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Effect of tool pin profile on microstructure and mechanical properties of friction stir welded pure copper joints

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ABSTRACT

In the present study, the effect of tool pin profile on microstructure and mechanical properties of friction stir welded pure copper joints were investigated. Two different tools with threaded cylindrical and square pin profiles were used to fabricate the joints at constant rotation rate of 600 rpm and traverse speed of 75 mm/min. Four K-type thermocouples were used to record the temperature histories of samples during FSW. Microstructure features of the joints were characterized by optical microscopy and the obtained images were quantified using image analysis technique. Tension test and Vickers hardness measurements were also performed to characterize the mechanical properties of the joints. Obtained results showed that sample welded using square pin profile had finer recrystallized grain structure and higher mechanical properties relative to sample welded by threaded cylindrical one. These results were attributed to higher eccentricity of the square pin profile and its pulsation effect which led to higher degree of plastic deformation and higher heat input into the joints.

1. Introduction

Copper has been considered as an acceptable material for use in many industrial areas, because it possesses the essential characteristics of high electrical and thermal conductivities, favorable combination of strength and ductility, and excellent resistance to corrosion [1–3]. Therefore, there is an increasing demand for the welding of this structural material. While fusion welding of copper is limited because of its high thermal diffusivity and high oxidation rate at melting temperature [4,5], a relatively new solid state process called friction stir welding (FSW) can be applied to weld this material successfully [6]. FSW which was invented by The Welding Institute (TWI) of the UK in 1991 [7] is a welding process in which a non-consumable welding tool is used to generate both the frictional heat and mechanical deformation simultaneously in order to make a solid state joint.

Although FSW has been investigated extensively in the case of aluminum alloys [8–10] and magnesium alloys [11,12], there are only a few studies investigating FSW of pure copper and its alloys [13–16]. Xie et al. [14] investigated the effect of tool rotation rate on microstructure and properties of friction stir welded (FSWed) copper joints at constant traverse speed. They reported that grain size decreased in the stirred zone (SZ) with decreasing rotation rate where both of the microhardness and yield strength increased through Hall–Petch relationship. Shen et al. [15] investigated the effect of traverse speed on the microstructure and hardness of FSWed copper at constant rotation rate and reported that as the traverse speed increased, the grain size of SZ first increased and then decreased. Hardness values of the SZ were considerably lower than that of the base metal (BM) which can be related to the microstructural changes.

More recently, authors of the paper have investigated the effect of traverse speed and tool rotation rate on the microstructure and mechanical properties as well as strain hardening behavior of FSWed copper joints [16]. It was found that samples welded with rotation rate of 600 rpm and traverse speed of 75 mm/min showed the optimum condition, i.e., finer microstructure and improved mechanical properties [16].

Along with the rotation rate and traverse speed, some authors have investigated the effect of tool pin profile on microstructure and mechanical properties of FSWed aluminum [17–19] and magnesium alloys [20]. Elangovan and Balasubramanian have published some papers investigating simultaneous effects of tool design and welding parameters on defect formation in friction stir processing of aluminum alloys [18,19]. They used five pin profiles i.e., straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins to fabricate the joints. Their results showed that although tool profile has significant effect on microstructure and mechanical properties of the aluminum joints, defect free joints with superior tensile properties were achieved by using square pin profile irrespective of other parameters.

Although a few studies could be found in the literature investigating the effects of tool pin profile on microstructure and mechanical

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properties of FSWed aluminum [17–19] and magnesium alloys [20], no efforts have been devoted to investigate the subject in the case of FSWed copper joints. Importance of tool pin profile and its significant effect on microstructure and properties of weldment as well as the lack of information in this field in the case of copper and its alloys promoted the authors to investigate the subject. Therefore, the aim of this paper is to investigate the effect of tool pin profile on microstructure and mechanical properties of FSWed copper joints. For this purpose, two different tool pin profiles, i.e. threaded cylindrical and square pins were used to fabricate the joints, whereas the other welding parameters (i.e. rotation rate and traverse speed) were kept constant. Microstructural and mechanical properties of the joints were compared with joints welded using these two different pin profiles. Thermal cycles around the weld centerline were also recorded in order to explain the microstructure and properties variation.

2. Experimental procedure

Commercial pure copper plate with a thickness of 5 mm was joined by FSW perpendicular to the rolling direction. An indigenously designed and developed machine has been used to fabricate the joints. The workpieces were fixed during FSW with a well designed fixture. Fig. 1a shows a photograph of FSW machine equipped with the fixture. Two different tools with threaded cylindrical and square pin profiles (both having 6 mm of pin diameter, 20 mm of shoulder diameter and 4.7 mm of pin length) have been used to fabricate the joints, as shown in Fig. 1b. Constant tool rotation rate of 600 rpm and traverse speed of 75 mm/min were considered according to the findings of our previous work [16].

Four K-type grounded thermocouples with a sheath diameter of 1 mm were used to record the temperature histories during FSW. Small holes with a diameter of 1 mm were drilled on the workpiece and the sensing head of the thermocouples were securely embedded in the holes. The thermocouples were connected to a computer using a digital thermometer in order to collect temperature data.

