Joining Technologies of Commercial Importance

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Lecture – 23
Solid State Joining Technologies: Fundamentals

Hello, I welcome you all in this presentation based on the solid state joining principles and this presentation is basically related with the solid state joining – joining technologies for the metals.

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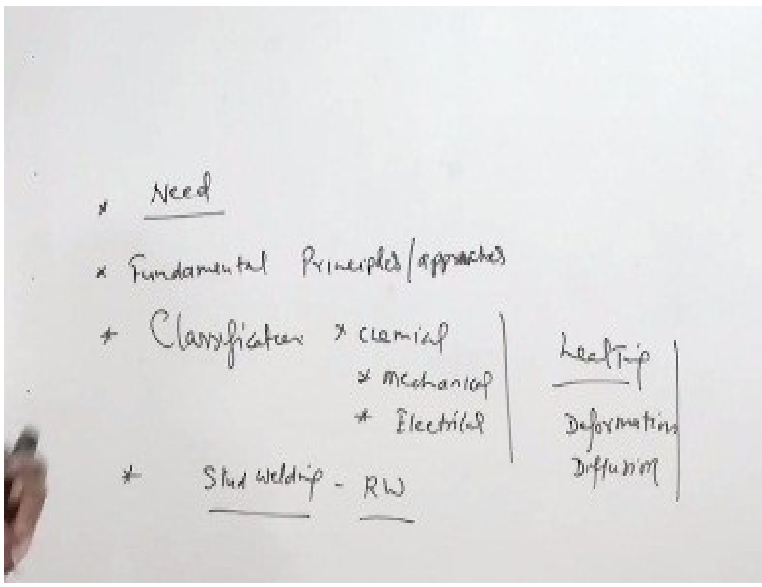

In this presentation, primarily we will be talking about the need of the solid state joining techniques and thereafter we will see what are the fundamentals principles based on which solid state joining techniques work, so the fundamental principles or the approaches which are used in solid state joining processes. And thereafter, we will see what are the underlying fundamental principles based on which the joining are takes place.

Also on the – you can say bigger classification, based on the parameters which are used or significant parameters, the solid state joining that govern the success of the process. Like the way, which energy is applied which maybe in form of say chemical energy, mechanical energy, and electrical energy. These are the different forms of the energy which can be used in solid state joining techniques which may be used for facilitating the deformation or heating, like purpose of this energy is like heating.

So that softening can take place, this is one and another one is like facilitating the deformation. So when the two happens and annotation to that also to facilitate the diffusion, so these are the purposes which are actually achieved when the energy in different forms is used for in the solid state joining processes and then we will see one typical solid state joining process which is the stud of welding process.

Basically, this falls in the resistance welding category and all resistance welding processes fall in this category of the solid state joining processes. So one by one we will be going through the different aspects related with the solid state joining as mentioned here. So we will start with the need of the solid state joining processes.

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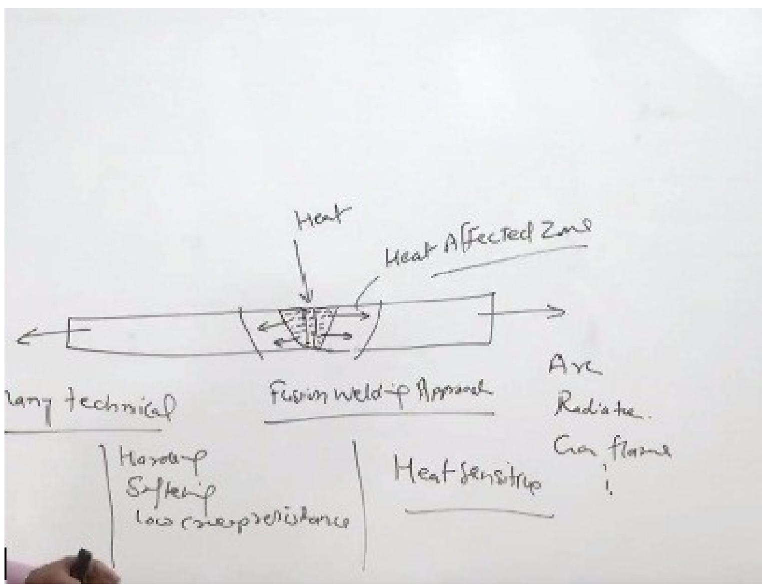

We know that in conventional joining processes like fusion welding, lot of heat is required to be supplied so that the fusion of the faying surfaces can take place and metallurgical bond can—metallurgical joint can be developed for having weld join between the two, so this is the most conventional like say the fusion welding approach. In this approach basically heat can be applied either through arc, through radiations, or through gas flame.

There can be different sources likewise. But since the amount of the heat which is required to be supplied in this processes too high, so it results in the various issues. Like the heat flow to into the underlying base metal develops lot of heat affected zone so the heat affected zone being formed in the base metal—heat affected zone formed in the base metal due to the heat delivery or delivery of lot of heat especially deteriorates the mechanical performance, corrosion performance of the weld joint.

So this heat affected zone poses many technical problems. And this maybe in form of the hardening, softening, and like say reduce the low creep resistance due to the refinement of the grain structure in heat affected zone at a high temperature. So these problems are very severe especially in those systems which are extremely heat sensitive. So heat sensitive metals pose all these problems related with the heat affected zone.

So we prefer that they are joined using the lesser they are joined using the processes which apply or which use lesser heat or no heat. So this is one aspect related with the delivery of the high heat input.

