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Microstructure and mechanical properties of friction stir welded copper

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Abstract The main objective of this investigation was to apply friction stir welding technique (FSW) for joining of 2 mm thick copper sheet. The defect free weld was obtained at a tool rotational and travel speed of 1,000 rpm and 30 mm/min, respectively. Mechanical and microstructural analysis has been performed to evaluate the characteristics of friction stir welded copper. The microstructure of the weld nugget (WN) consists of fine equiaxed grains. Similarly, the elongated grains in the thermomechanically affected zone (TMAZ) and coarse grains in the heat-affected zone (HAZ) were observed. The hardness values in the WN were higher than the base material. Eventually HAZ shows lowest hardness values because of few coarse grains presence. Friction stir welded copper joints passes 85% weld efficiency as compared to the parent metal.

Introduction

Friction stir welding (FSW) is relatively a new solid-state welding process, which is attracting the vast interest since it was invented. FSW is becoming an important joining process because it makes high quality welds for number of materials as compared to the conventional welding techniques. In FSW process, a non-consumable welding tool is used to generate the frictional heat between the tool and the work piece [1, 2]. This facilitates the tool movement along the joint line. As a result, the plasticized material is transformed from the leading edge of the tool to trailing side. Subsequently, it produces a high quality joint between the two plates by the translation movement of the work piece along with applied pressure of the tool. FSW has several advantages, such as low energy input, short welding time, low welding temperatures and relatively low distortion [1–10]. This process is considered to be the most significant development in metal joining in the last decade. Accordingly, FSW has been developed as an effective welding technique for aerospace, automotive, petrochemical, marine and other nuclear industries [1, 3].

Extensive studies on FSW of aluminium and its alloy have been reported but in the case of copper limited studies are available. Won-Bace Lee et al. has reported on FSW of 4 mm thick copper sheet. Joining of copper is usually difficult by conventional fusion welding technique because of its higher thermal diffusivity, which is about 10–100 times higher than the many steels and nickel alloys. The heat input required to join the copper is higher than the nearly other material and weld speeds are quiet low [9]. The main objectives of this investigation were to apply FSW technique for joining of copper sheet and microstructure, mechanical properties characterization. The results presented in this investigation represent an evaluation of the FSW capability to produce 2 mm thick copper joint.

Experimental details

The nominal composition of the copper base material used in this work was Cu-98.70, Zn-1.042 in wt%. The copper plate dimensions of 150 mm (L) × 110 mm (W) × 2 mm (T) was used in the present study. The copper plates were

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clamped rigidly on backup plate to produce butt joint using the FSW technique as shown in Fig. 1. Before clamping the plates, the edges of the plates were properly cleaned. Copper butt joint was made using hardened steel (Hardness 55 RC) under the welding condition of 1,000 rpm tool rotational speed and 30 mm/min travel speed. Samples for tensile and microstructural evaluation were sectioned from the welded plate transverse to the welding direction. The transverse tensile tests were conducted on an Instron (Model No: 5582) at a constant cross head speed of 2.54 mm/min at room temperature. Vickers hardness measurements were performed on cross section at mid thickness of the welded plate at a 300 gm load and 10 s dwell time. Similarly, the sectioned sample was prepared using standard metallographic procedure for microstructural investigation. The sample was etched using 100 ml H_2O, 4 ml saturated NaCl, 2 gm potassium dichromate, 5 ml H_2SO_4. The microstructure analyses were performed using optical microscope (OM) and scanning electron microscopy (SEM).

