Weldability of Metals
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Lecture - 35
Weldability of Martensitic Stainless Steels - I

Hello, I welcome you all in this presentation related with the subject weldability of metals and you know we are talking about the weldability of the stainless steels. In the previous presentations we have talked about the general compositions, properties, and the weldability aspects of the stainless steels. In this presentation we will start with the specific properties of the different grades of the stainless steels which will help us in relating these properties with the weldability of the different types of the steels.

And thereafter we will talk specifically about the weldability of the martensitic stainless steel. So we know that these steels primarily have the chromium content apart from the other alloying elements and which helps in imparting the stainless effect to this category of the steels.

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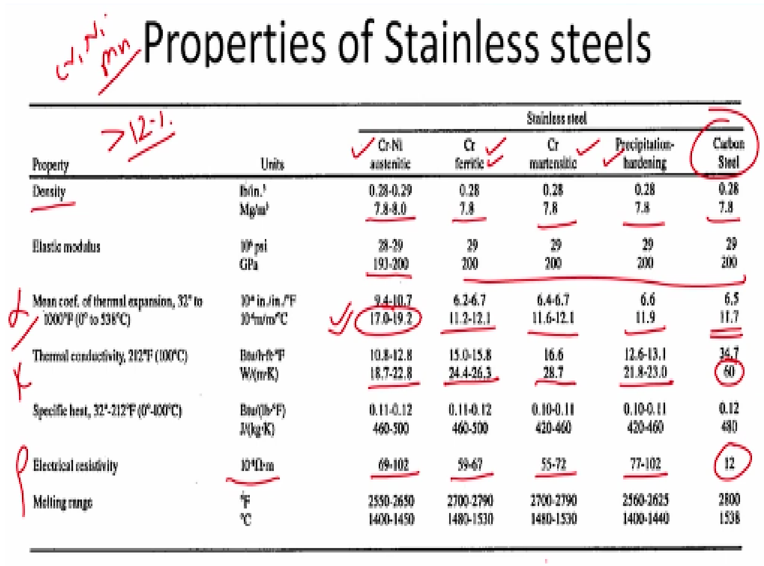

Property	Units	Stainless steel: Cr-Ni austenitic	Cr ferritic	Cr martensitic	Precipitation-hardening	Carbon Steel
Density	lb/in.^{3}	0.28-0.29	0.28	0.28	0.28	0.28
	Mg/m^3	7.8-8.0	7.8	7.8	7.8	7.8
Elastic modulus	10^6 psi	28-29	29	29	29	29
	GPa	193-200	200	200	200	200
Mean coef. of thermal expansion, 32° to 1000°F (0° to 538°C)	10^{-6} in./in./°F	9.4-10.7	6.2-6.7	6.4-6.7	6.6	6.5
	10^{-6}m/m/°C	17.0-19.2	11.2-12.1	11.6-12.1	11.9	11.7
Thermal conductivity, 212°F (100°C)	Btu/h·ft·°F	10.8-12.8	15.0-15.8	16.6	12.6-13.1	34.7
	W/(m·K)	18.7-22.8	24.4-26.3	28.7	21.8-23.0	60
Specific heat, 32°-212°F (0°-100°C)	Btu/(lb·°F)	0.11-0.12	0.11-0.12	0.10-0.11	0.10-0.11	0.12
	J/(kg·K)	460-500	460-500	420-460	420-460	480
Electrical resistivity	$10^{-8}\Omega\cdot m$	69-102	59-67	55-72	77-102	12
Melting range	°F	2550-2650	2700-2790	2700-2790	2560-2625	2800
	°C	1400-1450	1480-1530	1480-1530	1400-1440	1538

So mostly these steels have the chromium content generally greater than 12% which helps in having the stainless effect. But the addition of the alloying elements primarily in form of chromium, nickel, manganese while the carbon content is low results in the completely different set of the various physical properties and because of which, because of this large difference in physical properties of the stainless steels with respect to the carbon steel, stainless steels offer significantly different weldability.

So if we see the density, density of the stainless steels they are like 4 different category of the stainless steels like this austenitic stainless steel, ferritic stainless steel, martensitic stainless steel and precipitation hardening stainless steel. So for the austenitic stainless steel density ranges from 7.8–8 mg/m cube and it is 7.8 for the ferritic, 7.8 for martensitic, 7.8 for precipitation hardening. So for ferritic, martensitic and precipitation hardening steel density is almost same as that of the carbon steel.

