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INFLUENCE OF TOOL ROTATIONAL SPEED ON MECHANICAL AND MICROSTRUCTURAL PROPERTIS OF FRICTION STIR WELDING OF HIGH STRENGTH LOW ALLOY STEEL JOINTS

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ABSTRACT

Naval grade high strength low alloy (HSLA) steel plates were welded using friction stir welding (FSW) process with five different tool rotational speeds varying from 500 rpm to 700 rpm to study the effect of tool rotational speed on FSW joint characteristics. Microstructural characteristics of the weld joints were analyzed using optical microscopy (OM). Of the five tool rotational speed, the tool rotational speed of 600 rpm yielded defect free sound joint with acceptable impact toughness properties. Tensile strength and hardness of the stir zone are higher (overmatched) compared to that of the base metal due to the formation of finer grains with high dislocation density caused by the stirring action of the rotating tool.

Key words: *Friction stir welding; HSLA steel, Tool rotational speed, Microstructure, Tensile properties.*

1. Introduction

Now-a-days, the micro-alloyed high strength low alloy (HSLA) steels become an indispensable class for different applications like construction of pressure vessels, piping, storage tanks, etc. HSLA steels demonstrate unique properties such as high strength, excellent ductility, and good weldability, and also exhibit outstanding low temperature impact toughness superior to that of high yield strength (HY) steels [1]. Fusion welding of these grade steels is affected both by the temperature and composition which extensively affects the microstructure evolution. In these grade steels, the heat affected zone (HAZ) is prone to failure due to the possibility of hydrogen induced cracking and only way to weld such steels is to use low hydrogen ferritic steel filler wire [2]. The resistance to hydrogen-induced cracking and stress corrosion cracking was improved by coarse grain heat affected zone which consists of martensite-austenite constituents, and thus showing the importance of reduction in carbon content of these steels [3]. Steels used in shipbuilding are joined as structural components that are welded on panel lines. Weld distortion increases substantially as component thickness decreases below 13 mm which makes increased fabrication costs and weld repair work [4].

Friction stir welding (FSW) process, a novel solid state joining technique, is presently attracting significant attention on welding of hard metals such as steels and titanium alloys [5]. FSW has appeared as a simple, ecological and promising productive welding method that reduces material waste and avoids radiation and harmful gas emissions, usually associated with the fusion welding processes. Mechanical action, in the form of frictional stirring, on the base material has modified the microstructure from the coarse grains to very fine grains due to plastic deformation and fast cooling rate [6]. Welding of steels is affected by both the temperature and composition which extensively affects the microstructure evolution. Friction stir welding enables to control these factors and produce superior joint strength [7]. The rewards of FSW process also includes low residual stress, low energy input and a fine homogeneous microstructure compared to the conventional fusion welding processes. The application of FSW to high temperature materials has been limited due to the durability of the tool material, which isrequired to sustain its microstructure and properties at temperatures higher than 1000 ^{o}C. Much of the tool degradation may be attributed to the high heat (temperature around 1200 ^{o}C) and the stresses generated during friction stir welding of these high strength

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materials [5]. Gan et al. reported as the physical tool wear is often affected by the particulates in the base material and also chemical interaction between the material being welded and the tool materials [8]. However, the development of the wear resistant tool materials has benefited the FSW process and paved way for the rapid implementation of this process in the fabrication of high strength steel structures [9]. The non-consumable rotating tool has different portions known as pin, shoulder and shank. Among these, the shoulder diameter and pin diameter controls the frictional heat generated during the welding process. The former i.e. the shoulder diameter is the primary heat generating source as the contact area between shoulder and surface of the base metal is higher [10].

The above-mentioned literature study revealed that FSW has more advantages than fusion welding. Also, many investigations [4-10] have been carried out to understand the mechanical properties and metallurgical characteristics of FSW joints. However, not many investigations are carried out to study the effect of tool rotational speed on achieving defect free joint without tool wear. Hence, determination of the tool rotation speeds for attaining defect free joints without tool wear and with acceptable values of mechanical properties of HSLA steel joint was aimed in this study.

