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Achieving friction stir welded pure copper joints with nearly equal strength to the parent metal via additional rapid cooling

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Friction stir welded (FSW) pure copper joints with nearly equal strength to the parent metal were obtained at 400 rpm/50 mm min^{-1} via additional rapid cooling with flowing water. Significantly reduced heat input with a peak temperature of 130 °C and duration of 4 s above 100 °C in the thermal cycle was achieved in the heat-affected zone, resulting in the retainment of the original high dislocation density of the parent metal. This work provides an effective strategy to enhance the strength of FSW joints.

Keywords: Friction stir welding; Copper; Heat-affected zone; Strength; Dislocation

Through two decades of development, friction stir welding (FSW) has become a viable and important welding and manufacturing technology, especially in aerospace and automotive applications involving aluminum alloys [1,2]. There have also been many studies of the joining of other alloys, such as magnesium alloys, copper alloys and steels, by FSW in recent years [3–11]. Based on microstructural characterization, three distinct zones, the stirred zone (SZ), the thermo-mechanically affected zone and the heat-affected zone (HAZ), have been identified in FSW joints.

For precipitation-hardened and work-hardened materials, the HAZ is the weakest zone of FSW joints due to accompanying softening processes, which result from the disappearance of dislocations, the dissolving/coarsening of precipitates and the coarsening of grains [1,2], and tensile fracture occurs in the HAZ, resulting in the strength of the joints being lower than that of the parent metal (PM). For example, in the HAZ of precipitation-hardened aluminum alloys, the coarsening of precipitates and the widening of the precipitate-free zones occurs due to a temperature rise above 250 °C, resulting in an obviously reduced weld strength compared to that of the PM [1,12–16]. For FSW pure copper joints, the yield strength (YS) of the joints was found to be only about 100 MPa even at a relatively low rotation rate of 800 rpm, which was much lower than that of the PM with 1/2H condition (~270 MPa) [7].

Clearly, controlling the microstructure of the HAZ is a key issue for FSW, especially for work-hardened and precipitation-hardened materials. Previous studies indicated that the weld strength increased linearly with the lowest hardness value in the HAZ [17–19]. Generally, the lowest hardness value and the strength of the FSW joints could be enhanced by reducing the heat input, e.g. decreasing the rotation rate and increasing the traverse speed [10,11,17]. However, defects form easily at a very low rotation rate and/or a very high traverse speed, and it is difficult for the FSW machine to run regularly in this case [10,11]. It has been demonstrated in the FSW of Al alloys that the heat input can also be decreased by employing additional rapid cooling, but tunnel defects form easily and the weld strength is only slightly enhanced (~10%) [20,21].

It is expected that a weld strength nearly equal to that of the PM can be achieved in FSW joints provided that the heat input is reduced to a very low level to avoid the softening effect. In this study, we chose the work-hardened pure copper (H condition), which was mainly strengthened by a high density of dislocations, as our target material. Additional rapid cooling was employed during FSW. This study aims to establish a simple procedure to enhance the strength of FSW joints and to elucidate the relationship between the microstructure evolution and the mechanical properties.

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Cold-rolled commercially pure copper plate, 3 mm in thickness and in the H condition, was used in this study. Plates 300 mm in length and 70 mm in width were welded using a gantry FSW machine. Both the surfaces and side faces of the plates were polished with 400-grit emery paper and cleaned with acetone before undergoing the welding procedure. In order to obtain a very low heat input, the Cu plates were first fixed in water with room temperature and additional rapid cooling with flowing water was used during the FSW process. The water left the 4 mm diameter outlet at a velocity of about 7 l min^{-1}, and the thickness of the water layer in the flume was about 50 mm during FSW. FSW was conducted at a constant traverse speed of 50 mm min^{-1} with different tool rotation rates of 400 and 800 rpm, defined as 400-water and 800-water, respectively. For comparison, regular FSW processes were also performed in air at the same welding parameters, and defined as 400-air and 800-air, respectively. A tool with a concave shoulder 14 mm in diameter and a cylindrical threaded pin 4 mm in diameter and 2.7 mm in length was used. A tilting angle of 2.5° was used for all FSW processes and the plunge depth of the shoulder was controlled at ~0.2 mm.

The Vickers microhardness test was performed on the cross-section of the FSW samples perpendicular to the welding direction using a 50 g load for 10 s to obtain the hardness profiles and identify the locations of the HAZ for various FSW samples. The temperature history of the HAZ during FSW was monitored and recorded using K-type thermocouples, which were embedded in the HAZ at the retreating side of the mid-plane height.

The microstructural features of the PM and HAZ were characterized by transmission electron microscopy (TEM). TEM samples were prepared by means of double-jet electrolytic polishing in an electrolyte consisting of 25% (vol.%) alcohol, 25% phosphorus acid and 50% deionized water at about -10 °C with a current of ~90 mA. The tensile specimens, with a gauge length of 40 mm and a width of 10 mm, were machined perpendicular to the FSW direction. The tensile test was carried out at an initial strain rate of 1×10^{-3} s^{-1}.