On the other hand modulus of elasticity is somewhat lower for the austenitic stainless steels but in other cases it is almost similar to the carbon steels. If we talk of the thermal expansion coefficient, thermal expansion coefficient of the austenitic stainless steel is significantly higher, 17–19.2 while the thermal expansion coefficient of the ferritic stainless steel, martensitic stainless steel and the precipitation hardening stainless steel is almost similar to that of the carbon steel.

So from the thermal expansion coefficient point of view austenitic stainless steel is having the significantly higher thermal expansion coefficient and which can be problematic as compared to the, more problematic as compared to that of the ferritic, martensitic and precipitation hardening stainless steel. On the other hand, thermal conductivity wise, thermal conductivity of the austenitic stainless steel is like 17.7–22.8 W/m Kelvin.

And it is higher in case of the ferritic stainless steel like say 24.4–26.3 and further higher for the martensitic stainless steel like 28.7 and precipitation hardening stainless steel is like 21.8–23. But all these values are significantly lower than the carbon steel which is about like 60 units. On the other hand if you talk of the electrical resistivity which is very commonly used in case of the resistance welding which plays a big role in resistance welding of the stainless steels and the other steels.

So electrical resistivity of the austenitic stainless steel is very high which is varying from like 69–102. This is the unit and for ferritic stainless steel is also higher but lower than the austenitic stainless steel. It is in range of 59–67. And for chromium molybdenum stainless steel it is 55–72. Whereas precipitation hardening stainless steel 77–102. But the electrical resistivity as compared to these stainless steels is significantly lower.

It is just 12. So here if we see the thermal expansion coefficient alpha, thermal conductivity K and the electrical resistivity row these are the 3 different properties of the austenitic stainless steel and the carbon steels which are significantly different. While in other cases there is also, these properties are also in the higher or the lower side as per the kind of property.

So because of this great difference in the thermal expansion coefficient or thermal conductivity and electrical resistivity as compared to the carbon steels we find there is a lot of difference in the weldability of the stainless steels with respect to the carbon steels.

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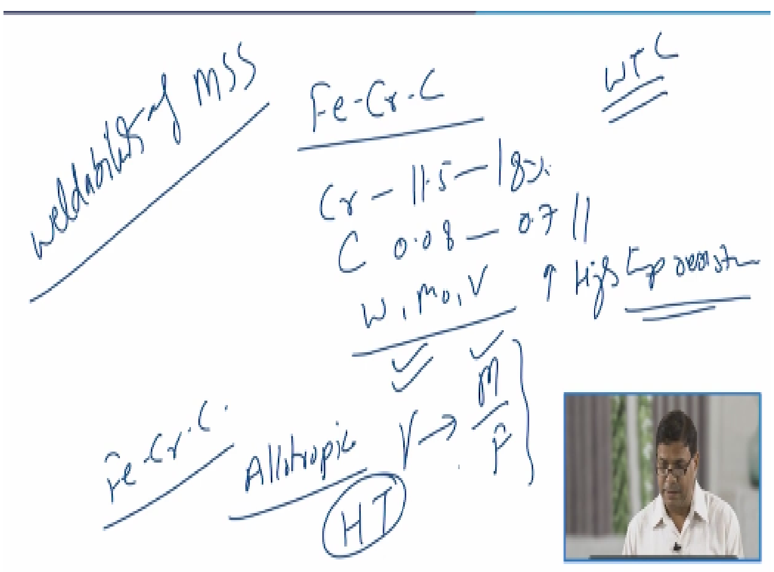

Now we will see the martensitic stainless steel, weldability of the martensitic stainless steels. In general these martensitic stainless steels are like iron, chromium, carbon system where chromium generally varies from 11.5–18% while carbon can range from like say 0.08–0.7. For a very select category the higher carbon additions are used.

Apart from these two other alloying additions in form of like tungsten, molybdenum and vanadium these are used primarily to enhance the high temperature resistance of the stainless steel like high temperature hardness and the impact resistance is enhanced with the addition of these alloying elements. So these alloying elements will certainly be affecting the carbon equivalent and so the hardenability of these steels.

