**Weldability of Metals**

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**Lecture - 40**
**Weldability of PH Stainless Steels**

Hello, I welcome you all in this presentation related with the subject weldability of metals and so far we have talked about the weldability of the martensitic stainless steel, ferritic stainless steel and some of the aspects related with the austenitic stainless steels also. In this presentation initially we will be talking about the some of the weldability related aspects of the austenitic stainless steel.

And then we will talk about the weldability of the precipitation hardenable stainless steel. So we have seen that the welding of the austenitic stainless steel imposes various types of the problems during the welding. So in this presentation, basically I will be talking about the problems which are caused due to the solid state transformation or the phase transformation.

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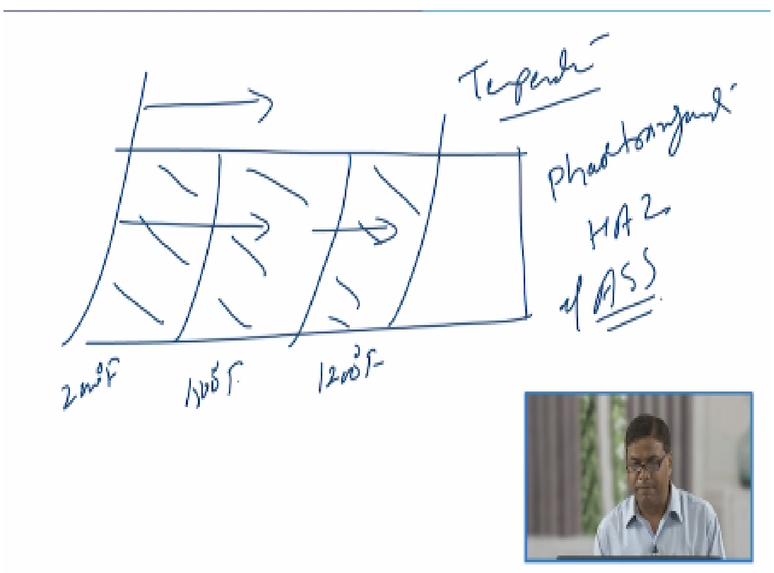


We know that when the welding of the ASS is carried out so there will be different zones which will be heated away from the fusion boundary which will be heated to the high temperatures. There will be different zones in the base metal which will be heated to the different temperatures like will be heated to the temperatures well above 2000 degree Fahrenheit. Few will be heated above 1500 degree Fahrenheit and likewise.

Few will be heated above 1200 degree Fahrenheit. So according to the kind of the temperature which is experienced by the different zones, the different changes will be experienced in these areas and accordingly different types of the phase transformations will be occurring in the heat affected zone of the austenitic stainless steel. There are two types of the most common problems which are encountered during the welding of the ASS as far as the phase transformation is concerned.

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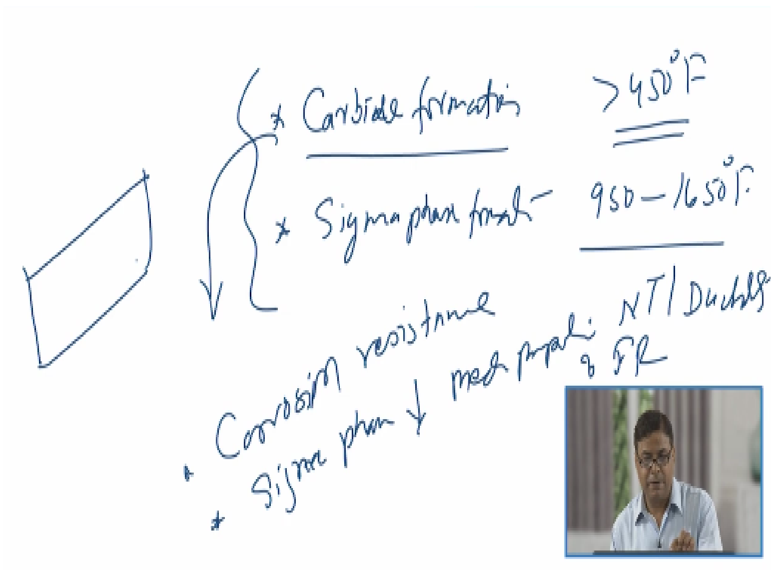


One is the chromium carbide formation. All the zones which are heated above the temperature of 450 degree Fahrenheit, they will be experiencing the carbide formation. Further at higher temperature sigma phase formation is also encountered and which is normally observed in the temperature range of 950-1650 degree Fahrenheit.

So these are the two kind of the phase transformations which are commonly observed and which adversely affects the performance of the weld joints of the austenitic stainless steel especially in the heat affected zone. Like because of the carbide formation, chromium carbide formation corrosion resistance is reduced.

And on the other hand sigma phase formation this reduces the mechanical properties especially with regard to the notch toughness, ductility and the fatigue resistance. So these are some of the adverse effects associated with the welding of the ASS occurring due to the phase transformation in the heat affected zone of the ASS weld joints. So we will try to understand these aspects related with the ASS welding.

