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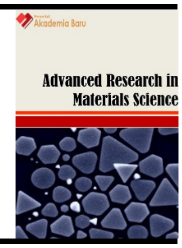

Effect of welding phenomenon on the microstructure and mechanical properties of ferritic stainless steel - A review

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ABSTRACT

Ferritic stainless steel comprised with ferrite and less nickel shows its strength and resistance to stress corrosion in many violent environments based on exceptional functioning over the last many years, attracting a great attention for researchers, manufacturers and end users. The current worldwide prompt growth, requirement, and consumption of ferritic stainless steels, particularly in petrochemical, marine, power plant and other engineering applications, where the nickel free steels are being consumed that require welding for fabrication of components. Main production and applications sectors are increasingly captured by ferritic stainless steels worldwide as the Ni price unpredictability breaching the backbone of producers and end users. Although ferritic stainless steel gain considerable popularity as compared to austenitic steel due to low cost and good stress corrosion cracking along with other mechanical properties in wrought condition, but it too, has some weldability issues. Some issues, that reported repeatedly, are grain growth, embrittlement, grain bundies carbides and sigma phase etc. Due to such problems, mechanical properties like toughness, ductility, high temperature strength and corrosion resistance is seriously affected. Joining of ferritic alloys is a challenging, due to number of embrittling precipitates and metallurgical changes. Moreover, incorrect welding conditions, imbalance phase ratio of ferritic/martensitic leads to solidification cracking, corrosion susceptibility, and increased brittleness. As the requirement for higher efficiency is increasing globally in many spheres like oil pipeline, shipbuilding sectors etc., where the thick sections are used, which approves the necessity of greater heat input, optimization of interpass temperature, cooling rate, proper selection of consumables, defect free joints for fast and rapid productivity. However, numerous progressive techniques like plasma, laser, PCGTAW, A-TIG and hybrid welding techniques are developing to fulfil the necessities for increased productivity without distortion. This review paper systematically highlights the effect of welding processes and conditions on microstructure and mechanical properties of ferritic stainless steels.

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1. Introduction

Stainless steel is noteworthy for its corrosion resistance, and it is extensively used for food handling and cutlery among many other applications. Stainless steel does not readily corrode, rust or stain with water as ordinary steel does. However, it is not fully stain-proof in low-oxygen, high-salinity, or poor air-circulation environments. Stainless steel are iron base alloys with minimum chromium content 10.5% and carbon normally from 0.03% to 0.12%. Other alloying element in addition to Cr and Ni, such as molybdenum, manganese, silicon, niobium, sulpher, phosphorus, and titanium are added to improve other properties like machining, mechanical properties and weldability [1-3].

Ferritic stainless steel is considered important type in the family of stainless steel due to high strength, better ductility and good corrosion resistance in chloride, acidic and petrochemical and nuclear power industries [4, 5]. Low thermal expansion, high heat conduction and resistance to stress corrosion are some important characteristics for ferritic stainless steel. Ferritic steel when compared with their counterpart family of stainless steel such as austenitic type, it is found more suitable for commercial use due to lack of Nickel content, that's made it more economical [6]. The ferritic stainless steel is Ferrous Chromium (Fe-Cr) base alloys with alloy elements chromium and carbon. Due to good machinability and formability it is used in fabrication work to convert to different useful products. The coefficient of thermal expansion of ferritic steel is low as compared to austenitic steel which make it more useful in high temperature environment [7, 8]. Apart from these, there are certain applications where nickel free stainless steel is required, making ferritic steel as a best alternative in such situations.

Although ferritic stainless steel gain considerable popularity as compared to austenitic steel due to low cost and good stress corrosion cracking and other mechanical properties in wrought condition but it too, has some weldability issues. Some issues, that reported recurrently, are grain growth, embrittlement, grain boundaries carbides and sigma phase etc. Due to such problems, mechanical properties like toughness, ductility, high temperature strength and corrosion resistance is seriously affected [8-18]. These difficulties have seriously affected the use of this economical material in many structures.

Many researchers have contributed enormously to improve the weldability of ferritic stainless steel. Some researchers worked on the welding processes to find optimize welding process for the improvement of metallurgical and mechanical properties [17]. Other reported the addition of interstitial elements to improve the grain size and precipitates [18-20]. To improve the weldability, many researchers work on the friction stir welding (FSW) along with tungsten inert gas welding (TIG) to decrease the heat input and improve the grain size, melting/solidification problem and cracking [7, 21-24].

The welding of stainless steel, specifically in ferritic steel has been the subject of researchers during past years. The present work is to critically analyze the findings of other researchers based on the welding conditions of ferritic stainless steel. These findings address issues in ferritic stainless steel, such as welding (grain growth, embrittlement and intergranular corrosion etc.), type of welding process (including arc welding, friction stir welding and resistance welding) and welding conditions (heat input, speed of welding, filler material, addition of extra elements and fluxes etc) that effect mechanical properties and corrosion resistance.

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2. Phase Formation in Ferritic Stainless Steels

Modification in microstructure features affects the properties and corrosion resistance, hence it is very important to control the microstructural changes during welding with the recommendation, that the final ferrite microstructure should be free from harmful phases like nitrides, carbides and inclusions etc. The microstructure of FSS at room temperature is mainly ferritic and martensitic, depending on the carbon content.

