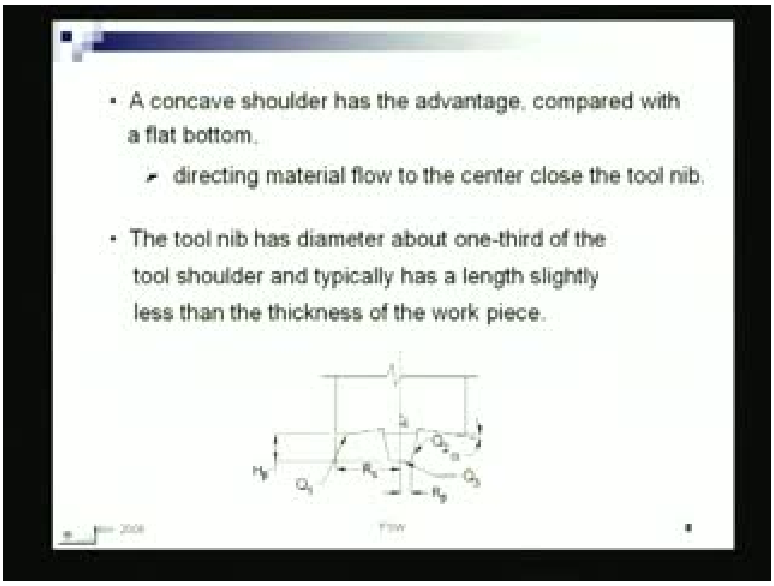

- A concave shoulder has the advantage, compared with a flat bottom.
  - directing material flow to the center close the tool nib.
- The tool nib has diameter about one-third of the tool shoulder and typically has a length slightly less than the thickness of the work piece.

So, a concave shoulder has an advantage; as I was saying, compared with the flat shoulder that, that shoulder so, this is the nib, a small cross section of a... So, this part is the shoulder of the nib; this part is the shoulder of the nib, so, a concave one. This is a concave one, has an advantage; what is that? It directs material flow to the center, close to the tool nib; firstly, it has some space here, right? It has been concaved with an angle of alpha; some some concaving has been done, right? So, there is a small additional gap is there where the extra metal, when that this nib is plunging into the plate.

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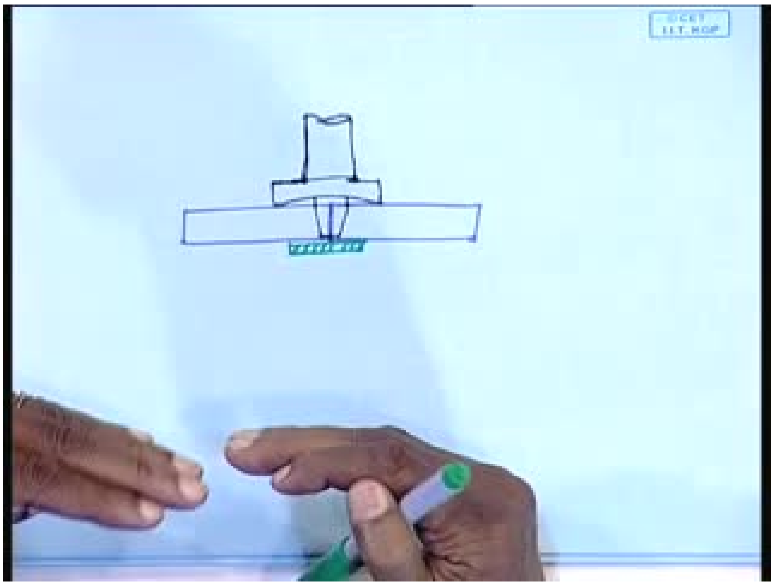

Some material is getting displaced, some metal will tend to come out; so, when the metal is tending to come out, because at the back you have a backing strip, a backing strip is holding the plate, that means, in the welding not may be you; you have the there is a backing strip there, a flat piece of plate is kept at the back, right? There is no need of here, the question of bottom-top; reinforcement does not arise. After welding, it will become one flat uniform plate; in in all other fusion of welding, we had a top reinforcement, we had a bottom reinforcement, right?

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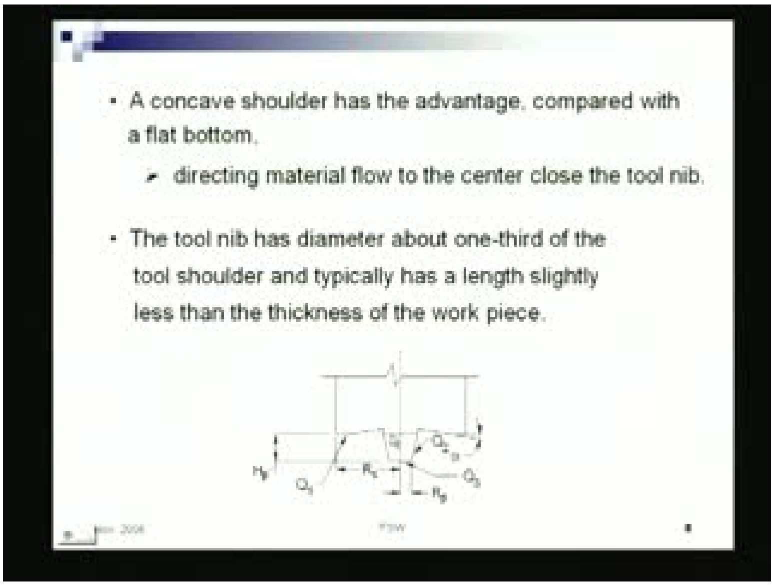

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Additional metal was deposited here; it is not there, it will be a flat both at the top as well as at the bottom; some, so once the tool is there, so once the tool nib is plunged inside, right. So, the surfaces is like this; you have a small gap between the back surface of the shoulder, and this plate; so, when the nib is plunged inside, some metal will try to come out, so, a convex surface can give a can accommodate, that material, so, a convex, sorry concave; a concave shoulder will have that advantage and it will also direct the material to flow in that; a better flow will be there

Well, the tool nib is this. What is called, referred to as nib has a diameter about one-third of the tool shoulder and typically, has a length slightly less than the thickness of the work piece; that one third of the tool shoulder means nib at the root. The diameter here, the diameter of the nib at the root is generally one-third. These these are all, I mean, there is no harder and fast rule; that it has to be so much or that much. What will decide this diameter?

If the diameter is too small, it has too lesser strength, so, the translational force it would not be able to withstand, it may break off; if it is too big, too much of translational force is necessary that also may not be good, right? So, you will have to, these are the aspects what which are to be looked into while designing or decide the component, what should be the diameter of this? This one-third business is nothing but the ratio of these two diameters, right.

If this nib diameter root at the root is more, this has to be more; the entire shoulder diameter will be more if the nib diameter is less; the shoulder diameter also can be made less, it is generally on the ratio of 1 is to 3, that is what. So, if I am welding, assume I am welding two aluminum plates; suppose, for for and a certain thickness of aluminum plates say, 10 millimeter thick aluminum plates are being welded. So, for that, I need a certain kind of a tool geometry having the this pin diameter of say 8 millimeter. Now, if I want to weld a twenty millimeter thick aluminum plate, may be this 8 millimeter will be too less; you will have to increase that.

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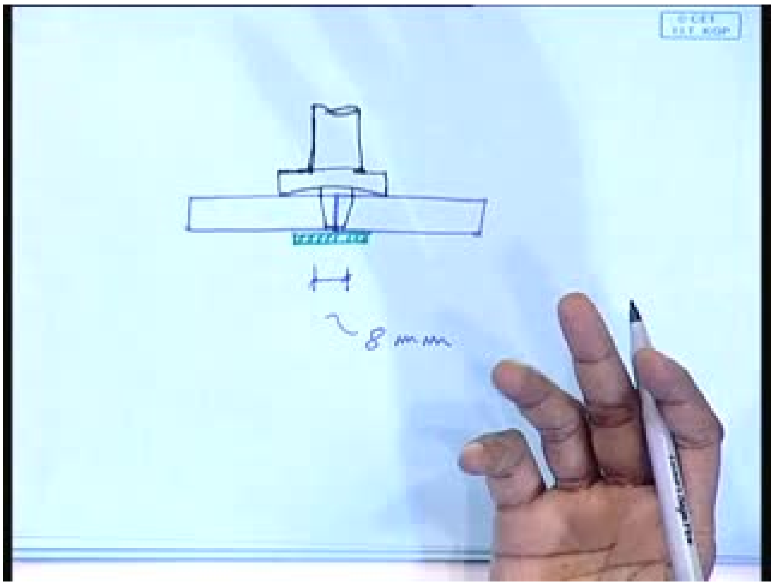

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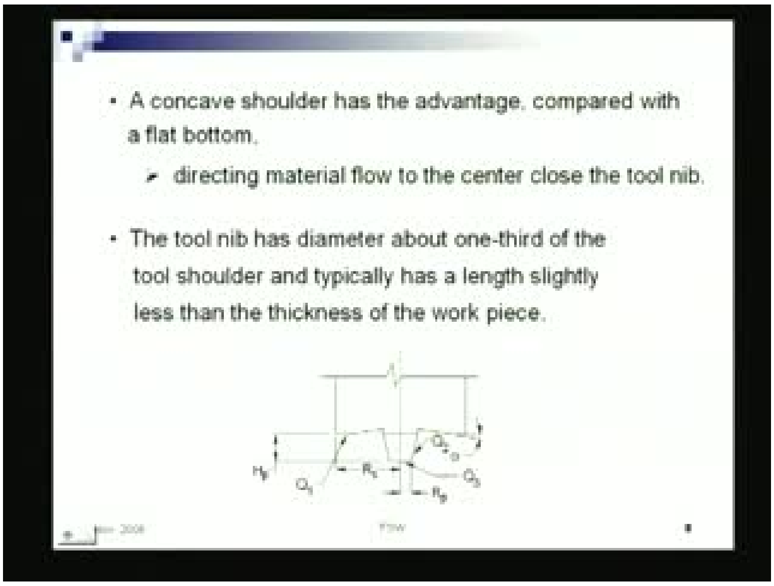

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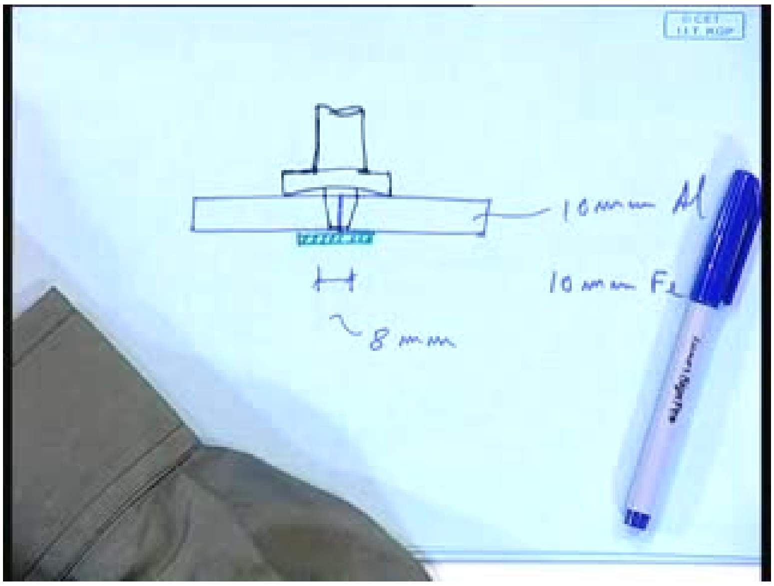

Otherwise, it will not have enough strength, it may break off; or, think of it is 10 millimeter aluminum. Now, assume you are welding 10 millimeter steel; it can be different altogether; because, for this steel, you need much higher. The material is much much much more, I mean, stronger; much harder than aluminum, right? And, to make it sufficiently softer, to apply the solid state welding process, you have to raise the temperature much more. You will have to attain around 800, 900 or probably 1000 degree centigrade, right?

