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MICROSTRUCTURAL FEATURES AND MECHANICAL PROPERTIES OF AISI430 FERRITIC STAINLESS STEEL WELDS - A REVIEW

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ABSTRACT

The lower cost of ferritic stainless steels together with their excellent resistance to stress corrosion cracking contributed to their current growth requirements and consumption in many industries particularly, petrochemical, marine, power plant, automobile and other engineering applications, where the nickel free steels are being consumed. However, the application of ferritic steel is limited especially, in those areas that require welding for fabrication of components because of poor ductility and notch impact toughness of its weld section due to the grain growth. Different techniques have been explored by several researchers to control the grain features of the weld zone in order to minimize these problems. In the present study, a review of these different techniques in relation to the microstructure and mechanical properties such as notch impact toughness, tensile strength, ductility and hardness was specifically carried out to create a better understanding on the microstructural-properties relationship in ferritic stainless steel weldments. Previous studies have proven that AC-TIG welding mode is the most effective technique for welding ferritic stainless steels and reported mechanical properties improvement of about 65% of the base metal. Finally, it can be concluded from the findings that, the net energy input and the rate of heat transfer during ferritic stainless steel welding mainly determine the resulting microstructure of the welds and hence, the mechanical properties.

Keywords: Microstructure, grain growth, mechanical property, ferritic stainless steel weld, welding techniques

INTRODUCTION

Among the various types of arc welding processes, tungsten inert gas (TIG) welding technology is being increasingly used as a suitable heat source for welding of steels as well as surface treatment of steel alloy components (Maleque *et al.*, 2015). It has the advantage of producing quality weldment with minimum heat energy input.

Stainless steels are iron base alloys having minimum chromium content 11% and carbon ranges from 0.002% to 0.12%. Apart from these two elements, stainless steels contain other alloying elements; such Nickel (Ni), molybdenum (Mo), manganese (Mn), silicon (Si), niobium (Nb), sulphur (S), titanium (Ti) and phosphorus. These elements are usually added to impart some properties like machining, mechanical properties and to improve the weldability of the steels (Cramer *et al*., 2005; Razaullah *et al*., 2007). Stainless steels are one of the important engineering materials that are capable of meeting a broad range of design criteria. They are important class of materials developed for applications, especially in corrosive environments (Amuda and Mridha, 2010). These steels are corrosion resistant because of the formation of a thin tenacious oxide layer and are therefore widely applied in oil and gas industries, automobile and aircraft industries exhaust gas emissions control systems for vehicles (Lippold *et al*., 2005; Oku *et al*., 1999). They also found application in electrical appliances, heat exchangers, storage vessel, solar water heaters, nuclear reactor, pressure vessel application, transport, agriculture and mining (Holmber, 2009; Greef and Toit, 2006).

Ferritic stainless steels (FSS) are iron-chromium alloys with body-centered cubic crystal structure (BCC) having chromium content usually in the range of 11–27wt% (Balasubramanian *et al*., 2008). These steels exhibit good ductility, formability, moderate yield strength and better resistant to stress corrosion cracking relative to those of the austenitic grades, but the high temperature strength has been reported to be poor (Pecker and Bernstein, 1997). Ferritic stainless steel has low thermal expansion when compared with their counterpart family of stainless steels such as austenitic and martensitic type which makes it suitable materials in high temperature applications (Ramkumar *et al*., 2015; Sabioni *et al.*, 2013). It is also very economical due to the little or lack of nickel content in this grade of stainless steels (Santos *et al*., 2012). The low thermal expansion of ferritic stainless steel makes their welding easier compared to austenitic stainless steel which has relatively higher coefficient of thermal expansion.

