Welding Metallurgy of Stainless Steels

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Introduction

Stainless steels are being used in a wide variety of industrial applications. Stainless steel fabricated parts are to withstand widely varying temperatures, corrosive media and stresses. There are many stainless steels developed since World War II and these are classified by AISI. One of the main methods of fabricating units is welding and this paper deals with the metallurgy of stainless steels in general and their behaviour to welding variables such as thermal cycle, fluxes, filler rods, coatings on the electrodes, heat treatment etc. in particular. Some reference is also made to the effect of service conditions on the weld-fabricated components.

Classifications

Stainless steel may be classified from the metallurgical micro-structural point of view into three or four broad groups.

1. Ferritic stainless steels
2. Martensitic stainless steels
3. Austenitic stainless steels
4. Maraging stainless steels

The main constituent alloying element is chromium which imparts the corrosion resistance property. The addition of other elements such as Ni, Mo, Ti, Cb and Co modify its microstructure in a useful way. Chromium, Molybdenum, Vanadium and Silicon tend to stabilise ferrite. Nickel, Manganese, Cobalt, Nitrogen and Carbon tend to stabilise austenite.

Thermal cycles of various welding processes

The mechanical properties of the welded joint mainly depend on the microstructure of the weld metal and its surroundings affected by the thermal cycle during welding. It is always possible to change the thermal cycle by preheating, external coolants, and the technique of welding. However, in all fusion welding processes, there exist rapid heating of fusion surfaces, deposition of filler, solidification and conducting away of the heat by the adjacent parent material. There exists a region close to weld metal, where microsstructural changes, grain refinement, grain growth, and other metallurgical phenomena take place due to the rapidly changing temperature, called 'heat affected zone' or HAZ.

The various processes employed are shielded metal arc welding, gas metal arc welding, gas tungsten arc welding, submerged arc welding and electroslag welding, resistance welding processes and some of the more recently developed welding processes. The rates of heating, time of peak temperature and rates of cooling are of sufficient order to cause microstructural and metallurgical changes. The rate of cooling is slow in submerged arc welding, and still less in electroslag welding. The rate of cooling is fastest in resistance welding processes especially in spot and seam welding. The width of H.A.Z. is maximum in electroslag welding and less in submerged arc welding. The metallurgical effects of these thermal changes will be discussed under the respective steels.

Ferritic stainless steels

These are mostly straight chromium stainless steels, classified AISI 400 series. The chromium content is more than 14 percent upto 30 percent. Because

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chromium is a strong ferrite former, transformation during heating and cooling is eliminated. This results in a micro-structure of ferrite and carbide. Such steels do not form austenite on heating, and therefore cannot form martensite on cooling. 14 percent to 20 percent Chromium steels are called transition alloys. Higher carbon steels (greater than 0.1 percent C) will respond to heat treatment, the proportion of martensite to ferrite varying with the specific composition of steel. The effect of carbon in extending the gamma loop is shown in Figure 1.

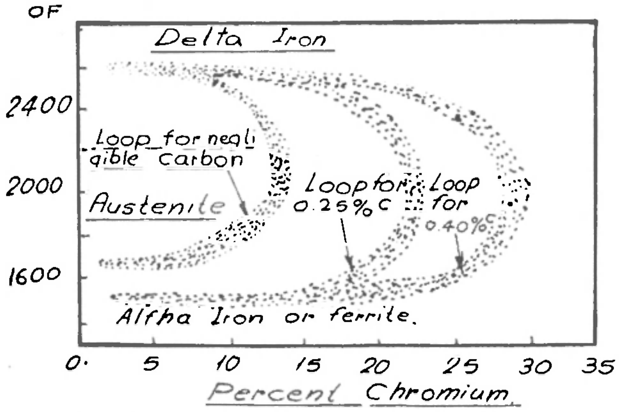

Fig. 1. Curves showing the effect of Carbon and Chromium content on the equilibrium gamma loop.

The greatest disadvantage of ferritic stainless steels, from the welding stand point, is their susceptibility to grain growth. Since these steels do not undergo transformation, the only way of refining coarse grains is through mechanical working. The larger columnar ferrite grains reduce ductility and toughness of weld metal, making it extremely notch sensitive. The notch sensitivity stemming from large unrefined grains in the weld and heat-affected zone of the ferritic stainless steels makes this an especially pertinent consideration for these steels.

