Materials Science & Engineering A 607 (2014) 277–286

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

# Effect of zinc interlayer on ultrasonic spot welded aluminum-to-copper joints

R. Balasundaram, V.K. Patel, S.D. Bhole*, D.L. Chen

*Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada*

ARTICLE INFO

*Article history:*
Received 2 February 2014
Received in revised form
30 March 2014
Accepted 31 March 2014
Available online 5 April 2014

*Keywords:*
Ultrasonic spot welding
Aluminum alloy
Copper
Zinc interlayer
Intermetallic compound

ABSTRACT

Dissimilar aluminum (Al) and copper (Cu) metals were joined together using ultrasonic spot welding (USW), a solid state welding technology. The welds were made with and without a zinc (Zn) interlayer to study the microstructural and mechanical properties of weld joints to analyze the effect of the Zn interlayer. USWed Al-to-Cu joints did not produce any intermetallic compounds (IMCs), and only swirls and voids were observed. It was determined through energy dispersive X-ray spectroscopy and X-ray diffraction scans that welds with a Zn interlayer placed in-between the faying surfaces of the base metals formed a composite-like eutectic structure of Al and $Al_2Cu$ at the center and Al–Zn and $CuZn_5$ at the edges of the welded joint. Al–Cu joints welded with a Zn interlayer in-between displayed lap shear tensile strengths 25–170% greater than those of the welds without any interlayer.


## 1. Introduction

The joining of dissimilar metals has many potential engineering and design applications in the automotive and electronics industries to fulfill the objective of weight reduction and mechanical properties enhancement [1–3]. Dissimilar joints of aluminum (Al) and copper (Cu) are preferred for certain electrical applications owing to their higher electrical and heat conductivity, corrosion resistance and mechanical properties, which is why Al–Cu joints are starting to take over steel in electrical systems [4,5]. Joining dissimilar metals through conventional fusion welding process produces brittle intermetallic compound (IMCs), which easily leads to fracture due to contrasting thermal, chemical and mechanical properties of the metals [6,7,3]. This makes the fusion welding process more complex and ineffective, creating the need of alternate welding processes such as solid state welding like friction stir welding (FSW), friction stir spot welding (FSSW), linear friction welding and ultrasonic spot welding (USW). However, there are still some disadvantages present in these alternate processes. For example, a study of friction welded Al-to-Cu by Sahin [4] showed poor tensile strength as a result of an accumulation of alloying elements at the interface of the joint. Studies of friction stir welding of Al-to-Cu published by both Ouyang et al. [8] and Saeid et al. [6] observed brittle IMCs of $Al_2Cu$ and $Al_4Cu_9$ along with microcracks in the welds, which are generally unfavorable to the quality of joints.

The focus of this study is the joining of Al and Cu using the USW process, which produces coalescence through the application of high frequency vibratory energy and moderate clamping forces [9,10]. The short welding time and reduced energy requirement makes USW more efficient than FSW and FSSW [3,11] and hence, can save costs and increase production in the manufacturing process. There have been few studies [2,3] that joined Al and Cu using USW process. Zhao et al. [3] observed an $Al_4Cu_9$ IMC to be the major cause of joint failure; however, it did not incorporate any means to address the issue and improve the joint. Therefore, the aim of this research was to improve USWed Al–Cu joints by inserting a Zn interlayer in between the two dissimilar metals. Zn was chosen with regard to its ability to interact well with both Al and Cu at high temperatures as seen in the Al–Zn [12,13] and Cu–Zn [14] binary phase diagrams. This study will determine if Zn can inhibit the formation of brittle Al–Cu IMCs and instead form high strength bearing, Zn-based IMCs. Also, the joints will be analyzed to see the effect of Zn on mechanical deformations in the USWed samples.

