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Investigation of resistance heat assisted ultrasonic welding of 6061 aluminum alloys to pure copper

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ABSTRACT

This paper proposes a new welding method for joining non-ferrous metals: resistance heat assisted ultrasonic welding. Resistance heat generated by the electric Joule effect is used as an additional electrical energy source to assist ultrasonic welding process. A comparison is conducted between two dissimilar Al–Cu joints, one produced by ultrasonic welding and the other by resistance heat assisted ultrasonic welding. In the resistance heat assisted ultrasonic process, the peak power of ultrasonic vibration increases significantly. The interfacial reaction between aluminum and copper is studied as a function of the current. The thickness of the intermetallic compound layer, which is predominantly composed of $CuAl_2$, increases with the current. At a relatively high current (1500 A), resistance heat assisted ultrasonic welding produced a dendritic solidification microstructure at the interface, due to the occurrence of a eutectic reaction, α-Al + $\theta \rightarrow L$, during the welding process. The influence of current on the mechanical properties of the joints is also discussed.

1. Introduction

Joints of dissimilar materials have a large number of potential industrial applications because of their economic and technical advantages [1]. Copper and aluminum, with their high electrical and thermal conductivity, are preferred in the electronics industries and battery electric vehicles. Hence, a significant amount of Al–Cu joining is needed to transmit electricity. Unfortunately, joining of Al–Cu by conventional fusion welding methods is difficult due to poor weldability, high levels of distortion and rapid formation of bulk intermetallic compound (IMC). Therefore, solid-state welding methods, such as friction stir welding (FSW) [2–4], ultrasonic welding (USW) [5–7], have received much attention as alternative joining techniques for Al–Cu.

FSW is a relatively new solid-state joining technique invented by The Welding Institute (TWI) in 1991 [8]. FSW is demonstrably better than traditional welding technique at joining dissimilar material combinations such as Al–Cu because of its lower temperatures and heat inputs. However, the FSW technique has difficulty meeting with the challenges of the electronics industries and battery electric vehicles, which require the joining of irregular miniature work pieces and multiple dissimilar materials with varying thickness combinations.

Ultrasonic welding is another kind of solid-state joining technique that produces coalescence through high frequency vibration and moderate clamping forces. Although USW has been successfully used for more than 50 years, it has been mainly used in joining thin foils because of the limitation of power of the welding system [5,9–11]. The temperature of the interface is less than 300 °C and very little interfacial interaction happens with most dissimilar material combinations [5,12,13]. Hence, the quality of the joint is not always very high. More recently, with the development of high power USW equipment, much research has been reported on joining thicker similar and dissimilar metal sheets, such as Al–Al, Al–Mg and Al–Fe [14–18]. With higher energy input, the temperature of the weld zone is much higher and an IMC layer is observed at the joint interface. The quality of the joints was effectively improved. From the previous studies, it can be concluded that energy/power is a key factor for dissimilar joints formed by USW, since it affects the growth and size of the IMC layer, which determines the mechanical performance of the joints.

However, the high power USW technique is also difficult to apply to the joining of miniature work pieces. This challenge results from the area of the weld tip, which limits the ultrasonic power delivered in the weld zone. An effective solution to this problem is to utilize an additional form of energy, such as Joule heat, during the USW process. In this study, a new hybrid welding technique, the resistance heat assisted USW (RUSW) technique, is proposed to further contribute to the improvement of USW quality.

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Sound dissimilar Al–Cu joints were successfully produced by RUSW. The microstructures of the faying surface were analyzed in detail. The influence of the microstructure development on the mechanical properties was also studied.

2. Experimental

As introduced by Cao and Yang [19], RUSW is a hybrid joining technique, as shown in Fig. 1a. The high intensity direct current (DC) flows from the sonotrode, through the contact interface and coupons, and into the anvil where it generates resistance heat by the Joule effect, as depicted in Fig. 1b. Compared with USW, the RUSW technique takes advantage of resistant heat generated by the Joule effect as an additional heat source. Therefore, more heat can be generated in the RUSW process while keeping other parameters, such as welding time and clamping pressure, unchanged. The RUSW system employed was a lateral drive device operating at a frequency of 25 kHz and a maximum output power of 1 kW, which is considered to be a low power USW machine [10,18,20]. The specially designed 3 mm × 3 mm knurled sonotrode (Fig. 1c) was also used as an electrode to deliver the DC. The DC could be adjusted from 0 to 2 kA continuously during the joining process. The ultrasonic energy could be coupled precisely and freely with the DC by the RUSW generator. In this study, ultrasonic energy was synchronized to the DC in the welding process (Fig. 2). The welding time was 0.4 s, the clamping force was 1480 N, and the DC ranged from 1100 to 1500 A.

