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Effect of pin profile on microstructure and mechanical properties of friction stir spot welded Al-Cu dissimilar metals

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ABSTRACT

Pin profile exerts an important influence on heat production and material flow in friction stir spot welding, thereby affecting microstructure evolution and mechanical properties of the welded joint. Thus, the relationship between pin profiles and resultant microstructure of the joint as well as the mechanical properties needs to be revealed. In the present study, three types of tools with different pin profiles were designed to join aluminum and copper by friction stir spot welding. Optical microscope, scanning electron microscope and X-ray diffraction were conducted to characterize macrostructure and microstructure in welded joints. Tensile shear and micro-hardness test were used to evaluate the mechanical properties of joints. Well-formed joints were obtained using different tools under proper process parameters. Higher heat generation and temperature were produced during welding process by using threaded pin tool. Several intermetallic compounds, including $CuAl_2$, CuAl and Al_4Cu_9, were formed at the interface between aluminum and copper. No distinct difference was observed for micro-hardness distribution in the joints using various pin profiles. The tensile shear failure load was largely dependent on the pin profiles with the maximum value got in the joint obtained by using threaded pin. The tensile shear fracture of joint by using featureless pin presented the brittle fracture characteristics, and other welded joints showed the mixed fracture characteristics.

1. Introduction

The joining of aluminum and copper has a wide application in many industries, such as electronics and refrigeration industries, due to its cost saving and weight reduction by substituting of aluminum for copper [1,2]. Achieving good joining of aluminum and copper is inevitable in these industries. However, excellent quality for Al-Cu dissimilar joint is difficult to be acquired by conventional fusion welding due to the accompanied problems of porosity, crack and brittle intermetallic compounds (IMCs) [3]. Friction stir welding (FSW) is an advanced solid state joining process invented by The Welding Institute (TWI) in 1991, which provides a novel method for the joining of dissimilar materials [4]. The joining is achieved at the temperature lower than material melting temperature. Therefore, the technique enjoys great advantages in terms of IMC control during dissimilar materials joining [5,6]. On the basis of conventional FSW, friction stir spot welding (FSSW) was proposed by Mazda Motor Company of Japan as a replacement of conventional resistance joining process. During FSSW process, a non-consumable rotating tool is inserted into the lap joint and held for a desired time at the predetermined position, and then withdrawn from the welded joint. Notably, unlike the conventional FSW, the tool does not move forward during welding process [7].

It has been proved that the pin profile exerts a significant influence on heat production and material flow during FSW besides welding process parameters. Several studies were conducted to investigate the effect of pin profile on the microstructure and mechanical properties of FSW joints, such as aluminum alloys [8–10], magnesium alloys [11,12], copper alloys [13] as well as dissimilar joints [14–16]. In the case of aluminum to copper FSW, optimization of tool pin profile is quite important. Three different pin profiles were used by Muthu et al. [17] to conducted experiments. Defect-free stir zone with the maximum joint properties were obtained in the joint produced by plain taper pin rather than whorl pin and taper threaded pin. Mehta et al. [18] demonstrated the inapplicability of polygonal pin profiles for FSW of aluminum to copper. Many defects were found in the stir zone owing to the uneven scratching of Cu particles. The comparative experiment was also implemented by Zhao et al. [19] using threaded, taper and straight cylindrical pin profiles, in which taper pin is proved to be most effective

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to obtain the dissimilar joint with high strength.

As for the FSSW of aluminum to copper, limited literatures appear until now. Most of the studies focus on the influence of welding parameters on the microstructure and mechanical properties of welded joint [20–22]. Heideman et al. [20] employed a series of parameters to produce the spot welds. The results revealed that the existence of hook promoted the joining between two plates and the weld strength was increased. Mubiayi et al. [22] used two different tools in their experiments, flat pin/flat shoulder and conical pin/concave shoulder. The optimum parameter was determined at tool rotation speed of 800 rpm and shoulder plunge depth of 1 mm using the flat pin and flat shoulder tool. However, no systematic researches concerning the effect of pin profile on microstructure evolution and resultant mechanical properties is available for aluminum to copper FSSW until now. In the present study, 2 mm thick 1060 aluminum alloy sheet was FSSWed to T2 copper using tools with different pin profiles, and the effects of pin profile on microstructural characteristics and mechanical properties of welded joints were investigated.

2. Experimental procedure

In the present study, plates of 1060 aluminum alloy and T2 copper with the dimensions of 100 × 40 × 2 mm were employed as base materials, whose chemical composition is given in Table 1. The sheets were FSSWed using the lap joint form with the aluminum sheet on the top (Fig. 1). The tools with cylindrical pin were made of hot die steel (AISI H13) in this experiment. Shoulder diameter and pin diameter were maintained to be 14 mm and 4.6 mm, respectively. To ensure the good mixing between two plates, pin length of 2.85 mm was chosen. Three different pin features, featureless pin, threaded pin and threaded pin with flutes as shown in Fig. 2, were designed to produce the spot welds. The process was conducted at tool rotation speed of 2250 rpm, dwell time of 5 s and shoulder plunge depth of 0.1 mm based on preliminary experimental results. The welded joints were simply marked as sample 1, sample 2 and sample 3 hereinafter.

