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Tool travel speed effects on the microstructure of friction stir welded aluminum–copper joints

M. Felix Xavier Muthu[a,*], V. Jayabalan[b]

[a] Department of Mechanical Engineering, St Xavier's Catholic College of Engineering, Chunkankadai 629003, Tamil Nadu, India
[b] Department of Manufacturing Engineering, College of Engineering Guindy, Anna University, Chennai 600025, Tamil Nadu, India

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ABSTRACT

Friction stir welding of aluminum and copper were carried out by varying the tool travel speed from 50 mm/min to 90 mm/min. The joint properties were evaluated and characterized with respect to the stir zone formation, intermetallics formation and its distribution. Tool traverse speed of 70 mm/min and 80 mm/min resulted in the optimum range of heat input to form defect free stir zone. The reduced diffusion rate and time prevailing at tool traverse speed of 80 mm/min resulted in lower intermetallic thickness of 1.9 μm. The continuous nano scaled thin intermetallic layers resulted in higher tensile strength and joint efficiency of 113 MPa and 70% respectively. The intermetallics layers were identified and confirmed as Al_2Cu, AlCu, Al_4Cu_9 using transmission electron microscope (TEM), X ray diffraction technique (XRD) and energy diffraction spectrum (EDS). The higher tensile strength is attributed to the dispersion strengthening of the fine Cu particles distributed over the Al material in the stir zone region.

1. Introduction

The fabrication of Al–Cu dissimilar joints using a fusion welding process is found to be difficult due to the material incompatibility. The diffusion of dissimilar materials results in intermetallics formation at the interface during welding (Torkamany et al., 2010) and micro level cracks occurred in the weld region (Pooya and Mehrdad, 2013). In addition to the problem, Liu et al. (2007) observed that fusion welding also creates solidification defects like porosity, hot cracking, etc. Many researchers have concluded that Friction Stir Welding (FSW) can overcome the problems that occur during the fusion welding process. It was also concluded that FSW is a potential candidate capable of joining dissimilar materials which are highly incompatible. Since FSW puts together materials at solid state, many metallurgical reactions above the melting temperature can be avoided. FSW was previously introduced to join the dissimilar combinations like Al to Mg (Malarvizhi and Balasubramanian, 2012), Al to brass (Esmaeili et al., 2011), Al to steel (Takehiko et al., 2006) and dissimilar grades of the same materials (Leitao et al., 2009). Murr (2010) investigated 25 combinations of dissimilar FSW joints. The investigation showed that FSW results in defect free sound dissimilar joints with respect to the mechanical interlocking and flow behavior of the materials. The operation parameters of FSW are the controlling factors which determine the heat input required for the fabric flow and defect free stir zone formation. Of the process parameters, tool travel speed is a significant parameter which has greater effect on heat input. Moataz and Attallah Hanadi Salem (2005) have reported that the tool travel speed has greater force on the grain growth of friction stir welded AA 2095 aluminum alloy. It was also reported that the variation in both the strength and ductility was a part of the tool travel speed. Lakshminarayanan and Balasubramanian (2008) evaluated the percentage of the contribution of the different FSW process parameters. The survey concluded that the tool travel speed contribution was 33% towards the tensile force of the FSW joints. Galvao et al. (2011) looked into the influence of the welding parameters on the establishment and distribution of brittle intermetallic phase during aluminum–copper FSW. The study concluded that varying the tool travel speed alters the heat input available in the weld region. Since heat is the predominant factor influence the diffusion of dissimilar materials, the thickness of the intermetallic layer along the aluminum/copper interface can be controlled by varying the tool travel speed. Therefore, tool travel speed is a critical process parameter in the making of sound FSW joints.

The effect of tool traverse speed on the flow behavior of similar welding and the resulting mechanical properties were previously investigated by many researchers. But the effect of the tool traverse speed on the complex material flow pattern and the resultant

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* Corresponding author. Tel.: +91 8903455836; fax: +91 046952259664.
E-mail address: umailfelix@gmail.com (M.F.X. Muthu).

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properties have not yet been revealed in detail for the A–Cu dissimilar materials in the present research scenario. Hence, an investigation is framed to study the upshot of the tool travel speed on the macrostructure, microstructure and the mechanical properties of Al–Cu friction stir welded joints.

2. Experimental procedure

Rolled plates of AA1100-H14 aluminum alloy and commercially pure copper were used for the friction stir welding. The copper plates were annealed and placed in the advanced side. A square butt configuration of $100 \times 100 \times 6\,\mathrm{mm}^3$ was used for the investigation. The process parameters and the welding condition used for fabricating FSW joints were shown in the Table 1. The tool travel speed varied from 50 to 90 mm/min for fabricating FSW joints and all the other parameters were kept constant. The welds were fabricated along the perpendicular direction to the rolling direction using computer controlled FSW machine. The welds were produced in position. The tool was 2 mm, offset in the Al side from the butt center line.