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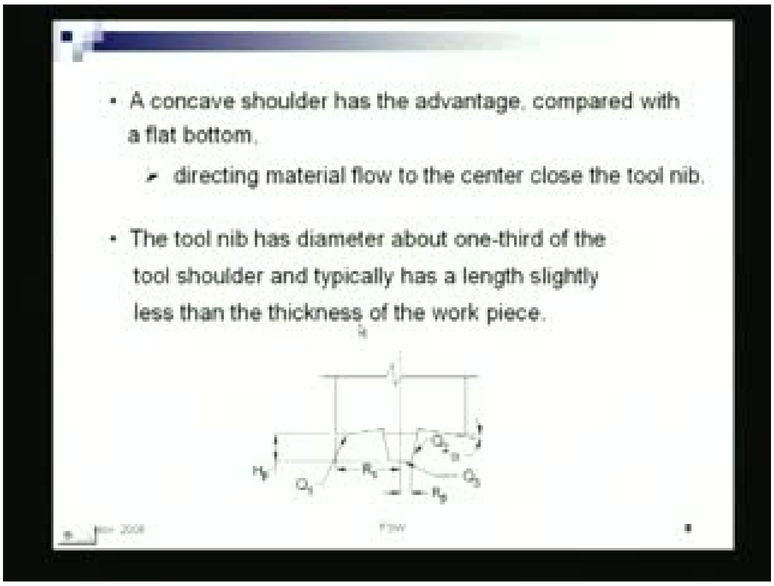

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So, there again, this diameter will matter, that how much you are putting, right? Anyway, so, these are some of the aspects which will decide on the diameter of the tool nib; and another thing is the length the height of the nib, how much is that?

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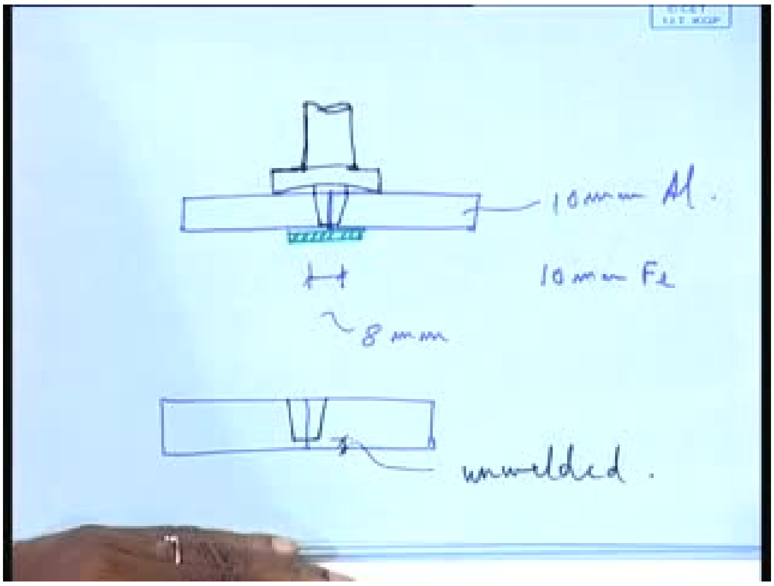

Just less than the thickness of the work piece; for, you can see the configuration, how the welding is done? If if it is more than the thickness of the work piece it will cut through, right? If it is little less, somewhat less, than that then there will be an un-fused zone, so called un-welded zone; that means, if the plate thicknesses, plate thicknesses this, and so this is my the butt, and the nib is such that it plunges inside, up to this much.

Then, what happens? This part remains un-welded; this part remains un-welded which will be a gross defect, because that un-welded part will act as an essentially a discontinuity in the structure, that will act as a crack equivalent to that of a crack, so obviously, the structure will fall at that point. So, you will have to have that, how much not exactly equal to that of the plate thickness, being welded little less than that, why? Because, under the pressure, it will plunge further inside.

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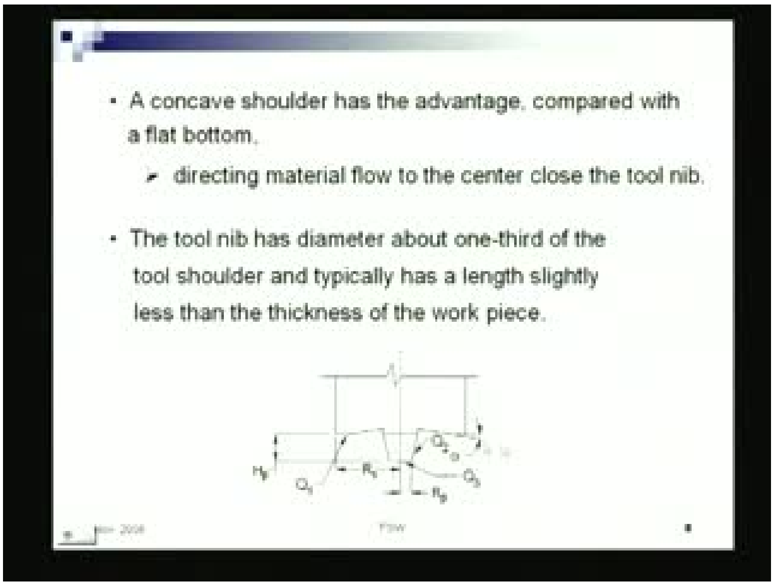

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So, that again brings in another limitation; that means, for every thickness of plate, you will have to have a tool like a single welding torch, can weld plate of 5 millimeter as well as plate of 50 millimeter; it depends on how many run you go on giving, you go on depositing. But here, a tool for 10 millimeter will not be suitable for welding a 12 millimeter plate or 8 millimeter plate; you will have to have, for every thickness of plate, you will have to have a tool for that, because of the nib dimension.

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So, these are some of the types of tool; as you can see, have been these nibs, you have all kinds of configurations, right? All kinds of different configurations, so, this is what is the shoulder, right? This this this part is referred to as the shoulder of the of the tool, right? And, this is the nib which plunges inside.

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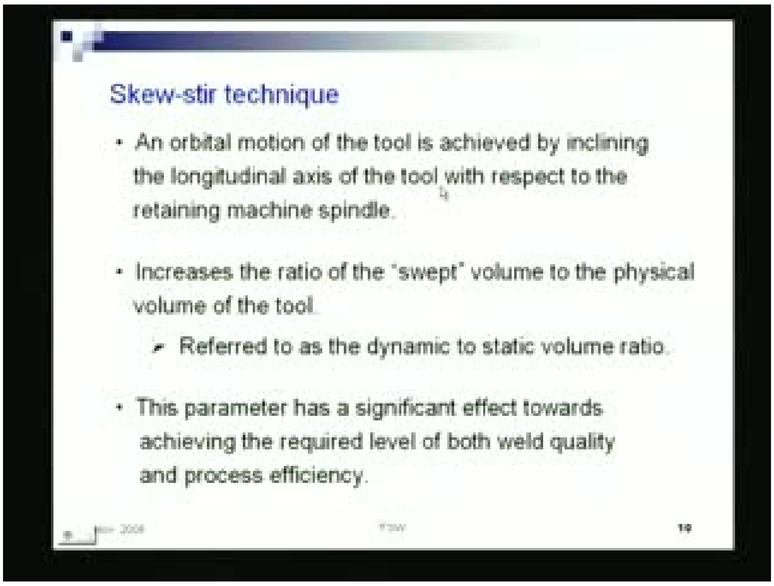

Skew-stir technique

- An orbital motion of the tool is achieved by inclining the longitudinal axis of the tool with respect to the retaining machine spindle.
- Increases the ratio of the "swept" volume to the physical volume of the tool.
    - Referred to as the dynamic to static volume ratio.
- This parameter has a significant effect towards achieving the required level of both weld quality and process efficiency.

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This another technique within that welding it is it is a it is an orbital motion of the tool, is given, is achieved by inclining the longitudinal axis of the tool; in these cases, my longitudinal axis is perpendicular to the plate surface.

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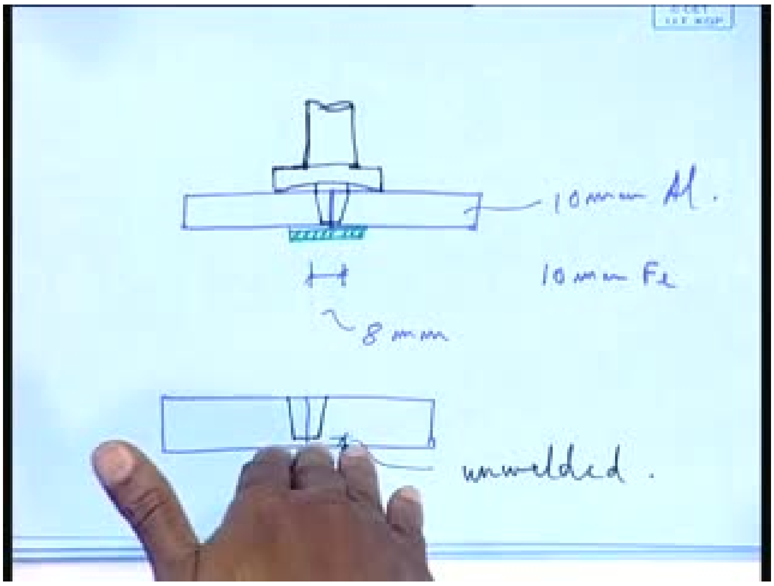

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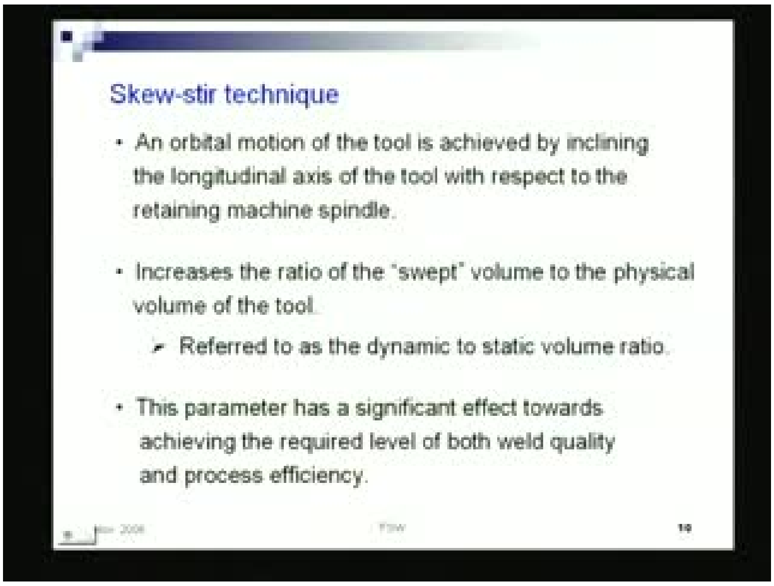

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Now, if I incline it a little bit, then what happens? It will give a squeezed motion, it will give a squeezed motion; an electrical motion will be executed, right? So, that increases the ratio of the swept volume to the physical volume of the tool. When the tool axis is perpendicular to that of the plate, then the amount of metal being swept, being moved from the trilling edge to the, from the forward edge, leading edge to the trilling edge; the metal being stirred metal being moved is equal to the volume of the tool nib.

