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Surface Morphology and Mechanical Properties of Aluminum-Copper Joints Welded by Friction Stir Welding

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Abstract. A butt welding aluminum with copper by friction stir welding has been investigated in this study. The rotation direction of the tool and the probe offset with respect to center of butt line are the main welding parameters affecting the welding quality founded in this study. A sound welding has been obtained when aluminum arranged on advancing side, with sufficient probe offset to aluminum side. Also, defect free Al-Cu welded joint produced when the copper arranged on advancing side with probe offset to aluminum side. So, probe offset play as important factor rather than direction of rotation in welding Al-Cu by friction stir welding.

1. Introduction

Joining dissimilar metals, such as aluminum and copper, (Al-Cu), is of great interest in engineering and design applications. Nevertheless, fusion welding of metals with very different melting temperatures and high chemical affinity at elevated temperatures, which gives rise to the formation of brittle intermetallic compounds (IMCs), makes such joining very difficult and the quality of the welds very poor (Weigl et al. 2011). In this context, friction stir welding (FSW), which enables the joining of materials at temperatures lower than their melting temperatures, is a promising technology for joining metals with very different chemical and physical properties (Debroy et al. 2010). Friction stir welding is relatively new technique developed by The Welding Institute (TWI) for the joining of aluminum alloys (Xue et al. 2010). Friction stir welding is the most significant development in metal joining process that is presently attracting considerable interest (Sun et al 2010; Cavalier 2005; and Liu et al 2003).

Friction stir welding of dissimilar materials faced many generic issues include, for example, the different deformation behaviors of the dissimilar materials, the possible formation of detrimental intermetallic compounds, and differences in physical properties such as thermal conductivity. These factors and others contribute to the asymmetry in both heat generation and material flow during FSW (Nadan et al. 2007). Indeed, it is necessary to choose which side of the joint should contain the advancing or retreating part of the weld. The application of FSW to dissimilar alloys clearly poses a unique set of challenges (lietao et al. 2009). Since the main issues regarding the weld ability of Al-Cu the mixture of base materials in the solid state and the formation of brittle IMCs, are common to Al-Cu dissimilar systems and because the joining of aluminum to copper does not require the production of tools from very expensive materials, this system is considered very interesting for research purposes (Saad andToshiya 2008).

Friction stir welding of dissimilar materials have different processing parameters affecting the quality of the welded joints produced unlike FSW of similar materials; Position of hard material relative to the rotation direction of the welding tool, Probe offset, direction of probe offset, rotational speed and welding speed; these parameters will affect type of IMC produced and its distribution in the nugget zone [Xue et al. 2011; and Tan et al. 2013). Previous studies succeed in producing defect-free joints of Al-Cu with good mechanical properties, by position of hard material (Cu) on advancing side with probe offset to Al side (Avettand et al 2010; and Okamura and Aota 2004). They attribute these results to easily of flew for the soft material (Al) when it position in the retreat side so that material will transported normally to the advancing side which could result in good mixing of dissimilar material in the nugget zone. Tan et al. were produced sound welded joints of Al-Cu by position the hard materials on retreating side with 0.2 mm probe offset to Al side. However, position of hard material on retreating side would cause extruded of soft material from the nugget zone due to the difficulty of flew of hard material from the retreat side to the advance side which cause large volume defect in the welded joints (Sun et al 2010; and Xue et al. 2011).

Intermetallic compound structures have a significant influence on the mechanical properties of the welded joints. While a thin IMC layer or structure improves the mechanical properties, a thick layer decreases them dramatically (Ouyang et al. 2006). Thin layer of IMCs at the welding zone are needed to strengthen the nugget zone (Xue et al. 2011). Different processing parameters were affecting the size and amount of the formed IMCs at the nugget zone. Probe offset when this offset very small many large Cu pieces were stirred into the nugget zone (Xue et al. 2011). The Cu pieces were harder than the Al matrix, therefore, the large Cu pieces were hard to deform and flow in the Al matrix, and the mixing between the large Cu pieces and the Al matrix would be very difficult. This led to the poor surface bonding and the formation of many voids and many Al–Cu IMCs would be formed. Thus the joining between the Al and Cu became poor due to the brittle nature of the IMCs. On the other hand, when the probe offset was larger, only few Cu pieces with relatively small size were scratched from the Cu bulk. It is easy for the small Cu pieces to mix and react into the Al base in the nugget zone, and therefore sound metallurgical bonding would be obtained at the nugget zone (Glvao et al. 2010).

