

# A Review on Welding Related Problems and Remedy of Austenitic Stainless Steels

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**Abstract** - Austenitic stainless steels (ASS) are one of the most widely used industrial material today due to their inherent corrosion resistance and good mechanical properties at high and low temperature. Although ASS are considered the most weldable of stainless steel class still there are some conditions when welding can result in some changes in the form of microstructure or mechanical properties in weld and heat affected zone (HAZ) rendering the material useless. This paper reviews the problems associated with the welding of ASS and the solution which could be employed to avoid those welding issues.

A thorough study of solidification mode, hot cracking, Schaeffler, Delong and Welding Research Center (WRC) constitution diagram has been presented in this paper along with the effect of impurities such as S, P, Si, N and Nb on hot cracking susceptibility. Sensitization, intermetallic precipitation such as Sigma phase, Chi phase Laves phase etc. and their effect on corrosion resistance & mechanical properties of ASS have also been studied.

**Key Words:** Austenitic stainless steel, Welding, Hot cracking, intermetallic precipitates

## 1. INTRODUCTION

### 1.1 Stainless steel

Stainless steels are iron-base alloys that contain a minimum of about 12% Cr which forms an adherent, protective and transparent oxide scale on the surface. This oxide forms and heals itself in the presence of oxygen. Carbon is normally present in amounts ranging from less than 0.03% to over 0.1% in certain grades. Stainless steel can be divided into 5 families i.e. ferritic, austenitic, martensitic, duplex and precipitation hardened. Out of these 5 families austenitic stainless steels are the most commonly used alloys.

### 1.2 Austenitic stainless steel

Austenitic stainless steels are the class of stainless steel which has the combination of austenite stabilizers and

ferrite stabilizers in such a way that the austenite phase (face centered cubic, FCC) which is normally stable at high temperature becomes stable at room temperature and even down to cryogenic temperature.

Since there will not be any phase transformation at high temperature and hence these materials can't be strengthened by heat treatment. Therefore strengthening of these materials is achieved either by solid solution strengthening or by work hardening [1].

The most commonly used ASS is SS304 which contains about 18-20% chromium, 8-11% nickel, 2% manganese, 1% silicon, 0.08% carbon and some impurities such as sulfur and phosphorus [1, 2]. Types 321 and 347 are essentially type 304 with addition of strong carbide formers titanium and niobium respectively, which stabilize carbides and provide resistance against sensitization. Molybdenum is added in type 316 to provide pitting resistance. As the amounts of chromium and/or nickel content increases in these materials high-temperature oxidation resistance also increases.

ASS has good corrosion resistance, strength, toughness and formability from cryogenic to elevated temperature and hence is used in vast applications. Their use varies from cryogenic temperatures, where they exhibit good toughness, to elevated temperatures of nearly 600 °C (1110 °F), where they exhibit good strength and oxidation resistance. The most commonly used ASS are UNS S30000 alloys (AISI 300 series).

Austenitic stainless steels are further classified into 3 three groups depending on the carbon content. The "L" grades, straight grades and "H" grades. The L grades contain maximum 0.03wt% C, the straight grades contain 0.03–0.08wt% C and the H grades contain anywhere from 0.04–0.10wt% C. The higher carbon content of the H grades produces more carbides in material providing more strength at the expense of ductility and hence used in high temperature applications. All these grades of materials has different applications depending on their properties such as the high carbon content in H grade form carbide precipitates in material which improves the creep resistance and hence used at elevated temperature and the L grade material has

good resistance to sensitization and hence used in application where the material is to be exposed to corrosive atmosphere after welding. Although ASS are having predominantly FCC crystal structure, they often contain small amount of body centered cubic (BCC) ferrite as well specially in weld metal. This ferrite is called delta ferrite ( $\delta$ -ferrite) as it forms at high temperature rather than alfa ferrite ( $\alpha$ -ferrite) which form at lower temperature in carbon steel. The term "ferrite" in this paper refers to delta ferrite unless noted otherwise. These alloys may also contain some martensite which is normally formed due to cold working in this class of materials and their inherent property of having low stacking fault energy (SFE).

ASS are considered the most weldable of all the grades of stainless steels still there are some problems associated with their welding. In order to understand the problems first one needs to understand the Fe-Cr-Ni ternary phase diagram.

### 2.1 Fe-Cr-Ni Phase diagram (Ni-Cr Pseudo binary diagram)

Since the Fe-Cr-Ni ternary phase diagram is very difficult to understand so for the sake of simplicity we will keep the iron percentage constant and vary Cr & Ni. Almost all the ASS contains more than 50% Fe and hence we will study three phase diagrams with 55%, 60% and 70% Fe, same are shown in figure 1 [3].

