WELDABILITY ASPECTS OF FERRITIC STAINLESS STEELS

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Ferritic stainless steels have recently drawn greater attention owing to their lower costs and better resistance to stress corrosion cracking than austenitic stainless steels. Although these properties make the alloy commercially attractive they still exhibit several significant draw backs that limit their use. Ferritic stainless steels are less weldable than austenitic ones. A pronounced grain growth takes place in the heat affected zone and carbide precipitation occur at the grain boundaries. This makes the weld more brittle and decreases its corrosion resistance. Furthermore cracks can occur in the weld metal when it cools down.

When welding stainless steels care must be taken that welding process does not affect either the corrosion resistance of the weldment or its mechanical properties. This article covers what effects the welding process can have on the metallurgy of ferritic stainless steels, selection of consumable and suggests practical advice on how potential problems can overcome.

INTRODUCTION

At present a large variety of stainless steels with different properties is available; properties such as toughness at very low temperatures and high temperature strength. The most important property is of course, resistance to corrosion in many different types of environment.

The properties of stainless steels vary with the chemical composition which determines their microstructure. The stainless steels can be broadly grouped into five categories depending on their metallurgical structure. They are (a) martensite (b) Ferritic (c) Austenitic (d) precipitation hardening and (e) Duplex. By suitably varying the addition of alloying elements particulary carbon, chromium, Nickel (and precipitation hardening elements like Cu, Al, Cb etc in the case of precipitation hardening stainless steels), the matrix structure of the stainless steel can be modified and a specific structure can be retained at room temperature. The matrix structure of the stainless steel influences not only the mechanical properties of the stainless steel but also enhances the resistance to corrosion on specific media. Each group finds specific application and forms the most economical choice for a service condition. Of the above groups, the most popular group, the austenitic stainless steels, is widely used and therefore its weldability and related phenomenon have become quite common. The martensitic and ferritic stainless steels, though not so popular, have specific properties especially mechanical and corrosion properties which make them candidate material for several applications.

Table 1 compositions of typical ferritic stainless steels

	Analysis, wt-%							
Designation	C	Si	Mn	Cr	Al	Mo	Nb	Ti
AISI 405	0.06	0.25	0.40	13.5	0.20	-	-	-
AISI 409	0.06	0.25	0.40	11.0	-	-	-	0.40
AISI 429	0.06	0.40	0.40	15.0	-	-	-	-
AISI 430	0.06	0.40	0.40	17.0	-	-	-	-
AISI 430 Ti	0.07	0.25	0.40	17.0	-	-	-	0.50
AISI 430 Nb	0.05	0.25	0.40	17.0	-	-	0.50	-
AISI 434	0.05	0.25	0.40	17.0	-	0.90	-	-
AISI 436	0.05	0.25	0.40	17.0	-	0.80	0.50	-
AISI 442	0.08	0.25	0.40	21.0	-	-	-	-
AISI 446	0.08	0.25	0.40	25.0	-	-	-	-
18/2	0.02	0.40	0.40	18.0	-	2.0	-	-
18 SR*	0.05	1.00	0.50	18.0	2.0	-	-	-
HWT*	0.07	0.40	0.40	18.25	-	-	-	-
Sichromal 10*	0.10	1.00	0.40	18.00	1.00	-	-	-
E-brite 26-1	0.02	-	-	26.00	-	1.00	-	-

* This higher chromium grades containing high silicon, aluminium, or titanium are more usually used as heat-resisting grades.

The scope of this discussion is limited to ferritic stainless steels. These steels contain 17 - 26% Cr with varying alloying additions, form an increasingly important groups of materials (1,2) and present a challenge to the long established austenitic stainless steels in other than the most stringent service conditions. The chemical compositions of typical steels are given in table.1. There primary advantage include lower material cost than more commonly used austenitic stainless steels and greater resistance to stress corrosion cracking although these properties make the alloys commercially attractive. They still exhibit several significant draw backs that limit their use. These include reduced formability susceptibility to embrittlement, susceptibility to hot cracking during welding, and adverse effect of welding on their mechanical properties (toughness and ductility) and resistance to intergaranular corrosion.