Iron chromium equilibrium phase diagram is the starting point for the description of stainless steel stability and chromium is one of the important element in these steels, as shown in figure 1.

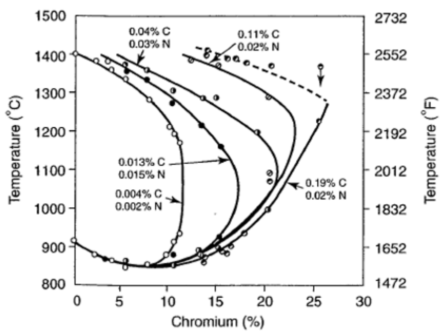

Fig. 1. Fe-Cr phase diagram [25]

There is a gamma loop from 912-1394 ºC with less than 12.7 % Cr, allowing steels (>12.7% Cr) to be fully ferritic at elevated temperatures. A low temperature, sigma phase is also present in Fe-Cr system [26]. The formation of sigma phase is very low speed process and required substantial time in the range of 600-800 ºC. Sigma phase has tetragonal and brittle structure [27-30]. There is also a low temperature phase at 475 °C called 475 °C embrittlement. This is due to chromium rich ferrite precipitate known as alpha prime α'. It form in the range of 400-540 °C and have severe embrittlement effect on alloys having greater than 14% Cr. [31, 32]

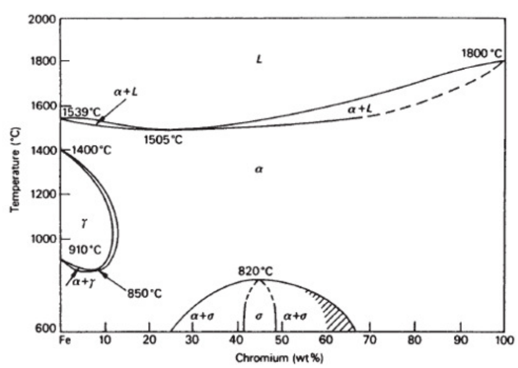

Fig. 2. Fe-Cr phase diagram[25]

The addition of carbon to the Fe-Cr alter the phase equilibrium significantly as shown in figure 2. The carbon is austenite promoter, as the carbon content increases the gamma loop becomes widen allowing austenite to be more stable at elevated temperature even in high chromium content. The addition of carbon is important for martensite formation at room temperature. For the ferritic grade the size of the gamma loop must be controlled such that little amount of austenite is form at elevated temperature [26]. The solidification transformation of fusion zone of ferritic stainless steel can follow different path depend on the alloying elements as shown in figure 3. The first and the simplest is the fully ferritic structure (L then L+F then F) carbon, medium Cr steel with addition of stabilizing elements (Nb, Ti) and high Cr steel where Chromium is highly dominant [33, 34]. Due to the absence of high temperature austenite the ferrite grain growth upon cooling from fusion zone is very high, especially in high heat input welding.

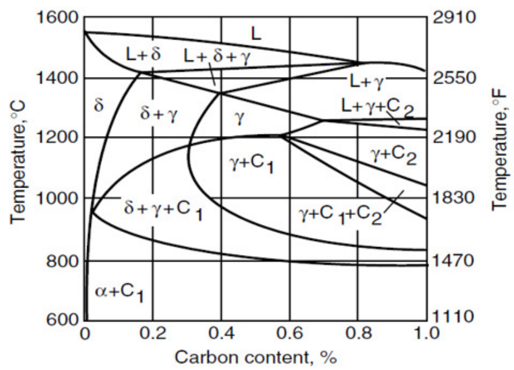

Fig. 3. 17% Cr pseudo-binary diagram [26]

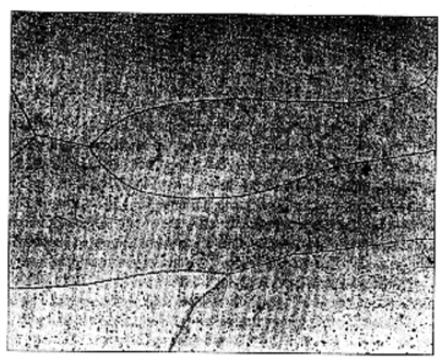

Fig. 4. Micrograph of GTA of AISI 409 [26]

Fig. 5. Microstructure of AISI 430 showing ferrite and intergranular martensitic features [26]

