# Welding Engineering
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## Module - 8
## Weldability of Metal
## Lecture - 1
## Understanding Weldability

Dear students, this is the 8th module and this module will be based on the Weldability of Metals. In the earlier modules, we have talked about the introduction of the welding engineering, welding processes, the power sources used in arc welding processes, physics of arc, heat flow in welding, design of the weld joints and the inspection and testing of the weld joints, so this module which primarily focuses on the understanding the weldability of the metal systems, and the factors that affect the weldability of metals.

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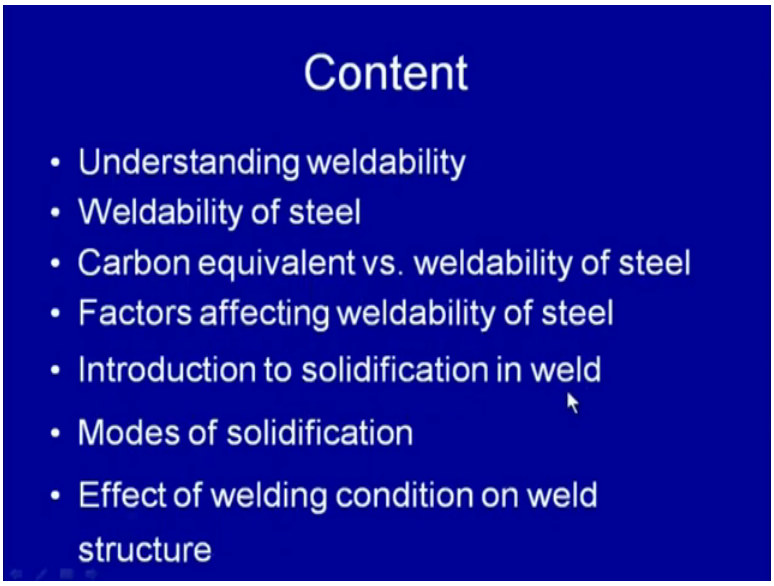


And in this presentation, we will be talking about, first trying to define the weldability of metals and the factors that affect the weldability of steels, and how can we relate the carbon equivalent for the weldability of steel, factors affecting the weldability of a steels. Then important aspects related to solidification of weld affecting the weldability, modes of solidification and the effect of welding conditions on the weld structure.

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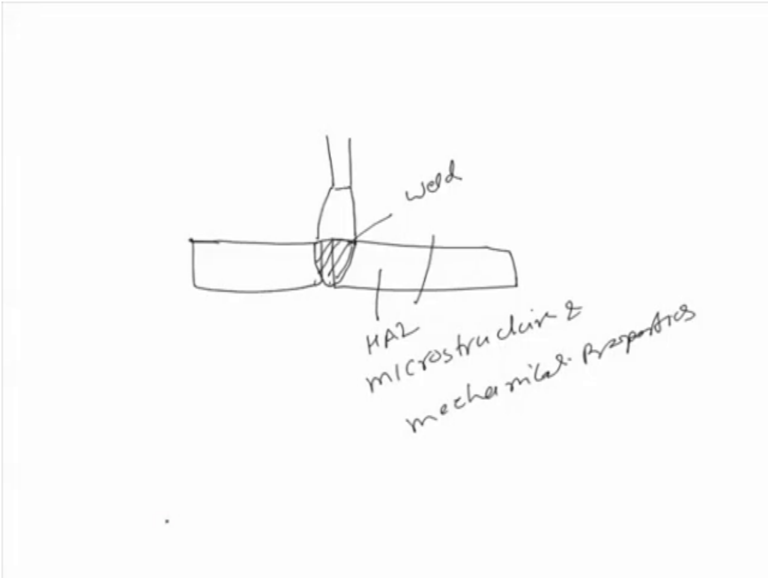


So, to understand this we will be starting with this schematic diagram, which we will be showing that, if we are required to develop a weld of a given metal, then heat is applied to melt the faying surfaces by fusion welding processes. So, the application of the heat using the suitable heat source, whether it is arc or the flame will be bringing the faying surfaces to the molten state. So means, basically we will be applying the heat to melt the things and develop a weld.

So, when a heat is applied, the regions close to the weld are affected by the application of heat. So, how the application of heat for developing a weld is affecting to the heat affected zone in terms of the macrostructure and mechanical properties, this is one aspect. So, effect of the application of heat on the structure and properties of the heat affected zone, this application of the heat in this zone can lead to have the favorable effect or unfavorable effect.

So, if we are getting the favorable effect then it is considered that, a given metal will be offering the good weldability or if the application of the heat in the region close to the weld zone is adversely effecting to the structure and mechanical performance of the weld joint. Or any other intended purpose, for which or in any other specific feature, which is expected to be delivered by the base material and the region close to the weld is being adversely effected. Then, we will say that the weldability of the metal is poor as far as the properties of the region close to the weld zone is concerned. So, this is one thing that is very important to consider in assessing the weldability of the any metal.

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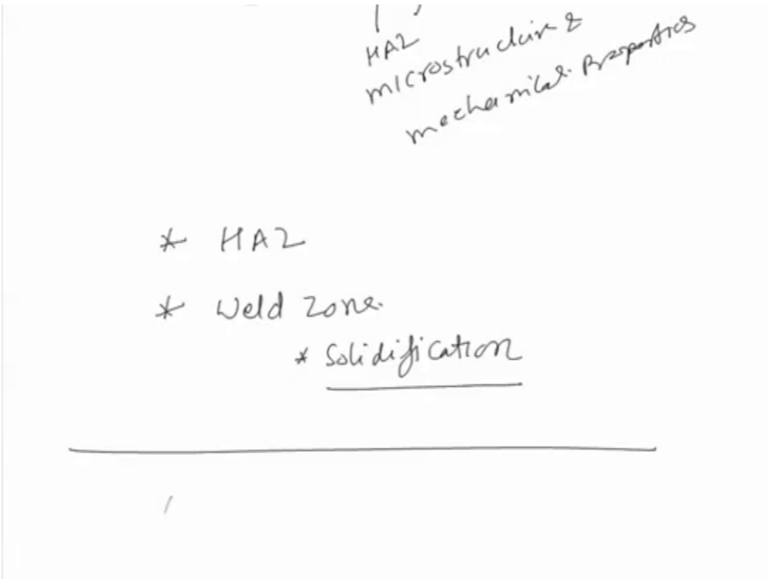


Like the, how the heat affected zone is developed and how it is affecting to the properties of the joint, as a whole. And the second important aspect is that, when the weld is developed after the solidification of the molten weld pool, what kind of properties it is offering. Those weld metals or the weld zones, which offer very fine refined grain structure with the equiaxed grains and good mechanical properties, they will be resulting in the better performance of the weld joint.

So, the weldability will be good but there are many situations and many metals, which during the welding or after the welding, when the weld metal solidifies leads to development of the cracks or development of the pores. And inclusions due to the variety of the reactions, which takes place in the weld pool zone like the formation of inclusions, porosity, evaporations, loss of alloying elements. So, there are certain things, which will be happening in the weld region due to the application of the heat.

So, another important will be to consider the things, which are happening in the weld zone so in the weld zone basically things, which happen are one like solidification. How the solidification of the weld metal is taking place, whether it is forming a very fine grain structure with the equiaxed grains or it is forming very big grains. And columnar dendritic structure is being formed, that will be deteriorating the mechanical performance or it is leading to the significant segregation of the alloying element and promoting the solidification cracking tendency.

Or the weld zone is very uniform in terms of composition and the structure, and developing very good mechanical properties as a whole to the weld joint. So, in another zone, which is considered is for assessing the weldability is the weld zone so as far as the weld zone is concerned, we try to look into the solidification related aspects and how the solidification of the weld metal will be leading to the development of the favorable or unfavorable properties.

So, that will form the basis for saying whether given metal is the weldable or not so there are two basically things, one is with the application of the heat for development of the weld joint, the heat affected zone is a favorable or not, or the weld zone is favorable or not. So, if the efforts and efforts required for developing the favorable weld zone and the favorable heat affected zone then that will decide, whether material is weldable or not.

So, if we have to define in respect of this fundamental aspect related with the weldability, if we require more efforts for developing weld zone having good mechanical properties and structure in the heat affected zone as well as in the weld region then that will have the poor weldability. If another metal system, which can be welded very easily with the favorable structure and properties in the weld row zone, and the heat affected zone then that will offer the better weldability.

So, in order to define the weldability just like any other performing, the just like any other fabrication technique say, ease of casting is termed as castability for given metal. Ease of forming is termed as formability of the given metal, how easily we can give a shape to a particular metal, that indicates that it is ability to get shaped or formed or manufactured by that particular process.

So, like the castability, formability or the machinability that is, ease of machining a given metal to get the desired size and shape, we also consider the weldability, which indicates that how easily a weld joint can be developed, which can serve that intended purpose. So, if the weld joint can be developed with the very ease without taking extra efforts and precautions then that weldability of for that metal will be good. If we require more efforts for developing reasonably good weld then that will decrease the weldability of the metal.

So, for accessing the weldability basically of a given metal, we try to consider basically 3 aspects.

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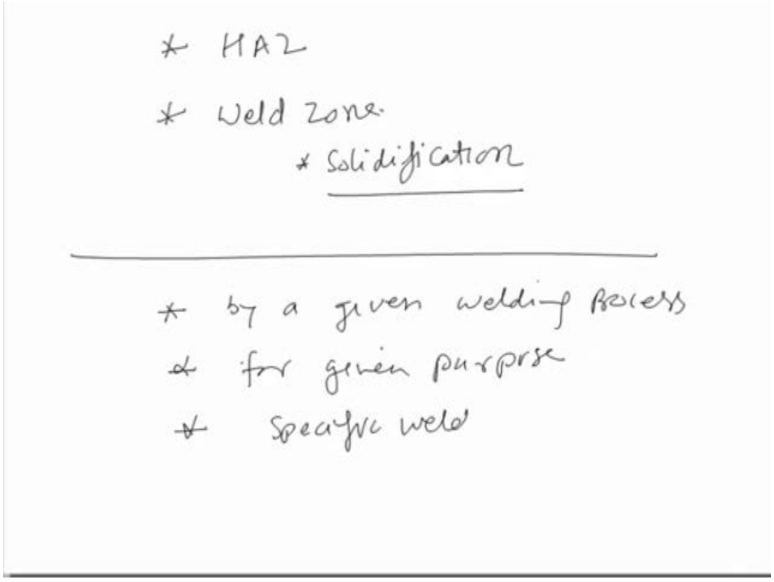


One is, that the ease of welding of a given metal by given welding process so when metal is being welded by a given process then how easily it can be welded. Another is, that for a given purpose, that when weld joint is developed then what for it will be used. A weld joint can be very good for one purpose and it can be very bad under the another set of conditions.

So, continuing with this, as I have said that, there are two important points that significantly affect the weldability of the metal. These are like the welding process, which is being used and the purpose for which weld joint is being used and the third important point is, the specific welding conditions, under which it is to be performed. And these may be in form of like the particular restrain condition where, welding is to be done or the position in which welding is to be done.

So, and in under the specific fabrication conditions, if the weld joint is to be developed then that those conditions also affect the weldability of the metal. So, the sequentially one by one will be going through the different aspects related with the weldability of the metals in detail. So, in the beginning, we will be talking about the general aspects related with the weldability and then we will go with the details of the each individual aspect related with the weldability of the steel.