2. EXPERIMENTAL DETAILS

The hot rolled plates of HSLA steel with thickness of 5 mm were cut to the required dimensions (150 mm × 300 mm) by abrasive cutting to prepare the joint configurations. The microstructure of base metal characterized by optical microscope (Fig. 1) showing predominantly ferrite with small amount of pearlite. The chemical composition and mechanical properties of base metal are presented in Table 1 and 2.

Non-consumable tool made of lanthanated tungsten (99%W-1%La_2O_3) was used to weld the joints using FSW process [8]. The tools were manufactured through powder metallurgy route having shoulder diameter of 25 mm with tapered pin, tapering from 12 mm at the shoulder to 8 mm at the pin tip (Fig. 2). Welding parameters used to fabricate the joints are presented in Table 2.

Table 1. chemical composition (wt. %) of parent metal

C	Mn	N	Si	Mo	Ti	V
0.08	1.42	0.015	0.19	0.02	0.016	0.032

Table 2. Mechanical Properties of the Parent Metal

0.2% offset yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 25 mm gauge length\ (%)	Impact toughness @ RT (J)	Hardness of base metal @ 4.95N load (HV)
540	610	24	62	270

Fig 1. Optical Micrograph of Parent Metal

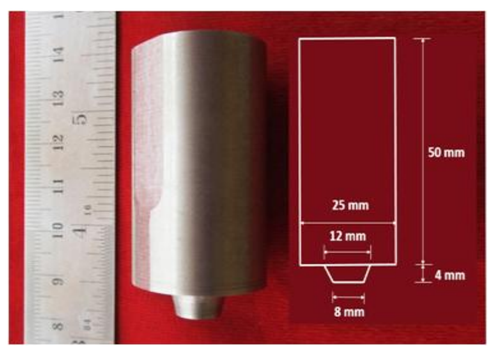

Fig 2. Photograph of Tungsten Based Alloy Tool and Tool Dimensions

The specimen for metallographic examination was sectioned to the required size from the joint comprising weld metal, HAZ (heat-affected zone), and base metal regions, and polished using different grades of emery papers. Final polishing was performed using diamond compound (particle size of 1 μm) on the rotating disc type polishing machine. Specimens were etched with 2% Nital solution to reveal the microstructural features of the joints. Vicker's microhardness tester was used for measuring the hardness distribution across the weld cross-section along the mid thickness region with a load of 4.95 N.

ASTM E8M-14 guidelines were followed for preparing the tensile test specimens from the welded joints. Electromechanical controlled universal testing machine (100 kN capacity) was used to evaluate the tensile properties. Impact testing was conducted on a pendulum-type impact testing machine (300 J capacity) at room temperature. The amount of energy absorbed in fracture was recorded. The absorbed energy is defined as the impact toughness of the joint.

3. RESULTS

3.1 Peak Temperature

The photographs of top surface of the five joints fabricated using tool rotational speeds varying from 500 to 700 rpm were displayed in Fig.3. Fig.3 (b) and (c) showing discontinuous weld bead and more weld flash due to insufficient heat generation rate (Fig. 4 (a) and (b)). Whereas, with the increase in tool rotational speed increases the heat generation rate (Fig. 4 (c)-(e)) results in good weld surface, and there is no evidence of surface defects (Fig. 3(d)-(f)).

The recorded temperature profiles of all the five joints are displayed in Fig. 4 (a)-(e). From this observation, it is clear that increase in tool rotational speed increased the peak temperature in the parent metal during FSW. In addition, recorded axial load was higher during plunging stage compared to mid stage (Fig. 4f). This is due to initial thermo-mechanical condition and chemical affinity of the base metal with tool material.

3.2 Effect of tool rotational speed on stir zone formation

The cross section of the all the joints were analyzed using optical microscopy and displayed in Fig. 5. Figs. 5 (a), (b) and (c) shows the macrostructure and microstructure of the joint fabricated using a tool rotational speed of 500 rpm.