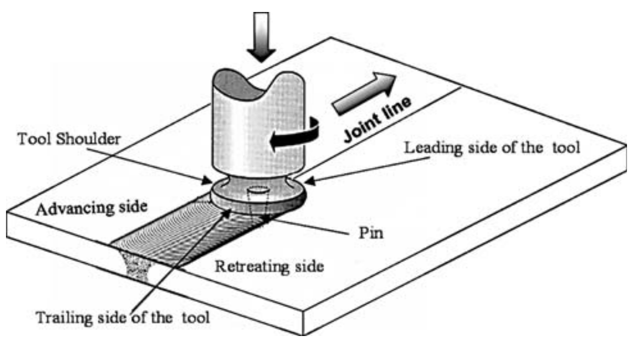
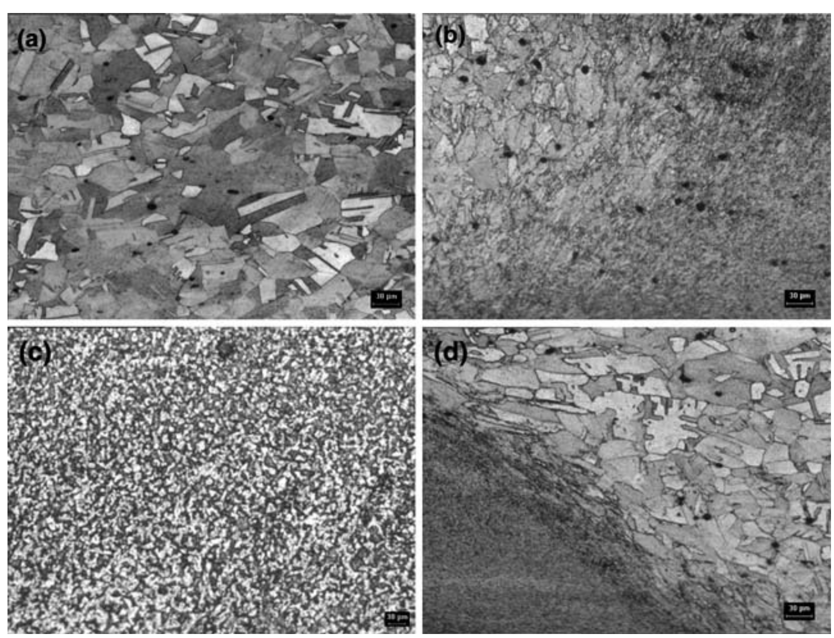


Fig. 1 Friction stir welding technique

Results and discussion

The butt joining of copper was successfully conducted by FSW. The microstructure of the FS welded copper joint consists of different zones such as (a) weld nugget (WN), (b) thermomechanically affected zone, (c) heat-affected zone, (d) parent metal. A typical microstructure of the copper sheet joint parent metal, WN and TMAZ are shown in Fig. 2a–d. The parent metal has elongated grains having the size of 30 µm. Weld nugget has extremely fine equiaxed grains size of 11 µm by dynamic recrystallization due to frictional heat and plastic deformation, which results in higher hardness as compared to the parent metal. The TMAZ has been plastically deformed and thermally affected. The elongated grains were observed at TMAZ on both advancing and retreating side of the weld. TMAZ is characterized by a rotation of the elongated grains up to 90° at both sides of the joint [7]. As compared to the retreating side TMAZ, elongated grains were observed at the advancing side of TMAZ, which is roughly transverse to the parent metal grains. Although both advancing and retreating side have a boundary with the WN, clear boundary exhibits at the advancing side of the weld than the retreating side [3, 6]. Adjacent to the TMAZ a few coarse grains were observed in the heat-affected zone as shown in Fig. 2d, this results in hardness variations as shown in Fig. 3. The hardness variation along the weld zone was highly correlated with microstructure. Figure 4

Fig. 2 Optical microstructure of the parent metal and weld zones of copper (**a**)–(**d**). (**a**) Parent metal, (**b**) TMAZ at the retreating side, (**c**) WN and (**d**) TMAZ at the advancing side



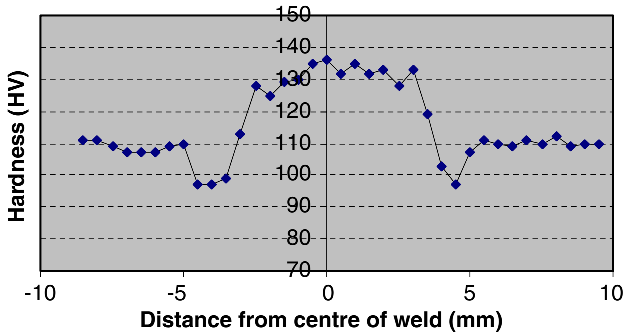


Fig. 3 Hardness profiles in cross section of the copper weld

illustrates the onion ring flow pattern in the weld zone. This pattern reveals the material flow during welding. The onion ring pattern clearly exhibits in the copper weld joint than the aluminium weld [3] because of its thermal properties.

