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Fatigue Behavior of Friction Stir Welded Joints of Pure Copper with Ultra-Fine Grains

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Abstract

In order to determine the long term durability of friction stir welded joints with ultra-fine grained microstructure, investigation of the mechanical response with specific emphasis on fatigue behaviour is critical. In this paper, fatigue behavior of friction stir welded joints of pure copper in low cycle; strain-controlled regime was investigated. Microstructural characterizations indicated the formation of recrystallized ultrafine-grained microstructure in the nugget zone (NZ) after friction stir welding. Fatigue properties were specified at a strain ratio of 0.1 with total strain amplitudes of 0.01, 0.1, and 0.2%. The results attained from the experiments demonstrated cyclic hardening effect at high strain amplitudes, while softening was observed in low strain amplitude of 0.01%. The hysteresis loops indicated the concavity along with the small portion of linear behavior after the reversal point. Localized deformation in the form of shear bands along with equiaxed cells and noticeable misorientation were observed on the fracture surface.

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Keywords: Friction stir welding; Pure copper; Low cycle fatigue; Cyclic response.

1. Introduction

There have been increasing demand for welding of pure copper in recent decades due to its application in heating coils and evaporators, stated by Lin et al. (2014). However, welding possibility of the pure copper, using typical welding methods such as fusion welding, is challenging due to the existence of oxygen and the rapid diffusion activities at high welding temperatures as suggested by Oates et al. and Mousavi et al. (1996, 2009). A relatively-

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new solid state welding method, called friction stir welding (FSW), has been applied to overcome the welding challenges in pure copper. From the microstructural perspective, Cheri and Leo (2010), Chen et al. (2011) showed that the elimination of porosities, cracks, tunnels and segregations makes FSW a promising choice for joining particulate reinforced aluminium matrix composites, copper and magnesium alloys.

Previous works on the FSW of copper joints have mainly concentrated on the microstructure characterization of weld zones, process parameters influence on the weld quality, the effect of tool pin profile on the joint strength, and the mechanical properties of the joints in the NZ under static loading. Initial investigations by Nadan et al. (2008) revealed that the welding heat input for copper welding is higher than that for aluminum alloys, while further investigations demonstrated the suitable welding parameters to obtain the defect-free joints. Salahi et al. (2013, 2014) investigated into the possible welding conditions for commercial pure copper joints and, distinguished the effect of various welding parameters including rotational speed, traverse speed, plunge depth, and axial force. It was reported that the higher hardness value in the NZ may be attributed to the formation of recrystallized, ultra-fine grained microstructure.

Concerning the fatigue performance of the FS-welded joints, few studies can be found on the high cycle fatigue (HCF) behavior of the FS-welded aluminum alloys and its composites. Hrishikesh et al. (2014) investigated the fatigue behavior of 6061 aluminum joints at different stress ratios and indicated that the fatigue behavior of the welds is sensitive to the microstructural features of each specified zone. An attempt to conduct low cycle fatigue (LCF) experiments at FS-welded joints of AZ91Mg alloy was made by Ni et al. (2014) and cyclic response was evaluated in the strain-controlled regime.

Significance of cyclic deformation characteristic of joints along with the relative lack of works on the LCF behavior encouraged the authors to pursue the current subject. In this study, an attempt is made to examine the LCF properties of FS-welded copper joints.

2. Experimental procedure

Commercially pure copper plates with the dimensions of 150 mm × 100 mm × 4 mm were exposed to friction stir welding in tool rotational speed of 600 rpm and traverse speed of 45 mm/min. A high carbon steel FSW tool (British standard right handed threads with 1 mm pitch) with dimensions, shown in Table 1, was adopted. The specimens for microstructural examination were cross-sectioned perpendicular to the FSW direction. The specimens were ground, polished, and etched, using a solution of 20 mL nitric acid and 10 mL acetic acid. Optical microscopy (OM) studies were conducted on the various weld zones and fracture surfaces to characterize the microstructure.

Table 1. Specification of tool profile and dimensions

Profile of pin	Thread characteristic	Pin diameter (mm)	Length of pin (mm)	Shoulder diameter(mm)
cylindrical threaded	British , right handed with 1 mm pitch	5	3.4	12

Vickers micro-hardness tests with 1 kgf load were carried out for 10 seconds to measure the hardness profile across the samples. The hardness profiles for the joints and the base metal were prepared along the mid-thickness of the plates at an interval of 0.5 mm on the cross-section of the weld zone.

Dog-bone shaped tensile specimens with the gage length of 15mm were electro discharge machined from the welded plates, perpendicular to the weld direction. The weld region was positioned in the middle of the gauge section of the test specimens. Strain-controlled fatigue experiments with a strain ratio of $R = 0.1$ and a frequency of 0.1 Hz were conducted using a servo-hydraulic Instron mechanical testing system. A sinusoidal waveform was applied with strain amplitudes varying from 0.01% to 2%.