Heat input to the welding area also controlled the formation and distribution of IMCs at nugget zone. Heat input could be controlled by rotational rate and traverse speed; lower heat input will reduce the mixing of dissimilar material in the nugget zone which results in defected welded joints (Sun et al 2010). However, higher heat input will result in excessive material flow which may cause Al to extrude out from the nugget zone resulting in tunnel defect reducing mechanical properties of the welded joints. On the other hand, higher heat input, may increase the capability of Al-Cu base materials to form IMCs with many Cu distributed in Al matrix which result in brittleness nature in the welding area. Sufficient heat input to the welding area will result in good material flow between Al-Cu which result in sound good defect free joints. On the other hand, small size of Cu material will distribute in Al matrix so that Cu will react with Al and forming IMCs distributed in a uniform manner in the nugget zone (Tan et al. 2013).

In this work, dissimilar FSW of commercial pure copper and 6061 aluminum alloy sheets was carried out, and the surface morphology and mechanical properties of the dissimilar joints were investigated. Based on the experimental results, the effect of welding process on the mechanical properties of produced joints was discussed.

2. Experimental Procedure

Two rectangular commercially pure copper and 6061 aluminum alloy plates of 250 x 100 x 3 mm size were butt-welded by friction stir welding process. The nominal chemical compositions are listed in table 1. Before welding the surfaces of the plates were ground with grit paper to remove the oxide film and then cleaned with ethanol. A conventional vertical milling machine was used for friction stir welding process, by using a fixture. The fixture is tightly fixed on the milling machine table to prevent vibration from occurring as a result of the frictional forces of the welding process. Welding tools with flat shoulder of 18 mm diameter, and 20 mm height, made of high carbon steel, were used. A 4 mm square pin profile and 2.75 mm in length was used to carry out the welding process. A spring-loaded unit was used to maintain the applied pressure on the shoulder face of the welding tool against the upper surface of the work piece constant at 3.6 MPa. The tilt angle of the tool was 1.5° from the normal surface of the plates toward the advancing side. The welding process was carried out using rotational speeds of 1118 rpm and welding (traverse) speed of 60 mm/min. In this study the effect of hard metal arranging either in advancing or in retreating side was carried out. Also, the effect of probe offset from the center of butt line either to hard or soft metal has been investigated. Table 2 shows all the combinations of parameters that carried out in producing Al-Cu welded joints by FSW. Vickers micro-hardness was measured with 0.5 kgf load and a dwell period of 10s. Several measurements were done for each hardness value. The micro-hardness readings were taken at the top and bottom surfaces of the welded joints. A sufficient reading was taken in each surface of the weldments, the indentation was taken every 1 mm from Al edge crossing the nugget zone toward the Cu edge. In addition, a tensile test was carried out on a WDW-20 computer controlled universal tensile testing machine. The tensile specimen is loaded at a rate of 0.5/s.

The load versus displacement has been recorded by the machine and ultimate tensile strength was determined. The tensile test specimens had a gauge width of 12 mm and gauge length of 90 mm.