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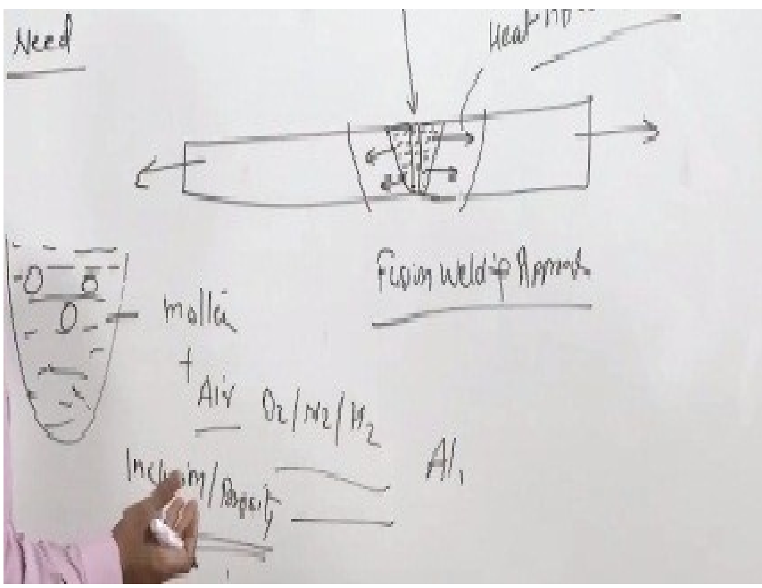

Another problem which is encountered in fusion welding is that the valve metal produced first is brought to the molten state and in the molten state it reacts it has tendency to react with the – the gases present in the atmosphere. So like oxygen, nitrogen maybe sometimes hydrogen also interact with the molten metal forms their oxide, nitride, hydrates or even the gases may get dissolved in the molten metal under the higher cooling rate conditions.

This can lead to the porosity. So the problems like inclusions and the porosity are extremely common in-- like fusion welded joints. So these problems especially in case of like aluminum welding or wherever like high speed welding is carried out of even common metals poses the problems of the porosity and the inclusions.

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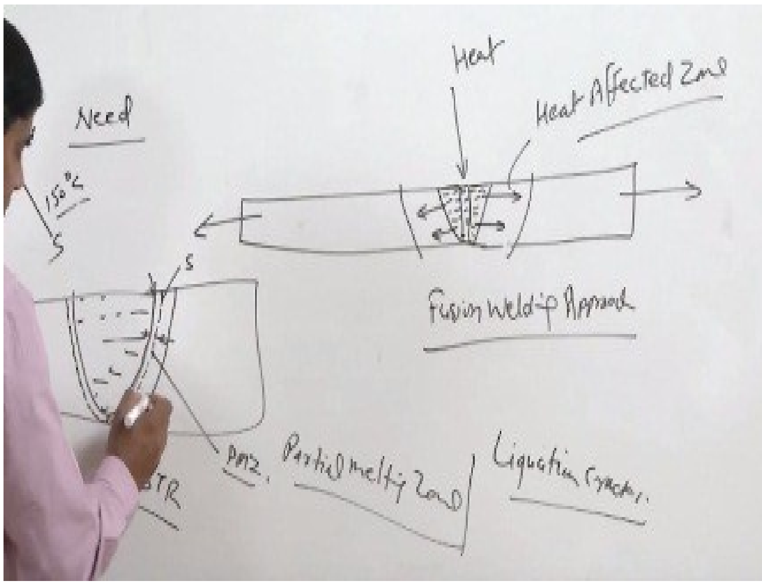

Apart from the problems related with atmospheric gases sometimes the typical nature of the solidification during the welding and the heat delivery infusion welded joints poses the two types of the problems. One is melting of the base metal near the fusion boundary partially. And this layer is very thin maybe 10 to 50 microns also depending upon the solidification temperature range of the metal being welded. So this is called PMZ- Partial Melting Zone problem.

This zone will have two phases both solid as well as liquid. Since the tensile stresses are usually formed in this area so these stresses show tendency for the cracking. So this partial melting zone basically causes the problem of the cracking which are called liquation cracks. So liquation cracks are formed next to the fusion boundary due to the typical nature of the formation of the two phase zone which is solid and liquid.

And this is mostly formed in case of the high solidification temperature range metals. High solidification temperature range metals. Because the boundary – these metals will have one liquidus and solidus so if the solidus is at very low temperature so this the where the things you have completely in solid state that will be solidus corresponding to solidus temperature line and the one which will be – the temperature corresponding liquidus will determine the distance up to which things will be in molten state.

So this temperature range basically determines the width of the partial melting zone. If this width is say 50 degree this solidification temperature range is 50 this will be very narrow; if this is 150 then it will be further wider means this will be the complete solid state and between these two will have both solid as well as liquid phases. So, partial melting zone will be much wider; will have much more cracking tendency.

So this kind of cracking tendency is observed mostly in case of the fusion welded joints of the high solidification temperature range metals. So its common there.

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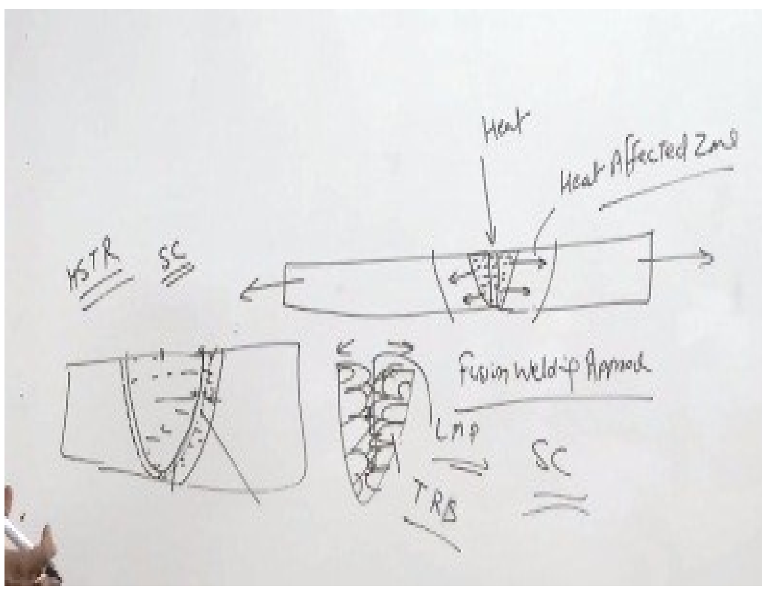

