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Original Research Article

Tensile behavior, microstructure, and substructure of the friction stir welded 70/30 brass joints: RSM, EBSD, and TEM study

Akbar Heidarzadeh

Department of Materials Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran

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ABSTRACT

The effect of bead on plate friction stir welding parameters on the tensile properties of the 70/30 brass joints was investigated using response surface method. The microstructures of the joints were characterized using optical microscopy, electron backscattered diffraction (EBSD), and transmission electron microscopy (TEM). The tensile test was conducted to measure the ultimate tensile strength and elongation of the joints. In addition, the fracture surfaces of the tensile specimens were analyzed by scanning electron microscopy (SEM). The results showed that the most effective parameters on the strength and elongation of the joints were tool rotational speed and axial force, respectively. Optimizing the parameters revealed that the maximum strength and elongation of 318.5 MPa and 54.9% can be achieved at a rotational speed of 1000 rpm, a traverse speed of 58.4 mm/min, and an axial force of 3 kN. The strengthening mechanisms of grain boundary and dislocation density effects were responsible for the higher ultimate tensile strength of the joints welded at the lower heat input conditions. Furthermore, the effect of friction stir parameters on the ultimate tensile strength and elongation of the joints has been discussed, thoroughly.

1. Introduction

The brasses (Cu–Zn alloys) have different physical and mechanical properties according to their Zn content. Therefore, a wide range of properties can be achieved in brasses by changing their chemical composition. In addition, brasses have high electrical and thermal conductivities, high corrosion resistance, good combination of strength and ductility, etc. [1]. These various properties of brasses have attracted many attentions in both the academic and industrial point of views. Thus, the demands have been increased for manufacturing and processing of the brass parts. One of the most important processes is welding and joining during production of brass parts.

Unfortunately, the conventional fusion welding processes are not suitable for joining the brasses, which is due to two major reasons. First, the high thermal conductivity of the brasses cause the need for high heat inputs during fusion welding processes, and hence wide heat affected zone (HAZ) can be formed in the structure of the joints. Second, fusion and solidification of the weld metal results in dendritic structures, macro and micro segregations, porosities, inclusions, shrinkages, large distortions, residual stresses, zinc evaporations,

E-mail addresses: ak.hz62@gmail.com, ac.heydarzadeh@azaruniv.ac.ir.
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color change, etc. in the joints [2]. These difficulties of the conventional fusion welding have encouraged the scientists to find new methods for joining the brasses.

Fortunately, it has been proved by researchers that the friction stir welding (FSW) is a suitable method to join the brasses [3,4]. In this process, a rotating non-consumable tool inserts into the work pieces and then traverses along the welding line. During FSW, the materials do not melt, in which the coexistence of heat and severe plastic deformation leads to sound joint formation. Thus, the conventional fusion welding problems, arisen from the melt and solidification steps, are eliminated by using FSW. On the other hand, the FSW joints have a deformed and recrystallized structure, which typically causes enhancement of the mechanical properties [5,6]. Thus, FSW can be a promising method to replace the conventional fusion methods for joining the brasses.

Some researchers have studied the FSW of brasses in recent years [7–15]. Heidarzadeh et al. [7] have compared the microstructure and mechanical properties of the single and double phase brass alloys, and found that the double phase joint had finer grain structure and better mechanical properties. Wang et al. [8] have used water flowing during FSW of Cu–30 wt.% Zn, which caused formation of grains inside the SZ of the joints with an average size smaller than 1 μm. Heidarzadeh et al. [9] have correlated between process parameters, grain size, and hardness of friction-stir-welded Cu–Zn alloys. They showed that the Hall–Petch equation deviates from its linear relationship due to formation of substructures inside the stir zone (SZ). Mironov et al. [10] have investigated the grain structure formation during FSW of Cu–30 wt.% Zn alloy. They demonstrated that the new grains form by bulging of the grain boundaries and nucleation mechanism during FSW, which causes finer grain sizes and high strengths in the joints. Xie et al. [11] have studied the effects of FSW parameters on microstructures and mechanical properties of brass joints. They showed that the tensile and yield strengths of the welds reached up to ~99 and 80% of the PM, respectively. In Ramesh et al. [12] research, the 6-mm-thick dual-phase brass plates were joined efficiently using FSW at various tool rotational speeds. They concluded that the recrystallization was inhomogeneous in SZ and the inhomogeneity reduced with increased tool rotational speed. Heidarzadeh et al. [13] investigated the Microstructure, texture, and mechanical properties of friction stir welded commercial brass alloy. They revealed that continuous and discontinuous dynamic recrystallizations (CDRX and DDRX) were the main mechanisms of the grain structure formation during FSW. Ozer et al. [14] explored the effect of FSW parameters on microstructure and fatigue strength of Cu–37 wt.% Zn brass alloys. Liu et al. [15] have studied the microstructural evolution during FSW of a single phase brass. They have shown DDRX in conjunction with annealing twinning are the grain structure formation during FSW.

According to the above literature, some researchers have investigated FSW of brass plates. However, an investigation into the optimizing the process parameters in conjunction with elucidating the origins of the improved mechanical properties in the optimum joint is lacking. The main novelty of this paper is the fact that it is the first time to use the response surface method (RSM) in conjunction with electron back-scattered microscopy (EBSD) and transmission electron microscopy (TEM) for FSW of single phase brasses. Therefore, the aims of this study can be divided into two categories. The first aim was optimizing the FSW parameters to enhance the tensile properties of the single phase brass joints. The second aim was elucidating the microstructure, substructure, and texture of the optimized joint.

2. Materials and methods

Single phase brass (Cu–30 wt.% Zn) plates with dimensions of 100 mm × 100 mm × 2 mm were used as the base materials (BMs). A H13 hot work steel tool consisted of a shoulder with a diameter of 12 mm, and a pin with a diameter and length of respectively 3 mm and 1.75 mm was employed. For experimental design and optimizing aim, the response surface method (RSM) in conjunction with central composite rotatable design was used using Design Expert software. The considered parameters with their symbols, units, levels, and actual values are summarized in Table 1. In addition, the experimental design matrix including 20 runs, the experimental and predicted ultimate tensile strength (UTS) and elongation (*E*) is summarized in Table 2.

The microstructure of the joints was first examined by using a light microscopy (LM). The LM specimens were cross sectioned from the joints perpendicular to the FSW direction, and they were then prepared by mechanical polishing and etching with a solution of 50 mL HCl, 10 mL H_2O and 5 g $FeCl_3$. The grain size of the joints were estimated by using the mean intercept method. In addition, tensile test was conducted to reveal the tensile properties of the joints. For this purpose, the longitudinal tensile samples were wire cut along the welding line with gage size of 12 mm (length), 3 mm (width), and 2 mm (thickness). The schematic of the tensile specimens with dimensions is illustrated in Fig. 1. Tensile tests were conducted at a stain rate of 1 mm/min. It is notable that four tensile tests were carried out for each FSW parameters.

A Philips XL30 E-SEM field emission gun scanning electron microscope equipped with EBSD system was employed for OIM of the joint welded at optimum condition. The EBSD scans were taken from the center of the SZs of the joints. The

Table 1 – Coded and actual values of FSW parameters.

Parameters	Unit	Levels				
		−1.68	−1	0	1	1.68
Rotational speed (A)	rpm	463	600	800	1000	1136
Traverse speed (B)	mm/min	16	50	100	150	184
Axial force (C)	kN	1.66	2	2.5	3	3.34