Materials Science and Engineering A 527 (2010) 6879–6886

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Investigation of the welding parameter dependent microstructure and mechanical properties of friction stir welded pure copper

Y.F. Sun, H. Fujii*

Joining and Welding Research Institute, Osaka University, Ibaraki 567-0047, Japan

ARTICLE INFO

Article history:
Received 22 February 2010
Received in revised form 9 June 2010
Accepted 9 July 2010

Keywords:
Friction stir welding
Microstructure
Mechanical properties
Copper

ABSTRACT

The process window for friction stir welding of commercially pure copper was obtained, which included a welding speed ranged from 200 to 800 mm/min, a rotation speed ranged from 400 to 1200 rpm and an applied load ranged from 1000 to 1500 kg. In the stir zone, a remarkably refined microstructure with average grain size of 3.8 μm can be obtained by increasing the applied load to 1500 kg. In addition, higher applied load can promote the formation of dislocation cells, while annealing twins and dislocation entanglements are easy to form under lower applied load. The mechanical properties of the joints can be improved further by increasing the applied load, rather than only decreasing the rotation speed at lower applied load. The mechanism of the mechanical property changes in the copper joints were put forward and clarified from the viewpoint of microstructural evolution.

1. Introduction

Friction stir welding (FSW), which is as a solid-state joining process, was invented by The Welding Institute (TWI) of UK in 1991 in an attempt to weld aluminum alloys [1]. With the successful application of FSW in the aluminum industries and the rapid development of high temperature durable rotation tools, this technique has been quickly expanded to many other metals or alloys, such as Mg, Cu, Steel, Ti and Ni alloys [2–7]. Recently, with the increasing application of copper or copper alloys as structural materials, for example, the use of copper canisters for nuclear waste, there is an increasing demand for the welding of these materials [8]. Although copper and copper alloys can be joined by most of the commonly used methods such as gas welding, arc welding, resistance welding, brazing and soldering, the joining of copper is usually difficult by conventional fusion welding methods because copper has a thermal diffusivity of about 401 W/mK, which is almost the highest among all the metallic materials. During welding, much higher heat input is required due to the rapid heat dissipation into the workpieces and the welding speeds are therefore quiet low. In addition, the serious oxidation at melting temperature and the thermal crack in the joint are also a stubborn problem and will inevitably deteriorate the mechanical properties of the copper weld [9,10]. To overcome these problems, FSW has been regarded as a promising welding method for the joining of copper.

To overcome the rapid dissipation of heat, much heat input is necessary during FSW of copper and therefore the welding processes were usually carried out with high rotation speed and low welding speed [11–15]. However, it was found that the stir zone of the welded copper usually exhibit a lower hardness value than that of the base metal, even though the stir zone has a much refined microstructure comparing with the base metal. For example, Lee et al. found that the grain size decreased from 210 μm for the base metals to 100 μm for the stir zone, but the hardness value decreased slightly due to the reduction in dislocation density relative to base metal [16]. While Xie et al. also observed this hardness reduction phenomena and contributed this hardness reduction to the annealing soft of the stir zone resulted form the FSW process [17]. Although the mechanical properties in the stir zone can be improved by decreasing the rotation speed, the risk of the defect formation increases due to insufficient heat input [17,18]. Moreover, the FSW of Cu was carried out with a few welding variables and the effect of applied load on the microstructure and mechanical properties of FSW processed copper has never been considered so far.

In this study, the FSW technique was applied to the welding of 2 mm thick pure copper plates under 1/2H condition. Various welding conditions within a wide range which includes welding speed, tool rotation speed as well as the applied load were tried to obtain the process window for the FSW of pure copper. Since the microstructure evolution in the stir zone is often regarded as one of the key issues of FSW/FSP and the microstructure characterizations of FSW processed Cu have been reported previously but were mainly focused on the grain size of the equiaxial grain structure in the stir zone. However, the misorientation distribution, twin

* Corresponding author. Tel.: +81 6 68798663; fax: +81 6 68798663.
E-mail address: fujii@jwri.osaka-u.ac.jp (H. Fujii).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2010.07.030

Table 1
Welding parameters used in the FSW of copper.

Tool material	Tool dimension	Rotation speed (rpm)	Welding speed (mm/min)	Applied load (kg)
WC-based alloy	ϕ12 mm shoulder ϕ 4 mm probe 2 mm probe length	200–1200	200–800	1000–1500

fraction and dislocation densities are also important factors that can greatly influence the mechanical properties of the work-piece. After welding, the relationship between the microstructure evolution and mechanical properties of the FSW processed specimen were investigated and discussed.

2. Experimental procedure

Commercially pure Cu plates with a dimension of 200 mm length × 50 mm width × 2 mm thickness were subjected to the FSW process in this study, which were as-received in 1/2H state with average grain size, Vickers hardness and tensile strength of about 20 μm, 100 HV and 266 MPa, respectively. First, the Cu plates were placed on the steel back plate and clamped tightly. The welding process was then performed on a load-controlled FSW machine. WC-based alloy tools, which had a 12 mm-dia concaved shoulder, 4 mm-dia unthreaded probe and 2.0 mm probe height, were used and tilted by 3° during the welding process. To obtain the suitable welding conditions, various travel speeds, rotation speed and applied loads were used for the FSW of copper. The detailed parameters were summarized in Table 1. To prevent the oxidation of copper, the FSW processes were carried out with argon gas flowing around the rotating tools.

