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Engineering tensile properties by controlling welding parameters and microstructure in a mild steel processed by friction stir welding

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ABSTRACT

In order to evaluate the effects of welding parameters on microstructure and tensile properties, a mild steel was stir welded under various conditions. The results revealed that carrying out the friction stir welding (FSW) process in lower rotation speeds or higher welding speeds due to lack of heat input and low flow-ability of the welding material, tunnel defect and flaky surface is appeared. In contrary, in higher rotation speed or lower welding speed, the temperature of stir zone (SZ) reached to single austenite region owing to significant increment of heat input. Consequently, refined microstructure involving ferrite and pearlite transformed from new fresh austenite can be formed. Tensile behavior of the FSW processed specimens exhibited relatively higher amount of yield strength and limited uniform elongation in comparison with the starting material. But, the samples has tunneling defect or any other welding defects showed very limited uniform elongation.

1. Introduction

Friction stir welding (FSW) is a powerful technique to join materials in solid state. This process includes three phases which are extrusion, shearing, and consolidation of material at high temperature [1,2]. The FSW is a near net-shape fabrication method that has many benefits over traditional joining processes, particularly where weld characteristics of material are poor. In FSW, a specially designed tool rotates and traverses along joint line under vertical forces. The process produces frictional heat and consequently a column of material softens underneath of the tool. Softened material flows due to extensive plastic deformation and is consolidated behind the tool to form a contiguous joint. Normally, intense plastic deformation at high temperature during welding leads to formation of fine and equiaxed recrystallized grains [3,4].

Steels are among the broadly used structural materials which demand for development and application of effective welding techniques. However, fusion welding of steel highlights major drawbacks such as grain growth, segregation of alloying elements, solidification cracking, porosity, hydrogen embrittlement and development of dendritic structure and result in problems for component integrity [5,6]. In addition, non-availability of economic tool material which can bear high plunging load at high temperature during welding causes major difficulties during FSW of ferrous alloys. At present, the most commonly used tool materials for FSW of steel are polycrystalline cubic boron nitride (PCBN) and tungsten-based alloys [7].

During a set of experiments in which FSW was performed by Cho et al. [8] for API grade100X steel, the presence of acicular bainite with weak shear texture at stir zone (SZ) was specified and they inferred that rearrangement of low-angle grain boundaries and continuous dynamic recrystallization accompanied by phase transformation causes grain refinement at SZ. This is similar to what Sato et al. [9] who found out in FSW of aluminum and shed lights which is one of the key benefits about FSW with regard to fusion welding processes. In a relevant research which was conducted by Reynolds et al. [10], the impact of weld rotational speed on the microstructure, strength and residual stresses of friction stir welds in 304L stainless steel was reported. It was found that welding at constant welding speed which is accompanied with variable rotational speed and hence weld power causes a microstructural refinement in the weld piece.

Although few studies were done to characterize change of microstructure or mechanical properties in several kind of steels processed by FSW process [11–13]. However, there is leak of systematic understanding concerning microstructure development and resultant mechanical properties of FSW processed mild steel with respect to FSW parameters such as rotation speed of the pin or welding speed. The present study aimed to clarify change in microstructure from different parts of the welds and obtained mechanical properties are interpreted by microstructural evolution.

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2. Experimental procedures

In the present research, hot rolled sheet of st37 steel, which chemical composition is given in Table 1 was used as the starting material. The starting material was cut from hot rolled sheet with initial dimensions of 300 mm in length, 100 mm in width and 2 mm in thickness.

The dimensions of the plates after welding were $300 \times 100 \times 2$ mm. A milling machine was used in order to perform the welding operation with usual steel fixture. FSW tool was made from tungsten alloy bar with 16 mm in diameter and length pin of 0.8 mm. The tool was produced with a very simple geometry that included a slightly tapered, and a shoulder diameter of 16 mm. The tool was tilted at an angle of 3° from normal to the welded plate. Welding parameters, tool dimension and sample nomenclature are shown in Table 2.

Scanning electron microscopy (SEM) using a conventional type gun (SEM, Philips-XL30) quipped with electron backscatter diffraction (EBSD) system operated at 15 kV and optical microscope were used in order to characterize microstructure of the FSW processed specimens. The sample were prepared from weldment using standard metallographic procedures followed by etching in 2% nital. Grain size and area fraction of phases were estimated using image analyzing software. The section of the specimen for EBSD observation was polished mechanically and then electrolytically in a 900 ml CH_3COOH + 100 ml $HClO_4$ solution at approximately 284 K with a voltage of 20 V.

Tensile test was performed by uniaxial tensile test machine based on ASTM E8 standard specimens at room temperature with extension rate of 0.017 mm/s. Gauge length of each specimen contained weld nugget, heat-affected zone, and partially base metal from both sides.