### 2. WELDING OF ASS

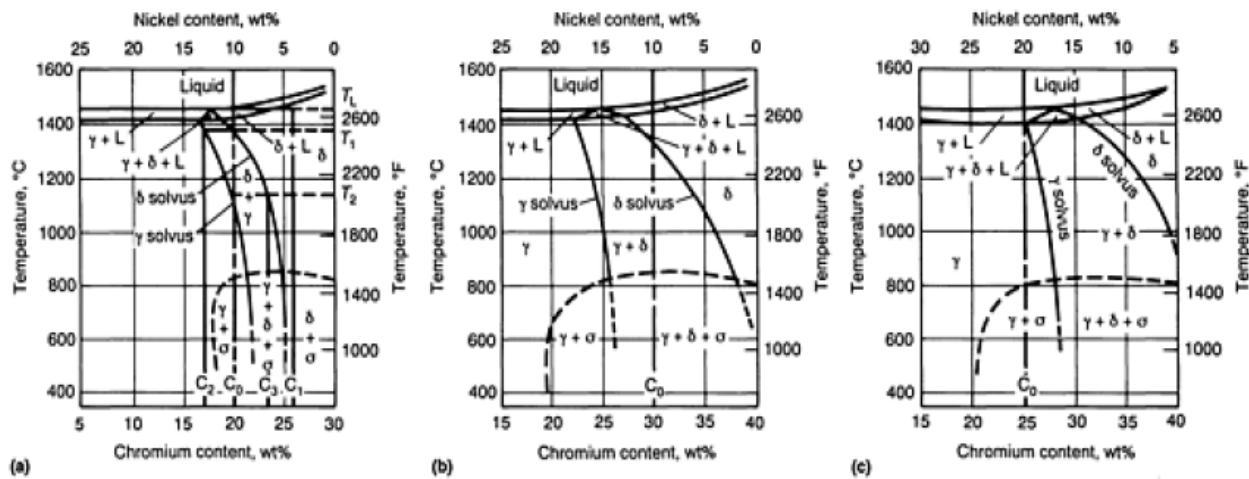


Fig-1: Fe-Cr-Ni phase diagrams with (a) 70wt% Fe (b) 60wt% Fe (c) 55wt% Fe [3]

Each diagram has a eutectic triangle with coexisting three phases ( $\gamma+\delta+L$ ) which indicates compositions in which austenite, ferrite, and liquid metal all can coexist. In all these 3 phase diagrams shown above nickel (austenite stabilizer) content decreases and chromium (ferrite stabilizer) increases on moving from left to right and hence the stability of austenite decreases and that of ferrite increases on moving from left to right.

but under the relatively rapid cooling conditions of welding, where there is much less time for diffusion some of this ferrite may survive to room temperature.

On the left (Ni-rich) side of each diagram are compositions that will solidify entirely as austenite as the concentration of ferrite stabilizer (Cr) is less in that region (Austenite or A-solidification mode) and remain austenite to room temperature. Close to, and within the left side of, the eutectic triangle are compositions that solidify as austenite by consuming maximum Ni and rejecting Cr in liquid in the early stages of solidification, but as the concentration of Cr increases in remaining liquid it will stabilize some ferrite and as a result some ferrite will appear in the final stage of solidification. This is called "primary austenite solidification" mode (austenite ferrite or AF mode). Further cooling can cause that ferrite to transform to austenite under equilibrium conditions by diffusing out of ferrite stabilizer,

Close to and within the right side of, the eutectic triangle are compositions that solidify as ferrite in the early stages of solidification by absorbing Cr and rejecting Ni in liquid, but again as the concentration of Ni increases in remaining liquid it stabilizes the austenite and as a result some austenite will appear in the last stages of solidification. This is called "primary ferrite solidification" mode (ferrite-austenite or FA mode). Further cooling can cause that ferrite to transform to austenite under equilibrium conditions by diffusion and redistribution of solutes, but under the relatively rapid cooling conditions of welding, some of this ferrite may, and usually does, survive to room temperature as the Cr concentration is on higher side in this case in comparison to previous two cases.

Further to the right are compositions that solidify entirely as ferrite as they have sufficient amount of Cr but, upon further cooling under equilibrium conditions they transform either

partly or entirely to austenite (F mode) depending on their chemical composition.

Ferritic stainless steels that have composition in further right of the above, solidify in ferrite or F mode and do not form any austenite at any temperature [3]. The solidification mode of any stainless steel can be determined from the composition. All the 4 above discussed modes are represented below in figure 2 [4].