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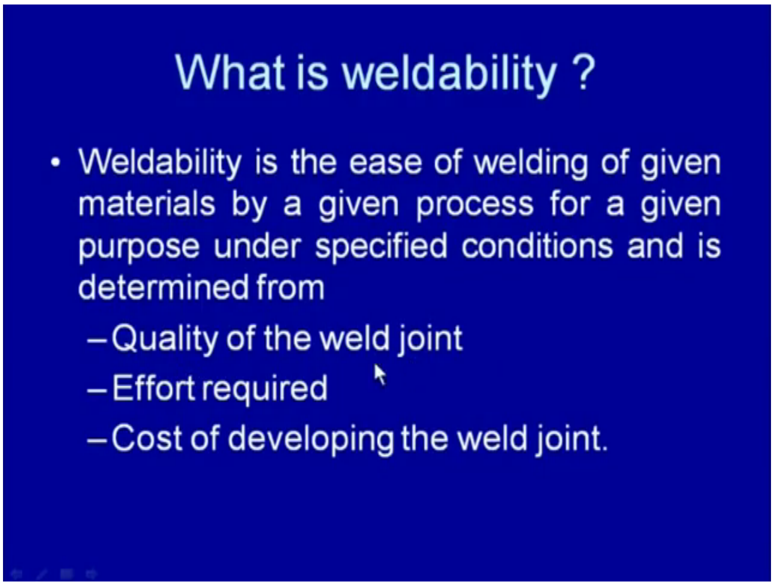


So, the weldability as I said the ease of the welding of a given material by a given process for given purpose and this… So, there are 3 important key words like the welding is done by given process then 3 given purpose and then under the specified welding conditions. So, when the welding is done under these specific conditions of the process, purpose and the fabrication conditions then the weldability for a given material is determined.

On the basis of the quality of the weld which is being developed, quality of the weld means, how the weld joint is fit for a given purpose and how does it satisfy the requirement, which are expected from the weld joint. Then efforts required, how much efforts we need to put in for developing the required weld joint and more is the efforts required then lesser will be the weldability of the material and the cost of developing the weld joint so if the higher is the cost, lower is the weldability of the material.

So, the quality of the weld that is being developed, efforts required for developing a quality weld joint and how much cost is to be paid for developing the quality weld joint, these 3 parameters significantly determine that, how easily a metal can be welded.

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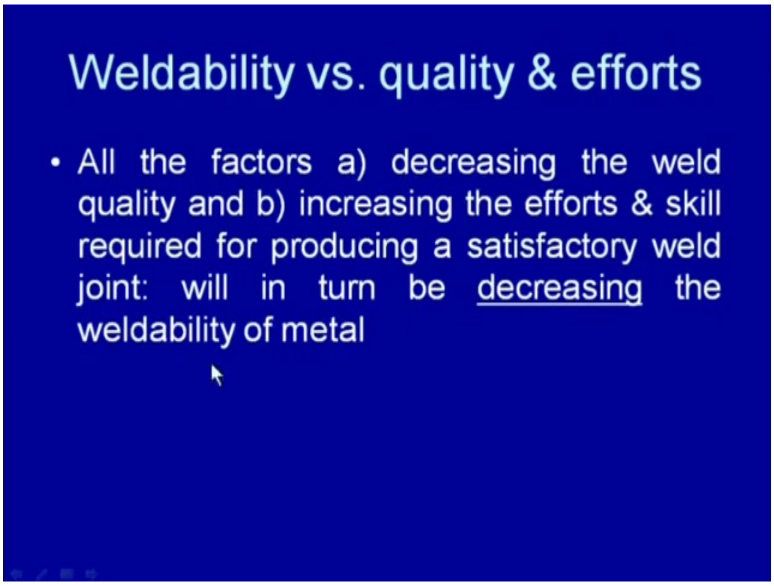


So, all the factors that decrease the quality of the weld and increase the efforts and skill required for producing a satisfactory joint. All these decrease the weldability of the metal means, the factors that are decreasing the weld quality and increasing the efforts and the skill required for developing a sound weld joint, which can serve the requires intended purpose then they will be decreasing the weldability of the metal.

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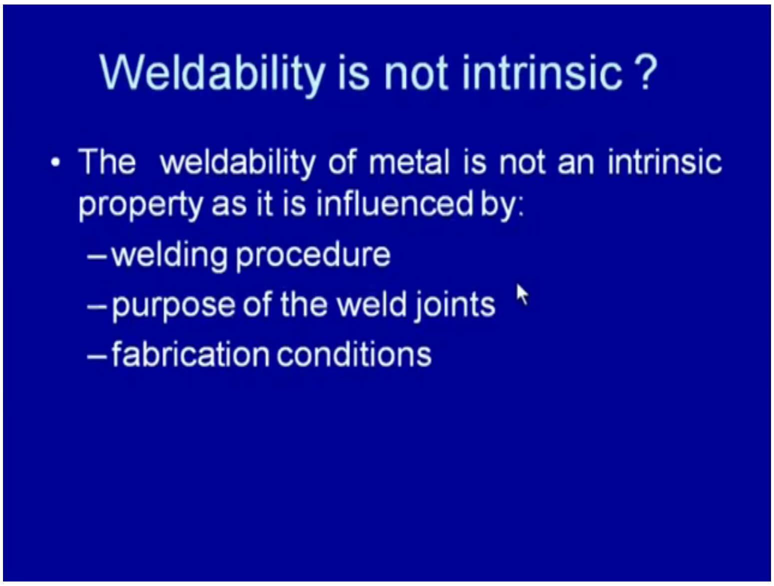


Weldability of the metal is not an intrinsic property because it is governed by the many other factors related with the welding like the welding procedure, which is being used affects the weldability in a big way. Because, ranging from the cleanliness, edge preparation of the weld, welding process, the preheating, post weld treatment, all these factors significantly affect the quality of the weld and the associated cost, and the efforts required.

And similarly, the purpose for which weld joint is being developed, weld joint of a particular metal may be very good under the normal ambient conditions but it may perform very badly under the specific special conditions. For example, the mild steel can be welded very easily for the applications in ambient conditions but when this joint is applied or used under the subzero conditions, minus below, minus 20 degree centigrade or below then it performs very badly.

Especially, it is a impact resistance is lost and it tends to fill in very brittle manner and then the fabrication conditions is another factor like the thickness of plate, the restrained conditions, the position in which welding is to be done, all these factors significantly affect the weldability. So, these are not very specific to the metal system but these are the external factors that will be dictating the weldability of a given metal.

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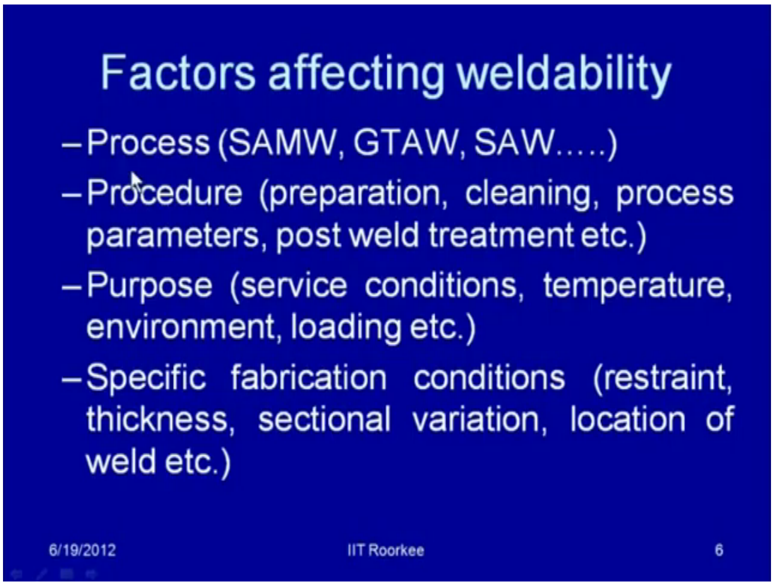


So, as far as the process is concerned, a given material can be of very good weldable, can be of very good weldability for by a particular process. But, may be poor by other process that is why, it is important to consider, which process is being used for developing a weld joint. For example, aluminum welding is found difficult to weld by the gas welding and shielded metal arc welding process, but when it is welded by the GTA or GMAW processes then it can be welded easily.

So, the process is important to be considered when we are looking for the weldability; similarly, the procedural aspects like preparation, cleanliness, the process parameters, post weld heat treatment, all these factors affect the weldability in a big way. The purpose for which weld joint is being developed with a change of the service conditions like temperature, environment and that the kind of loading, there will be great change in the performance of the weld joint.

So, what for weld joint is to be developed, that will significantly be dictating the weldability of a given metal and the specific fabrication conditions like restraint thickness, sectional variation or the location where weld is to be developed, will also be effecting especially in odd positions. Weldability of the low melting point metals is found difficult, because of the falling tendency of the weld metal during the welding and it makes difficult to place the required weld metal in the desired position.

But, apart from those welding related aspects like welding procedure or the purpose for which weld joint is to be developed or the fabrication conditions, under which it is to be developed, there are many metal properties that affect the weldability or the ease of welding. And these include chemical properties and in chemical properties like composition, with the change of composition, great change in properties especially in the weld region and the heat affected zone is observed and because of that, ease of the welding is affected.

Significantly, in case of the aluminum alloys, in case of the steels for example, in case of steels, increase in carbon content increases the hardenability of steels and thus, decreases the weldability. Similarly, in case of the aluminum alloys, very limited amount of the copper and the silicon in aluminum increases the solidification temperature, which in turn increases the solidification cracking tendencies significantly.

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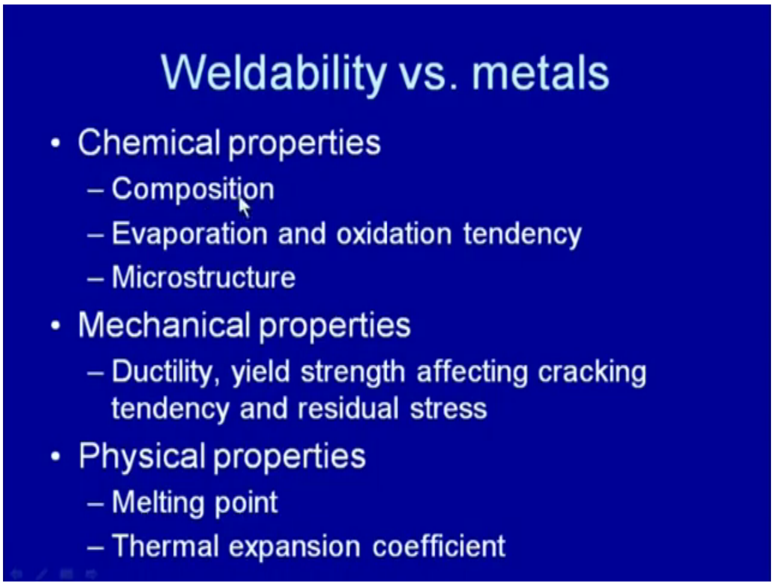


So, the chemical composition of the weld metal affects the weldability significantly like the presence of certain alloying element in the metals tends to evaporate or intends to get oxidized in the arc environment. And that will be leading to the change in chemical composition of the weld metal or it will be increasing the, due to the oxidation tendency there will be increasing the oxide inclusions in the weld metal.

And similarly, the macrostructure, the chemical properties significantly affect the macrostructure of the weld metal and the heat affected zone. Because, like the high carbon steels, they are very sensitive for the formation of the martensite especially in the heat affected zone, that tends to embrittle the structure and increase the residual stresses and the cracking tendency of the weld joint. Therefore, like the soft structures are being formed due to the slow cooling conditions as desired then that kind of cracking tendency can be reduced significantly thus, a chemical properties affecting the macrostructure and so the weldability.

Then mechanical properties, like the ductility, yield strength will be affecting the residual stress development tendency. And so the cracking tendency, the metal systems of the high ductility and the low yield strength develops the lower residual stresses and so there reduced the problems related with the residual stresses and distortion. At the same time, the low ductility and the high strength metal system show greater residual stresses and show the more cracking tendencies.