If martensite is present in the microstructure, then there are two transformation paths. The first is (L then L+F then F then F+A then F+M). On cooling some high temperature austenite form at the grain boundaries of ferrite. This austenite then transform to martensite upon cooling figure 5. This transformation occurs when the carbon content is within the range of 0.05 to 0.15% as shown in figure 3. With the increase of carbon content the austenite increases and the ferrite stability decreases. This is very important for grain growth because once the austenite form at the grain boundaries the grain growth stop. Austenite can also be formed at the end of solidification. At the start some austenite form at the grain boundaries and then at the time of solidification some austenite form because of some complicated eutectic reaction. This solidification path occur when the carbon content is above 0.15%. On solidification from fusion zone the initial ferrite content has large grain structure which is loss of ductility and toughness [7, 35, 36]. Ferritic stainless steel weld metal when cooled, form various precipitates with in the ferrite boundaries. These precipitates include Cr rich M23C6 and M23(CN)6 carbides and nitrides. These precipitates form inter and intra granularly depend upon the cooling rate. At high cooling rate intragranular and at low cooling rate intergranular precipitates are observed [37]. The type of precipitation influence the mechanical properties and corrosion resistance of FSS [38, 39]. The Cr-rich precipitates when formed at the ferrite boundaries create the chromium depletion region and cause sensitization. Various precipitates that encounter in ferritic stainless steel is tabulated in table 1.

Table 1
Different phases observed in FSS

Phase	Chemical formula	Structure	Temperature range °C	Ref.
Alpha (α)	-	bcc	-	
Gamma (ϒ)	-	fcc	-	
Alpha prime (α')	-	bcc	400-550 °C	[26,40]
Sigma (σ)	Fe-Cr	tetragonal	600-1000 °C	[41]
Carbide	M23 C6	fcc	600-950 °C	[26,40]
Carbide	M7C3		950-1050 °C	[42]
Nitride	CrN	Cubic	900-1000 °C	[42,43]

The prediction of the microstructures such as the ferrite and martensite content in the final solidified welded region is important for the evaluation of properties. The Schaeffler diagram (Fig. 6), published in 1949, has been widely used for approximating the ferrite content of stainless steel weld metals [44]. In this diagram the compositional limits of austenite, ferrite and martensite in term of nickel and chromium is plotted. Alternatively, the chromium equivalent or nickel equivalent can be determine for the required microstructure.

The schaeffler diagram is considered relatively inaccurate for predicting ferrite microstructure [26, 44]. Other diagrams such as DeLong and WRC 1992 is also used for predicting microstructure. Delong diagram is common for austenitic stainless steel. Balmforth diagram [45] is developed to predict the microstructure of ferritic and martensitic stainless steel shown in fig 6. In this diagram the alloy AISI 430 and 409 overlapped the ferrite and martensite region. And alloy AISI 439 which Ti stabilized is completely in ferritic region. This diagram shows that lower percentage of carbon (0.03%) AISI 409 has complete ferrite structure, but if carbon or nitrogen content increase it will shift to two phase region. Currently this diagram is most accurate for predicting the microstructure of ferritic stainless steel weld. It is to be noted that it is developed for specific composition range of alloy. It may be inaccurate for different alloy particularly (C less than 0.03% and Al+Ti exceed 1% by wt.) [26].

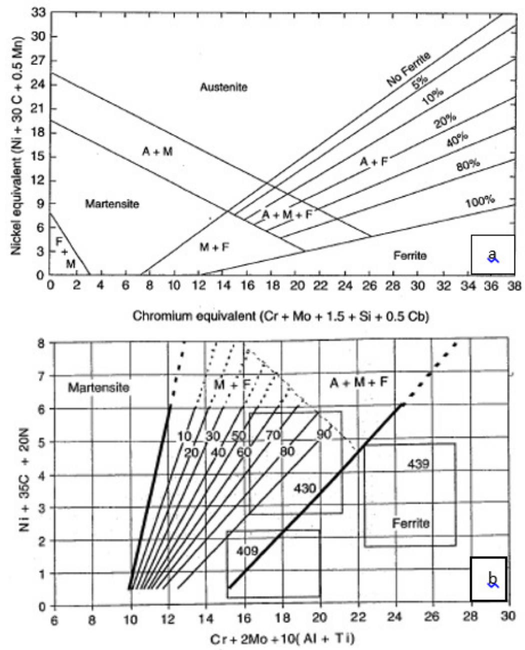

Fig. 6. (a) Shaeffler diagram (b) Balmforth diagram showing the microstructure prediction [26, 44]

3. Welding Behavior

3.1 Grain growth

Welding is generally used for joining of metals in engineering applications. Among the welding processes the fusion welding due to strong coalescence, feasibility and lower production cost is most widely used. However, the intense heat applied during fusion welding result microstructure changes in weld fool and heat effected zone (HAZ). The loss of mechanical properties due to fusion is very critical in ferritic stainless steel and hence limit its uses. Especially the loss of ductility and lower impact toughness is attributed to the columnar large grain structure in fusion zone [46, 47]. The amount of heat input in welding process also induce grain growth in HAZ and hence render mechanical properties [25, 35]. Therefore, a refined equiaxed grain structure is desirable in fusion welding materials in promoting good mechanical properties. The more the colonies of finer grains the better will be the mechanical properties of the weld [48]. Different methods are applied to overcome the grain growth and increase the quantity of equiaxed grains in welding fusion zone and HAZ area.

