ABSTRACT

AISI 316L austenitic stainless steel is the second widely used marine grade steel in the industrial sectors like nuclear, marine, petrochemical, food processing, etc. for the fabrication of components and structures. The wide application of the AISI 316L stainless steel is owing to its unique properties and good weldability characteristics. In spite of good weldability, the fusion welded 316L stainless steel joints face the serious consequence of the metallurgical problems such as evolution of secondary phases, coarsening of grains in the HAZ, hot cracking, etc. at the condition of higher heat input in a conventional welding process. The release of hexavalent chromium rich fumes and fine particles of size 0.25µm, owing to the boiling of the weld pool in fusion welding process face serious consequences of health and environment related issues. Prolong exposure to such welding environments can lead to severe risk of respiratory and cancer disorders.

The problem associated with higher heat input and serious risk of health disorders has compelled the researchers to explore the possibility of implementing low heat input solid state processes for the thermal joining of austenitic stainless steels. Friction Stir Welding (FSW), being one of the solid state welding processes was identified as the primitive and potential candidate for thermal joining of high melting temperature (HMT) materials. From the available literatures, it was found that AISI 316L stainless steels were less experimented by FSW and the comprehensive investigation on mechanical, metallurgical and corrosion characteristics of friction stir (FS) welded AISI 316L joints were less explored.

In the present work, AISI 316L stainless steel sheets of 3 mm thick was friction stir (FS) welded using a developed FSW tool material and the influence of primary FSW process parameters on mechanical, metallurgical and corrosion properties of FS welded 316L joints were investigated. A novel concept of

submerged FSW was employed for joining of AISI 316L stainless steel and the evaluated joint properties of the submerged FSW were compared with the traditional FSW process.

In order to perform FSW of AISI316L stainless steel, the tungsten based FSW tool materials were identified as the prominent choice. Three tungsten base FSW tools were developed (tungsten carbide-6% cobalt, tungsten heavy alloy and tungsten-1% lanthanum oxide) to study the performance of tools and weld quality of FS welded 316L stainless steel butt joints. The performance of the tools was examined by photographic and mass loss techniques, whereas the quality of the welds was ascertained by x-ray non-destructive test, optical microscopy and scanning electron microscopy. From experimental analysis, it was found that the FSW tool made of tungsten -1% lanthanum oxide was identified as the potential FSW tool for thermal joining of 316L stainless steel sheets, as the developed tool was subjected to minimal plastic deformation with negligible loss to tool wear.

Using the developed FSW tool, AISI 316L stainless steel sheets were successfully butt joined using the FSW process. The best working range of the primary FSW process parameters such as tool rotational speed, welding speed, axial force and tool tilt angle was determined by conducting trial and error runs. The actual experimental trials were performed using response surface design, preferably, Box- Bhenkhen Design (BBD) comprising of 27 trial runs to evaluate the ultimate tensile strength (UTS) of the friction stir welded AISI 316L butt joints. A second order regression equation was developed based on the evaluated results of the experimental UTS. The adequacy of the model was verified by analysis of variance (ANOVA), adjusted R^2, tabulated F- ratio and conformity tests. From the regression analysis, it was found that the primary FSW process parameters has a significant effect on the UTS of the FSW joints and within the working range, good joints were produced with acceptable joint strength. The generalized reduced gradient (GRG) method was used to determine the optimized FSW process parameters for the condition of maximum UTS. The optimal combination of FSW process parameters are tool rotational speed of 597 rpm, welding speed of 74 mm/min, axial force of 13 kN and tool tilt angle of 1.5 degrees. The weld joint was fabricated and tested at the optimized condition exhibited UTS of 618 MPa (98% of the strength of the base steel). The result of experimental UTS was found in agreement with the optimized result obtained from the regression model.

The mechanical and microstructural properties of the FSW joints were further explored to study the influence of tool rotational speed, welding speed and tool tilt angle. Mechanical tests like tensile test, charpy test and microhardness test was performed to evaluate the properties such as strength, toughness and hardness of the FSW joints. Whereas, the metallurgical characterization studies such as Optical Microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), electron back scattered diffraction (EBSD), energy dispersive spectroscopy (EDS) and x-ray diffraction (XRD) were used to study the microstructure evolution at the weld joint interface.

The weld zone was comprised of various zones like stir zone (SZ), thermomechanically affected zone (TMAZ) and the base metal (BM). Heat affected zone (HAZ) was observed only in high heat input cases with coarse grains due to the influence of the higher temperature. The base steel consisted of coarse austenite grain boundaries with tiny amount of ferrite. The grain refinement was preceded by the dominance of discontinuous dynamic recrystallization (DDRX) mechanism observed in FSW of austenitic stainless steels. After FSW, the SZ consisted of fine equiaxed austenite grains, whereas the TMAZ was comprised of elongated and dislocated grains. The decrease in the size of the grains at the SZ and TMAZ resulted in higher hardness than the base steel. The results of the EDS analysis confirmed that the weld zone was retained with the more or less same chemical composition as the base steel after FSW. The characterization techniques like XRD and TEM did not show any significance to secondary phase evolution in the FS welded joint, owing to lower peak temperatures in FSW process.

The cyclic polarization technique was used to study the pitting corrosion behaviour of the traditional FSW joints and the base steel in a 3.5 NaCl solution. The base steel and the weld joints depicted a similar corrosion behavior with stable pitting potential after activation controlled anodic region. The base steel and FSW joints did not reveal the active-passive region. The pitting corrosion was slightly higher in low and high heat generated FSW joints, but the FSW joint produced at a moderate level of heat generation depicted almost similar pitting corrosion behavior as the base steel.

Submerged FSW of 316L austenitic stainless steel was performed in an artificially prepared 3.5 NaCl solution as the cooling medium. The fixture was designed for circulating cooling medium from the reservoir using a pump. The welding trials performed in submerged FSW depicted a wider working window than the traditional FSW process. An assessment on mechanical and microstructural properties of the submerged FS welded AISI 316L weld joints was explored to study the influence of tool rotational speeds. The highest joint strength more than the base steel was obtained at a tool rotational speed of 1000 rev/min in submerged FSW. Overall, the weld joint characteristics and corrosion properties of the submerged FSW joints were superior to that of the traditional FSW joints.