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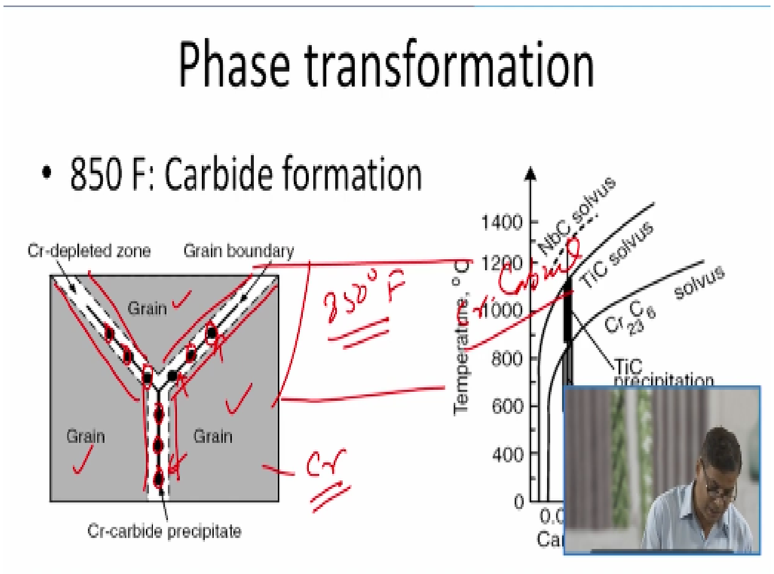


Like all the zones which are heated in the temperature range of the like say up to the 850 degree Fahrenheit, there the chromium carbide precipitation takes place. And wherever the chromium carbide precipitation takes place that zone will be experiencing the depletion of the chromium say these are the 3 different austenite grains having the chromium in solid solution.

But when the temperature exposure is given over a certain range of the temperature which is called sensitization temperature range, in that temperature range due to the rejection of the carbon at the grain boundaries, the carbon particles interact with the chromium available nearby and which leads to the depletion of the chromium in the zones along the grain boundary.

So this depletion or deficiency of the chromium selectively along the grain boundaries will be leading to their reduced corrosion resistance. So what we can do as far as this chromium carbide formation is concerned.

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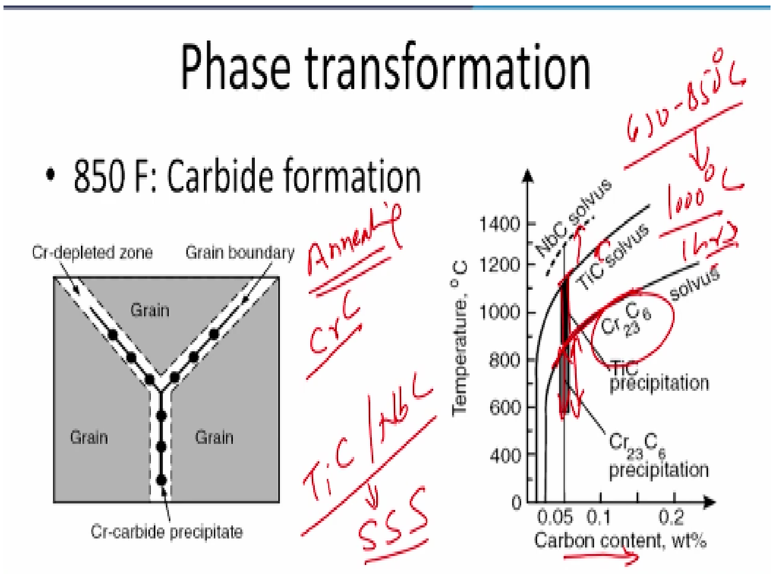


So what basically we have to see is that the different types of the carbides which are found in the austenitic stainless steels like mostly it is the formation of the chromium carbide but other carbides like titanium carbide and niobium carbides can also be formed but these will be found in case of the stabilized austenitic stainless steels. And these are formed at higher temperature.

And accordingly these will be dissolving at a higher temperature. What this diagram shows that as a function of the carbon content at what temperature the different types of the carbides will be getting dissolved. So this is the temperature range for the sensitization or the chromium carbide formation and above this temperature the chromium carbide will get dissolved.

This is the sensitization temperature range or the temperature range over which titanium carbide will be formed and above which the titanium carbide will get dissolved and likewise the tungsten carbide will be getting dissolved at a much higher temperature. So to restore the corrosion resistance it is important that whatever chromium carbide is being formed over sensitization temperature range that must be dissolved.

And for dissolving that normally it is required to perform the annealing temperature since in degree centigrade it is the temperature range of the 650 to the 850 degree centigrade. So the heating at 1000 degree for about 1 hour helps in dissolving the chromium carbide and making the distribution of the chromium more uniform in the matrix in order to restore the corrosion resistance.

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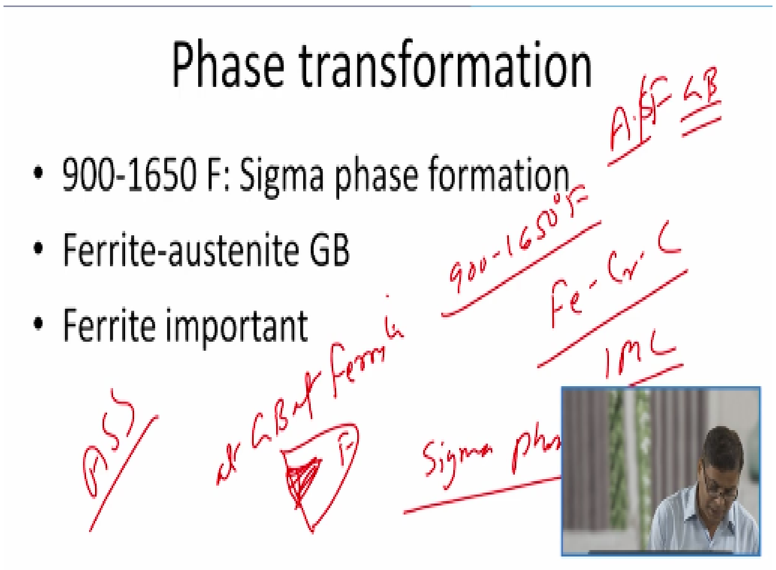


As I have said at higher temperature like say 900–1650 degree Fahrenheit. In this temperature range iron, chromium, carbon intermetallic compounds IMCs are found in form of the sigma phase formation. This sigma phase is formed at the grain boundary of the ferrite phases which are present in the ASS, the heat affected zone or in the weld metal.