Because, that the nib is penetrating in the metal, that much of amount of metal is getting displaced; but, if I incline the axis of the same tool, then what will happen? It will move in in this fashion, a skewed fashion, right? And, execute a motion, wherein the swept volume will be more than the physical volume of the tool.

Right, so, that is what is being said that the it increases the ratio of the swept volume to the physical volume of that tool, which is referred to as the dynamic to static volume ratio. Static volume is the one, is the volume of the tool of the nib of the probe; it is referred to as nib, it is referred to as probe, right? A small part; and in dynamic state, it is sweeping a bigger volume, so, these parameters has a significant effect towards assuming, required level of both, weld quality as well as process efficiency, this this ratio.

Anyway, that they are not much. We have said that, how it will affect if the volume is more or less; but, this another technique which also can have a have have a significant effect on the process efficiency .

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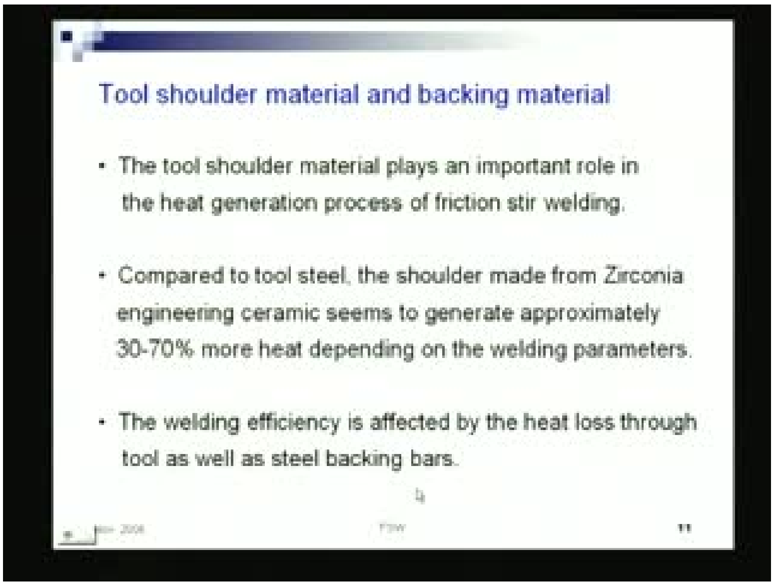

Tool shoulder material and backing material

- The tool shoulder material plays an important role in the heat generation process of friction stir welding.
- Compared to tool steel, the shoulder made from Zirconia engineering ceramic seems to generate approximately 30-70% more heat depending on the welding parameters.
- The welding efficiency is affected by the heat loss through tool as well as steel backing bars.

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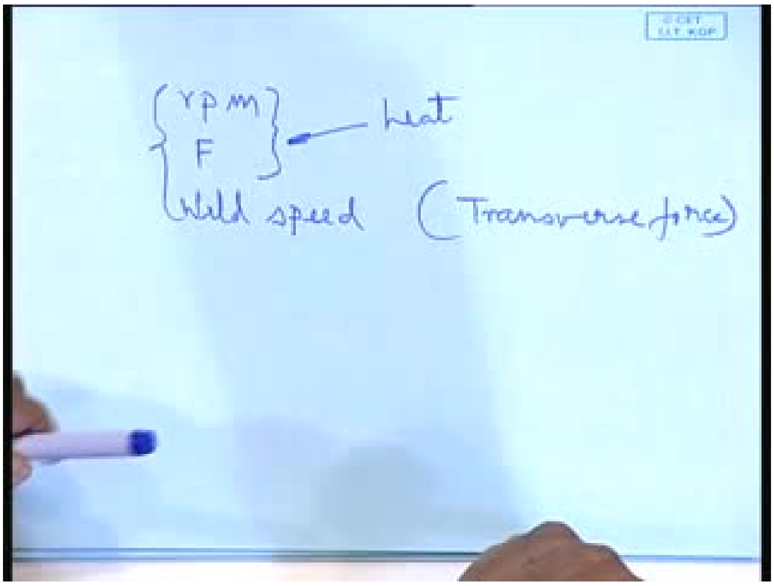

Well, let us go to the tool shoulder material and the backing material; as I already mentioned, the tool shoulder material plays an important role in the heat generation process. Because, here you see in the friction stir welding, we said that the primary parameters are nothing; but your primary primary parameters are, well, RPM downward force, right? And and what is that? And the weld speed, we can say, instated of this will correlate to transverse force, transverse force or translational force; that means, to move, make it move; but controllable parameters are this increasing weld speed, decreasing weld speed; well, this force may be more or less etcetera, right?

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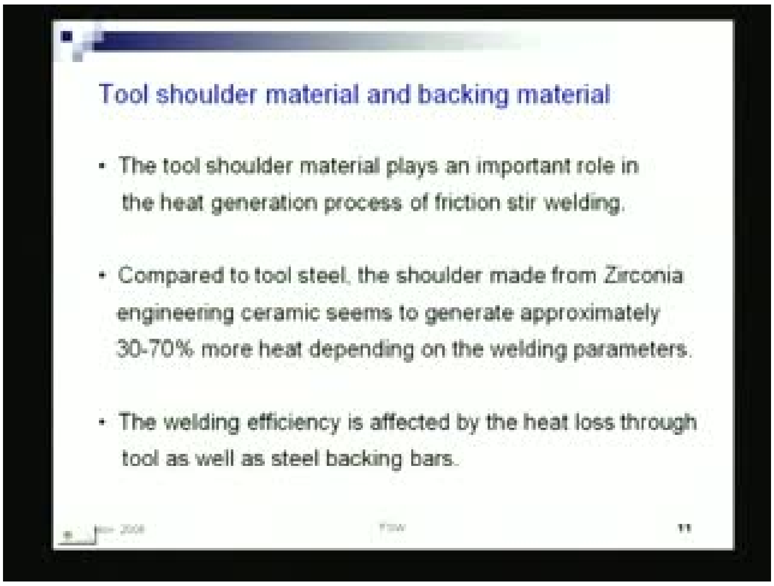

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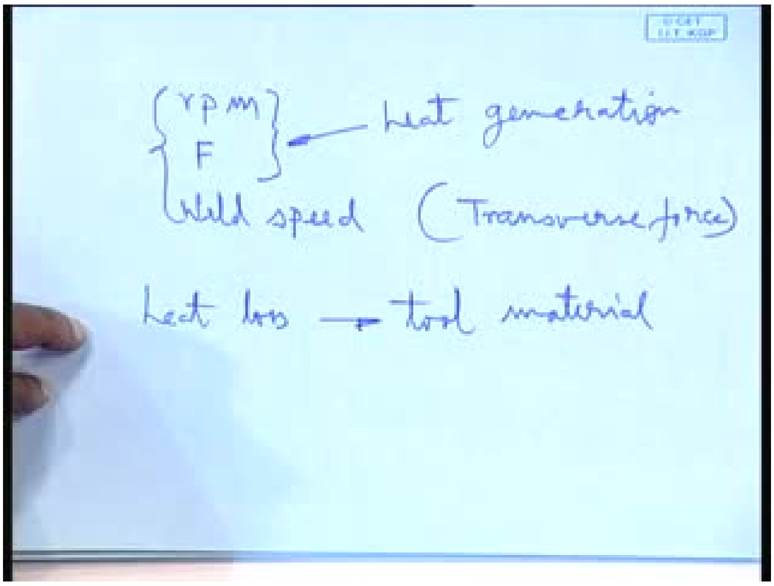

$\left.\begin{matrix} rpm \\ F \end{matrix}\right\} \leftarrow$ heat generation

Weld speed (Transverse force)

heat loss → tool material

But, essentially, if these two are responsible for the heat generation, more the RPM, more is the heat, right? More the force, more is the frictional frictional for a given material, more is the frictional force, so, more is the heat. So, the total heat generation depends on the downward force, and the RPM, they are the two basic parameters, so downward force and RPM gives the controls, the heat generation - primary thing and then comes, how much heat is utilized.

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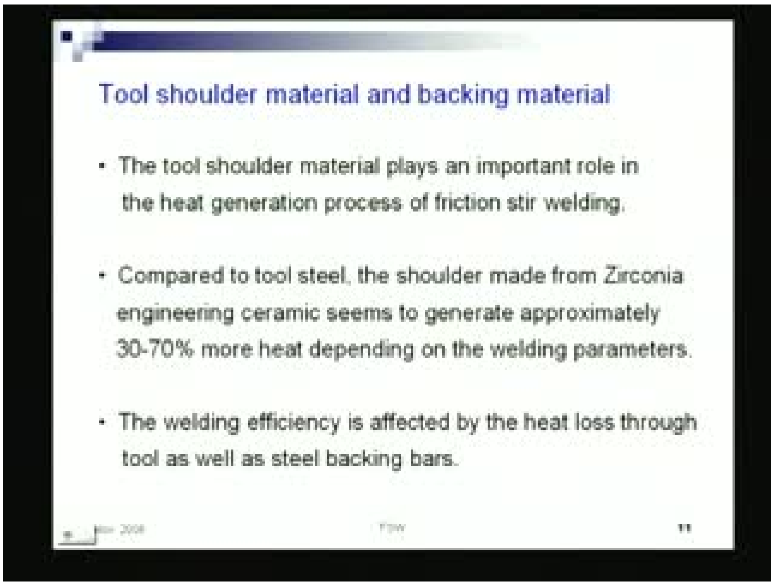

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That means, what is the heat loss? So, heat loss, if we talk about one of the most important, is the tool material; because, you see, the the whatever heat is generated, that is generated locally, like in case of fusion welding, because of the arc heat, the immediate metal gets melted and that heat gets conducted, and thereby further metal is melted and other aspects or deformation of stresses are formed here, because of the local friction. Locally, heat is generated, and the heat gets conducted to further plastify the material, right? So, the entire heat is content in the location where the nib is, where the tool is, right? So, here, the case of heat loss, like in case of in case of electric arc welding, say gas metal arc welding, we will say thermal efficiency is of the order of 0.6

Why that? What does that mean? That means 40 percent of the heat generated is wasted. How is it wasted? One of the waste was because of the inert gas shielding is being given; that means, you are putting in a jet of inert gas, so, that is taking out the heat by way of convection. convection Then, some part is lost by way of conduction in the plate; some part is lost by way of conduction in the electrode; some part is lost by way of radiation from the surface, right?