3. Results and Discussion

3.1 Welding appearance:

FSW of dissimilar metal joints between copper and aluminum as well as the properties of the welds were studied. The varied welding parameters the sideways position of the tool (in the centre of the butt line, on copper side, or on aluminum side), and the rotation direction (should the hard material be on the advancing or on the retreating side of the weld) were studied. In this study the rotation and traverse speed combinations were kept constant at 1118 rpm and 60 mm/min respectively, and the tilt angle was kept constant at 1.5 degree from the vertical axis toward the advancing side. Fig. 1 shows the effect of rotation direction on the welding quality of Al-Cu welded joints produced by FSW, where the probe was located at butt line. Arranging the hard materials, Cu, either on advancing side or in retreating side resulted in poor welding. Large voids, cracks and poor surface quality was obtained in these welding due to difficult mixing of Cu particles with aluminum matrix (Avettand et al. 2010). Fig. 4.1b shows a continuous crack at butt line, and a large void between copper and aluminum leads to poor quality of welding. In welding of dissimilar materials, the arrangement of the base materials in regard to FSW is important. It has been recommended that the hard strength material should be on the advancing side (Okamura et al. 2004; and watanabe et al. 2006). Another important aspect in FSW of dissimilar metals is the location of the probe in relation to the butt line (Xue et al. 2010; and Debroy 2010). Fig. 2 shows the welding surface appearance of Al-Cu welded joints produced by FSW, where Cu was kept on advancing side. In this investigation the used welding tool has 4 mm square pin. A sufficiently large offset of the probe to aluminum side with slightly touching copper, (2 mm), it considered a sufficient displacement as recommended by Xue et al.(2011), to obtain defect-free weld surface of Al-Cu joints. Fig. 2a shows the resulted weld joint exhibited a good surface quality and defect-free weld. This result is agreed with previous studies (Saffari et al. 2011; Savolinaen et al. 2004). In their studies, offset the probe significantly to the side of the softer material, barely touching the harder material. According to them, it makes the joining of materials with different properties feasible. The temperature is lower as compared to welding at the centre of the butt line, leading to the formation of a smaller amount of brittle IMC layers, but also less mixing of the base materials. However, by offset the probe 2 mm in the copper side give a sound weld as shown in Fig. 2b. Avettand et al. (2010) suggests that the tool offset should be to the copper side in order to obtain higher deformability of copper. Savolainen et al. (2005) obtained good quality Al-Cu dissimilar weld by slightly offset the probe to the copper side.

However, sound welding was obtained in this study when aluminum was arranged on advancing side with 2 mm offset of probe to copper side. Fig. 3a shows a good surface quality, small voids and cracks formed in copper side. Also, sound welding was obtained when the probe displaced 2 mm to aluminum side and aluminum arranged in advancing side as shown in Fig. 3b. Tan et al. (2013) obtained a sound welding of Al-Cu system by arranging the aluminum on advancing side with 0.2 mm offset of the probe to the Al side, relative to the butt line.

3.2 Mechanical properties

Vickers micro-hardness distribution profile on the transverse cross-section of the welded joints was measured. Indentation was taken every 1 mm starting from aluminum side crossing the nugget zone toward the copper side. Enough indentations were taken in both aluminum and copper. The micro-hardness readings were taken at the top and bottom surfaces of the welded joints. The average hardness values of base metals Al and copper were 68 HV and 104 HV, respectively. Fig. 4 shows the hardness profile of the resulted Al-Cu joints welded by FSW, where aluminum arranged on advancing side. The hardness of heat affected zone (HAZ) in Al side was lower than that of base metal due to HAZ softening. The occurrence could be probably attributed to the grain coarsening and dissolution of strengthening precipitates induced by the thermal cycle of the FSW process (Singh et al. 2011). An inhomogeneous distribution of hardness values was observed in the nugget zone (NZ). Also the hardness value in the NZ is higher than the hardness of base metals Al or Cu. This result also, was found previously by Tan et al. (2013). The higher value of hardness may be due to formation of intermetallic compounds.

Fig. 5 shows the hardness profile of the Al-Cu welded joints, where Cu arranged on advancing side. The probe had three positions first, it was at the center of butt line, offset 2 mm to Al side and offset 2 mm to Cu side. It has been shown that the NZ has higher value of hardness with inhomogeneous distribution. The eutectic phase of Al-Cu binary system can be obtained at a temperature of 548^0C lower than that of Al molten temperature. Ouyang et al.(2006) were found that the temperature was 420^0C at the shoulder edge and reached 580^0C at the butt line which is slightly lower than the melting point (582^0C) of the 6062 Al alloy . They attribute the formation of the intermetallic compounds ($CuAl_2$, CuAl, Cu_9Al_4) due to high temperature associated with strong stirring of Al and Cu. These intermetallic compounds lead to inhomogeneous hardness distribution in nugget zone. However, it has been noticed that in general the hardness in NZ is lower than that obtained when Al arranged on advancing side for the same probe position as shown in Fig. 4.

