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Grain Refinement in Ferritic Stainless Steel Welds: The Journey so Far

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Abstract. The ferritic stainless steel is a low cost alternative to the most often adopted austenitic stainless steel due to its higher strength, better ductility and superior corrosion resistance in caustic and chloride environments. However, the application of ferritic steel is limited because of poor ductility and notch impact toughness of its weld section with differential grain structures. Several techniques have been explored to control the grain features of the weld to minimize these problems. In the present effort, a review of these options in relation to the degree of grain refinement in ferritic stainless steel weld is conducted in order to have a better understanding about the grain refining phenomenon in the weld microstructure. So far, the most effective technique is found to be the pulse AC TIG welding which can produce weld with mechanical properties equivalent to 65% to those of the base metal. The refinement in this process occurred through dendrite fragmentation and grain detachment in the weld pool producing small-grained microstructures with a large fraction of equiaxed grains. However, in friction welding process where heat input and heat transfer are effectively controlled, the strength can be as high as 95% of the parent metal. This suggests that the total energy input for welding and heat transfer phenomenon mainly control the development of microstructural feature in the weld pool and hence the strength.

Introduction

Stainless steels are important class of engineering materials developed for applications, especially in corrosive environments; these steels are corrosion resistant because of the formation of a thin tenacious oxide layer [1]. Typical application areas include exhaust gas emissions control systems for vehicles [2], lower temperature segments of boilers and piping in power generating plant, heat exchangers tubing for moisture separator in light water reactors [3], nuclear reactor, pressure vessel application [4], transport, agriculture and mining [5]. The application area is in exhaustive. Among several types of stainless steels, austenitic grade is the most popular of all the classes, however, it is relatively expensive. The ferritic grade is less costly compared to austenitic grade and it offers better strength to weight ratio and enhanced corrosion resistance. The ferritic grade steels contain very low or no nickel and hence they are cheaper compared to the austenitic grade steels which contain high percentage of costly nickel. This is of great concern to industries, particularly when there is growing deficit of nickel bearing raw material in the market.

Welding is generally used for the fabrication and joining of engineering components. Among the welding processes, fusion welding, due to its flexibility, lower production cost and ability to provide strong metallic joint, is the most prominent and widely used process [6]. However, the intense heat applied in fusion welding creates metallurgical and physical in-homogeneity in the melt pool leading to different properties in the weld section. This scenario is true for welded section of almost all materials. For instance, after long time exposure to an elevated temperature in the range 482-871^{0}C, austenitic stainless steel experiences sensitization [7, 8]. This is due to the formation of

chromium carbide at the austenite grain boundaries via the depletion of chromium level in the matrix to below the concentration necessary to maintain passivation leading to the well-known intergranular corrosion. Besides, austenitic stainless steels possess low thermal conductivity and high thermal expansion resulting in higher distortion when welded with the other grades [9]. Inspite of these problems, the austenitic grade is still considered weldable [10]. Ferritic stainless steel weld suffers poor ductility leading to low notch impact toughness, susceptibility to intergranular corrosion due to the formation of intermetallic sigma phase particularly in the high chromium series and ductile –brittle transition phenomenon [11]. However, the loss in mechanical properties due to fusion heat is acute in ferritic stainless steel welds and hence limits the service areas.

The poor ductility and low notch impact toughness of welds have been attributed to the microstructure, especially the grain structure of the weld section. This is probably caused by the normal weld pool solidification, which permits the development of columnar grains in the re-solidified weld zone and large grain structure in the HAZ. Several welding techniques have been explored to control these grain characteristics in order to improve the strength and ductility of the weld. Some of the options applied in this exercise are electromagnetic stirring, AC/DC continuous welding, AC/DC pulse welding, low heat input welding, addition of metal powders (titanium, aluminum, copper) and liquid metal chilling.

In this paper, a review of these options in relation to the degree of grain refinement generated in ferritic stainless steel weld is presented in order to have a better understanding about the development of microstructure in the weld pool.