The major concern in industrial application is the loss of ductility and toughness due to intense heat input, which result grain coarsening. Several techniques in literature is reported for grain refinement in FSS. Anbazhagan and Nagalakshmi [49] reported the grain refinement on AISI 430 by using pulsed and non-pulsed gas tungsten arc welding (GTA) and shielded metal arc welding (SMA). They found that pulsed GTA present appreciable grain refinement leading to increase the ductility of about 60% as compared to SMA 40% improvement in ductility. The high ductility in pulse GTA is probably due to low heat input as compared to non-pulse GTA and SMA. Reddy and Meshram [50] work on the AISI 430 FSS for grain refinement using external alternating magnetic field. They observed that magnetic oscillation break the columnar structure to equaiaxed grain structure. They achieved superior strength in the weld as compared to the conventional welding. Villafuerte et al. [51] achieved grain refinement and hence mechanical properties in FSS by addition of Aluminum and Titanium. In this work the increased volume of equiaxed grain is favored by addition of both these elements and welding speed. But the increased fraction of equaxed grain could not be related to improved mechanical properties.

Another method for grain refinement is stabilization. Stabilized elements containing titanium, niobium or zirconium are added to form carbides, nitrides or carbonitrides tend to precipitate at high temperatures and may even form in the melting stage [52]. Mallaiah *et al*. [20] reported the effect of addition of grain refinement element titanium on the AISI 430 FSS using GTA. In this work they use titanium powder of 100µm mesh from 1g-3g and found that 2g Ti (0.7% by wt) in post weld annealed condition present improved mechanical properties. This improvement is attributed to the fine grain size of weld metal. Mohandas *et al*. [47] investigated the types of welding process, shielding gas and the addition of grain refinement elements on the tensile properties of AISI 430 FSS. They found that GTA present good equiaxed grain structure than SMA weld. Moreover, the addition of titanium and copper increased the tensile strength as compared to base metal but the ductility is generally low as compared to base metal.

From the literature survey, it can be concluded that the refined and equiaxed grain structure and hence improved mechanical properties can be attributed to low heat input during welding. This opinion is supported by the work of Sathiya *et al*. [53] friction stir welding (FSW) in which they achieved 95% properties of base metal. Similarly, Lakshminarayanan and Balasubramanian [54] reported strength comparison of FSW of AISI 409 FSS. This was due to the fine duplex structure of martensite ferrite in the weld microstructure resulted from the rapid cooling rate. Cerri and Leo [55] reported the same view that fine and equaxed grain structure in the FSW resulted the improved mechanical properties.

Amuda and Mridha [4] reported the effect of welding parameters (heat input and welding speed) and found that the grain morphologies alternates between the coarse columnar and equiaxed grain structure. This grain structure depends on the welding speed and hence heat input, and concluded that welding speed of 3.5 mm/s generally lead to equiaxed grain structure.

The grain morphologies alternates between columnar and equiaxed grains depending on the welding speed within a given current. However, welding speed of 3.5mm/s appears generally lead to the production of equiaxed grains. Reddy and Mohandas [56] reported that the addition of alloying element Ti, Al and Cu as controlling element for the heat input. They found that these elements when added in the weld acting as heat sink and controlling the heat input. Furthermore, these elements acting as nucleation sites and leading to equiaxed grain and hence improved mechanical properties. Amuda [57] reported the effect of two strategies including cryogenic cooling and elemental powder element addition in the welding using GTW process with many welding parameters. The two methods offer good grain refinement strategies however; the elemental powder addition have improved equiaxed grain structure. Further they concluded that cryogenic cooling produce good mechanical properties comparable to FSW (95% of the base metal).

The literature of grain refinement has been presented here. Grain refinement procedure include the welding conditions, alloying elements, cooling rates, stirring and oscillation to produce refined grain structure in FSS. Most of the work focused on the grain refinement but there is no clear correlation between grain size and mechanical properties except few researchers. Friction stir welding is more convenient method for mechanical properties enhancement which produce 95% properties of the base metal. Further the work of Amuda [5] also claimed the 95% properties using cryogenic cooling in GTA.

3.2 Intergranular Corrosion

The problem of grain coarsening in the ferritic stainless steel weld is the major problem which result the loss of ductility and toughness. Other than this susceptibility to intergranular corrosion due to chromium content depletion in the weldment HAZ and fusion zone is another major problem. This susceptibility to intergranular corrosion is termed as sensitization. Despite of attractive economic advantages and corrosion resistance in acidic and chloride environment these issues limit the use of this alloy. In the absence of nickel it is strong candidate to use in the chloride environment instead of costly austenitic stainless steel.

Sensitization is very sensitive to welding and then become the major cause of stress corrosion cracking [26, 58]. Several models for sensitization are reported but the depletion of chromium carbide is widely accepted. In this mechanism chromium rich carbide and/or nitrides are depleted in the grain boundaries which then susceptible to corrosion attack [26, 59]. When the chromium content become depleted beyond the concentration required for the corrosion resistance in stainless steel it become susceptible to inergranular corrosion. The depletion of chromium content is indicated by formation of chromium carbide in the form of M23C6 or M7C3 in intragranular and intergranular sites. This phenomenon occurred in the HAZ area and is major cause of stress corrosion cracking failures [60-62]. The mechanism of sensitization varies and categorized as (1) chromium depletion theory, (2) strain theory, (3) electrochemical theory, and (4) solute segregation theory. In all these theories, the chromium depletion theory is mostly accepted [62-65].