But since the iron, chromium, carbon system alloying addition is such that it shows the allotropic behavior which means during the heating it forms the austenite and as per the cooling conditions imposed it may form martensite or it may form ferrite. So it responds. Therefore it responds very good to the heat application or it responds with regard to the HAZ properties to the weld thermal cycle.

So but these phase formations means the transformation of austenite into the other phases will depend upon the kind of the cooling conditions which are imposed during the welding in the weld as well as the heat affected zone and accordingly will be having the martensite or the ferrite in the weld metal or the heat affected zone.

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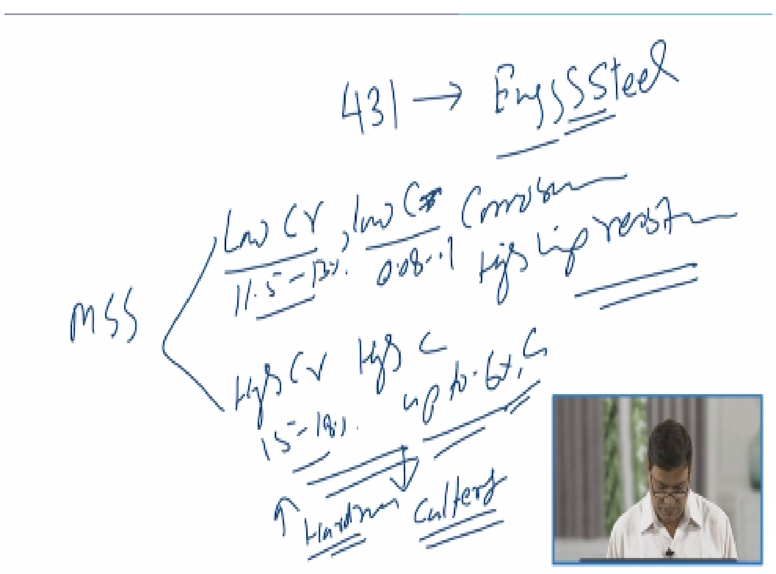

There is one typical category of the martensitic stainless steel is 431 which offers very good this engineering stainless steel for engineering applications stainless steel and it offers very good corrosion resistance as well as the high temperature resistance. Apart from this most of the stainless steels are grouped in the 2 category. One is where the chromium is low**.**

But chromium is low means like it is 11.5–13% and the carbon is low, low carbon, where carbon content is like 0.08–1. On the other hand high chromium may be like 15–18% of the chromium and high carbon where carbon content may be up to 0.6%. So such high percentage of the carbon will be leading to the higher hardness of the martensite which is being formed in case of the high chromium, high carbon stainless steel.

So this kind of the system or stainless steel is particularly used for the applications where we want the stainless effect at the same we want the high hardness in applications like the stainless steel used for fabrication or making the cutlery parts and the cutlery components, surgical components.

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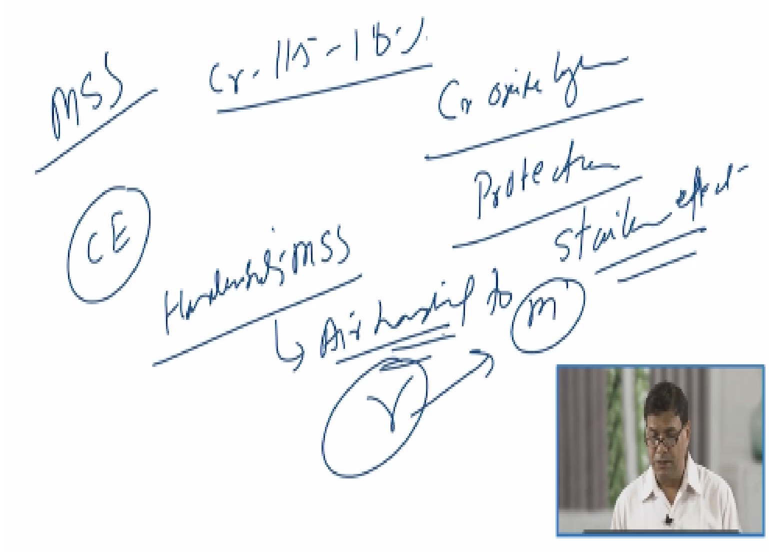

As far as the metallurgical aspects of the martensitic stainless steel is concerned since it is having the chromium in the range of 11.5–18% so it forms the chromium oxide layer at the surface and which provides the necessary protection to the martensitic stainless steels and so the stainless effect is offered by the chromium oxide layer. But since the carbon equivalent in this case becomes very high which is high enough to form the martensite and therefore the hardenability of the MSS is high and sometimes even air hardening leads to the martensite formation.

