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Comparative evaluation of grain refinement in AISI 430 FSS welds by elemental metal powder addition and cryogenic cooling

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ABSTRACT

Two strategies for grain refinement in the Ferritic Stainless Steel (FSS) welds involving cryogenic cooling and elemental metal powder addition into the melt pool are investigated and their performances are evaluated. Full-penetration-bead single pass weld tracks were produced on AISI 430 FSS plate using a Gas Tungsten Arc (GTA). The two grain refinement strategies constricted the weld geometry; however, the metal powder addition produced greater constriction of about 50% of the size of the heat affected zone (HAZ) of the conventional welds compared to 36% in the cryogenic cooling. Both paradigms produced generally equiaxed and refined grain structure; the degree of refinement is higher with the metal powder addition but contains embrittling intermetallic phases, which negatively affect the ductility of the weld. Such phases are absent in the welds processed with cryogenic cooling, and thus the welds produced with this method provide a better combination of mechanical properties than those treated with metal powder addition. Cryogenic cooling improved the ductility of the welds to 80% of the base metal whereas metal powder addition gave 20–65% of the base metal's ductility depending on the type of metal powder introduced into the melt pool.

1. Introduction

A major concern in the industrial application of FSS is the loss of ductility and impact toughness in the weld section due to the intense welding heat which induces grain coarsening. It may be possible to improve the ductility of fusion welded FSS if refined grain structure is produced in the microstructure [1].

Several techniques for grain refinement in fusion welds have been reported in the literature. Anbazhagan and Nagalakshmi [2] conducted grain refinement on AISI 430 FSS weld using constant and pulsed GTA as well as shielded metal arc (SMA) process. They established that pulsed current GTA offers appreciable grain refinement in the weld leading to about 60% increase in ductility. The SMA process with E430Nb electrode gave 40% improvement in ductility. The lower ductility obtained with the SMA compared to the GTA process is probably due to the relatively coarse microstructure in the SMA welds which is caused by the higher energy density of the SMA process. In the same vein, Reddy and Meshram [3] attempted grain refinement in AISI 430 FSS welds via an external alternating magnetic field and observed that the use of magnetic oscillation changed the predominantly columnar structure to equiaxed grain structure. This produced superior strength in the weld compared to the un-oscillated conventional welds. Villafuerte et al. [4] reported grain refinement in FSS welds processed with specific range of welding conditions containing different amounts of titanium and aluminum. In this work, the fraction of equiaxed grain in the microstructure is *favored* by both the increases in the concentration of the elements and the welding speeds. Though, the work could not relate the increased volume fraction of equiaxed grains to improved mechanical properties. Similarly, Wang et al. [5] noted that 12 wt% Cr FSS treated with Ti and Nb dual stabilization produced a narrower window of grain coarsening temperature resulting in smaller HAZ width as well as reduced grain size with improved mechanical properties. This was attributed to the presence of ferrite–austenite transformation in such steels which permits the formation of low-carbon martensite. Mohandas et al. [6] investigated on the effects of types of welding process, shielding gas and grain refining elements on the tensile properties of AISI 430 FSS welds and found that GTA welds with equiaxed grain morphology had better tensile properties compared to SMA 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. Meanwhile, in all these previous works, the degree of grain refinement was not related to the grain structure of the base metal but to the conventional

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welds. Thus, it was quite difficult to establish the effectiveness of the various grain refinement strategies.

However, one thing is clear and that is, it appears that conditions which guarantee low heat input dynamics in fusion welding facilitates the development of equiaxed and refined grain structure in FSS welds leading to improved properties. This presumption is strengthened by the work of Sathiya et al. [7] on friction stir welded (FSWed) AISI 430 FSS in which about 95% property of the base metal was achieved. In a similar trend, Lakshminarayanan and Balasubramanian [8] reported strength overmatch in the nugget zone of FSWed AISI 409 M FSS. This was due to the presence of very fine duplex structure of ferrite and martensite in the weld microstructure formed consequent upon the rapid cooling rate and high strain induced by the severe plastic deformation created by frictional stirring. Song et al. [9] equally achieved about 10% tensile strength overmatch in the joints of Inconel 600 alloy produced via FSW which was attributed to the grain refinement induced in the stir zone via dynamic recrystallization. In another work, Cerri and Leo [10] reported that the very fine and equiaxed grain structure in the weld nugget of FSWed material resulted in improved mechanical properties. A major consideration in FSW process is that there is no fusion and coalescence of the substrates rather joining is ensured via macroscopic plastic flow between the adjacent surfaces. This indicates that the energy dynamics in the process is lower compared to the fusion welding process. This suggest that a net low heat input and faster heat dissipation dynamics in the fusion welding process can control grain growth in the FSS welds. This may be achieved by controlling the proportion of arc heat input that is actually delivered to the workpiece or enhancing the resolidification process by artificially agitating the weld pool.