During the fabrication of stainless steel components or equipment, manufacturers usually employ TIG fusion welding process due to its flexibility, lower production cost and ability to produce strong weld joint (Bello *et al*., 2015). However, the intense heat produced during fusion welding process creates metallurgical and physical in-homogeneity in the weld pool leading to different microstructural changes and properties in the weld section (Dauda *et al*., 2010). This scenario is true for welded section of almost all materials but more pronounced in ferritic stainless steel welds especially, AISI 430 type. Gas-Tungsten Arc welding process is one of the principals joining methods employed for this steel grade because, minimum heat energy input and high-quality welds are obtainable with this process [Bello *et al.* 2013]. A major concern in the industrial application of FSS weld is the loss of mechanical properties like notch impact toughness, ductility, high temperature strength and corrosion resistance (Bilgin *et al.,* 2012; Parameswaran *et al.*, 2010; Laha *et al.,* 2009; Francis *et al.*, 2006) in the fusion and heat effected zone of the weld section. This loss of mechanical properties of ferritic stainless steel welds has been attributed to the intense welding heat which induces grain coarsening. Katundi *et al*., (2010) reported that grain growth in the fusion zone (FZ) and heat affected zone (HAZ) occur due to high temperatures during welding. It may be possible to improve the ductility of fusion welded FSS if refined grain structure is produced in the microstructure (Amuda and Mridha, 2012). Some of the major weldability issues of ferritic stainless steel reported so far are grain growth in the weld and heat affected zone and sigma phase formation (Reddy and Meshran, 2006; Reddy and Mohandas,2001; Muhammad *et al*., 2017). Several Attempts have been made by different researchers to address this weldability problems associated with ferritic stainless steel. Anbazhagan *et.al*., (2002) conducted grain refinement on AISI 430 FSS weld using constant and pulsed TIG as well as shielded metal arc welding (SMAW) process. They reported that pulsed current TIG offers appreciable grain refinement in the weld, producing about 60% increase in ductility. The SMAW process with E430Nb electrode gave 40% improvement in ductility. They also concluded that the reduction in ductility with the SMAW compared to the TIG process is probably due to the large grain structures produced in SMAW welds caused by the higher energy density of this process.

Some researchers worked on the welding processes parameters to obtain the optimum welding process that will give the minimum heat input for the improvement of Metallurgical and Mechanical properties of ferritic stainless steel weld (Ramkumar *et al*., 2015). Others conducted the effects of elemental powder addition, such as Titanium and Aluminium on the grain size and mechanical properties of FSS weld (Amuda and Mridha, 2013).

Therefore, the present study is a review on the findings of various researchers in relation to the grain size and mechanical properties of ferritic stainless steel weld. Most of these researchers reported grain growth and embrittlement in the FZ and HAZ as the major problems associated with ferritic stainless steel weld. Therefore, they concluded that addition of certain alloying elements (such as aluminium, titanium, copper etc.), the choice of welding processes (including arc welding, friction stir welding and resistance welding) and controlling of welding conditions (welding current, speed of welding, filler material) can be used to control the microstructural evaluation and improve the Mechanical properties of FSS weldment.

Microstructural Changes in Ferritic Stainless Steel Welds

The structure of ferrittic stainless steel undergoes several phase changes and phase formations during welding. It is recommended that the resulting 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. The microstructural changes that occurs during welding of ferritic stainless steels have been explained using Fe-Cr phase diagram as shown in Figure 1 (Bhadeshia, *et al.,* 2017).