Means heating to the high temperature to the austenitic state and then the rapid cooling will be leading to the martensite transformation. So the hardenability is so high that even air hardening helps in transformation of austenite into the martensite formation.

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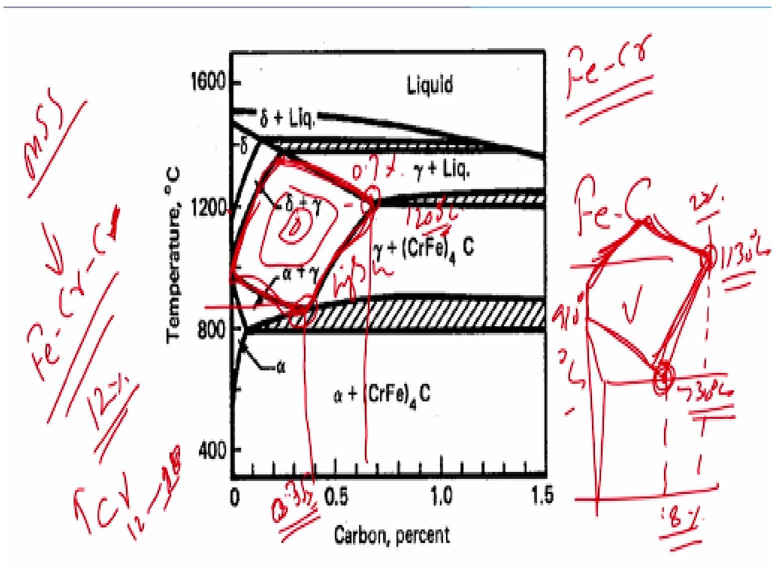

To understand this in better way we know that, I will come to this table subsequently. We know that in case of the iron carbon system we know that, this is alpha, iron carbon system is like this. This is corresponding to the 0.8% carbon at 730 degree centigrade, lower critical temperature line, upper critical temperature line 910 degree centigrade and here this is the gamma loop.

So in the gamma loop this normally occurs at a temperature of 730 degree centigrade. Means this eutectoid point occurs at 730 degree centigrade and 0.8% carbon and this gamma loop size is reduced. The region where the austenite is formed is known as the gamma loop and the maximum solubility of the carbon in the plane carbon systems is like

2% at 1130 degree centigrade. But the eutectoid point as well as this, the maximum solubility of the carbon in case of the iron chromium systems is reduced.

So if we talk of the martensitic stainless steel having the iron – chromium – carbon system so for this kind of system if we see the kind of the phase diagram that we get the eutectoid is formed in this case. When there is a chromium in case of the martensitic stainless steel it will be leading to the eutectoid point at about 0.35% of the carbon and this point is shifted towards the higher temperature.

Earlier it was occurring like at 730 degree centigrade. Now you can notice that eutectoid is occurring at a higher temperature like 850 degree centigrade or so. And this the maximum solubility of the carbon is also getting reduced and it is reduced to about 0.7% at about 1200 degree centigrade. So this temperature is also increased. So in this case the gamma loop size is this much when there is a chromium of say 12%.

And so for the 12% chromium situation as a function of the carbon the kind of phase diagram that we get looks like this. So with the addition of the carbon or with the addition of the chromium in this iron – chromium – carbon system, the size of this gamma loop is affected. In general the increase in the chromium content say from 12–18% or 20% the size of the gamma loop will keep on decreasing.

So there may be situation where we may notice that the gamma loop is eliminated with the higher chromium contents. So that is the kind of the effect that we will be seeing subsequently in another diagram.