Similarly, the melting point like the difficult to weld metals like having the higher melting point or very low melting point leading to the easy means leading to the high fluidity of the weld metal making it difficult to weld sometimes. But, sometimes it becomes the easy also like the development of the joints by soldering and the brazing is facilitated, because of the low melting point.

And the thermal expansion coefficient, it directly effects the expansion and contraction during the welding and so the residual stresses and distortion tendency and the stress growth and cracking tendency is also effected by thermal expansion coefficient. So now, since there are very wide range of the metal systems, which are welded for variety of the engineering applications.

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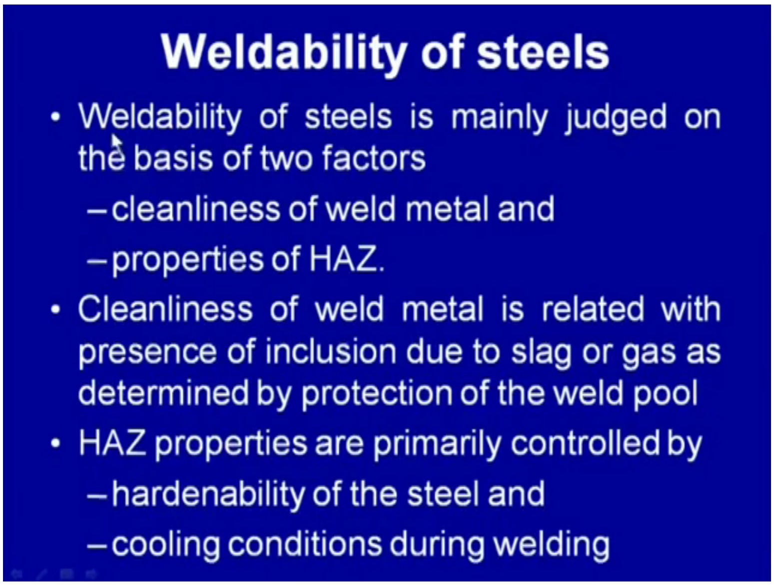


But, the steels are one of the most commonly used metal system, which is extensively used in variety of the engineering industries ranging from the general purpose applications to the construction, railways, military and pressure vessel industry. In variety of the industries, the steel is extensively used because of very good properties and ability to alter the properties using suitable thermal and mechanical treatments.

So, because of this advantage related with the steels, these are very frequently welded to get the desired size and shape. But, as far as weldability of steel is concerned, there are mainly 2 factors that are considered to assess the weldability of a steels. These are that, how clean weld can be produced for a given steel and the how properties are affected with the application of the welding. So, those steels means, the steels after the welding can produce very clean weld they are considered to be better weldable or more weldable as compare to the others, which lead to have the development of the inclusions.

And the similarly, the steels which offer very tough and the strong weld joint and the heat affected zone, they will be considered weldable while others, which tend to embrittle and show greater cracking tendency, they will be showing poor weldability. So, the cleanliness, we know that of the weld metal is related with that, how are we actually protecting the weld pool from the gases present in the atmosphere. So, because if the more gases are reaching in the arc environment, they will be reacting with the elements present in the steel forming the slag.

And the entrapment of the slag will be leading to the presence of the slag in form of inclusions so the cleanliness of the weld metal is basically related with the presence of inclusions due to the slag or the gases as determined by the protection of the weld pool. If the protection of the weld pool is proper during the welding then the weld will be cleaner as compare to the case, when no proper protection is not being provided.

So, this protection will be governed by the process which is being used, different processes use the different protection approaches, as we have discussed earlier like in the submerged arc welding, molten pool weld, molten flux is used in the GTA and GMAW processes. The inert gas and inactive gases like Co 2, are used to protect the weld pool and in the SMAW processes, the inactive gases are generated by thermal liquid decomposition of the fluxes, which are used for protecting the weld pool from the atmospheric contamination of that atmospheric gases.

So, this is about the cleanliness aspect then HAZ properties are primarily controlled by the hardenability of the steel and the cooling conditions, which are experienced by the steel during the welding. So, hardenability of the steel indicates that, how easily steel can be hardened under the given conditions. In general, if the steel's hardenability is high then it can be hardened easily and if it can be hardened easily, it will show greater embrittlement tendency and cracking tendency during the welding.

So in general, the higher the hardenability of the steel, lower is the weldability of the steel similarly, the HAZ properties are also affected by the cooling conditions, if using the high heat input and the high preheating temperature. Preheat temperature, we can facilitate the low cooling rates then the properties of the HAZ will be softer one and there no embrittlement will be taking place.

But, if the situation is reverse like low heat input is being used and low preheat is there or no preheat is done then high cooling rate will facilitate the martensitic transformation in the heat affected zone and that will tend to embrittle the heat affected zone. So, hardness and brittleness will be increasing, if the cooling conditions are high means, the cooling rate is high, especially in the heat affected zone.

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So, as far as the cleanliness of the weld is concerned, this is mainly governed by that how properly we are cleaning the faying surfaces of the base metal before welding and the solidification rate. If the solidification rate is low means, the solidification time is long then the impurities being formed in form of slag in the weld metal then these will be having enough time to come up to the surface and get removed.

So, this solidification rate will be although governed by the heat input and the initial plate temperature, higher heat input and the higher preheating will increase the solidification time and will reduce the these inclusions and the gas entrapment tendency in the weld metal. And thus, producing the cleaner weld and then the weld joint design the wide means large groove angled. V grooves offer the better possibility for these impurities to come up to the surface and to produce a cleaner weld as compare to the U and the J groove joint designs.

So, the higher groove angle promotes the impurities to come up to surface and the produce the cleaner weld. Then protection of the weld pool as per the process, which is being used so if the protection is good then all the gases present in the atmosphere like oxygen, nitrogen, hydrogen, they will be kept away from the weld pool. And their adverse affect can be avoided but if these are able to reach up to the weld pool then it will be leading to have the gas metal reactions and the gas metal reactions will be leading to the development of the inclusions and the porosity in the weld zone.

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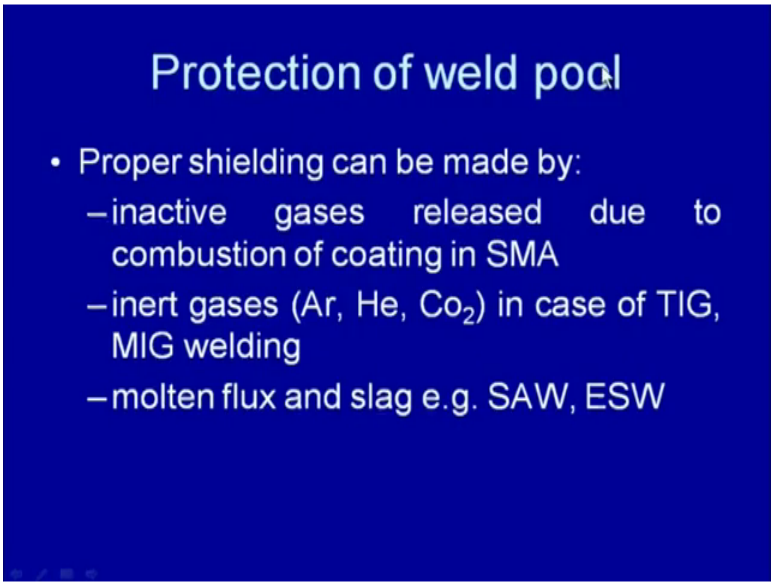


Similarly, the slag metal reactions will also be occurring due to the entrapment of slag inclusions will be developed. But, all these reactions will be governed by that, how effectively the weld pool is being protected. So, the processes which provide very effective weld pool, they will be producing the cleaner weld. So, the weldability of the metal will be better and because of this, the weldability of the metal becomes sensitive to the process.

And then the protection of the weld pool will also consider like a different processes use the different approaches for protecting the weld pool. For example, inactive gases are used, which are produced by the combustion of the coating material in the shielded metal arc welding process. And inert gases are used like argon, helium and inactive gas like Co 2 in case of the GTA and GMAW processes like and the molten flux and slag is used in case of electro slag and the submerged arc welding process.

Now, as far as HAZ properties are concerned, there are 2 important aspects like whether hardening of the heat affected zone is taking place or it softening is occurring.

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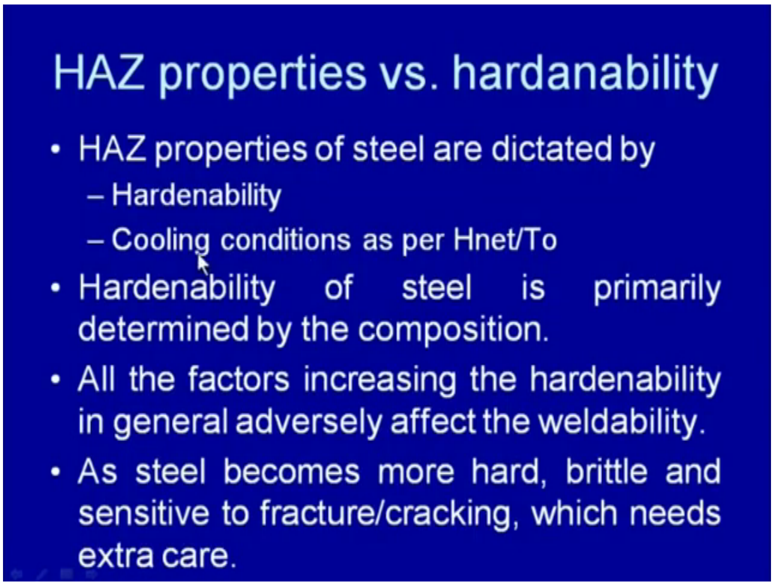


If the too much hardening is occurring then it will be embrittling the heat effected zone and increasing the cracking tendency, that in turn will be decreasing the weldability of the steel. So, especially in case of the steels, HAZ properties are dictated by the hardenability and the cooling conditions as per the HAZ and the initial plate temperature. So, hardenability of the steel is primarily determined by the composition, so steel composition will be basically affecting it is hardenability.

And all the factors which are increasing the hardenability, they will be making the steel heat affected zone brittle and of the higher hardness and the lower toughness. And so it will be adversely effecting the weldability, as a steel becomes more hard, brittle and sensitive to the cracking and fracture. Therefore, it requires extra precaution to have the softer heat affected zone and the extra precautions increase the cost of the welding especially, in case of the steels of the higher hardenability.

And because of this although the steels having the higher hardenability, their weldability is considered to be low, then the important factor that affects the hardenability of the steel is the carbon content and the presence of alloying elements in the steels.

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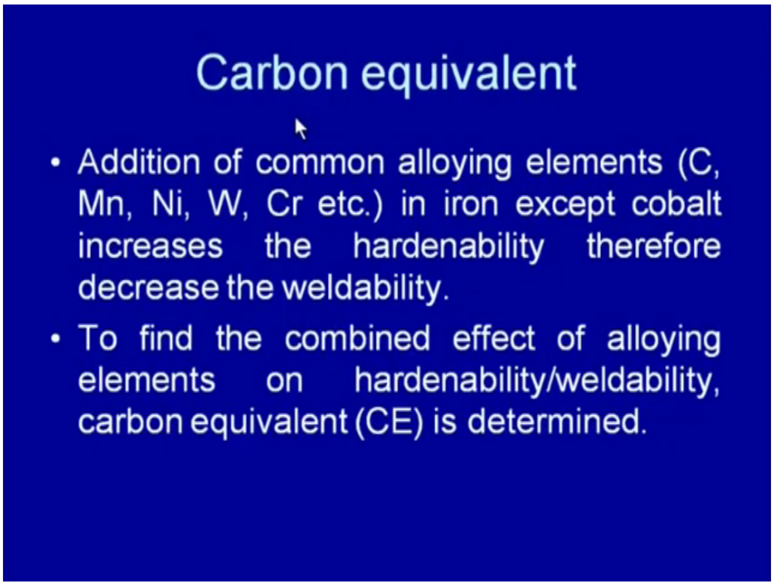


Most of the alloying elements like carbon, manganese, nickel, tungsten, chromium present in the steel, they increase the hardenability of the steel except the cobalt and because of this, presence of all these alloying elements decrease the weldability. However, relative effect of each of the element is found to be the different and to find the combined effect of all alloying elements on the hardenability and so the weldability of steel basically, carbon equivalent is calculated. And the carbon equivalent for the steel is calculated using the different formulas, which are used for the different category of the steels.