Defect-free FSW butt joints of pure copper plates were successfully obtained at the four welding conditions in this study. Figure 1 shows the Vicker's hardness profiles along the centerline across the SZ of the FSW Cu joints under different welding parameters. Three important findings were revealed. First, the PM exhibited very high hardness values of 110–115 Hv due to the initial work-hardened state. By comparison, the FSW samples exhibited reduced hardness throughout the weld region, with the lowest hardness value in the HAZ, which is attributed to the softening effect of the annealing [7,17]. Second, under a higher heat input of 800 rpm, a wide low-hardness zone was clearly observed in the HAZ, with a lowest hardness value of about 60 Hv. Decreasing the heat input by reducing the rotation rate from 800 to 400 rpm reduced the width of the low-hardness zone in the HAZ and increased its hardness values, with the lowest hardness value of ~77 Hv. Third, under the rapid cooling condition, the low-hardness zone was significantly narrowed in width and increased in hardness values at both 800 and 400 rpm. In particular, the lowest hardness value of the 400-water FSW joint in the HAZ increased to 104 Hv, which was close to that of the PM (110–115 Hv). Clearly, the lowest hardness value in the HAZ was significantly enhanced under the lower rotation rate with additional rapid cooling, indicating that a low heat input was achieved.

The temperature histories of the HAZ at various parameters are shown in Figure 2. It is clear that, under the same FSW parameters, the peak temperatures of the HAZ were significantly reduced when rapid cooling by flowing water was applied during FSW. The peak temperature in the HAZ was as high as 375 °C for the 800-air FSW joint; however, it was reduced to only about 130 °C for the 400-water FSW joint. It can be seen from Figure 2 that the duration above 100 °C in the HAZ of the 800-water and 400-water joints was much shorter than that of the 800-air and 400-air joints, respectively. Furthermore, though similar peak temperatures were achieved, the duration above 100 °C of the 800-water joint (~30 s) was much shorter than that of the 400-air joint (~70 s). Upadhyay and Reynolds [18] obtained similar results in underwater FSW of 7050 aluminum joints. Clearly, the peak temperature decreased and the duration at higher temperatures was shortened in the thermal cycle under rapid cooling. Even though not measured, it could be inferred that the peak temperature and the duration at higher temperatures in the SZ would decrease, based on the higher hardness observed in the 800-water and 400-water joints. That is to say, the low heat input was achieved by enhanced heat transfer from the tool and plate into the surrounding water in this case.

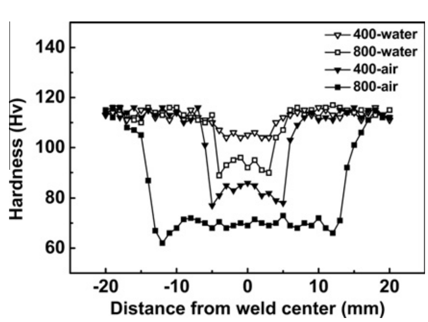

Figure 1. Hardness profiles in cross-sections of the FSW Cu joints at various parameters.

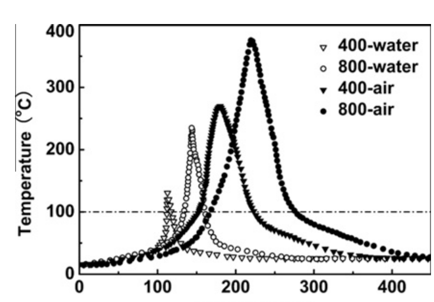

Figure 2. Temperature histories of the FSW Cu joints at various parameters.

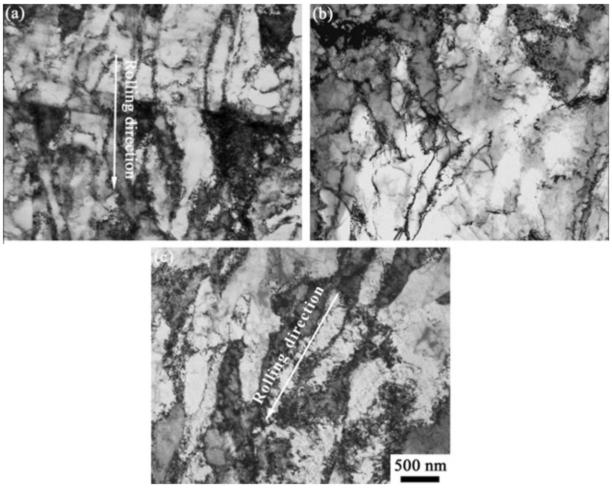

Figure 3. Typical bright-field TEM images of the PM and the HAZs of the FSW Cu joints: (a) PM, (b) 800-air and (c) 400-water.