The joints investigated were produced between 0.3 mm thick 6061 aluminum and 0.3 mm thick copper with no cleaning or surface preparation before welding. The chemical composition (wt.%) of 6061 aluminum is Al–1.3Mg–0.53Si–0.4Fe–0.25Zn–0.33Cu–0.1Mn and the copper is commercially pure C1100 copper. The coupons, which are 75 mm long by 25 mm wide, were welded at the center of the 25 mm overlap.

The vibration amplitude was measured in real time by a KEYENCE LK-G5001 laser displacement sensor and the DC by a CHB-2000SJ Hall current sensor. K-type thermocouples of 0.15 mm diameter were embedded into a machined groove between the 6061 Al and C1100 Cu to measure the temperature of the weld interface, as shown in Fig. 3. Vibration, DC and temperature values were recorded by the NI-6133 data acquisition system.

Microstructural analysis was performed in the cross-section of the joints by using a Hitachi S-3700N microscope complemented by an energy dispersive spectroscopy. The phase constituents of the dissimilar joints were studied by X-ray diffraction (XRD) analysis using a Bruker D8 Advance XRD system. Tensile lap shear tests were carried out at a constant crosshead speed of 1.0 mm/min by using an AGX-50kNXD testing system. A computerized microhardness testing machine was employed for the Vickers microhardness tests diagonally across the cross-section using 25 g load for 15 s.

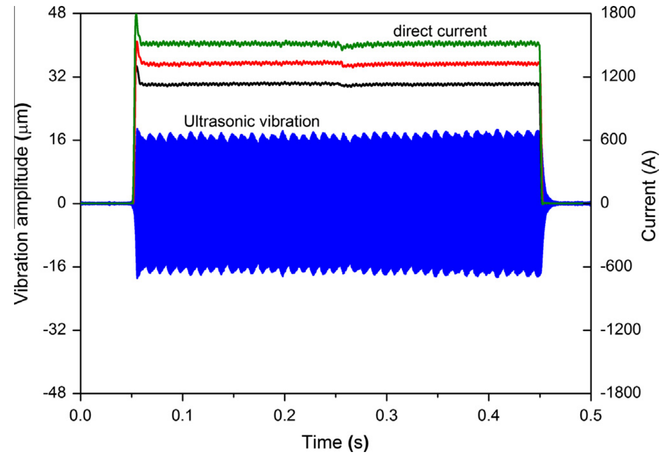

Fig. 2. Hybrid process of ultrasonic vibration and high intensity DC.

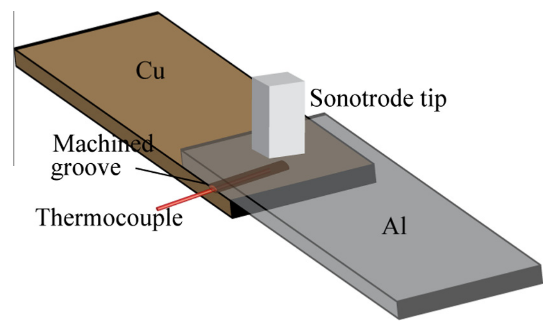

Fig. 3. A schematic demonstrating of the thermal couple position for temperature measurement.

3. Results and discussion

3.1. Ultrasonic power and weld temperatures

The ultrasonic powers of RUSW for various DC inputs are plotted against the time (t), as shown in Fig. 4a. The peak power increased with increasing input DC and reached a maximum of

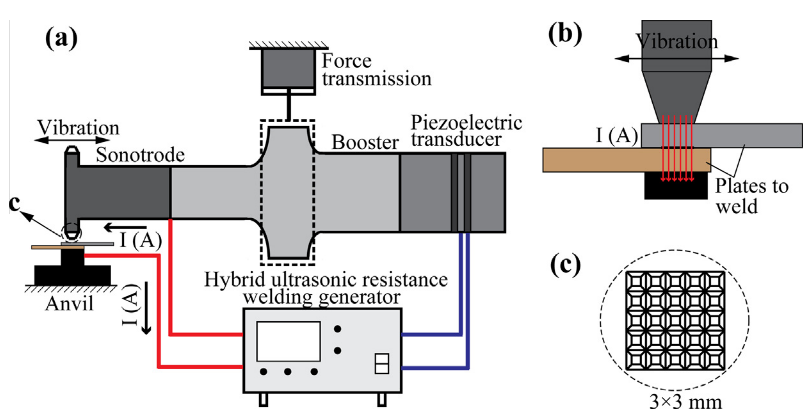

Fig. 1. (a) A schematic diagram of the electric Joule effect assisted ultrasonic welding system, (b) closer detail of the previous and (c) a schematic diagram of the knurled sonotrode tips.