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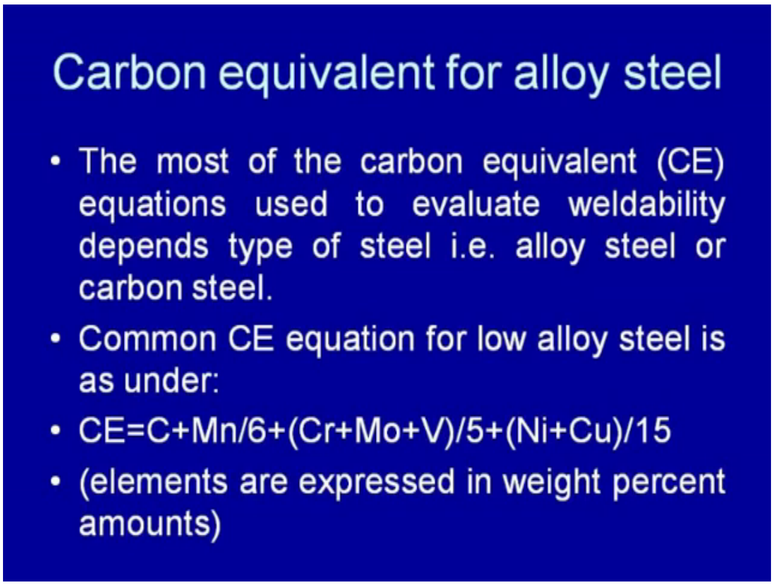


For example, like for the common low alloy steels, the carbon equivalent equation is this like the CE is equal to C plus Mn by 6 and Cr, Mo and V, that is vanadium divided by 5 plus Ni nickel plus copper divided by 15. So here, all these symbols indicates the weight percentage of those elements, which are there in the steel. So, those weight percentages are kept in place of the symbols and then calculation is made to find out the carbon equivalent, other carbon equivalent equations which are used for the low carbon steels.

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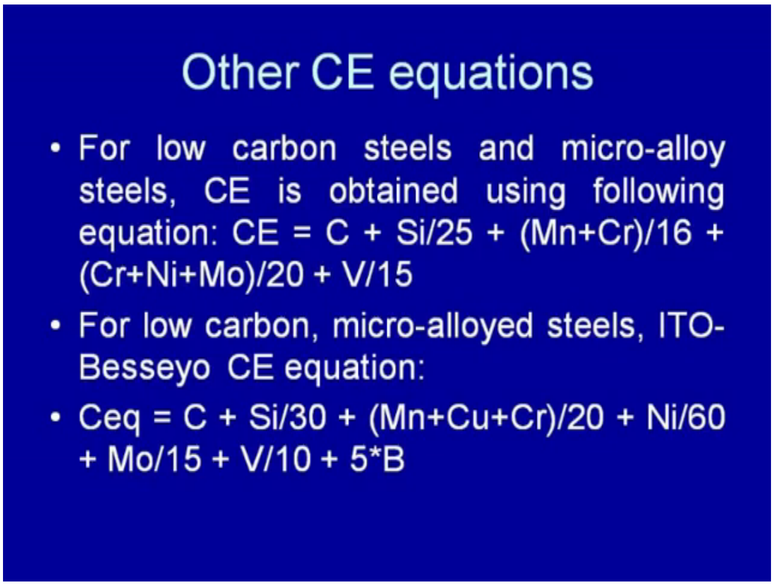


And the micro alloy steels is, this is one of the equations where, carbon equivalent is obtained from the C plus silicon by 30 divided by manganese plus chromium divided by 16 and chromium plus nickel plus molybdenum divided by 20 plus vanadium divided by 15 and this is a another equation. So, these equations can be used in, all these can be used to calculate the carbon equivalent and based on the carbon equivalent, we determine the hardenability means, hardenability of the steel is determined.

So, higher is the carbon equivalent, higher will be the hardenability of the steels and so the lower will be the weldability of the steel. If we see any of these equations then we can see that, carbon equivalent is directly dependent upon the carbon content plus presence of the other alloying elements. And the greater is the value, by which we are dividing a particular the weight percentage that will indicate the relative effect of that particular element.

For example, here the vanadium divided by 50 indicates that, it is effect on the hardenability or carbon equivalent is more, it is effect on the hardenability of the steel is more as compare to that of the silicon. So, this is how, we can determine the effect of each element on the carbon equivalent is different and that is divided, that depends upon the coefficient that is being divided.

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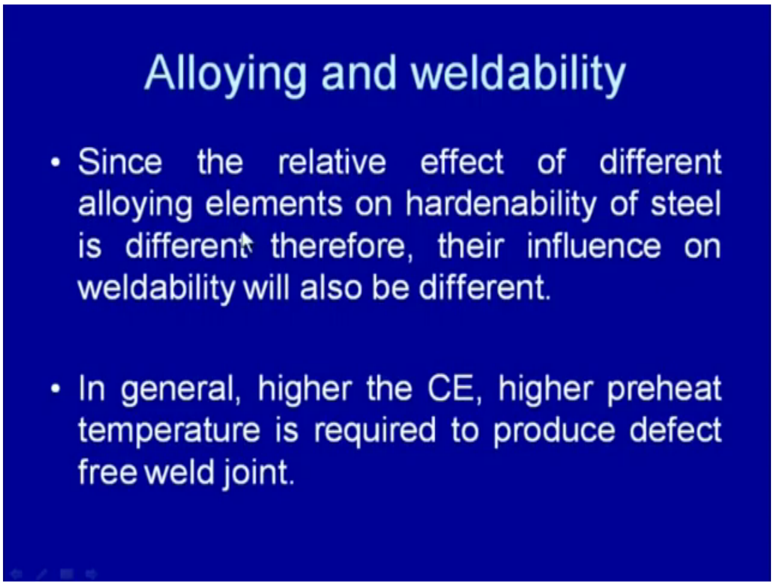


So, the maximum effect of all these elements, maximum effect is of the carbon on the carbon equivalent and it is added directly means, whatever is the weight percentage of carbon present in the steel, that is added directly in the chromium equivalent plus, while in other cases some coefficient is divided. So, this indicates, that effect of the carbon is maximum on the hardenability and on the carbon equivalent.

If we see above equations, since the relative effect of the different alloying elements of the hardenability is different therefore, their influence on the weldability will also be different. In general, higher is the carbon equivalent, higher will be the preheat temperature required to produce a defect free weld, because of the reduced the weldability. So that, because any higher carbon equivalent results in the higher hardenability and so the increased tendency of the embrittlement and cracking. And to avoid those, that cracking tendency basically, the preheating is done so that the cracking can be avoided.

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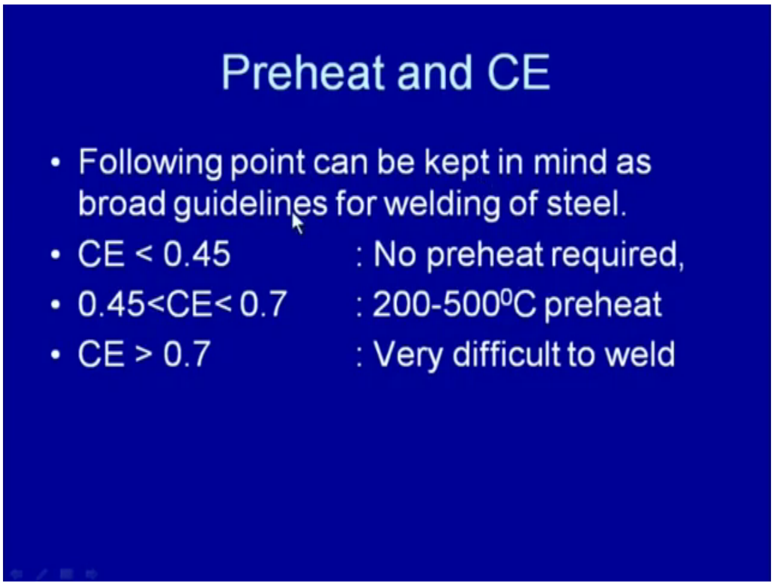


As a guideline, the following points can be kept in mind to avoid the cracking in the welding of the steel. And so that the satisfactory weld joint can be developed say, if the carbon equivalent is less than 0.45, as calculated using above equations then no preheating is done. But, if the carbon equivalent is in the range of 0.45 to the 0.7 then preheating of 200 to 500 degree centigrade is done and if it is more than 0.7 then it is found very difficult to weld.

We know that, the cooling rate directly effects the cracking tendency and the hardening of the steel. So, if the thickness of the plate is considered then we can have the more representative and better picture of the weldability of the steels. And for this purpose, apart from the compositional aspects, thickness of plate is also a considered for calculating and for looking into the weldability and the hardenability aspects.

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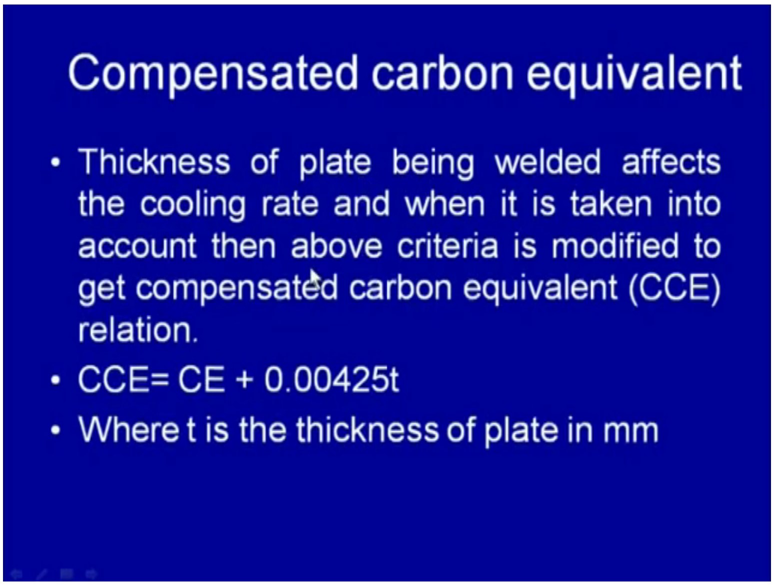


Like the thickness of the plate being welded affects the cooling rate when it is taken to account above then above criteria is modified to get the compensated carbon equivalent means, to consider the hardenability aspects of the steels, if apart from the composition. If the thickness of the plate is also considered then we need to have the another equation and that will be showing the carbon equivalent plus the thickness. And this is given another name means, this is another criteria, where thickness and the composition both are considered and it is named as the compensated carbon equivalent. It considers carbon equivalent as described earlier and the thickness of the plate, which is to be welded. So, if the greater is the thickness of the plate, the higher will be the compensated carbon equivalent and this accordingly, will be increasing the preheat requirements.