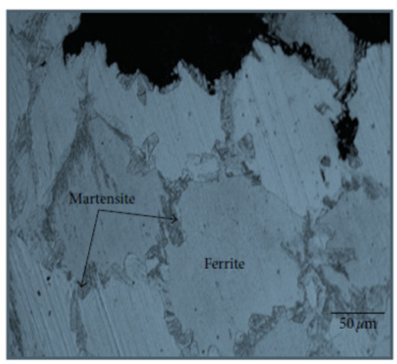

Fig. 7. Mode 2 sensitization [62]

There are four modes responsible for sensitization, these modes differentiate the depletion of chromium zones in the form of how and where will these zones will be formed. Mode 1 is related to the single pass of weld and linked to the untemperred martensite present in the parent material due to incorrect annealing [66, 67]. In mode 2 sensitization is caused by double pass welding, while in mode 1 due to untampered martensite shown in figure 7. It depends on weld configuration, weld sequence, and the joint geometry. Mode 2 sensitization has been observed in double fillet weld, double butt weld, weld repair and tacking [50].

Sensitization due high cooling rate at low heat input is termed as mod 3 sensitization. This type is independent of material conditions and previous treatment. Rapid cooling rate prevent austenite nucleation as the dual phase (α and γ) field gives rise to fully ferritic microstructure. Hence the solubility decreases at low temperature resulting ferrite structure fully saturated in carbon which ultimately increase the carbides at the grain boundaries. Mode 3 sensitization decreases when quantity of austenite increases as it absorbed maximum amount of carbon and chromium depleted region cannot formed [68]. Mode 3 type sensitization can be overcome by applying high heat input (not less than 0.5kj/mm) and material with large amount of austenite to promote austenite upon cooling [69]. The very less common type mode 4 sensitization occur at very slow cooling rate. This type occurs in a very narrow range between the high heat affected zone and low heat affected zones.

It can be inferred from the preceding discussion that heat cycle in the welding is very critical for the sensitization dynamics of ferritic stainless steel. This indicate that the heat cycle (heat input and cooling rate) is very important together with the material properties to produce high quality weld. A comprehensive detail of all sensitization modes can be found in [62].

Sensitization is intergranular corrosion phenomena during welding process which limit the use of ferritic stainless steel. It is important to overcome this issue. Several techniques are explored and practiced to prevent sensitization. These options include control of interstitial elements (C+N), creating a high ferrite number, stabilization and controlling the heat input and cooling rate.

Since sensitization is promoted due to consumption of chromium matrix by interstitial (C+N) elements. So the minimization of interstitial constituent is one method reported in literature. Due to very low solubility of carbon in BCC, ferrite carbide precipitation is hard to minimize. FSS containing interstitial constituents greater than 1000ppm has greater tendency to sensitization. And intergranular corrosion cannot be avoided even by rapid quenching. [26, 70] Optimize the ductility and sensitization by controlling the amount of (C+N) constituents and showed that for 19% Cr the amount of (C+N) must be limited to 60-80 ppm and for 35% Cr (C+N) must not exceed 250 ppm. It is also reported that the FSS having greater amount of carbon (0.07%) form large amount of martensite providing better resistance to sensitization [71]. The low amount of interstitial constituent may decrease the susceptibility but it may not be practical in ferritic stainless steel as they effect on the other properties. [72] Investigated ferritic stainless steel 430 and 444L for hot cracking and intergranular corrosion by analyzing the effect of C+N and stabilizing elements (Ti, Nb, Ta). They found that these steels with C+N content less than 0.04 % are not susceptible to IGC when stabilized with Ti with the relation Ti > 12.5(C+N) or Ta > 27.5 (C+N). They also reveal that the effect of these elements has no detrimental effect on the mechanical properties.

Other method to control sensitization is adjusting the ferrite factor introduced by Kaltenhauser [73]. The ferrite factor is the factor that determine the relative strength of austenite and ferrite in the weld microstructure. Kaltenhauser ferrite factor (KFF) is a number that determine the amount of martensite in the weld range from 13.5 for low chromium to 17 for high chromium steel. The high ferrite factor for a given alloy shows the large amount of ferrite with improved corrosion resistance due to the absence of intergranular carbides. The intergranular martensite induce the residual stresses in the grain boundaries leading to reduced toughness [66].

However recent development aimed to decrease the ferrite factor, thereby promote the austenite formation and hence maximizing martensite. And this produce significant grain refinement in the weld region [66]. From the literature, it is concluded that formation of martensite at the grain boundaries promote grain refinement and hence improved mechanical properties. Fully martensite after tempering induce improved mechanical properties and less susceptibility to corrosion. This is verified by [71, 74, 75] and reported that greater amount of austenite with same amount of chromium can lead to martensite and good corrosion resistance. Therefore by the suitable adjustment of austenite and interstiical constituent and hence KFF can reduce the sensitization.

The corrosion resistance can also be improved by addition of stabilizing elements such as titanium and niobium. These elements form stable carbides and resist to high temperature dissolution. Titanium or niobium or combination of both are used to prevent sensitization. However the use of titanium reduce the toughness and surface finish [62].

