**Weldability of Metals**
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**Lecture - 38**
**Weldability of Austenitic Stainless Steels - I**

Hello, I welcome you all in this presentation related with the subject weldability of metals and in this presentation I will be talking about the weldability of the austenitic stainless steel. So in order to understand the weldability of the austenitic stainless steel we need to understand the various types of the austenitic stainless steels which are used, their compositions, properties and the way by which these properties can affect the weldability.

So we will be starting with the basic understanding related with the austenitic stainless steel, ASS.

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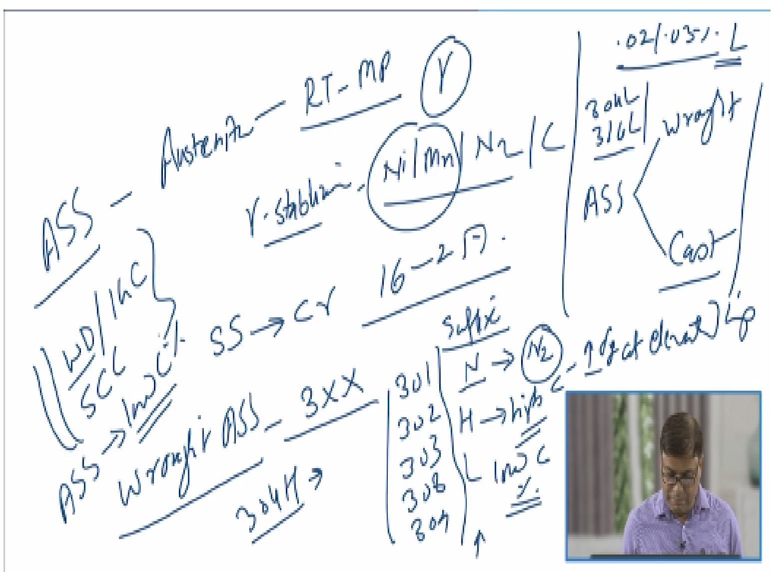


So this type of steels will have the austenite stable over a entire range of temperature from the room temperature to the melting point. So this type of the steel primarily will have the austenite which is stable throughout the range of the temperature from the room temperature to the melting point and this kind of the property is important through the addition of the suitable austenite stabilizers which are mostly in form of nickel, manganese and sometimes even nitrogen and carbon.

But mostly the nickel and the manganese are used as austenite stabilizers. In order to give the stainless effect, the chromium in these steels is normally added in the range of 16 – 25%. We know that like any category of the steels, these austenitic stainless steels are also used in the two forms. One is wrought form and another is the cast form and their designations are also different.

So I will give the complete list of the austenitic stainless steels in wrought as well as the cast form. So the wrought austenitic stainless steels are most commonly used and they are of the 300 series. So starting from 301, 302, 303, 308 and so many 304, 309, 310, 312, 316, 347, 321 so many grades are there. When these grades are suffixed with the sum of the letters like the letter N with a particular grade of steel, if N is added as a suffix which indicates that the steel has been added or modified with the nitrogen for austenite stabilization and for imparting the required strength.

When the letter H is used means that grade of the steel is having the high carbon percentage primarily for high strength of the steel especially at elevated temperature. So the grade of the steel having like 304H suggesting the higher carbon content for strengthening the steel at elevated temperature. Likewise whenever any grade of the steel is suffixed with the letter H which indicates this particular grade of steel is having very low carbon percentage.

And this is particularly used when we want heat resistant or higher intergranular corrosion resistance we want to control the stress corrosion cracking. So in order to overcome specific issues related with the weld joints of the austenitic stainless steels like the weld decay leading to the intergranular corrosion, stress corrosion cracking. So these issues to some extent can be reduced if the austenitic stainless steel is having very low carbon percentage.

So those grades having very low carbon content they are, so there are limits like the steel is having 0.02 or 0.03% of the carbon maybe suffixed with the letter L like 304L or 316L indicating very low carbon content with the steel reducing the problems associated with the intergranular corrosion of the weld joints stress corrosion cracking under the specific environments.