And the sigma phase will be formed at the grain boundary and it will be proceeding towards the center of the ferrite grains. Say this is the ferrite grain so this sigma phase will be formed at the boundary and it will be growing towards the center of the ferrite. It is also commonly observed at the austenite and the ferrite grain boundaries. It is observed that the ferrite content present in the austenitic stainless steel promotes the sigma phase formation.

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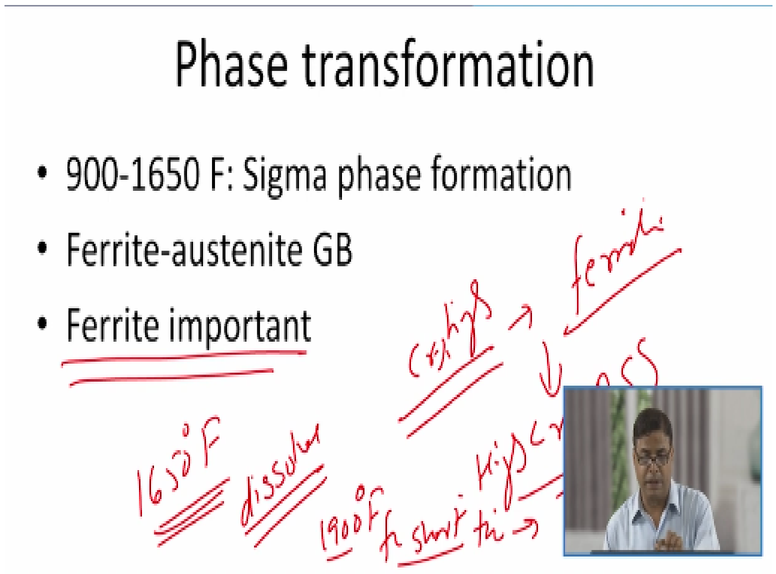


So in all those cases where the chromium content is high leading to the formation of the sufficient amount of the ferrite that will be promoting the sigma phase formation. So high chromium austenitic stainless steel will have the tendency to form the sigma phase more frequently. So here it is important that ferrite percentage in the austenite is controlled suitably so that undesirable sigma phase formation can be avoided.

It has been observed that on heating above 1650 degree Fahrenheit these phases start to get dissolved. Dissolution of these phases above 1650 degree Fahrenheit starts and when the exposure is given of the austenitic stainless steel weld joint having the sigma phases and the chromium carbide.

So short exposure at 1900 Fahrenheit for short period means exposure of the weld joint at 1900 degree Fahrenheit for short time leads to the dissolution of these carbides and the phases and which in turn helps in restoring the ductility and the corrosion resistance of the weld joint. This is what we can see here.

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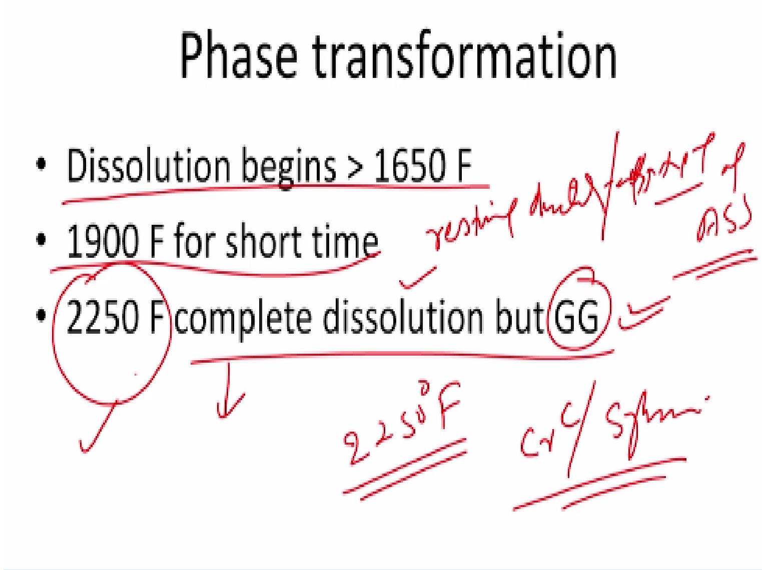


As soon as exposure is given above 1650 degree Fahrenheit, the dissolution of the sigma phase and the chromium carbide things will start and exposure at 1900 degree Fahrenheit for very short period helps in restoring the ductility and notch toughness of the ASS weld joint in the heat affected zone.

And if the exposure is given at 2250 degree Fahrenheit then it will be leading to the complete dissolution of these chromium carbides as well as the sigma phases which have been formed. But high temperature exposure can lead to the grain growth in the heat affected zone. So we need to see that exposure is given for very short period and unnecessary grain growth is avoided.