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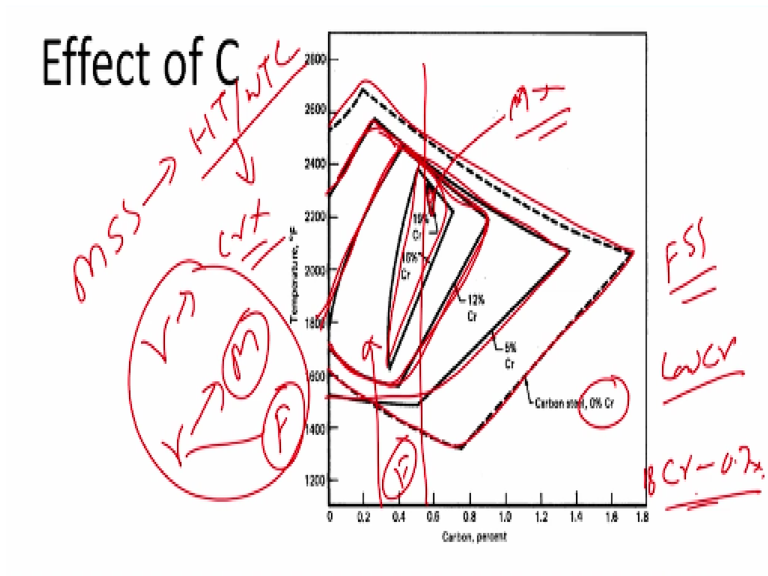

This is the diagram about which I am talking. So in case of the simple carbon steel when there is no chromium we get the typical gamma loop of this kind. But when the chromium is added 5% then the gamma loop size is somewhat reduced. And when the chromium is added 12% the gamma loop size is further reduced. When it is 15% it is further reduced.

And with 18% gamma loop size with 19% of the chromium, the gamma loop size is negligible which means whatever is our carbon content, we will not be able to have the austenite while heating from the room temperature to the melting point and that will be the situation of the ferritic stainless steel. So hardening in that case since there is no austenite formation during the heating from the room temperature to the high temperature then there would not be any phase transformation.

If it is ferritic at room temperature, it will remain ferritic up to the melting point. And on subsequent cooling again there would not be any allotropic behavior but since in those cases where we have like 12% chromium, like this, this gamma loop is being formed, then on the heating it will form the gamma and then as per the cooling rate it may form martensite or it may form ferrite as per the cooling rate which is imposed.

So that is why the response of the martensite to the heat treatment or the weld thermal cycle WTC is influenced by the chromium content present in the martensitic stainless steel. So low chromium martensitic stainless steels will respond heavily while high chromium martensitic stainless steels like the chromium 18% chromium and then 0.7% carbon the response to the weld thermal cycle will be reduced or eliminated because in that case there would not be any formation of the austenite.

So now we will be talking about the kind of the reason behind this kind of the response of the martensitic stainless steel to the weld thermal cycle.

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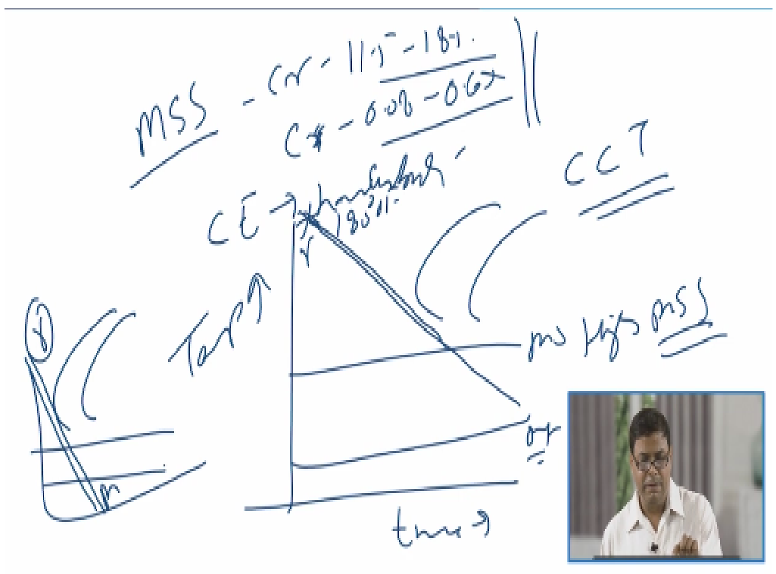

As I have said the martensitic stainless steels having the chromium 11.5–18% and the carbon also can vary from 0.08–0.6% and these high concentration of the alloying elements leads to the higher carbon equivalent and so the higher hardenability which means that if we have the continuous cooling diagram which is showing the temperature in Y axis and the time in X axis then these lines of the CCT continuous cooling transformation diagram are found to be far away from this axis.