The hard and brittle constituent, sigma phase, may develop, particularly in highly stressed or cold worked metal subjected to prolonged heating or slow cooling. Ferritic chromium steels which usually are ductile at elevated temperatures may be brittle at room temperature particularly when sigma phase is present or grains are large either in the weld metal or in the heat affected zone. About 0.1 percent to 0.25 percent nitrogen is added to refine the grain structure and inhibit the grain growth at high temperatures which may not however improve the impact properties.

Filler wires or electrodes are also chosen which contain elements such as Ti, Al or V either in the core or in the coating which prevents grain growth. Arc welding is preferred to gas welding. Fast welding gives less time for grain growth. Preheating and stress relief annealing is given to lower the residual stresses and avoid cracking during welding. Austenitic Cr-Ni fillers are employed to avoid hot cracking.

Martensitic steels

Martensitic stainless steels are mostly 12 percent straight chromium or modified by additions of Molybdenum, Tungsten and Nickel. Carbon percent varies from 0.05 to 0.25. These steels possess satisfactory strength properties at both room and elevated temperature, resistance to corrosion and erosion.

These steels are air-hardening. The weld and its H.A.Z. cool rapidly and both harden greatly. Since hardness is related to carbon content, greater hardness will be obtained with higher carbon content. The reduction in ductility accompanies increased hardness. Hence proper preheat, and post heat treatments are applied. Weld metal containing less than 0.05 percent carbon usually retains sufficient ductility at relatively high hardness so that lower preheats can be used. Carbide forming agents such as columbium and titanium are some times added to reduce the hardness. These elements tend to form stable carbides preventing martensite formation unless temperatures are sufficiently high to take the elements back into solution. This explains why mixed results are obtained in welding.

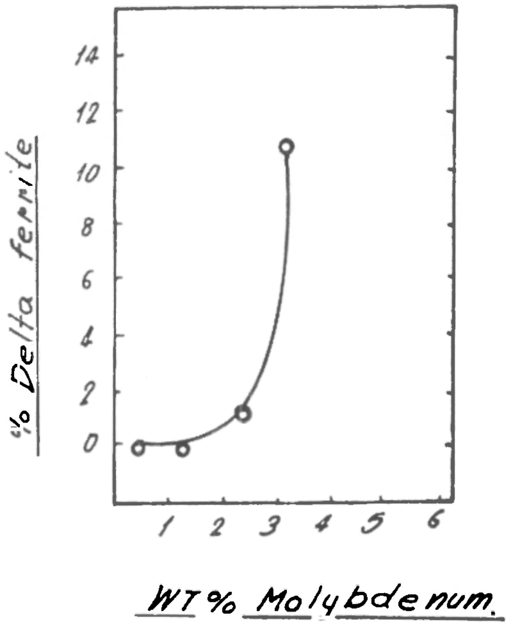

Fig. 2. The effect of molybdenum on the amount of delta ferrite in 0.20% Carbon, 12% Chromium, 0.40% nickel steel hardened from 1100°C.

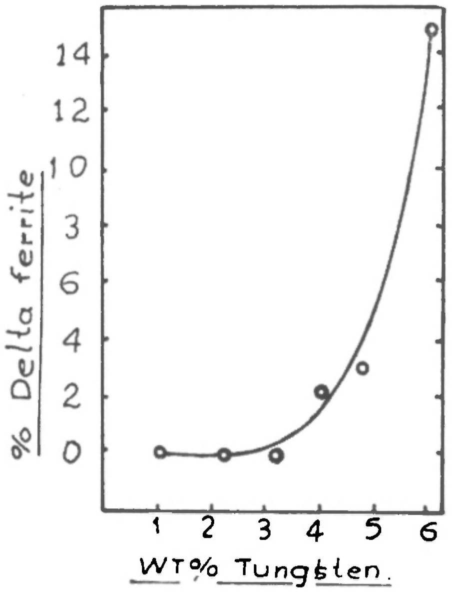

Fig. 3. The effect of Tungsten on the amount of delta-ferrite in 0.2% carbon, 12% chromium, 0.40% nickel steel hardnened from 1100°C.

In modifying the composition of the 12 percent Cr steels the composition is balanced in order to avoid formation of delta-ferrite at the austenitising temperature. Delta-ferrite has harmful effects on fatigue and impact strength. The influence of tungsten and molybdenum on delta-ferrite formation is shown in figures 2, 3. It can be seen that 3 percent tungsten and 2 percent molybdenum by weight can be tolerated without the formation of delta-ferrite.