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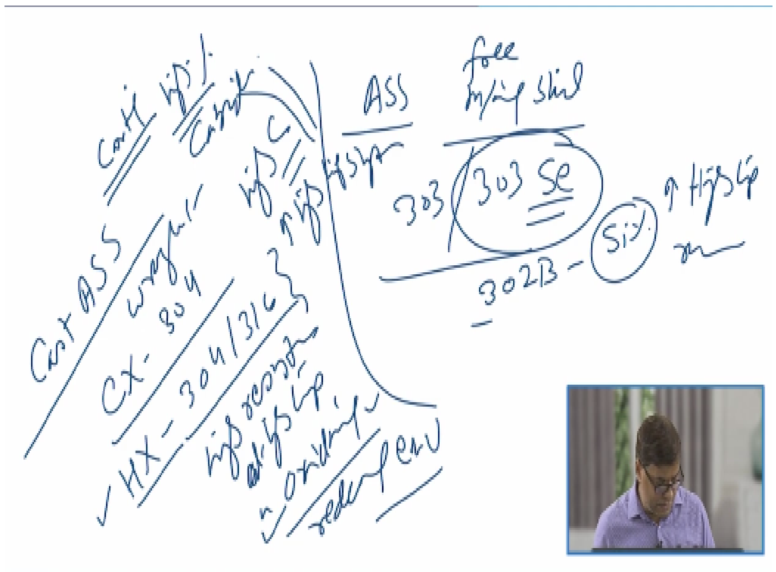


Then there is another type of the ASS wherein which is we can say as free machining steel. These are added with the specific alloying elements and these are like selenium is added and with the designation itself it is added like one without selenium or one with the selenium will be mentioned like this indicating that particular element has been added for making the steel as a free machining type.

Likewise some of the grades of the steels are such that where silicon is intentionally added for increasing the high temperature resistance like 302B suggesting the silicon addition especially for increasing the high temperature resistance. So this is about the kind of, the designations and their significance.

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**Compositions of typical wrought austenitic stainless steels**

| Type | UNS number | Composition, percent[a] | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | C | Mn | Si | Cr | Ni[b] | P | S | Others |
| 201 | S20100 | 0.15 | 5.5-7.5 | 1.00 | 16.0-18.0 | 3.5-5.5 | 0.06 | 0.03 | 0.25 N |
| 202 | S20200 | 0.15 | 7.5-10.0 | 1.00 | 17.0-19.0 | 4.0-6.0 | 0.06 | 0.03 | 0.25 N |
| 301 | S30100 | 0.15 | 2.00 | 1.00 | 16.0-18.0 | 6.0-8.0 | 0.045 | 0.03 | |
| 302 | S30200 | 0.15 | 2.00 | 1.00 | 17.0-19.0 | 8.0-10.0 | 0.045 | 0.03 | |
| 302B | S30215 | 0.15 | 2.00 | 2.0-3.0 | 17.0-19.0 | 8.0-10.0 | 0.045 | 0.03 | |
| 303 | S30300 | 0.15 | 2.00 | 1.00 | 17.0-19.0 | 8.0-10.0 | 0.20 | 0.15 min | 0-0.6 Mo |
| 303Se | S30323 | 0.15 | 2.00 | 1.00 | 17.0-19.0 | 8.0-10.0 | 0.20 | 0.06 | 0.15 Se min |
| 304 | S30400 | 0.08 | 2.00 | 1.00 | 18.0-20.0 | 8.0-10.5 | 0.045 | 0.03 | |
| 304L | S30403 | 0.03 | 2.00 | 1.00 | 18.0-20.0 | 8.0-12.0 | 0.045 | 0.03 | |
| 305 | S30500 | 0.12 | 2.00 | 1.00 | 17.0-19.0 | 10.5-13.0 | 0.045 | 0.03 | |
| 308 | S30800 | 0.08 | 2.00 | 1.00 | 19.0-21.0 | 10.0-12.0 | 0.045 | 0.03 | |
| 309 | S30900 | 0.20 | 2.00 | 1.00 | 22.0-24.0 | 12.0-15.0 | 0.045 | 0.03 | |
| 309S | S30908 | 0.08 | 2.00 | 1.00 | 22.0-24.0 | 12.0-15.0 | 0.045 | 0.03 | |
| 310 | S31000 | 0.25 | 2.00 | 1.50 | 24.09-26.0 | 19.0-22.0 | 0.045 | 0.03 | |
| 310S | S31008 | 0.08 | 2.00 | 1.50 | 24.0-26.0 | 19.0-22.0 | 0.045 | 0.03 | |
| 314 | S31400 | 0.25 | 2.00 | 1.5-3.0 | 23.0-26.0 | 19.0-22.0 | 0.045 | 0.03 | |
| 316 | S31600 | 0.08 | 2.00 | 1.00 | 16.0-18.0 | 10.0-14.0 | 0.045 | 0.03 | 2.0-3.0 Mo |
| 316L | S31603 | 0.03 | 2.00 | 1.00 | 16.0-18.0 | 10.0-14.0 | 0.045 | 0.03 | 2.0-3.0 Mo |
| 317 | S31700 | 0.08 | 2.00 | 1.00 | 18.0-20.0 | 11.0-15.0 | 0.045 | 0.03 | 3.0-4.0 Mo |
| 317L | S31703 | 0.03 | 2.00 | 1.00 | 18.0-20.0 | 11.0-15.0 | 0.045 | 0.03 | 3.0-4.0 Mo |
| 321 | S32100 | 0.08 | 2.00 | 1.00 | 17.0-19.0 | 9.0-12.0 | 0.045 | 0.03 | 5 × %C Ti min |
| 329 | S32900 | 0.10 | 2.00 | 1.00 | 25.0-30.0 | 3.0-6.0 | 0.045 | 0.03 | 1.0-2.0 Mo |
| 330 | N08330 | 0.08 | 2.00 | 0.75-1.5 | 17.0-20.0 | 34.0-37.0 | 0.04 | 0.03 | |
| 347 | S34700 | 0.08 | 2.00 | 1.00 | 17.0-19.0 | 9.0-13.0 | 0.045 | 0.03 | c |
| 348 | S34800 | 0.08 | 2.00 | 1.00 | 17.0-19.0 | 9.0-13.0 | 0.045 | 0.03 | 0.2 Cu, c, d |
| 384 | S38400 | 0.08 | 2.00 | 1.00 | 15.0-17.0 | 17.0-19.0 | 0.045 | 0.03 | |