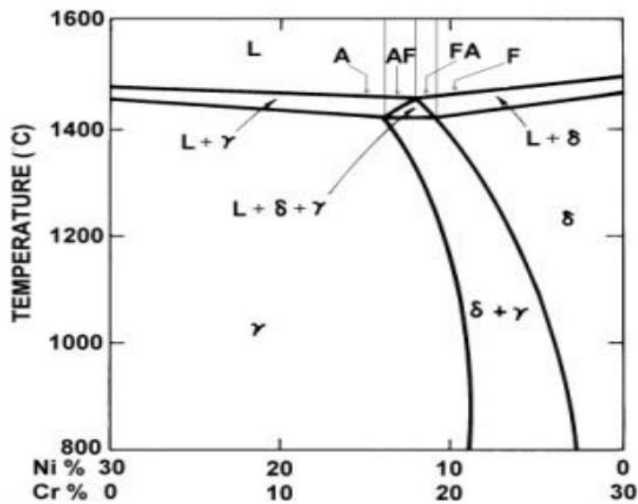


Fig-2: Different solidification modes in ASS [4]

Alloys solidifying in “A or austenite” mode will not go through any further transformation during cooling, while those solidifying as “AF” would form some ferrite during solidification and that ferrite may change to austenite during cooling. Alloys solidifying in FA or F mode passes through the two phase region ( $\gamma + \delta$ ) and either may remain in two phase or enter single phase austenitic region depending on composition and cooling rate.

Now let us try to understand these solidification modes in terms of  $Cr_{eq}/Ni_{eq}$  ratio. For low  $Cr_{eq}/Ni_{eq}$  ratio, “A” mode solidification will take place which will result in 100% austenite. For higher  $Cr_{eq}/Ni_{eq}$ , “AF” mode solidification occurs in which austenite is the primary phase and a part of remaining liquid solidifies as ferrite. For further higher  $Cr_{eq}/Ni_{eq}$  ratios during FA and F mode solidification, the high temperature microstructure has been found containing 70–100% ferrite. Most of this ferrite transforms to austenite during cooling and the residual ferrite left behind in the Cr-rich dendritic cores gives rise to the vermicular ferrite structure [4].

## 2.2 Hot Cracking:

Sometimes during solidification of welds or casting, cracks appear at the end of solidification generally at the centre line of the weld in ASS these are called hot cracking or

solidification cracking. These cracks occur due to rejection of impurities such as sulphur and phosphorus by solid. Due to this rejection the concentration of impurities keeps on increasing in the remaining liquid also these impurities form low melting compound with other elements present in ASS. At the same time due to shrinkage during solidification there will be tensile stress generated at the centre of weld joint and the weld cracks form due to synergistic effect of solidification tensile stress and formation of low melting compound [4-7].

It is well-known that sulphur and phosphorus combine with iron to form low-melting compounds such as FeS (1190 °C) and Fe<sub>3</sub>P (1166 °C), which in turn could form low melting eutectics such as FeS-Fe (988 °C) and Fe<sub>3</sub>P-Fe (1050 °C). There also exist other low-melting eutectics in ASS, such as Ni<sub>3</sub>S<sub>2</sub>-Ni (637 °C) and Ni<sub>3</sub>P-Ni (875 °C). These constituents which increase hot-cracking susceptibility are considered to form when sulphur and phosphorus segregate at the grain boundaries during solidification.

Silicon increases the hot cracking susceptibility in fully austenitic stainless steel. However if present in amount which causes the formation of some  $\delta$ -ferrite will improve the hot cracking resistance. Niobium has also been found to impact the hot cracking resistance negatively. The effect of these impurities has been proven experimentally by vareststraint test [5, 8].

Addition of small amount of nitrogen in welding of fully ASS decreases the cracking susceptibility as same decreases the segregation of silicon along grain boundaries. However if nitrogen is added by some means in welding of general ASS such as 304 or 316 it decreases the amount of ferrite in weld metal and hence increases the hot cracking susceptibility. Because these impurities are more soluble in  $\delta$  ferrite than in austenite, the presence of some ferrite during solidification is thought to serve as a kind of impurity absorber.

A lot of researchers have studied the theory of hot cracking and they have divided the complete solidification in 4 stages. In stage 1 nucleation of solids take place resulting in Mushy liquid in which both solids and liquid are free to move. In stage 2, both solid and liquid phases are continuous but the solids connect together and form network and hence can not move but any crack formed during this stage will be filled by the liquid. In stage 3, solids grow at the expense of liquid reducing the amount of liquid to very low. In this case if crack is formed can not be healed by liquid and this is the zone where crack initiation takes place. This temperature range is called critical solidification range (CSR). In stage 4, cracking cannot occur as no liquid is available [4, 6, 9].

It has also been stated that the chance of hot cracking are minimum if the liquid in stage 3 is present in the form of globules rather than a thin layer along the grain boundaries. This nature of last liquid is dependent on the surface tension

of the solid-solid and solid-liquid interface which affects the wettability [4, 9, 10].

