Materials & Design 127 (2017) 311–319

Contents lists available at ScienceDirect

Materials & Design

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

Metallurgical and mechanical properties of continuous drive friction welded copper/alumina dissimilar joints

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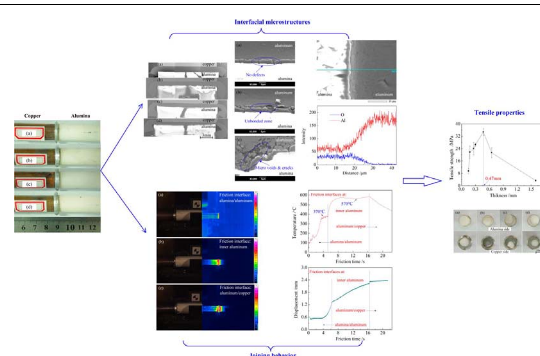
ARTICLE INFO

Keywords:
Continuous drive friction welding
Copper/alumina dissimilar joint
Microstructure
Mechanical property
Welding mechanism

ABSTRACT

Wettability and stress concentration are the main challenges affecting the engineering application of copper/alumina dissimilar joints. In this paper, continuous drive friction welding of copper to alumina was conducted using 2.5 mm thick AA1100 aluminum as interlayer. The effects of friction pressure and friction time on the tensile strength of joints were evaluated, and the interface microstructure evolution and fracture morphologies were also analyzed. Obvious mutual diffusion occurred at the alumina/aluminum and aluminum/copper interfaces, enhancing wettability and proving metallurgical bonding. Microcracks formed in alumina base due to thermo-mechanical coupling effect in welding. As increasing friction pressure and friction time, the tensile strength increased till reaching a peak value of 35 MPa, and then decreased. The optimized parameters were determined as friction pressure of 12 MPa and friction time of 12 s. All samples failed at the aluminum/alumina interface, leaving a pit structure on alumina base. The application of pure aluminum interlayer is essential to obtain sound copper/alumina joints by diminishing stress concentration and wetting alumina, and the optimized residual aluminum layer is about 0.47 mm thick. The friction interface transferred from alumina/aluminum to inner plasticized aluminum layer, and then moved to aluminum/copper till the welding process finished.

GRAPHICAL ABSTRACT



1. Introduction

Alumina ceramics, which possess the favorable properties of high temperature strength, corrosion resistance, wear resistance, high dielectrics strength, low dielectric loss and stable electrical performance, etc., have been widely applied in electrical industries. In addition, application of copper in electrical industries is also quite prominent due to its excellent conductivities of heat and electric. The dissimilar joint

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http://dx.doi.org/10.1016/j.matdes.2017.04.093
Received 18 January 2017; Received in revised form 23 April 2017; Accepted 26 April 2017
Available online 27 April 2017
0264-1275/

Table 1
Welding parameters used in this study.

Group number	#1	#2	#3	#4	#5	#6	#7
Friction pressure/MPa	6	12	18	24	12	12	12
Friction time/s	12	12	12	12	9	15	18

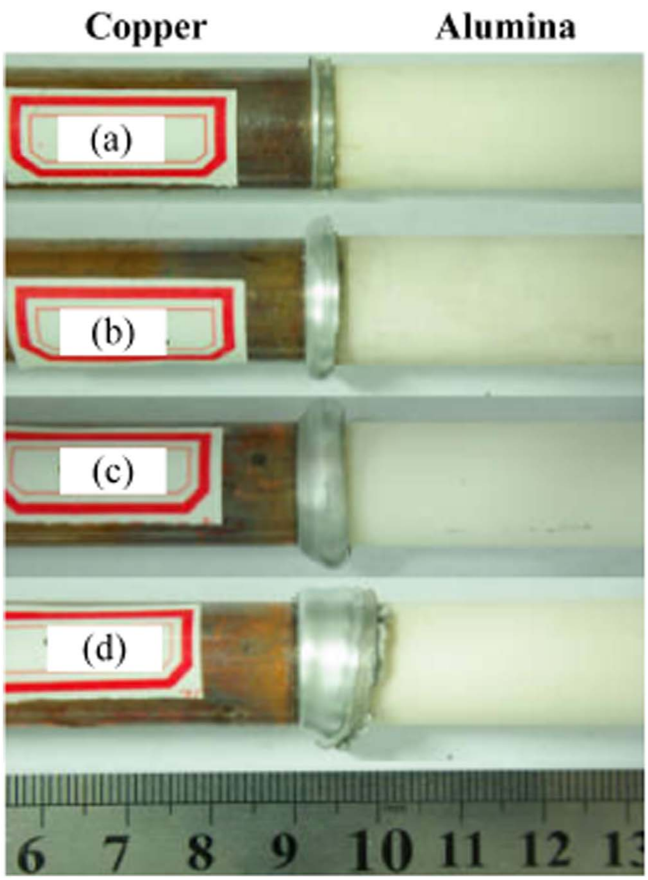

Fig. 1. Appearances of the joints welded at different friction pressures of (a) 6 MPa, (b) 12 MPa, (c) 18 MPa and (d) 24 MPa.