To the welding engineer, therefore, it becomes necessary to understand the welding of ferritic stainless steels in order to fabricate components which will operate satisfactorily in the intended service.

In this paper, an attempt has been made to present in a concise form, the weldability of ferritic stainless steels, the various consumable, techniques, heat treatment for the same in order to obtain sound joints.

Structural Changes During Welding

It is to be expected that the mechanical, chemical properties of ferritic stainless steel weldments will be strongly dependent on the features of the microstructure. In order to consider these relationships in detail it is necessary to understand the structural transformation that could occur as the steel is heated and cooled during welding. To describe the structural transformations caused by the welding operation, two region must be distinguished within the weld; A typical example of the weld microstructure of 430 stainless steel is shown in Figure 1.(3)

A region `A' of the heat affected zone (HAZ) in which the metal has reached the austenitic formation ranges (i.e. $\delta + r + \varepsilon$ and $\delta + r$ in figure 2) As shown in figure 1. austenite formed along the grain boundaries and upon fast cooling during welding, transformed to martensite, appearing as the dark etching areas in figure 1 (region A) little grain growth takes place in this region.

In region B, the metal has reached the pure delta ferrite range, and excessive grain growth took place. During cooling through the austenite formation ranges, a considerable amount of austenite formed at the grain boundaries. The austenite formed in region `B' is then transformed into martensite as the weld cools to room temperature.

It will noted that there is no marked structural difference between the weld metal and the portion of HAZ raised into fully delta ferrite range. It is however, possible to distinguish between these regions, because the metal of the HAZ retains an equiaxed grain structure, whereas the weldmetal possesses a columnar structure resulting from the directional solidification.

Table 2 - Probable Weld Pool Shape for Different Welding Conditions

Condition	Process	Consumable Diameter, mm	Voltage, V	Current, A	Travel Speed mm/min	Heat Input kJ/mm,	Probable Pool Shape
1	SMA	3.2	20	100	180	0.7	Elliptical
2	SMA	4.0	21	145	130	1.4	Elliptical
3	GMA(spray)	1.2	31	320	450	1.3	Teardrop
4.	GMA(spray)	1.2	27	240	230	1.7	Elliptical
5.	GMA(globular dip)	1.2	23	180	125	2.0	Eliptical
6	Submerged-arc	2.4	28	270	250	1.8	Elliptical
7.	Submerged-arc	2.4	32	370	620	1.1	Teardrop

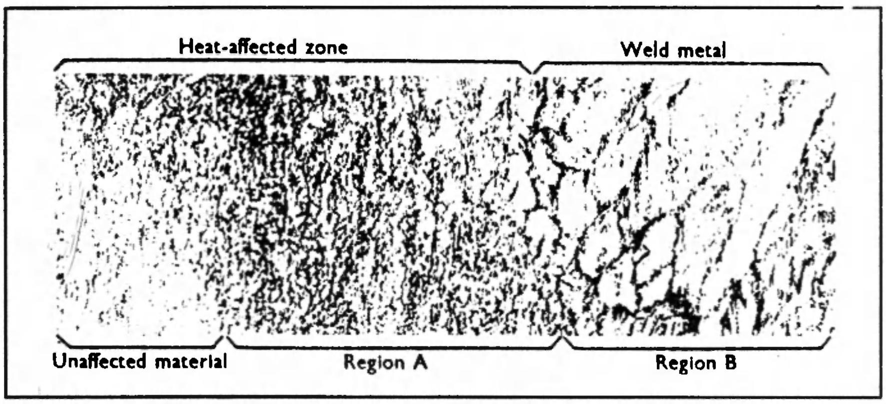

Fig 2 : Section of a fusion weld in a 17% chromium steel (X35) [3]