Solidification of Welds. In welding, the solidification process does commence from the parent metal partially -molten zone requiring minimum degree of undercooling [12]. For this solidification, it does not require any nucleation event leading to the well-known epitaxial growth. It produces columnar grain structure with a preferred orientation. This is the normal solidification sequence and causes a serious deleterious effect on certain mechanical properties of the weld. Columnar grain is, therefore, not desirable in the welds of most metals [13]. The extent of the welding heat also induces grain growth in the HAZ leading to very poor mechanical properties of the weld [14, 15]. Thus, a refined equiaxed structure is most desirable in fusion-welded materials in promoting good mechanical properties [16]. The more the colonies of small sized equiaxed grains the better the mechanical properties of the weld. Different methods have been adopted to increase the volume of the equiaxed grains in the weld structure. These options are discussed in sections below

Influence of Welding Parameters. Energy input and welding speed play important roles in the modification of weld microstructures and thus the mechanical properties. It is suggested that heat input is the most important factor to control the grain morphology in fusion weld [17-20]. Large heat input has been reported[17] not only to promote the formation of columnar grains in the fusion zone but also cause grain coarsening in the HAZ due to longer thermal cycle and lower cooling rate; this produces a weld of poor mechanical property particularly the notch impact toughness [18]. This is because the large heat input generates wider weld pool with the attendant complex solidification structure. Submerged arc welding and electro-slag welding generally apply large heat input. So low heat input welding techniques such as TIG and MIG are being explored for grain refinement investigation. The solidification morphologies of these low heat input welds could be readily regulated. The controlling parameters in heat input are the arc current and the transverse speed. It is therefore desirable to quantify the change in grain size with current and welding speed. However, not much information is available in literature on the effects of current and speed on grain refinement. Meanwhile, too much low a heat input condition (less than 31j/mm) has been reported to be insufficient to produce complete penetration [21]. The hypothesis of low heat input in friction welding for grain refinement is supported by the work of Sathiya et al [22] in which tensile strength in the region of 95 percent of the base metal is achieved in the weld joint of a friction welded

material. The quantum of heat delivered to friction weld is quite low compared to that delivered in TIG welding. The heat in friction welding is not enough to cause melting of the metal but the joining is ensured by macroscopic diffusion supported by plastic deformation. However, literature is scarce on what quantum of heat energy input can be classified as low as far as the welding of stainless steel is concerned. Thus, the effect of different level of low heat input on grain refinement of stainless steel weld is yet to be investigated. However, Yu et al [23] in 2008 reported that grain refinement is possible in the HAZ of HSLA steel by large heat input welding. It is presumed that this refinement is not be due to the large heat input welding but due to the presence of other alloying elements that acted as nucleation sites for the development of equiaxed grains.

While literature is scarce on the influence of welding current on grain size, a lot has been reported on the effect of welding speed on grain refinement. Villafuerte et al [24], Villafuerte and Kerr [25] and Clarke et al [26] reported the influence of welding speed on grain refinement in ferritic stainless steel using a constant welding current of 110A. They produced weld with 3, 8 and 14 mm/s speeds. In these works, grain refinement was assessed by the fraction and size of equiaxed grains in the columnar equiaxed transition morphology. The studies established that irrespective of the addition of alloying elements such as Ti and Al in the weld, the size of the equiaxed grains generally decreased with increase the welding speed (Fig.1). However, at high titanium addition, welding speed has less effect on the size and fractions of the equiaxed grains [24]

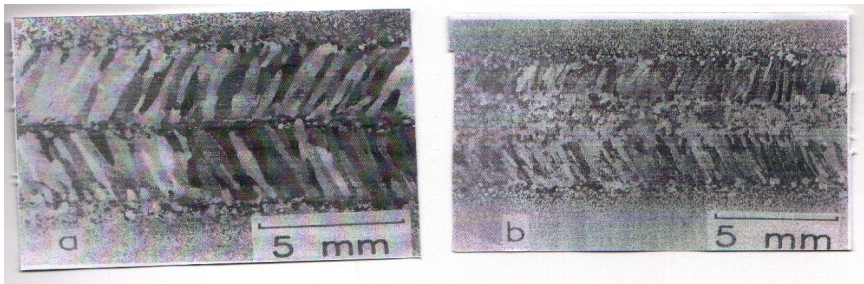

Fig.1, Effect of welding speed on equiaxed grain formation in welds containing 0.32 wt% Ti at welding speed: (a) 3mm/s and (b) 14mm/s [24]