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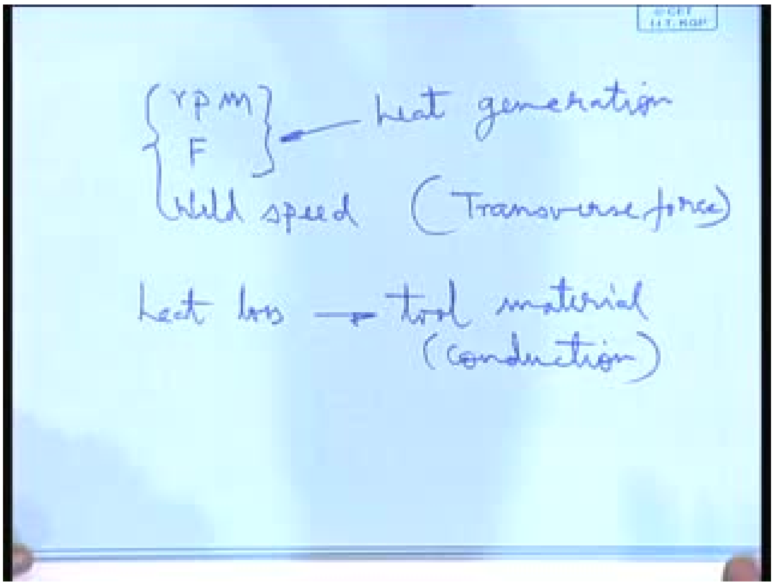

rpm
F
Weld speed
← heat generation
(Transverse force)

heat loss → tool material
(conduction)

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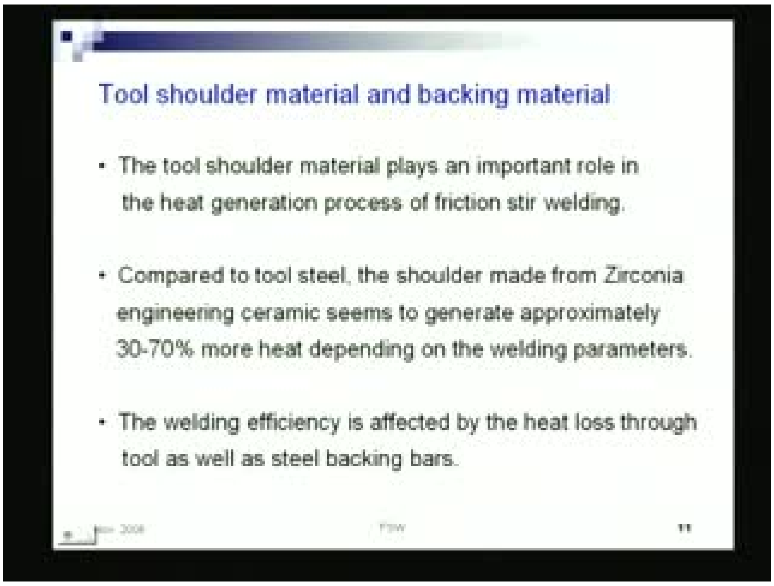

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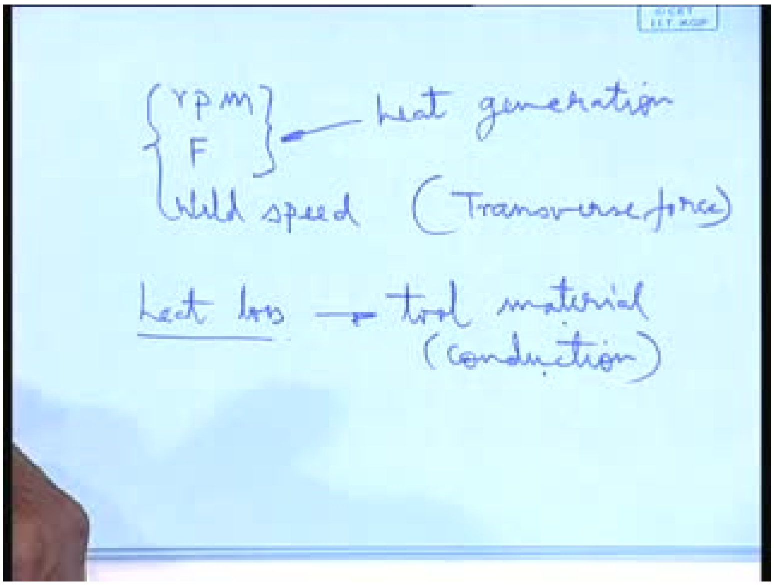

rpm
F
Weld speed

heat generation

(Transverse force)

Heat loss → tool material
(conduction)

Here, the primary loss is conduction through the tool material; because, there is no inert gas flowing in the thing, such that, a convectional loss would be there. There is no much of radiation loss, because, the heat generated is much less radiation loss, as you know it is proportional to the t to the power 4, right?

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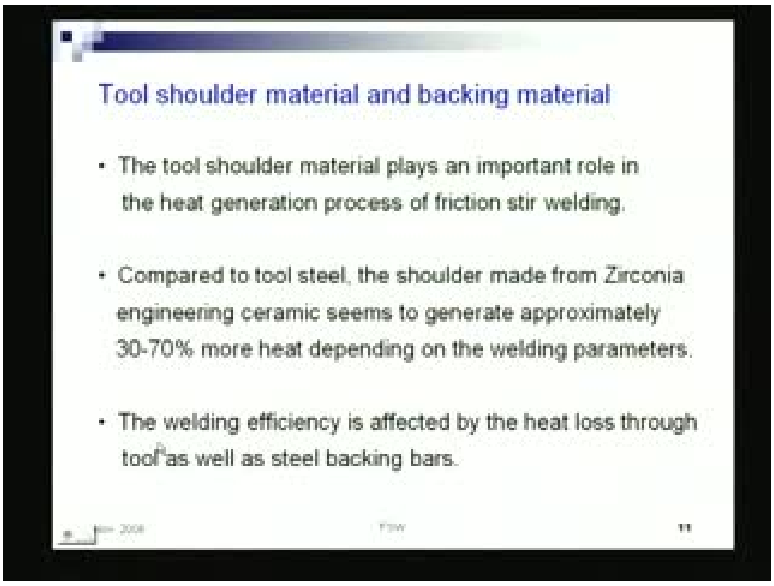

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And, the primary heat which is generated is covered by the shoulder material so total heat loss would be by your conduction through the tool material so that is how the tool material plays an important role in the process.

So, if we use a very conducting material and make a tool out of it, your weld will be of of a of, I mean, you may not be able to achieve required required quality of the weld, because much of heat will be lost, right?

So, that is how that plays an important role; compared to tool, steel, the shoulder here, some example has been given. The shoulder made from Zirconia Engineering Ceramic seems to generate approximately, you see the difference, 30 to 70 percent more heat depending on the weld parameters; weld parameters means nothing but F and RPM, downward force and the RPM; these are the two basic parameters.

What is this tool steel? Tool steel is nothing but a type of steel which is, I mean, from, which you generally make those lathe lathe machine, tool beads, drill beads all that; that means they are of sufficient hard, I mean, sufficient strength, they have; and also, they can use in sense, sufficient raise in temperature, sufficient level of high temperature and still maintain the required strength.

So, it says that the shoulder, the shoulder portion, if it is made of zirconia, then it can give more heat, what extent? It can be as high as even 70 percent extra heat; why? Essentially, this zirconia increases the coefficient of friction that is number 1; and number 2, it is a very good insulator; that means, heat loss is reduced substantially, provided one can use this then you have this benefit.

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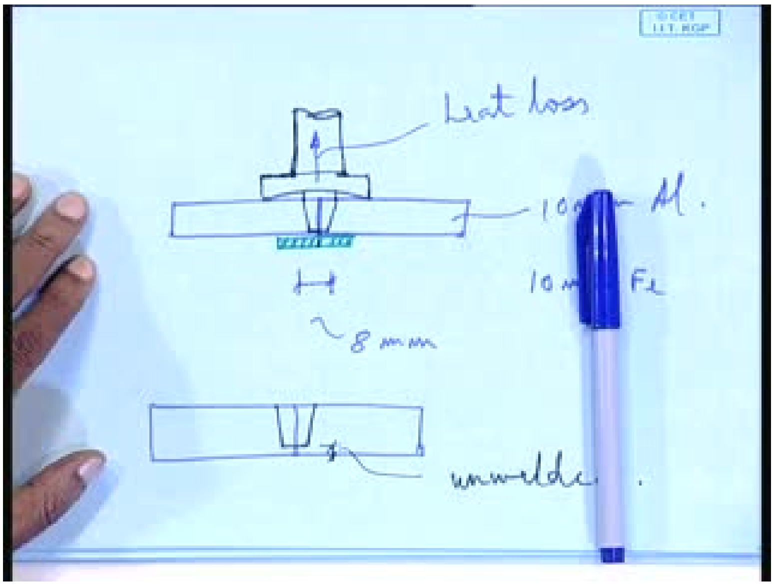

Welding efficiency is affected by the heat loss through the tool as well as the backing bar; so, that is also is there, the backing bar. So, as you can see the heat is generated here, so, heat loss would be through the through the tool as well as through the backing bar; also, heat loss would be there in the bar, that means, the backing bar also will take out heat, right.

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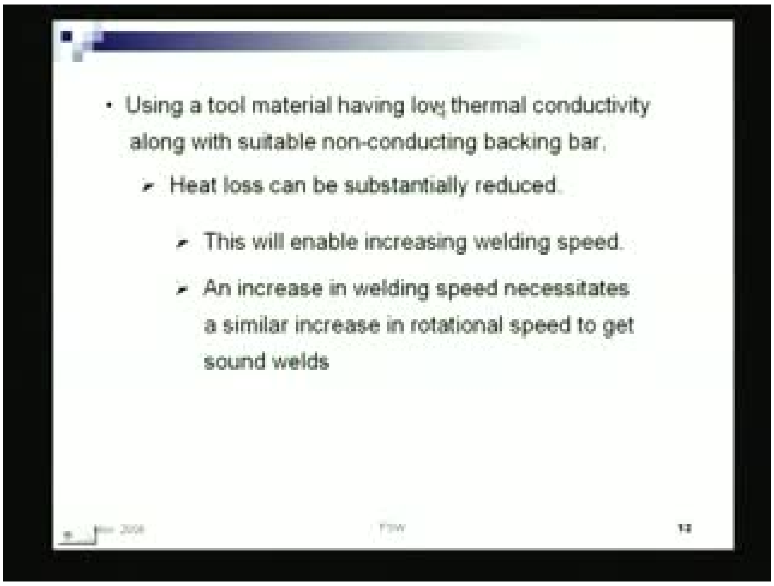

- Using a tool material having low thermal conductivity along with suitable non-conducting backing bar.
  - Heat loss can be substantially reduced.
    - This will enable increasing welding speed.
    - An increase in welding speed necessitates a similar increase in rotational speed to get sound welds.