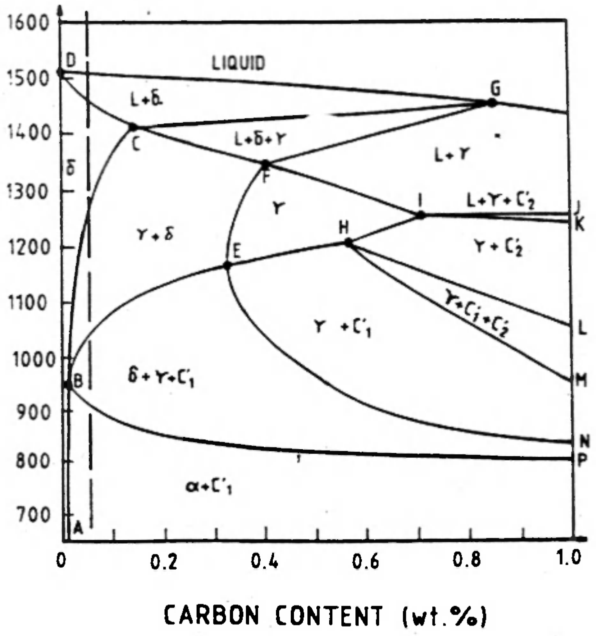

Fig 2 : Vertical section at 17% Chromium of the Fe-Cr-C Phase Diagram From Castro and De Cadenet (3)

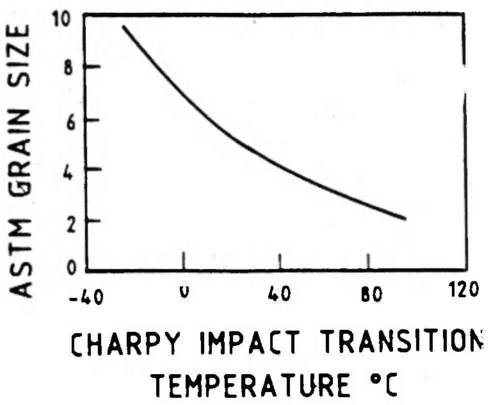

Fig 3 :Reduction of impact properties with Grain Growth in a Ferritic stainless Steel (6)

During multipass welding the HAZ experiances additional thermal cycles. Dissolution as well as precipitation may occur depending on temperature and time but the net effect usually are an increase in the austenite fraction and accumulation and growth of precipitates (12).

High weld heat inputs and high preheat and interpass temperatures promote. coarse grained weld deposits and heat effected zones. extend the width of the HAZ and encourage precipitation. These structural changes may affect adversely the properties of the weldment. On the other hand, very low heatinputs tend to rapid cooling which restrict grain growth and precipitation effects. However, the fast cooling suppresses the delta-gama transformation and the consequent reduction in austenite content may also be undesirable in many respects.

Welding Metallurgy

Most ferritic stainless steels have compositions that ensure a ductile ferritic structure at room temperature. Variations in composition within the standard composition limits can result in the formation of small amounts of austenite during heating to elevated temperatures, on cooling, the austenite transforms to martensite, thus embrittling the weldments by its presence at the grain boundaries (4).

Unlike martensitic steels, the ferritic stainless steels are not hardenable and during welding therefore do not require a high degree of preheat (4) Successful utilization of ferritic stainless steels over a wide range of engineering technologies largely depends upon the response of the steel to welding. There are several weldability issues critical to successful implementation of these steels in welded structure, which include;

- Grain coarsening and subsequent loss of toughness
- Sensitization
- Notch sensitivity
- Embrittlement
- Formation of sigma phase
- Susceptibility to hot cracking.

Grain Coarsening

In many ferritic stainless steels grain growth is rapid. Due to the greater atomic mobility in ferritic structures, they show more rapid grain growth and lower grain coarsening temperatures than to the austenitic stainless steels (5)

During welding owing to the heat of welding the single phase ferritic structure coarsens in the HAZ. The extent of grain coarsening is dependent on the time and temperature to which the base material was exposed during welding. The thermal conductivity of ferritic stainless steels is only half that of carbon steels but higher than austenitic grades. Hence large heatinput, excessive heating during welding are not preferred for this material. Figure 3 shows the reduction of impact transition properties with increasing grain size (6). The higher

