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Low-current resistance spot welding of pure copper using silver oxide paste

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ABSTRACT

Silver oxide particles were used as an insert material to reduce the current necessary for resistance spot welding of pure copper plates. To form a conduction path for successful bonding, silver-oxide particles were reduced before bonding by preheating with a reducing solvent at 120 °C for 3 min to cover the particles with silver nanoparticles. At 2200 A, bonding could be achieved with silver-oxide particles, whereas bonding was not successful in welding experiments conducted without insert materials or with fine silver particles. Bonding was accomplished through the formation of a dense sintered layer. When such silver oxide particles are used for resistance spot welding, the joining is achieved by the high sinterability of the generated silver nanoparticles.

1. Introduction

Resistance spot welding (RSW) is a bonding technique widely used in the manufacturing industry and conventionally applied to body sheets composed of ferrous materials, such as sheet metal for vehicles [1,2]. Bonding is conventionally achieved by melting target materials with heat generated from electric resistance. RSW is superior to other bonding techniques in that joining takes little time and because it forms a narrow heat affected zone. Therefore, in recent years, resistance spot welding has also been applied to the fabrication of electric devices [3,4]. However, these electric devices are made of nonferrous materials such as copper or aluminum, which have low electric resistivities [5]. In particular, the electric resistivities at room temperature of iron, copper, and aluminum are 10.1, 1.694, and 2.67 [μΩ cm], respectively [6]. The heat generated by electric resistance can be expressed as

$$Q = I^2Rt \tag{1}$$

where Q is the generated heat, I is the welding current, R is the electric resistance, and t is the welding time. As shown above, the generated heat is proportional to the electric resistance. Therefore, it is difficult to heat a nonferrous material with low electric resistivity to its melting point and achieve joining [7–9] using conventional RSW.

Regarding joining methods for materials with low electric resistivities, sintering has been a primary focus because it operates at a temperature lower than the melting point [10,11]. In the sintering process, solid-state powdery materials become a coherent mass upon heating without melting. Silver nanoparticles are well known as a sintering material for power electronics packaging [12,13] because silver has better thermal and electric conductivities than the commonly used Sn–Pb or Pb-free joints [14]. Because there are fewer atoms per particle and the ratio of surface area to volume is higher, the sintering temperature is lower for nanoparticles than for bulk materials because of the large surface energy contribution [15]. Therefore, bonding processes using silver metal–organic nanoparticles have been developed [16–20]. Thus, if silver nanoparticles are used for RSW of nonferrous materials, bonding with a short holding time can be achieved at a temperature lower than the melting point of the target materials by sintering the silver nanoparticles between the target materials. Thus, low-electric-current bonding of nonferrous materials can be achieved by RSW. In fact, Mei et al. have applied current-assisted sintering technology for the sintering of nanosilver paste and achieved rapid sintering of a nanosilver joint [21].

As a low-cost alternative, we have proposed the use of silver oxide particles in the bonding process [22–28]. Silver nanoparticles can be formed from silver oxide particles in situ through a redox reaction during the bonding process. These silver-oxide-derived nanoparticles have the same high sinterability as conventional nanoparticles and can be used to achieve metal-to-metal bonding. This enables adequate strength to be obtained in a copper-to-copper joint sintered with silver oxide particles [26,27]. Thus, the in-situ generation of silver nanoparticles by electric current is expected to facilitate low-electric-current bonding of nonferrous materials by RSW. This low-electric-current RSW can enable rapid localized melting of components and devices without the use of brazing filler metals.

The objective of the present study was to bond copper plates, which cannot be bonded using conventional RSW, using nanoparticles

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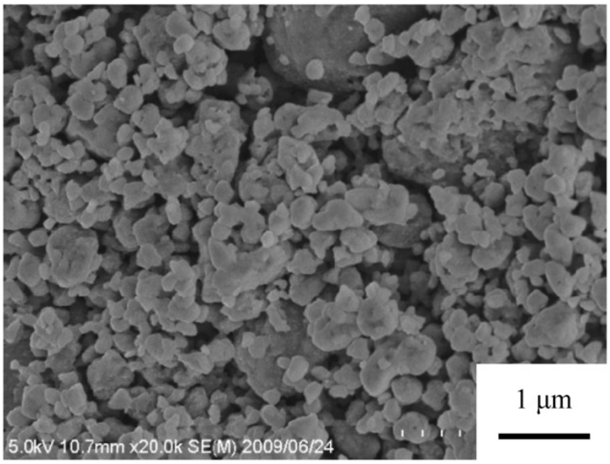

Fig. 1. SEM image of silver oxide particles.

generated in situ with low electric current. We used silver-oxide particles as an insert material and investigated the quality of the resulting bond by measuring the tensile shear strength and observing the cross section and fracture surface of the joint.