Likewise, in case of the cast alloys, so if we see the wrought alloys, these are the various wrought alloys composition starting from like there are various 200 category and many are of the 300 series alloys having like 303 selenium free machining steel, 302B the silicon modified or silicon added 304L low carbon and 310S. So 304L, sorry 316L and 317L. So these are the different grades of the steels.

There are a few special category steels like the 347 and the 321. If we see these two special category steels. So these steels will be having the specific elements in form of like titanium, molybdenum, or niobium which will impart the specific set of the properties to the austenitic stainless steels. Now we will see there is another category that is about the cast austenitic stainless steel.

So the cast austenitic stainless steels are similar to that of the wrought category but the letter which is commonly added is the CX like 304. So we will be indicating the cast 304 steel. When these steels are added with HX and the particular grade like 304 or 316 indicating the cast austenitic stainless steel of that particular grade which is suitable for the high resistance at high temperature in oxidizing or reducing environment.

So the steel having the good resistance against the high temperature in the oxidizing and the reducing environment, they are represented with the HX grade and these grades of the steels in general have the higher carbon content to impart the high temperature strength to these category of the steels. Since the carbon content in these category of the steels are high and these are produced by the casting root.

So these will be having the higher percentage of the carbides distributed in the matrix which in turn will be affecting the weldability of the austenitic stainless steel subsequently.

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**Compositions of typical cast austenitic stainless steels**

| Alloy designation | UNS Number | Similar wrought type[a] | Composition, percent[a] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | C | Si | Cr | Ni | Mo[c] | Other |
| CE-30 | J93423 | 312 | 0.30 | 2.00 | 26-30 | 8-11 | – | – |
| CF-3 | J92700 | 304L | 0.03 | 2.00 | 17-21 | 8-12 | – | – |
| CF-3M | J92800 | 316L | 0.03 | 1.50 | 17-21 | 9-13 | 2.0-3.0 | – |
| CF-8 | J92600 | 304 | 0.08 | 2.00 | 18-21 | 8-11 | – | – |
| CF-8C | J92710 | 347 | 0.08 | 2.00 | 18-21 | 9-12 | – | d |
| CF-8M | J92900 | 316 | 0.08 | 1.50 | 18-21 | 9-12 | 2.0-3.0 | – |
| CF-12M | – | 316 | 0.12 | 1.50 | 18-21 | 9-12 | 2.0-3.0 | – |
| CF-16F | J92701 | 303 | 0.16 | 2.00 | 18-21 | 9-12 | 1.5 | 0.20-0.35 Se |
| CF-20 | J92602 | 302 | 0.20 | 2.00 | 18-21 | 8-11 | – | – |
| CG-8M | – | 317 | 0.08 | 1.50 | 18-21 | 9-13 | 3.0-4.0 | – |
| CH-20 | J93402 | 309 | 0.20 | 2.00 | 22-26 | 12-15 | – | – |
| CK-20 | J94202 | 310 | 0.20 | 2.00 | 23-27 | 19-22 | – | – |
| CN-7M | J95150 | – | 0.07 | 1.50 | 18-22 | 27.5-30.5 | 2.0-3.0 | 3-4 Cu |
| HE | J93403 | – | 0.2-0.5 | 2.0 | 26-30 | 8-11 | – | – |
| HF | J92603 | 304 | 0.2-0.4 | 2.0 | 19-23 | 9-12 | – | – |
| HH | J93503 | 309 | 0.2-0.5 | 2.0 | 24-28 | 11-14 | – | 0.2 N |
| HI | J94003 | – | 0.2-0.5 | 2.0 | 26-30 | 14-18 | – | – |
| HK | J94224 | 310 | 0.2-0.6 | 2.0 | 24-28 | 18-22 | – | – |
| HL | J94604 | – | 0.2-0.6 | 2.0 | 28-32 | 18-22 | – | – |
| HN | J94213 | – | 0.2-0.5 | 2.0 | 19-23 | 23-27 | – | – |
| HP | – | – | 0.35-0.75 | 2.0 | 24-28 | 33-37 | – | – |
| HT | J94605 | 330 | 0.35-0.75 | 2.5 | 15-19 | 33-37 | – | – |