But if it has taken place then we must take a careful consideration we must take careful decision about the kind of exposure at 2250 degree Fahrenheit temperature to dissolve all these phases. Because the grain growth may deteriorate the mechanical property significantly so this aspect must be considered while taking decision about the kind of exposure to be given for dissolving such kind of the undesirable phases which have been formed.

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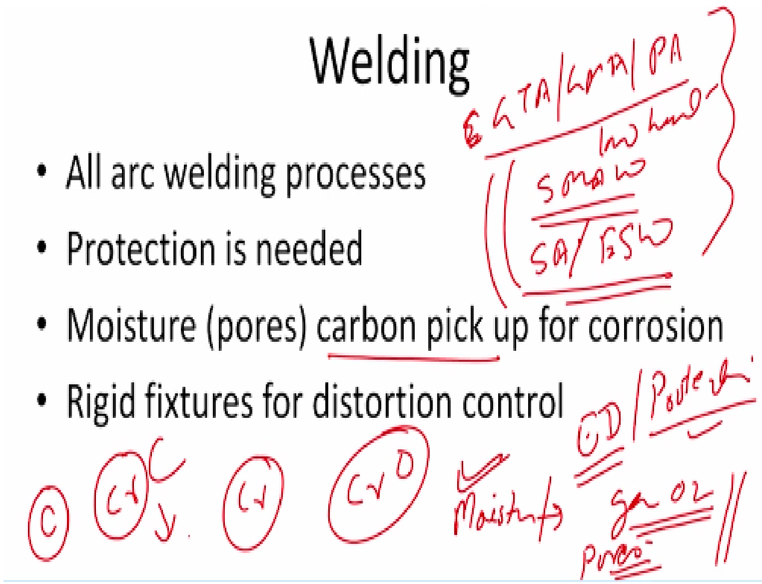


As far as the welding of the austenitic stainless steel is concerned all types of the arc welding processes can be utilized for welding of the ASS be it GTAW or GMAW or plasma arc welding. These are the processes which will be applying the low heat input. On the other hand if the high heat input process is used like SAW and electroslag welding then the high heat input will be causing more damage to the heat affected zone and likewise the shielded metal arc welding can also be used.

But each process offers the different energy density and so the net heat input varies accordingly for development of the weld joint of the ASS. So high energy density process will be using the lower heat input. So that is one aspect and another one is the kind of protection which is provided to the weld pool. So weld pool, since the chromium is present which has good affinity to the oxygen forms the chromium oxide very easily and which may interfere in welding.

That is why it is important that formation of such kind of the refractory oxides is avoided through the proper protection of the weld pool. And that is why in this regard like gas tungsten arc welding or the gas metal arc welding and plasma arc welding process can more effectively protect the weld pool from the atmospheric gases like oxygen and nitrogen.

And if there is moisture with the flux coatings or with the flux in case of SMAW or electrode coatings in case of the or if there is moisture with the flux in case of the submerged arc welding or moisture is present in the coating of the shielding metal arc welding process then this moisture which in arc environment will provide the lot of the gases, oxygen. And these can lead to the development of the pores in the weld metal.

So in order to avoid the porosity it is important that the low moisture or the moisture is driven off from the flux as well as coatings to avoid the development of the pores. Likewise if there are impurities like dust, dirt, carbon, and the paint, oil etc. if these impurities are present then these will be providing the carbon and if the carbon is going in the weld metal then carbon will be picked up which in association with the chromium will be forming the chromium carbide and it will be reducing the corrosion resistance.

So moisture as well as carbon pick up must be avoided during the welding of the ASS.

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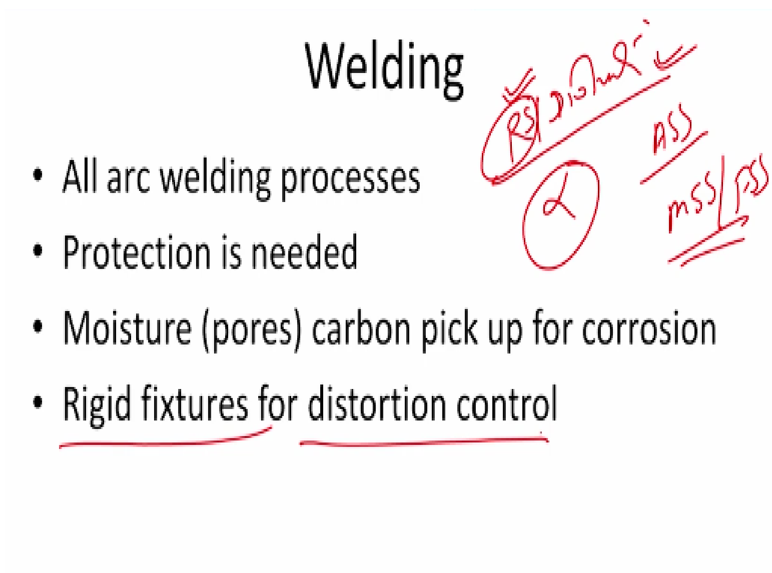


And another aspect is the kind of the residual stresses and the distortion which is experienced during the welding of the ASS. Since the thermal expansion coefficient alpha of the ASS is much higher than the martensitic stainless steel and the ferritic stainless steel. Therefore during the heating it will be expanding more and contraction will also be occurring significantly so that will be leading to the development of the residual stresses and promoting the distortion.

So while welding the ASS especially we need to design the very rigid fixtures so that the differential expansion and contraction can be handled very effectively in order to avoid the distortion of the ASS weld joints.

