Failure Analysis & Prevention

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Lecture – 08
Fundamental Sources of Failures: Improper Manufacturing II

Hello, I welcome you all in this presentation related with the subject Failure Analysis and Prevention. And, we are talking about the failures which are caused by the improper manufacturing. We had we have talked about the general aspects related with the causes which lead to the failure of the components manufactured due to the inappropriate manufacturing. So, there various general cause and there are specific causes related with the each process.

So, the general causes we have already talked like the welding the procedure manufacturing procedure has not been properly established or it has been manufacture it has been modified inappropriately without giving proper thought for it is effect on the performance of the products which will manufactured or there is in non-clarity and ambiguity or incomplete specifications are there in manufacturing procedure or the procedure is not followed is properly due to the inability to follow the procedure, like the system is not available or system capacity is not available or materials are not available and then some inadvertent errors are made by the operators or some accidental changes which are taking place in course of the manufacturing.

So, those are the general causes which can lead to the deficient manufacturing. And, deficient manufacturing promotes the deficiency discontinuities and defects in the manufactured product reduced mechanical performance and a increased sensitivity for crack nucleation and growth which can cause the premature failure.

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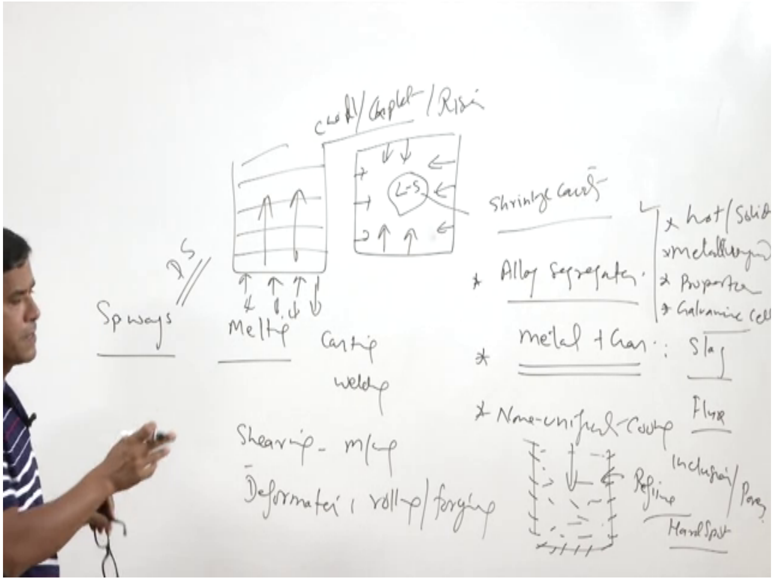

So, now we will be talking about the specific issues or the specific ways by which the failures can occur like in the in the processes which are the melting based like casting and welding and then like where the mechanical forces are involved where shearing is taking place like in machining and then the deformation based processes like rolling and the forging, so rolling, forging etcetera. So, inappropriate conditions can also lead to the defects in various categories.

We know that whenever any metal is heated to the molten state it becomes sensitive. It shows lot of affinity towards the atmospheric gases of the gases prevent present all around. So, these gases atmospheric gases interact with the metal. So, metal with the gases interact and forms the slag and sometimes the slag is taken care of by using flux, but if it is not properly removed then it leads to the presence of inclusions in slag inclusions flux inclusions etcetera can be there, they it can also lead to the presence of the pores. So, this is what about the metal and the gas interactions and this tendency becomes too high at high temperature.

Another thing which happens in case of the casting is the alloy segregation tendency, you know that most of the metals are used in alloy form. So, that because they have good strength. So, but whenever they are brought to the molten state due to the various regions it tends to segregate. So, alloy segregation tendency leads to the lot of metallurgical variations in the different zones, metallurgical variations then there is variation in terms of the mechanical properties, increased galvanic cell formation tendency, so, increased corrosion tendency. So, all these the things are promoted and increased presence of alloying elements and absence of the alloying elements and other locations also promotes the hot tearing or the solidification cracking in the weld or in the casting. So, these are some of the undesirable features which are caused by the alloy segregation.

Then, we have in castings we can have the non uniform cooling. So, at the surface metal is cooled rapidly as compared to the inner portions. So, rapid cooling leads to the higher like say in the casting if the in the molten metal comes in contact of the mould wall and transfers the heat quickly. So, the surface layer experience the higher cooling rate and because of this where refined grain structure is produced, but if the metal is hardenable then it can lead to the hard spot formation due to the high hardening hardenability or hard micro constraint formation tendency.

So, apart from the refinement hard spots can also be formed if the metal is showing high hardenability due to the non-uniform cooling rate. We know that the core will be cooled at lower rates as compared to the surface zones and this in turn bring lot of heterogeneity in terms of the grain structure and the properties and saw unfavourable solidification pattern can also lead to the development of the crack development of the defects.

For example if the solidification proceeds from all around then the region last to solidify in this case will represent at the centre and when the liquid to solid state transformation at the centre takes place, then it develops the shrinkage cavity at the centre. So, piping defectors shrinkage cavities are the typical examples of the unfavourable solidification pattern.

And, therefore, it is always preferred that solidification proceeds from one side like the heat is extracted in opposite direction and the solidification proceeds from one side to another in one direction. So, this kind of solidification is called directional solidification in it and if it happens then it will be reducing the shrinkage porosity formation, chances of the entrapment of inclusions and the pores formation and for that purpose only to have the directional solidification only suitable chills, chaplets, and the risers are used. So, that suitable temperature gradient can be established. So, the presence of these defects inside the cast components can be avoided because if these are present this will simply act as a source of the weakness and the stress concentration.