## 2. Experimental details

In this study, a commercial 1.5 mm thick sheet of Al5754–O Al alloy (composition in wt%: Al–3.42Mg–0.63Mn–0.23Sc–0.22Zr) provided by General Motors Company and a 1 mm thick sheet of soft annealed C110 copper alloy (composition in wt% 99.99Cu) were selected for USW. The specimens, 80 mm long and 15 mm wide, were sheared, with the faying surfaces ground using 120 emery papers. Next, they were cleaned with ethanol followed by

* Corresponding author. Tel.: +1 416 979 5000x7215; fax: +1 416 979 5265.
*E-mail address:* sdbhole@ryerson.ca (S.D. Bhole).

http://dx.doi.org/10.1016/j.msea.2014.03.135
0921-5093/

acetone, and dried before welding. A 50 μm thick pure Zn interlayer was placed in between the workpiece of the Al and Cu weld samples. The welding was done with a dual wedge reed Sonobond-MH2016 HP-USW system. The samples were welded at energy inputs ranging from 500 to 2000 J at 500 J intervals with a constant power setting of 2000 W, an impedance setting of 8, and a pressure of 0.414 MPa on the machine. Four samples were welded for each energy input of the two types of welds – with and without Zn interlayer. Two of them were used for microstructural examination and microhardness tests, and the other two were used for lap shear tensile tests and X-ray diffraction (XRD) analyses. Cross-sectional samples for scanning electron microscopy (SEM) were polished using diamond paste and MasterPrep. A computerized Buehler microhardness testing machine was used for the microhardness tests measured diagonally across the welded joints using a load of 100 g with a 15 s dwell time except for the thin IMC interlayer (~7–20 μm), where a load of 10 g was used for 15 s. The mean value of three indentations along the IMC interlayer was taken for better accuracy. To evaluate the mechanical strength of the joints and establish the optimum welding conditions, tensile shear tests of the welds were conducted to measure the lap shear failure load using a fully computerized United testing machine in air at room temperature with a constant crosshead speed of 1 mm/min. In the tensile lap shear testing, restraining shims or spacers were used to minimize the rotation of the joints and maintain the shear loading for as long as possible. XRD was carried out on both matching weld interfaces of Al and Cu sides after tensile shear tests using Cu $K_\alpha$ radiation at 45 kV and 40 mA. The diffraction angle ($2\theta$) at which the X-rays were incident on the samples varied from 20° to 100°, with a step size of 0.05°, and 2 s in each step.

## 3. Results and discussion

### 3.1. Microstructure

#### 3.1.1. SEM analysis on cross-sections of welds

Fig. 1(a) and (b) shows the SEM micrographs at the center of the USWed Al-to-Cu joint using 2000 J of energy input. The notable feature in these images is the large swirling deformations of the metals at the highest tested energy input (indicated by an arrow in Fig. 1(a)). This interesting phenomenon was also observed in another study of USWed Al-to-Cu joints by Zhao et al. [3]. The development of the swirls in the USW joints are because of, with higher energies, as the sonotrode tips sink further into the sheets, the coarse scale wave-like displacement becomes more extreme, and the wave peaks develop crests, or folds, in some regions [15]. This swirling effect has the potential to increase the lap shear tensile strength due to the localized interlocking of the two metals, which will be elaborated upon in the lap shear tensile strength sections below. Another feature observed in the USWed Al-to-Cu joint was the void as indicated in Fig. 1(b). This void was formed due to the swirls at the faying surfaces of the Al and Cu base metals not being able to create a flat, tight weld like the samples welded with a Zn interlayer.