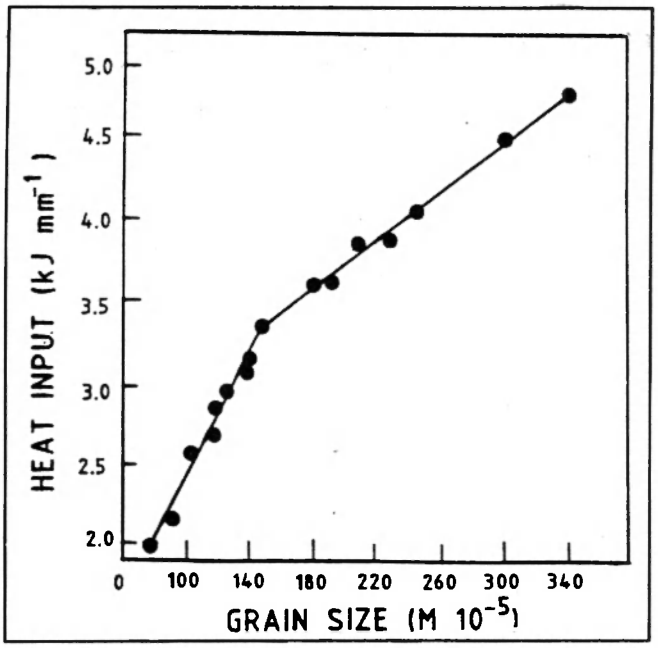

Fig 4 : Effect of heat input on the Grain Growth of a ferritic steel [10]

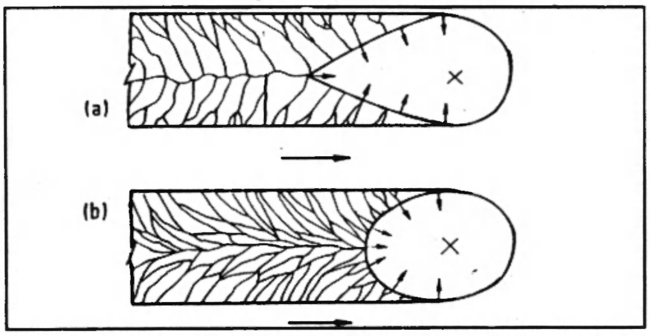

Fig 5 : Effect of pool shapes on solidification sturcture and segregation.
Columnar development in :

a) Tear-shaped weld pool. Arrows show almost invariant direction of maximum thermal gradient with early elimination of unfavourably oriented grains. Few columnar grains survives and centreline segregation occurs.
b) Elliptical weld pool; progressive change in direction of maximum thermal gradient survival of more columnar grains and segregation is spread across weld metal [18]

Table 3 : Effect of Alloying Elements in ferritic Stainless Steels

Element	Effects
Aluminium	Ferrite former Scaling resistance Grain refiner Improves electrical properties
Columbium	Carbide former Ferritic stabilizer Makes steel less susceptible Makes steel less susceptible to high temperature embrittlement improves corrosion resistance
Molybdenum	Ferrite former, suppresses austenite formation Improves corrosion resistance improves weldability
Nitrogen	Grain refiner Austenite former
Phosphorus	Improves weldability At specific levels improves toughness produces hot shortness at high levels Reduces corrosion resistance
Silicon	Ferrite former High Si content produce large grain size
Sulphur	Improves free machining characteristics
Titanium	Grain refiner Ferrite former
Tungsten	Grain refinement greater affinity to C,N.

heatinput employed the larger will be the grain size and the lower the impact performance. The grain growth in both weld bead and HAZ is restricted by addition of niobium or titanium (7,8 & 9), grain growth is restricted by the production of carbo-nitrides which pin the grain boundaries, these precipitates are however, resoluble, if the diffusion parameters (time & temp) are extended (10). In the welding context this means that heat inputs must be minimized and kept below about 3kJ/mm so that precipitation dissolution does not occur and grain growth does not become extreme see figure (4).

It has also been suggested that nitrogen in the shielding gas can refine the weld metal grain size by the formation of nitride (11).