Another one is, high solidification temperature range metals also high solidification range metals also show tendency for the cracking at the same turn which is called Solidification Cracking. Solidification cracking occurs when the weld metal starts solidification at the fusion boundary and ends at the center. So in this case whatever the liquid metal is left at the end to solidify accumulates at the center.

So low melting point phase's basically low melting point phases accumulated the center and in the meantime solidified portion when cools down to the lower temperatures it develops the tensile residual stresses. So the presence of the tensile residual stresses and the low melting point both creates the problem of the solidification crack. So the solidification cracking, liquation cracking, hardening and softening of the heat affected zone, crane refinement.

And lower creep resistance of the basement metal of the heat affected zone, porosity and inclusions all these are associated with the fusion welded joints. So those systems which are sensitive for such kind of problems they are preferred to be join by the solid state processes. So in the solid state joining processes material is-- the metallic continuity is obtained in the solid itself and there is no need to have the things in the molten state.

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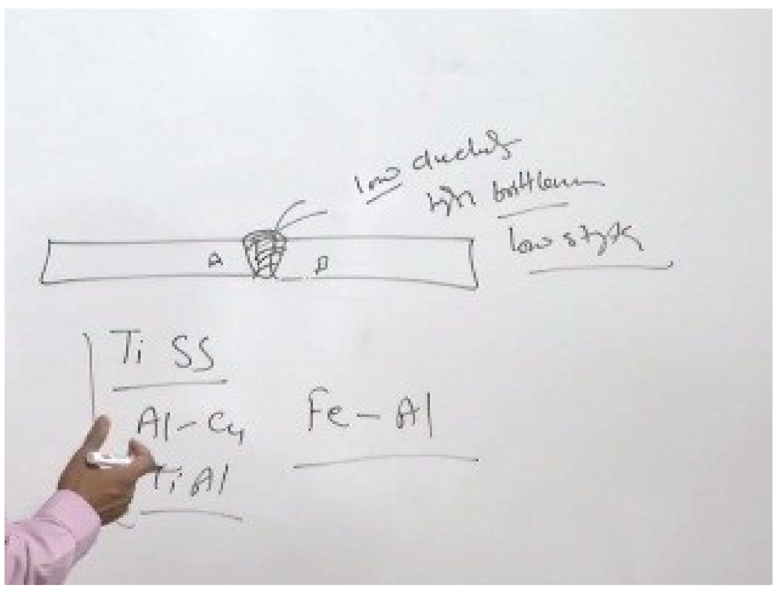

Another one is like a – the two completely different two metallurgical incompatible systems. Incompatible systems also can be joined using the solid state processes. Like, in the molten state if the two incompatible systems say A and B are brought together and brought to the molten state for developing the weld joint then may form such a unfavorable compounds or the inter-metallic compounds in the weld which will have very undesirable properties like very low ductility, very high brittleness and very low strength.

So such kind of the joints will not sever any purpose and that is why they are not preferred to be joint using the-- the fusion welding processes. So metallurgical incompatible systems it maybe like titanium, stainless steel, or aluminum-copper, titanium-aluminum and steel-aluminum these systems are not compatible with each other metallurgical so when they are brought together they create the unfavorable metallurgical compounds which in turn leads to the reduced mechanical performance of the weld due to the formation of the undesirable metallurgical characteristics.

So this is what has been summarized here, what is the need of going through—going for the solid state joining processes.

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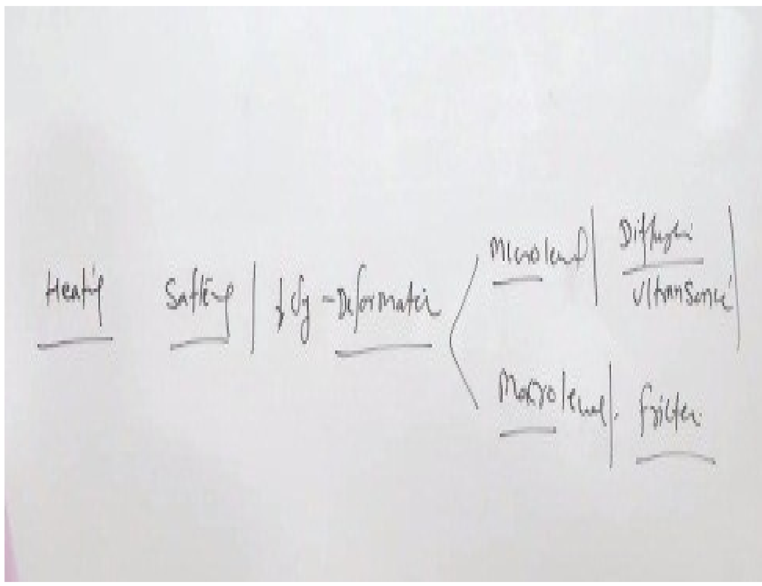

So since solid state joining processes basically involves just a heating. This is not necessary but – but if at all heating is there heating is just for softening purpose. And so that the yield strength, strength of the metal can be reduced so that the deformation can be facilitated. Sometimes this deformation, this deformation can be at the two scales, one is just at the micro level and another is macro level.