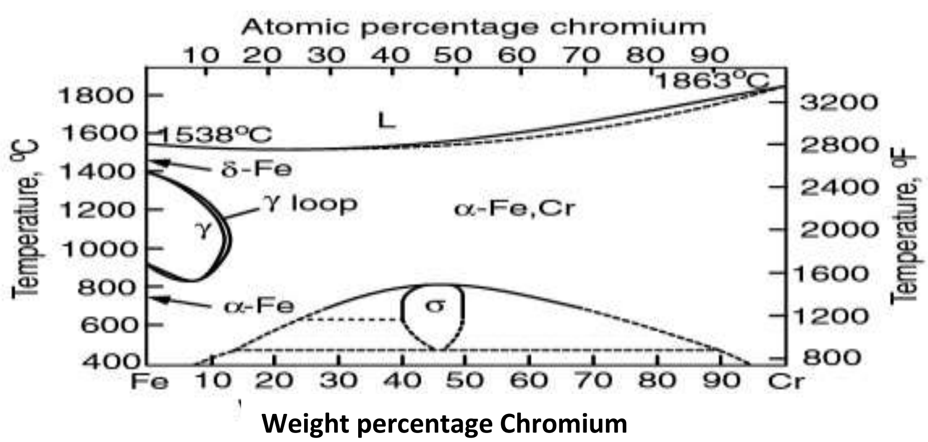

Fig. 1: Fe-Cr phase diagram in FSS **(**Bhadeshia, *et al.*, 2017**)**

From Figure 1, there is a gamma loop between the temperature range of 912-1394°C having less than 12.7%Cr. This shows that steels with less than 12.7%Cr consists fully ferritic microstructure at all temperatures below the melting point, showing little transformations of austenite to martensite on solidification during welding. Ferritic stainless steel welds are susceptible to grain growth because they solidify directly from the liquid to the ferrite phase without any intermediate phase transformation (Hedge, 1995; Miller, 1999). The formation of sigma phase is a very slow process and required enough time in the temperature range of 600-800°C. Sigma phase has tetragonal and brittle structure. 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 forms in the range of 400-540°C and have severe embrittlement effect on alloys having greater than 14% Cr. (Kotecki and Lippold, 1998; Uematsu *et al.,* 2008; Sahu *et al.,* 2009).

Effects of Grain Refinement on the Mechanical Property of FSS Weld

It has been reported by many researchers that the poor mechanical properties of ferritic stainless steel welds are due to the problem of grain coarsening in the WZ of FSS welds. In order to improve the mechanical properties of this steel weld, several approaches have been employed by different researchers to control the grain size of the steel weld.

Mallaiah *et al*., (2012) investigated the effect of grain refining elements such as copper, titanium and aluminum on transverse tensile strength, ductility, impact toughness, microhardness and austenite content of as-welded AISI 430 ferritic stainless steel produced by gas tungsten arc welding (GTAW) process. They observed that the mechanical properties and austenite content is correlated with microstructural features of the resulting weld. The summary of their findings as well as the working ranges are presented in Table 1 and 2 respectively. As seen in Table 1, the optimum conditions and the optimum values obtained for all the mechanical properties considered are presented.

Table 1: Optimum values of the quality characteristics (Mallaiah *et al*.., 2012)

Quality characteristics	Optimum conditions	Optimum value
Ultimate tensile strength (MPa)		455
Yield strength (MPa)	$A_3B_2C_1$	377
Percentage elongation (%EL)	i.e. Cu at level 3	5.8
Impact toughness (J)	Ti at level 2	6
Microhardness (Hv)	Al at level 1	359
Austenite content (wt%)		18.32

Table 2: Working range of grain refining elements (Mallaiah *et al*., 2012).

Symbol	Element	Units	Lower level (1)	Medium level (2)	Higher level (3)
A	Copper	g	1	2	3
B	Titanium	g	1	2	3
C	Aluminium	g	1	2	3

In the same vein, Villafuerte *et al*., (1990) also reported grain refinement in ferritic stainless steel welds with a specific range of welding conditions using different amounts of titanium and aluminum. According to the study, the fraction of equiaxed grain in the microstructure is favored by the increases in both the concentration of the elements and the welding speeds. Their study showed that welding speed has little effects on the fraction of equiaxed grains formed, but dependent significantly on the addition of grain refining elements. The work also reveals that there was no uniform distribution of the equiaxed grain across the weld section. While the surface of the weld showed increased in the fraction of equiaxed grain with titanium content greater than 0.18wt% and produce finer grains, lower titanium content gave a combination of small and large equiaxed grains with implication of little improvement in mechanical properties. For a given amount of titanium, the fraction of equiaxed grains formed also depends on the level of aluminum added to the weld. Based on these, the study concluded that ferritic stainless steel welds containing 0.29wt% titanium and 0.040wt% aluminum added to the weld pool during welding refined the grain structure by producing appreciable fraction of equiaxed grains in the weld zone which is uniform across the weld depth. However, the report of their study could not relate the increased volume fraction of equiaxed grains to improved mechanical properties.

Mohandas *et al*., (1999) conducted a comparative study on the effects of types of welding process and grain refining elements on the tensile properties of AISI 430 FSS welds and found that GTAW welds having equiaxed grain morphology had better tensile properties compared to SMAW welds. The addition of titanium and copper, however, in the two welding processes increased the tensile strength over that of the base metal, though the ductility of the welds is in general low compared to that of the base metal.

In another work, Reddy *et al*., (2001) reported the addition of alloying elements such as titanium, aluminum and copper in the weld pool as one of the effective methods for controlling the net energy input during fusion welding. It was found that the elements when introduced into the weld pool, they act as heat sinks, thereby reducing the amount of heat input into the weld pool. The elements also facilitate the formation of nucleation sites where solidification of the weld is initiated with increasing formation of equiaxed grains leading to improved mechanical properties.