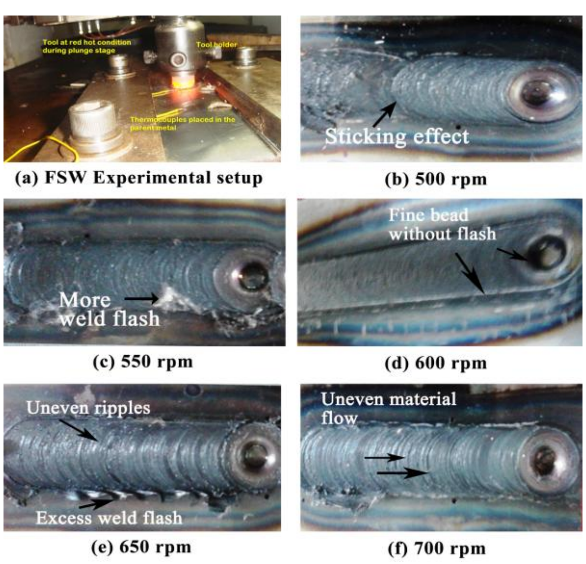

Fig 3. FSW Experimental Setup and Images of Top Surface of Joints

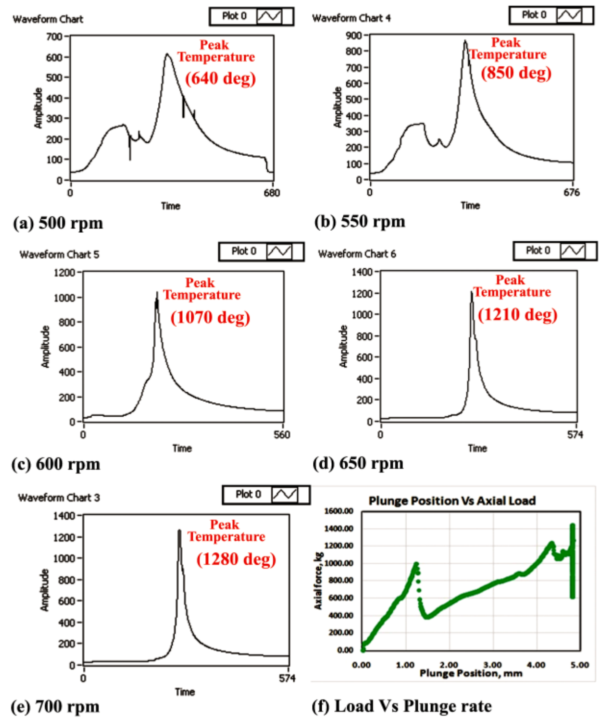

Fig 4. Temperature and Axial Load Recorded During FSW

Since the macrostructure shows defect free, presence of tungsten particles (tool debris) in the stir zone have been observed (Fig. 5a). Formation of coarse grain microstructure in the shoulder influenced region (Fig. 5b) and banded structure in the pin influenced region (Fig. 5c) are clearly visible. This is due to the low frictional heat generation rate in the stir zone region during FSW. The microstructure presented in Figs. 5 (d), (e) and (f) reveal the sudden change in grain orientation due to the metal excavation from advancing side to deposit in the retreating side with tungsten tool debris. Even though the pin influenced region shows the defect free joint, tool wear was observed in the retreating side pin influenced region (Fig. 5d).

Similarly in the Fig. 5 ((j)-(o)), severe deformation of the material is observed in the shoulder influenced region along with higher tungsten particles in the pin influenced region. Whereas, joint fabricated using a tool rotational speed of 600 rpm achieved proper coalescence of the parent metal without tool wear and it is evident from the Figs. 5 ((g), (h) and (i), which may be contributed by the appropriate temperature required for thermo-mechanical process during FSW.