Sensitization

The sensitizing range for ferritic steels lies above 925°C. Because of their high sensitizing temperature ramge, the weld decay in ferritic stainless steels occurs at the area immediately adjacent to the weld metal rather than some distance away as in the case of austenitic stainless steels. Furthermore, unlike the case of austenitic stainless steels, lowering the carbon content is not very effective in preventing the weld decay in ferritic stainless steels. Since the diffusion rates of carbon and chromium are much higher in b.c.c (ferrite) than in f.c.c(austenitic lattice, the rapid cooling from above 925°C during welding does not really suppress the precipitation of chromium carbide at the grain boundaries of ferritic stainless steels. For the some reason, lowering the carbon content does not effectively prevent chromium carbide from precipitating unless the carbon content is extremely low (e.g. 0.002% in 446 stainless steel). According to Uhlig (11) post annealing at 650 to 815°C encourages the diffusion of chromium atmos to the chromium depleted region adjacent to chromium carbide precipitates, and thus helps reestablish a uniform chromium composition, consequently the HAZ is resistant to intergranular corrosion.(12)

Notch Sensitivity

The notch sensitivity of these steels is affected by temperature in a manner similar to that of carbon and alloy steels i.e, they exhibit ductile to brittle transition temperature. The ductile-brittle transition for ferritic stainless steels is well above room temperature also with higher percentage of chromium the material becomes brittle. Therefore, the ferritic stainless steels are used normally on elevated temperature applications. However, the grain-size plays an important role in determining the ductile brittle transition temperature. Here again the grain coarsening leads to an increase of transition temperature. In these alloys an improvement in the transition temperature is most readily achieved by way of decrease in the interstitial content (C + N) and secondly, by a decrease in grain size (13,14), careful welding practice is necessary with respect to welding process, welding consumable, welding procedure etc., to avoid notch sensitivity.

Embrittlement

Ferritic stainless steels are prone to embrittlement due to the formation of super lattice of iron & chromium which is rich in chromium contents. This is proposed to be due to the miscibility in the Fe-Cr system leads to sphenoidal decomposition (14,15).

Normally in welding FS steels, this embrittlement does not occur unless the material is exposed in this temperature range for long periods such as in welds of thicker plates.

Formation of Sigma Phase

Sigma phase is hard, brittle intermetallic compound. Sigma phase has deleterious effects on ductility and toughness. The occurance of sigma phase is only when the stainless steel is exposed for very long periods in the temperature range of 540-815°C (12,15 & 24). The alloy content, the time of exposure decide the temperature range at which considerable amount of sigma is precipitated. Normally in welding this phase does not form but prolonged heat treatments and slow cooling in this temperature range can cause the formation of a sigma phase.

Hot Cracking

Solidification hot cracking in austenitic stainless steels during welding has been the subject of numerous investigations (15 & 16) However, because of their generally inferior weldability, the suspectibility of ferritic stainless steels to solidification hot cracking has not been examined in detail. A number of theories have been proposed to explain the existence of the hot cracking phenomenon. In essence, solidification cracking takes place because of the existence of residual liquid films between the solidifying units

Table 4 : Electrodes for ferritic stainless steels

Electrode classification	Grades welded
E 430	405, 446, 430, 405
E 309/E310	405, 430, 430F, 430F(sc)., 446 and their joints with mild steel.

Table 5 : Typical Heat-Inputs of Various Welding Process

Welding process	Heatinput KJ/mm
Manual GTAW	3.0
Automatic GTAW	1.0
Plasma	2.1
Electron beam	0.28

such that weld cannot accommodate the imposed cooling strains.

Because cracking is associated with residual liquid films, considerable attention should be paid to elements causing a wide freezing range such as p.s etc., (16).

Susceptibility to solidification cracking is widely held to increase at high heat input (17). In general this view point is valid. Welds of similar composition can be deposited using SMAW and gas metal arc (GMA) process at closely comparable heat inputs, but cracking tends to be more pronounced with later process. This process dependance of cracking stems from the influence of pool shape. If deposition condition are such as to cause a teardrop shaped pool, the growth of columnar grains during solidification occur as in Fig 5a(18). This results in marked centre line segregation of solute material and the final metal to solidify may contain such a high concentration of deleterious elements that the ferrite present can not suppress cracking. In contrast development of the columnar structure in an elliptical pool as in figure 5b, results in segregation of solute elements during solidification being more spread out, and the risk of cracking is diminished.