As far as, so if we see this few grades of the cast austenitic stainless steels so like these are like CF or CX and then HX or the C or H kind of the letters are there for the two to distinguish the different categories and these are the different grades of the stainless steel along with the austenitic stainless steel along with their compositions.

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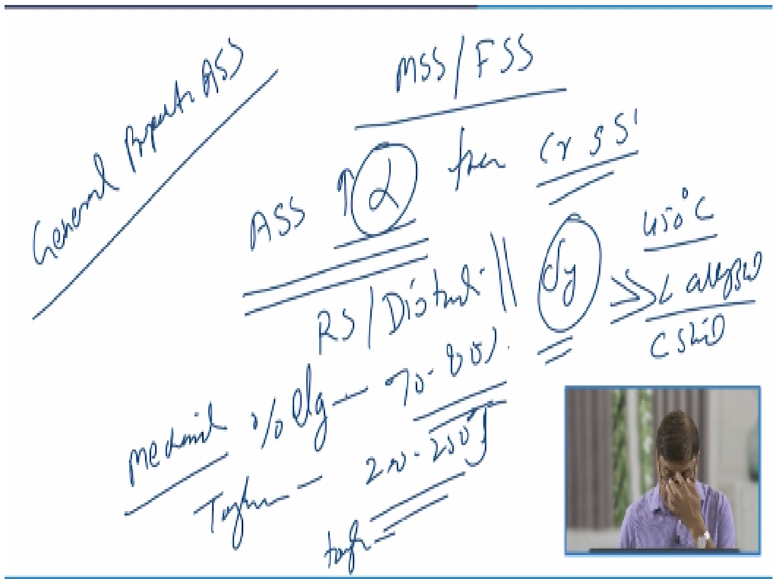


Now as far as the general properties of the austenitic stainless steel we have very simple understanding about the ASS as compared to the other chromium steels like martensitic stainless steel or ferritic stainless steel is that ASS has got much higher thermal expansion coefficient than other chromium based stainless steel like ferritic or the martensitic stainless steel.

So during the welding due to the localized heating leading to the expansion and contraction will be causing the greater problems related with the residual stresses and distortion in welding of the ASS as compared to the martensitic and the ferritic stainless steel. As far as the other mechanical property, so we need more care while welding the austenitic stainless steel than the ferritic and the martensitic stainless steel primarily due to the higher thermal expansion coefficient.

Other mechanical properties of the austenitic stainless steels like percentage elongation of the ASS is extremely high, may range from 70–80% elongation. The toughness is also extremely good, notch toughness we can say like Charpy V-notch toughness which will be like 200–250 J.

And the ability of these steels to sustain the higher temperature especially at the temperature greater than 450 degree centigrade yield strength of the austenitic stainless steel is found much better than the other low alloy steels and the carbon steels because those steels show significant thermal softening at elevated temperature as compared to the austenitic stainless steels and that is why these find lot of applications for fabrication of the components to be used at a higher temperature.

Another very attractive property of the austenitic stainless steel is their ability to retain the toughness even under the cryogenic temperature conditions. So they do not lose their toughness. They do not get embrittled under the cryogenic temperature conditions. So that is another very good advantage or very attractive property associated with the austenitic stainless steel.

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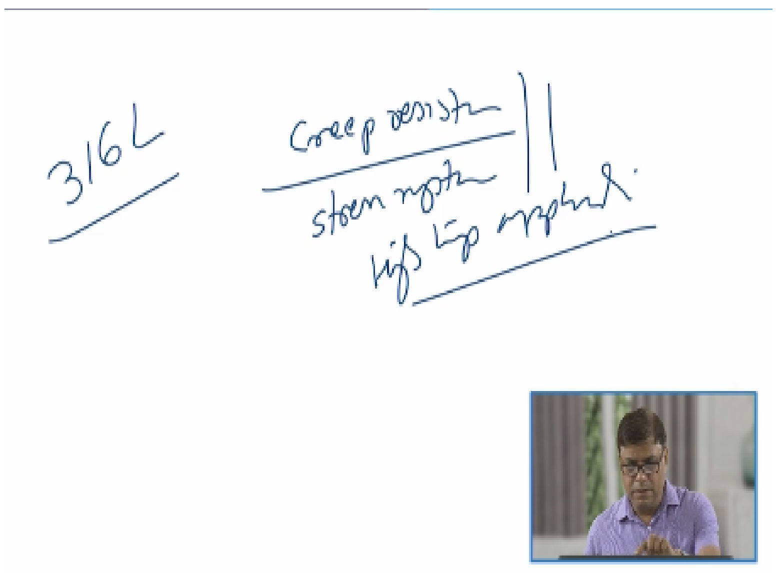