When welding the straight chromium steels having predominantly martensite microstructure, preheat and post heat must be applied if the weld metal or H.A.Z. cracking is to be avoided. The craking occurs because of low ductility of untempered martensite. Hydrogen induced cracking is also likely if preheat temperature is not maintained during welding.

Precipitation hardenable martensitic stainless steels are another type having 4-5 percent Ni and 2-3 percent Mo. These display a combination of high strength and low susceptibility of hydrogen-induced cracking. When these steels are welded, a range of microstructures are present across weld metal and H.A.Z. The weld metal has solution treated structure, the adjacent region in H.A.Z. has aged structure followed by overaged structure and then the parent plate. The hardness values across a section as welded and after an agehardening (precipitation) treatment are shown in figures 4,5. These figures show a certain area of H.A.Z. not brought to hardness level with the rest, the reason being it is overaged. Degree of softening in the overaged region is not affected by the increased heat input. The only advantage of low heat input is that the region of reduced hardness which is not recovered during postweld aging is confined to a narrow region. The amount of delta ferrite can be controlled by the solution heat treatment temperature. Delta-ferrite is not subjected to precipitation hardening and hence is weak and segregated.

Austenitic stainless steels

The widely used composition is 18 Cr—8 Ni, with less than 0.11 percent C and other elements in small quantities. This is a border line composition in which the rate of transformation to ferrite is very low although its austenite is not truly stable as more ferrite is formed on cold working. The austenite of 18/8 can hold only about 0.2 percent carbon in complete stable solid solution. At any higher carbon

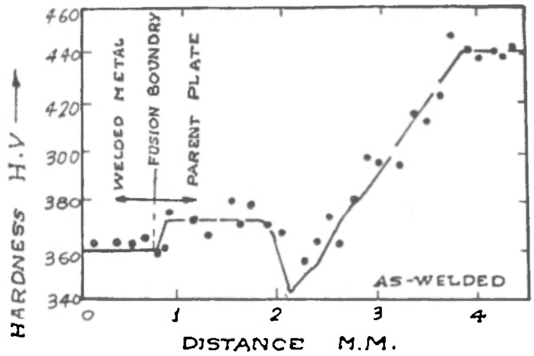

Fig. 4. Hardness values obtained across a TIG bead on the fully hardened plate in the as-welded condition. (300 gm. load)

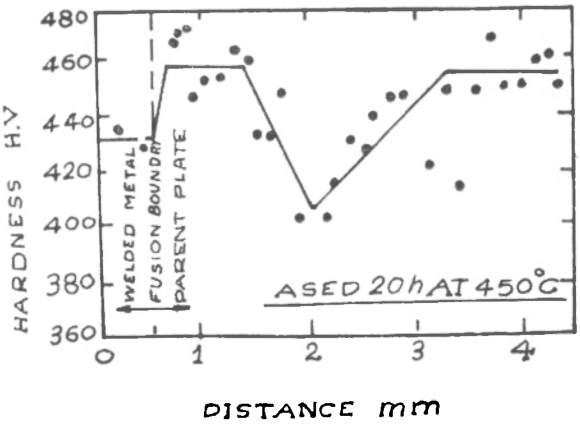

Fig. 5. Hardness values obtained across a TIG bead on the fully hardened plate after post weld heat treatment. (300 gm. load)

content, carbides try to separate out and hence steel is supplied in quench annealed condition. The solubility of C in austenite and the range of carbide precipitation is shown in figure 6.

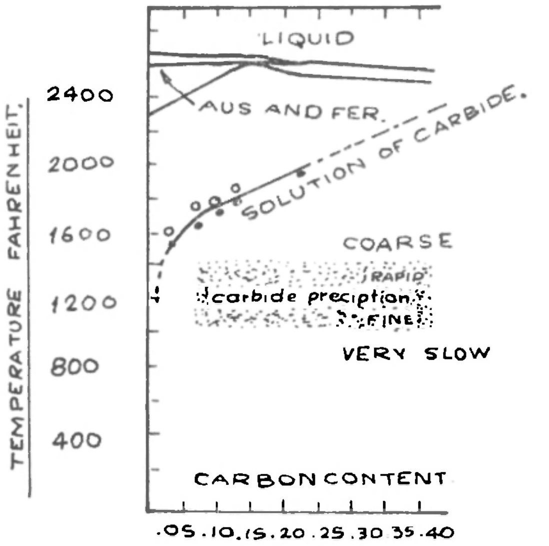

Fig. 6. Solubility of C in the austenite of 18% Cr 8% Ni steel.