Amuda and Mridha, (2012) conducted an extensive study on the grain refinement of TIG-welded AISI 430 ferritic stainless steel via two strategies which are cryogenic cooling and elemental metal powder addition. It was reported that the two grain refinement methods caused constriction in the weld geometry. The study showed that elemental metal powder addition produced greater grain constrictions of about 50% of the size of the heat affected zone (HAZ) in the conventional welds while only 36% was recorded with cryogenic cooling gave. Both strategies generally produced refined grain structures by forming equiaxed grains in the fusion and heat affected zones of the resolidified weldment. In addition, the degree of grain refinement is higher with the elemental metal powder addition, but, contains embrittling intermetallic phases that affect the mechanical properties, particularly the ductility of the weld. Such intermetallic phases do not form during cryogenic cooling, and thus the welds produced with this method showed better combination of mechanical properties when compared with those treated with metal powder addition. From the finding, it was concluded that cryogenic cooling improved the ductility of the welds for about 80% of the base metal whereas the ductility obtained with the metal powder addition is between 20–65% of the base metal depending on the type of metal powder introduced into the melt pool. Table 3 shows the tensile properties of the welds produced under different metal treatment conditions. As presented in the Table, the two grain refinement strategies (i.e. cryogenic cooling and elemental metal powder addition) resulted in improving the tensile properties when compared with the conventional weld (CW). Cryogenic cooling gave better mechanical properties relative to elemental metal powder addition. However, while the addition of aluminum and mixture of titanium + aluminum powder increased both the tensile and ductility properties of the welds, addition of titanium powder slightly improved the tensile and yield strengths relative to the conventional weld but the ductility is seen to have reduced. The results in the Table reveal that the grain size is probably the controlling variable when evaluating the effect of grain refinement on weld properties; but when comparing different grain refinement conditions, it appears that the percent δ- ferrite is the controlling variable (Amuda and Mridha, 2012).

Table 3: Tensile properties of weld produced with different grain refinement conditions (Amuda and Mridha, 2012).

Process condition	Grain size (µm)	δ-Ferrite (%)	0.2% YS (MPa)	TS (MPa)	EL (%)
CW	40	70-72	164	328	11
Al powder	27	93-96	183	373	17.41
Ti powder	8	90-95	175	304	6.38
(Al+Ti) powder	10	96-98	180	352	14.61
Liquid nitrogen	22	81-85	189	391	21.91

In addition, Folkhard (1998) had proved that the presence of δ ferrite above 80% in the microstructure of ferritic stainless steel welds significantly lowers the ductility; but if the δ ferrite in the welds is in the range 50–80%, the reduction in ductility may not be significant. However, the results in table 3 show average of 83% δ ferrite in the weld cooled with cryogenic method while those treated with metal powder gave around 95% on the average.

The welds cooled with liquid nitrogen result in ductility almost twice that of the conventional weld. Also, the ductility of the titanium treated weld is lower than that of the conventional weld whereas Al and mixture of Al+Ti gave ductility higher than that of conventional welds. The liquid nitrogen cooled weld has higher ductility than the elemental metal powder treated welds but with coarser grains. Therefore, it can be concluded that within a given grain refinement condition, the microstructure determines the mechanical properties but when considering different grain refinement conditions, the amount of the δ ferrite becomes the determining variables.

The ductility of the welds produced under different grain refinement conditions can be understood further by using the relative ductility curves shown in Figure 2. It shows that cryogenic cooling provided the highest ductility compared to the metal powder welded sample. Cryogenic cooling gave ductility of about 80% of the base metal, aluminum treated weld gave ductility of 50–65% of the base metal while 35–55% and 20% ductility were recorded with the metal powder mixture (Al+Ti) and titanium treated weld respectively. From this level of ductility obtained from titanium treated welds, it can also be inferred that grain refinement might not necessarily improve the mechanical properties of the weld even with presence of refined and equiaxed grain structure. Similar findings have also been reported by Mohandas *et al*., (1999).