So sometimes the deformation is large macro level; so this kind of thing is observed in like say friction welding or friction stir welding and micro level deformation occur say like say in case of the diffusion welding when high pressure is used or maybe like ultrasonic welding very little pressure is used. So they are different levels. So heating either there is no heating if at all heating is there it is used for softening purpose.

Then softening will facilitate lower down the yield strength increase the ductility which will facilitate the interfacial deformation and interfacial deformation can be at the two levels micro level or macro level. So macro level will definitely involve larger scale deformation or the movement -- flow of the material as compare to the micro level deformation.

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So the purpose of the heating heat here is primarily to soften not to achieve the molten state. And that is why under the conditions when conventional welding processes develop lot of a heat affected zone very large size heat affected zone so in order to reduce that reducing the excess heat so that the heat affected zone size can be reduced and it can also be used another conditions when the metallurgical incompatible system have to be joined.

Then the solid state joining processes can be used. So for avoiding the metallurgical interactions between the incompatible systems such kind of process can be used, or when we want that the material is not brought to the liquid state at all to avoid the problems like solidification cracking, partial melting zone or liquation cracking, porosity and inclusion formation due to the liquid state transformation.

So if the fusion is to avoided then also solid state processes can be effectively used and joining of the heat sensitive metals. Like some of the metals respond very rapidly significantly to the heat as compared to the other system. So such kind of system should definitely be—their performance is well adversely affected when heated is applied so it is always good to either join them using the minimum possible heat or if at all heat is to be applied and minimum amount of heat should be applied.

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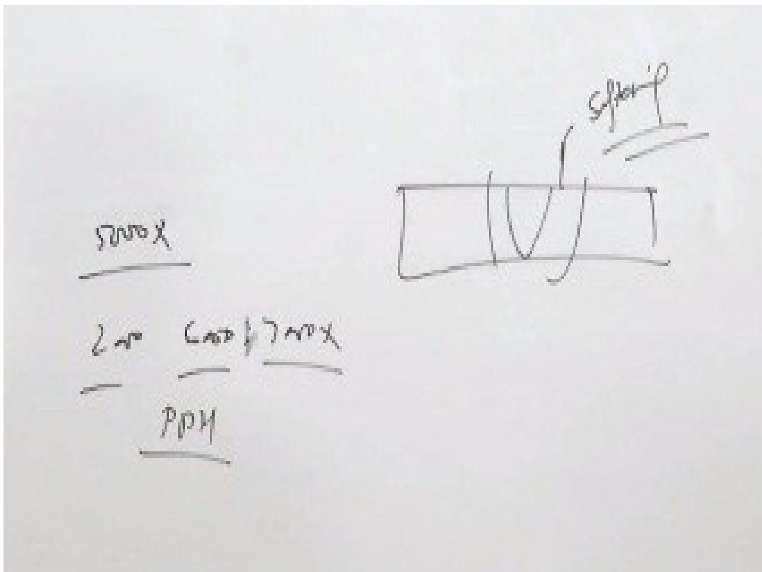

So like such kind of metal system like in aluminum category say 5,000 series aluminum alloys can be welded using the fusion welding without the much compromise on the performance of the weld join. But if we talk of 2000 series, 6000 series and 7000 series aluminum alloys then we will find they are all precipitation hardness aluminum alloys; so these precipitation hardness aluminum systems their heat affected zone properties are very adversely affected due to the application of heat.

And we see lot of softening and lot of strength take place especially in the heat affected zone due to the formation of soft zone in the heat affected area and this heat affected zone, degrades the mechanical as well as sometimes the corrosion performance of the weld joints. So it is always prefer it to either minimum possible heat using the pulse GTW or use them or develop the weld joints using the solid state process like friction stir welding or similarly other kind of the joining process of the solid state category.

So what are the typical features of those solid state joining process, what are the type of the solid state joining process we talk of like it may be explosive welding, it maybe ultrasonic welding, friction welding, all resistance welding processes is some of the cases partial melting takes place but it is not like the fusion which typically observed in case of the fusion welding processes. In the some of the welding processes there is just micro level plastic deformation.

In some of the cases, there is a macro level plastic deformation and in some of the cases even melting also takes place, partial melting takes places or little bit melting takes place, that happen especially in case of the resistance with based of welding processes.

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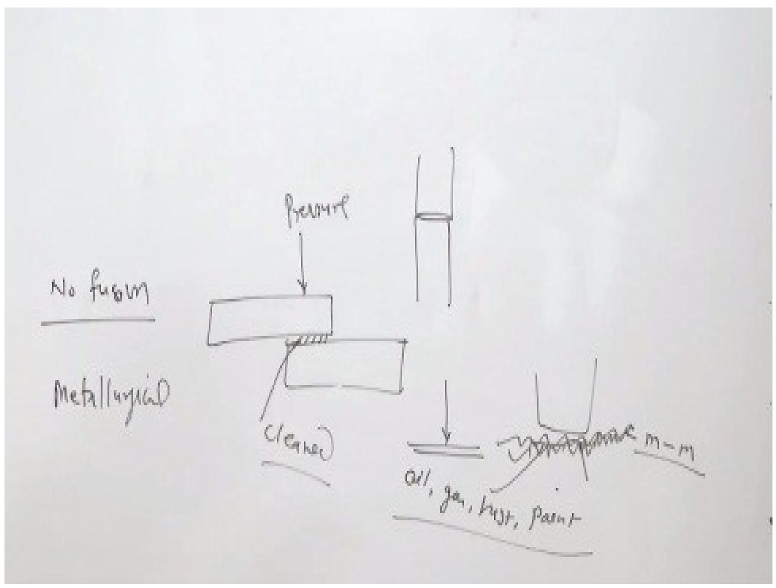

So here as far as typical features are concerned it involves 'No fusion' of the metals. No fusion of the metal and mostly 'No filler' is used in the processes. And mostly the joining is performed in the solid state. So the joint which is formed is mostly metallurgical, so what is the meaning of this, that is what we will explain.