Intergranular Corrosion

The austenitic chromium nickel steels make mechanically satisfactory welds but the weld metal and the H.A.Z. pass through the temperature zone indicated in figure 6. When the steel is heated or cooled within this temperature range, the carbon is precipitated from the solid solution preferentially on grain boundaries, that is, intergranularly. This carbon unites with chromium to form chromium rich carbides. Hence the metal immediately around the grain boundaries is depleted in chromium to below the level necessary to maintain necessary passivity and becomes susceptible to preferential corrosive attack. $(Cr\,Fe)_{23}C_6$—chromium rich carbide is precipitated. There will be a base metal zone parallel to weld deposit which is heated to this temperature range. This is the zone of carbide precipitation, the amount of which depends on carbon content, time and temperature range through which the particular portion of metal passes. The 18/8 type retains a maximum of about 0.02 percent carbon in solid solution under all conditions. As the carbon content increases to about 0.08 percent the amount of carbon which can be precipitated increases slowly; in many cases this will not lower its corrosion resistance. At higher carbon levels, carbide precipitation increases rapidly. Although a single bead of weld metal usually does not show evidence of carbide formation because of rapid cooling from molten temperature, the heat effect from subsequent passes in a multipass weld will show bands of carbide precipitation in H.A.Z. and in the passes already deposited.

The separation of carbide is a precipitation hardening type phenomenon. Carbon originally in solution in the austenite at high temperature tends to form chromium carbide in the temperature range shown in figure 6. If it separates well scattered within the grains, the effect is minor but at 550°-800°C the tendency is strong for the carbide to separate at grain boundaries. This depletes the edge of the grains in C and Cr and the lowered Cr content at the edge of the surface grains makes them more readily corroded. Local stress appears to be set up in the matrix surrounding the carbide and this favours the formation of ferrite, much as cold work does. The lower carbon also favours ferrite.

Fine grained material has more grain boundary than the coarse grained one and so the carbide films are thinner, less continuous and exert less effect. After precipitation has occurred, further heating at higher temperatures tend to dissolve the carbides into solution. The effect of carbide precipitation depends not only on carbon content but also on both the temperature and the time the material has been at that temperature. Intergranular corrosion resulting from carbide precipitation is generally less when ferrite is present because most of the carbides precipitate within ferrite patches and correspondingly are fewer at grain boundaries.

The amount of carbide precipitated is reduced if percentage of carbon present is less than 0.05 and also Chromium carbide precipitation is less if other elements such as Titanium and Niobium, which form compounds with C in preference to Cr are added to the steel. These steels are called stabilised stainless steels. These elements are added in proportion to C about 8 times (Titanium) and 12 times (Niobium) in order to fix the carbon by forming respective carbides.

Ferrite

Presence of delta ferrite in an austenite matrix is often observed in the weld metal. The characteristics of stainless steel are dependent on ferrite content. Corrosion resistance and ductility at low temperature are decreased due to presence of ferrite. A minimum of ferrite is necessary to reduce the susceptibility to hot-short cracking. On the other hand, ferrite exerts a noticeable influence on the formability of the austenite steels. Figure 7 shows the effect of ferrite content on the mechanical properties of an austenitic weld deposit of 19/9/Nb type. It raises the yield point and tensile strength but at the same time elongation value is reduced. For this reason, ferrite content is limited to a maximum of 10 percent.

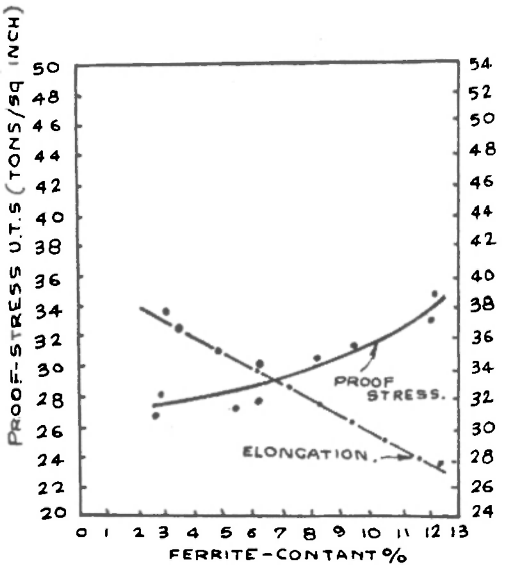

Fig. 7. Influence of ferrite content on mechanical properties of austenite weld deposit.