So, that again tells us, the what the backing bar material should be. That means, it also ought to be of a material which has a lesser thermal conductivity; using a tool material having low thermal conductivity along with suitable non-conducting backing bar heat loss can be substantially reduced; this will, and once this can be reduced, it will enable increasing welding speed, right? Increase in welding speed necessitates a similar increase in rotational speed to get sound sound welds.

So, once the once you can reduce the heat loss by providing suitable material for tool as well as backing bar, you can go for a high heat generation, means, you can increase the weld speed; and once you increase the weld speed, then also it says to have the simultaneous; in the rotational speed also may need to be increased to get sound welds.

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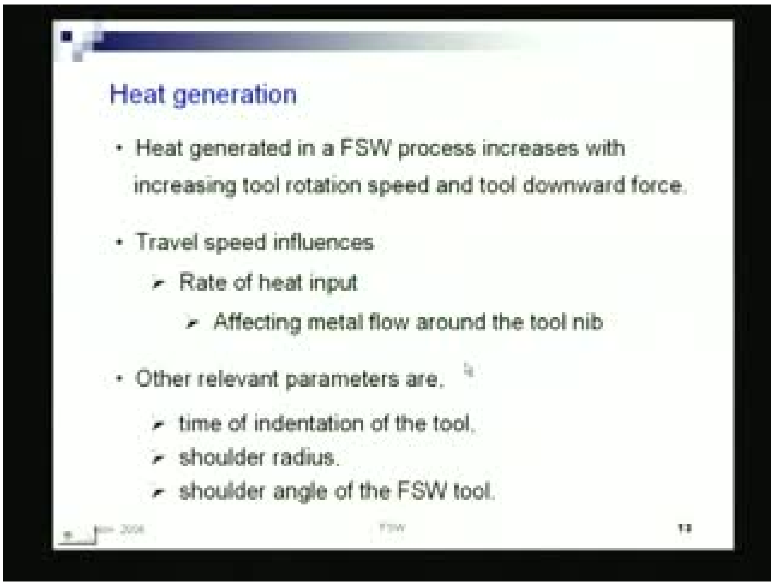

Heat generation

- Heat generated in a FSW process increases with increasing tool rotation speed and tool downward force.
- Travel speed influences
  - Rate of heat input
    - Affecting metal flow around the tool nib
- Other relevant parameters are,
  - time of indentation of the tool.
  - shoulder radius.
  - shoulder angle of the FSW tool.

So, then we come to see how heat is generated and how it is quantified in this. So, heat generated in FSW process increases, right? As we have already said, with increasing tool rotational speed as well as downward force, the simple reason as the downward force increases your frictional force increases. Travel rate influences rate of heat input same as that of fusion welding; with the travel rate higher, the travel speed higher; the welding speed less is the rate of heat input; and here, it affects a metal flow around the tool nib.

Metal flow around the tool nib is so, very high travel speed, you may not be able to have the material stirring action properly like in fusion welding; at very high travel speed, what happen? Very high travel speed may lead to defects like undercut, that means, the metal could not flow or fill up the entire gap, entire root gap, entire entire joint, geometry such that you achieve a proper top bead profile, top top top reinforcement. So, there is a lack of deposition on the sides of the weld bead or the top reinforcement, if there is a lack of deposition on the side that leads to undercut, that defect is called undercut.

So, that would have happen if you have a high welding speed? Because, before the molten metal could distribute your itself evenly, as well as sufficient of base metal has been melted, it moves out high welding speed; means, what you are moving away, the heat source you are not allowing the heat to remain in the place for a longer time or in other words, heat residence time is reduced; once the heat residence time is reduced means, what faster freezing will take place metal, will solidify very fast.

There can be lesser melting of the parent metal; it will take place because, parent metal is not getting enough heat. So, it will lead to defects like undercut; it will leads to defects like porosity, because, gas will get interrupted; it cannot come out, it might lead to defects like slag inclusion, because the molten slag may remain interrupt; because, it should float up when the welding is being done; there is a channing action going on in the molten metal. So, in the channing action, the metal is moving above the molten slag, is moving above; they are all mixed, so, it should have time to float up. Now, if I move the heat very fast, it will solidify, right? So, all those defects may occur. Similarly, here the travel speed, the rate of it will affect the rate of heat input.

Here, it will affect the material flow, because here, the physical metal flow is taking place from the leading edge to the trailing edge around the nib; the metal is getting stirred, right? All the relevant parameters are for heat generation; this is a time of indentation of the tool, the shoulder radius, how big is the radius. Obviously, because the shoulder adds to it, supplements; the heat, the friction from the shoulder, the shoulder angle and the FSW tool of the FSW tool, that angle which we were talking about.

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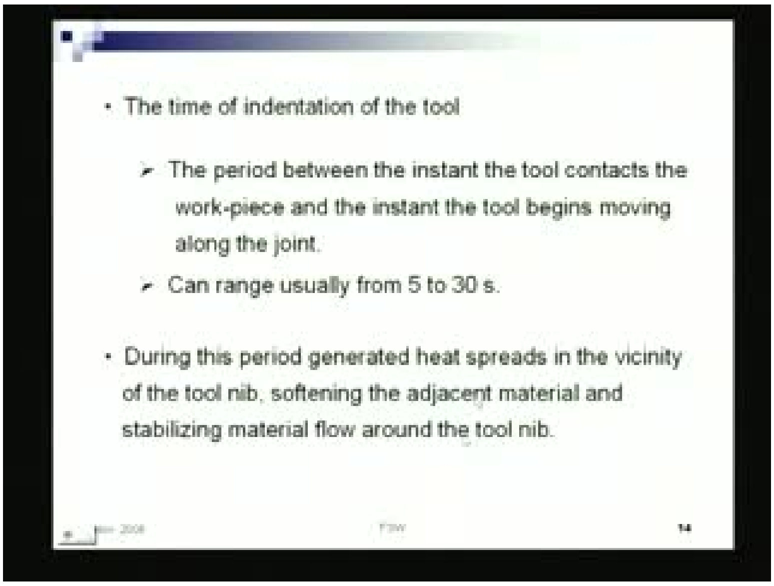

- The time of indentation of the tool
  - The period between the instant the tool contacts the work-piece and the instant the tool begins moving along the joint.
  - Can range usually from 5 to 30 s.
- During this period generated heat spreads in the vicinity of the tool nib, softening the adjacent material and stabilizing material flow around the tool nib.

Well, the time of indentation of the tool, that indentation means, the period between the instant, the tool contacts the work piece and the instant the tool begins moving along the joint, that time is important. When? Because, when the tool is, it is it is rotating and it touches the surface.

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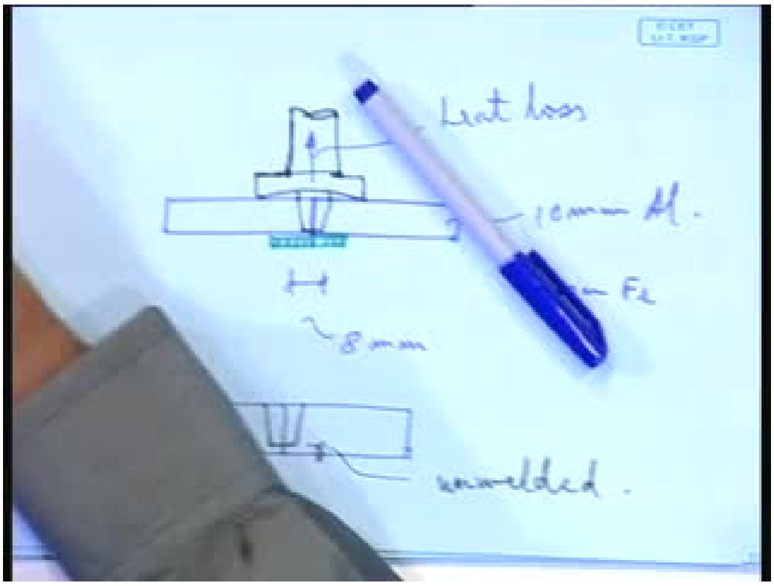

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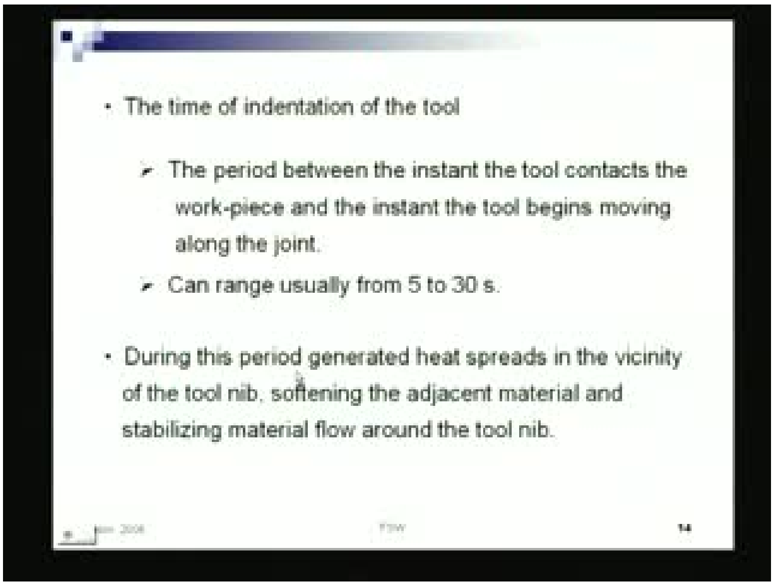

- The time of indentation of the tool
  - The period between the instant the tool contacts the work-piece and the instant the tool begins moving along the joint.
  - Can range usually from 5 to 30 s.
- During this period generated heat spreads in the vicinity of the tool nib, softening the adjacent material and stabilizing material flow around the tool nib.

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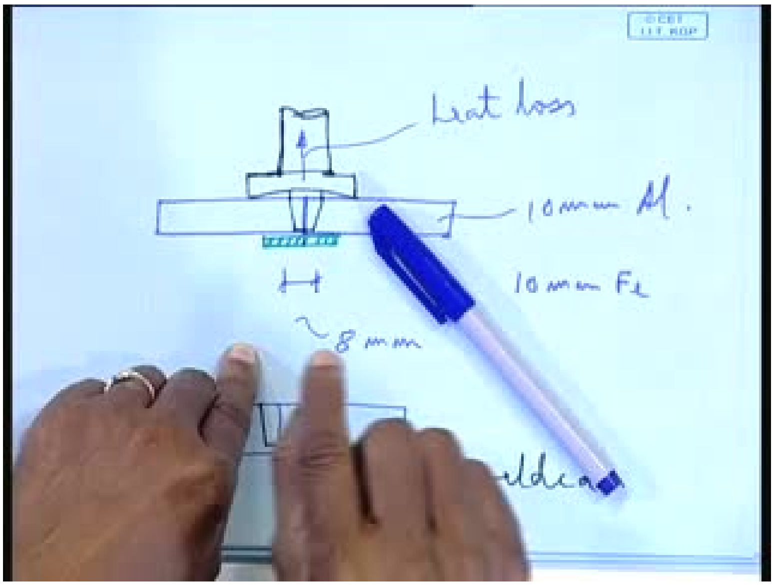

It is still rotating and you are applying a downward force. So, it will plunge inside and then, you will start moving it, right? Then you will start moving it; so, how long you have hold it at that place and then, started moving it? That is the indentation time, that time can range from 50 to 30 seconds; because, longer it is, there it is generating more and more heat, but after some time, it attains a steady state; it does not generate further heat, but the cooling starts, because when it is rotating, it has gone inside; the friction is decreased. Because, the, it has, initial friction will be very high, but the plate has material, has become softer; under the heat, friction has decreased. So, there can be a reduction in heat generation.