Table 1. The tensile properties of the PM and FSW pure Cu joints under different conditions.

	YS (MPa)	UTS (MPa)	Elongation (%)
PM	330	350	9
800-Air	100	220	21
400-Air	200	270	11
800-Water	250	285	10
400-Water	315	340	8

The temperature history plays a significant role in determining the microstructure of the HAZ. Figure 3 shows the typical TEM microstructure of the Cu PM and the HAZ of the 800-air and 400-water FSW joints. The microstructure of the PM was characterized by a typical rolling deformed structure (Fig. 3a). Many tangled dislocations and ultrafine cells or subgrains bounded by dislocation walls could be observed in the elongated grains, resulting in high dislocation density. However, the dislocation density decreased significantly in the HAZ of the 800-air FSW joint (Fig. 3b) due to the severe softening effect during the FSW process [1,5,17], which is consistent with the temperature histories, as shown in Figure 2. Though some dislocation structures may disappear in the HAZ of the 400-water FSW joint due to the recovery process, the dislocation density was still very high, which was similar to that of the PM (Fig. 3c).

All the joints at various parameters fractured in the HAZ during tensile tests, and the tensile properties of the PM and the FSW joints are shown in Table 1. The PM exhibited a very high YS of 330 MPa and a low elongation of 9%, which are consistent with the H condition, where a great number of dislocation walls, tangles, cell walls or subgrain boundaries (Fig. 3a) increased the YS of the PM. However, the 800-air and 400-air FSW joints showed much lower YS compared to that of the PM due to an obvious annealing softening effect, as evidenced by TEM examinations (Fig. 3b). Under additional rapid cooling condition with flowing water, substantially enhanced strength of the joints was obtained (Table 1). The YS of the 400-water joint was as high as 315 MPa, which is about 95% of that of the PM, i.e. nearly equal strength to the PM was achieved.

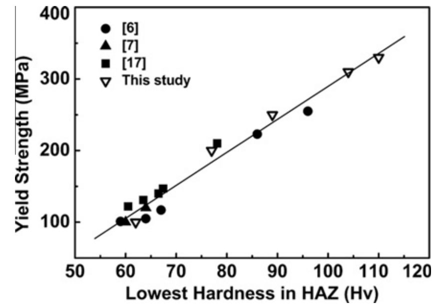

Figure 4. Variation of YS of FSW Cu joints with the lowest hardness values of HAZ.

During FSW, the thermal cycle resulted in annealing softening in the HAZ [1,5,7,17], because various dislocation structures disappeared in the recovery and/or recrystallization processes. There is no doubt that the softening degree of the HAZ was decided by the peak temperature and the duration at higher temperatures. For the 400-water joint, the duration above 100 °C was only 4 s, and the peak temperature was about 130 °C. This brought almost no annealing softening in the HAZ, as shown in Figure 3a and c. Therefore, nearly equal tensile strength to the PM was obtained for the 400-water joint.

It is widely accepted that the HAZ is the softest zone and decides the mechanical properties of the whole of FSW Cu joints [4–7,17]. Similar to the previous studies [5,7,17], all the FSW Cu joints failed in the HAZ with the lowest hardness values in this study, indicating that the weld strength was consistent with the lowest hardness value. Figure 4 shows the variation of the YS of the FSW Cu joints with the lowest hardness values in the HAZ. It is clear from the figure that there is a strong linear correlation. A similar phenomenon was also observed in FSW of 6063 and 7050 aluminum joints [18,19]. Therefore, the YS of the FSW joints were governed by the lowest hardness value in the HAZ.

In order to obtain sound FSW joints with nearly equal weld strength to the PM, it is necessary to decrease the heat input to eliminate or greatly reduce the annealing softening in the HAZ. Besides changing the welding parameters, additional rapid cooling with flowing water undoubtedly helps decrease the heat input further. Moreover, employing a smaller tool size and a more efficient cooling medium will decrease the heat input more effectively. In principle, as long as the thermal cycle in the HAZ is reduced to a very low level that can prohibit any annealing softening effect, a nearly equal weld strength to the PM would be achieved for the FSW joints.

In summary, the following conclusions are reached:

1. Defect-free FSW pure copper joints were achieved at 800 and 400 rpm without and with additional rapid water cooling. While the HAZ of the 800-air FSW joint exhibited a very low dislocation density, the HAZ of the 400-water joint almost retained the initial microstructure of the PM with a high dislocation density.

2. The peak temperature and the duration at higher temperatures of the HAZ were significantly reduced when rapid cooling by flowing water was applied during FSW. For the 400-water joint, the peak temperature of about 130 °C and the duration of 4 s above 100 °C indicated a significantly reduced heat input.
3. The YS of the FSW Cu joints exhibited a strong linear correlation with the lowest hardness values in the HAZ, which was determined by the heat input. A weld with nearly equal strength to the PM was achieved at 400 rpm with rapid water cooling.

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