The cross-section of the USWed Al-to-Cu joints using 2000 J of energy input with a Zn interlayer placed in-between the faying surface are shown in Fig. 1(c) and (d). Although it can be seen in Fig. 1(c) that there are no voids that can have a detrimental effect on the tight joint, on closer inspection, it can be seen in Fig. 1(d) that there is a formation of a discontinuous IMC layer due to the non-uniform pressure applied by the grooved welding tip. These intermittent layers are mostly on the copper side owing to the higher solubility of Al in Cu (~80 at% Al) in contrast to Cu in Al (~2.5 at% Cu) as seen in the Al–Cu binary phase diagram [16]. Another possible explanation is that when grinding the metals, the softer copper metal had deeper scratches on a micro scale, into which the IMC could settle more easily. The characteristics and causes of this IMC layer will be discussed further in the energy dispersive X-ray spectroscopy (EDS) and XRD analyses. The reason for the absence of swirls in this joint could be that molten Zn situated in-between Al and Cu during the initial ultrasonic vibration erodes the rough surfaces of the faying surfaces and creates new, smoother surfaces. Fig. 1(e) and (f) illustrates macro-cracks formed at the edge of the weld on the Cu side. As seen in these images, liquid Zn mixed with traces of Al and Cu (confirmed by EDS analysis and shown later) has squeezed outwards from the weld line into the Cu metal through the intergranular cracks. The most likely cause for this crack is liquid metal embrittlement (LME), which is the reduction in elongation to failure that can occur when normally ductile metals or alloys are stressed while in contact with liquid metals – that is, making ductile metals such as copper unconventionally brittle and therefore causing it to crack [17]. This effect was the root cause of a particular industrial accident where molten Zn induced LME in stainless steel when in contact with it and created a destructive crack [18]. Therefore, a similar case in which molten Zn embrittles the copper metal and induces cracking at a smaller scale is possible. Fig. 1(g) illustrates this crack which has propagated to the outside of the copper metal. These characteristics were observed in all four 2000 J USWed Al-to-Cu samples with Zn interlayer.

#### 3.1.2. Energy dispersive X-ray spectroscopy analysis of intermetallic compounds

The ~20 μm thick intermetallic layer which was shown earlier in Fig. 1(d) was magnified and presented in Fig. 2(a), which shows a heterogeneous composition and a small homogeneous area in the bottom right corner of the IMC. An EDS line scan across the dotted line in Fig. 2(a) was conducted on the USWed Al-to-Cu joint using 2000 J of energy input with Zn interlayer. As evident in the graph (Fig. 2(b)), the amount of Zn present in the IMC was so negligible. Since molten Zn has been squeezed out from the center of the weld nugget, the intermetallic observed in the middle should be comprised of Al and Cu and is confirmed as such with EDS point analysis scans (see Table 1 for a summary of points scanned as indicated in Fig. 2). The chemical composition at points A and B (see Fig. 2(a)) on the heterogeneous part of the IMC were (in at%) 70.1Al–29.9Cu and 70.9Al–29.1Cu, respectively. Point C on the homogeneous semi-circle section has an approximate composition of 70.4Al–29.6Cu. From the ratio of Al to Cu atomic composition given by the EDS results and the binary phase diagram of Al and Cu, the intermetallic layer formed is probably $Al_2Cu$. Xue et al. [19] reported that $Al_2Cu$ is one of the first IMCs to form during the Al and Cu reaction at high temperatures. The ultrasonic welder used in this study has the potential [20] to reach the lowest Al–Cu eutectic melting point of 548.2 °C [16] within as low as ~0.2–0.5 s, and therefore the probability of finding $Al_2Cu$ in the weld zone is high. Since this eutectic point is located in-between the Al and $\theta$-$Al_2Cu$ phase, the IMC illustrated in Fig. 2(a) is likely composed of Al+$Al_2Cu$. The reason that $Al_2Cu$ can be formed easier than the second most likely $Al_4Cu_9$ is because the diffusivity of Cu in Al is higher than Al in Cu [16]. Fig. 2(c) shows a magnified image of the heterogeneous region indicated by the box in Fig. 2(a). The chemical composition of one of the black regions, point D, was determined by an EDS point analysis scan to be (in at %) 87.1Al–12.9Cu, which suggests that it is the layer of pure Al. The gray regions indicated by point E, with a chemical composition of (in at%) 76.7Al–23.3Cu, is the IMCs of $Al_2Cu$. Therefore, it can be concluded that the heterogeneous features of the IMC is due to the eutectic structure, and that the small homogeneous, semi-circular