Similarly, the residual stresses also develop in the casting say due to the improper gating and rising design and the development of the special residual tensile stresses promote the cracking in form of say hot tearing or it may be cold cracking after the solidification of the castings of the hardenable metals like steels and the cast iron, like it is easy to recognise whether the product has been made by the casting or not. So, all the cast products will be showing the dendritic structures. So, this is a typically structure which is which show somewhat poor mechanical properties as compared to the other products made by the other approaches.

So, the cast structure is one typical feature which is observed in the casting apart from that the casting completely show the poor hardness, strength, toughness and ductility and there is also increase the tendency of the defects in form of the inclusions porosity, shrinkage, cavities in case of the casting and invariably the alloying elements are rejected during the solidification into the liquid metal and so, the segregation is very integral part of the castings.

And, which is also known as micro level segregation is termed as coring while the macro scale segregation if lot of things segregated the centre then it promotes the hot tearing and which is generally observed in terms of the increased presence of certain alloying elements at the centre of the casting or which will be increasingly tendency for the hot tearing as well as will be having the difference in the structure and the properties of the casting.

So; these are the some of the technical features related to the casting, which promote the discontinuities and increases the tendency for a defects as well as the reduction in mechanical properties, in the cast component and which frequently become the source of the failure.

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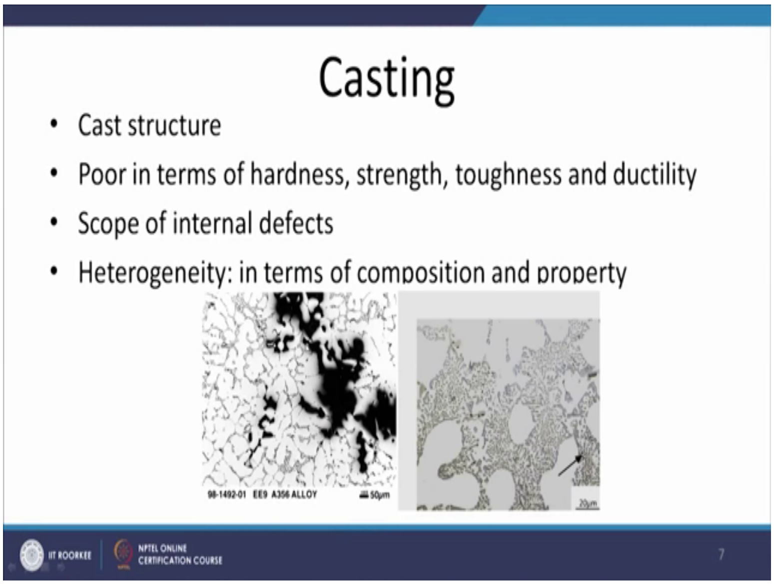

In case of casting these are this one typical example wherein the inclusions and the pores are left within the inside the casting well all around will we can see the good dendritic structure, but they are some impurities and shrinkage pores which have not been filled in and these discontinuities will be acting as a source of stress concentration which will be promoting the nucleation and growth of the crack. This is the typical, both these are showing the typical dendritic structure, this is the sound one and this is where some discontinuities and defects are present in the casting.

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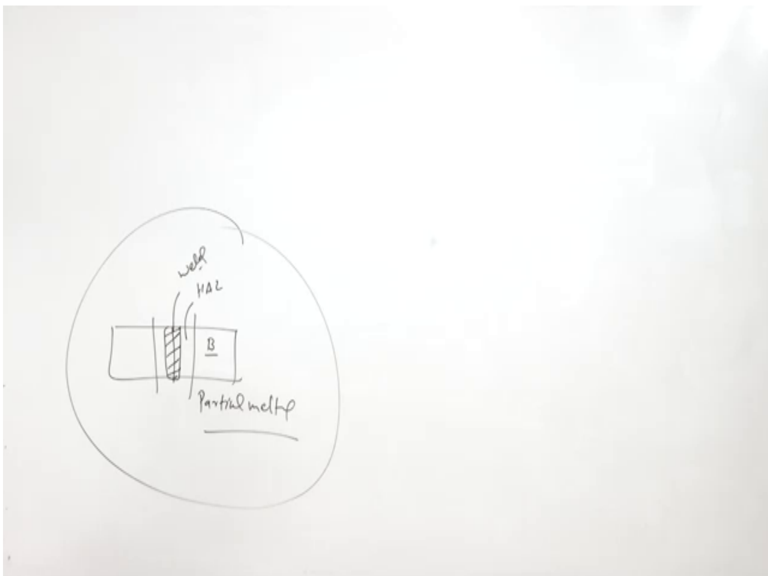

We know that for the welding the three types of the approaches which are used means for the joining purpose there are three types of the approaches which are used one is where the edges of the components to be joined are brought to the molten state means the face surfaces are brought to the molten state like this like the two component. So, edges will be brought to the molten state and after solidification will be getting the metallic continuity.

So, basically it involves the partial melting which is coupled with the heat affected zone for machine. So, base metal H Z formation and the weld metal. So, these are the three zones which are formed will have the different structure and different properties which may, so, the now weld may be stronger or weaker than the base metal, similarly, H Z may be stronger or weaker than the base metal. So, depending upon the type of metal and it is strengthening mechanism weld joined may be weaker or a stronger than the base metal.

So, we try to make efforts in such a way that at least joined can sustain the service load conditions, but if the process selection is an improper, if the procedures are not followed properly, if the post while heat treatments are not performed properly then it will lead to the presence of lot of discontinuities in the weld join lot of weaknesses in the heat affected zone and which will promote which will cause the premature failure of the weld joined.