If the weld metal solidifies as ferrite first, with austenite appearing only in the latter stages of solidification if at all (F/FA solidification mode), then the weld metal will be hot cracking resistant as the impurities which cause the hot cracking has better solubility in ferrite than austenite and hence will get trapped in ferrite leaving relatively cleaner liquid metal for further solidification. However, if the weld metal solidifies as austenite first with ferrite only appearing in the latter stages of solidification, if at all (A/AF solidification mode), then the weld metal is at risk for hot cracking [4].

In fully austenitic weld metals the hot cracking susceptibility increases remarkably for phosphorus and sulphur content in excess of 0.015% and 0.010% respectively. If both S & P can be reduced below 0.002% problem of hot cracking could be eliminated [5].

Since the presence of  $\delta$  ferrite in ASS weld is very important in order to minimize the chances of hot cracking the selection of filler wire and welding procedure has to be in such a way that during solidification some ferrite will form which will absorb the impurity and prevent the hot cracking. Also while selecting the filler, dilution effect due to melting of base metal must be considered. This task of selecting a filler wire is best accomplished with the help of constitution diagram for the stainless steel weld metals such as Schaeffler diagram, De-long diagram, WRC 1988 and WRC 1992 diagram.

In 1949, Anton Schaeffler published the well-known Schaeffler diagram. This diagram provides a relationship among austenite stabilizers (nickel-equivalent elements) and ferrite stabilizers (chromium-equivalent elements) commonly present in ASS. In order to use this diagram, first Ni equivalent and Cr-equivalent are calculated and are plotted on the diagram. The diagram contains some iso-ferrite lines and the ferrite content for the weld composition can be found with the help of those lines. It has been experienced that this diagram is reasonably accurate when conventional 300 steels ASS if welded with covered electrode. But has limitation with less conventional compositions or welding process which allows the nitrogen pickup [11]. Following formulae were used by Schaeffler for calculating Ni equivalent and Cr equivalent:

$$Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb$$

$$Ni_{eq} = Ni + 30C + 0.5Mn$$

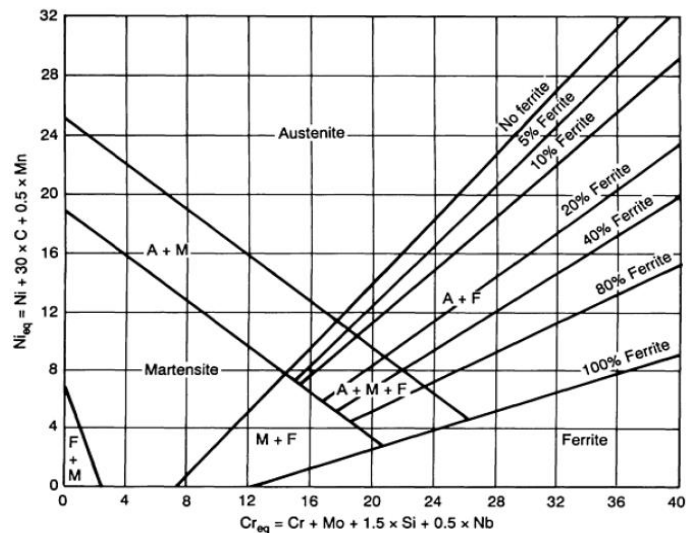


Fig-3: Schaeffler Diagram [11]

W.T. DeLong modified the Schaeffler diagram by including the effect of nitrogen in promoting austenite at the expense of ferrite. Generally, the Delong diagram correlates better with the processes that allow the nitrogen pickup such as Gas tungsten arc welding and Gas metal arc welding [11, 12]. Still two limitations were identified in Delong diagram:

1. Underestimating the ferrite content of high manganese weld metals.
2. Overestimate the FN (ferrite number) of highly alloyed weld metals

Following formulae were used by Delong for calculating Ni equivalent and Cr equivalent:

$$Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb$$

$$Ni_{eq} = Ni + 30C + 0.5Mn + 30N$$

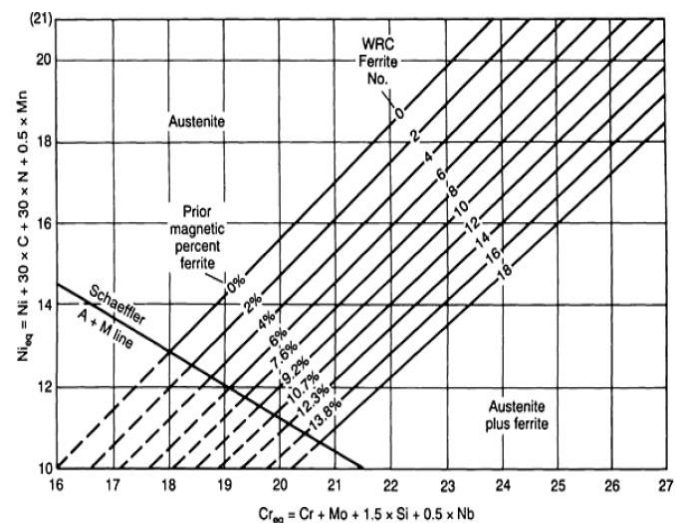


Fig-4: Delong Diagram [11]