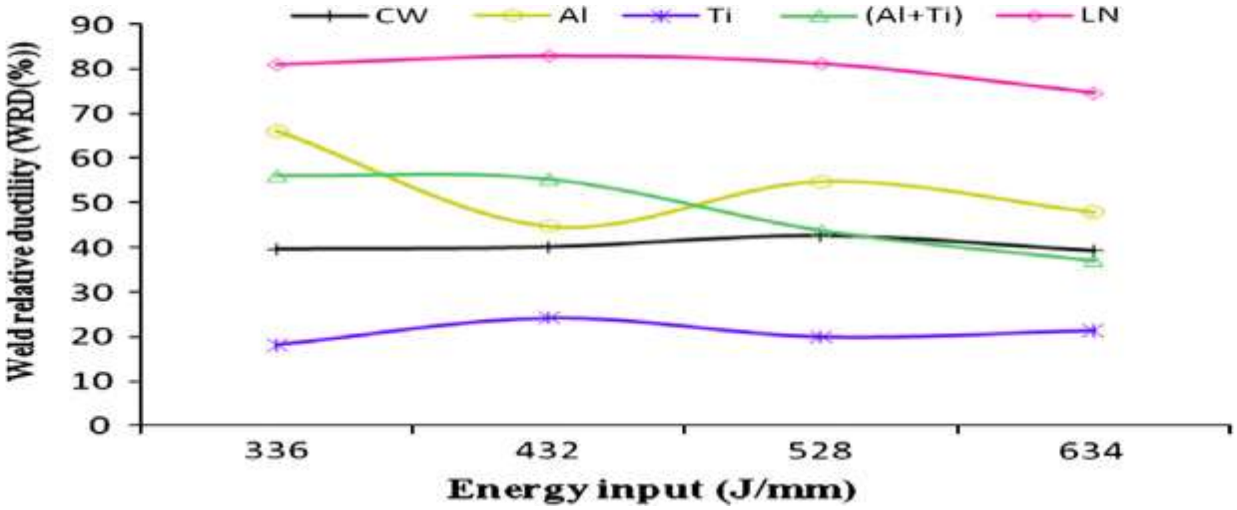

Figure 2: Effect of different grain refinement conditions on weld relative ductility (Amuda and Mridha, 2012).

The characteristics of the welds produced at different grain refinement conditions were examined through optical microscope. The microstructures presented in Figure 3 clearly indicated a refined and equiaxed grain structures which is in contrast to the columnar and elongated structure in the welds produced conventionally as indicated in Figure 4. The addition of titanium and a mixture of aluminum + titanium powder produced welds with the finest and equiaxed structures as shown in Figure 3(b) and (c) respectively, while those treated with aluminum alone and cryogenic cooling also refined but relatively coarser.