between copper and alumina combines their advantages and finds promising application in the field of vacuum interrupters and vacuum electronic packaging [1–4]. However, challenges still exist in joining the two parent materials due to large differences in thermal-physical properties, such as linear thermal expansion coefficient (alumina: $7.4 \times 10^{-6}\,K^{-1}$, copper: $17.5 \times 10^{-6}\,K^{-1}$) and melting point (alumina: 2050 °C, copper: 1083 °C), which will lead to high residual stress and excessive distortion. The joint strength and structure integrity are thus destroyed.

Several welding methods including fusion welding, brazing, and solid-state welding have been attempted to obtain ceramic-metal dissimilar joints [5–11]. Among these methods, friction welding has gained great attentions due to its solid-state nature and short welding cycle, which can greatly decrease the thermal mismatch between the parent materials [12]. Sound joint was thus formed. There has been considerable effort towards friction welding of ceramics and metal couples [13–19]. However, to our knowledge, no literature has publicly reported the accomplishment of friction welding between copper and alumina. The prevalently used methods to join this couple of materials are brazing and diffusion bonding, which suffer from the disadvantages of the working temperature governed by properties of brazing filler metal and the stress concentration caused by high welding temperature. Essa et al. [20] investigated the friction joining of metals to ceramics and found that it was not possible to friction weld mild steel or copper to alumina directly. The reason for this could be that steel and copper could not directly wet the alumina, while the aluminum can wet the alumina well due to the admirable chemical compatibility [21,22]. Noh et al. [23] investigated the friction welding of mild steel to alumina by using aluminum interlayer, and found that the joint strength was highly dependent on the wettability of aluminum to alumina. The fracture mainly occurred at the aluminum/alumina interface due to weak joining resulted from differences in melting points and higher surface energy compared to aluminum/steel interface. Seli et al. [24] also found that aluminum interlayer was essential for friction welding of mild steel to alumina and the fracture occurred between aluminum and alumina. Accordingly, aluminum was selected as the interlayer in this study.

The aim of this investigation is to fabricate a credible combination between commercially pure copper and 95% alumina by using continuous drive friction welding. The effects of friction pressure and friction time on the interfacial microstructure evolution and joining behavior were innovatively revealed by comprehensively analyzing the high speed images and infrared thermal images. The mechanical properties and welding mechanism of the joints were also discussed.

2. Materials and experimental procedures

Rods of commercially available pure copper and 95% alumina in diameter of 14 mm were used as base materials. Prior to welding, the faying surfaces were polished with emery paper, ultrasonically cleaned in ethanol and dried in air. Friction welding was carried out using a continuous drive friction welding machine (C40, Changchun CNC Machine Tool Co. Ltd., China). The axial displacement and joining behavior were recorded by a high speed camera (Vision Research Inc. Phantom v310) at a frame rate of 500 fps. The surface temperature field was measured by an infrared thermal imaging camera (InfraTec VarioCAM® hr head-HS) at a frame rate of 50 fps. Table 1 shows the friction welding parameters used in this study. The other constant parameters were set as a friction speed of 1900 rpm, an upsetting pressure of 36 MPa and an upsetting time of 5 s. A small level of friction pressure was used to suppress the cracking of alumina during the friction welding operations.

Before welding, an AA1100 aluminum rod with the same diameter of 14 mm was firstly friction welded to the copper base, and then it was machined to a certain thickness acting as a buffer interlayer. The welding parameters were set as the following combination: a friction pressure of 70 MPa, an upsetting pressure of 120 MPa, a friction time of 1 s, and an upsetting time of 5 s, under which the joint strength of 150 MPa was achieved. Considering that if the initial thickness of the aluminum interlayer is too thin, the sound joining could not be achieved due to insufficient heating of the welding interface and inefficient releasing effect of the residual stress. The larger initial thickness of the aluminum interlayer will not affect the final joint strength, however, the production efficiency will reduce and this would not be permitted in the industrial application. Through the experimental comparison, 2.5 mm thickness of the aluminum interlayer is applicable to coordinate these two aspects of the problem. It is known that alumina is hard and brittle, and even a small amount of deformation will cause fracture in it. On one hand, the extended length of alumina is set about 17 mm and kept constant to insure its rigidity. On the other hand, relatively low friction pressure will not affect the rigidity of samples. These two parameters make the ultimate joint strength stable and repeatable. The install way of samples also affects the property of dissimilar materials joints, especially dissimilar materials with large difference in hardnesses. Generally, the material with relatively lower hardness rotates, but that with higher hardness is held stationary and brought into contact with the rotated one during rotary friction welding, in order to avoid cutting of hard material on soft one. In addition, most researchers and TWI (The Welding Institute) also