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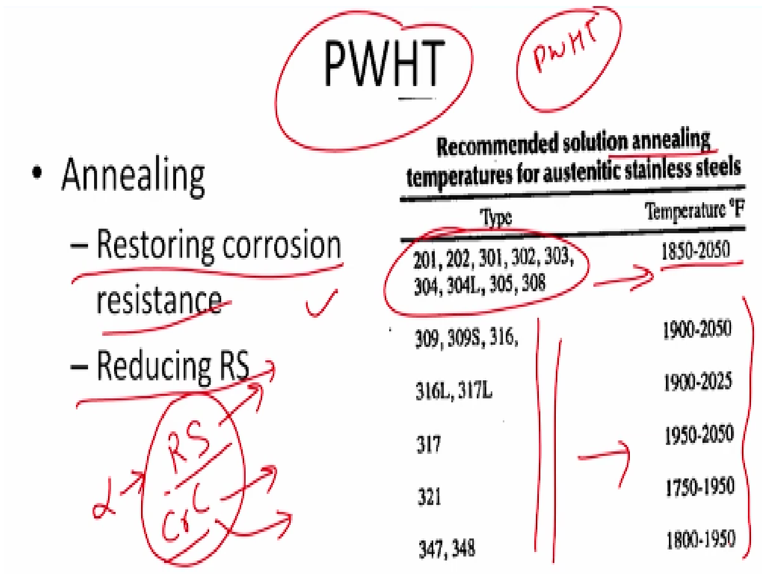


So this is how we can say that we need to be careful especially when we are performing the welding of the ASS especially with regard to the high thermal expansion coefficient because it will be trying to promote the distortion and development of the residual stresses.

We have seen that since the thermal expansion coefficient is high leading to the higher residual stresses as well as especially during the welding if the cooling conditions are slow during the sensitization temperature then it will be leading to the formation of the chromium carbide. So in order to neutralize or negate the adverse effects associated with the development of residual stresses and chromium carbide formation it is important to give whenever it is possible it is important to give the post weld heat treatment.

So the primary purpose of the post weld heat treatment of the ASS weld joint is to restore the corrosion resistance so the dissolution of the chromium carbide if it has been formed and reduce the residual stresses so that unnecessary distortion tendency can be eliminated or can be reduced. So here this slide shows the kind of the temperatures which are used for the annealing purpose, solution annealing purpose so that the residual stresses can be reduced and the corrosion resistance can be restored.

So this is the group of the austenitic stainless steel which should be heated to the temperature of 1850–2050 degree centigrade and likewise the table shows the different kind of the stainless steels and the kind of temperature for which these should be heated to restore the corrosion resistance.

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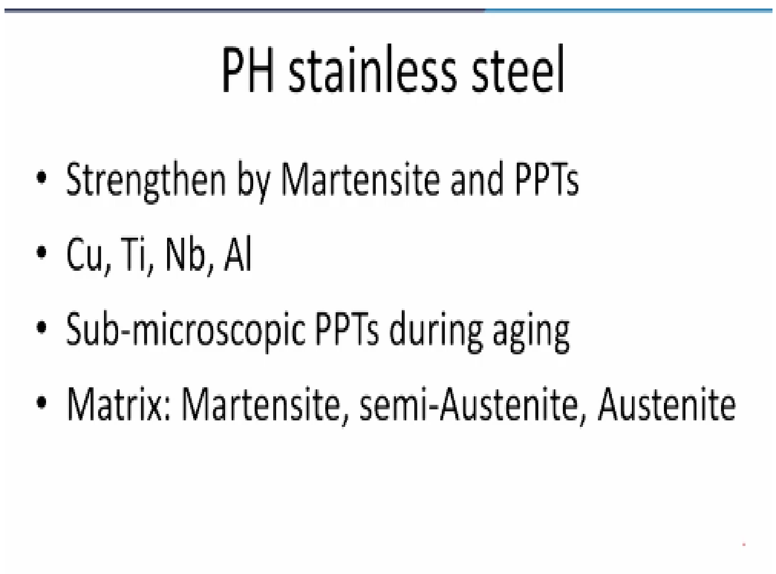


Now we will see the another type of the stainless steel, weldability of the precipitation hardenable stainless steel.

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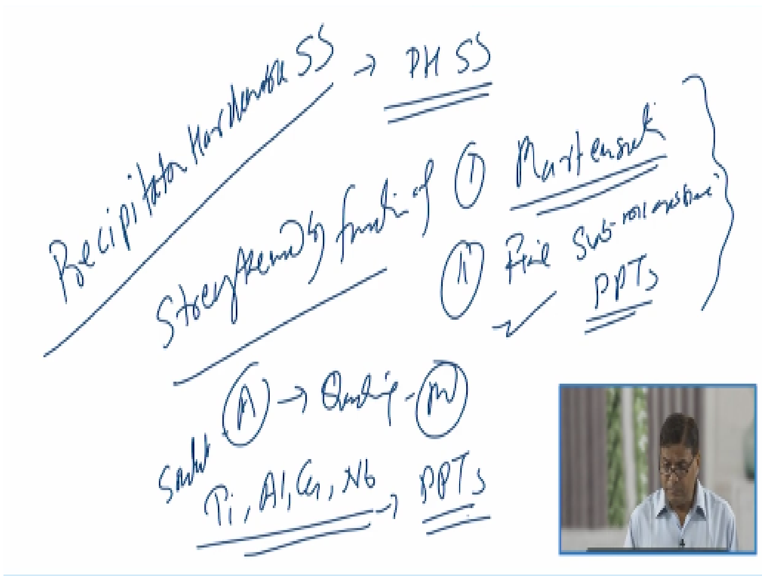


In short it is termed as PH SS, precipitation hardenable stainless steel. These are designed to be strengthened by formation of two types of the constituents. One is martensite and another is formation of the fine submicron size precipitates. So these are the two ways by which the strength to the precipitation hardenable stainless steel is provided. So either singly or both the mechanisms or both the approaches can be used to design the precipitation hardenable stainless steel to gain the required strength.