The hardness measurements were performed on copper butt joint, Fig. 3 shows the hardness profile along the mid thickness of the joint for weld and parent metal. The hardness of the parent metal is varying between 106 and 111 HV. As compared to the parent metal, significant increases in hardness were observed in the WN varying between 128 and 136 HV, due to the presence of extremely fine recrystallized equiaxed grains. Thermomechanically affected zones have shown not only lower hardness in comparison with the WN but also higher hardness than the parent metal and HAZ due to the presence of fine elongated grains. The observations were found to be valid for both advancing and retreating side. These grains orientation were more or less transverse to the parent metal grains. Though the TMAZ, WN passes higher hardness than the parent metal, the lowest hardness were observed on both the side at (HAZ) 4 mm distance from the centre of the weld joint as shown in Fig. 3.

Tensile properties

Tensile strength and percentage of elongation of the copper base material are 273 MPa and 3.1%, respectively. Friction stir weld copper joint tensile strength and elongation was observed about 231 MPa and 1.2%, respectively. Friction stir weld joint passes about 85% weld efficiency ([strength of the weld/strength of the parent metal] × 100) as compared to the parent metal. On the other hand, the value of the percentage elongation was lesser than the parent metal. Fracture location of the weld joint was in the heat-affected zone at the advancing side. However, the hardness variations across the weld zone addressed the tensile fracture location. This fractured sample surface were analyzed using scanning electron microscopy (JEOL 840A). Both parent metal and weld metal posses the ductile fracture morphology by micro void coalescence. But in case of FSW joint absence of large voids were observed than present metal as shown in Fig. 5a and b. It reveals that the FSW sample passes less ductile than parent metal before tensile fracture (Table 1).

Fig. 4 Onion ring pattern in the weld zone

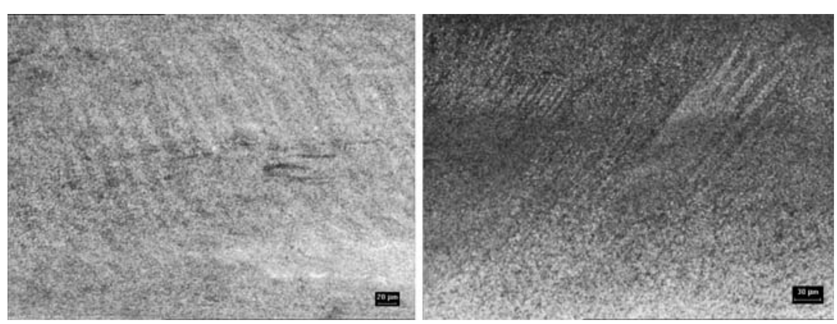


Fig. 5 SEM images of the tensile fracture surface (**a**) weld metal and (**b**) parent metal

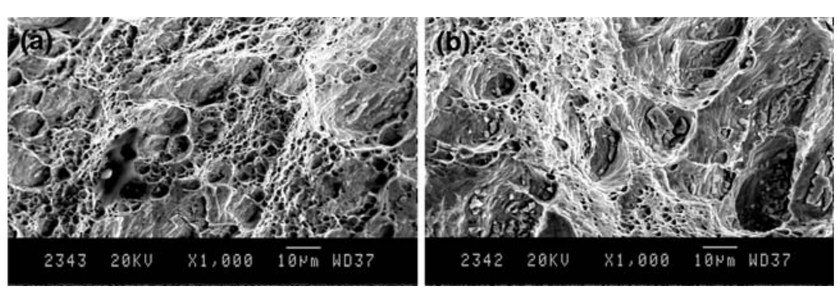


Table 1 Mechanical properties

Specimen	UTS (MPa)	% Elongation	Fracture location
Cu-base metal	273	3.1	–
Cu-FSW	231	1.2	HAZ-AS

Conclusions

The butt joining of copper was successfully carried out using FSW technique. The characterization of microstructure and mechanical properties of FS welded copper were performed. The following conclusions were drawn from the present investigation.

- The microstructure of the copper weld consists of four different zones such as (a) WN, (b) TMAZ, (c) HAZ, (d) parent metal. The microstructure of the WN has been observed to be finer than the parent metal due to dynamic recrystallization. In the HAZ few coarse grains presence were observed. Onion ring pattern clearly exhibits in the copper weld joint due to its thermal properties.
- The hardness of the WN was higher than the TMAZ, HAZ, and PM due to the presence of fine grains. The hardness values in the TMAZ were lower than in the WN but reverse were true as compared to the HAZ and parent metal. The HAZ exhibited lower hardness in the weld zone.
- Friction stir welding joint passes 85% weld efficiency as compared to the parent metal. The tensile fracture occurred in the HAZ at the advancing side of the weld due to the presence of few coarse grains. Similarly, the variations of the hardness values showed a relative correspondence to the fracture location.

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