So, the indentation time, if you keep for a very long time and then try to move, it wll not move; because, the heat it has, a plate has cooled down, right? Whereas, you you plunge it down, and immediately try to move, you may break the nib, because the plate ahead has not become soft enough.

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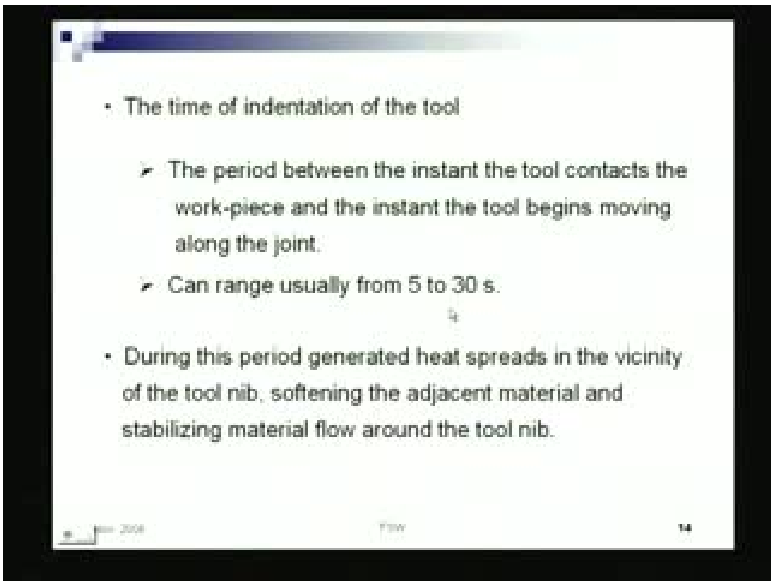

- The time of indentation of the tool
  - The period between the instant the tool contacts the work-piece and the instant the tool begins moving along the joint.
  - Can range usually from 5 to 30 s.
- During this period generated heat spreads in the vicinity of the tool nib, softening the adjacent material and stabilizing material flow around the tool nib.

You will have to give some time to heat also, enough heat to get generated and the heat to flow, right? So, that is what is the indentation time; it is around 50 to 30 seconds; so, these are the final kind of parameters one can say which controls the welding process. We said here, we have primarily three variables, weld variables, that is, your downward force, RPM and the travel speed. Indentation time is one of the final variables during this period; generated heat spreads in the vicinity of the tool nib, softening the adjacent material, and stabilizing material flow right around the tool nib.

So, that is how we can see, that is something equivalent to, like something equivalent to your plate cutting using oxyacetylene flame. You will have to heat it up to the required required temperature where the ignition process starts the oxidation process, rigorous oxidation process starts, right? And then, you keep moving continuously.

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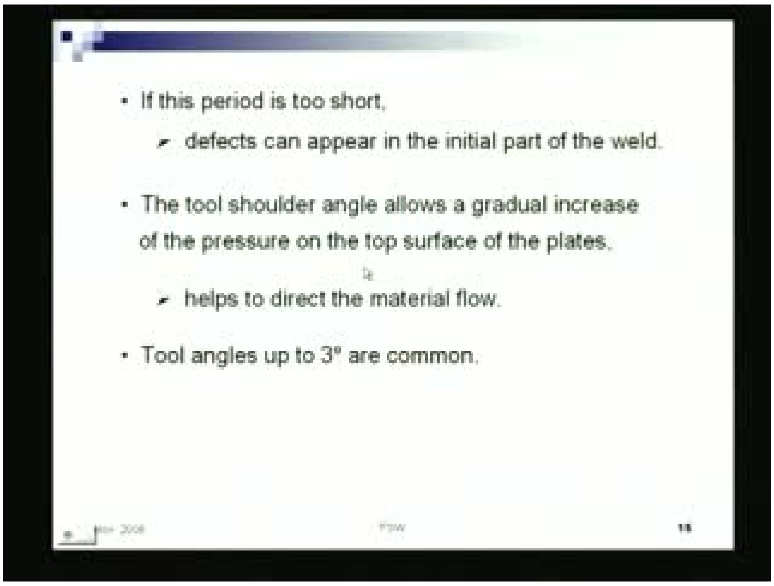

- If this period is too short,
  - defects can appear in the initial part of the weld.
- The tool shoulder angle allows a gradual increase of the pressure on the top surface of the plates.
  - helps to direct the material flow.
- Tool angles up to 3° are common.

Here, the indentation time is at the initial, and then you go on moving it; you would not have to stop anywhere. If the period is too short, defects can appear in the initial part of the weld; the tool shoulder angle allows a gradual decrease, allows a gradual increase of the pressure on the top surface of the plate, right? This about the shoulder angle; the angle is generally of the order of three degrees; this very nominal angle is provided.

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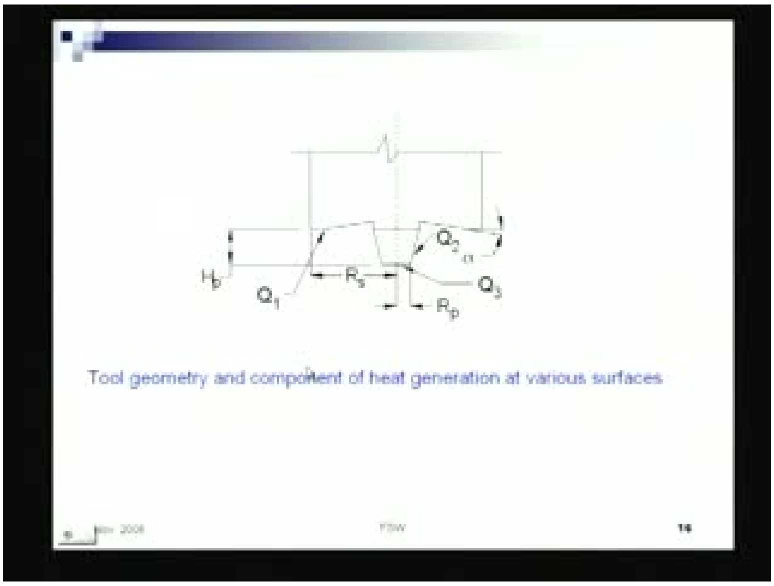

Tool geometry and component of heat generation at various surfaces

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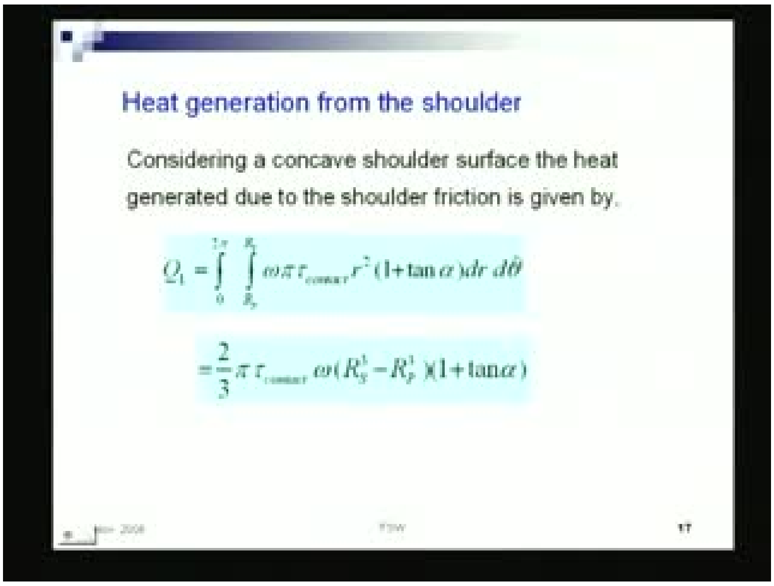

Heat generation from the shoulder

Considering a concave shoulder surface the heat generated due to the shoulder friction is given by.

$$Q_1 = \int_0^{2\pi} \int_{R_p}^{R_s} \omega \pi \tau_{contact} r^2 (1+\tan\alpha) dr\, d\theta$$

$$= \frac{2}{3} \pi \tau_{contact}\, \omega (R_S^3 - R_P^3)(1+\tan\alpha)$$

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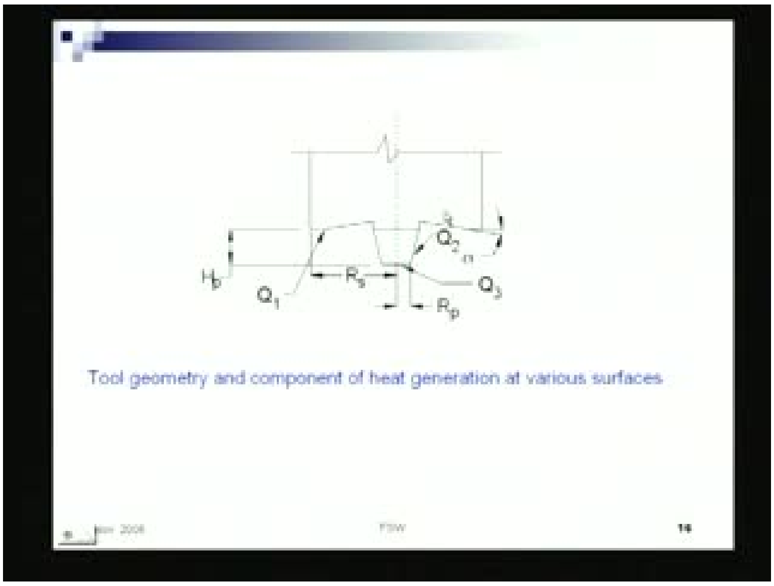

Tool geometry and component of heat generation at various surfaces

This geometry what we have already seen, this angle, this alpha, this angle is barely around 2 to 3 degrees anyway. These are some of the things; it is essentially, it depends the heat generation; because you see, the heat is generated from three surfaces; first it is the bottom surface, this flat part it touches; then, this surface of the nib; and then, shoulder and here, the shoulder also. You see, once it is concave, this shoulder does not generate any heat, because that is not in contact immediately.