3. Results and discussion

3.1. Microstructural evolution

Defect-free sound joints of pure copper were achieved using the FSW technique, with a cap-like welding zone. Microstructural characterization in the weld zone indicates that four zones can be identified as suggested by Nandan et al. (2008) and Khodaverdizadeh et al. (2013), i.e., the nugget zone (NZ), the thermo-mechanically affected zone (TMAZ), the heat affected zone (HAZ) and the base metal (BM). The NZ and the HAZ have been illustrated in Fig. 1a and b, respectively. Regions with ultra-fine and equiaxed grains were observed in the NZ due to exposure to the severe deformation under the tool's shoulder. However, distributed heat in the HAZ led to formation of coarse grains along the flow line.

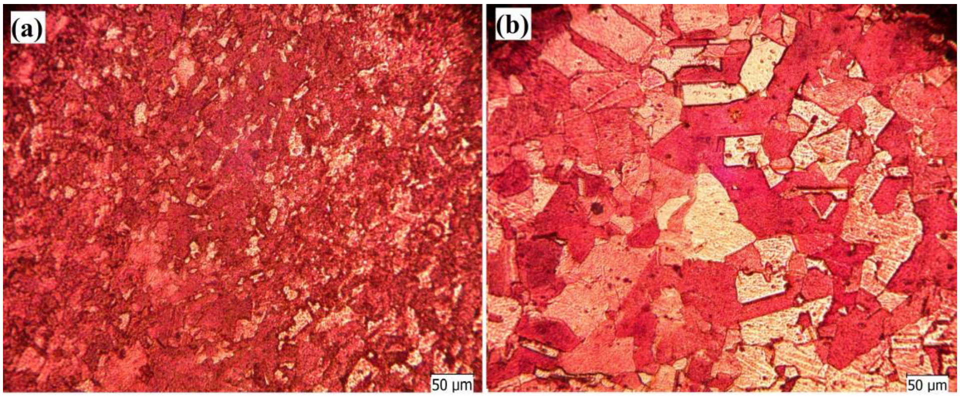

Fig. 1. Microstructure of FSW joints of pure copper (a) the NZ; (b) the HAZ.

3.2. Hardness properties

The microhardness profile across the weld line is illustrated in Fig. 2. Higher average hardness along with more uniform distribution was observed in the NZ (the center region under the shoulder) due to the presence of fine and equiaxed grains. As expected, the lowest hardness is observed in the HAZ due to exposure to the high heat input. Although slightly lower than the base metal, the hardness in the NZ exhibits decent joint strength.

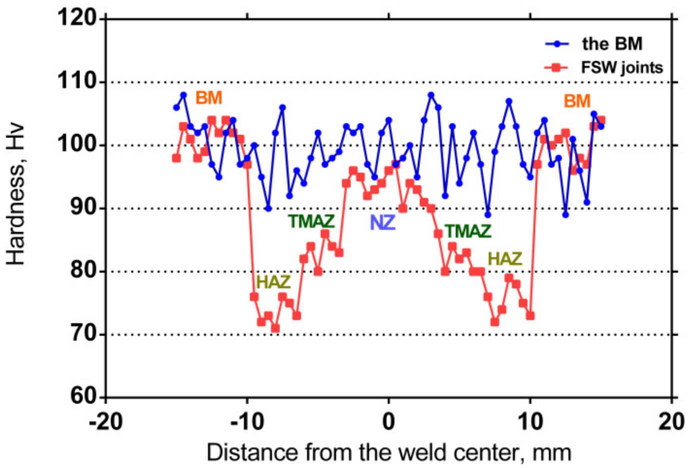

Fig. 2. Microhardness profile of FSW joint and the pure copper along the mid-thickness.

3.3. Cyclic deformation response

The stress amplitude versus the number of cycles at various total strain amplitudes is shown in Fig. 3a. It can be seen that by increasing the total strain amplitude, the stress amplitude increases. Considering the 0.01% strain amplitude, an order of magnitude increase indicated a negligible change in the fatigue life. Moreover, a two times increase in the strain amplitude to 0.2% results in a slight increase in the number of cycles. The stress amplitude level remains almost constant at the lowest strain amplitude of 0.01 % up to about 1000 cycles followed by cyclic softening. At the intermediate strain amplitude of 0.1%, an obvious cyclic hardening was observed especially above 1000 cycles. More importantly, the remarkable increase in the stress amplitude at the highest strain amplitude of 0.2% strikes attention. In the case of AZ91D magnesium alloy, Patel et al. (2010) attributed cyclic hardening at the high strain amplitude of 0.2% to the increase in dislocation density during micro-plastic deformation at cycles higher than 1000.