To overcome the limitations of Delong diagram Welding Research Centre came up with another diagram known as WRC-1988. Again WRC-1988 was modified to include the effect of Cu as austenite stabilizer and new generated diagram is known as WRC-1992 diagram which is the best tool for determining the ferrite content in weld based on the chemical composition [11]. Following formulae were used WRC for calculating Ni equivalent and Cr equivalent:

$$Cr_{eq} = Cr + Mo + 1.5Si + 0.7Nb$$

$$Ni_{eq} = Ni + 35C + 20N + 0.25Cu$$

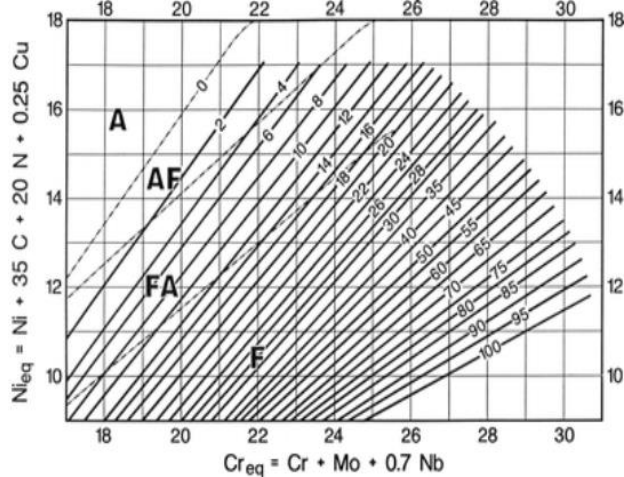


Fig-5: WRC 1992 Diagram [11]

Nowadays portable ferrite measurement instruments are being used to measure the ferrite number of weld joints at field. However, the ferrite that survives at room temperature after solidification is only a fraction of what existed during solidification as some of that might have transformed to austenite at lower temperature. Therefore finding ferrite at room temperature is only an indirect indication of the solidification mode. However, this is difficult and time-consuming to assess the solidification mode, whereas the Ferrite Number, measured at room temperature is easy to measure using any portable instrument (ferritoscope, magne-gauge etc.) calibrated to the ANSI/AWS A4.2 specification, and the inter laboratory reproducibility of measurement is good. Another method of measuring ferrite content is by microstructure analysis but this method is highly dependent on operator skill for etching and microstructure evaluation [13]. A minimum of 3 FN shall be ensured in order to make weld joint free from hot cracking problems in most nominally austenitic stainless steel weld metals and minimum of 5 FN is required in SS347[14]. A few factors that explain the effectiveness of  $\delta$ -ferrite in decreasing the hot cracking susceptibility are as follow:

1. The higher solubility of problematic solutes in ferrite does not allow the segregation at grain boundaries.
2. Crack growth is arrested due to presence of two phases.

3. Lower wettability of  $\gamma$ - $\delta$  interface by low melting liquid.
4. The ductility of ferrite at high temperatures is greater than that of austenite therefore allowing relaxation of thermal stresses.
5. The lower thermal expansion coefficient of ferrite as compared to austenite results in generation of less tensile stress.

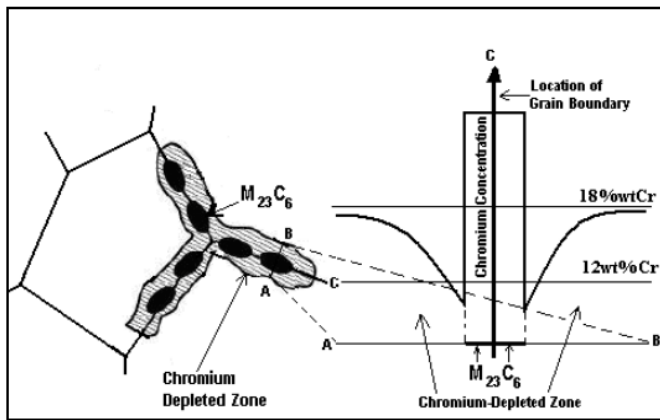
There are certain limitations to ferrite measurement by these devices:

1. Measurements are to be made along the top centre line of an as-welded weld bead. Ferrite measurement either after post weld heat treatment or at all points across a multi-pass overlay is inappropriate because heat treatment or reheating by a subsequent weld pass reduces ferrite toward its equilibrium value.
2. Maintaining ferrite percentage not always ensures the cracking resistance such as in the case of high impurities free-machining stainless steels which often renders the metal susceptible to hot cracking at any ferrite level. On the other hand, extraordinarily low impurity levels can make low or even zero ferrite weld metals fairly crack resistant.
3. The hot cracking susceptibility for autogeneous welding shall not be decided based on the ferrite measurement on unwelded base metal. The hot working in base metal will erase/reduce the ferrite and cold working will produce some strain induced martensite which is magnetic in nature and hence results in overestimation of ferrite content.
4. Apart from the manufacturer's certificate indicating a FN 3 welding parameters also affect the weld ferrite number.