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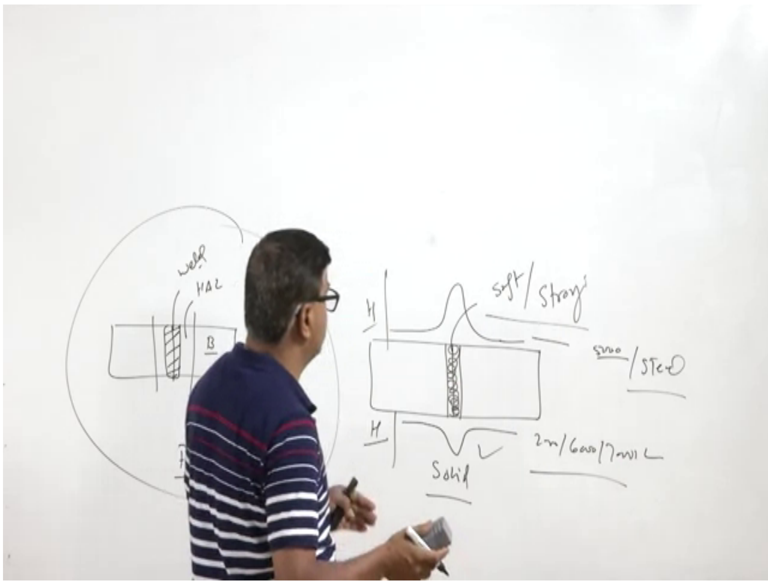

Similarly, there is another kind of another group of process, where the components to be join joined in the solid state whether without any fusion. So, in this case fusion is involved we can say liquid state welding processes and this is the solid state joining process where the mechanical deformation at the edges is achieved through the use of the force so that the metallic continuity between the two is realised. So, depending upon the strengthening mechanism of the metal, this zone may be soft or this zone may be strong or hard.

So, those metals which are work hardenable they will be leading to the lot of increase in strength and hardness as compared to the precipitation hardenable alloys, which because of the deformation they get softened. So, the softening we can see in terms of the dip in term of dip in the hardness in the heat affected in the weld nugget zone while in case when the hardening is taking place of the weld nugget will be stronger. So, this is what you can say the variation in the hardness as a function of distance from the base metal across the weld joints.

So, most of the, like say, 5000 series aluminium alloys and the steel show this kind of trend while the 2000 and 6000 and 7000 series aluminium alloys show this kind of trend, where the softening takes place, because these do not show appreciable hardening tendency. So, depending upon the metal systems different metal show the different behaviour under the influence of the external deformation caused by the external stresses and that in turn may lead to the increase in strength and increase in hardness of the weld or sometimes softening also.

So, there is another category of the process. If the process parameters like the rotational speed the forces which are being applied, the design of the tool which is being used, if they are not appropriate then it can lead to the presence of number of discontinuities in the weld nugget and which can become which can act as a source of the weakness. So, sometimes despite of having the good metallurgical continuity the joint may be weaker or stronger and accordingly we need to see where from the joint will fail.

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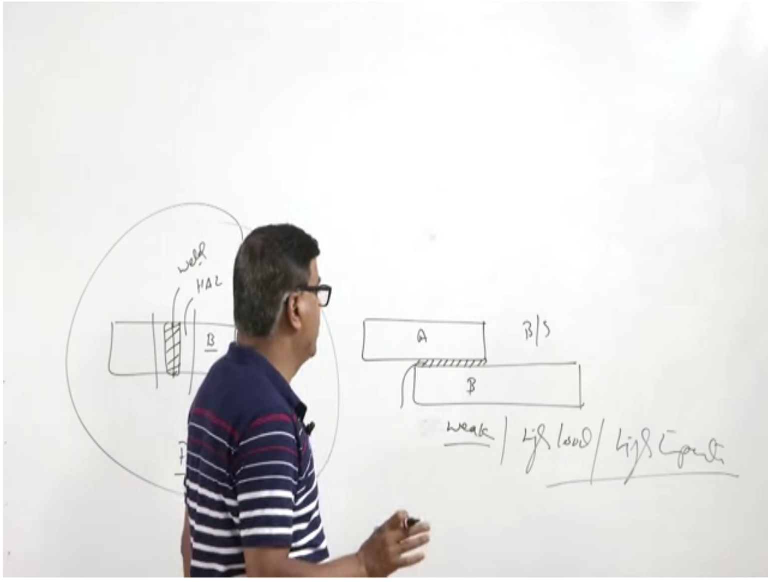

Third category of the process is the solid liquid base process under this category we have brazing and soldering kind of process where both the components to be joined, remain in solid state, only thing is that low melting point metal is brought in between the spring surfaces which after the solidification gives the metallurgical continuity, but these joints become weak and not becomes strong enough. So, they cannot take high load or they cannot sustain the high temperature. So, these are good for reasonable or very moderate kind of the loading and moderate temperature conditions say for just to have the joints for electronic circuits such kind of the joints are used.

So, as for the application we can use the different joints for the different purposes ah. So, what I am trying to say that there different category of the processes and each process results in the different kind of the structure and properties of the weld as well as our the zones next to the weld region and which in turn affects the properties of the weld and therefore, we need to see that our welding processes, welding procedure is appropriate.

So, that at least the weld joint is metallurgically a sound, mechanically and it is free from the defect, at the same time it has the required set of the properties not just in the weld zone, but also in the heat affected zone. And, for that purpose sometimes it may be required to perform the post weld heat treatments so that the properties can be restored and brought to the similar brought as the properties can be brought at the same level as that of the base metal.

