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Effect of friction stir welding (FSW) parameters on strain hardening behavior of pure copper joints

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ABSTRACT

Effect of tool rotation rate and traverse speed on strain hardening behavior of friction stir welded (FSWed) copper joints were investigated using hardening capacity and strain hardening exponent concepts. Kocks–Mecking type plots were used to show different stages of strain hardening. FSWed samples reveals higher hardening capacity and lower strain hardening exponent relative to base metal. With increasing rotation rate and/or decreasing traverse speed, FSWed samples show higher hardening capacity and lower strain hardening exponent. The strain hardening behavior was discussed by dislocation density and grain size variation during FSW. In addition, the microstructure and mechanical properties of the samples were investigated in detail. Four different zones were observed in microstructure of FSWed joints. The joints showed finer grain structure and weaker mechanical properties relative to base metal due to dynamic recrystallization and lower dislocation density.

1. Introduction

Special features of copper such as high electrical and thermal conductivities, favorable combinations of strength and ductility, and excellent resistance to corrosion have made it an acceptable material for use in many industrial areas [1–3]. In contrast with its advantages, fusion welding of copper is difficult because of its high thermal diffusivity and high oxidation rate at melting temperature [4,5]. One way to overcome these problems is friction stir welding (FSW). FSW is a solid state welding process in which a non-consumable welding tool is used to generate the frictional heat between the tool and the work piece in order to make a solid state joint [6]. While the research and applications of FSW have mainly focused on the aluminum alloys [7,8], investigations into the FSW of copper and copper alloys is quite limited [9–12]. This is attributed to the high heat input requirement during FSW of copper to achieve defect-free joints [6].

Xie et al. [11] investigated effect of tool rotation rate on microstructure and properties of friction stir welded (FSWed) copper joints under low heat input condition. They reported the grain size of the stirred zone (SZ) decreased from 9 to 3.5 μm with decreasing rotation rate from 800 to 400 rpm at constant traverse speed of 50 mm/min. They indicated that variations of both microhardness and yield strength of the SZ are related to grain size with the Hall–Petch relationship.

Shen et al. [12] investigated effect of traverse speed on the microstructure and hardness of FSWed copper at constant rotation rate of 600 rpm and traverse speed in the range of 25–150 mm/min. They reported that as the traverse speed increased, the grain size of SZ first increased and then decreased, the thermomechanically affected zone (TMAZ) became narrow and the boundary between these two zones got distinct; the heat affected zone (HAZ) was almost not changed. Hardness values of SZ were considerably lower than that of the base metal (BM) which can be related to the microstructural changes.

Along with the microstructure and mechanical properties, strain hardening behavior of the FSWed joints plays an important role in the material load bearing properties. Strain hardening is one of the most common methods to enhance the mechanical strength of materials through imposing plastic deformations. Additionally, some authors who investigated grain boundary strengthening of polycrystals showed that the major source of such strengthening was also due to the enhanced strain hardening [13]. Strain hardening behavior is greatly influenced by grain size and dislocation density [14–16]. Therefore, it can play an important role in determining of mechanical properties, due to sever plastic deformation in FSW process.

Afrin et al. [17] investigated strain hardening behavior of FSWed magnesium alloy using two modified equations of hardening capacity and strain hardening exponent where the elastic deformation stage was excluded. Kocks–Mecking type plots were used to show different stages of strain hardening. They reported that the hardening capacity and the strain hardening exponent of the FSWed samples were observed to be about respectively twice

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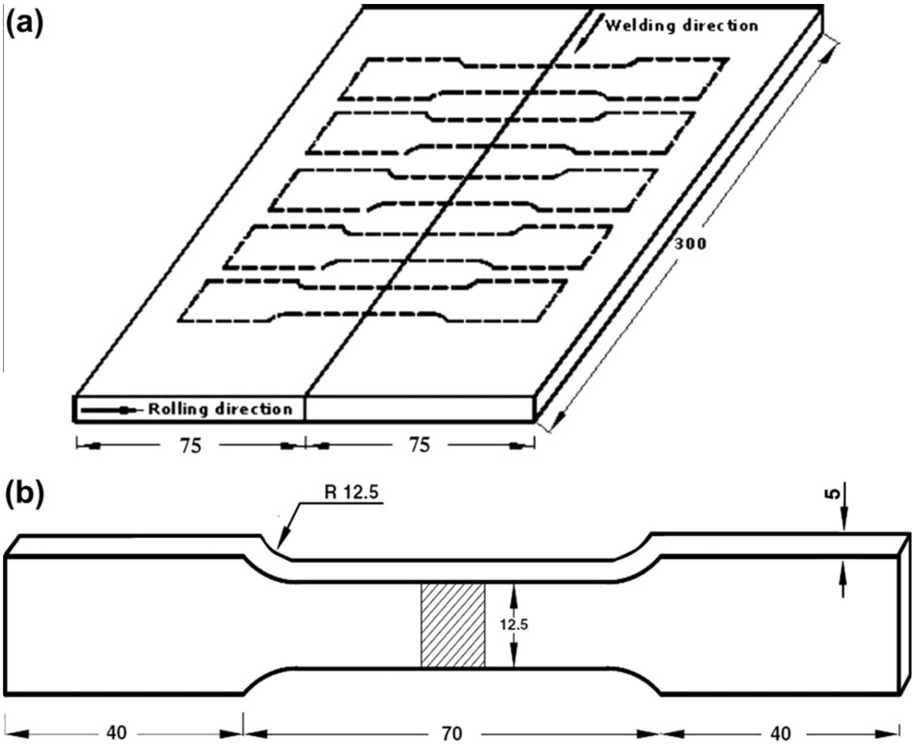