The as-prepared weld cross-section metallographic specimens were etched with Keller reagent and observed by an optical microscope (OM) for examination of macroscopic morphology. A scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS) was used for microstructural observation and compositional analysis. X-ray diffraction (XRD) was conducted to determine the phase composition of the joint. Vickers hardness distribution was measured every 0.5 mm along the lines on the cross-section which were 1 mm above and below the interface under test load of 200 g for 10 s (Fig. 3). The tensile shear test specimen was prepared by adding supporting plates to each end of the sample and tested at loading rate of 1 mm/min using a universal mechanical tester. The welding temperatures were estimated by K type thermocouples fixed at the interface of plates with the distance of 4 mm (Point A) and 8 mm (Point B) from welding spot (Fig. 3).

3. Results and discussion

3.1. Weld temperature history

The elevated temperature softens the material and enhances the plastic flow under the severe stirring action by pin tool for the heterogeneous mixing of Al-Cu during welding process [9]. In addition, elevated temperature could promote the nucleation and growth of IMC due to the thermally activated formation process [23]. Therefore, it is of great importance to study the temperature history during welding process.

Fig. 4 presents the temperature history at point A and point B. Generally, the measured temperature histories show a similar tendency under various pin profiles. The temperature rising rate have changed twice during welding. The occurrence of first change is due to the softening of materials. The frictional heat generated between tool and material decreases, resulting in a slower temperature rising rate. Then when the shoulder contacts the upper aluminum plate, the abruptly enlarged contact surface accelerates temperature rising rate, causing the second change. The pin profiles play a significant role in heat generation, which caused different peak temperature. The highest temperature is measured to be 560 °C at point A and 396 °C at point B in sample 2, which is higher than that in sample 1 and sample 3. In sample 1, the peak temperature obtained is the lowest among three samples, which is 513 °C and 370 °C. Since the featureless pin has less contact area with material compared with other samples [11]. When adding the thread to the pin, the friction between pin and material tends to increase resulting in the increased temperature in sample 2. Further adding the flutes promotes the material plastic flow in sample 3, but the temperature decreases because of the reduction of contact area, which measures to be 541 °C and 385 °C. The difference in thermal history will surely have a significant impact on the formation of resultant microstructures, thus influencing the mechanical properties of welded joints. It must also be mentioned that the actual temperature at the weld center was definitely higher than that of point A during welding, and several equilibrium intermetallic phases could be possibly formed under this high temperature [20], which will be discussed later.

3.2. Macroscopic characteristics of welded joint

The surface appearances and cross-sections of welded joints by different tools are illustrated in Fig. 5. Well-formed joints are obtained due to sufficient heat input and material flow during welding process. The flash and keyhole, quite common phenomenons in FSSW, could be observed at all samples. Based on microstructural characteristics, the weld zone could be separated into stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). In addition, the associated severe material plastic flow along the vertical direction results in the appearance of hook [23]. Hook is a distinctive characteristic of friction stir lap welding joints, which could be ascribed to the penetration of copper into aluminum. It could facilitate the interlocking and joining between the plates, thereby affecting the mechanical properties of joint.

Different pin profiles results in different material flow patterns, which causes different morphology of SZ and hook. Therefore, the size of SZ and the angle between the hook and copper plate are measured to evaluate the effect of pin profiles on the macroscopic characteristics of welded joint. Among the three samples, sample 1 shows the smallest size of SZ area and angle, since the featureless pin produces less heat generation than the other two pins. In sample 2, the added thread increases the friction between pin and material and enhances the material flow. Therefore, the SZ area enlarges and the hook tends to be perpendicular to the copper plate. For sample 3, the size of SZ area and the angle are larger than that in sample 1, but a bit smaller than that in sample 2. It could be explained the flutes machined in sample 3 reduce the contact area between pin and material, which results in the decrease of frictional heat, so the size of SZ area and the angle slightly decrease. Although the friction is decreased, the area between hook and keyhole increases, since the existence of flutes allows material flow occurring in a larger area.

It should be emphasized that the hook is a special structure in friction stir spot welded joint, whose configuration greatly reflects the

Table 1
Chemical composition of 1060 aluminum alloy and T2 copper.

Material	Chemical composition (wt.%)							
AA 1060	Al	Cu	Si	Fe	Mn	Mg	Zn	Ti
	Bal.	0.05	0.25	0.35	0.03	0.03	0.1	0.03
T2 copper	Cu	P	Ni	Si	Fe	Zn	S	Ag
	Bal.	0.07	0.02	0.04	0.08	0.09	0.09	0.1