Like whatever type of the process we take like the two components to be joined together like this in overlap joint configuration or in the butt joint configuration like this, we need to apply sufficient pressure. And the surfaces to be joined must be cleaned, so that there is a direct metal to metal contact and application of the pressures brings them close enough so surface regularities they get closed they get deformed and the complete metal to metal contact is established.

And the pressure has to high enough so that the atoms of the two sides come extremely close to each other. This is important and if the impurity are left in between in form of oil, gas, dust or paint or anything else which is present then it will act as a barrier for the metal to metal connectivity and the gap will be left and if the gap is left then atoms will not be able to come close to each other enough and then the interatomic force will not be enough for forming the metallic bond.

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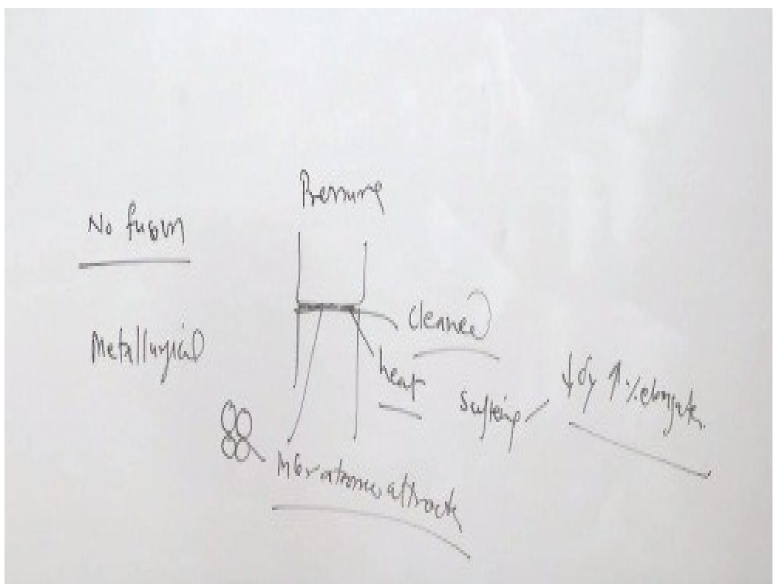

That is why what is important pressure is applied so that that things can really come close to each other, these much be cleaned and to facilitate this metal to metal contact application of the heat is heat is applied so heat will be softening the metal by lowering yield strength increasing the percentage elongation and ductility of the metal so under pressure peaks and valleys will collapse and things will come closer to have much closer metal to metal contact.

And whenever it happens the atoms will become in extremely close range so that by the interatomic attraction the bond is formed between them. So basically the bond is metallurgical which is achieved through either plastic deformation or the diffusion across the interface.

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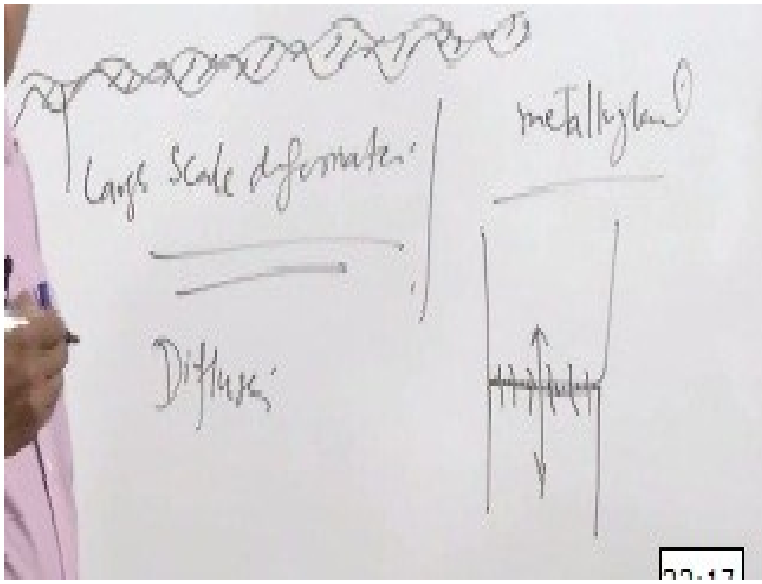

So for the deformation as I have just explained all real systems will have the ups and downs, peaks and valleys at the surface like this and when they are brought together initially contact is very localized but application of the pressure will bring them further too closer so for the metallic connectivity is established. Then enough pressure is applied. So in this case a large scale deformation can be there to have the thing close enough.

So that the bond between them can be formed. Apart from that the metallurgical continuity is obtained so through transformation reactions so that the grain boundary is formed across the two components being joined. This may involve lot of plastic deformation. Another is diffusion waste where the deformation is extremely negligible the two systems are brought in direct metal to metal contact under pressure.

So here the peak the first the gap is close to the deformation of the peaks and valleys by the creep by the yielding and then the diffusion across the interface facilitates the formation of the grain boundaries for developing the metallurgical continuity and metallurgical bond across the interface-- the diffusion place-- diffusion performs a crucial role here in development of the joints.

And under such conditions the deformation at the interface is very limited so deformation is very less at the interface. Under such conditions, and we need to really provide enough conditions so that the enough conditions so that the diffusion across the interface can be achieved. So bonding can be there primary or secondary.