Tear drop shaped pools are most likely with high travel speeds as commonly found with GMA welding. This SMA process will normally gives an elliptical pool. With concomitant lower cracking, table 2, gives representative welding conditions for various processes, covering the arc energy range encountered in normal fabrication.

Joint geometry affects cracking behaviour by influencing the solidification pattern. Root runs are deep penetration passes, are especially prove to the problem as heat extraction takes place in two dimensions promoting centre line segregation. In multipass welding solidification cracking can also occur if the passes are too wide and concave. This is illustrated in figure 6(19). Deep and narrow welds can be rather susceptible to weld centre line cracking owing to the steep angle of abutment between columnar grains growing from opposite sides of the weld pool. This is illustrated in figure.7 (19).

At present, the effect and control of restraint are best handled by experiance. Broad guidelines can be proposed (20) such as thick meterial being more likely to give cracking than thin steel, fillet welds potentially being worse than but welds etc. but restraint cannot yet be adequately quantified in terms of cracking behaviour.

Effect of Alloying Additions

Table : 3 Shows the various alloy additions made to ferritic steels and their relavent effects.

Welding Consumable

Consumable for the welding of ferritic stainless steels can be of the same composition as the parent metal or of an austenitic type. To some degree choice of consumable type depends on the intended use. Austenitic consumable may be preferred to improve weld toughness, but these may not fully match parent steel corrosion resistance. The major advantage of welds made from ferritic electrodes is that their coefficient of expansion is similar to that of the ferritic stainless parent metal. This is of particular importance in service applications in which the welded components experiences constant or even occasional cooling cycles (thermal fatigue).

If the use of an austenitic filler metal is not desirable from the corrosion stand point (particularly stress corrosion), the joint can be buttered with an austenitic filler metal and then a ferritic filler metal used for the top layer.

Problems can be encountered with austenitic filler materials due to difference in expansion between ferritic and austenite may cause high stress during repeated heating and cooling cycles and ultimately tend to failure in the weld join. However, in actual practice, failures between austenitic and ferritic stainless steels are very rarely caused by the difference in coefficient of expansion. The relatively low yield strength of the austenitic weld bead minimizes the chance that a sufficient concentration of stress will develop in areas adjacent to the ferrite or the brittle martensite zone of the parent metal. Thus the soft austenite acts as a cushion or spring to distribute the stress uniformly. Only in cases where a great many heat cycles (thermal fatigue) are experienced by the dissimilar-metal joint have failures been caused by the difference in coefficients of expansion. (4,21)

For weldments that are to be annealed after welding, the use of austenitic filler metal can introduce several problems. The normal range of annealing temperature for ferritic stainless steels falls within the sensitizing temperature range for austenitic steels. Consequently, unless the

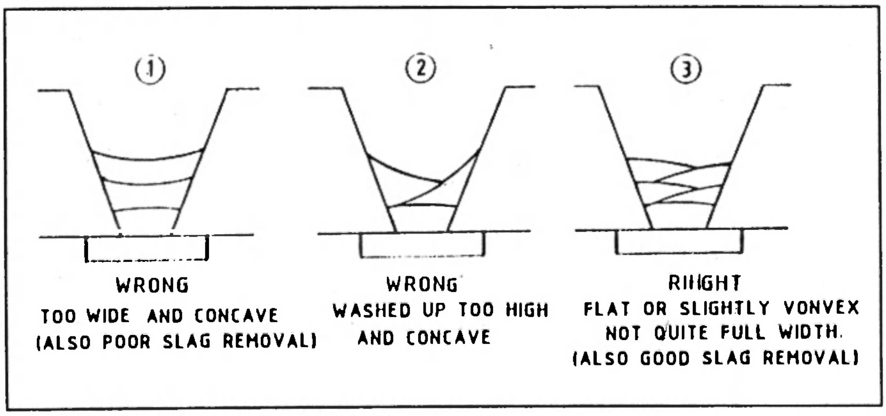

Fig 6 : Effect of weld bead shape on solidification cracking in multipass weld (17) austenitic weldmetal is of extra carbon content or is stabilized with niobium or titanium, its corrosion resistance may seriously impaired.