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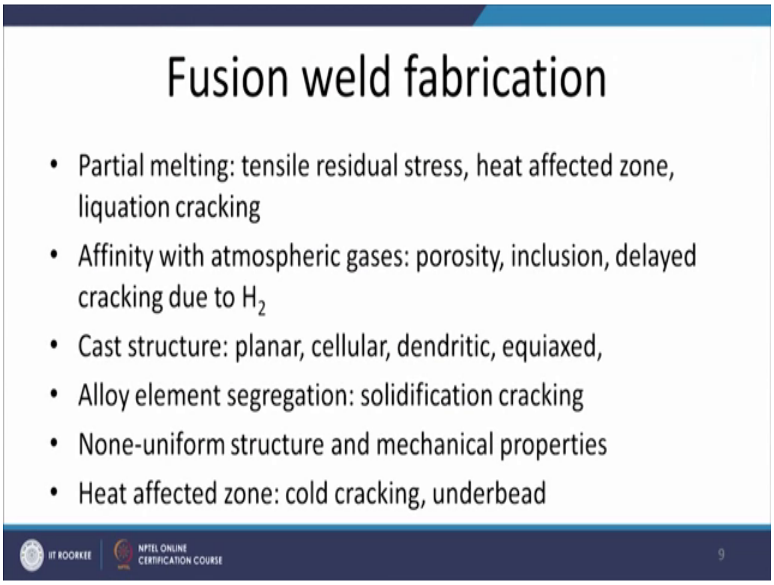

So, now will be seeing that what happens actually this what I have already talked in case of the weld fusion weld fabrication, partial melting is involved because of the partial melting the edges are heated and some of the so, the along the weld fusion line the metal under the application of the heat will be expanding and subsequently during the cooling it will try to contract.

So, this localised expansion and contraction leads to the tensile stress development, at the same time it also causes the heat affected zone and, with this combination of these two sometimes leads to the liquation cracking especially the zone which is very next to the fusion boundary.

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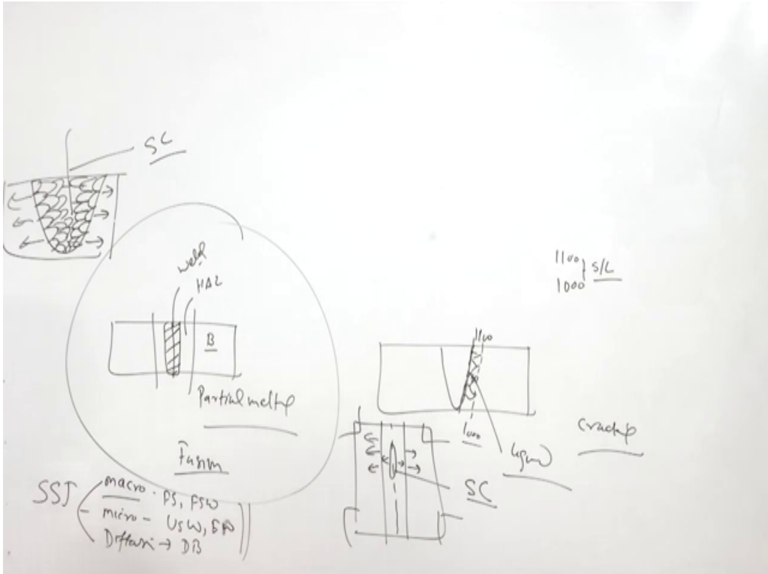

What it is in this case the like, say this is an alloy having the liquid to solidification temperature range say from 1100 to 1000 degree centigrade. So, this is the boundary line which is corresponding to the 1100 degree centigrade and the line which is experiencing 1000 degree centigrade is this one. In between these two will have both solid as well as liquid, this is called as mushy zone or the two phase zone where both solid and liquid will be present this zone becomes very thin. So, in this case some of the things will be in the solid state, some of the things will be in the liquid state.

So, the low melting points things will be brought to the molten state. So, the liquid things will not be able to sustain the tensile stresses if they are being developed and such kinds of tensile stresses promote the cracking next to the fusion boundary. So, fusion boundary is this one and the zones which are next to the fusion boundary where both solid and liquid phases are present there these zones under the presence of a in presence of the tensile residual stresses promote the cracking which is called liquation cracking.

Similarly, in fusion weld fabrication like if the hydrogen is introduced in the weld metal especially, in case of the hardenably steels this hydrogen gets into the heat affected zone and if the heat affected zone due to the high cooling rate if it forms, the metal site and high hardness then it promotes the delayed cracking or hydrogen induced cracking. Hydrogen also causes like the porosity and the presence of the atmospheric gases like the oxygen and nitrogen in the weld promotes the inclusion.

So, in the fusion welding presence of these gases from atmosphere in form of oxygen nitrogen and hydrogen promotes the inclusion force as well as delayed cracking and all these will be acting as a source of weakness, source of stress concentration usually promoting easily and the nucleation and growth of crack to cause the premature failure under the influence of the external stresses.

Now, another thing alloy element segregation also like in the casting alloying elements will be segregating at the centre. we know that whenever there is like say this is the weld metal and the solidification is proceeding from the fusion boundary towards the centre because heat is extracted in direction away from the base metal. So, this solidification proceeds with the rejection of the alloying element in the liquid metal and these alloying elements will be getting enriched into the liquid metal. So, this is how the alloying elements will be getting segregated at the weld centre line.

So, here this weld centre line has a lot of low melting point alloying elements, so, which will be promoting to the solidification cracking, because presence of low melting point will be reducing the presence of high concentration of the alloying element will be reducing the melting point of the molten melt or reducing the solidification temperature of the molten metal and which in turn will be increasing tendency for the solidification cracking.