Now the kind of the elements which help in realizing, we know that how the martensite will be formed. We have to get a, through the solutionizing we will be having the austenite then the rapid quenching will be leading to the formation of the martensite. But to have the fine some micronsize precipitate so that the required strength can be realized, it is required to add the titanium, aluminium, copper, and niobium. These are the elements which help in developing the required strengthening precipitates in the PH steels.

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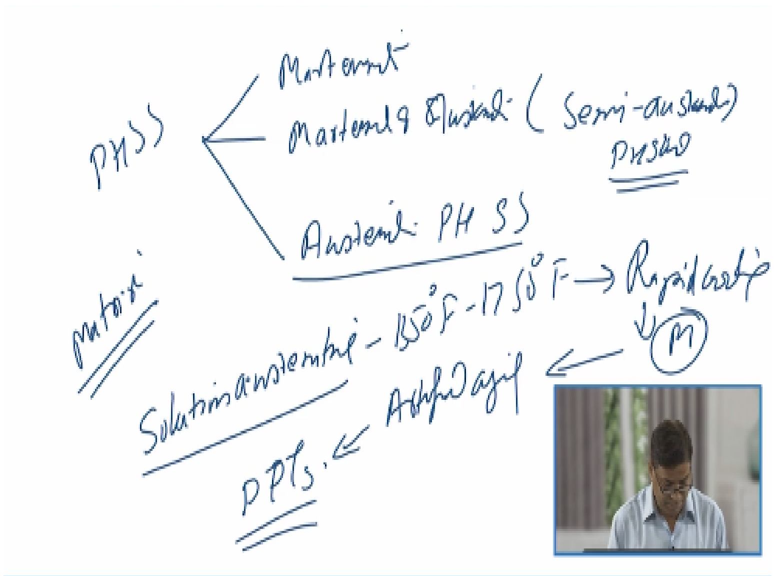


So the matrix of the PH SS can be of the martensite only or it can have both martensite and austenite both which is termed as semi-austenite PH stainless steel and austenitic means the matrix is of the austenite austenitic precipitation hardenable stainless steel. So these are the 3 broad categories based on the matrix precipitation hardenable steel.

And to realize these kind of the stainless steels the simple thing is that solution austenitizing is done in the temperature range of the 1350 degree Fahrenheit to the 1750 degree Fahrenheit. Thereafter rapid cooling will allow us to have the martensite and thereafter artificial ageing or you can say ageing, artificial ageing carried out at a higher temperature will be helping us to have the required precipitates for the strengthening purpose.

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# PH SS compositions

**Nominal compositions of typical precipitation-hardening stainless steels**

| Type | Designation[a] | UNS No. | C | Mn | Si | Cr | Ni | Mo | Al | Other elements |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nominal composition, weight percent | | | | | | | |
| Martensitic (moderate strength) | 17-4 PH | S17400 | 0.04 | 0.30 | 0.60 | 16.0 | 4.2 | – | – | 3.4 CU, 0.25 Cb |
| | 15-5 PH | S15500 | 0.04 | 0.30 | 0.40 | 15.0 | 4.5 | – | | 3.4 Cu, 0.25 Cb |
| | Custom 450 | S45000 | 0.03 | 0.25 | 0.25 | 15.0 | 6.0 | 0.8 | – | 1.5 Cu, 0.3 Cb |
| | Stainless W | S17600 | 0.06 | 0.50 | 0.50 | 16.75 | 6.25 | – | 0.2 | 0.8 Ti |
| Martensitic (high strength) | PH 13-8 Mo | S13800 | 0.04 | 0.03 | 0.03 | 12.7 | 8.2 | 2.2 | 1.1 | – |
| | Custom 455 | S45500 | 0.03 | 0.25 | 0.25 | 11.75 | 8.5 | – | – | 2.5 Cu, 1.2 Ti, 0.3 Cb |
| Semi-austenitic | 17-7 PH | S17700 | 0.07 | 0.50 | 0.30 | 17.0 | 7.1 | [illegible] | [illegible] | [illegible] |
| | Ph 15-7 Mo | S15700 | 0.07 | 0.50 | 0.30 | 15.2 | 7.1 | [illegible] | [illegible] | [illegible] |
| | PH 14-8 Mo | S14800 | 0.04 | 0.02 | 0.02 | 15.1 | 8.2 | [illegible] | [illegible] | [illegible] |
| | AM-350 | S35000 | 0.10 | 0.75 | 0.35 | 16.5 | 4.25 | [illegible] | [illegible] | [illegible] |
| | AM-355 | S35500 | 0.13 | 0.85 | 0.35 | 15.5 | 4.25 | [illegible] | [illegible] | [illegible] |
| Austenitic | A-286 | K66286 | 0.05 | 1.45 | 0.50 | 14.75 | 25.25 | [illegible] | [illegible] | [illegible] |
| | 17-10 P | – | 0.10 | 0.60 | 0.50 | 17.0 | 11.0 | [illegible] | [illegible] | [illegible] |
| | HNM | – | 0.30 | 3.50 | 0.50 | 18.50 | 9.50 | – | – | 0.25 P |

These steels when subjected to the, so as far as the different types of the precipitation hardenable stainless steels are concerned there are 3 categories as I have said; martensitic type, moderate strength martensitic type, high strength semi-austenitic and the austenitic where matrix is austenitic in the precipitation hardenable stainless steel and the corresponding composition is like 17.4 precipitation hardenable is one of the most commonly used.