And among the different grades of the austenitic stainless steel if we see 316L is the one austenitic stainless steel which offers extremely good creep resistance as well as the high resistance to the stress rupture and that is why these are preferred for a high temperature applications. However their welding poses lot of difficulty so we need to see how to resolve, how to take care of those issues related with the welding of such kind of the stainless steels.

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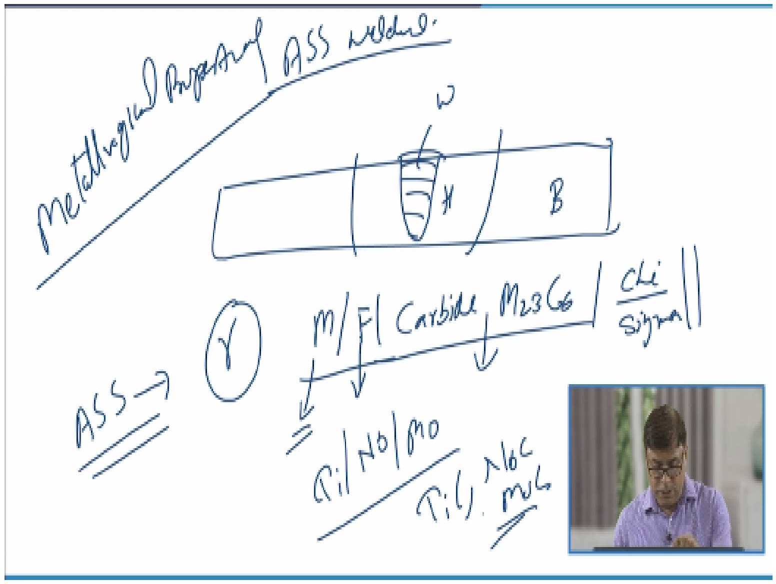


Now coming to the metallurgical properties of the austenitic stainless steel weldments. So we know that there will be in weldment there is a weld metal. Then there is a heat affected zone and the base metal. So these are the 3 different zones which are formed in weldment of the austenitic stainless steel and response of the weldment to the weld thermal cycle will be different and that we need to understand in order to have the proper understanding about the weldability of the austenitic stainless steel.

So as far as the austenitic stainless steel is concerned in the base metal these are designed to have the primarily the austenite but apart from the austenite these can have depending upon the cooling rate or thermo mechanical cycle which is being applied these may have little amount of the martensite, maybe ferrite, delta ferrite and the carbides, complex carbides, maybe M 23C 6 kind of the carbide. So these are the various constituents.

Apart from this it may have some intermetallic compounds in form of like chi phase or sigma phase. So both these phases are undesirable phases which deteriorate the notch toughness and the ductility of the steels while the carbide formation will be reducing the resistance to the corrosion especially intergranular corrosion resistance is reduced. Ferrite formation in limited quantity is good to control the hot cracking.

But excessive amount of the ferrite will be reducing the corrosion resistance and the ferrite formation little bit martensite formation can enhance the properties but at the cost of the corrosion resistance. So these are the various kind of the phases which can be there in the steels. And those austenitic stainless steels wherein the stabilization has been realized through the titanium, niobium and molybdenum addition the carbides of these elements can be there in form of TiC or NbC or molybdenum carbide.

So the steels may have these different phases but which phase in what quantity what fraction will be formed, that will depend upon the kind of the weld thermal cycle which is being imposed during the welding of these steels.