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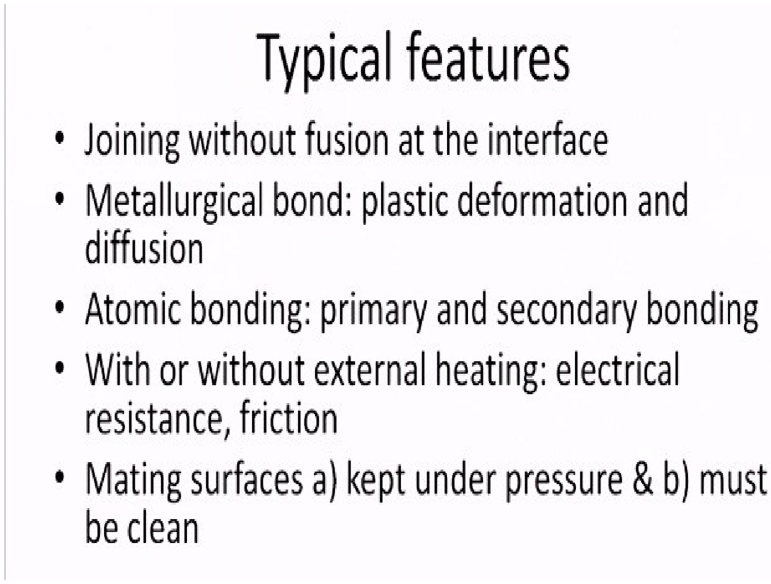

Primary bonds are always stronger secondary bonds. Primary bonds may be in the form of ionic bond, covalent bond or metallic bond while the secondary bonds are very weak maybe of 10% of the--- strength the primary bonds. So secondary bonds like a hydrogen bond or the Van der Waals forces. These bonds this solid state joining can be achieved with or without external heating if external heating is applied.

Then, there can be different ways through the electrical resistance heating, frication welding, induction effect et cetera., and as I have said the importance of the cleanliness that surfaces must be clean to remove the impurities present at the surface in form of the observed gases impurity is oil, dust et cetera all that should be cleaned. So that the metal to metal contact can be established and the atoms can be brought closed enough for having metallurgical bond.

So that is why enough the metal surfaces are generally kept under pressure and surfaces must be cleaned. What for these are cleaned?

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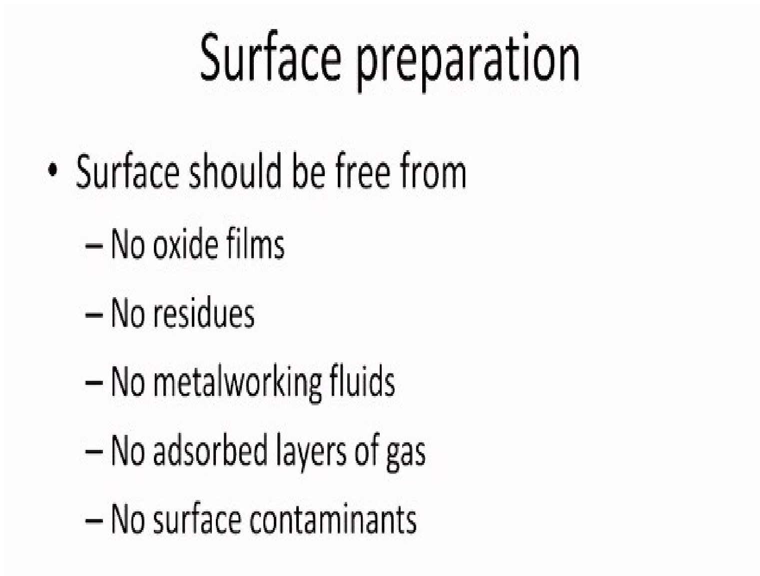

Cleaning is done to remove all kind of oxides, residues, metalworking fluids, adsorbed gases and the surfaces contaminants. These must be removed from the surface so that the direct metal to metal contact can be established. Now as I have said, the deformation can be facilitated with the application of the heat or with the pressure.

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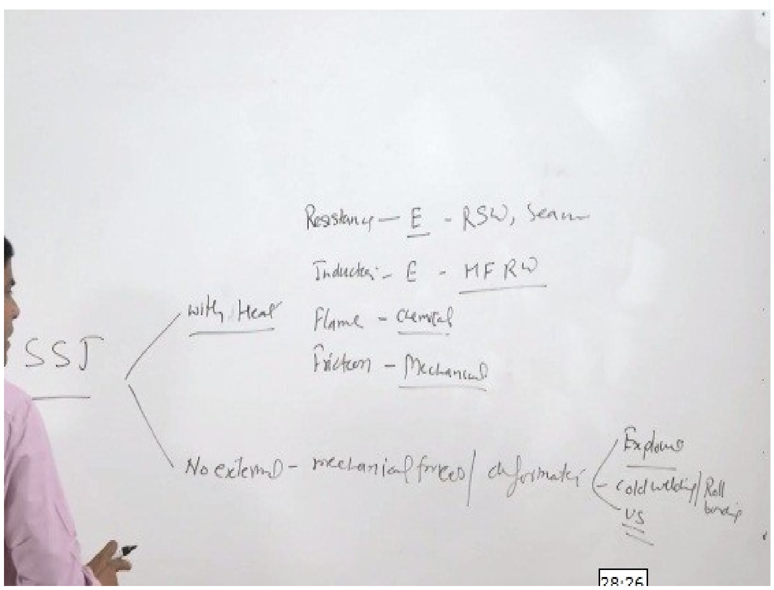

So in the solid state joining processes they are two categories with, with heat application or no external heat. No external heat is applied so with heat means heat is applied using the external sources of which maybe in form of a resistance heating, induction heating, flame heating, or it may be like intentionally we develop the apply the friction, so frictional heating is involved. In other cases, no other external heat is there.