2. Experimental procedure

The prepared silver oxide particles are shown in Fig. 1. For bonding, the silver oxide particles were milled for 10 min, mixed with diethylene glycol (DEG) to a concentration of 180 μl/g, and processed into a paste. Pure copper (99.6%) plates were used for bonding. Pastes were applied to the lower copper plate using a 50-μm-thick mask and preheated to reduce the silver oxide particles. After preheating, the upper plate was placed on the lower plate, and the sample was joined. We also performed bonding using fine silver particles as a reference; their average size was 739 nm, and they were mixed with triethylene glycol (TEG) to form a paste. The fine silver particle paste was applied to the lower copper plate using a 50-μm-thick mask and dried for 12 h. Subsequently, the upper plate was placed on top and bonded. The joining process was performed with a Micro Denshi Co., Ltd. TH-2600 inverter-type DC power supply and a Micro Denshi Co., Ltd. MRH-101 weld head. Cu–Cr electrodes with diameters of 5 mm were used. Small-scale RSW was performed with a welding current of 2200 A and weld time of 99 ms. The electrode force was 5 MPa. A schematic illustration of the bonding apparatus is shown in Fig. 2. The thermal characteristics of the reduction reaction of the silver oxide particles were measured by a combination of differential thermal analysis (DTA) and thermogravimetry (TG) at a heating rate of 10 °C/min in ambient atmosphere. The strength was measured by performing a tensile shear test at a cross-head speed of 1 μm/s. The cross section and fracture surface of the joint were observed using field-emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM) and analyzed using energy-dispersive X-ray spectroscopy (EDX).

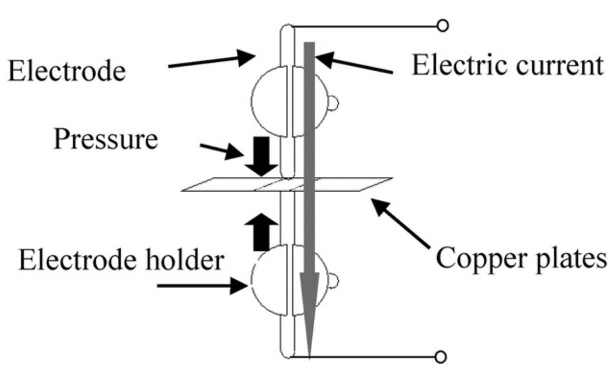

Fig. 2. Bonding apparatus.

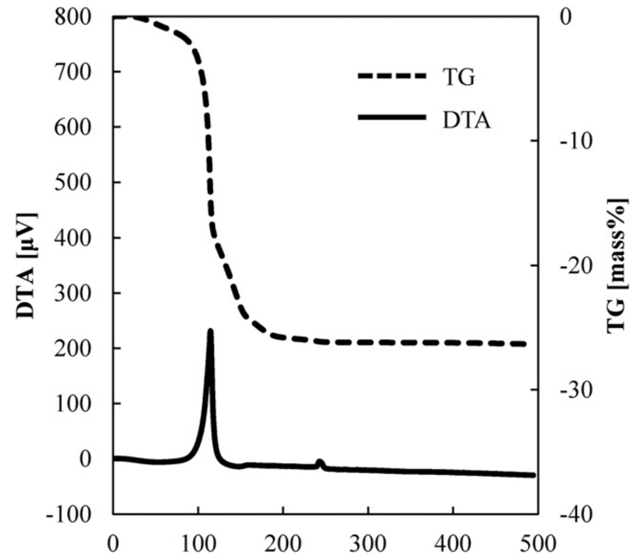

Fig. 3. TG-DTA trace of DEG paste heated up to 500 °C at a rate of 10 °C/min.

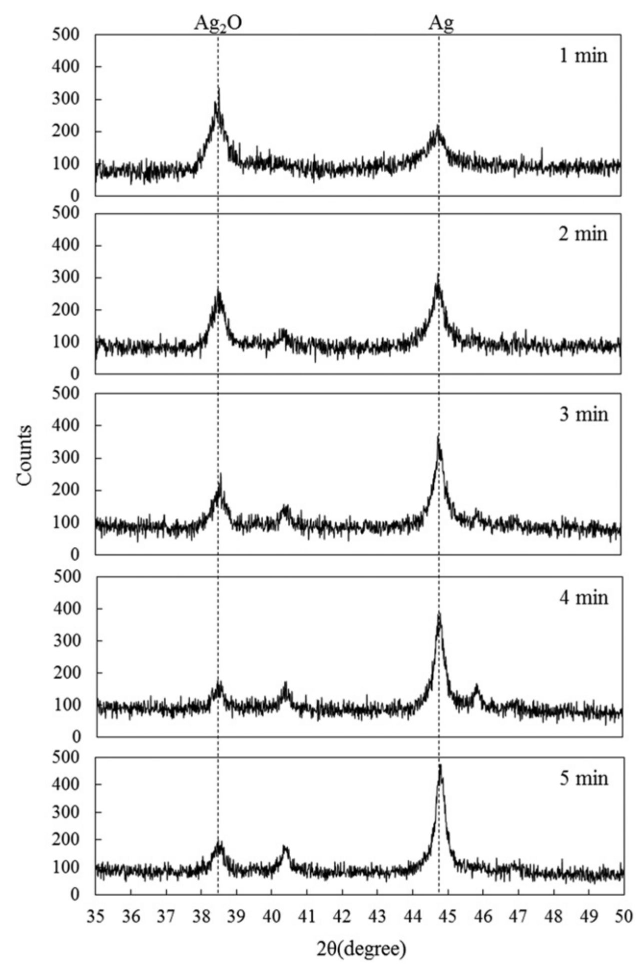

Fig. 4. XRD analysis of DEG paste preheated at 120 °C for 1 to 5 min.