And, how does it happen? We will see this. In this diagram say at the centre line if here we have lot of liquid metal yet to solidify, but at the same time sometime some tensile stress is being set in due to the due to the restrain from the sites then the tensile stresses cause the separation of the liquid under the influence substance weld stresses and which will be leading to the formation of solidification crack. This is particularly formed along the weld centre line and this is primarily attributed to the segregation of the alloying elements at the weld centreline.

Ah, you know that the different zones in the fusion welding will be experiencing the different composition, will be experiencing the different cooling rates and due to the variation in cooling rate and compositions will be having the different microstructure and variation microstructure in turn leads to the variation mechanical properties.

So, non-uniform structure and non-uniform mechanical properties are primarily attributed to the variation in composition, as well as wherein cooling rates which are experienced by the metal during the welding. You know that heat effected zone is the unique phenomenon of the welding wherein which is formed next to the weld zone and it becomes very sensitive for cracking especially in case of hardenable metals like steel and cast iron and which may appear in form of the cold cracks and under bead cracks and whenever these cracks are present they will be providing very high stress concentration and highest concentration high stress concentration value promoting the crack nucleation and then their growth.

Apart from the fusion welding process what will see, when saw join is carried out using the solid state joining processes lot of deformation ah. These processes may be of the two categories solid state joining process they are two category of the process; one where the macro scale deformation takes place like friction welding friction stir welding or there is a micro level deformation like in ultrasonic welding, explosive welding explosive welding and then there is a category of process where micro deformation plus diffusion is also involved like the diffusion bonding.

So, in these processes the kind of the discontinuities which are formed are of the different in nature. Like in solid state joining process the two metals are being joined if they do not mix, they do not metallurgically bond with each other then it can form the interface which will be acting as a source of weakness source of stress concentration and this is what we can say.

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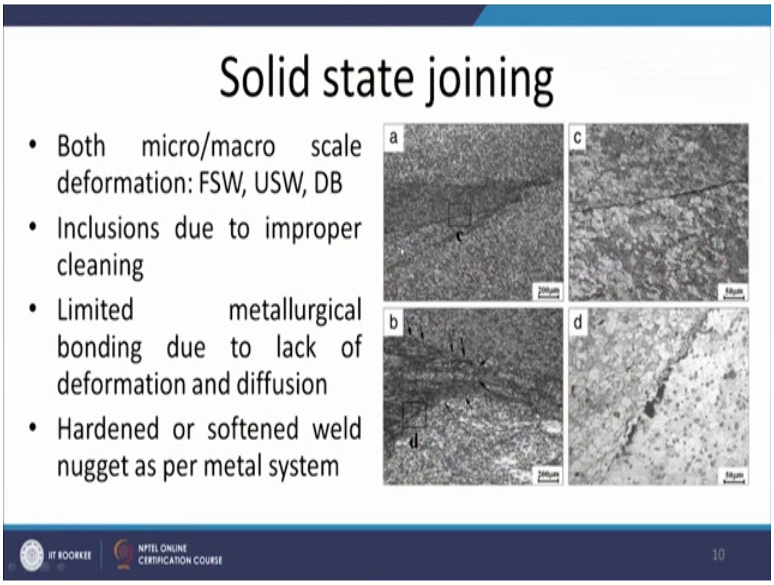

If the surfaces being joined have not been cleaned properly then they will present in form of the then the impurities will be present in form of the inclusions or the that if that the deformation between the deformation and the flow of the metal which is coming from both the sides means the flow of the metal which is coming both the sides is not getting mixed properly, not forming good metallurgical bond then due to the limited metallurgical bonding there may be interface or there may be suppressor from that zone which can act as a source of weakness.

Similarly, hard and soft zone is also found as for the kind of metal system as I have explained like some of the metal system which due to the deformation always so, higher hardness and strength in the weld nugget area like the aluminium 5000 series aluminium alloys and the steels because a lot of hardening work hardening takes place the systems.

While another impressive hardenable systems, they get softened due to the dissolution and reversion of the precipitates because such kind of alloys get strength from the precipitates and if these get dissolved then the strength is reduced. So, hardening and softening in solid state joining can take place as per the kind of metal system which is present.

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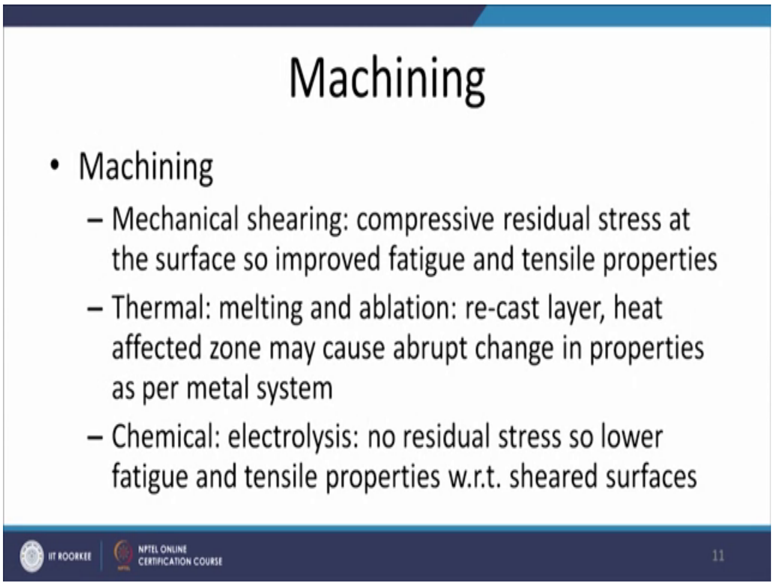

Now, the another process is the machining one wherein we know that machining can be carried out by various approaches and these approaches they are three category of the process for removing the material, one is mechanical one.