Addition of Alloying Elements. Villafuerte et al [24] studied the influence of titanium and aluminum additions on grain refinement in autogenous gas-tungsten arc welded ferritic stainless steel by measuring the columnar-equiaxed transition. Their work revealed that the fraction of equiaxed grains is partly a function of welding speed but more significantly dependent on the titanium and aluminum content; however, the grain refinement did not occur throughout the weld cross section. At the surface, the equiaxed grain fraction increased with titanium content above 0.18 wt%. Within the equiaxed zone, the grain size was dependent on the titanium content. Higher titanium content tends to produce finer grains while with lower titanium content, a combination of small and large equiaxed grains resulted. The implication of this is that at lower titanium levels, the columnar-equiaxed band was quite thin and little improvement in mechanical properties is expected. The amount of aluminum for a given level of titanium, also affected the fraction of equiaxed grains. For a titanium content of 0.29 wt%, an increase in aluminum content from 0.010 to 0.040 wt% is reported to result in a significant increase in the equiaxed fraction (Fig.2). The grain size was also reported to decrease with the increase in aluminum content. The work conclusively established that ferritic stainless steel welds containing 0.29 wt% titanium and 0.040wt% aluminum exhibited equiaxed grain structure throughout the weld thickness. At these alloying conditions, the equiaxed structure is continuous. However, this work did not assess the mechanical properties of the weld in relation to those of the base steel.

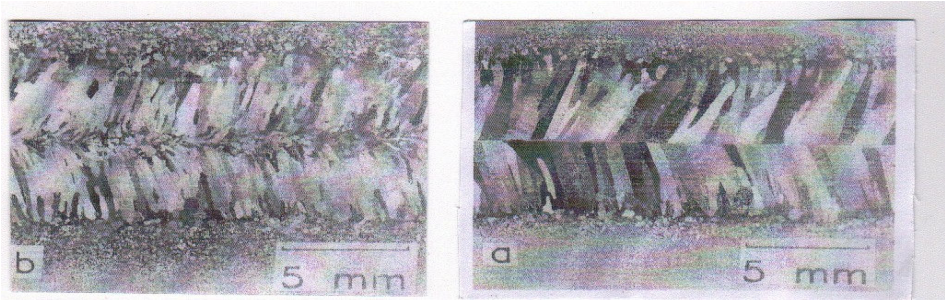

Fig.2, Effect of composition on columnar-equiaxed transition in ferritic stainless steel weld: (a) 0.18wt%Ti, 0.012wt%Al; (b) 0.36wt%Ti, 0.044wt% Al [24]

AC/DC Continuous and Pulsed Welding. Reddy and Mohandas [27] reported weld zone grain refinement through modification in welding technique. They engaged in comparative analysis of AC/DC continuous and pulsed welding with 3 mm thick AISI 430 ferritic stainless steel sheet using autogenous TIG welding. In this study, they used an arc current of 180A and arc voltage of 20V at a travel speed of 5mm/s for continuous AC/DC work. For the pulsed AC/DC welding, the current was pulsed between 300A and 30A with an arc voltage between 18 -20 V and a travel speed of 2.7 mm/s. DC and AC continuous current welds gave columnar grains, though AC continuous current welds exhibited finer grains, the equiaxed grains were sparsely distributed. However, the introduction of pulsed current in both AC and DC produced equiaxed grains in the weld zone. The AC current welding technique was more predominant and the welds produced finer and more equiaxed grains than the DC pulsed welds. However, the fraction of columnar and equiaxed grains was not quantified. The AC weld, irrespective of whether it is continuous or pulsed, exhibited an improvement in strength and ductility by 33% and 55% respectively compared to the DC weld. The pulsed AC weld, however, exhibited better mechanical properties. But, the degree of refinement has not been evaluated in terms of the fraction and size of the equiaxed grain. Their optical microscopic analysis could not establish whether the grain refinement was throughout the weld depth or just at the surface. Their claim of 70 percent improvement in ductility property could not be substantiated because the property of the as-received ferritic stainless steel was not measured. With continuous and pulse current TIG welding of ultra high strength steel, Mohandas and Reddy [28] correlated the average fusion-zone size to the mechanical property. However this may not be applicable in ferritic stainless steel welds due to different metallurgies of the two materials.