Then there is like 1710. So there are various grades of the moderate strength, high strength and high strength martensitic precipitation hardenable steels or the austenitic and the semi-austenitic precipitation hardenable steels. And the different elements present with these different grades of the stainless steel is shown in this table.

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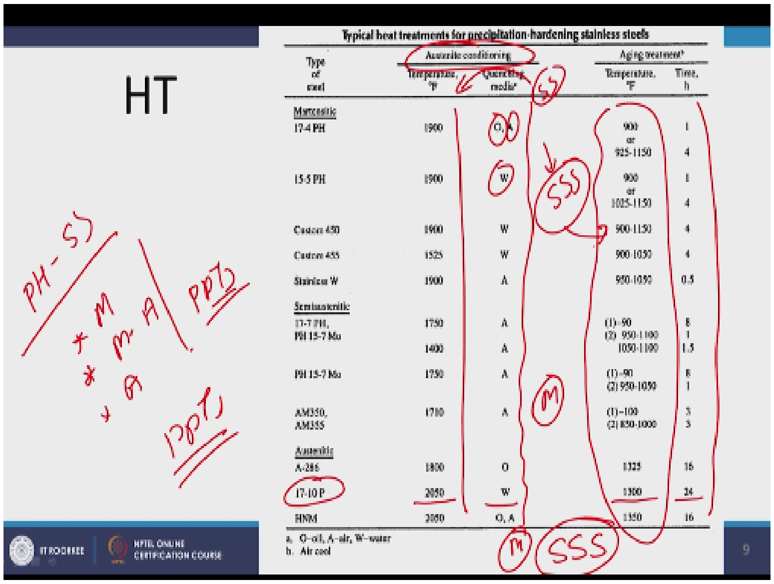


Now, in order to realize the required phases in these precipitation hardenable stainless steel whether to have the martensite or the mixture of the martensite and the austenite or the austenite or the different along with the required precipitates the different kind of the heat treatment conditions are used which of course will be involving like austenitizing by heating at higher temperature like this followed by quenching in water or oil or in air.

Like O stands for oil, A for air and W for water. So after heating we have to quench in the suitable media and then after quenching we will be having the martensite or the austenite as per the kind of the composition and thereafter, and this purpose of this quenching is to have either to form the martensite or to have the supersaturated solid solution of the different constituents which are present in the matrix.

Because heating at a high temperature will be facilitating the dissolution of the different elements thereafter rapid cooling will be leading to the development of the homogenous solid solution of those different constituents present in the matrix. And thereafter ageing at higher temperature, these are the ageing temperature conditions for different times will help us to have the required precipitates in the matrix.

Say for this 1710 austenitic precipitation hardenable stainless steel heating temperature is 2050 followed by water quenching and then heating at 1300 degree Fahrenheit and the ageing for 24 hours to realize the required strength. So this step is for the development of the homogenous solutionizing the things and then quenching is for the means austenitizing is for the formation of the homogenous solid solution.

And then quenching is for the supersaturated solid solution through the quenching followed by ageing. So that whatever the things were there beyond their solubility limit they start getting precipitates and precipitates are formed of the different types as per the composition of the steels.

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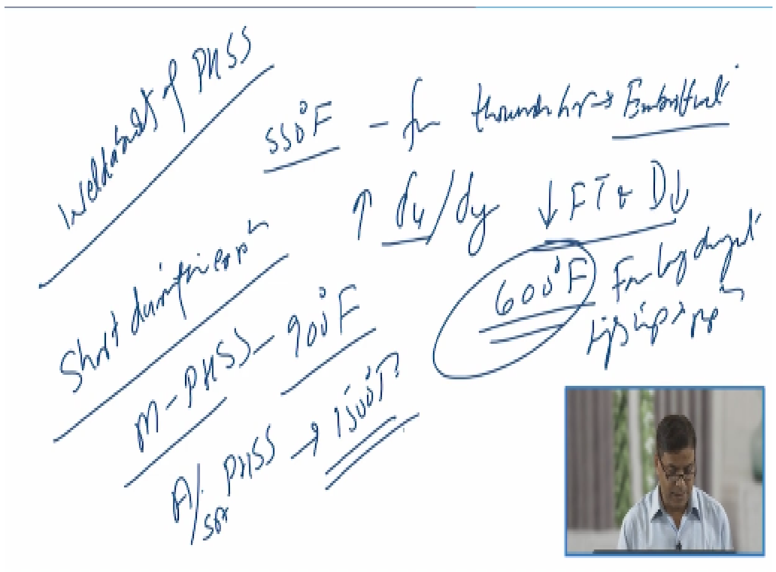

Whenever these steels are subjected to like as far as the welding aspect is concerned, weldability of the precipitation hardenable stainless steel, whenever these steels are heated above 550 degree Fahrenheit for thousands of hours it shows the embrittlement. Embrittlement will be leading to the increased or increase in yield strength and the ultimate strength.