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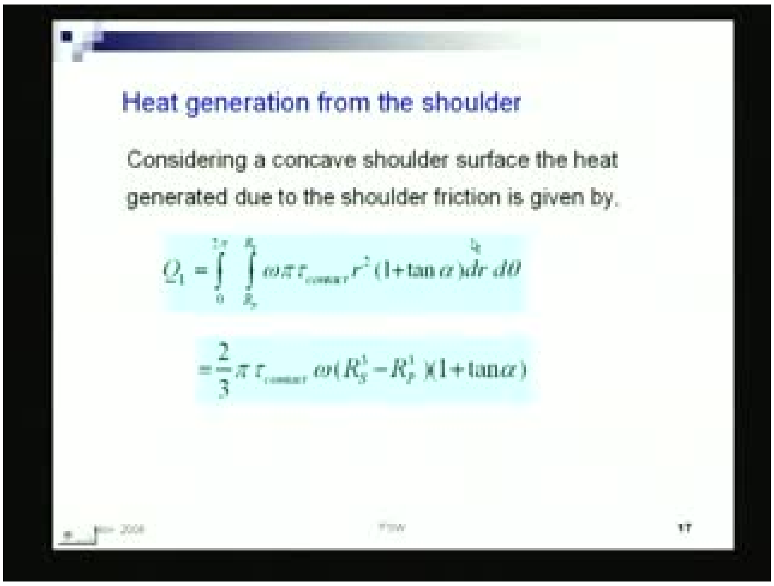

Heat generation from the shoulder

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$$Q_1 = \int_0^{2\pi} \int_{R_p}^{R_s} \omega \pi \tau_{contact} r^2 (1+\tan\alpha) dr\, d\theta$$

$$= \frac{2}{3} \pi \tau_{contact}\, \omega (R_S^3 - R_p^3)(1+\tan\alpha)$$

Only when some metal is getting expelled; if it is, then there will be some contact; otherwise, the shoulder at the periphery which is flat again, which is being contact; so, there are the components of the... So, considering the concave shoulder, the heat generated is calculated; it is primarily, the omega is the it is your RPM, the angular velocity.

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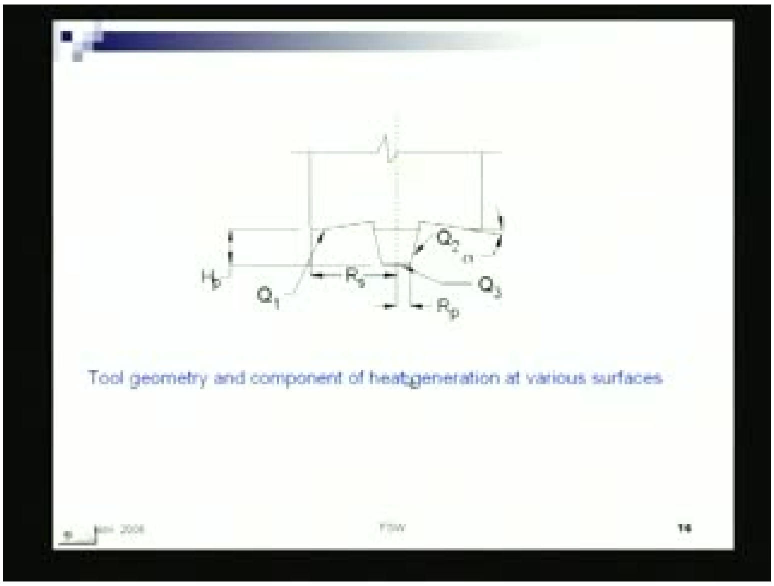

Tool geometry and component of heat generation at various surfaces

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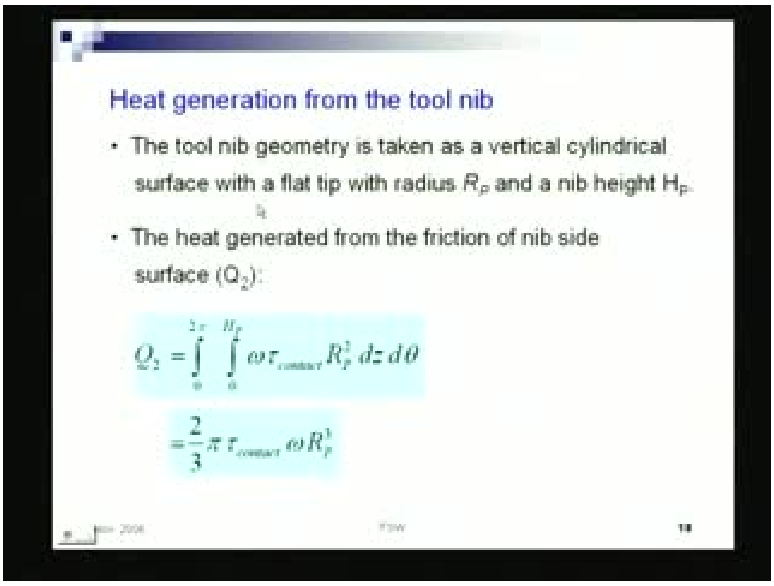

Heat generation from the tool nib

- The tool nib geometry is taken as a vertical cylindrical surface with a flat tip with radius R_p and a nib height H_p.
- The heat generated from the friction of nib side surface (Q_2):

$$Q_2 = \int_0^{2\pi} \int_0^{H_p} \omega \tau_{contact} R_p^2 \, dz \, d\theta$$

$$= \frac{2}{3} \pi \tau_{contact} \omega R_p^3$$

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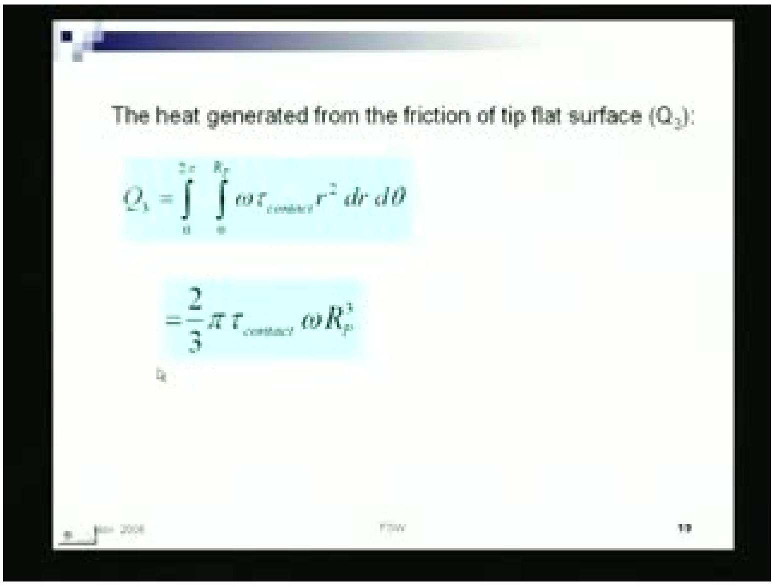

The heat generated from the friction of tip flat surface (Q_3):

$$Q_3 = \int_0^{2\pi} \int_0^{R_p} \omega \tau_{contact} r^2 \, dr \, d\theta$$

$$= \frac{2}{3} \pi \tau_{contact} \omega R_p^3$$

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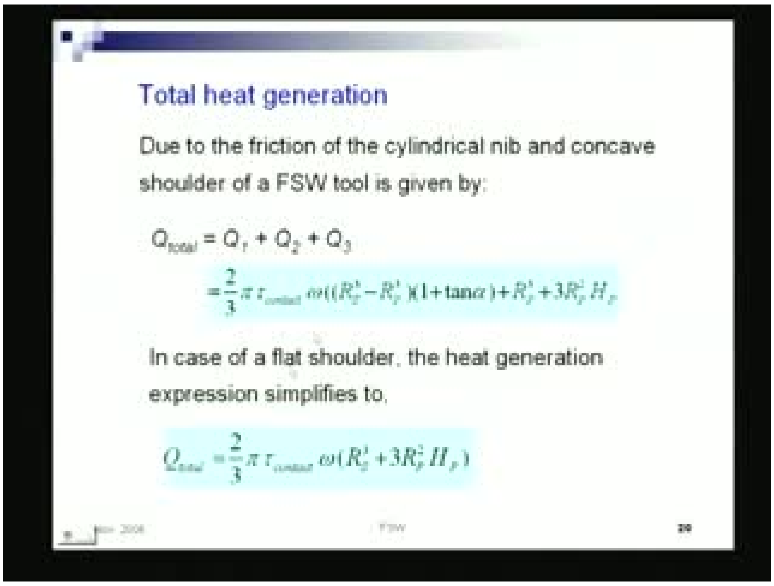

Total heat generation

Due to the friction of the cylindrical nib and concave shoulder of a FSW tool is given by:

$$Q_{total} = Q_1 + Q_2 + Q_3$$

$$= \frac{2}{3}\pi \tau_{contact}\, \omega((R_s^3 - R_p^3)(1+\tan\alpha) + R_p^3 + 3R_p^2 H_p$$

In case of a flat shoulder, the heat generation expression simplifies to,

$$Q_{total} = \frac{2}{3}\pi \tau_{contact}\, \omega(R_s^3 + 3R_p^2 H_p)$$

Right, on that it depends. And, well these r s and r p are physical dimensions, that means, this, this part, the outer radius and the inner radius, this r p is the radius of this, and the nib and this is the radius to this tool shoulder. So, that is how; and then, they are the heat generated from the nib side, that is say, q 2 on the side surface; and then, q 3 is the heat generated from the tip, flat surface; so, one is that the shoulder, the nib flat surface and the nib side surface, so, the total heat is obviously the summation of all these three.

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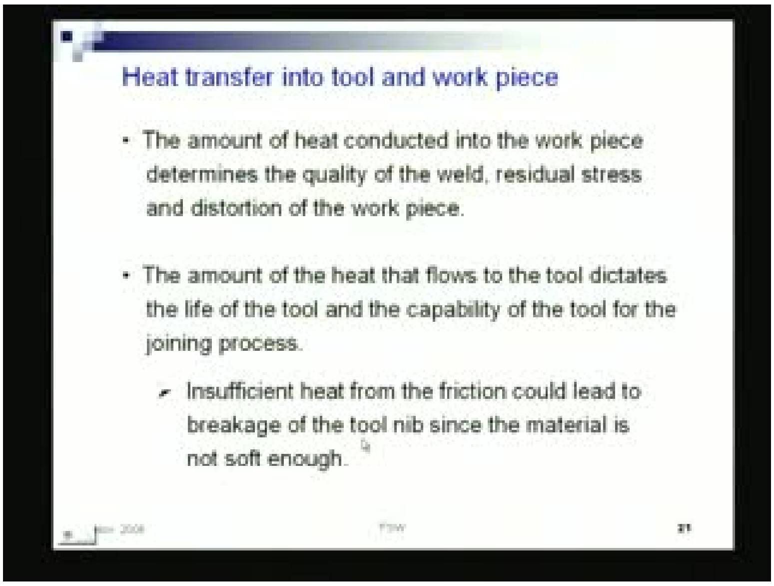

Heat transfer into tool and work piece

- The amount of heat conducted into the work piece determines the quality of the weld, residual stress and distortion of the work piece.
- The amount of the heat that flows to the tool dictates the life of the tool and the capability of the tool for the joining process.
  - Insufficient heat from the friction could lead to breakage of the tool nib since the material is not soft enough.

And then, heat transfer into the tool and work piece we have talked about it; depending on the on the material, thermal conductivity your heat, heat gets dissipated in the tool, so, if there is insufficient heat from the friction, that could lead to breakage of the tool nib; so, these are the important aspects.

That means, it not only you; you would not be able to weld, but you will damage the tool nib; the tool nib gets damaged, right? So, these are also important, like in fusion welding, if welding if the heat insufficient, well, you may not have proper deposition; you may not have proper fusion, that means, there can be lack of fusion, lack of deposition, but as such to the welding equipment, there is no damage, right?