Liquid Metal Chilling. Villafuerte and co –workers [29] investigated on liquid tin metal to assess the columnar equiaxed transition (CET) in GTA welds using DC straight polarity in ferritic stainless steel. They quenched the weld puddles by pouring liquid tin at 350^0C through a moving stainless steel funnel inserted into an auxiliary shielding chamber. They found that the relatively cold liquid was effective in fast cooling of the weld melt closer to the advancing solid-liquid interface. This changed the solidification morphology from the central region towards the fusion boundary leading to an improved equiaxed grain structure. It was suggested that the changes in solidification morphology were due to gradual changes in local thermal conditions across the weld. The works of [30-34] corroborate this. Near the fusion boundary, the gradient G is relatively high and local solidification velocity R is relatively low, while closer to the centre line G is lower and R is higher. The decrease in G/R favours a transition from cell to more branched dendrites from the fusion boundary towards the weld centerline. Though, the formation of equiaxed grains in ferritic stainless steel welds was established but there was no quantification in terms of columnar equiaxed transition (CET) and mechanical property. It appears that the use of liquid tin metal is probably only apt in the understanding of the mechanism of grain refinement in ferritic stainless steel welds.

Weld Pool Stirring. Stirring is an important grain-refining technique in casting. It is equally being applied to fusion welding process [35] to suppress the growth of advancing columnar grains.

The stirring option could be either self-induced stirring, which is brought about by imbalance in Lorentz forces due to pressure gradient arising from the asymmetric conditions in the conducting column of the fluid or external induced stirring in the form of arc modulation or electromagnetic stirring. It is to be noted, however, that except for the works of Woods and Milner [36] and Telford [37], literature is scarce on the success of self-induced stirring grain refining technique. On the other hand, using electromagnetic stirring, pulsed arc or imposed amplitude modulation of pulsed arc current has become an important field in current research. Davies and Garland [38] first gave the direction for this work in a classical treatise in the international metallurgical review. Building on this, Villafuerte and Kerr [25] investigated columnar-equiaxed transition in full penetration GTA welds in austenitic and ferritic stainless steels having different amount of titanium and aluminum as minor elements for a range of welding conditions under the imposition of external magnetic fields. Two types of external magnetic fields of different orientations and frequencies were investigated. They are alternating current longitudinal magnetic field parallel to the electrode axis and transverse and parallel field. The work evaluated the contribution of magnetic field intensity and direction to the grain refinement and revealed that imposition of AC longitudinal magnetic field increased the fraction of equiaxed grains in ferritic stainless steel welds, particularly when welded with frequencies less than 1.0 H_Z and welding speed of 3mm/s irrespective of the amount of titanium in the weld. Though this is mainly a surface effect, the increase in equiaxed fraction did occur throughout the thickness of the weld (Fig.3). However, at higher frequencies there is less time available for the thermal conditions to change during each cycle and as such, the equiaxed grain fractions approached that observed in welds with no imposed magnetic fields. This implies that at high magnetic field frequencies, the effect on columnar equiaxed transition is insignificant. In the same manner, parallel and transverse magnetic field produced similar effects of equiaxed grain formation to those observed in longitudinal fields. The following facts were apparent from their works:

- *GTA welds using various orientations and frequencies of imposed magnetic fields in thin sheet ferritic stainless steel produced increased fraction of equiaxed grain implying improved grain refinement.*

- *Frequencies less than 1.0 Hz produced maximum wavy pattern equiaxed-grain fraction at the weld surface. Frequencies above 3.0 Hz produced equiaxed surface fractions comparable to those in welds made without imposed fields.*

- *Imposed parallel and transverse fields produced similar amount of equiaxed grains as in longitudinal fields. This can be explained by changes in local solidification conditions, though the maximum field strengths of these field orientations were less than those for longitudinal fields due to arc blow effects.*

- *However, all these effects were only observed in ferritic stainless steel but not in austenitic steel welds. This means that externally induced electromagnetic stirring irrespective of the orientations is only effective in generating improved equiaxed grains in ferritic stainless steel welds.*

The discussion of the findings in this work was based on microstructural characterization only. The fraction and the size of the equiaxed grains generated from the influence of electromagnetic stirring have not been investigated. The ductility and toughness of the weld with this grain refinement are yet to be determined. However, Davies and Garland [38] reported that meaningful grain refinement in TIG welded aluminum sheet can be achieved using simple physical technique of arc vibration parallel to the welding direction.