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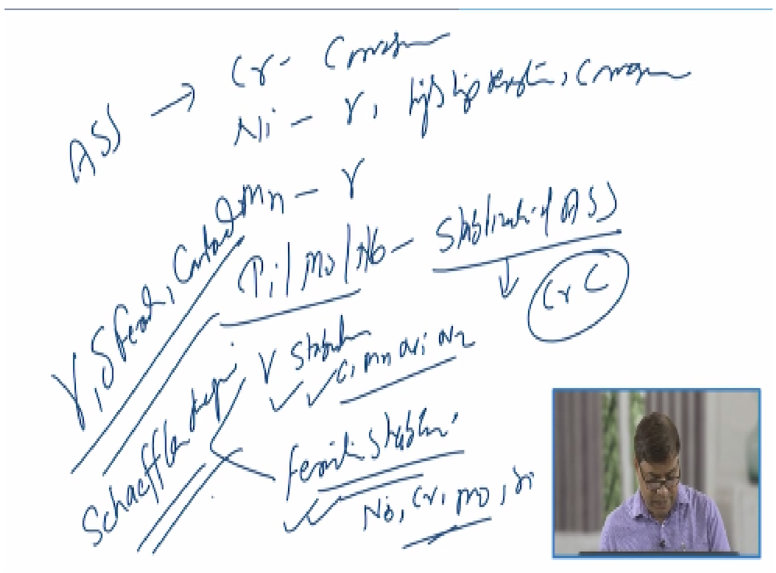

So as far as the specific role of these elements are concerned in the austenitic stainless steel, chromium is added primarily for good corrosion resistance. Nickel is added for austenite stabilization for increasing the high temperature resistance and improving the corrosion resistance.

Manganese also does the austenite stabilization and additionally when the elements are added in form of titanium, molybdenum and niobium these additions are primarily done for stabilization of the austenitic stainless steel so that the resistance to the formation of the chromium carbide can be increased in order to increase the intergranular corrosion or the weld decay tendency in these types of the steels. So if we see here there are 2 category of the elements. One is like those which are austenite stabilizers and another is the ferrite stabilizer.

So depending upon the proportion of the alloying elements which are trying to stabilize the austenite like carbon, manganese, nickel, nitrogen and the ferrite stabilizers like niobium, chromium, molybdenum, silicon, so these will be trying to stabilize and according to the relative fraction of these relative amount of the austenite and ferrite stabilizers, the different phases which will be there in steel will be determined which are primarily there in form of austenite delta ferrite and the carbides.

And estimation of these phases is carried out with the help of one diagram which takes into account the fractions of the ferrite stabilizers and austenitic stabilizers and that diagram is known as Schaeffler diagram. So about this I will be talking little later.

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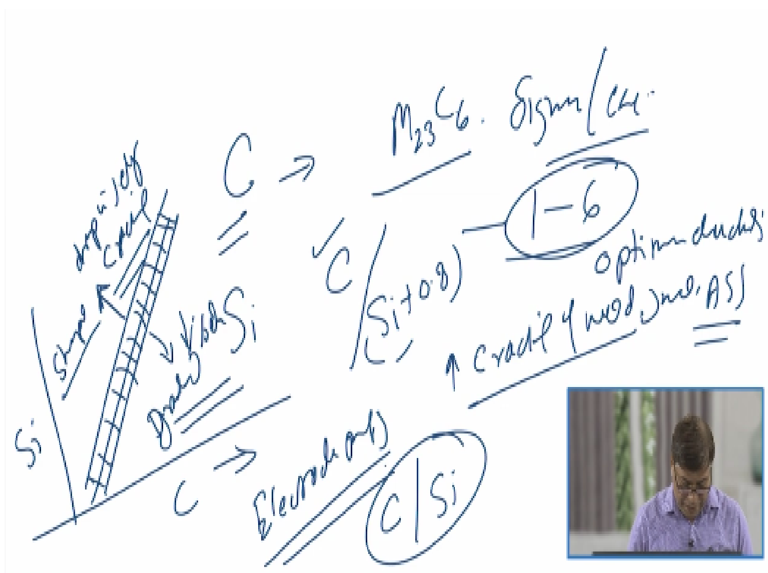


So apart from these there are other alloying elements which significantly affect the ease of welding and that is about the carbon content and the silicon percentage. Higher carbon content increases the tendency to form the carbides of this kind or it also increases the tendency to form the sigma phase formation or the chi phase formation. So these will be reducing the corrosion resistance as well as the mechanical properties.

On the other hand if the carbon to the silicon proportion like this, if this ratio is found to vary between 1– 6 then we find the optimum ductility. If the ratio of the carbon to silicon is disturbed and if it goes beyond this region then we will find that there is a sharp drop, there is significant drop in the ductility and which in turn increases the cracking tendency of the weld joints of such kind of the stainless steel where carbon and silicon proportion has not been maintained within the optimum range.

That is what we can simply see here if we take the carbon in x axis and silicon in y axis there a particular proportion or combination of the carbon and silicon ratio along which we get the optimum ductility. Either side there is a drop in the percentage elongation, both the sides there is drop in the percentage elongation. So on the left side this drop is more sharp and this drop is gradual on the right side.