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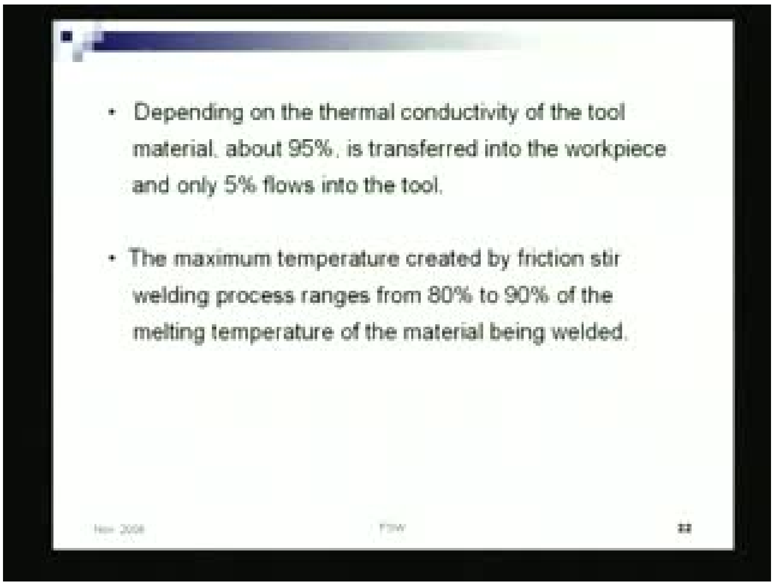

- Depending on the thermal conductivity of the tool material, about 95%, is transferred into the workpiece and only 5% flows into the tool.
- The maximum temperature created by friction stir welding process ranges from 80% to 90% of the melting temperature of the material being welded.

But here, the welding equipment, the the tool will get damaged; so, depending on thermal conductivity of the tool material, 95 percent transferred to the work piece; only 5 percent to the tool. This is provided, the material is highly non-conducting if you chose a wrong material; if the tool is made up of a material which is, that means, this kind of heat distribution, if it is there; that, so, it is, that means, the heat loss is much less ideally; it should have been zero, right?

Since that is not feasible, so, at least 95 percent can be should be transferred to the work piece, maximum temperature created by friction; stir welding process is generally of the order of 80 percent, 80 to 90 percent of the melting temperature.

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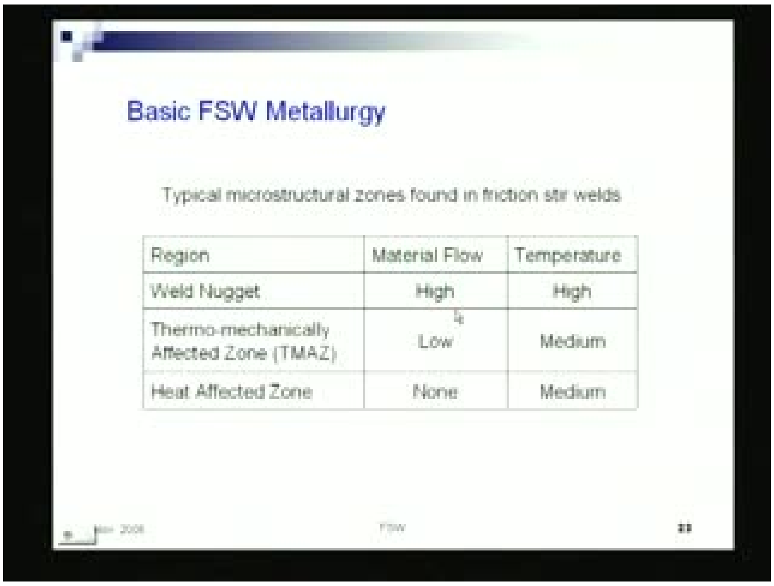

Basic FSW Metallurgy

Typical microstructural zones found in friction stir welds

Region	Material Flow	Temperature
Weld Nugget	High	High
Thermo-mechanically Affected Zone (TMAZ)	Low	Medium
Heat Affected Zone	None	Medium

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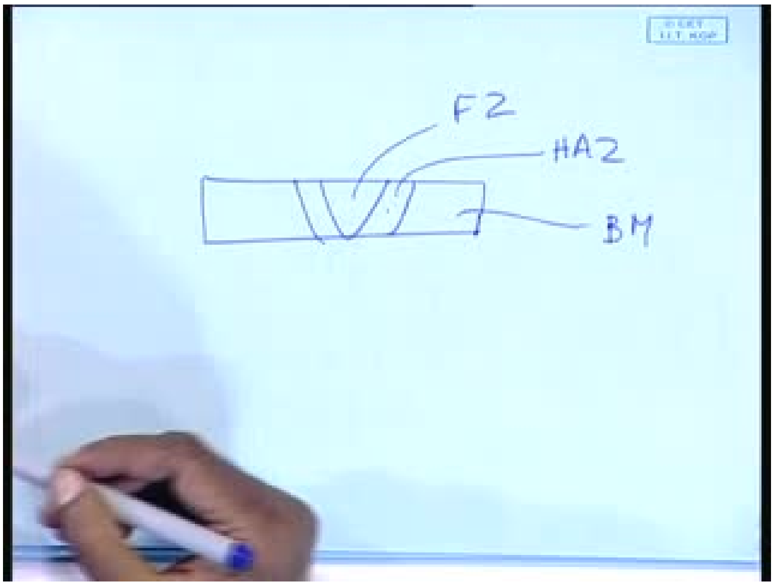

Well, little more about the, I mean, what happens in this, like in welding thermal welding, what we have seen? The fusion welding we had, as far as the micro structure aspects are concerned what you saw is, you have a fusion zone; you have a heat affected zone. This is the fusion zone, and then you have heat affected zone, and this is your parent metal or the base metal.

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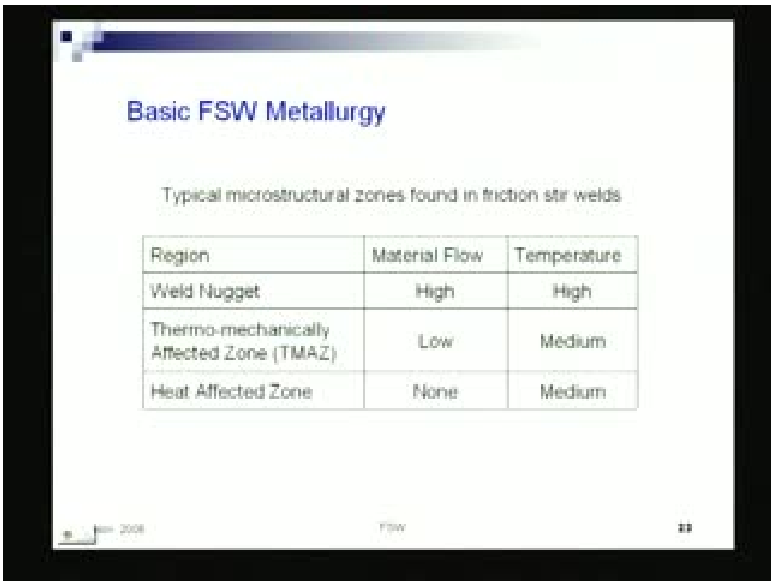

Basic FSW Metallurgy

Typical microstructural zones found in friction stir welds

Region	Material Flow	Temperature
Weld Nugget	High	High
Thermo-mechanically Affected Zone (TMAZ)	Low	Medium
Heat Affected Zone	None	Medium

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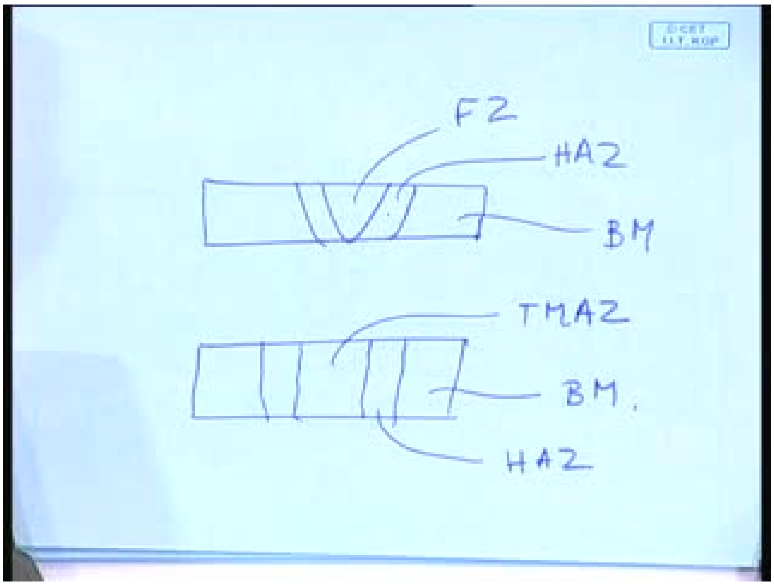

So, in the base metal, there is no change in microstructure; only in the heat affected zone there’ll be some change; and fusion zone, here you have what is called the equivalent of that is TMAZ Thermo Mechanically Affected Zone and heat affected zone; this is base metal, right?

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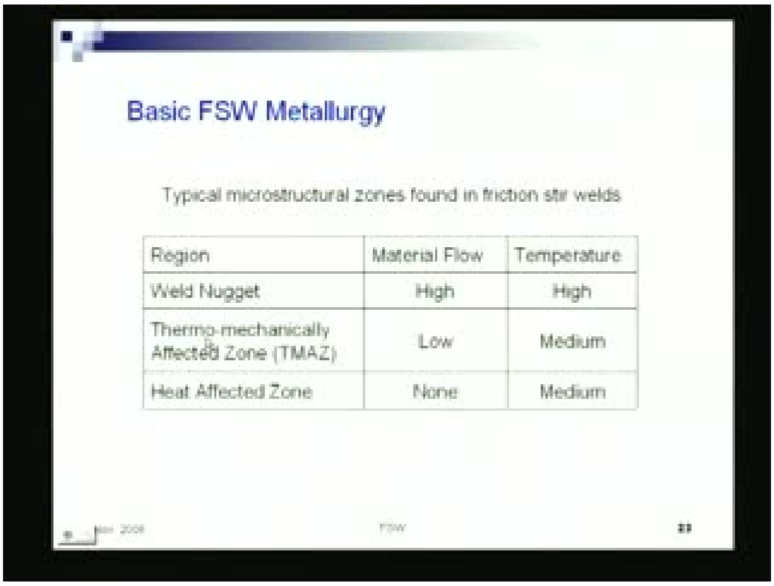

Basic FSW Metallurgy

Typical microstructural zones found in friction stir welds

Region	Material Flow	Temperature
Weld Nugget	High	High
Thermo-mechanically Affected Zone (TMAZ)	Low	Medium
Heat Affected Zone	None	Medium

You have Thermo Mechanically Affected Zone, within that, the weld nugget; I mean, where ever the welding the the two has has got, I mean, the both the plates have got the so called metal; starting has taken place, and the the so called weld deposit has formed; that is the weld nugget, that is within the thermo mechanical effected zone; that means, this part is thermo mechanically affected. In welding, it was only fusion and that heat effected, so little more will see tomorrow.