Fig. 6 shows the ultimate tensile strength (UTS) of the produced welded joints of aluminum to copper by friction stir welding process. It has been shown that higher UTS (170 MPa) obtained when Al arranged on advancing side with probe offset 2 mm to Al side, Fig. 6(a). Also when Cu arranged on advancing side a high value of UTS (140 MPa) was obtained, by keeping the probe offset 2 mm to Al side, Fig.6b. However, a week joints were obtained when the probe was at the center of butt line, in both direction of rotation. Located the probe in copper side resulted in lower value of UTS, either the copper arranged on advancing side or retreating side as shown in Fig. 6a and 6b. Pen et al.(2008) achieved maximum UTS value of 296 MPa in FSwelds of aluminum and copper when the tool rotational speed is 950 rpm, and the travel speed is 150 mm/min. The located of probe at the center of butt line leads to the poor surface bonding and the formation of many voids and many Al–Cu IMCs would be formed (Sun et al. 2010). Thus the joining between the Al and Cu became poor due to the brittle nature of the IMCs.

Conclusion

In this study, FSW of aluminum with commercial pure copper sheets were performed. We concluded the following:

1. A sound weld with defect-free joint can be produced by arranging Al either on advancing or retreating side with sufficient probe offset to Al side.
2. Sufficient offset distance of the probe to soft materials (just to touch the hard materials), may considered the most important factor to produce defect-free joint in dissimilar FSW.
3. Inhomogeneous distribution of the hardness in nugget zone it may attributes to the formation of intermetallic compounds.
4. The formations of the intermetallic compound during the welding process, detrimental the strength of welding joints.

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Table 1: Nominal chemical composition of Al alloy and copper

	Si	Cu	Cr	Mn	Ni	Mg	Zn	Ti	Pb	Fe	Al
Al	0.6	0.1	0.08	0.01	-	1.1	0.1	0.01	-	0.25	balance
Cu	0.008	balance	-	-	0.009	-	0.025	-	0.014	0.009	0.032

Table 2: Combination of FSW parameters

No.	Material on advancing side	probe offset
1	Copper	2mm to Copper
2	Copper	none
3	Copper	2 mm to Aluminum
4	Aluminum	2 mm to Aluminum
5	Aluminum	none
6	Aluminum	2 mm to Copper

