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Technical paper

Influence of rotational speed on the formation of friction stir processed zone in pure copper at low-heat input conditions

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ABSTRACT

The aim of this work is to study the influence of rotational speed on the formation of friction stir processing (FSP) zone in commercial pure copper at low-heat input conditions. The experiments were conducted using K-type thermocouples to record the peak temperature history at different locations on the workpiece. The results suggest that the temperature achieved during processing plays an important role in determining the microstructure and properties of the processed metal. FSP produced very fine and homogenous grain structure and it is observed that smaller grain size structure is obtained at lower rotational speed whereas a tunnel defect was formed at lower speed of 250 rpm. It is also observed that the hardness of the processed copper depends strongly on the heat input during FSP. Tensile tests were carried out and the tensile strength of the FSPed samples was compared to that of the base metal. For a successful FSP at low-heat input condition, the minimum rotational speed was found to be 350 rpm.

1. Introduction

Friction stir processing (FSP) is a cost-effective, energy efficient and a one-step solid state processing route for surface modification of metals and alloys based on the basic principles of friction stir welding (FSW) [1–3]. The process has been successfully applied to alter the grain structures of various metals and alloys to change the surface properties without influencing properties of the bulk material. Actually, FSP is a novel grain refinement method applied to light metal alloys for various end applications [2].

FSP is based on strong couplings of thermo-mechanical phenomena. FSP utilizes a non-consumable tool with shoulder and pin. The rotating tool plunges into the workpiece and moves along a definite path leaving a thermo-mechanically processed zone along the tool path. This thermo-mechanically modified zone consists of three distinct regions namely stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) as shown in Fig. 1.

The selected process parameters and tool design mainly influence the material flow pattern at the stir zone. The degree of plastic deformation and the heat generation during FSP are the dominant factors in determining grain refinement at processed zone [3]. Nevertheless, the amount of heat generation during FSP is a decisive issue to produce a defect-free FSPed zone and therefore, is of interest.

Copper and its alloys have found extensive applications because of its high thermal and electrical conductivity, plasticity, softness and formability. However, copper in pure form has poor strength, wear and fatigue resistance and hence is not preferred for high-end applications like contact terminals of electrical switches and sliding surfaces. Heat inputs using a rotational tool during FSP closely affect the microstructure in the stirred zone [4]. Actually, FSP with lower heat input produces a finer grain size and higher hardness. For a given tool geometry and depth of penetration, the maximum temperature was observed to be a strong function of the rotation speed while the rate of heating is a strong function of traverse speed [3]. It has been reported that a decrease in heat input can reduce the size of the recrystallized grains in FSW copper significantly [5].

Xie et al. [5] demonstrated that copper can be friction stir welded at low-heat input conditions by varying the rotation speed (400, 600, 800) at constant traverse speed of 50 mm/min and has shown that fine grain size was obtained in copper with increased hardness, strength and ductility. Surekha and Els-Botes [6] developed a high strength with high conductivity copper at low-heat input conditions by varying the travel speed from 50 to 250 mm/min at a constant rotation speed of 300 rpm and concluded that peak temperature is the dominant factor determining grain size in their study. Cartigueyen and Mahadevan [7] studied the effect of FSP on pure copper with six different tool pin profiles at low-heat input condition and observed that threaded cylindrical pin profile tool

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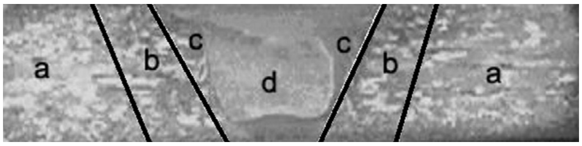

Fig. 1. Different regions in FSP: (a) unaffected base metal (BM), (b) heat affected zone (HAZ), (c) thermo-mechanically affected zone (TMAZ) and (d) stir zone (SZ) [11].

was more effective in bringing about a favourable mechanical modification in pure copper than other pin profiles under low-heat input condition.

However, still there is a lack of information on the influence of tool rotation speed at low-heat input conditions and its significant effect on microstructure and properties of FSP zone for pure copper. Therefore, in the present work, friction stir processing of pure copper is carried out to study the influence of rotational speed on the formation of FSP zone at relatively low-heat input conditions, at a constant traverse speed of 50 mm/min. The effects of the rotational speed on the formation of stir zone were analyzed by heat generation studies during processing and the microstructure, mechanical properties were compared with as received copper.

2. Experimental procedure

In this study, commercial pure copper plates of 150 mm length, 50 mm width and 6 mm thickness were used for FSP. The nominal compositions of copper were 0.005Mg–0.005S–0.001Ti – rest Cu (in wt%). The process is carried out in a conventional vertical milling machine (3 HP and 2000 rpm). Fig. 2 depicts the experimental setup showing the arrangement of copper plate and the selected FSP tool. Mild steel plate was used as the backing plate and a straight cylindrical threaded pin profiled tool was used. The FSP tool was fabricated from high carbon high chromium (HCHCr) tool steel followed by hardening and tempering process to increase the hardness to 55–58 HRC. The manufactured tool along with its geometry is shown in Fig. 3. The data related to the tool dimensions and FSP parameters are presented in Table 1.