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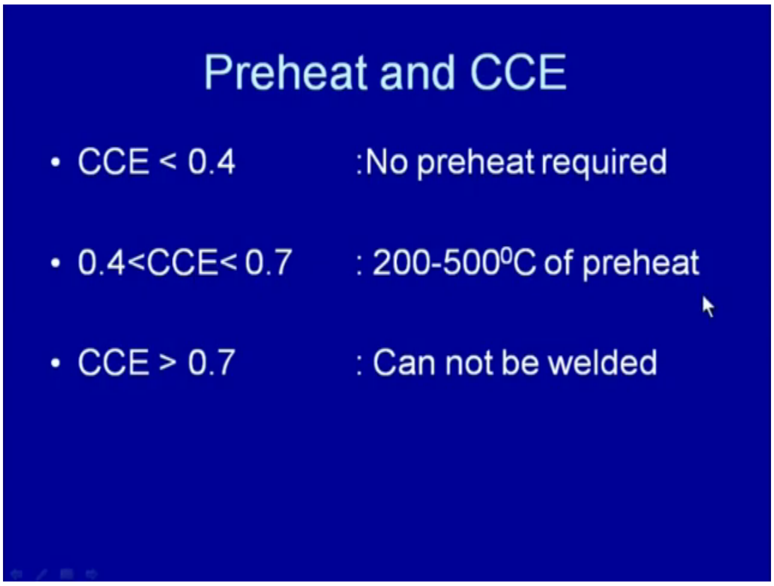


So, with the compensated carbon equivalent, no preheat requirement comes out to be there, if it is less than 0.45. And if it is in the range of 0.4 to 0.7 then the 200 to 500 degree centigrade preheat is required and above this, it is found very difficult to weld or cannot be welded. In general, there are variety of the steels, which are used for the fabrication purpose and require welding very commonly. And these steels are of the 5 different categories and these categories are mainly based on the following factors.

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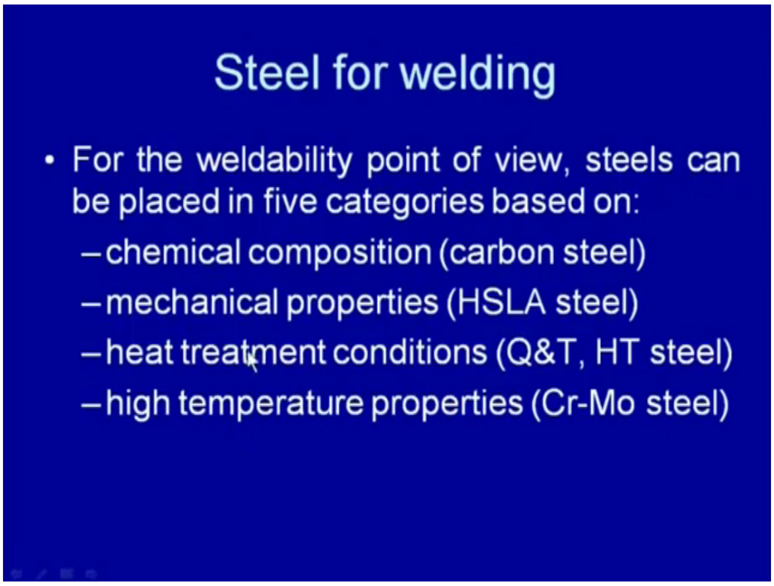

One is the chemical composition so this from the weldability point of view, steel can be categorized in 5 different types and these classification is based on one composition. So, here, there is a carbon steels, which can be of low carbon steel, medium carbon steel and high carbon steel, in which there is no presence of the other alloying elements to achieve this specific set of properties. So, they will be termed as the, this is one classification based on the chemical composition mainly, we have carbon steels under this heading.

Another classification is based on the mechanical properties and in this, we have like high strength, low alloy steels where the strength of the steel. So, these steels will have the yield strength in particular band say, from 275 to 550 MPa and then another category is of the heat treatment. Based on the heated conditions, we have the quenched and tempered steels, which have this strength in the band of 350 to 1050 MPa. And the heat treatable steels is another category, the heat treatable steels can be the carbon steel or the HSLA steel, which is having the higher carbon content.

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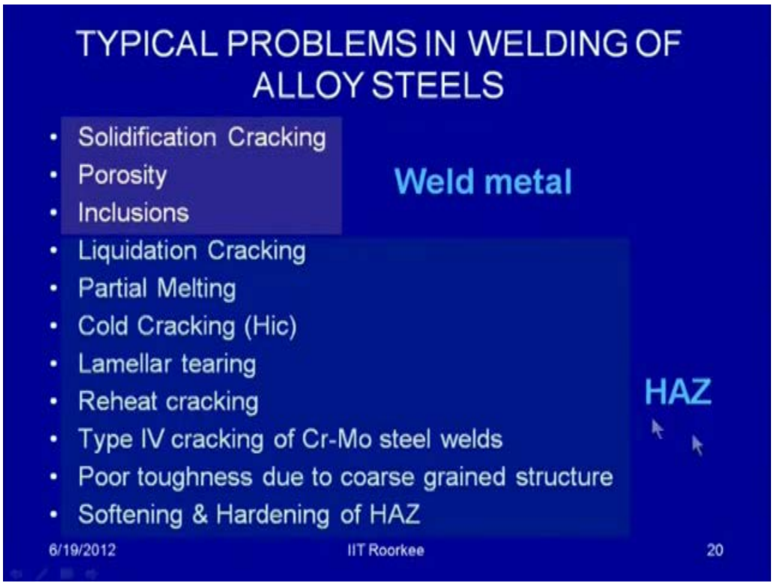


So that, on heat treatment, it gives us the desired properties so which are expected from it but because of the high carbon content, these show the lower toughness and the greater cracking tendencies. So, these steels will require greater precaution while welding then the certain steels, which have the capability to serve under the high temperature conditions like chromium molybdenum steels. So, the kind of problems which are experienced by the each category of the steel is found to be different and therefore, that different welding approaches used for each category of the steel.

As far as problems in welding of these steels is are concerned, all problems can be means, most of the problems can be a groped under the 2 headings. One is those problems, which are encountered in the weld metal zone and another set of the problems, which are encountered mainly in the heat affected zone. So, the problems encountered in the weld zone like solidification cracking, the porosity and the inclusions, these are the 3 kind of problems which are encountered in the weld zone and the proper steps are taken to avoid this.

And other problems like the liquation cracking, partial melting, cold cracking, lamellar tearing, reheating, type 4 cracking in chromium molybdenum steels, poor toughness due to the coarse gained structures, softening and hardening of the heat affected zone, all these are basically related with the heat affected zone. And these problems are basically the steel or the material sensitive, some of the steels are sensitive for the liquation cracking, others are sensitive for the lamellar tearing.

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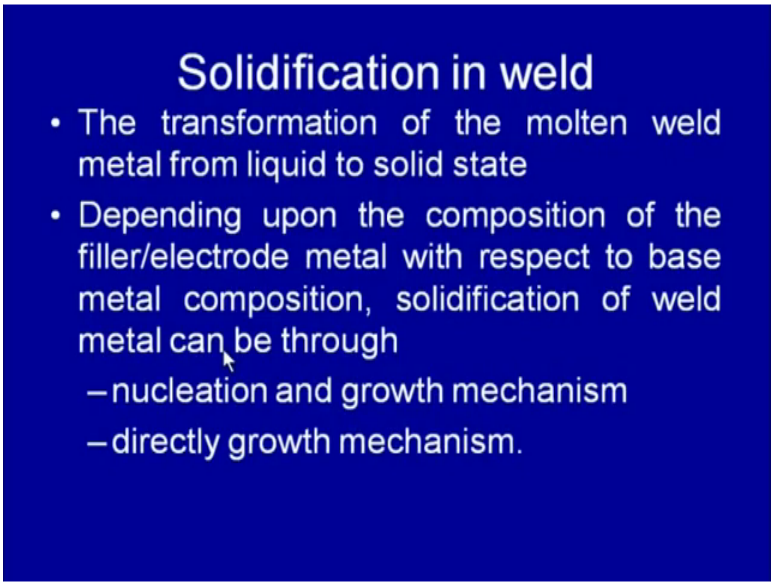


So, depending upon the kind of steel or the metal system which is being welded, they are found sensitive for the different kind of the problems. So, we will be starting with the like as I said in the beginning. for considering the weldability of the steels, we need to focus on the properties and the performance that will be getting after development of joint from the 2 regions, one is the weld zone, another is the heat affected zone. So, what kind of performance after the welding we are getting from the weld zone, that is looked into for considering it is weldability and the another set is of the heat affected zone so we will be starting with that.

What are things, which dictate the weldability of the steel especially, from the weld metal point of view. So, for this first, there are various aspects like that will be, they are related with the weld zone.

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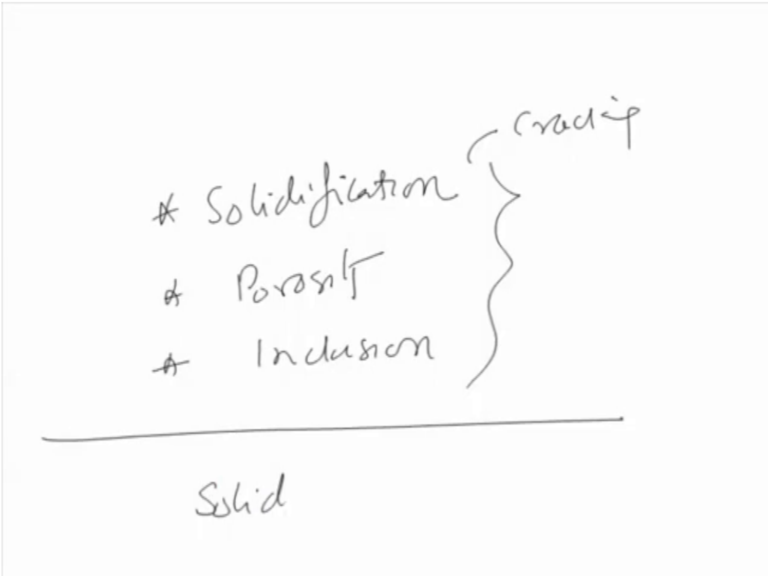


So, the one is the solidification, the second is the development of the porosity and the inclusions, these are the 3 main problems as far as the weld metal is concerned. And the solidification, if the solidification is not proper means then it can lead to the development of the solidification cracks especially, in the metal systems having the high solidification temperature range. While the porosity and inclusions are developed due to the improper protection of the weld pool from the atmospheric gasses.

So, we need to see that, the solidification of the weld metal takes properly with the desired structure. So that, the alloy segregation tendency along the weld center line can be avoided in order to control the solidification cracking tendency. So, solidification cracking is one, and the porosity and inclusions are another, so here if the solidification of the we know that, solidification of the any metal system will generally occurs.