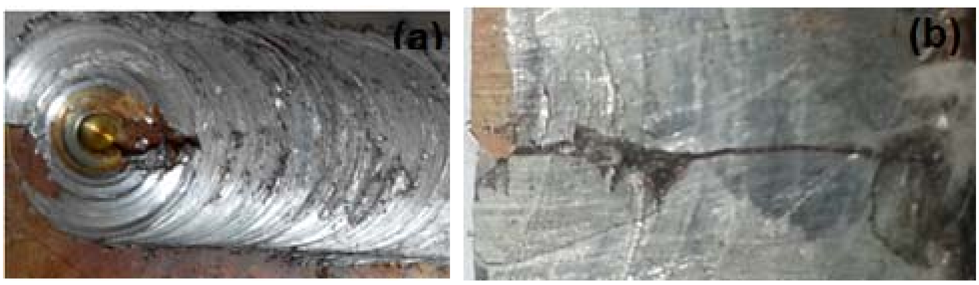

Fig.1: FSW of Al-Cu system arranged on advancing side as (a) Al and (b) Cu

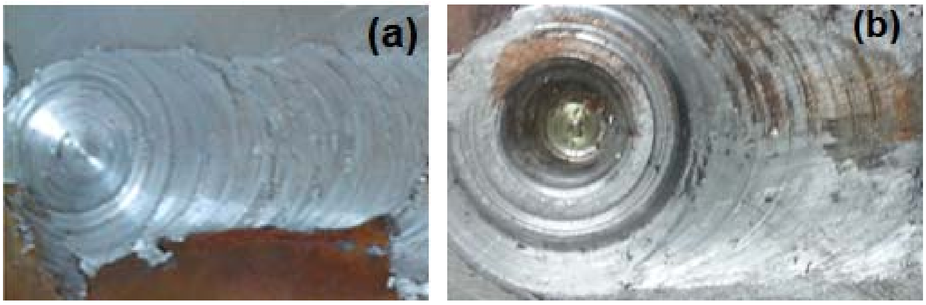

Fig. 2: Copper on advancing side and the probe was offset 2 mm from center of butt line to (a) aluminum side, and (b) copper side.

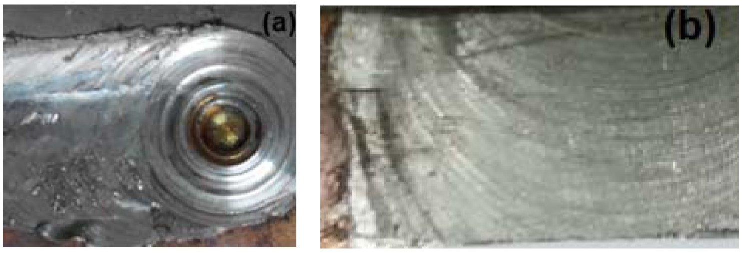

Fig. 3: Aluminum on advancing side and the probe was offset 2 mm to (a) Al side and (b) copper side.

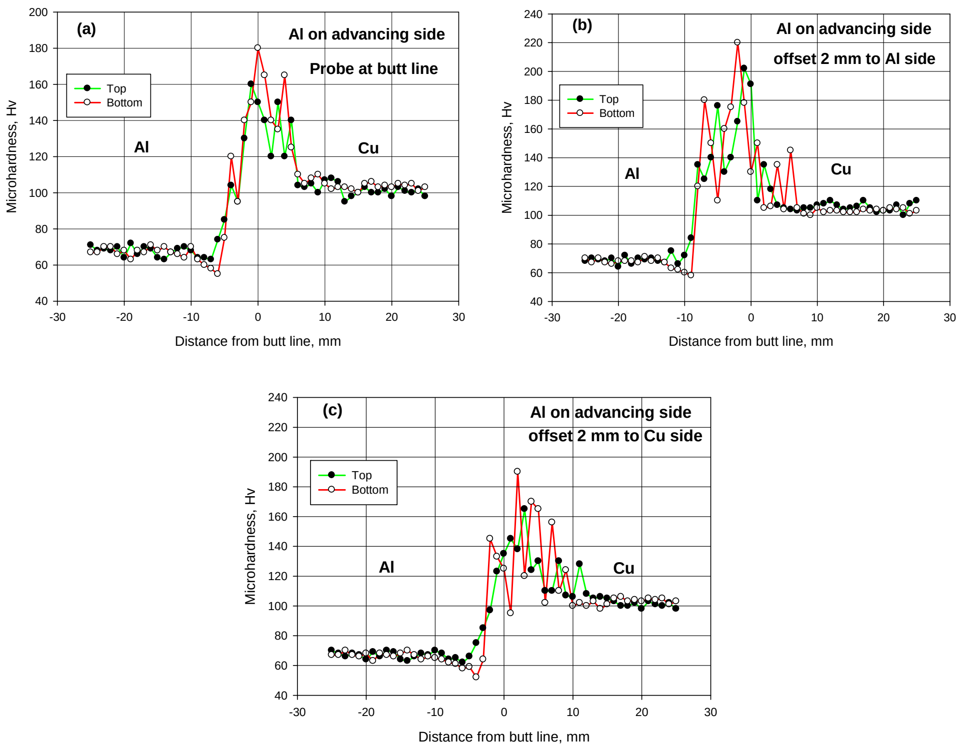

Fig. 4: Micro-hardness profile, Al placed on advancing side and the probe (a) located at center of butt line (b) offset 2 mm to Al side (c) offset 2 mm to Cu side