Fig. 1. (a) Position of tensile test specimens in the FSWed joints and (b) schematic illustration of the tensile test specimen.

and threefold higher than those of the base alloy. They discussed the results by dislocation storage theory. Simar et al. [18] developed a mathematical model for predicting strain hardening of FSWed aluminum alloy 6005A-T6.

Although a few studies can be found in the literatures investigating the effects of FSW parameters on the strain hardening behavior of FSWed aluminum [18] and magnesium alloys [17], no efforts have been devoted to strain hardening behavior of FSWed copper joints. The lack of information in this field promoted the authors to investigate the subject. Therefore, the aim of this paper is to establish a relationship between FSW parameters (tool rotation rate and traverse speed) and strain hardening behavior of FSWed copper joints.

2. Experimental procedure

Commercial pure copper plate with a thickness of 5 mm was joined by FSW perpendicular to the rolling direction. Two traverse speeds of 25 and 75 mm/min at constant rotation rate of 600 rpm (R600T25 and R600T75 samples) and two rotation rates of 600 and 900 rpm at constant traverse speed of 75 mm/min (R600T75 and R900T75 samples) were conducted to study the effect of traverse speed and rotation rate, respectively. Microstructure features of the FSWed joints were characterized by optical microscopy. Grain size was determined using linear intercept method. Five tensile test specimens were cut from the welded joints perpendicular to the welding direction using a power hacksaw, as shown in Fig. 1a. The specimens prepared according to ASTM-E8 M standard [19] and tension test were performed using a universal tensile test machine at room temperature and constant strain rate of $1.6 \times 10^{-3}\ s^{-1}$. Schematic illustration of the tensile test specimen was shown in Fig. 1b. The Vickers hardness profile of the weld was measured on a cross section and perpendicular to the welding direction using a Vickers indenter of 200 gf load for 10 s.

3. Results and discussion

3.1. Microstructure characterization

From previous literatures based on microstructural characterizations, four distinct zones, i.e., parent material (PM), SZ, TMAZ and HAZ, were usually identified in FSW joints [6,20]. Xue et al. [21] investigated effect of heat input conditions on microstructure and mechanical properties of FSWed pure copper and observed the stated four zones at low heat input condition i.e., rotation speed of 400 rpm and traverse speed of 50 mm/min. Fig. 2 shows microstructure of sample R600T75 in which SZ, TMAZ and HAZ are clearly distinct. As can be seen, the SZ of the FSWed joints exhibits nearly equiaxed grain structure where the TMAZ were characterized by

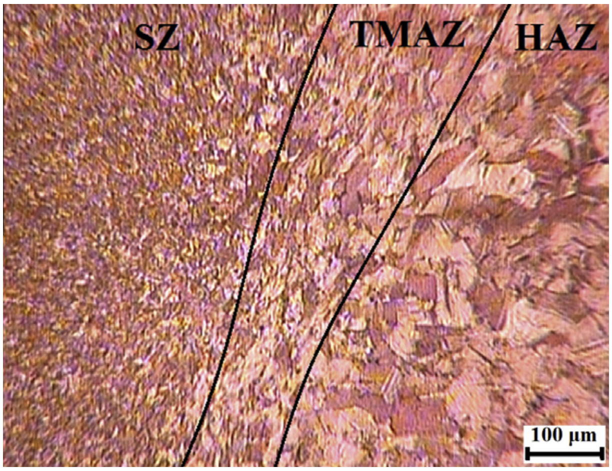

Fig. 2. Microstructure of sample R600T75 showing the SZ, TMAZ and HAZ.