Some researchers study on 18Cr-2Mo and 26Cr-Mo ferritic stainless steel and proposed the minimum content of titanium as [76].

$$Ti = 0.2\% + 4 * (C + N) \tag{1}$$

where Ti is minimum content of titanium and C, N are concentration of Carbon and Nitrogen respectively. Fritz and Franson [77] proposed a new relation as follows:

$$Ti + Nb = 0.8\% + 8 * (C + N) \tag{2}$$

Where *Ti* and *Nb* are minimum content of titanium and Niobium and C, N are concentration of Carbon and Nitrogen respectively.

The sensitization in ferritic steel can also be suppressed by controlling the heat input and cooling rate during welding. The low heat input in ferritic steel result high cooling rate and can suppress the austenite formation producing fully ferritic microstructure. As the solubility of carbon in ferritic is very low therefore it supersaturated in carbon which produce large amount of carbide precipitates at the grain bounties [67]. The amount of carbon retained in the martensite depend on the cooling rate. Martensite with fast cooling rate retain high amount of carbon. In slow cooling rate the martensite is formed by carbon precipitate in austenite and less carbon is retained. Thus high heat input with slow cooling rate is necessary for the controlling of sensitization [62]. Although the amount of heat input and cooling rate is necessary for the sensitization control but it also depend on the interstitial constituent as discussed before. Base on the previous work heat input in the range of 0.5-1.5 kj/mm is recommended [58, 67].

In summary the sensitization in ferritic stainless steel during welding can be controlled in a number ways. The methods discussed are controlling the interstitial constituents (C+N), ferritic factor, addition of stabilization elements (Ti,Nb) and heat input and cooling rate. For welding, addition of stabilizing elements and heat input is the good options for sensitization control, provided that other factors of welding are optimized.

3.3 Embrittlement

Ferritic stainless steel is important family due to economic advantage over austenitic steel. These steels particularly the high Cr content have excellent corrosion resistance in many environments. Owing to advantages it have some limitations, particularly those with high Cr content where they have tendency to embrittlement.

Generally, there are three embrittlement phenomena which deteriorate the mechanical properties of ferritic stainless steel. These are high temperature embrittlement (HTE), 475 °C embrittlement and sigma phase embrittlement. The latter two are not normally the problems associated with welding ferritic stainless steel but due to long term exposure to high temperature during service. The intermediate temperature embrittlement of welded structures is insensitive to the welding processes of ferritic stainless steel but depend on engineering applications [26]. Both embrittlement phenomena are associated with high Cr content of base metal and filler material and post weld heat treatment.

3.3.1 475 °C embrittlement

(Fe-Cr) alloys having high Cr content (>15%) are severely embrittled when heated to temperature range of 428-550 °C. The 475 embrittlement is a result of formation of coherent precipitate due to the presence of miscibility gap in Fe-Cr system bellow 550 °C. Williams and Paxton [78] were the investigators to conclude that this embrittlement is the cause of α’ precipitates at temperature bellow 550 °C as shown in figure 8. At times this phenomena was related to the sigma phase.

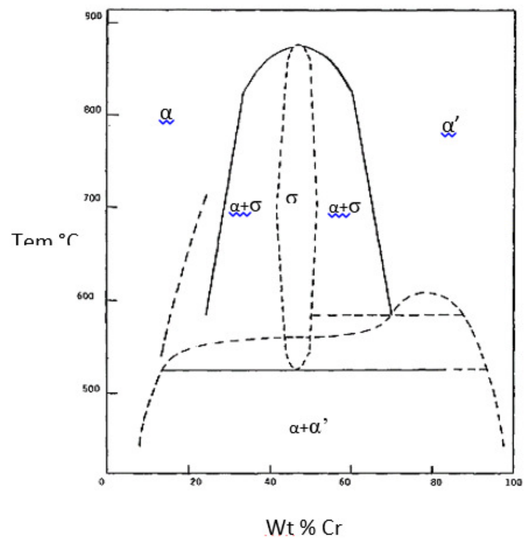

Fig. 8. Partial phase diagram of Fe-Cr system [79]

The alloys aged bellow 550 °C form Cr rich ferrite and called Alpha prime and iron rich ferrite called alpha. The alpha prime precipitate is nonmagnetic and have BCC structure with 61-83 % Cr [31, 32, 80]. It was found that at temperature 520 °C the sigma phase decompose eutectoidally into two solid solution namely α and α’ and was confirmed by [81, 82] through Mossbauer effect spectroscopy. [83] Present the atom probe method for the evaluation of 475 °C embrittlement. They found that at intermediate temperature in Fe-Cr alloys the major microstructure evaluation is α and α’ spinodal decomposition. [84] Studied the effect of alloy element (Ni, Mn and Cu) on the Fe-Cr alloys using mechanical properties and atom probe tomography for structure evaluation. They found that the addition of Ni and Mn accelerate the decomposition of ferrite during ageing at 500 °C for 10 hours. However, the addition of Cu have no effect on ferrite decomposition.

