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Original Research Article

Enhancing the properties of friction stir welded stainless steel joints via multi-criteria optimization

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ABSTRACT

An attempt is made to establish empirical relationships to predict the properties of friction stir welded stainless steel joints. The process parameters namely, rotational speed, welding speed and shoulder diameter and the properties such as tensile strength, notch tensile strength, impact toughness and degree of sensitization are considered. The investigated properties are correlated with the macrostructure and microstructural characteristics of different zones of FSW joints to understand the influence of process parameters. Multi-criteria optimization is used to obtain optimum welding conditions that can yield enhanced properties of FSW joints. The optimized results indicated that, the properties can be enhanced with the use of rotational speed of 441 rpm, welding speed of 118 mm/min, and shoulder diameter of 17.5 mm. This is mainly due to very fine stir zone grain structure in the order of 5.5 μm and the presence of thin layer of banded structure at the advancing side of fabricated joints under optimum parameters.

1. Introduction

Friction stir welding (FSW) of high melting temperature materials is gaining importance among the researchers for its applications in oil and gas pipeline, marine and nuclear industries. Now, this process is commercially available for soft materials like aluminum, magnesium and copper alloys in various applications like car body constructions, rolling stock, ocean vessels and aircrafts structures [1–3]. Though the very first feasibility study by Thomas et al. [4], on FSW of high melting temperature materials exist, still, the applicability of this process to weld steels are at the infant stage. Austenitic stainless steels finds wide range of applications in nuclear power plants, components with high operating temperature such as reactors, heat exchanger and pressure vessels etc., due to its superior mechanical and corrosion properties, when compared to other steels [5]. However, the structural application heavily depends on the welded joint performance. Though, they are readily weldable by conventional welding processes such as shielded metal arc welding, gas metal arc welding, gas tungsten arc welding and flux cored arc welding, the welded joints still suffers from the hot cracking susceptibility, loss of corrosion resistance due to the effect of carbon and oxygen, micro segregation and susceptible microstructure to intergranular corrosion [6]. Hence, more careful precautions are needed to retain both mechanical properties and corrosion resistance. To alleviate or even eliminate the problems mentioned above, solid state welding process is preferred. In the recent past, attempts were made by researchers to study the effect of friction stir welding on the microstructural changes, microhardness variations, tensile strength and sensitization resistance of austenitic stainless steels.

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Park et al. [7] observed sigma phase in the advancing side of FSW joints made from 304 grade stainless steel and claimed that, these phases were formed due to the higher strain rate and dynamic recrystallization during austenite to delta ferrite transformation. Park et al. [8] revealed that the advancing side was greatly affected by sensitization due to the formation of chromium carbides and sigma phases. Kokawa et al. [9] observed small ferrite along the grain boundaries of austenitic phase formed in the advancing side of FSW joint made from thin sheets. However, sigma phase was observed in the same location of thick plate welds and this was correlated with the cooling rate after welding. Ishikawa et al. [10] indicated that the corrosion resistance of friction stir welded stainless steel joints can be enhanced through higher welding speed and thereby reducing the sigma phase band width at the advancing side. Rodríguez et al. [11] investigated the effect of post weld heat treatment on the sensitization resistance of FSW joints made of 304 grade stainless steel and witnessed higher sensitization resistance of stir zone, when compared to the base metal. Meran et al. [12] reported that the friction stir welded stainless steel joints fabricated using too lower or too high rotational and welding speeds yielded lower joint strength due to the poor material consolidation.

From the published literature to date on FSW of stainless steels, it is inferred that, the weld metal tensile properties are overmatched with respect to the base metal and hence the failure during tensile testing were always located at the base metal region. However, in the recent effort by Sabooni et al., [13] showed that, the FSW weld metal are undermatched, when compared to the ultrafine grained 304 L grade stainless steel base metal. This was mainly due to the grain coarsening effect caused by friction stirring. Hence, it is clear that, the failure location mainly depends on the process parameters and base metal initial conditions like grain size, composition etc. For any successful structural application, in addition to the tensile strength based joint efficiency of 100%, other aspects like toughness and corrosion need to be considered. Although several investigation on FSW of stainless steel were reported, they are mostly limited to a single response optimization procedure based on the joint tensile strength. However, the influence of friction stir welding process parameters on the multiple quality characteristics must be studied for accomplishing wide range of structural applications. In this investigation, four responses such as tensile strength, notch tensile strength, impact toughness and degree of sensitization were recorded for friction stir welded austenitic stainless steel joints and empirical relationships were developed based on the process parameters such as rotational speed, welding speed and tool shoulder diameter. Further numerical optimization procedure is adopted to simultaneously optimize the multiple quality characteristics of friction stir welded austenitic stainless steel joints.

2. Experimental methodology

2.1. Choosing primary process parameters and its range

Though many primary and secondary factors are affecting the quality characteristics of friction stir welded stainless steel joints, it is clearly evidenced from literature [14,15], the process factors such as rotational speed, welding speed and the tool parameters such as shoulder diameter influences the weld nugget consolidation, defect formation, grain size, band formation in the advancing side, fracture location, mechanical and metallurgical properties. Hence, tool rotational speed, welding speed and tool shoulder diameter are considered in this investigation.

2.2. Fixing feasible working limits of process parameters

Pilot FSW experiments were carried out on a 3 mm thick AISI 304 grade stainless steel plates using a tungsten-1% lanthanum oxide alloy tools to fix the working range of individual factors. A tool pin tapered from 9 mm to 6 mm with pin of length 2.7 mm was used throughout the experiments. To establish the range of individual factor, it was varied from minimum to maximum value, while keeping other factors at a constant value. The feasible working limits were fixed based on the visual inspection considering non uniform weld bead profile (e.g., width of the weld not equal to shoulder diameter), defects and undercut due to the excessive flash formation, sub surface voids etc. The outcome of the above analysis is summarized in Table 1. The upper and lower limits of process parameters were +1.414 and −1.414 respectively and the coded values were calculated using the relationship given in Eq. (1).

$$X_i = \frac{1.414[2X-(X_{\max}+X_{\min})]}{(X_{\max}-X_{\min})} \tag{1}$$

where X_i is the coded value of a variable X which varies from $X_{\min}$ to $X_{\max}$. The working limits of process parameters with its range are presented in Table 2.

2.3. FSW experiments as per design matrix

A three factors, three levels, central composite rotatable small design matrix (Table 3) was used to carry out the friction stir welding experiments. A computer controlled indigenously designed and developed FSW system was operated under position control mode to fabricate the joints. Argon shielding with a flow rate 15 lpm was supplied at the trialing edge for all experimental runs to avoid atmospheric contamination.

2.4. Properties evaluation

The fabricated joints were sliced perpendicular to the welding direction using abrasive cutting and then machined to required dimensions to prepare unnotched smooth tensile, notched tensile, impact and corrosion test specimens. Three sub size tensile samples of both unnotched smooth tensile specimens and center notched tensile specimens were prepared from each welded joint to assess the transverse tensile strength and the average values were recorded. A 100 kN electromechanical controlled Universal Testing Machines (Make: Bluestar, India; Model LW-50) was used to apply tensile loading at the rate of 1.5 kN/min. Sub size impact samples were prepared as ASTM E23-6 guidelines with notch located at the advancing side and a pendulum type impact testing machine (ENKAY, India) was used to evaluate to the room temperature impact toughness. Sensitization resistance was qualitatively measured using a