And if the cooling is taking place from the temperature like 800 degree Fahrenheit then there is a very lot of time available for start of the transformation into the other phases. And this also like martensite start and martensite finish temperature is also high in case of the martensitic stainless steel. So it takes very long to start the transformation of austenite into the other phases.

So even the air hardening facilitates in transforming the austenite into the martensite while in other low carbon steels where this CCT diagram is very close to the, this our axis which indicates that critical cooling rate is very high and the very high cooling rates need to be imposed for transformation of austenite into the martensite like this.

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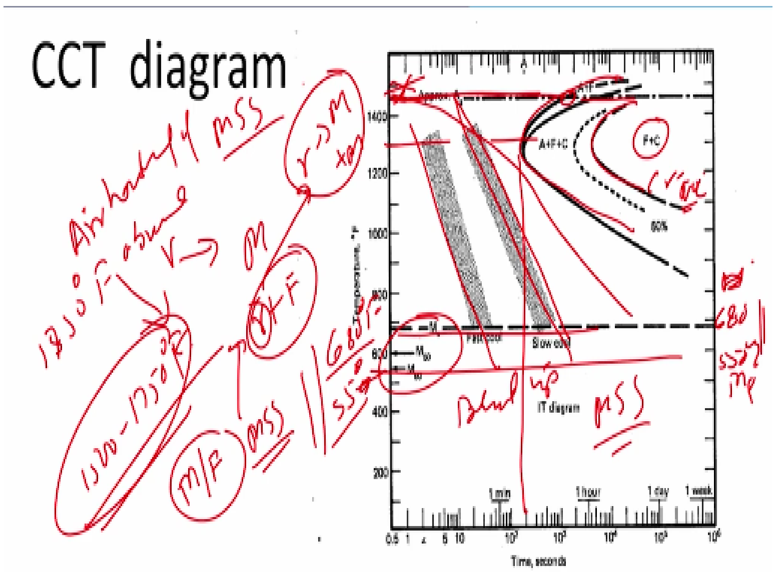

So this is what we will be seeing in case of this, this is the CCT diagram for the martensitic stainless steel and what it shows that this is the kind of the homogeneous austenitic state due to the heating which has been obtained in case of the austenitic stainless steel and when we expose, when we give the constant temperature exposure the austenite transforms into the first ferrite transformation will start and ferrite transformation will finish.

At the same time it will also form some amount of the carbides, iron carbide or other carbides, carbides of the other alloying elements like chromium carbide or vanadium carbide, molybdenum carbide as per the alloying elements present in the steel. Since this nose of the continuous cooling diagram is very far away like the cooling transformation will start after 100 seconds.

So that too when it is cooled at this temperature around 1300 degree Fahrenheit. So the slow cooling in this case also leading to the formation, leading to start the formation of the martensite at around like say 680 degree Fahrenheit. So the martensitic start transformation temperature is also very high and finish temperature is also almost like say the 550 degree centigrade.

So the martensite start and martensite finish temperatures for MS martensitic stainless steels are high and this is the reason, the main reason behind the air hardening possibilities for the martensitic stainless steel is the availability of the low critical cooling rates, low critical cooling rates applicable to the martensitic stainless steel. So fast cooling as well as the slow cooling, both will be leading to the formation of the martensite from the austenite and this kind of transformation also takes place at a high temperature.

So this is what we have to keep in mind while deciding the preheat temperature. Since the martensitic start and martensite finish temperatures are very high, 680, 552, 680 degree centigrade. This is MF temperature and this is MS temperature. So this is one reason behind the air hardening of the martensitic stainless steel. So if we see this kind of the transformation from the like say 1750 degree Fahrenheit or above.