Just the mechanical forces are applied mechanical forces are applied to facilitate the deformation at the interface so that the bonds can be developed. So if we see those processes which use heat or which do not use heat. So the resistance heating is involved so this will be obviously using the electrical current this will also we will be using electrical current, this will be using the chemical gas mixture combustion for heating purpose.

And this will be using the mechanical energy for application of the heat. Whenever resistance is used then I square RT principle; I square RT heating is involved and this like resistance Spot welding, Seam welding are such kind of processes were external heat is applied through the electrical resistance heating or the high frequency resistance welding process is used whenever induction is involved.

And the flame heating is used in case of the chemical of when the combustion of combustible gases and the oxygen is used for the softening of the surfaces and then application of the force for the purpose of the deformation so that the metallurgical connectivity can be achieved continuity can be achieved. And in case of the friction direct metal to metal contact are – mating surfaces are rubbed against each other.

So the enough frictional heat is generated for the softening purpose. And then under pressure the joint is formed. And then we will see the another category where no external heat is applied mainly the forces are used like Explosive welding is one, cold welding is another or you can say roll bonding is also there of the similar kind. And then ultrasonic welding, no external heat is applied.

And very extremely small amount of the heat is generated through the interfacial friction in case of the ultrasonic welding processes. So this one category where heat is applied and no heat is applied, and how another way to look into is this that in which way energy is applied. So for that what we have to see.

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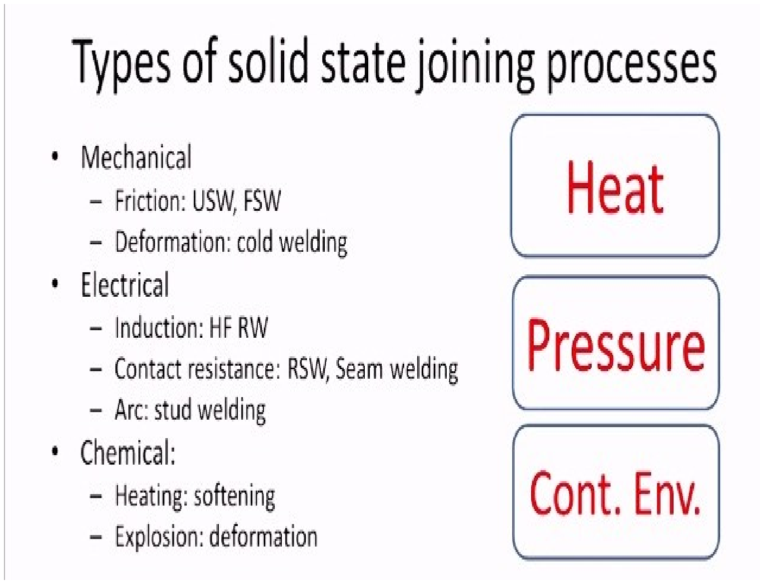

The different solid state joining processes based on the mechanical energy which we will be using the mechanical energy for having the frictional heating or frictional effect like ultrasonic welding and the friction welding. And for the purpose of the deformation like only the surface layer deformation is achieved to such an extent that metallic bond is created. In case of the cold welding, electrical energy is used like induction.

In case of the high frequency resistance welding process, contact resistance and in case of the resistance spot welding, seam welding et cetera. And arc is used in case of the stud welding. And the chemical energy is used in case of heating for softening purpose using the flame were chemical reaction between the combustible gases and oxygen is used for developing the heat enough.

And the Explosion which is the impact force is generated for developing the large-- for developing the deformation at the interface.

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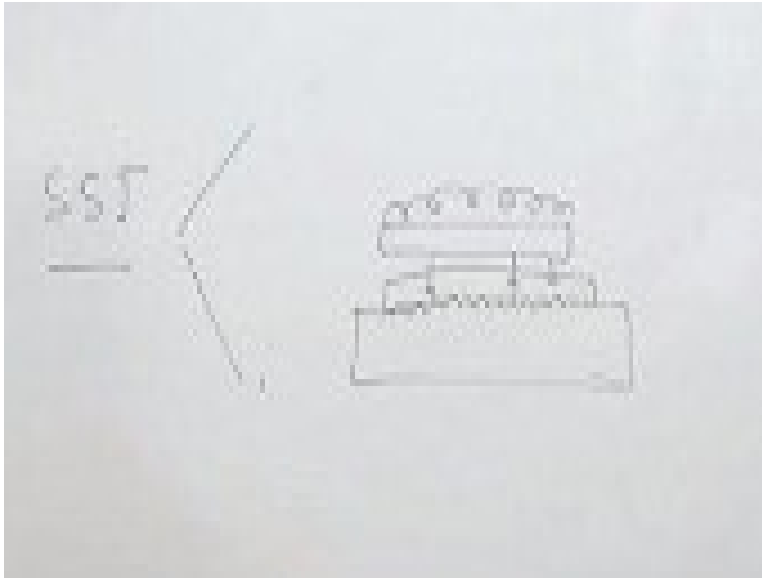

So in case of the explosion the explosive material is kept at the surface and then it is exploded so that it hits or impacts with another surface with which it is to be joined and in this case large scale means the interfacial deformation takes place at the two sides for developing the metallurgical bond between the two components being joined using the explosive approach. So the main parameters are here like heat, pressure and the environment.

Environment is certainly important because when heat is applied sometimes we need to apply a controlled environment in form of or inert gases or inactive gases or even the vacuum is applied like in solid state joining processes of the diffusion bonding.