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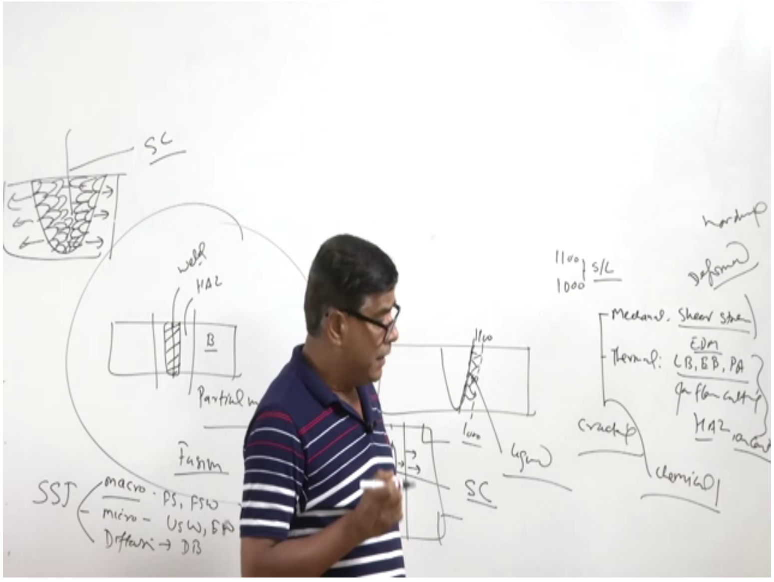

Basically, we use shear stresses for removing the material like in all conventional machining, then there is another category of process of thermal where thermal energy is used we may use laser beam or we may use electron beam or electron beam machining or there may be plasma arc then ah. So, these are also like the flame cutting is also used, the gas flame cutting is also used for preparation of the groups in the metal systems. In all these cases either melting is involved or ablation is involved for material in very control way, but whenever it happens will be seeing that there is heat affected zone formation there is as cast layer at the surface which is being formed.

Similarly, there is electric discharge machining also where thermal energy is used for removing the material in very controlled way. In mechanical like near surface layers will be having the deformed layer which results in the hardening of the surface and improve the strength and the fatigue performance. Then, there is a chemical based approach, where chemical interactions with controlled chemical interaction between the base metal and chemicals is used for control dissolution of the metal so that the material can be removed in control way in order to have the desired size and shape.

In this case, especially whenever material is removed by the chemical methods there is no deformed layer like in conventional machining so, there is no residual stresses or residual compressive stresses and because of this we will find that the tensile strength and the fatigue strength of the components processed by the chemical methods are not that good as compared to that of the mechanical methods where compressive residual stresses are present at the surface.

So, what we can say here in thermal methods we have melting and ablation leading to the development of the recast layer or means whatever portion, part of the metal melted is removed, but a part of the metal melted is redeposit again and then the heat affected zone is also formed. So, this will these things will be leading to the lot of metallurgical and mechanical heterogeneity especially near the surface layer and if such kind of components are processed are subjected to the fatigue loading or the high tensile loading especially with the stress razors then this promote the nucleation and the growth of crack and which in turn promotes the premature failure of the component.

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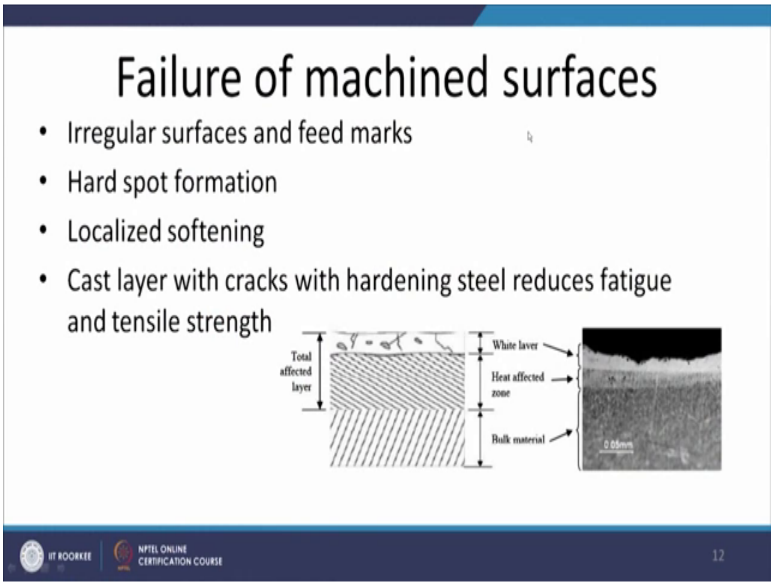

This one typical example; wherein factors that will be leading to the failure in case of the machine surfaces. We know the machine surfaces will be having lot of feed marks, rough marks; so, this feed and rough marks will be leading will be acting as a source of a stress concentration which in turn promotes the nucleation and growth of crack easily.

Similarly, in the process in the grinding processes, like in grinding if the lot of heat is generated and under the effect of the coolant if the hardened steel surface if the hardening steel surface gets hardened then it leads to the formation of the hard spot. Such hard spots will have the tendency for easy formation of the cracks and nucleation. It it can also lead to the softening due to the localised heating under dissolution of the precipitates.

Similarly, in case of the machining all those machine surfaces wherein thermal energy is used for removing the material a cast layer is produced with the cracks especially in case of the hardening steels which reduces the fatigue and tensile strength, this is what we can see. If the components is processed using thermal energy based approach, then this is the bulk material then there is a region which is affected by the heat and the one layer which is present at the top.