If the annealing treatment is intended to relief residual stress in the weldment, it cannot be fully effective because of difference in the coefficients of thermal expansion of the weldmetal and the base metal. These steels are particularly sensitivity to hydrogen embrittlement in the heat affected zone (HAZ) of the parent metal, where lattice imperfections and precipitated carbides can form trapping sites for hydrogen. The use of austenitic stainless steel consumable reduce the susceptibility to hydrogen cracking, because hydrogen has higher solubility and lower diffusivity in austenite than ferrite (16,22). Therefore hydrogen tends to remain in the weldmetal rather than diffuse into the HAZ and cause cracking.

Apart from these two, use of nickel alloy electrodes and semiferritic electrodes are also used . The nickel electrodes have the same features like austenitic stainless steel electrodes, but however, their coefficient of thermal expansion and contraction on which decided the residual stress and distortion is less but however costly. Semi ferritic electrodes similar thermal expansion and contraction & better ductility and toughness compared to the ferritic stainless steels.

A judicious choice of the welding consumable is necessary keeping in mind the job requirements and the easiness of producing a sound weld. Table 4 shows the electrodes for various stainless steels.

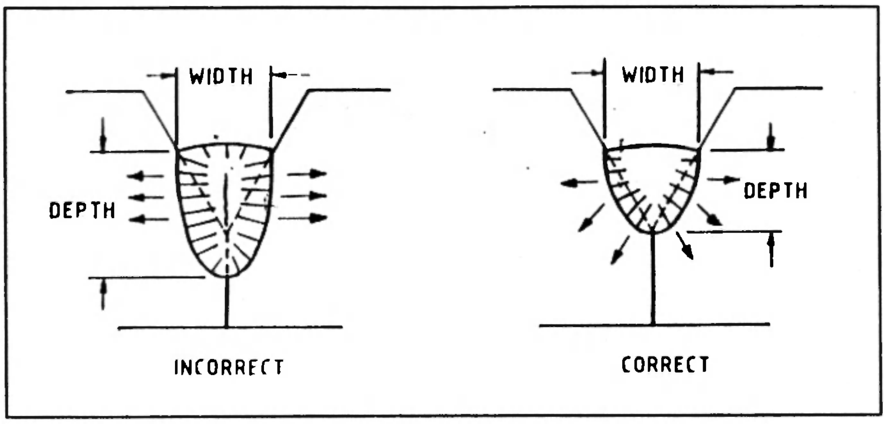

Fig 7 : Effect of weld width to depth ratio on centreline cracking [17]

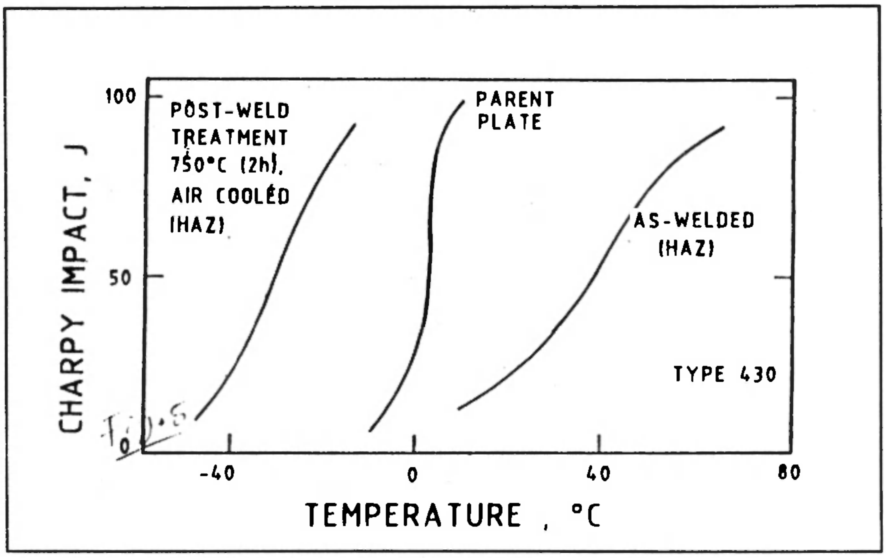

Fig 8 : Effect of post-weld annealing on impact properties of 17%Cr steel (Pickering [6])