The samples were extracted for macro and microstructure analysis in a way that the specimen comprised various regions of the weld joint. Optical microscope was used for analyzing the joint appearance, macrostructure and material flow behavior of the Al–Cu dissimilar joints. The samples were polished using rough emery, followed by water emery sheets of various grit sizes ranging from 1000 to 3000 μm. The mirror polished samples were then subjected to chemical etching which enabled the visibilities of the microstructural features. The side of aluminum was etched using modified Kellers reagent made of 190 ml of distilled water, 5 ml of HNO_3, 3 ml of HCl and 3 ml of HF. Copper side was etched, using a solution made of 5 g $FeCl_3$, 50 ml HCl and 100 ml H_2O. The thickness, size and distribution of the intermetallic compounds were analyzed using scanning electron microscope (SEM). The fracture surfaces of the tensile tested specimens were characterized using SEM analysis.

The features in the weld region were characterized using Transmission electron microscope (TEM). The electron dispersive spectrum (EDS) analysis was used to determine the composition of the various intermetallics formed in the Al–Cu weld interface. XRD analysis was carried out using $\mathrm{CuK}\alpha_1$ X ray of 1.5406 Å wavelengths under a working voltage of 40 kV and current of 40 A. Based on the peak intensity in the diffractograms, the phases were identified using JCPDS software.

The transverse tensile specimens were extracted from the weld joint and tested using electromechanical controlled universal testing machine as per ASTM E8 M-04 guidelines. The microhardness values were evaluated at the mid thickness region across the transverse cross section of the various zones of FSW joint. The indentation was made by applying the load of 50 g for a dwell time of 15 s using Vickers micro hardness tester.

Table 1
FSW parameters and tool dimensions used in this investigation.

Process parameters	Values
Tool rotational speed (rpm)	1075
Traverse speed (mm/min)	50, 60, 70, 80, 90
Tool shoulder diameter (mm)	18
Shoulder profile	Concave
Pin length (mm)	5.8
Pin diameter (mm)	5.5–7.2
Pin profile	Plain taper
Tool material	Hardened super high speed steel

3. Results

3.1. Tensile properties

Table 2 shows the tensile properties and fractographs for different tool travel speeds ranging from 50 to 90 mm/min. At the lower tool travel speed of 50 mm/min, it resulted in lower tensile strength of 68 MPa which has the joint efficiency of 42.5%. The tensile fracture was located at the Al–Cu interface following zigzag path. The photographs showed the presence of Cu particles embedded in the fracture surface. No dimples were observed and this means that the weld joints failed in the brittle mode of failure. The tensile strength of 89 MPa was the result at the tool travel speed of 60 mm/min. The zig-zag fracture path was reduced and followed normal to the loading direction. The fractographs showed that failure was observed at the interface, showing a few shear ridges and flat featureless surfaces. The tensile strength was drastically improved to 104 MPa and 113 MPa at the tool traverse speeds of 70 and 80 mm/min. The fracture occurred at the Al side thermo mechanical heat affected zone for both the welding conditions. The fine Cu particles were seen in the fracture surface of 70 mm/min. The reduced number of large sized dimples oriented towards the loading direction was observed. In addition, few featureless flat surfaces were also observed.

Fine populated dimples were observed on the fracture surface of the weld joint fabricated at 80 mm/min. The interface between matrix and particles were acting as the crack initiation sites during the tensile loading. This confirms the fact that the weld joint failed in the ductile mode of failure. At 90 mm/min, tensile strength of 86 MPa and joint efficiency of 53.75% was observed which is lower than the previous case. The weld region gets weaker and fracture falls in the weld region. The tensile fractographs shows decohesive faces with featureless surface.

3.2. Macrostructure

Table 3 shows the effect of the tool traverse speed on the joint appearance and the cross section macrostructure. At the lower tool traverse speed of 50 mm/min, few surface level defects were observed in the weld centerline. At 1 mm depth, the top surface showed discontinuities on the Cu side. Complex intercalated material flow and lamellar mixture of Al and Cu were observed in the cross section macrostructure. At the increased tool travel speed of 60 mm/min, the defect free surface morphology was observed. Transport of materials from Al to Cu side and Cu to Al side was observed at the top surface macrostructure. At the cross section, Orbital type of material flow was observed in the stir zone along with the tunnel defect. The Cu material in bulk contributed to the stir zone formation.

At the tool travel speed of 70 mm/min, regular ripples were observed in the stir zone. Clear interfaces of the Al–Cu materials were observed at the top surface macrostructure. The Cu material was fragmented into different sizes and they were distributed all over the stir zone. Regular ripples with a little flash were formed at the tool traverse speed of 80 mm/min. Transport of Al material to Cu side was observed at the top surface macrostructure. In the cross section macrostructure, the fragmented Cu particles were distributed mainly in the pin influenced region. At the higher tool traverse speed of 90 mm/min, surface discontinuities were observed. Mutual amount of each material was transported to the other side. Relatively, large amounts of Cu particles were transported to the periphery of the stir zone. Tunnel defects were also observed on the advancing side of the stir zone.

At the tool travel speeds of 70 and 80 mm/min, optimal range of heat input was resulted in the defect free weld region. A clear, distinct interface was observed between Al and Cu since the optimum heat was not adequate to mix up the materials in the stir zone. At