### 2.3 Sensitization:

When austenitic stainless steels are subjected to high temperature (400-850 °C) for long time precipitation of chromium rich carbide ( $Cr_{23}C_6$ ) takes place along the grain boundaries (region C). Due to this precipitation of carbides the region around the grain boundaries becomes depleted in chromium with  $Cr < 12\%$  (region A & B). Since chromium is the main component providing corrosion resistance, grain boundary region (chrome depleted) becomes susceptible to corrosion. This phenomenon of carbide precipitation in known as sensitization and the corrosion taking place due to this phenomenon is known as inter granular corrosion (IGC). Sensitization may take place during cooling from high temperature, welding or heat treatment. Since the electrochemical reduction potential of carbide precipitate is more than that of ferrite depleted region leading to the formation of micro galvanic cell leading to localized corrosion. Figure 6 represents the carbide precipitation,

chrome depleted zone and variation of Cr concentration with respect to distance from grain boundary [15].

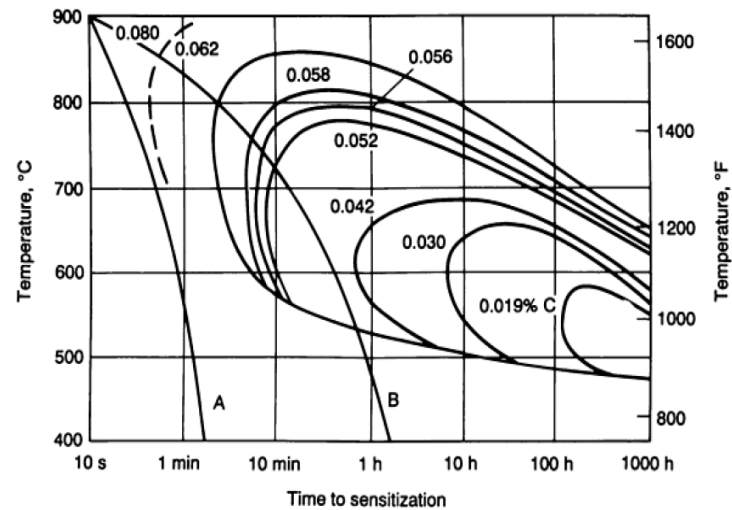


**Fig-6:** Schematic representation of  $Cr_{23}C_6$ , chrome depleted region and variation of chromium around grain boundary area [15]

Sensitization can take place during welding and/or post weld heat treatment and there are prevention and control measures to avoid or reduce this occurrence during welding/manufacturing. It has been found that the cold worked ASS are more resistant to sensitization than hot finished due to deformation of structure and leading to the formation of twins, slip bands, stacking fault and grain refinement [16]. To identify chromium depletion due to sensitization, there is a requirement of a specialized micro structural study of the welded material. Oxalic acid etch test is a rapid observation method of screening specimens for susceptibility to inter angular attack associated with chromium carbide precipitates. However this test is used for acceptance but not for rejection of material [17]. If material does not pass this test further analysis is required to conclude whether material is having sufficient resistance to IGC or not [18].

The solubility of carbon in austenite is over 0.4% at solidification temperature but decreases greatly with decrease in temperature. Chromium carbides ( $M_{23}C_6$ ) form whenever carbon reaches levels of super saturation in austenite, and diffusion rates are sufficient for carbon and chromium to segregate into precipitates. Most of the carbon present in even "L" grade ASS is in supersaturated solution and will try to come out of solution and form some stable precipitate still no or negligible amount of carbide is observed before sensitization, this could be attributed due to low diffusivity of carbon and chromium at low temperature. This results in varying precipitation rate at different temperature and carbon concentration. The diffusion of solute species is always easier through grain boundaries than bulk diffusion also grain boundaries provide excellent nucleation sites which leads to the precipitation along grain boundaries. The diffusion coefficient of carbon is much higher than that of Cr due to its smaller atomic size resulting in Cr depleted region just around the carbide precipitate [19].

Below figure indicates that the time required for sensitization decreases with increase in carbon percentage & temperature and reaches the maximum at around 800 °C.