This is its schematic diagram showing the top layer as a cast layer or is recast layer and this entire zone can be termed as the zone which is affected by the heat and below that we have the bulk material and for actual system what we can see here, the these three zones can be seen from the different shades the top layer is white. So, we can say it is the white layer although it is recast layer or as cast layer and then another zone is which one which is just affected by the heat and third one is the bulk material.

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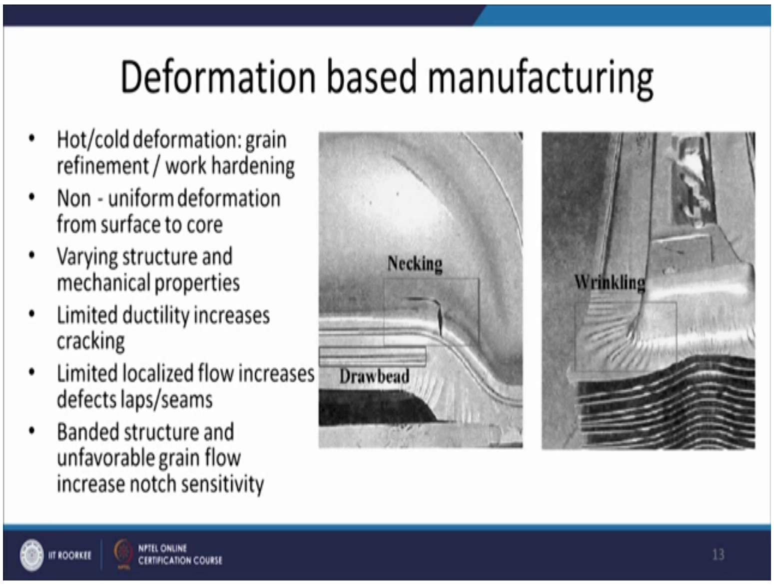

Now, coming to the deformation based manufacturing processes, we have the two broad categories; in that deformation based manufacturing process one is a hot and another is cold deformation. We know that the two processes work on the different principles, strength in case of the hot deformation based processes is obtained, so, the grain refinement and in case of cold deformation, strength is achieved through the work hardening.

So, these are the two different approaches by which the hot deformed or a cold deformed metals; will have the different strength from the different mechanisms. And, since the deformation is not uniform especially under the cold working conditions; deformation is more at the surface and less at the core portion. So, that in turn leads to the non-uniform deformation and so, non-uniformity in the mechanical properties.

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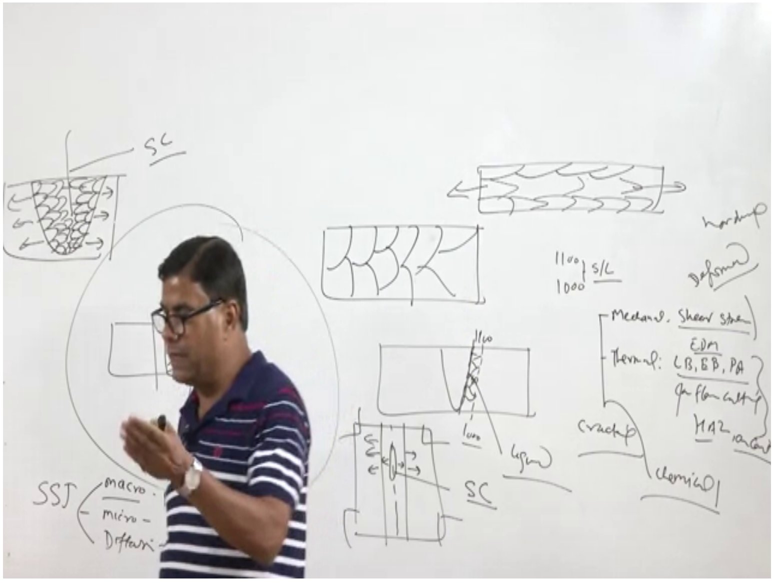

And, that is why apart from this will also be seen that in case of the deformed components whether it is hot and cold working normally we have the annealed; in annealed metals we have equates grain structure, but after the deformation what means you can see when the thickness is reduced all these grains get elongated in the direction of the deformation, whether it is rolling or the expression.

So, this the controlled deformation of the grain in one particular deformation leads to the higher strength in direction of the in the direction of the grain flow as compared to the direction perpendicular to that. So, this direction in which the grains will is flowing is termed as the longitudinal direction and perpendicular to that will be termed as transverse direction.

So, in general, metal show the greater strength in the longitudinal direction as compared to the transverse direction ah. So, this is what we can see there is variation in the structure; in terms of the direction which in turn literally variation in mechanical properties. Similarly, the surface layers at the surface layers in the component or subjected to the greater deformation as compared to the inner portion and that in turn also lead to the lot of variation in mechanical properties.

Apart from this, cold deformation especially decreases the ductility and which in turn increases the cracking tendency. Similarly, the limited localised flow increases, if this is the kind of situation due to the improper control of the temperature in proper plastic deformation, ability of the metal in appropriate ductility of the metal. Then the limited plastic flow can lead to the defects presence or defects like lapse and seems in the components being made by the deformation base processes and which can become as a source of the weakness source of stress concentration and so, these can promote the premature failure.

That banded structure is another one where one typical face is present in very localised way in the direction of the rolling or unfavourable grain flow is present both these factors, banded structure as well as unfavourable grain flow with respect to the externally applied load direction leads to the weakness. Sometimes this increases the notch sensitivity, promotes the nucleation and growth of crack from such locations and that in turn can become the source of can be the source of the weakness source of failure in case of the deformed component.