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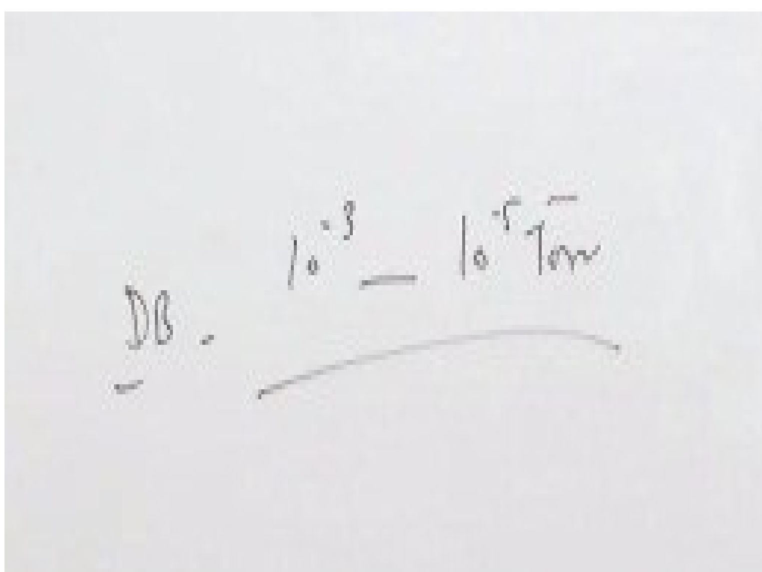

So vacuum like say 10 to 0 -3, 10 to -5 Tor is extremely common because it helps in removing the impurities or from the interfaces and having the direct metal to metal contact under pressure at high temperature so that diffusion across the interface can be facilitated.

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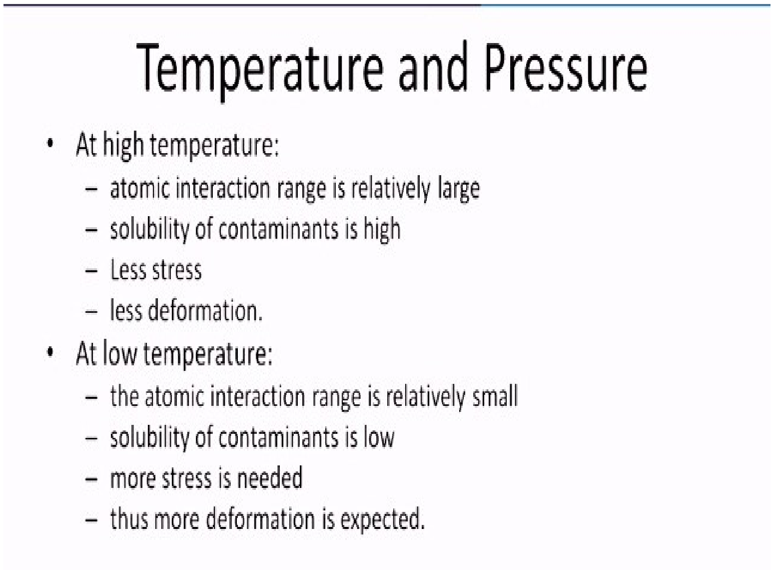

Now the two important things to be observed when the solid state bonding is achieved at high temperature interatomic range the atomic interaction range is really large, solubility of the contaminant is high so it requires lesser stresses and the deformation at the interface is less.

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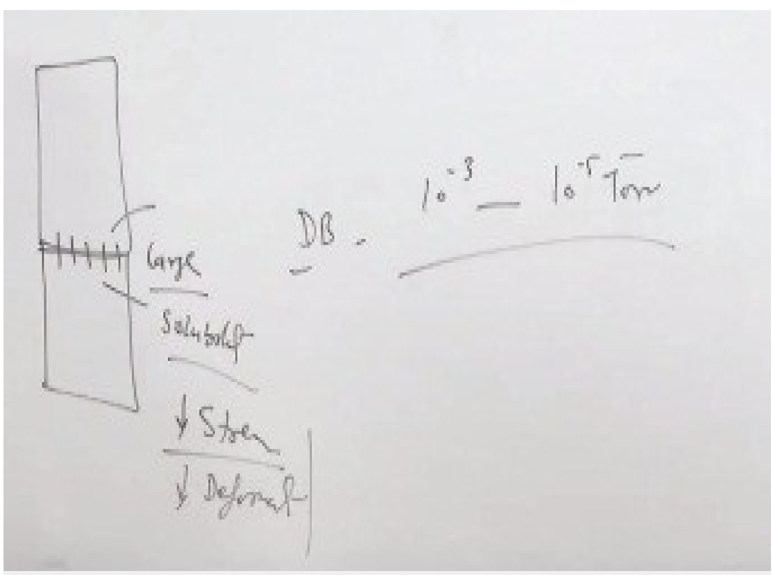

So if the two components to be joined at high temperature then the interaction interatomic interaction across the components across the interface between the two components is large and the of course all impurities alloying elements can diffuse a lot so they will have solubility if they have high solubility interatomic interactions is occurring over a large distance and so under this conditions we need very less stresses and when the stresses are less the deformation is limited at the surface.

So this is one thing when the solid state joining is achieved at high temperature on the other hand when it is done at low temperature atomic interaction range is relatively less, solubility to contaminants is low and therefore we require more stresses and therefore more deformation is expected in such conditions. So now I will conclude this presentation here. In this presentation, I have talked the fundamental principles based on which solid state joining techniques work.

And they are basically two approaches one is this interfacial deformation so that things can really come close enough to have the atomic bonding range, and another is the diffusion wherein the diffusion across the interface helps to form the grain boundaries and achieve the metallic continuity through the diffusion during the process. So thank you for your attention. In the next presentation, I will talk about one of the solid state joining process which is called Diffusion Bonding. Thank you for your attention.