The 475 °C is intermediate temperature phenomena that limit the use of stainless steel and particularly ferritic stainless steel in high temperature environment. Therefore, extreme care should be taken especially for high Cr FSS in these environments.

3.3.2 High temperature embrittlement

High temperature embrittlement (HTE) is one of the most damaging phenomena to ferritic stainless steel associated with welding. HTE result the dramatic loss of ductility in ferritic stainless steel especially in the HAZ area. This form of embrittlement is a function of various parameters including composition and microstructure (interstitial elements C+N), grain size and chromium content etc. [26, 85].

The level of interstitial constituent particularly Carbon, Nitrogen and Oxygen greatly affect the HTE. At high temperature (welding) these elements present in the ferrite and austenite matrix. On cooling it form precipitates like Cr-rich-carbides, carbonitrdes and nitrides inter and intra-granularly. The intra-granular precipitates promote the loss of toughness while the other decrease the corrosion resistance as discussed in this document [59, 61, 86-88]. The effect of high temperature on the toughness with (C+N) is shown in figure 9. The N content above 0.02% wt. there is dramatic reduction in toughness.

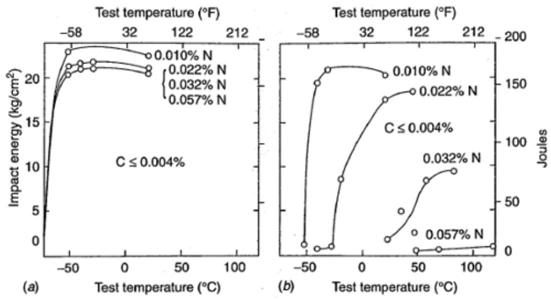

Fig. 9. Effect of high temperature on 17% Cr alloy with (C+N) level heat treated at (a) 815 °C and (b) 1150 °C [18]

The Cr-rich carbides and nitrides precipitates form when cooling from high temperature at the grain boundaries contribute to HTE [61, 89, 90]. Low Cr content is also insensitive to embrittlement. The cooling rate from high temperature also effect HTE but it depend on the interstitial composition [91]. From the literature, it appear that the C+N content is the most prominent reason of HTE and can be controlled by the interstitial content [26, 62, 92, 93]. The method to control the sensitization and hence high temperature embrittlement is already discussed in this document under the sensitization heading.

High temperature embrittlement is high temperature phenomena; the grain growth is also a factor that influence HTE. As discussed in this document the grain growth is associated with welding of FSS. Although the grain growth alone cannot influence the embrittlement but in combination with the C+N content it reduces the toughness dramatically. The work of [94] shown in figure 10 reveal the toughness as a function of C+N content and grain size.

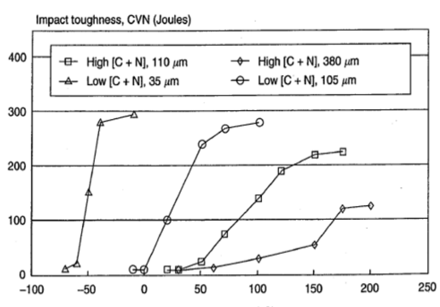

Fig. 10. Effect of grain size on the toughness of Fe-Cr [94]

High temperature embrittlement is due to various factors as discussed is summarize in table 2. The high level of interstitial element is most damaging and therefore care should be taken. Therefore most commercial alloys contains extremely low level of interstitials. At low level of interstitials however, the grain size is more important and even small amount of interstitial, large grain size result severe HTE. The phenomena of HTE is the consequences of different precipitates formation inter and intragranularly. The work of [89, 94] shows that HTE is damaging due to the formation of precipitates which restrict motion of dislocations. Since brittle fracture in material is due to transgranular so the intragranular precipitates will be more damaging to HTE. Other has also reveal that intragranular precipitates cause the initiation of cracks and cause HTE [95, 96]. The actual mechanism seems to result from both inter and intragranularly with intragranular precipitates is more dominant especially at high cooling rate [26, 67].

Table 2
Effect of composition and microstructure on HTE

Variable	HTE effect
C+N	Intensifies severely
Cr	intensifies
Grain size	Small for high C+N, large for high Cr and low C+N
Oxygen	Intensifies slightly

4. Welding Consumables

Ferritic stainless steel can be welded autogenously or using filler rod. Variety of filler rod can be used depend on the service conditions and properties required. Matching or near matching consumables or normally used which are compatible with the base metal. However, when matching filler is commercially not available then austenitic filler metal or high nickel filler alloy may be used depend on the service environment. Before selecting the welding consumables consideration should be given to mechanical properties as well as corrosion resistance required for application [26, 97]. The matching filler metal for common grades such as 409 and 430 are available in the form of solid wire, metal cored and flux cored. Due to the reactivity of titanium and aluminum and poor transfer of these elements across the arc the availability is limited to bare rod only. The common filler material used in welding FSS is listed in table 3.