So this side the drop is gradual, on the other side the drop in the ductility is very sharp and it leads to the cracking. So it is important for maximum ductility the ratio of the carbon and silicon must be maintained.

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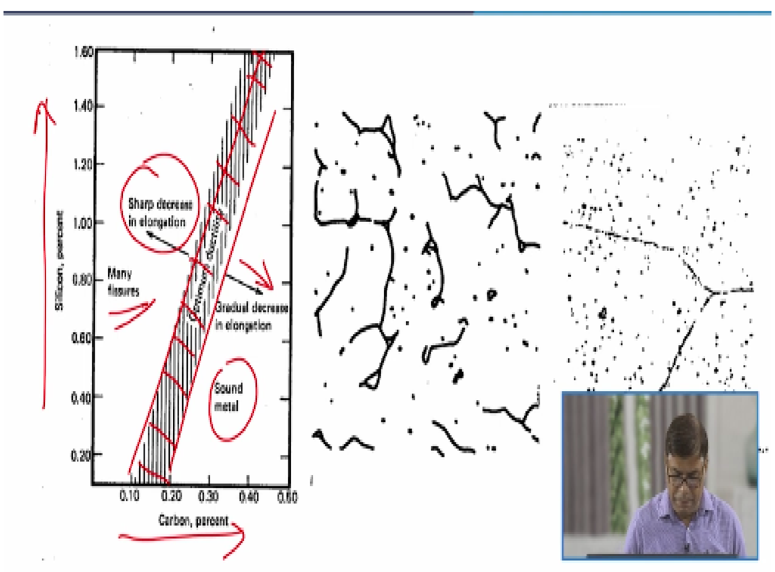


And that is what we can see from this diagram. What it shows, in the y axis we are having the silicon and in x axis there is a carbon and for a particular band of the carbon to silicon combination where ductility is optimum, this side there is a gradual drop in the elongation. Still the metal is sound but on the other hand when the silicon is more for a given carbon content then we will see there is a sharp drop in the percentage elongation and it leads to the cracking.

So it is important that silicon and carbon proportions are controlled properly and that is why the electrode manufacturers they give lot of attention over the control of the carbon and silicon proportion so that whatever weld metal is produced that is capable to resist such kind of the cracks.

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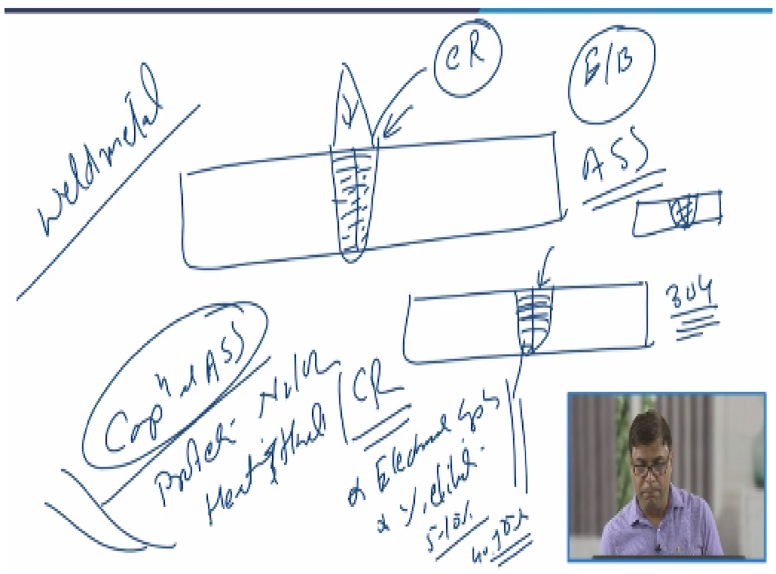


Now we will be talking about the weld metal aspects, weld metal. So we know that this is the austenitic stainless steel based metal and for the welding purpose when the heat is applied from the external source there will be fusion and then according to the thickness heat input, the weld metal will be solidified at a different cooling rate. So the cooling rate is the one aspect that will be determining the time required for the solidification.

And the homogeneity of the composition will also be affected by the cooling rate of the weld metal. So depending upon the composition of the ASS and the kind of the protection from the atmospheric gases like nitrogen and oxygen and the kind of the heat input that is

H net governing the cooling rate. So these are the 3 aspects which will determine the kind of phases which will be formed.

If the nitrogen is getting into the weld metal, it will increase the austenite formation, reduce the delta formation or ferrite formation tendency in austenitic stainless steel weldment and likewise the cooling rate also suppresses the delta ferrite formation. So under those low cooling rate conditions the delta ferrite formation tendency will be more as compared to that under the high cooling rate conditions.