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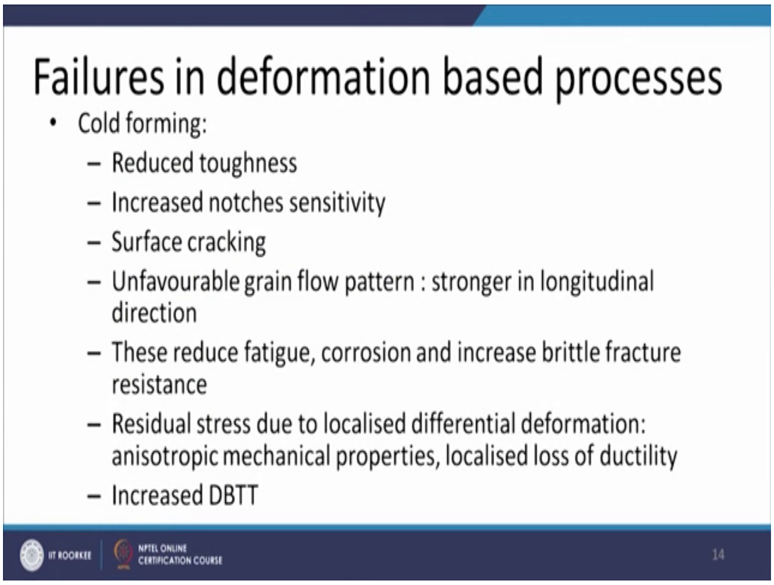

Now, the failures in deformation based processes can occur due to the variety of the reasons, variety of the features which are imparted to the product during the manufacturing by the deformation based process. Like if the product is a produced by the cold working or the cold deformation based processes, then the fracture can occur due to the limited toughness or the poor toughness due to the increased sensitivity increased. Surface cracking; surface cracking especially happens when the material is having the limited ductility temperature or it is the extent of the reduction which is achieved in one pass is also too high then excessive surface layer deformation can promote the surface cracking.

Unfavourable grain flow pattern, because the metal is stronger in the longitudinal direction as compared to the transverse direction and is so, it is always preferred that the loading is there in the direction of the grain flow or in the longitudinal direction. These factors in combination reduce the fatigue strength, reduce the corrosion resistance in increases the tendency for the brittle fracture.

Residual stress due to the localised differential deformation means the more deformation at the surface and less in the core and increased anisotropic mechanical properties, increased loss of the ductility, all these increase the tendency for the failure especially in case of the cold deformation base processes.

And another undesirable feature is also for especially for the steels which are produced if by the cold forming or cold working base processes then it will be leading to the reduction in the ductile to brittle transition temperatures. So, those components which are to be used under the low temperature conditions it must be kept in mind that there ductile to brittle transition temperature is within the safe limit as the cold deformed component, cold worked component can fail due to the high ductile to brittle transition temperature.

Now, we will see like hot forming or hot working does not cause much of the problem related with the cracking or related with the anisotropic ah, but these gain because these the products hot work which are produced by hot working they gain their strength from the controlled grain refinement ah, but apart from that the component can since the component is to be heated to the high temperature for hot working means that is above the recrystallization temperature of the metal.

So, if the metal is heated to the high temperature than it will have the tendency for oxidation at the same time due to the poor dimensional control is also observed, poor dimensional control is also observed in hot work component because whenever metal is hot work it will be expending, so, material is subjected to the deformation according for a given size and shape at high temperature when it is in expanded form.

But, subsequent cooling will be leading to the differential contraction when the system is cooled to the room temperature, because all sections will not be having the same volume, same length, same thicknesses, so, variation in dimensions variation section sizes and thicknesses will be leading to the different kind of the contraction. So, this aspect has to be controlled very properly and inappropriate control can lead to the poor control over the dimensions and due to the oxidation also we get the poor surface finish in case of the deformed component.

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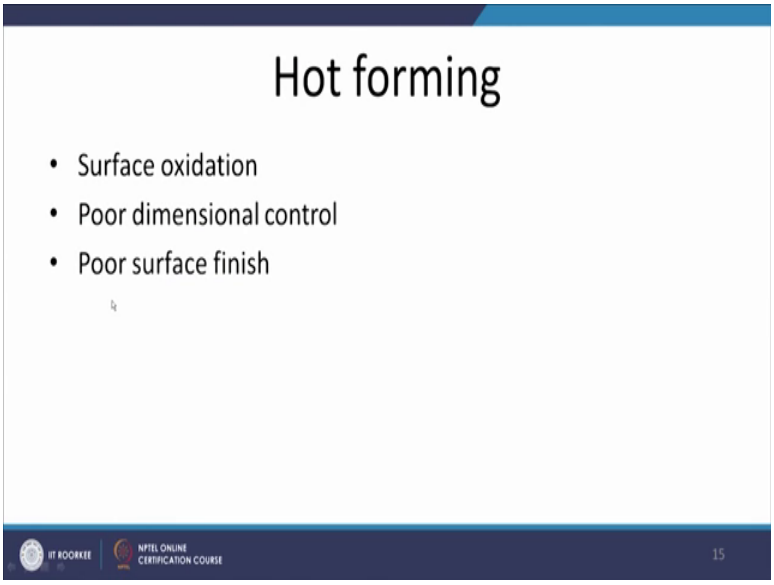

So, here, I will now summarise this presentation in this presentation basically, I have talked about the specific the issues specific discontinuities and defects which frequently lead to the failure of the component. Especially which are produced by the casting welding machining and the deformation based processes.

Thank you for your attention.