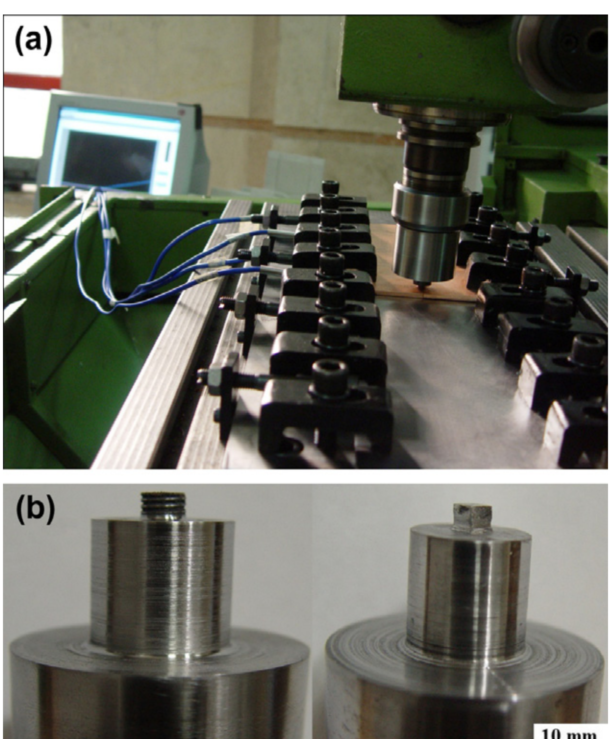

Fig. 1. Photograph of: (a) FSW machine equipped with fixture and (b) two different FSW tools.

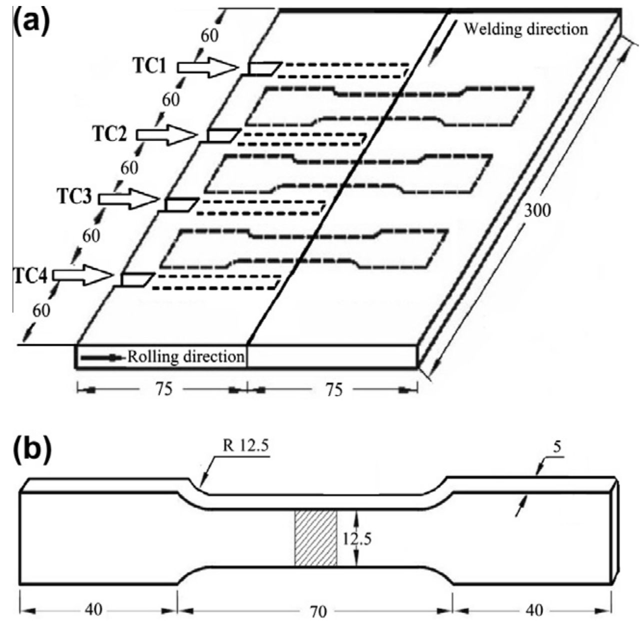

Fig. 2. Schematic illustration of: (a) tensile specimens and thermocouples positions in the workpiece and (b) dimensions of tensile test specimen.

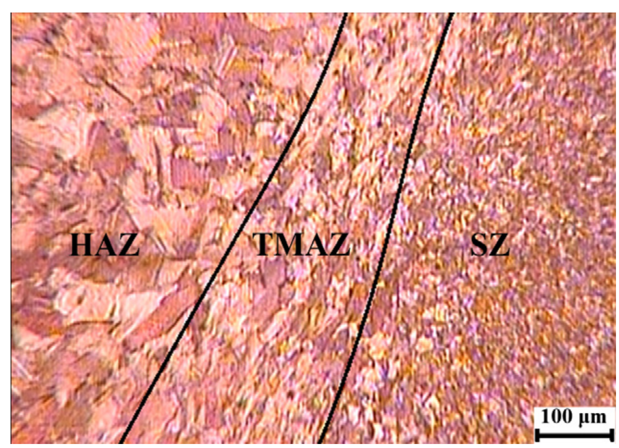

Fig. 3. Microstructure of sample welded by threaded cylindrical pin profile showing the SZ, TMAZ and HAZ (rotation rate of 600 rpm and traverse speed of 75 mm/min).

The positions of the thermocouples inside the workpiece are shown in Fig. 2a.

The metallographic specimens were cross-sectioned from the FSW joints transverse to the welding direction. The specimens were prepared using conventional grinding and polishing technique. Polished samples then etched with a solution of 20 mL nitric acid and 10 mL acetic acid. Microstructure features of the FSWed joints were characterized by optical microscopy. Average grain size and size distribution histograms were obtained by analyzing at least 3 images using CLEMEX image analyzing software [21]. The software distinguishes different grains using various color contrast, and then calculates equivalent diameter (D_{Eq}) of each grain from its area according to the following equation [21]:

$$D_{Eq} = 1.2247 \times \sqrt{\frac{4A}{\pi}} \quad (1)$$

where A is area in μm^2.

For tension test, three tensile test specimens were cut from the welded joints perpendicular to the welding direction using a power