Apart from the composition related aspects, so to understand this only what will be formed like if this is the ASS of particular grade like 304 and when it is welded using the filler metal or electrode of the different composition then there can be a change of the weld metal composition. So weld metal composition may be different from the base metal if the electrode of the different type is used.

Or because of the two regions, one either the electrode composition is different and then the percentage dilution which is taking place due to the melting intermixing of the metal coming from the electrode and the melting of the base metal. So the composition of the weld metal can differ significantly from the electrode composition as well as base metal because depending upon the heat input the melting maybe very limited.

Or melting of the base metal maybe large and accordingly we will have the different percentage dilution which may range from like 5–10% in case of the high energy density processes and to the like 40–50% in case of the low energy density processes. So the dilution is the one thing that can affect the composition of the weld metal significantly. So now we will see, I will come to this diagram subsequently.

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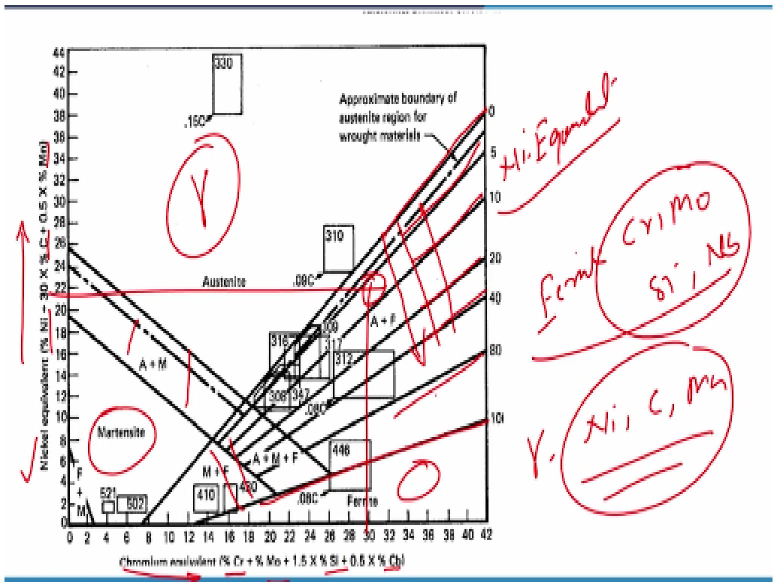


Now we need to see that if the composition of the weld metal is affected then accordingly the alloying elements which are trying to stabilize the ferrite in form of say chromium, molybdenum, silicon or niobium that will be changing. Likewise the austenite stabilizer alloying elements which are trying to stabilize the austenite that the proportion of those will also be changing in form of nickel or carbon or manganese.

So because for a particular percentage of these alloying elements there will be a particular value of the nickel equivalent. Nickel equivalent is the kind of parameter which indicates the ability of those all austenite stabilizing elements to stabilize the austenites. So what is the value of the nickel equivalent which will be tending to stabilize the austenite.

On the other hand, the chromium equivalent indicates the cumulative effect of all those alloying elements which are trying to stabilize the ferrite. So both are calculated separately according to the weight percentage of the ferrite and the austenite stabilizers. So austenite stabilizers, effect of all austenite stabilizers is taken into account through the nickel equivalent using nickel, carbon and manganese.

While the effect of all ferrite stabilizing element is taken care of through the consideration of the effect of chromium, molybdenum, silicon and niobium or columbium. So here we can see for the low chromium low nickel equivalents we get the martensite, for very high chromium equivalent and low nickel equivalent we get the ferrite, for very high nickel equivalent and low chromium equivalents we are having the austenite.

And in between we have austenite martensite, ferrite martensite, and the austenitic and ferrite. So intermediate compositions like for a particular value of the nickel equivalent and particular value of the chromium equivalent what we have? We are in the range of the austenite and the ferrite mixture. So there are further different lines corresponding to the like 0% ferrite 100% austenite and 100% ferrite 0% austenite.

And in between we will be having the lines corresponding to the different proportions of the austenite and ferrite. So on moving from this side to this side we will be having the increasing fraction of the ferrite and reducing fraction of the austenite. Since the fraction of the ferrite is important from the solidification cracking point of view that is why it is important that composition of the weld metal is adjusted in such a way that the weld metal is having 3–4% or like say 5–10% of the delta ferrite.

And for that purpose we need to adjust our weld metal composition along this line of the nickel and the chromium equivalents. So for that we need to adjust the electrode selections as per the composition of the base metal and the dilution expected during the welding. Now I will summarize this presentation.

In this presentation basically I have talked about the general properties of the austenitic stainless steels, different compositions, and what are the metallurgical aspects associated with the welding of the austenitic stainless steel. Thank you for your attention.