**Fig-7:** Relationship between temperature, time to sensitization and carbon content [11]

There are a few ways to overcome sensitization:

1. Use a low carbon base and filler metal ( $C < 0.03\%$ )
2. Minimize the time in sensitization temperature range (400-850 °C) by minimizing the heat input, increasing the cooling rate and better joint design.
3. Use of stabilized grade base material and filler wire.
4. Use of high Cr alloy so that even after some precipitation corrosion resistance is maintained in the material.
5. Solution annealing heat treatment

## 2.4 Intermetallic Phases

Several intermetallic phases have been observed in austenitic stainless steels. These intermetallic phases are hard, brittle and have a tendency to precipitate on the grain boundaries and are thus detrimental to the mechanical properties of the alloys. Precipitation of these phases depletes the matrix of important solid solution elements leading to a reduction in the corrosion resistance.

### 2.4.1 Sigma Phase

The phase is usually defined as Fe-Cr and is intermetallic compound with approximate 30wt% -50wt% Cr but it can dissolve significant amounts of nickel and other elements as well. It forms at about 538-927 °C and is very hard & brittle constituent. Sigma phase is renowned for its detrimental effects on the mechanical properties such as increase in hardness and reduction in toughness & ductility of stainless steels [20]. Sigma ( $\sigma$ ) phase is formed by transformation of  $\delta$  ferrite in the high Cr-concentrated region. This happens

because Cr is a ferrite stabilizer and hence its concentration will be more in ferrite than in austenite also the diffusion of Cr is more in ferrite than in austenite. Furthermore, the  $\sigma$  phase can also precipitate from  $\gamma$ -austenite when there is no  $\delta$ -ferrite in the stainless steels although it is unlikely [21, 22]. The contents of Cr and Mo of  $\delta$ -ferrite decreased and the Ni contents increased simultaneously after the  $\sigma$  phase precipitation. The above result leads to the formation of secondary austenite ( $\gamma_2$ ) phases from  $\delta$ -ferrite ( $\delta \rightarrow \sigma + \gamma_2$ ). The precipitation rate of  $\sigma$  phase has been found to be maximum at about 800-850 °C and increases with increase in Cr content, decrease in C content and increase in  $\delta$ -ferrite.

Since material require exposure at high temperature for longer time for sigma phase to form (such as in heater tubes) and hence it is of main concern when material is to be used in high temperature although it can also form during welding sometimes. Sigma phase transformation process is a nucleation controlled phenomena. That means once the nucleation has started within much lesser time the ferrite will be converted into sigma phase [23]. The best way to minimize the formation of sigma phase is by minimizing the delta ferrite in initial weld. In order to minimize the ferrite in weld without impacting its hot cracking resistance high purity material shall be used along with application of high purity and low FN filler/electrode such as 18-8-2 which has low ferrite number between 1-6 FN.

#### 2.4.2 Laves Phase:

It is an intermetallic compound of Fe along with Mo, Nb and Ti. The most commonly found laves phase in austenitic stainless steels are  $Fe_2Mo$ ,  $Fe_2Nb$ ,  $Fe_2Ti$  or a combination of three such as  $Fe_2(Mo, Nb, Ti)$ . Laves phase is also formed during high temperature exposure (700-900 °C) for long time. Since it is hard and brittle phase it reduces the ductility, toughness and corrosion resistance of the material however, if fine distributed precipitates are formed by addition of some alloying elements then creep resistance of material can be improved significantly [24].

#### 2.4.3 Chi Phase( $\chi$ ):

Chi phase is observed in austenitic stainless alloys when either titanium or molybdenum is present which primarily contain Fe, Cr, Mo and Ti [ $Fe_{36}Cr_{12}Mo_{10}$ ,  $(Fe,Ni)_{36}Cr_{18}Mo_4$ ]. This precipitate has been found in material exposed to high temperature between 649-950 °C for long time. Chi phase formation is increased by increasing Mo content, increasing Ti content, increasing Cr content and decreasing N content. Chi phase has been observed to form at austenite/eutectic ferrite interface but does not form at austenite/primary ferrite interface as primary ferrite has lower Mo content [25, 26]. So if the composition of weld metal is maintained in such a way that the solidification mode is FA then formation of Chi phase can be minimized.

#### 2.4.4 Eta, G, R, Gamma Prime( $\gamma'$ ) and gamma double prime ( $\gamma''$ ) phases:

Above described three phases i.e. sigma phase, laves phase and chi phase are the mostly present intermetallic precipitates in austenitic stainless steel. Other than this sometimes small fraction of eta ( $Ni_3Ti$ ), G phase [ $(Ni,Fe,Cr)_{16}(Nb,Ti)_6Si_7$ ], R phase [ $Fe_{22}Mo_{18}Cr_{13}(Fe,Ni)_{10}Cr_5Mo_3Si_2$ ],  $\gamma'$  [ $(Fe,Ni,Cr)_3(Al,Ti)$ ] and  $\gamma''$  ( $Ni_3Nb$ ) may be present and depending upon their size and distribution will affect the mechanical properties of the stainless steel [26].