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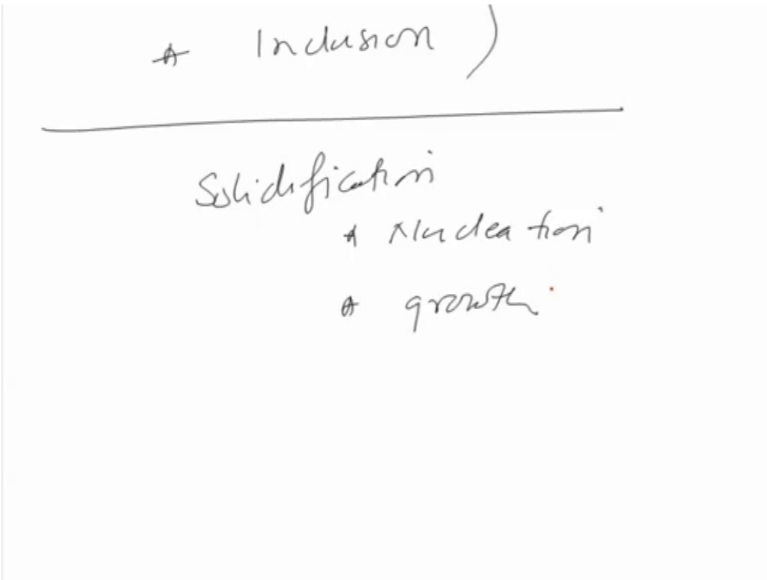


Solidification occurs in normally in 2 stages, one is nucleation and another is growth so for the nucleation means, from the molten metalize the heat is extracted, first the nucleation takes place and once nucleation is over the weld metal means, the metal solidification completes through the growth stage. So, in case of the welding, depending upon the composition of the weld metal or the filler metal or electrode which is being used, the solidification of the weld metal can take place, either through the nucleation and growth stages both or it can directly take place through the growth stage.

So, this is the typical kind of situation, which is experienced in case of the welding when the weld metal composition is similar to that of the base metal then no nucleation is done or it is required. But, directly solidification completes through the growth stage only and this kind of solidification is called epitaxial solidification. While in case of the metal systems, where composition of the base metal is different from the filler metal or the electrode then this solidification requires both nucleation as well as growth stages.

And under those conditions, normal solidification will be occurring where, both the stages will be required and no epitaxial solidification will be occurring in those conditions.

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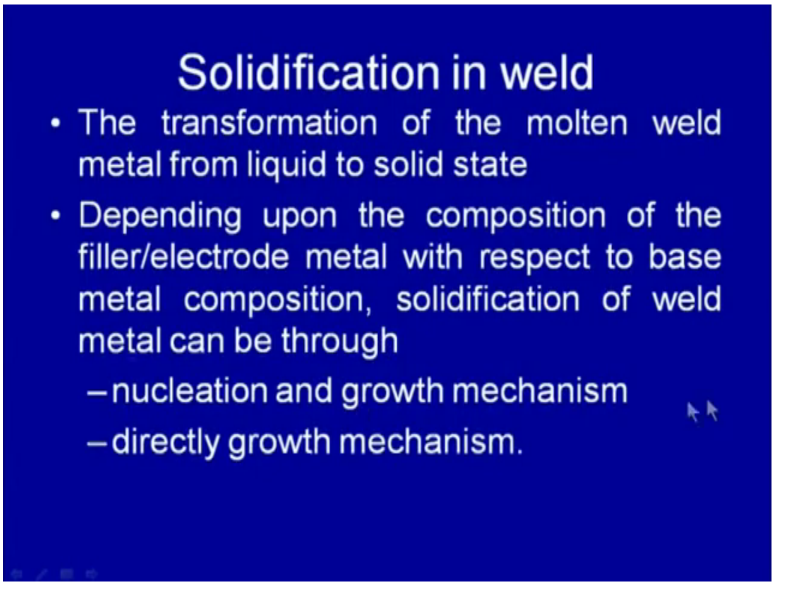


So, this is what is required for solidification to happen, that the nucleation and the growth mechanisms both are required or it can happen directly through the growth mechanism. So, depending upon the composition of the filler metal and the electrode material with respect to the base metals, solidification can happen in through these two ways.

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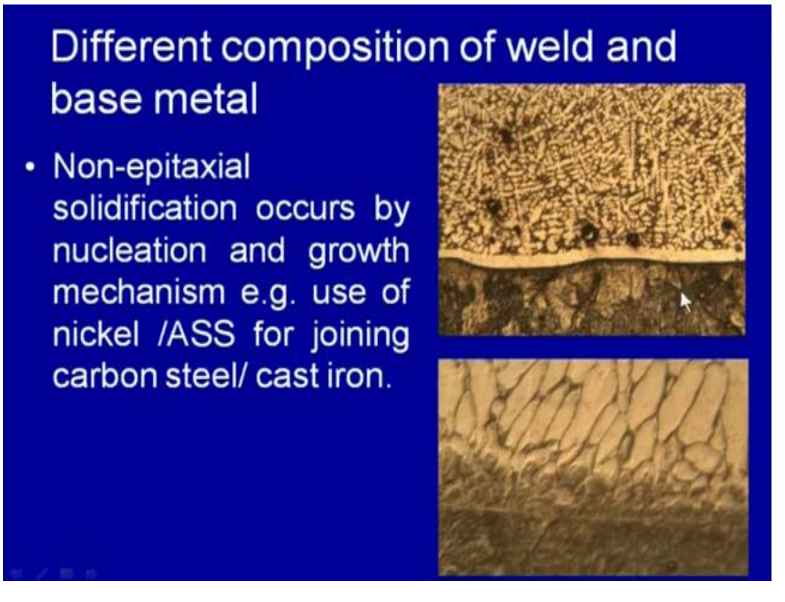


So, one situation where, composition of the weld metal and the base metal are completely different then first the nucleation will be taking place through some sort of the planar solidification and then thereafter, the growth will be occurring. So, in this situation, the first the nucleation will be occurring and thereafter, the growth will be taking place. And this can be situation like, the nickel electrode or the austenitic stainless steel electrodes are used for developing the weld of weld joint of the carbon steel and the cast irons. So, in this condition, the both nucleation and the growth stages are required and this kind of solidification in case of welding is termed as non epitaxial solidification.

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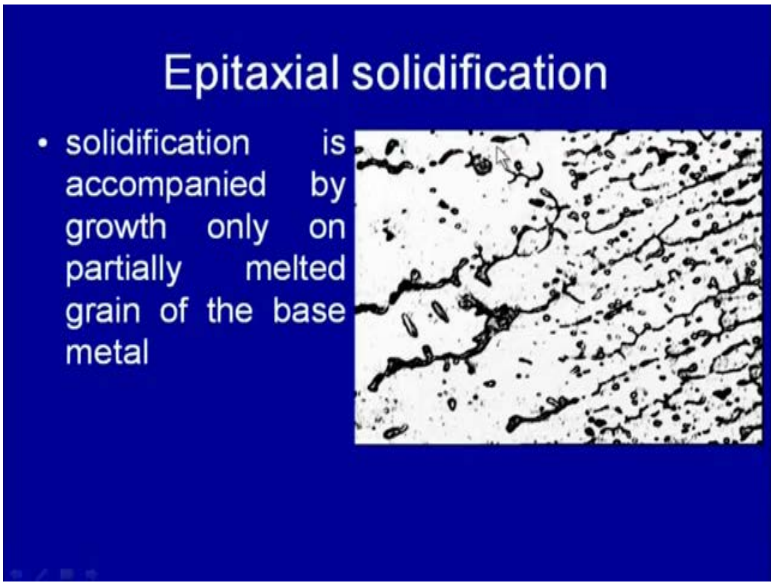


In other situation where, the weld metal composition is similar to that of the base metal then the partially melted grains start to grow directly by consuming the liquid weld metal. And this kind of solidification does not require nucleation stage but the solidification is completed through the growth stage only. And so this kind of solidification where, the partially melted grains like this starts to grow directly so this kind of solidification is termed as epitaxial solidification. And it is very commonly encountered in case of the welding of the steels where, the weld metal or the electrode metal is similar to that of the base metal.

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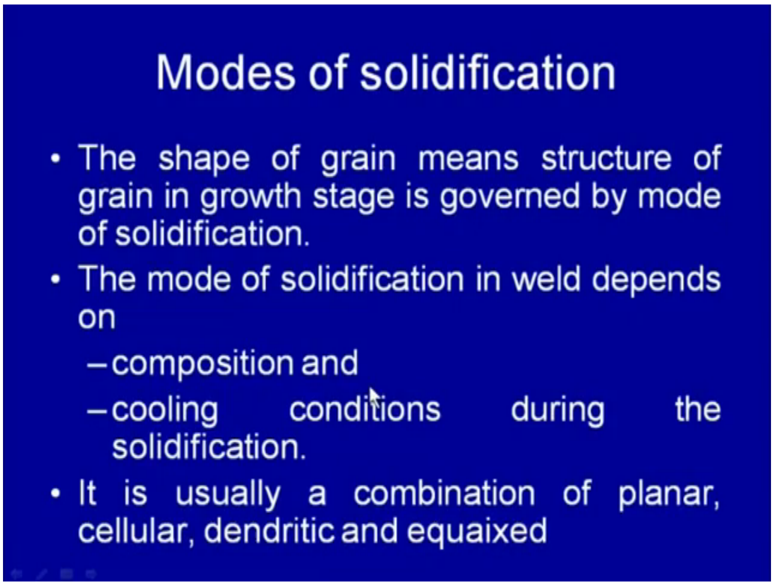


So, there are certain stages, there are certain particular patterns or the modes through which solidification takes place and these modes basically, dictate the structure of the weld, which is developed after the solidification. And these mode of the solidification and depend upon the composition of the weld metal and the cooling conditions experienced during the welding, and these can take place means, the solidification can take place in different modes like planar, cellular, dendritic and the equiaxed.

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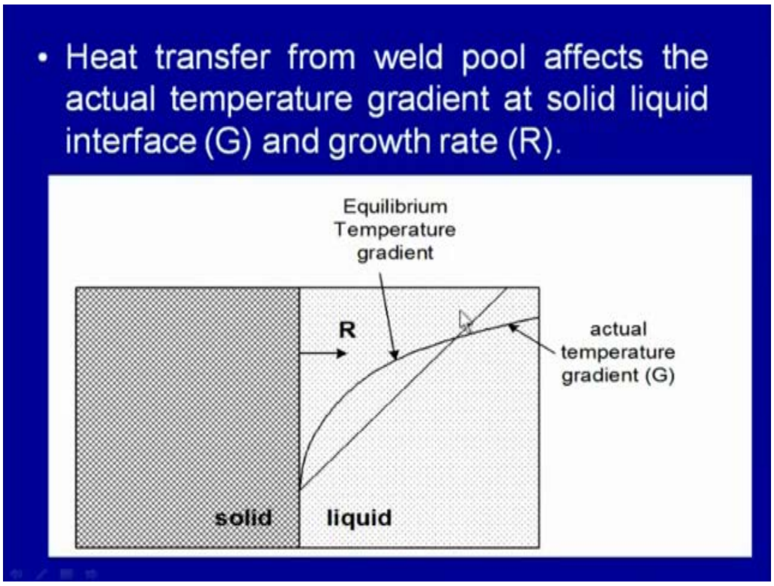


Depending upon the cooling conditions being experienced by the weld metal during the solidification say, this is a solid and this is the liquid, this is a solid liquid interface. So, due to the extraction of the heat away, the solid liquid metal interface will be moving at certain speed and so that will be governed by that the rate, at which is being extracted. If the R can be high or low and another aspect is the actual temperature gradient that is G.. So, the combination of these two parameters, the actual temperature gradient can be high or can be low, if it is low then it will be like this, if it is high it will go like this.

And the growth rate means, how fast the interface is moving, these two factors significantly affect the kind of the mode of solidification, which will be experienced by the weld zone. So, heat transfer from the weld pool affects the actual temperature gradient at the solid liquid interface and the growth rate. These two parameters significantly dictate the kind of the grain structure, which will be developed.