Selection of Welding processes

Ferritic stainless steels require more care in welding than austenitic stainless steels. Because of their pronounced susceptibility to grain growth, the lowest possible heatinput is particularly important to minimize the HAZ and thereby the possibility of grain growth and reduction in notch sensitivity. The welding process has an effect upon the mechanical properties of steel welds because of determines the width of the HAZ. The welding process also influences the cooling rate and hence affects the time during which grain coarsening can occur, and the amount of austenite formed in the HAZ and weldmetal.

For the above reasons, the selection of the welding process should be based on the heatinput and thickness of the parent metal. Typical heat input of the various welding processes are listed in Table 5.

Shielded metal arc welding (SMAW) is more popularly used while the gas shielded process like gas tungsten arc (GTAW) welding, gas metal arc welding (GMAW) process are used for welding of extra low interstitial grades of ferritic stainless steels. GMAW, flux cored, submerged arc welding process are characterized by the potential high heatinput. If coarse grain size is concern, heatinput must controlled through higher travels lower interpass temperature and the use of heat sinks.(4,21)

The short circuiting metal transfer of GMAW process is advantageous because it produce relatively low heat input, that tends to limit grain growth in the heat affected zone.

In the gas shielded process, it is preferable to employ pure argon for gas tungsten arc welding and argon with 1% oxygen for MIG welding. Flux shielded processes deposit weldmetals which can contain oxide and slag particles that reduce toughness and also probably impair corrosion resistance. While the toughness could be improved by selection of basic rather than acidic fluxes. The more recent plasma and electron beam, pulsed arc welding process are particularly suitable for the fully ferritic high chromium alloys because of high heat density, narrow HAZ (1)

Where the geometry of the component and design permit it is worth to consider solidphase welding such as friction welding this has the advantage of small grain size (10 to 15 mm) because of the heavy working that interface undergoes during friction as well as forging stages of the welding process in addition as the process does not involve melting defects associated with melting and solidification are absent in this process.

Conventional techniques of joint preparation cleaning, fit up and welding are applicable to ferritic stainless steels also (23).

Post weld Heat-Treatment

If appropriate filler metals and welding procedure are used, the properties of as welded joints are usually advantage for most purposes, Nevertheless, for thick-sections, heavy restraint joints and those likely to encounter severly corrosive environments in service, a post weld heat treatments may be necessary. For improving stress corrosion resistance and for dimensional stability, a stress receiving heat treatment may be appropriate. It must be remembered, however, that the ferritic stainless steels are susceptible to embrittlement 475°C(precipitation of alpha prima) and if heated in the temperature range 580 - 815°C. It may also be embrittled by formation of sigma phase. A heat treatment of 600°C or slightly less than 600°C followed by rapid cooling eliminated 475°C embrittlement. Dissolution of sigma phase is possibly by solution annealing heat treatment at 870°C. Post weld annealing can alleviate the martensite embrittlement by tempering figure 8 (11), but can not refine the ferrite grain size.

CONCLUSIONS

Current understanding of welding behaviour of ferritic stainless steels is reviewed in detail. Achievement of satisfactory weld joints is critically dependent on the development of reliable welding procedures. A knowledge of the various phenomena that occur during welding of these materials will be of immense help in producing a sound joint, which will perform satisfactorily in service. Choices exist for selection of welding consumable, welding processes based on the service requirements. This article has aimed to elucidate intricacies involved in the welding of ferritic stainless steels. Methods to overcome the same. It is felt that much more to be done to understand the problems and enable the usage of the material for a wide range of applications.

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