The temperature measurement during FSP can be made by different measurement techniques like embedded thermocouples, optical pyrometer and infra-red techniques. Infra-red technique is quite expensive and it is not possible to measure the temperature below the FSP tool shoulder instantaneously [8,9]. Embedded thermocouples and optical pyrometer techniques were found in close agreement [10]. Therefore, in this work, K-type thermocouples (1.6 mm diameter/ ± 1.1 °C accuracy) were used. Thermocouples were inserted into the holes drilled and embedded at the bottom of the plate. Fig. 4 shows the thermocouple (TC) placements along the FSP path. One in the middle of stir zone (TC3), one each in advancing (TC4) and retreating (TC2) side offset by 8.2 mm and two others (TC1 and TC5) were offset by 19.2 mm on either side of SZC in the staggered arrangement along the processing path. This thermocouple placement was intended to assess the peak temperature variation (heat input variations) across the SZ and HAZs in Cu plate

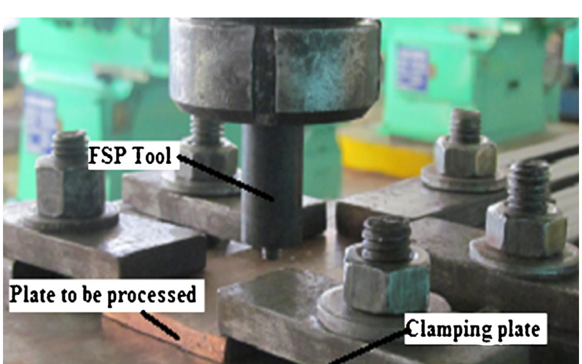

Fig. 2. Experimental set up showing arrangements of Cu plate and FSP tool attachment.

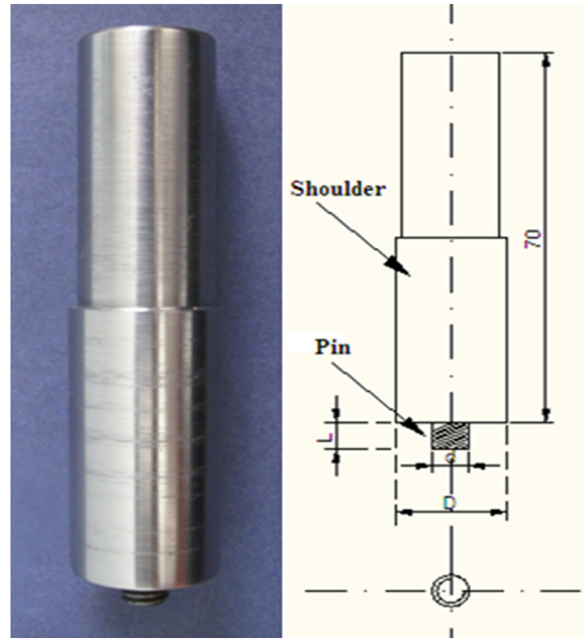

Fig. 3. Manufactured tool with its geometry.

Table 1
FSP parameters and tool dimensions.

FSP parameters	Values
Rotational speed (rpm)	250, 350, 500
Traverse speed (mm/min)	50
Tool shoulder diameter (*D*)	18 mm
Tool pin diameter (*d*)	6 mm
D/*d* ratio of tool	3.0
Pin length (*L*)	4.70 mm
Tool inclined angle	0°
Shoulder plunge into the surface of base metal	0.1 mm
Pitch of RH threaded pin	1.0 mm
Shoulder concavity angle	2°
Included angle of threaded pin	60°

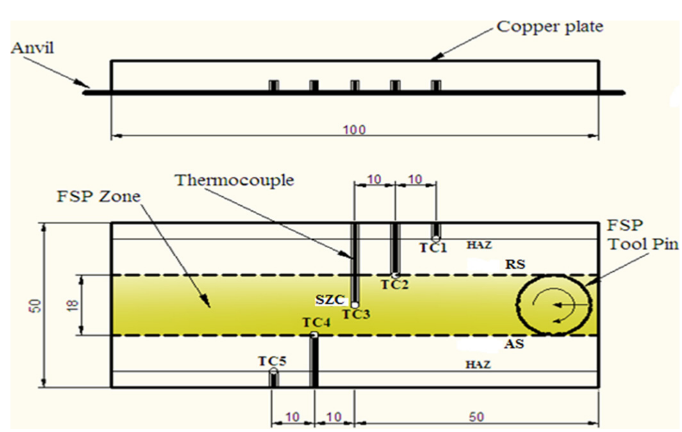

Fig. 4. Schematic diagrams illustrating thermocouple locations (SZC – stir zone center, AS – advancing side, RS – retreating side, HAZ – heat affected zone, TC – thermocouple) along the FSP path.