#### 2.5 Loss of corrosion resistance:

The corrosion resistance of the stainless steel is because of presence of protective oxide film at certain range of potential. If potential of solution is at low level oxide can't form and if the potential is above that level then hexavalent chromium ions will form which are soluble in water. Now even if the potential is being maintained in passive zone and if there is a weak point on the surface due to inclusion, mixed oxide formed during welding or local alloy element depletion (due to segregation). Surface oxide gets removed from those weak location and form anode and rest of the surface become cathode leading to high localized corrosion [27]. Normally welds of ASS are less corrosion resistant than the base metal of similar chemical composition due to segregation of alloying elements in weld. In order to compensate for this loss of corrosion resistance, filler/electrode for welding shall contain somewhat high alloying elements so that even the area with relatively low concentration of corrosion resistance providing alloying elements is comparable to that of the base metal. Also homogenization heat treatment of autogenously welded super austenitic steel helps in coping up the problem of segregation. Normally pickling to remove the mixed oxide layer, weak spots and heat tint formed during welding and then passivation for the formation of fresh and protective chromium oxide layer are carried out after welding. Which restores the corrosion resistance of weld and heat affected area.

#### 2.6 Distortion, residual stresses and Stress corrosion cracking (SCC):

Since ASS has higher coefficient of thermal expansion than ferritic steels that results in more expansion during heating cycle and more contraction during cooling cycle of the welding leading to distortion and residual stresses in the material. ASS are inherently susceptible to SCC and presence of tensile residual stress assist in that process. The chances of SCC can be reduced by post weld heat treatment which reduces the residual stresses. Another way to minimize the residual stresses is by minimizing the heat input during welding. SCC is affected by some other parameters as well such as amount, size and distribution of ferrite, intermetallic precipitates and segregation of alloying elements [28].

### 3. CONCLUSION

The problem of hot cracking in austenitic stainless steels could be eliminated by choosing filler/electrode in such a way that the solidification takes place in FA mode (Primary ferrite solidification) in which the first solidifying ferrite traps the impurities such as sulphur and phosphorus and hence avoid the formation of low melting compounds at the end of solidification. The adequacy of filler/electrode for producing FA solidification mode is checked by measuring ferrite content in 3 ways. One is by use of Schaeffler, Delong and WRC constitution diagrams second by portable ferrite measurement tools and the third is by microstructure evaluation. If the ferrite content in weld metal is found above 3 FN then it can be considered that the solidification mode was in FA mode and weld will be having good resistance to hot cracking. However there is also an upper limit on the ferrite number at 10 FN to avoid the loss of mechanical properties of the material at very low or very high temperatures. In the case of Nb bearing ASS such as SS347 this limit is modified to 5-11 FN as Nb itself is an alloying element which increases hot cracking susceptibility.

The second biggest problem in welding of ASS is sensitization or formation of chromium carbide along the grain boundaries. Sensitization results in chrome depleted region around the grain boundaries and making the steel susceptible to corrosion (IGC).

During welding when material is subjected to high temperature and/or allowed to stay at that temperature for longer time some intermetallic phases such as Sigma, Chi, Lave, G, R, Gamma prime and Gamma double prime may precipitate out of matrix. These precipitates take the alloying elements out from the matrix and hence somewhat reduce the corrosion resistance. However some of these intermetallics are deliberately formed in materials used in high temperature as they improve creep resistance significantly.

Due to segregation ferrite will have more Cr, Mo and austenite will have more Ni leading to different corrosion resistance of both the microstructural constituents. Hence the filler metal shall be selected in such a way that even the less chrome constituent (austenite) will have the minimum required Cr & Mo concentration.

Due to relatively large coefficient of thermal expansion austenitic stainless steels are prone to distortion and residual stresses. Post weld heat treatment (PWHT) can be done to minimize the residual stresses but since PWHT will again involve heating the material that may lead to sensitization or intermetallic formation rendering the material useless.

If the material is already sensitized or intermetallics has formed in it. In that case the best way to recover its

properties is by solution annealing heat treatment. This involves heating the material above 1066 °C, keeping it at that temperature for some time so that all the precipitates get dissolved & homogenized and then rapid cooling to avoid any precipitation. But this process is not feasible in most of the cases also rapid cooling will generate more residual stresses. Hence avoiding these degradation mechanism (intermetallic precipitation, sensitization etc.) to act on material or use of material which are resistant to that particular problem (inherently safer material) such as "L" grade ASS (when welding and then exposure to corrosive environment is involved) is the best way to overcome the problems of ASS.

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