3. Results and discussion

3.1. Macroscopic analysis

Fig. 1 illustrates the macroscopic images of the specimens subjected to the FSW process in different rotation speeds or welding speeds. As can be seen, the directions of pin rotation and welding as well as advancing side (AS) and retreating side (RS) areas are also indicated [2]. Macroscopic images obtained from the sample 1 and 2 are relatively perfect and free of any welding defects as shown in Fig. 1a and b. In contrast, the sample 3 and 4 demonstrate flaky surfaces in the weldment indicating that the welding parameters have a crucial role to obtain perfect weldment during welding process. It can be proposed that increasing the transverse welding speed brought about decrease of heat input and as a result, flow-ability of the material would decrease. From another point of view, increasing welding speed resulted in a decrease of contact time between pin and work-piece [14]. Hence, whole of the material that are flown by the pin from the AS cannot perfectly reach to the RS and this causes formation of welding defect.

The cross section micrograph from different parts including base metal (BM), heat affected zone (HAZ) and stir zone (SZ) of the weldment originated from different welding conditions are shown in Fig. 2. It should be noted that no distinct thermos-mechanically affected zone (TMAZ) is observed in the studied mild steel after FSW process. This is in well consistent with previous reports [12,17] that are emphasized no appearance of TMAZ during FSW of mild steel. It has been well known that TMAZ in Al alloys shows a dynamic recovery features in the microstructure. However, in carbon steel alloy due to the allotropic transformation during cooling dynamic recovery feature can be destroyed [12].

The micrograph images for all of them show that the width of the welds in upper surface of the welds is almost equivalent to the diameter of the pin and it gradually decreases from upper to bottom surface in different rates. As can be seen, the maximum rate belongs to the sample 3 owing to the fact that by increasing the welding speed, heat input is decreased. Furthermore, in low rotating speed or high welding speeds, the heat input and flowability of the material are decreased and resultantly the volume

Table 1
Chemical composition of the studied steel (wt%).

Element	Mn	Si	C	Cr	P	Fe
Steel	0.49	0.27	0.18	0.086	0.025	98.7

Table 2
Welding parameters, tool dimension and sample nomenclature (sample ID).

Sample ID	Rotational rate (rpm)	Traversing speed (mm/min)
Sample-1	450	50
Sample-2	560	50
Sample-3	450	160
Sample-4	560	160

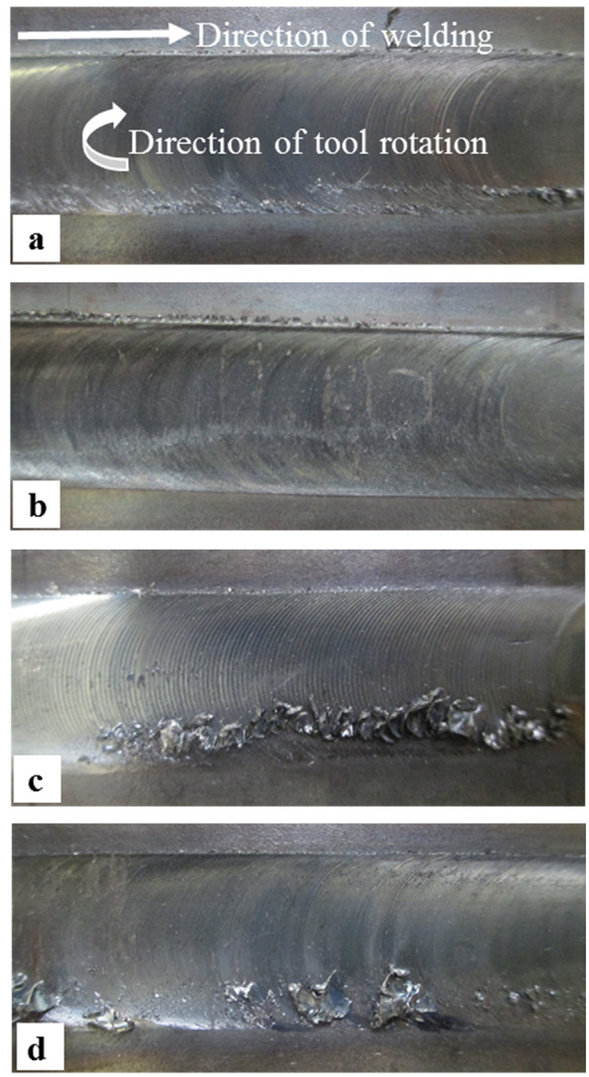

Fig. 1. Image of the weld bead a) Sample-1 b) Sample-2c) Sample-3 d) Sample-4.