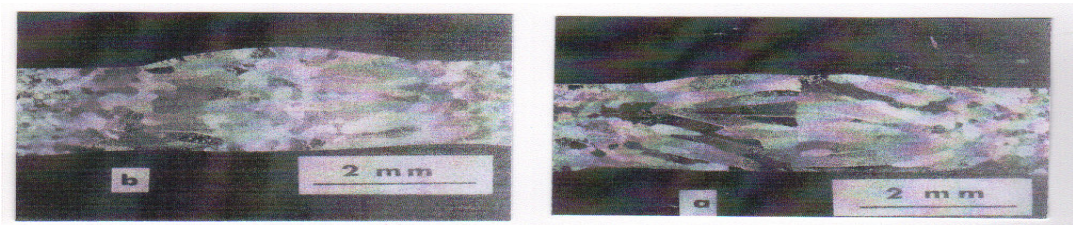

Fig. 3, Weld produced at 14mm/s speed in ferritic stainless steel containing 0.29wt%Ti and 0.04%Al: (a) no imposed field and (b) a longitudinal field frequency of 5.0 Hz [25].

The work of Reddy [39] with external magnetic arc oscillation on grain refinement of AISI 430 ferritic stainless steel weld rather provided a more comprehensive microstructural and tensile property characterization. The yield, tensile and ductility properties of the un-oscillated weld were found to be 325Mpa, 430Mpa and 3%, respectively compared to those of the as-received material values of 380Mpa, 488Mpa and 28%. The oscillated weld, however, produced much higher tensile and yield strength of 610 and 430MPa, respectively but ductility was only 10% compared to that with as-received material and the un-oscillated weld in Table 1. The findings suggest that grain refinement is optimum with an oscillation frequency of 6.0 Hz. At this frequency, the yield and tensile properties increased by 13% and 25 %, respectively compared to those in the un-welded base metal. However, the ductility in the two welding modes are poorer compared to the base metal and the reduction in ductility is more significant in the un-oscillated weld. One major achievement of this study is perhaps the reduction in residual stress in magnetic arc oscillated weld by an order of four.

Table 1, Comparison of tensile properties of AISI 430 ferritic stainless steel [39]

	UTS [MPa]	0.2%YS [MPa]	Elongation [%]
Parent Metal AISI 430	488	380	28
Un-oscillated Weld	430	325	3
Oscillated Weld	610	430	10

It is apparent from the various reviewed works that grain refinements in ferritic stainless steel weld have focussed on microstructure by the control of welding conditions, alloying, stirring and oscillation. So far, the degree of grain refinement is assessed based on the size and fraction of equiaxed grains in the columnar equiaxed transition morphology. This approach may be appropriate for the study of centerline cracking susceptibility in ferritic stainless steel weld. It is necessary to correlate microstructural features with mechanical property.

Different mechanisms have been provided to explain the grain refinement in ferritic stainless steel welds [40]. These are heterogeneous nucleation, dendrite fragmentation, grain detachment and partial molten zone grain detachment. These mechanisms are strongly contrasting.

It is obvious from the studies that the controlled heat removal from the weld zone of ferritic stainless steel is the recipe to enhance grain refinement and hence to improve mechanical property.

Conclusions

An exploratory review of grain refinement in ferritic stainless steel welds has been presented. Grain refinements efforts have focussed on microstructure through the control of welding conditions, alloying, stirring and oscillation to ensure better heat transfer features. These techniques have assessed mainly the grain refinement in terms of fraction and size of the equiaxed grains in the weld structure. Most of the works focused on characterizing the equiaxed grain without correlating with the mechanical property, except the work of Reddy [39]. It is essential to correlate microstructural features with mechanical property.

The friction welded ferritic stainless steel component, in which the total heat input and heat transfer can easily be controlled, is reported to have strength equal to 95% of the parent metal. This suggests that the total energy input and heat transfer factors during welding control the microstructural feature of the weld section and hence the strength. This implies that further effort, on grain refinement in ferritic stainless steel welds, should be focused on controlling both total energy input and heat transfer factors.

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