But the fracture toughness and the ductility is reduced significantly because of such kind of the embrittlement. And these steels are mostly used up to 600 degree Fahrenheit for long duration high temperature applications. So maximum temperature is 600 degree Fahrenheit for long duration high temperature applications like thousands of the hours the system is to be operated.

But if the short duration exposure is needed then martensitic precipitation hardenable stainless steels can be heated up to the 900 degree Fahrenheit and the austenitic precipitation hardenable or semi-austenitic precipitation hardenable stainless steels can be used even up to 1500 degree Fahrenheit as far as the application of these precipitation hardenable steel is concerned.

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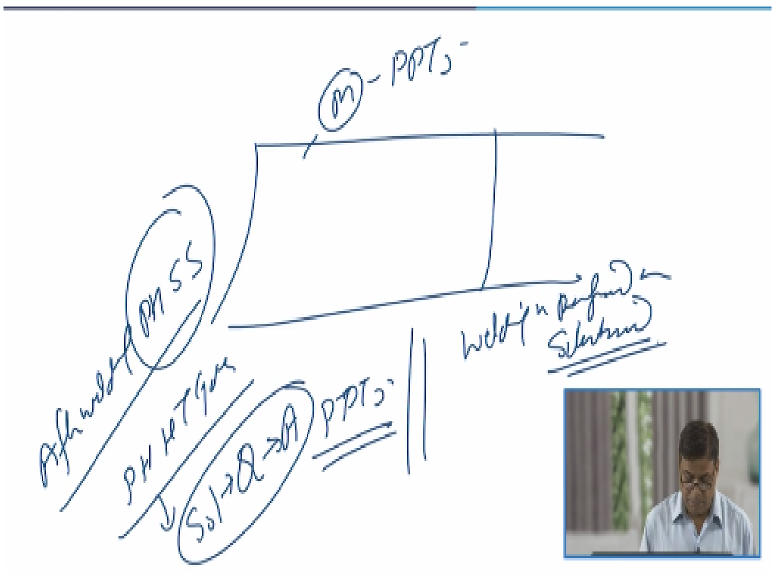

As we have seen that these steels will be gaining their strength from either development of the martensite or the development of the fine precipitates. So whenever heat is applied these precipitates will tend to get dissolved and thereby they will leading to the change in mechanical properties unfavorably. So it is always desired that after welding precipitation hardenable stainless steel are subjected to the precipitation heat treatment cycle.

Like it was solutionizing to have the austenite, thereafter quenching and thereafter ageing so that the properties in the weld joint can be restored. And if the post weld heat treatment of the precipitation hardenable stainless steel is not possible, in that case what we will be doing, it is preferred that welding is performed in the solutionized condition only where just austenitizing is done and in that condition the welding is performed.

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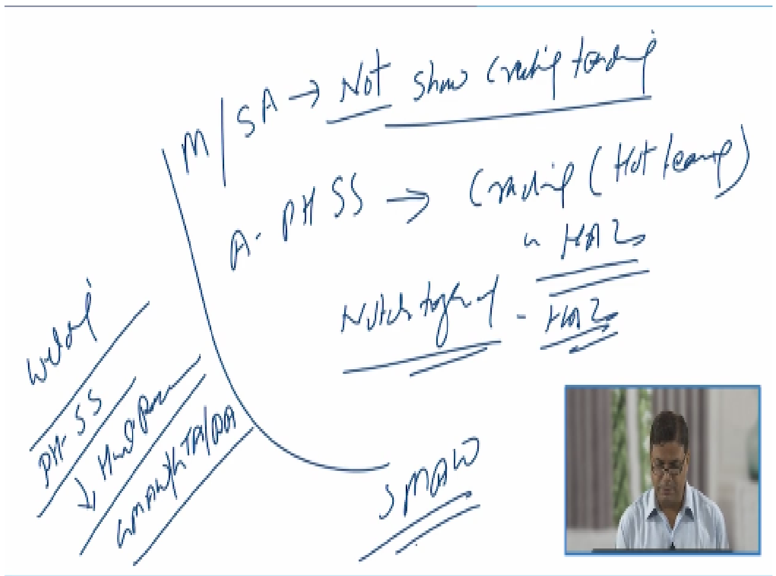


And then what we have is these steels whether it is the martensitic or the semi-austenitic stainless steel these do not show the cracking tendency of the weld joint. But austenitic precipitation hardenable stainless steel shows the cracking tendency. This is basically hot tearing in the heat affected zone is observed due to the low ductility at higher temperature and notch toughness of such kind of the weld joint in the HAZ is also poor.

So as far as the welding is concerned it is preferred that the precipitation hardenable stainless steel is welded using the low H net processes. Low H net processes are the high energy density process or comparatively high energy density processes. It is preferred to weld these precipitation hardenable stainless steel by the gas metal arc welding, gas tungsten arc welding, plasma arc welding.

And we do not like to weld it much with the SMAW, shielded metal arc welding because it offers the, it leads to the development of the wider heat affected zone which in turn adversely affects the strength of the weld joint. Now I will summarize this presentation. In this presentation basically I have talked about the various technological issues which are encountered during the welding of the austenitic stainless steel.

Like the chromium carbide formation reducing the corrosion resistance and the formation of the sigma phase formation decreasing the notch toughness and the ductility of the austenitic stainless steel weld joint so what we can do to overcome those issues that also I have talked about. And thereafter I have talked about the weldability of the precipitation hardenable stainless steels and what are the various issues related to the welding of these kind of steels. Thank you for your attention.