Table 3
Recommended filler material for some FSS [97], [stainless steel welding guide lincoln electric]

Type of steel	Coated electrode	Solid metal core wire	Flux core wire
405	E410NiMo, E430	ER410NiMo, ER430	E410NiMoTX-X
409		ER409, AM363, EC409	E409TX-X
429		ER409Cb	
430	E430	ER430	E430TX-X
444	E316L	ER316L	
446	E446	ER446	

To overcome the poor weld ductility and toughness, austenitic stainless steel consumables are often used. The grain growth which is outmost problem of FSS welding is usually overcome (because of austenite and ferrite dual phase) in fusion zone but HAZ has their own ferritic large grain structure. But some time austenitic consumables are problematic e.g. thermal expansion cause cracking, sensitization and stresses due to thermal expansion [26, 98]. High nickel alloy welding consumables are also used for the welding of FSS especially for Group III FSS to each other, duplex stainless steel, 300 series austenitic steel and nickel base alloys. Nickel base filler metals (ENiCrFe-2, ENiCrMo- 3, ERNiCrMo-1, and ERNiCrMo-3) have excellent corrosion resistance as well as same thermal expansion to ferritic steel [99].

Welding methods reported in literature for FSS are tungsten inert gas welding (TIG), gas metal arc welding (GMAW), shielded metal arc welding (SMAW) and friction stir welding (FSW). [47] Studied the effect of TIG and SMAW on the AISI 430 using stabilized elements Ti and Cu and found that TIG welding shows superior properties as compared to SMAW. In addition, using the refining elements show better results in term of strength and ductility. The superior properties of TIG welding is due to low heat input during welding. These alloys are welded using low heat input to avoid grain coarsening [100]. FSW using polycrystalline cubic boron nitride (PCBN) tool was used for the welding of AISI 430 FSS by [101]. The welded microstructure and mechanical properties was found very fine, equi-axed ferrite grains were produced as required in welding. Similarly, TIG welding is also very good option for welding FSS to produce fine welds. Activated flux TIG welding was studied by [102] using SIO2 as flux and found that high penetration with good quality weld can be produce.

Limited study is available on the welding of FSS using different consumables and different welding processes. As previously discussed in this documents the low heat input is very feasible for the retardation of grain growth and sensitization. Therefore the low heat input welding processes like TIG and FSW is mostly used.

5. Present and Future Prospective

As the worldwide corrosion resistance and high strength materials prices are increasing day by day, the ferritic steel is a good alternative for the use in the chloride environment and many uranium enrichment plants. In these applications welding is the main process for the construction of engineering structures which degrade their properties. Therefore, special attention is required for the improvement of mechanical properties of FSS during welding which have still some issues.

Formation of undesirable precipitates, grain morphologies, residual stresses in multi pass welding using arc welding processes (TIG, FSW,SMAS). While from the previous works it is shown that low energy welding processes is recommended but many applications require thick sections. Therefore, problem of incomplete penetration when joined by low energy processes. Sensitization is the main issue in FSS when welding multi pass as well as single pass depend on cooling rate, alloying elements and welding process.

Various studies has been conducted on the welding of ferritic stainless steel in term of grain refinement, intergranular corrosion and brittleness. Mechanical properties are extremely effected due to these variations in microstructure. In the previous research work the microstructural features are at some extant correlated to the mechanical properties. Similarly the welding processes FSW, TIG welding and SAW together with fluxes are used for low heat input to overcome the grain growth and intergranular corrosion. But more study is required on the welding processes, filler material and fluxes in term of overall mechanical properties improvement. Research has been done in the welding parameters independently for improving the weldability. But systematic study is required on the welding parameters like welding speed, current, welding process and addition of stabilizing elements. Limited work is reported on the welding parameters optimization. The well-known quality improvement tool design of experiment (DOE), used in many engineering applications can be effectively utilized for weldability issues. Particularly the interstitial contents and the cooling rate are very sensitive to the sensitization and hence brittlement and corrosion. And there is critical cooling rate and interstitial content exist over which sensitization can occur.

6. Conclusion

An overview of welding effects on ferritic stainless steel has been provided. These effects can be divided into: grain size enlargement, intergranular corrosion (sensitization) and embrittlement.

Grain refinement include the optimization of welding conditions, alloying elements, cooling rates, stirring and oscillation to produce refined grain structure in FSS. Low heat input welding FSW and GTA and the addition of stabilizing elements are effective methods to refine the grain size. FSW is more convenient method for mechanical properties enhancement which produce 95% properties of the base metal. Further the work of M.O.H. Amuda, S. Mridha also claimed the 95% properties using cryogenic cooling in GTA.

Sensitization is the phenomena that reduce the corrosion resistance and induce cracking. The chromium depletion theory is most popular in promoting sensitization. The sensitization in ferritic stainless steel during welding can be controlled in a number ways. The methods discussed are controlling the interstitial constituents (C+N), ferritic factor, addition of stabilization elements (Ti,Nb) and heat input and cooling rate.

Embrittlement is the most prominent effect of FSS welding. Different embrittlement phenomenon include sigma phase embrittlement, 475 ºC embrittlement and high temperature embrittlement. The former two are more related to functional environment but their control is very necessary. High temperature embrittlement is the brittleness induce due to inter and intragranular formation of carbide and nitride precipitates. The main reasons of HTE are grain size, interstitial and chromium content. Sensitizing control procedures are also applicable in HTE.

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