If the cooling is applied then austenite is able to transform into the martensite. But if we think of the other situations like the heating is done in the range of like say 1500–1750 degree centigrade then the transformation of the martensite or the ferrite present in the martensitic stainless steel this transformation into the austenite will be incomplete and it will be having the combination of both austenite plus ferrite.

So on subsequent cooling, we will be having the partial transformation of austenite into the martensite, remaining there will be ferrite. So actually when the heating is done in the band of 1500–1750 degree Fahrenheit then due to the partial transformation or partial formation of the austenite we get the partial transformation of austenite into the martensite and as a result after the cooling we get the mixture of the ferrite and the perlite both.

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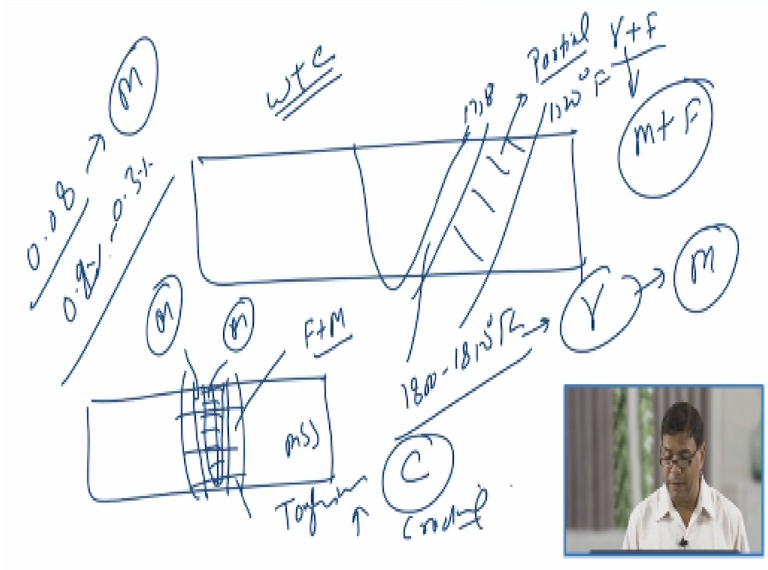

So like say if we try to relate it with the welding, so the heat affected zone which experiences the temperature in the range of like say 1500 degree Fahrenheit to the 1750 degree Fahrenheit. So this is the zone where there will be formation of the little amount of austenite plus ferrite because the complete transformation into the austenite does not take place.

And due to the rapid cooling especially in welding of thick sections this austenite will be transforming into the martensite. So we will be having a mixture of the ferrite and martensite in this heat affected zone. While the zone which are very close to the fusion boundary and where the temperature is like 800 or 850 degree Fahrenheit there we will be having the complete austenitic state and in that case the rapid cooling will be leading to the complete martensitic transformation.

So these are the situations and the way by which the weld thermal cycle can respond to the or can affect the HAZ properties. So if we apply the autogenous welding in case of the martensitic stainless steel like this, so the weld metal will be having the tendency to form the martensite completely and in the heat affected zone there will be tendency for formation of the martensite plus ferrite and the zone next to the fusion boundary also will be having the complete martensitic transformation.

Since the hardness of the martensite is governed by the carbon content directly, so in those cases where carbon is very low the martensite being formed will not be that hard and will not be that sensitive for cracking but in other cases if the carbon content is more like 0.2% or 0.3% then the formation of the hard martensite in the weld as well as heat affected zone will be decreasing the toughness of the weld.

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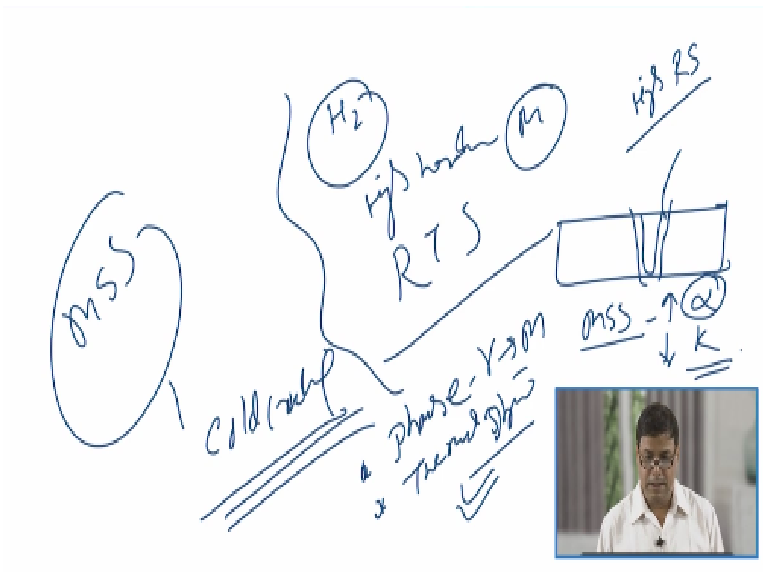