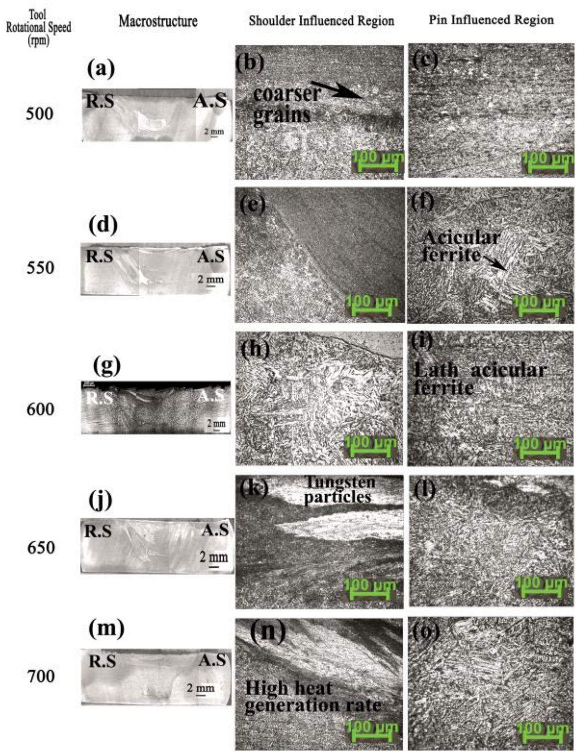

Fig 5. Effect of Tool Rotational Speed on Stir Zone Formation

3.3 Effect of tool rotational speed on mechanical properties

The tensile properties of the base metal and welded joints are presented in Table 3. The yield strength and tensile strength of base metal was 438 MPa and 610 MPa, respectively. Compared to the base metal, inferior tensile properties were yielded by the joints fabricated using tool rotational speed of 500 rpm (low level) and 700 rpm (higher level) as 560 and 590 MPa respectively. But the yield strength and tensile strength of FSW joint fabricated using tool rotational speed of 600 rpm are 502 MPa and 664 MPa, respectively. The joints fabricated using tool rotational speed of 600 rpm (mid level) by FSW process exhibited overmatched strength values compared to base metal due to refinement of microstructure.

Charpy impact toughness test results are presented in Table 3. The impact toughness of base metal is 78 J at room temperature. When the weld metal is welded by FSW process, it exhibits 48 J, which is 38% lower than that of the base metal. But the joints fabricated using lower and higher level tool rotational speed yielded the lowest impact strength compared to base metal.

3.4 Effect of tool rotational speed on hardness

Fig. 6 shows the hardness variations across the weld. The hardness of the as-received base metal is approximately 270 HV. The hardness of stir zone varies from 300 HV to 410 HV, depending on the grain size from each indentation.

Table 3. Mechanical Properties of the FSW Joints

Tool rotational speed (rpm) and Heat input (kJ/mm)	0.2% offset Yield strength (MPa)	Tensile strength (MPa)	Elongation in 25 mm gauge length (%)	Charpy impact toughness @ RT (J)
500 (0.8795)	479	560	14	36
600 (1.0555)	502	664	19	48
700 (1.2314)	487	590	16	39

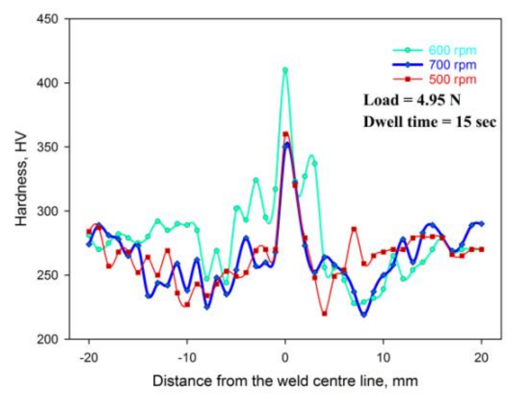

Fig. 6 Hardness Survey on Various Zones of FSW Joints Fabricated Using Tool Rotational Speed of 500, 600 and 700 rpm

The microhardness of stir regions zone of joints fabricated using tool rotational speed of 500 and 700 rpm varies from 350 HV to 380 HV, depending on the grain size from each indentation. Hardness is found to be very high in SZ of FSW joint fabricated at 600 rpm. The failure location of the welded joints is consistent with hardness distribution profile. The failure occurred in all the joints along the lowest hardness distribution region (LHDR).

4. DISCUSSION

Since FSW is difficult for hard alloys and not widely used, there is a lack of data and theory to enable the selection of process parameters to enhance the tool durability and to achieve better weld quality. Therefore, in order to improve the weld quality and tool life, it is important to optimize the tool rotation speed with an objective of producing defect free sound joint. If there is not enough heat supplied to the stir zone, it is difficult to achieve a plastic flow so that a groove defect will easily occur [2]. In addition, tool pressure and temperature are related with the time at different tool rotation speeds. Hence, by optimizing the tool rotational speed which in turn controls the heat generation rate to achieve defect free joint in the FSW of HSLA steel plates [6].