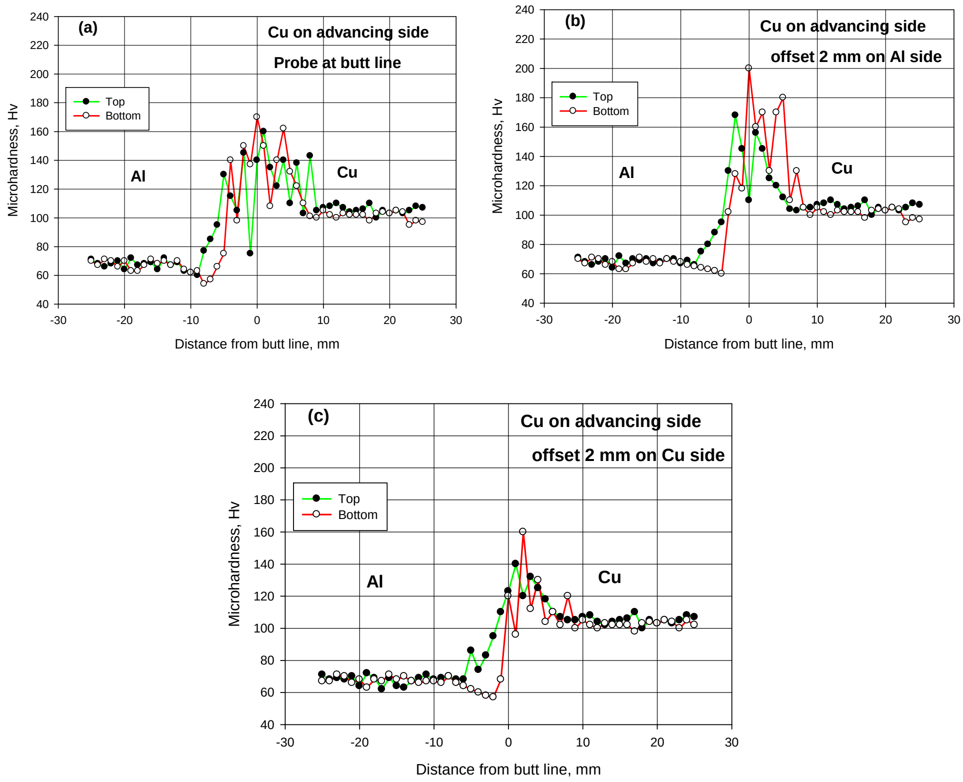

Fig. 5: Micro-hardness profile, Cu placed on advancing side and the probe (a) located at the center of butt line (b) offset 2 mm to Al side (c) offset 2 mm to Cu side

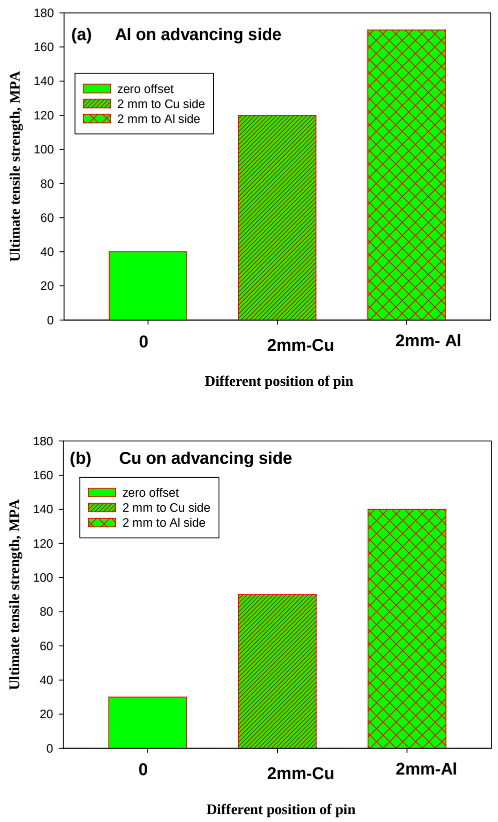

Fig. 6: Ultimate tensile strength of welded joints.

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