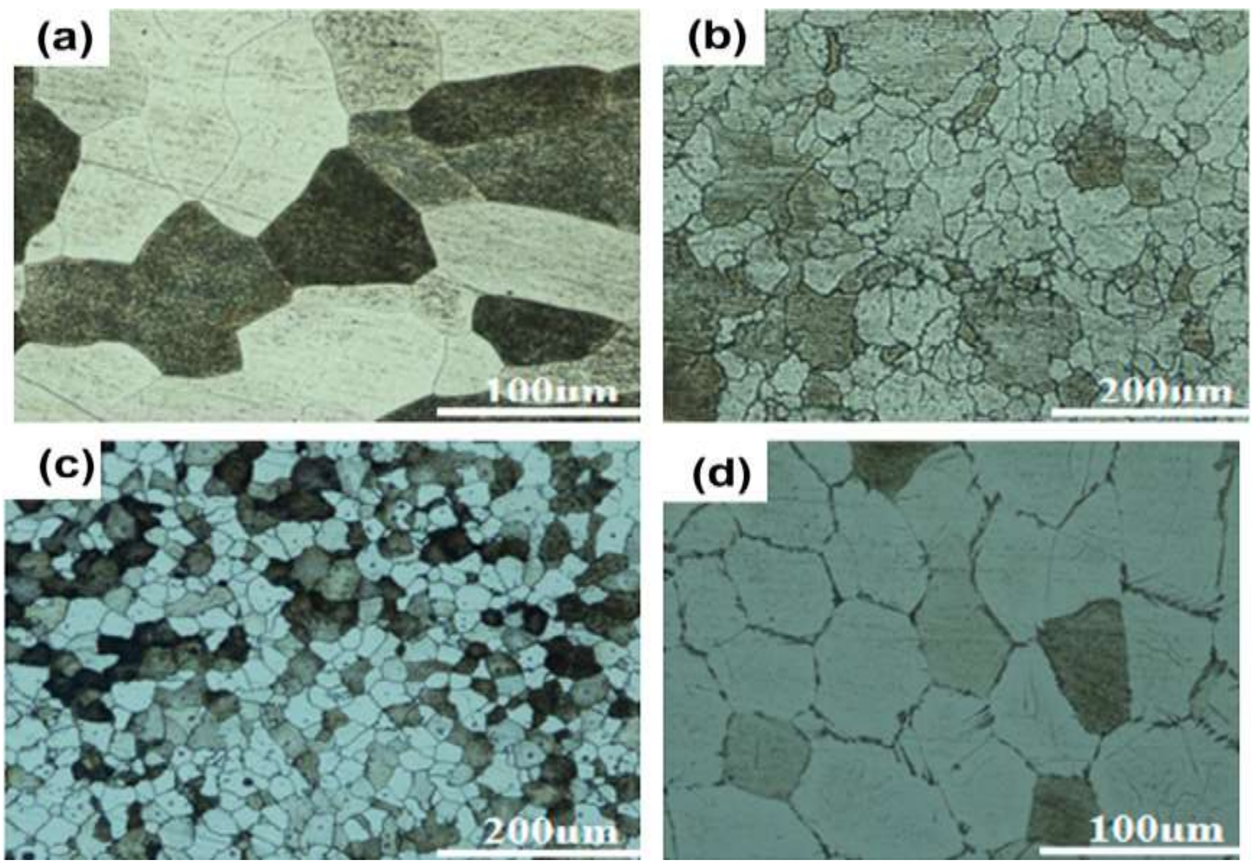

Fig. 3: Microstructure of welds at different grain refinement conditions: (a) aluminium (b) titanium (c) aluminium + titanium (d) cryogenic cooling (Amuda and Mridha, 2012).

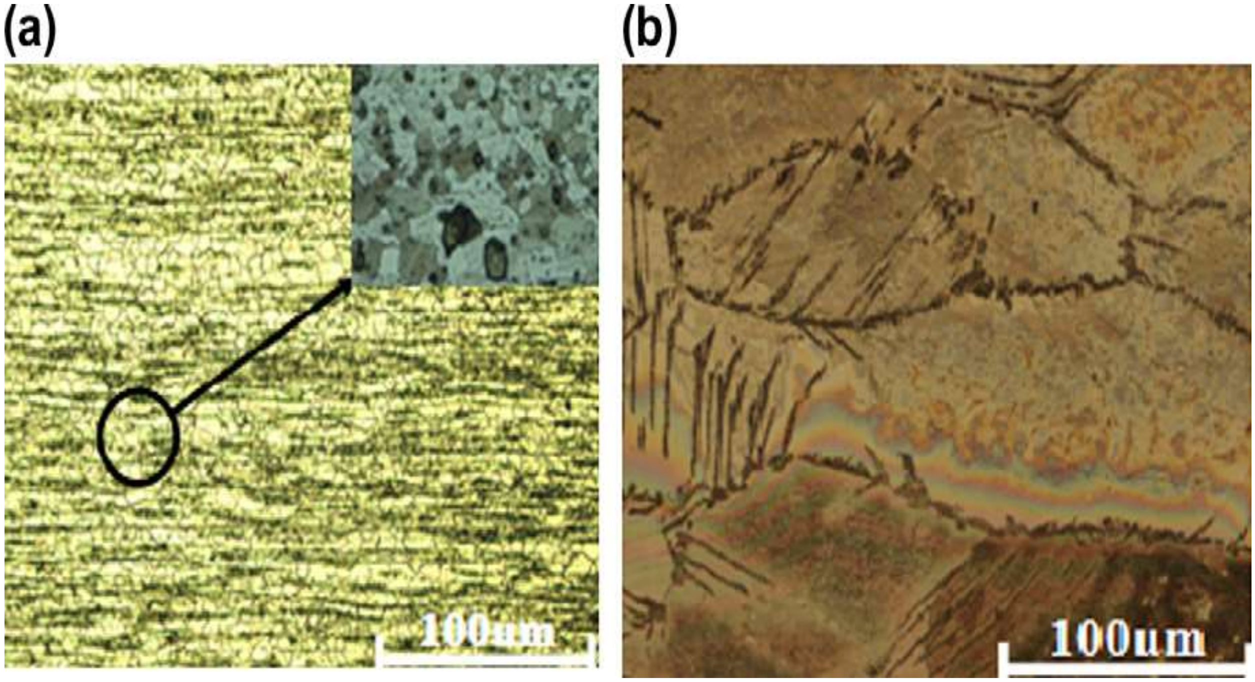

Fig. 4: Microstructure of (a) base metal (b) conventional weld (Amuda and Mridha, 2012).