And which in turn will be increasing the tendency for cracking and we know that if the weld metal is having the hydrogen high hardness due to the martensitic transformation coupled with the residual tensile stresses then this combination in case of the martensitic stainless steel can promote the cold cracking and that is why the weldability of the martensitic stainless steel is primarily limited by the cold cracking tendency.

So these are the some of the aspects related with the MSS welding. There is another aspect, since the martensitic stainless steel is having the higher thermal expansion coefficient and the lower thermal conductivity and therefore the heat will not be transferred much to the base metal and that is why very limited zone will be heated to the high temperature, will be experiencing the thermal expansion.

And subsequently contraction and that is why very little zone will be next to the fusion boundary will be experiencing the high residual stresses. So the residual stress formation is coupled with the phase transformation that is austenite to the martensitic formation. Second is the thermal stresses due to the rapid heating followed by cooling causing the thermal expansion and subsequently contraction.

So thermal stresses will be dominating in determining the magnitude of the residual stresses because narrow zone will be expanding to the greater extent due to the higher thermal expansion coefficient and narrow zone will be formed due to the lower thermal conductivity.

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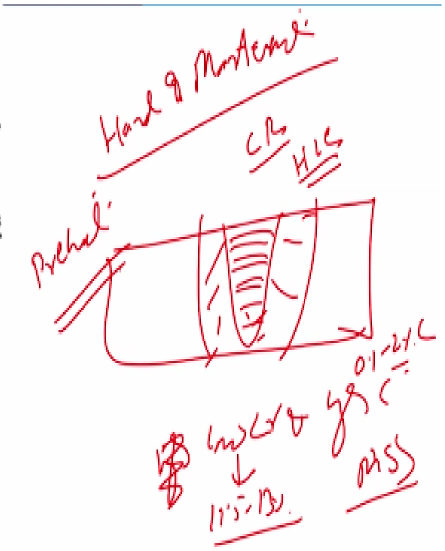
Suggested preheat, welding heat input, and postweld requirements for martensitic stainless steels

Carbon content, percent	Approx. preheat temperature, °F	Welding heat input	Postweld requirements
Less than 0.10	60 min.	Normal	Heat treatment optional
0.10 to 0.20	400-500	Normal	Cool slowly; heat treatment optional
0.20 to 0.50	500-600	Normal	Heat treatment required
Over 0.50	500-600	High	Heat treatment required



So if we see the kind of the weldability behavior of these steels then we will notice that we must be careful as far as the formation of the hard martensite is concerned. If the hard and brittle martensite is being formed in the weld as well as the heat affected zone in case of the low chromium and high carbon martensitic stainless steel.

Low chromium like 11.5–13% chromium and high carbon like 0.1–0.2% carbon then it will be leading to the formation of the hard and brittle martensite in the weld as well as heat affected zone. So to avoid the cracking tendency due to the formation of the hard and brittle martensitic structure in the weld as well as heat affected zone we must reduce the cooling rate so that such kind of the formation tendency can be reduced.

And if the weld is not really usable due to the low toughness and the high hydrogen induced cracking tendency then we must do the preheating of the plates. So the preheating of the plates helps in reducing the cooling rate and which in turn helps in reducing the residual stresses as well as developing the weld joints which will be less sensitive for cracking, which will have the reasonably good combination of the mechanical properties.

Other aspects related with the weldability of the martensitic stainless steel I will be talking in the next presentation. Now I will summarize this presentation. In this presentation basically I have talked about the different compositional aspects related with the martensitic stainless steel and the kind of the metallurgy involved in welding of the martensitic stainless steel. Thank you for your attention.