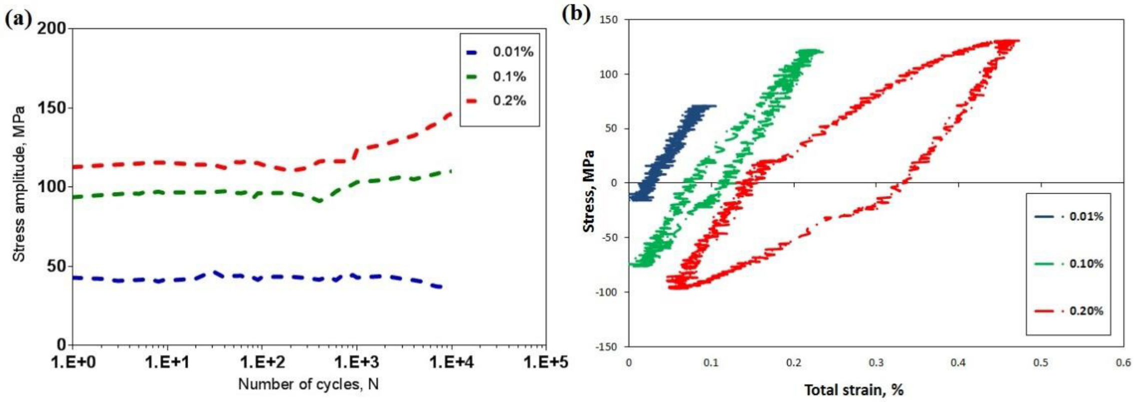

Fig. 3. (a) Stress amplitude vs. the number of cycles at different strain amplitudes; (b) typical hysteresis loops of FSW joints

3.4. Hysteresis loops

In order to investigate the effect of cyclic load on the mechanical behavior of the FS-welded joints, the hysteresis loops for the mid-life cycles of the FSW joints at all total strain amplitude levels are examined. It is apparent in Fig. 3b that the hysteresis loops for the FSW joints are relatively large in height and width at the high strain amplitude and present cyclic hardening effect. A relative concavity is observed for joints in both ascending and descending phases before the reversal points for strain amplitudes of 0.1 and 0.2% while hysteresis loops are hard to detect in strain amplitude of 0.01%. It is noted that at the strain amplitude of 0.01%, the tensile stress is considerably higher than the compressive stress, while by increasing strain amplitude, the ratio of maximum tensile stress to maximum compressive stress decreases significantly. Nearly symmetrical and clockwise tilted hysteresis loops are observed for the FSW joints at the high strain amplitude of 0.2%, exhibiting small portion of linear loading and unloading just after the reversal point.

3.5. Fractography

Fracture surface of the fatigued specimens were examined using optical microscopy. The failure mostly occurred in the HAZ which can be attributed to the microstructural instabilities and the grain coarsening in the HAZ. The microstructure of the specimen after cyclic deformation at the moderate strain amplitude of 0.1% is shown in Fig. 4. Localized deformation in the form of shear bands can be seen on the fracture surface as exhibited in Fig. 4a. Fig. 4b shows the substructure in the NZ having relatively large and equiaxed cells with noticeable misorientations among them. These microstructural features are commonly observed during low cycle fatigue of copper as mentioned by Agnew and Weertman (1998).

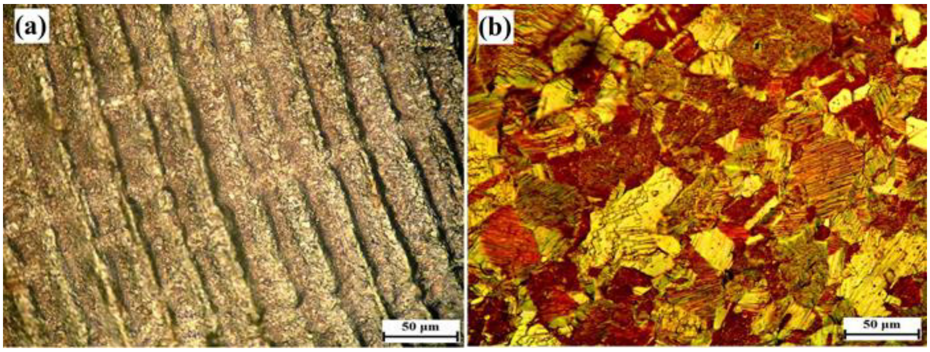

Fig. 4. (a) Shear bands in the fracture zone near the NZ; (b) misoriented substructure in the HAZ.

4. Conclusion

Cyclic deformation characteristics and fracture behavior of friction stir welded joints of pure copper were probed in the strain-controlled regime. FSW was able to produce a nugget zone with refined and equiaxed grains while coarse grains were observed in the HAZ due to distribution of heat in the flow line. The nugget zone presented a more uniform microhardness profile relative to the BM. The HAZ showed the lowest hardness value due to the formation of coarse grains, exposed to high heat input. At low strain amplitudes, softening occurred while cyclic hardening was observed at higher strain amplitudes. The hysteresis loops for the joints illustrated a relative concavity along with a small amount of linear loading and unloading portions after the reversal points. Shear bands and a misoriented substructure consisting of large and equiaxed grains were observed after cyclic deformation.

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