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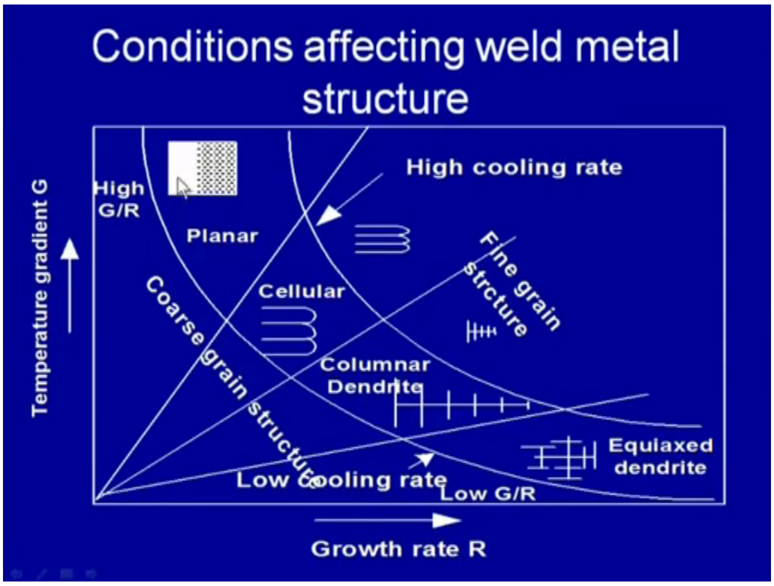


So, if we see here this, in the x axis we have growth rate that is, R and the temperature gradient that is, G on the y axis. So, if we take up the high value of G and low value of R then we will be getting the planner solidification so here, entire plane is developed. If we consider the very low value of G and the high value of R then we get the equiaxed grain structure, a structure of the grains will be like this. And in between, we will have the cellular structure like this and the dendritic structure like this.

So here, and if we come across the lower cooling rates or higher cooling rates then the higher cooling rates will be resulting in the finer grained structure as compare to that are obtained under the low cooling conditions. So basically, the G and R significantly dictate the kind of solidification, which will be occurring. Typically during the welding, all these modes of the solidification are experienced.

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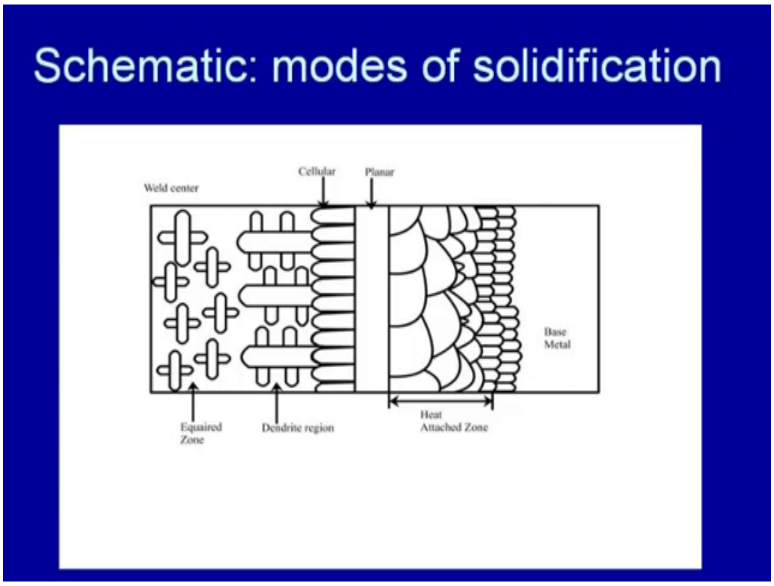


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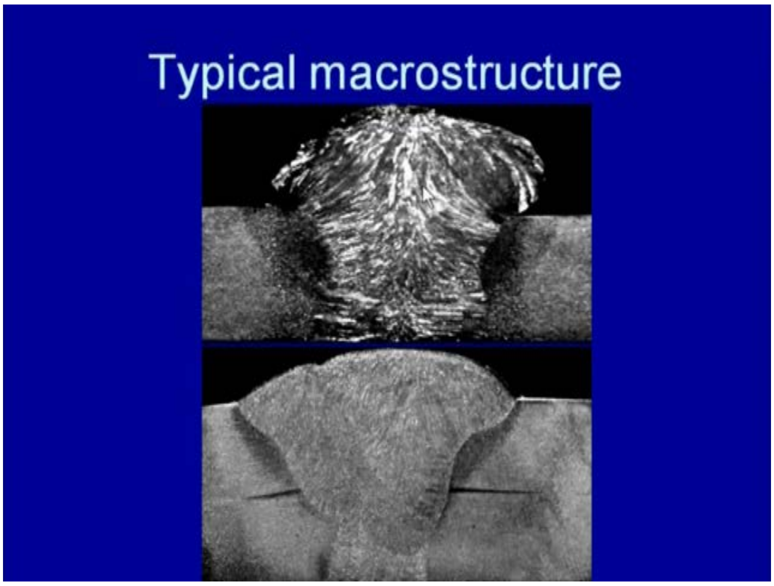

Like though first, we have the planar solidification because the G by R ratio is found high near the fusion boundary then we have the cellular structure slightly away from the fusion boundary then it is columnar, dendritic and finally, equiaxed at the weld center. So, because of the changing G by R ratios, which is very high at the fusion boundary and very low near the weld center, we come across all these 4 modes of the solidification especially, in the weld zone.

Typical macrostructure, here it shows that this is the fusion boundary and the columnar grains are growing perpendicular to the fusion boundary. This is very refining grain structure so here, we can say the columnar grains are not that big in the second case, as compare to that of the first case.

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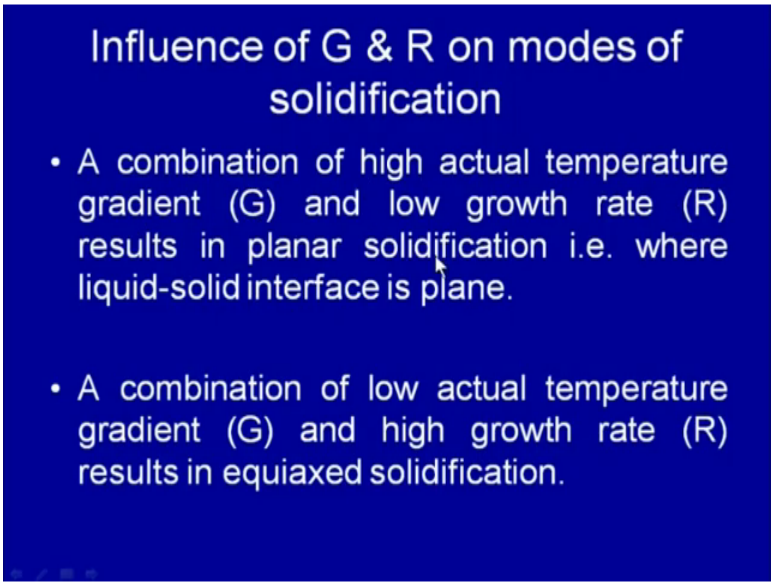


So, as far as G and R are concerned, a combination of the high means, high value of G and low R results in the planar solidification and a combination of the low G and high R results in the equiaxed solidification.

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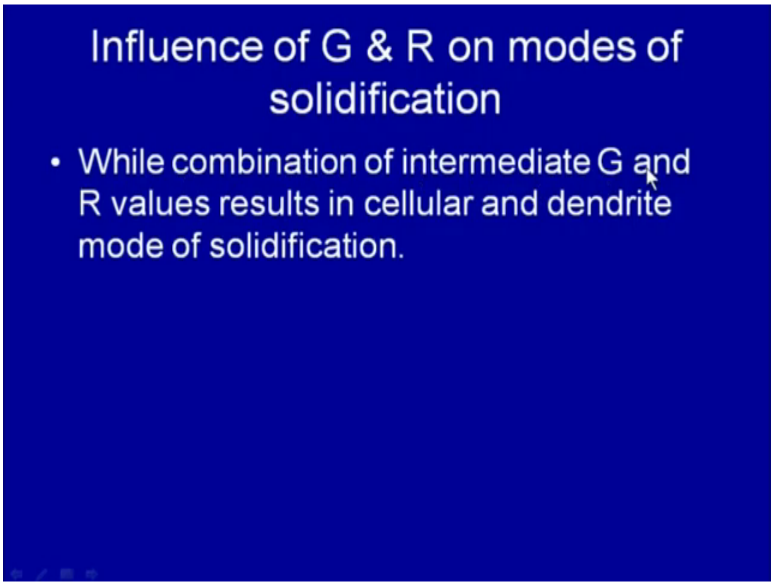


While a combination of the intermediate values of the G and R results in the cellular and the dendritic mode of the solidification.

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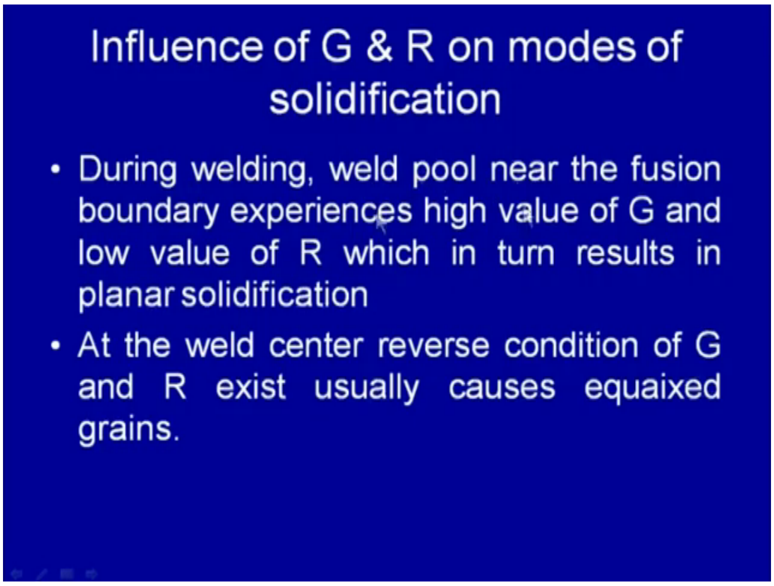


During the welding weld pool near the fusion boundary, experiences high value of G and low value of R which in turn, results the planar solidification, while the reverse happens and in case of the weld center, and that produces the equiaxed grained structure. Now, we know that, it is important to have very refined gradient structure in the weld zone so that, the good combination on the mechanical properties can be obtained and the solidification cracking tendency can be avoided.Therefore, efforts are always made to refine the grained structure in the weld zone so that, we have very fine equiaxed grain structure in the weld region. To achieve this, various approaches are used for refining the grain structure.

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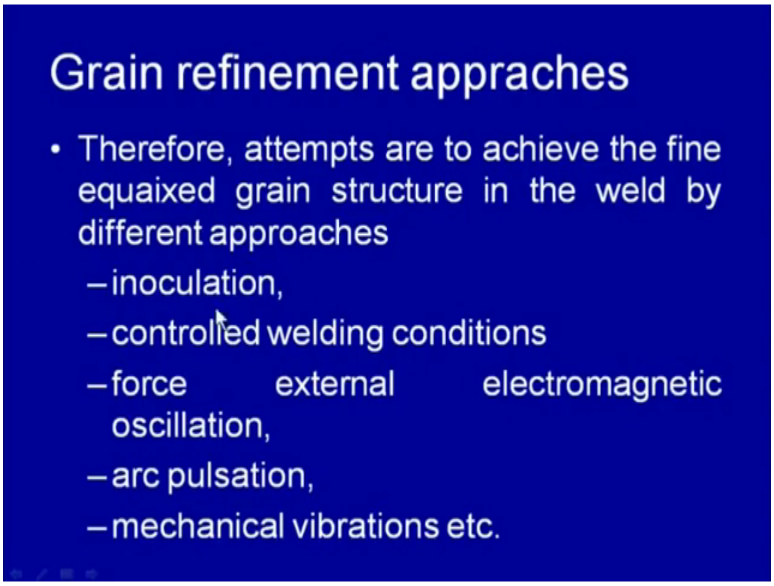


These are inoculation, which is nothing like just adding the alloying element so that, they can act as a nucleant to refine the grain structure. Then controlling the welding conditions so that, unnecessary high heat input can be avoided in order to achieve the high cooling rate in the weld zone. So that, the grain structure can be refined or the use of external force, this approach is basically used for braking the dendrites or the partially melted the grains of the base metal in order to break them so that, they can act as a nucleant.