After welding, optical microscopy (OM) was used to characterize the macrostructure of the joints. The samples for OM observation were cross-sectioned perpendicular to the welding direction, polished and then etched with a solution of iron chloride. The electron backscattered diffraction (EBSD) measurements were carried out by using a JEM 5200 scanning electron microscopy (SEM) with a TSL orientation imaging system. The microstructures in the stir zone and in the thermo-mechanically affected zone were also characterized by transmission electronic microscopy (TEM). For TEM sample preparation, thin plate were first cut at the desired locations and then mechanically polished to a thickness of about 100 μm. The polished thin plates were finally twin-jet electro-polished to make electron beam transparent thin film using a solution of HPO_4:CH_4O:H_2O = 1:1:2 at 5 V and 0 °C. The thin films were observed with a Hitachi 800 TEM at 200 kV. The Vickers hardness profiles of the joint were measured along the centerline of the cross-section and perpendicular to the welding direction by using a Vickers indenter with a load of 980 mN and dwell time of 15 s. The tensile specimens were electrical discharge machined into a dog-bone shape with a gauge length of 100 mm, width of 10 mm and thickness of 2 mm. The tensile tests were carried out using an Instron-type testing machine with a crosshead speed of 1 mm/min. The tensile direction is perpendicular to the welding direction. For those specimens fractured in the base metal during the tensile tests, a miniature tensile specimen was cut in dog-bone shape with the gauge length completely within the welded joint to evaluate the tensile strength.

3. Results and discussion

3.1. Determination of the process window

Based on the OM observation of the joints and the appearance of the welded samples, the available processing conditions or the process window for the FSW of pure copper can be obtained as shown in Fig. 1. Obviously, the process window for the FSW of copper is much narrower compared with that for the FSW of aluminum [19]. In Fig. 1, the shadowed area indicated the welding conditions applicable for the FSW of pure copper. The different color of the small squares within the shadowed area indicated the different applied load. It reveals that the process window for friction stir welding of commercially pure copper was defined by a welding speed ranged from 200 to 800 mm/min, a rotation speed ranged from 400 to 1200 rpm and an applied load ranged from 1000 to 1500 kg. It is worthy noting that lower applied load than 1000 kg in the process requires much higher rotation speed or lower welding speed, which will cause the welding process very unstable and difficult to obtain a weld with uniform quality from the start to the end of the welded seam. While higher applied load than 1500 kg will certainly cause too much flash on the advancing side, because the high pressure might exceeds the actual flow stress of the material at the operating temperature.

As typical examples, Fig. 2 shows the macrostructural evolution of the cross-section of the joints welded at a travel speed of 650 mm/min, but with different tool rotation speed and applied load. From the cross-sectional macrostructure, the formation of weld defects and the formation of the specific zones in the joints, namely, stir zone, thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ) and base metal, can be generally distinguished [20–22]. According to Fig. 2, basin-shaped stir zone can be observed in some copper joints and widens towards the surface of the work-piece. This phenomenon was also found in other FSW processed materials and was thought to be caused by the friction between the work-piece surface and the shoulder of the rotation tools [5]. For all the welded joints, no onion-rings can be observed in the stir zones, which is probably due to the unthreaded probe used in the present study. It is apparent that the outlines of the stir zones are quite different depending on the applied load. It was said that the shape variations of the stir zone depend on the processing parameter, tool geometry, temperature of the work-piece, and thermal conductivity of the materials [23]. In the present study, the sample welded under an applied load of 1000 kg exhibits a downward-concave boundary between the stir zone and the base metal. The downward-concave boundary between the stir zone and the base metal gradually becomes inconspicuous with

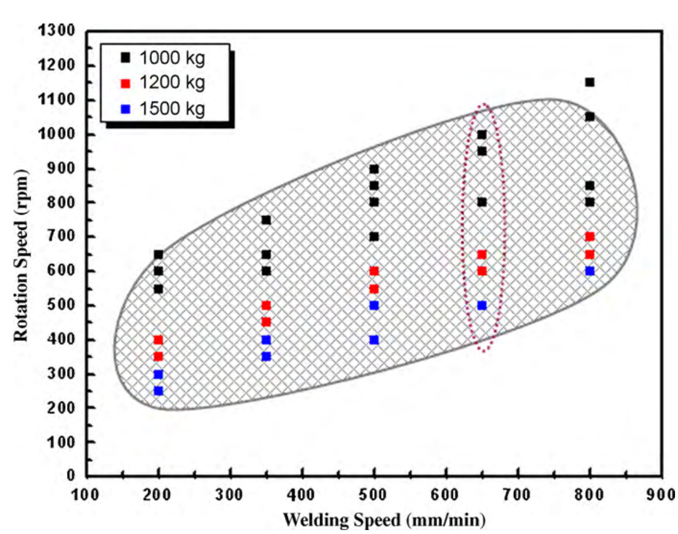

Fig. 1. Process window for the FSW of pure copper.