Sigma Phase

Besides the austenite, ferrite and carbides commonly found, an intermetallic compound of Fe and Cr called the 'sigma phase' is encountered. This phase usually transforms preferentially from ferrite when steel is held for long times at temperatures ranging from 650°—925°C depending on alloy contents. The phase may also develop in alloys initially austenitic. It has been encountered in alloys high in Titanium, Niobium, Molybdenum, Silicon or Chromium. The sigma phase may cause loss of corrosion resistance but it usually manifests in loss of ductility and impact strength. Although high temperature exposure is necessary for the formation of this phase, the evidence of its presence is reported in weld metals in as welded condition of stabilised steels. The large quantity of heat induced into material during submerged arc welding is conducive to the formation of sigma phase in the weld deposit. Sigma phase first forms on grain boundaries between ferrite and austenite and in course of time transforms the whole of ferrite. When making a multipass weld, the temperature range critical to formation of sigma phase is passed through several times. Sigma phase is likely in the weld deposit of 19/9/2Mo type as a result of more ferrite being present. Molybdenum, Niobium and Titanium promote the formation of delta ferrite in the structure and form carbides as well.

Cracking Phenomena

Cracking during welding of stainless steels can be separated into three types. Supersolidus cracking, subsolidus cracking and reheat cracking. The first type is confined to weld metal, the second type may occur in the weld metal or H.A.Z. or beyond the fusion zone. Reheating cracks occur during multipass welds or in service.

Low melting point segregates promote hot cracking. These phases are found to have been formed by S, P, Mn, Si, Nb, Fe, C and H_2. The solubility of these elements is higher in ferrite than in austenite. Consequently ferrite will suppress their detrimental influence while a high tendency to hot cracking is to be expected in fully austenitic weld deposits. Hot cracks observed in unstabilised weld deposits of 18/8 steel are inter-dendritic. They proceed along solidified ferrite and solidifying austenite. The extent of this cracking is usually very limited but it is important for two reasons. Firstly, cracks formed during welding can act as points of initiation for a more serious form of cracking during subsequent heat treatment. Grain boundary melting was observed in regions close to the primary Niobium Carbide particles present in the original structure. In the case of unstabilised steel, the cracking is to a smaller extent than in Nb-stabilised steel.

Carbides of Nb, Ti and Cr are face centered cubics and have the same structure as the parent austenite. When carbon content is low, plastic deformation is necessary before appreciable precipitation can occur along the grain boundaries, Dislocations can act as sites of nucleation of $(CrFe)_{23}C_6$ as they do in case of Nb C in Nb-bearing steels. Cracking may be due to stiffening of grains by the strain induced precipitate particles. This causes an increase in stress concentration at the grain boundaries which may result in the formation of inter crystalline cracks. H.A.Z. of 16 Cr/10Ni/2Mo steel has shown no cracking during a welding test. Ferrite reduces cracking because of its fine form, by increasing its grain boundary area spreads and disrupts the continuous carbide particles. Also, compositions containing a small amount of delta ferrite give a smaller freezing range than fully austenitic composition which aids segregation of low melting point eutectics and inter metallic compounds.

It is reported that in flash butt welding of super heater tubes of the titanium stabilised steels, cracks in weld metal and in H.A.Z. are observed. Excessive amounts of delta ferrite segregated in bands near the weld interface. Cracking is associated with the liquation due to Ti C particles in the grain boundaries. As much as 30 percent ferrite can form depending on welding cycle and this is conducive to sigma formation. In addition, sigma phase will be restricted to a narrow band which will be weakest in impact. Ferrite content is governed by heat input, applied strain, material composition and prior history. Higher the peak temperature, higher is the ferrite. Cracking is due to low hot ductility of ferrite.

Conclusions

Ferrite stainless steels used for high temperature and special corrosive medium equipment are weldable but require treatments, mechanical and stress relief.

Delta ferrite formation in martensitic stainless steels is controlled by limiting alloying elements, compositions and the temperature at which steel is solution annealed.

The problems concerned with welding of austenitic stainless steel are intergranular corrosion, sigma phase, ferrite amount and cracking. In unstabilised steels, intergranular corrosion is minimised using a very low carbon steel and a fast welding process with a minimum number of welding runs.

Delta ferrite and sigma phase are closely related to cracking during welding or post heat treatment or during service. An amount of 5 to 10 percent is desirable to inhibit cracking tendencies and, at the same time, limit the available ferrite for conversion into sigma phase, a very brittle compound.

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