Effect of welding techniques on the grain size and mechanical properties

Arc welding process

Reddy *et al.,* (2001`) had reported grain refinement in the weld zone of AISI 430 ferritic stainless steel by modifying the welding technique. The work was a comparative analysis between continuous and pulsed AC/DC autogenous TIG welding using 3-mm thick steel sheet. In this work, a constant arc current of 180 A, arc voltage of 20 V and a welding speed of 5 mm/s were used for continuous AC/DC welding. Voltage between 18 -20 V and welding speed of 2.7 mm/s was used in the pulsed AC/DC welding, and the current was pulsed between 300 A and 30 A. It was found that the introduction of pulsed current in both AC and DC produced equiaxed grains in the weld zone with improved mechanical properties. The equiaxed grains produced via AC current welding technique were more predominant with finer grains than the DC pulsed welds.

Friction welding process

Friction welding (FW) is a welding process that generates heat through mechanical friction between a moving work piece and a stationary component. In this welding process, the force and heat directed at the weld interface producing a relatively small HAZs. According to the reports from different researchers, friction welding techniques generally provide low heat input thereby preventing excessive grain growth in the microstructure of the weld. Sathiya *et al.,* (2007) investigated the effect of friction stir welding process on the structure and mechanical properties of ferritic stainless steel weld and reported about 95% property of the base metal. The high improvement in the properties was attributed to the ability to control the total heat input and heat transfer during the welding process. In a similar trend, Lakshminarayan and Balasubramanian, (2010) conducted an assessment on the microstructure and mechanical properties of friction welded AISI 409 ferritic stainless steel and claimed that the presence of fine duplex structure of ferrite and martensite formed in the microstructure of the weld due to high cooling rate and high strain induced by the severe plastic deformation refined the grains with improvement in the mechanical properties. Cerri and Leo, (2011) also worked on the mechanical properties' evolution of a post welding heat treatments double lap friction stir welded joints. Their results proved that the presence of fine and equiaxed grain structure in the weld nugget of friction welded material gave better mechanical properties.

Resistance welding process

Resistance welding process which consists of spot welding, butt welding, seam welding, flash welding etc. is the main joining process in automotive industry. This welding method creates a very low heat energy input in the weld joint. The heat energy is produced by the resistance to the localized current offered by the gap between the parts to be joined (Reddy and Meshran, 2006). According to the report by Chuko and Gould, (2002), the cooling rate of resistance welded material is extremely high (in the order of 1000–10,000 C/s) hence, it can be employed for welding ferritic stainless steel whereby the high cooling rate prevents the grain growth in the fusion and heat affected zone of the welds.

Alizadeh-Sh *et al.,* (2014) also investigated the metallurgical and mechanical properties of resistance spot welded AISI 430

FSS and reported a substantial increase in the mechanical properties.

Effect of welding conditions on the metallurgical and mechanical properties of FSS

Heat energy input and welding speed have been reported to play important roles in the modification of weld microstructures of ferritic stainless steel. The grain morphology in fusion weld can be controlled by controlling the net heat input into the weld joint (Easterling, 1992). Lancaster (1980) reported the formation of columnar grains in the fusion zone due to large heat input thereby causing grain growth in the HAZ of the welds. This is due to longer thermal cycle and lower cooling rate emanated from the excessive heat energy input resulting in the poor mechanical properties such as tensile strength and notch impact toughness. This problem can be attributed to the wider weld pool produced at the fusion zone. In order to avoid these problems, low heat input welding techniques such as tungsten inert gas welding, friction welding and resistance spot welding are being explored and recommended for grain refinement of FSS weld.

CONCLUSION

An overview of microstructural features and mechanical properties of AISI 430 ferritic stainless steel welds have been carried with the following conclusions. Grain refining elements such as Al, Ti, Cu etc. modify the microstructure of ferritic stainless steel with attendant improvement in the mechanical properties. The microstructure with equiaxed grain morphology favored the increase in the mechanical properties compared with the columnar grains. Among the different welding techniques study, friction welding process provides the highest mechanical properties with about 95% improvement compared with the base metal, followed by GTAW process. This was attributed to the low heat energy input obtainable with these welding processes.

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CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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