Reddy and Mohandas [11] reported that one method for controlling the net heat input during fusion welding is the addition of alloying elements such as titanium, aluminum and copper in the melt pool. These elements when introduced into the melt pool act as heat sinks and serve to control the heat input into the weld pool. Furthermore, they serve as nucleation sites for the initiation of solidification in the weld. This initiative enables the formation of equiaxed grains leading to improved mechanical properties. Another option involves increasing the heat dissipation rate from the melt pool upon resolidification and beyond. This may be achieved by inducing a turbulence flow in the weld pool. A typical illustration is the investigation undertaken by Villafuerte et al. [12] in which liquid tin was used for grain refinement in GTA welded FSS where it was found that the relatively cold liquid tin was effective in cooling the steel close to the advancing liquid–solid 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 the local thermal conditions across the weld. The enhanced heat dissipation increased the cooling rate from the peak temperature and this affected the grain structure in the weld. A slow cooling rate from a very high heat input fusion process will obviously lead to grain coarsening. Therefore, increasing the cooling rate might offer another option for grain refinement, though this must be with caution as too drastic cooling can induce brittleness in the workpiece. Higher cooling rate may be achieved by increasing the convective heat dissipation during the weld cooling cycle. This is feasible via an additional cooling system which can assists in the heat dissipation mechanism; and hence can be extremely beneficial to the control of the post-weld microstructure and helps in avoiding the grain growth. Such a technique is well practiced in the low stress no distortion (LSND) technique in laser welding. Gabzdyl [13] demonstrated that in this technique, pressurized liquid CO_2 expanded through a delivery nozzle and forms a mixture of gas and solid CO_2 snow. This mixture of gas/solid is directed at a point immediately behind the weld zone to enhance the post-weld cooling via the extraction of heat by the sublimation of the snow. The cryogenic cooling strategy was able to significantly reduce the distortion in the welds.

While the elemental metal powder addition and the cryogenic cooling are established procedures for controlling the microstructure in laser welding, such procedures are not reported in GTA welding of FSS. Therefore, in this work, two strategies for grain refinement in FSS weld involving elemental metal powder addition and cryogenic cooling are investigated and their relative performances are evaluated. The work reported in this paper is part of an on-going investigation on grain refinement in AISI 430 FSS welds produced via GTA melting.

2. Experimental method

Full weld beads were produced on a 1.5 mm thick FSS sheet metal conforming to AISI 430 using direct current, straight polarity GTA process. The composition of the material is provided in Table 1. The table indicates that the material approximate medium chromium FSS with 16 wt% Cr and 0.12 wt% C. The other elements are within the range permitted for this grade of FSS [14].

The weld pool was created by melting the flat surface of the prepared specimen under the torch generated using various combinations of arc current and electrode traverse speed with the type of metal powder or jet of liquid nitrogen as additional process variable. The design matrix for the investigation is provided in Table 2. The table shows that a total of 20 welds were produced at different combinations of heat flux, welding speed and grain refinement conditions.

The heat flux in the table was evaluated using Eq. (1) while Eq. (2) was used for the heat input.

$$q = \eta IV \tag{1}$$

$$HI = \frac{q}{v} \tag{2}$$

where q is the heat flux (W), η is the process efficiency, I is the arc current (A), V is the voltage (V) and υ is the welding speed (mm/s). The process efficiency (η) for the GTA welding process is roughly 48% [15]. The voltage in the present investigation is relatively constant at 30 V.

The details of the preparation of the organic binder for the elemental powder preplacement technique as well as the fabrication of the cryogenic cooling system are presented elsewhere in the literature [16]. However, the organic binder is a solution of polyvinyl alcohol (PVA) in the ratio of 40 g PVA to 960 ml of water.

The powder of titanium, aluminum or mixture of them separately formed into a paste using the PVA organic binder was preplaced onto the substrate and then oven dried at 60 °C for 30 min to remove the moisture. The cryogenic cooling of the welds was conducted by placing the workpiece on a copper chamber and directing pressurized liquid nitrogen at 2.5×10^6 Pa from a Dewar at the workpiece as it was welded by the GTA torch. The set-up for the elemental metal powder addition is shown in Fig. 1a while similar configuration for the cryogenic cooling is provided in Fig. 1b. The physical representation of the metal powder technique shown in Fig. 1a demonstrates that the torch melts the preplaced metal powder together with the FSS material; whereas the line diagram for the cryogenic cooling in Fig 1b shows that jet of liquid nitrogen is directed through the copper chamber at the resolidifying melt pool. The cryogenic cooling device made from copper plate is shown in Fig. 1c with the full description of the various components. The innovation and main element of the cryogenic cooling is the indirect contact between the melt pool and the jet of liquid nitrogen. This paradigm enhances post-weld solidification while