In general, higher heat input leads to slower cooling rate which results in the formation of coarse grain microstructure (Fig. 4b) in the stir zone [16-18]. However, lower heat input leads to fast cooling rate which results in the formation of fine grain microstructure (Fig. 4g). Although the lower heat input as preferred as it can produce finer grains however, the same can leads to inadequate plasticized material flow around the tool pin (Fig. 4m). This causes more tool wear due to increased flow stress to the tool pin. At the same time, high heat input caters the material to flow turbulently around the pin which results in excess weld flash formation.

Dynamic recrystallization is a phenomena occurring during the material movement in FSW. Table 3 illustrates the effect of different tool rotational speeds on strength and ductility. The increased strength is attributed to the fine grain microstructure consisting of acicular ferrite and upper bainite regions. Also, the elongated spherical inclusions of MnS may also be an important factor in reducing the ductility. This is because the plates of acicular ferrite nucleate intragranularly on non-metallic inclusions within large austenite grains, and then radiate in many different orientations from those inclusions whilst maintaining an orientation relationship with the austenite [15-19]. The impact strength of upper bainite adversely affected by the presence of cementite as thin film at the lath boundaries of bainite increases the presence of martensite which does not contribute to strength but lowers the toughness [20].

The recrystallization was accompanied by a change in the microstructure from coarse grains to fine grains [11]. This size of the recrystallized grains increased with rotation speed of the tool. The post weld microstructure of the SZ consists of shear transformed bainitic ferrite with carbides and lath acicular ferrite, which could be the reason for higher hardness values. The micro hardness values are less significant in affecting the mechanical properties because the inherent nature of the tool rotational speed has more influencing factors over the hardness values [20].

The tool rotational speed is directly proportional to heat generation due to frictional stirring [13]. If the rotational speed is higher, then heat generation rate due to friction will be high and vice versa. In this investigation it has been observed that the lower tool rotational speed (<600 rpm) has less frictional heating which leads to insufficient heat generation (0.875 kJ/mm). Thus the entrapment of tool debris is observed in the stir zone due to improper material flow because of inadequate plasticization of the base metal in the stir zone. It has also been observed that the higher tool rotational speed (>600 rpm) leads to more frictional heat generation (1.231 kJ/mm) and hence the turbulent flow of the plasticized material leads to excess weld flash formation. Whereas, the higher grain refinement was observed in the welds produced with the tool rotational speed of 600 rpm (mid level) due to optimum heat generation (1.05 kJ/mm). The higher material dragged and proper consolidation of that dragged material at the advancing side without any interface gap was achieved in this 600 rpm tool rotational speed. Therefore, the joint fabricated using tool rotation speed of 600 rpm showed the superior mechanical properties over the other joints, it is because of proper plasticized material flow and controlled cooling rate were achieved during stirring and resulted in homogeneous microstructure consisting of refined acicular ferrite and upper bainite without any tool debris.

5. CONCLUSIONS

In this investigation, an attempt has been made to study the effect of tool rotational speed on stir zone characteristics of friction stir welded naval grade HSLA steel joints. From this investigation, the following important conclusions are derived.

1. Of the five joints fabricated, joint made using a tool rotational speed of 600 rpm with tool traverse speed of 30 mm/min yielded defect free sound joint with 10% overmatched tensile strength (646 MPa). This combination of process parameters generated optimum level of heat input of 1.05 kJ/mm, is found to be sufficient to plasticize the material and to refine the grains in the stir zone.
2. The hardness of the stir zone of the HSLA steel joints is higher than base metal, irrespective of tool rotational speeds and heat input. This is mainly because of dynamic recrystallization caused by the severe plastic deformation and high rate of straining during the FSW process.
3. The stir zone microstructure evolved at the tool rotational speed of 600 rpm shows the formation of lathe upper bainitic microstructure. This could be the one of the reasons for higher tensile strength with acceptable impact toughness properties of the joint.

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