Arc pulsation helps to increase the cooling rate and also helps to develop the smaller weld pool in order to refine the grain structure in the weld region. And mechanical vibrations also work on the same principal, as that of the electromagnetic force where mechanically, the dendrites which are growing in the weld region are broken, so that they can act as a nucleant for refinement of the grain structure.

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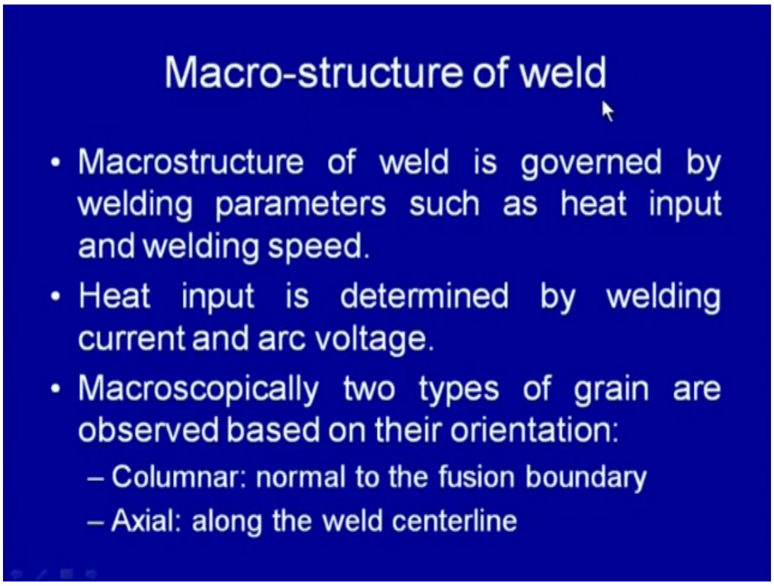


As far as the macrostructure of the weld metal is concerned, macrostructure of the weld metal is governed by the parameters like the heat input and the welding speed. The heat input is determined by the welding current and the arc voltage, higher current and the high arc voltage in general, increase heat input. Macroscopically, the two types of the grains are observed in the weld region, one is columnar which are perpendicular to the fusion boundary and the axial which are along the weld center line.

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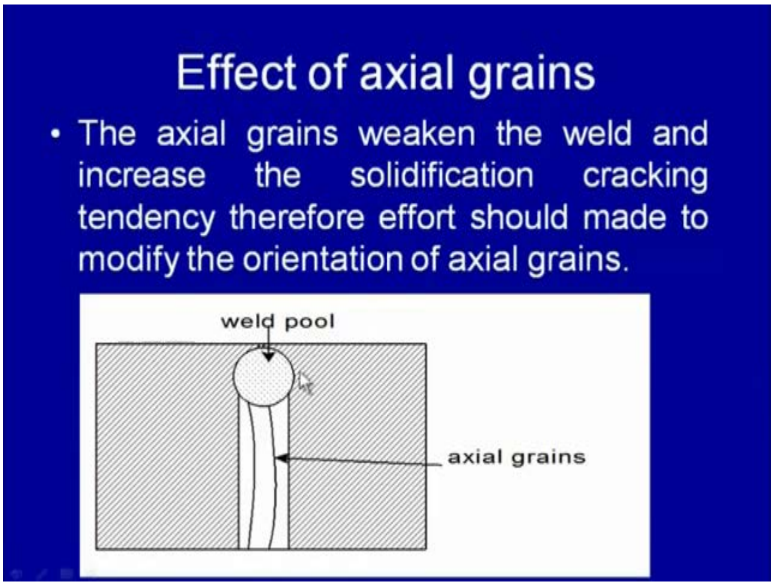

So, we can say this is the weld pool and the grains which are growing like lengthwise, they are axial grains and the grains which will be growing perpendicular to the fusion boundary, which has been of the base metal, which has been melted, they will be developing the columnar grained structure. So, axial grains weaken the weld and increase the solidification cracking tendency and therefore, efforts should be made to modify the orientation of the axial grain.

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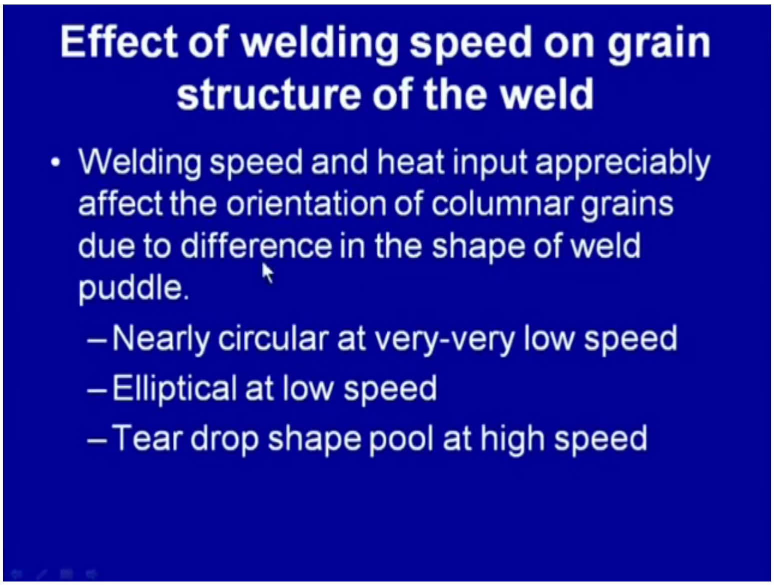


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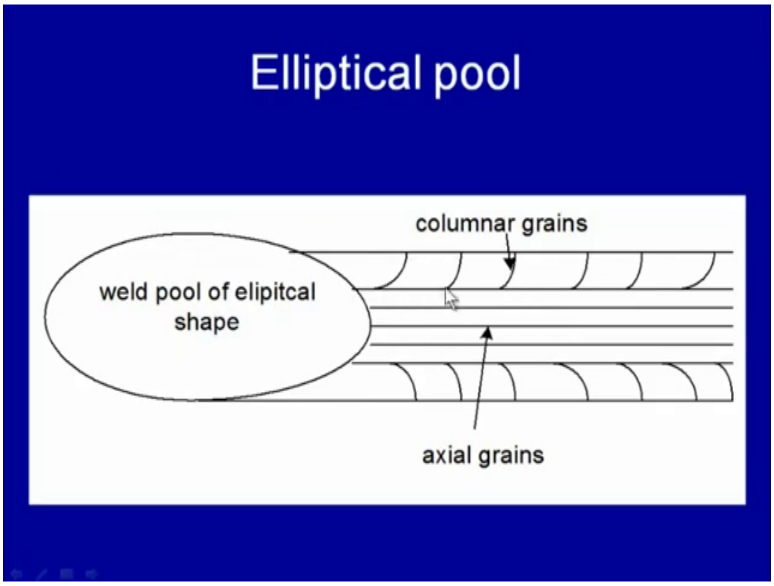


If we see the welding speed and the heat input, appreciably affect the orientation of the columnar grains due to the difference in shape of the weld pool. If we work with the very low speed then it will be developing the elliptical weld pool and the tear drop shape weld pool is obtained at the high speed. If we see these two diagrams, at low speed we will be getting very elliptical weld pool and the grains will be cord kind. But, in this case where, we get very wider the axial grain structure. In case so at high speed, the shape of the trailing end of the weld pool becomes the tear drop shape and the grains are mostly perpendicular to the fusion boundary.

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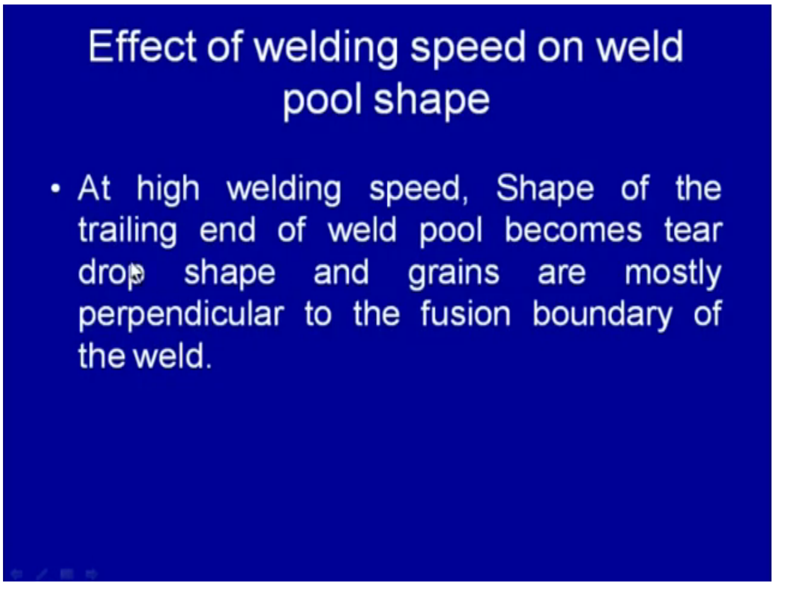


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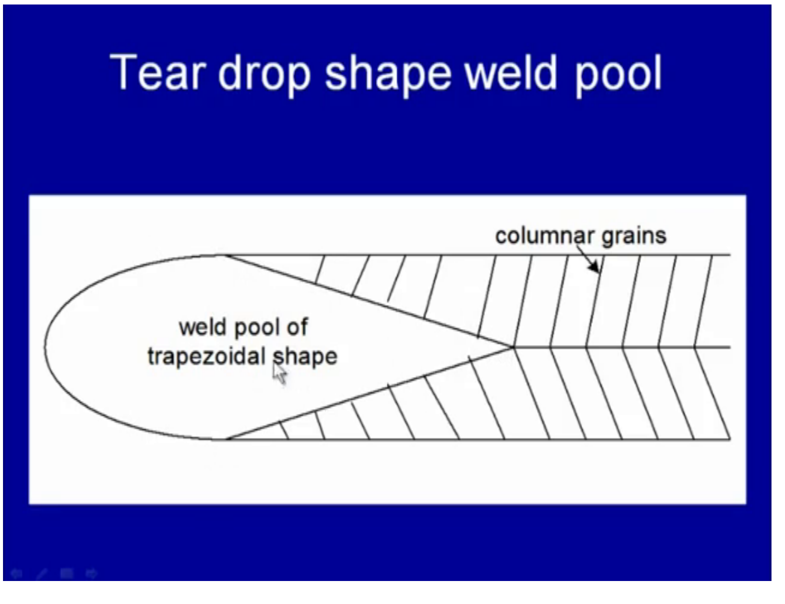

So, if we work with the higher welding speed then this will be resulting in the tear drop shape, trapezoidal shape of the weld pool and the grains will be largely perpendicular to the fusion boundary and they will be abutting at the weld center. This kind of the grained structure increases the alloy segregation tendency in the weld region. So now, I will summarize this presentation, in this presentation, we have tried to understand the weldability of the metals and thereafter, we observed that the different factors that affect the weldability of the steels.

And what are the factors, that affect the grained structure of the weld zone and what can be done in order to refined the grain structure of the weld zone. In detail, we will try to look into the various mechanisms related with the grain refinement of the weld zone. And we will also try to see in next presentation about the different reactions, which take place in the weld region and the heat affected zone. In the weld region basically, the gas metal and liquid metal reactions take place, which promote variety of the defects in the weld regions. So, how those can be avoided, that will be also observed in the next presentation.

Thank you for your attention.