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Microstructure and mechanical properties of similar and dissimilar joints of aluminium alloy and pure copper by friction stir welding☆

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Summary In the present study, the microstructure and mechanical properties of similar and dissimilar friction stir welded joints of aluminium alloy (AlA) and pure copper (Cu) were evaluated at variable tool rotational speeds from 150 to 900 rpm in steps of 150 rpm at 60 mm/min travel speed and constant tilt angle 2°. The interfacial microstructures of the joints were characterised by optical and scanning electron microscopy. The Al_4Cu_9, AlCu, Al_2Cu and Al_2Cu_3 intermetallic compounds have been observed at the interface and stir zone region of dissimilar Al/Cu FSWed joints. Variation in the grain size was observed in the stir zone depending upon the heat input value. Axial force, traverse force and torque value were analysed with variation in tool rotational speed. Residual stresses were measured at the stir zone by X-ray diffraction technique. Maximum ultimate tensile strength of ~75% of AlA strength for AlA—AlA joints has been obtained at 750 rpm and for Cu—Cu joint tensile strength of ~100% of tensile strength of Cu was obtained at 300 rpm. However, for Cu—AlA joint when processed at 600 rpm tool rotational speed achieved maximum ultimate tensile strength of ~77% of AlA.

Introduction

Friction Stir welding (FSW) is applied widely to join metallic materials such as aluminium, magnesium and copper alloys (Nandan et al., 2008). However, dissimilar materials joints by conventional fusion welding shows poor weldability arising due to the difference in chemical, mechanical,

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thermal properties of materials and formation of brittle intermetallic compounds at the weld interface (Wig et al., 2011; Liu et al., 2008). Recently, FSW is considered to be a potential candidate to join dissimilar metals and alloys effectively, and characteristics of FSWed joints of Al/Mg, Al/steel, Al/Ti, etc. has been studied (Somasekharan and Murr, 2006; Tsutomu et al., 2009; Chen and Nakata, 2009). Xie et al. (2007) reports that the defect free copper joints achieved at tool rotational speeds of 400, 600, and 800 rpm for a traverse speed of 50 mm/min under relatively low heat input conditions and obtained fine-grain (~3.5 μm) microstructure being produced at 400 rpm. Xue et al. (2011) studied the effects of FSW parameters on the microstructures and properties of Cu—1060Al dissimilar joints, and suggested that a continuous thin layer of intermetallics compound was necessary to achieve sound Cu—Al joints.

In the present study, similar and dissimilar joints of aluminium alloy (AA6351) and commercial pure Cu was carried out by FSW technique using tool rotational speeds of 150—900 rpm in step of 150 rpm with a traverse speed of 60 mm/min and also correlated the microstructure and tensile properties with the welding parameters of the similar and dissimilar joints.

Experimental procedure

Aluminium alloy (AA6351) of chemical composition (Mn-0.6, Mg-0.6, Si-1.1, and Bal) and pure copper (Fe-0.02, Mn-0.01, Zn-0.01, O_2-0.03, and Bal.) of dimension 140 mm long × 70 mm width x 3 mm thick were used in this study. The high speed steel tool of shoulder diameter 18 mm, pin height 2.7 mm and bottom pin diameter 2.5 mm were used. FSW joints were produced at rotational speeds of 150—900 rpm in step of 150 rpm using a traverse speed of 60 mm/min at a constant tilt angle of 2°. During the welding process, axial force, traverse force, and torque value were obtained by computer aided automated FSW machine.

For optical microscopy the samples were cut from a transverse section and prepared by conventional metallographic technique. Scanning electron microscope in back scattered mode (SEM-BSE) of the polished surface of the welded sample was done along with chemical analysis by energy dispersive spectroscopy (EDS). Tensile samples of the welded joints were prepared as per ASTM ID: E8M-96 specification and tests were carried out at a crosshead speed at 0.5 mm/min at room temperature. The presence of phases in the joints regions was identified by X ray diffraction using copper as target. Residual stress was measured by X-ray diffraction technique on the top surface of the joints in the stir zone region for AlA—AlA and Cu—Cu, while for AlA—Cu joints the residual stress were measured separately for copper and aluminium alloy at the bottom portion of the joints. Normal residual stresses were measured along the longitudinal and transverse directions of the weld.

Results and discussion

In AlA—AlA and Cu—Cu FSWed joints have shown a good surface continuity above 150 rpm tool rotational speed. The dragging effect of the tool was observed on the joint surface in Cu—Cu FSWed region at 450 rpm and 600 rpm tool rotational speed. For AlA—Cu FSWed joints surface discontinuity was observed up to 300 rpm tool rotational speed. Low heat input due to low tool rotational speed was supposed to cause these types of defects in the weld region. In the macrostructure of AlA—Cu FSWed joint at 150 rpm mixing of copper was observed only near the shoulder portion, however above this tool rotational speed good mixing of aluminium and copper were observed in the stir zone region. The flow of copper was found on AlA side.

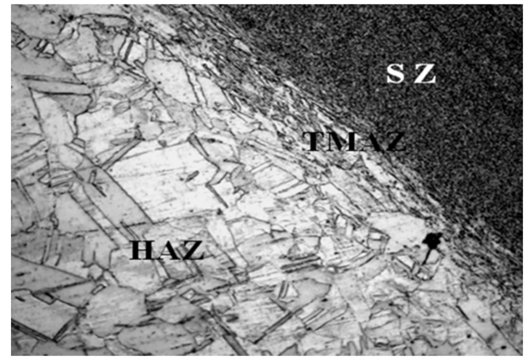

Figure 1 Optical micrographs of FSWed joint showing different regions in welded region.

The optical microstructure of the FSWed joints of different zone such as stir zone (SZ), thermomechanically affected zone (TMAZ) and heat affected zone (HAZ) have been observed shown in Fig. 1. The grains in the SZ were refined and recrystallised, while the grains in the TMAZ region of the joints were observed elongated and semi recrystallised. In the HAZ coarse grains were observed for all FSWed joints. Watanabe et al. reported that higher tool rotational speed produced the higher temperature due to friction as compared to the lower rotational speed (Watanabe et al., 2006). The fine recrystallised grains in the stir zone are due to the generation of high temperature and deformation during FSW. The heat input generated in the stir zone was found affecting the size of grains in AlA—AlA, Cu—Cu and AlA—Cu FSWed joints. The average minimum and maximum grain size of AlA—AlA, Cu—Cu and AlA—Cu FSWed joints were found in the range of ~1—4.1 μm, ~1—22.1 μm and ~2.3—9.5 μm respectively. In AlA—Cu FSWed joint dispersed copper particles were found distributed within the SZ.

The SEM-BSE images of AlA—Cu joints are shown in Fig. 2. The layer wise intermetallics have been observed at the interface of the welded joint. The formation of intermetallics layer took place in the order from the copper side to aluminium side were as Al_4Cu_9, Al_2Cu_3, AlCu, and Al_2Cu respectively were confirmed from SEM-EDS analysis. The thickness of the intermetallics at the interface of AlA—Cu joints from 150 to 900 rpm was measured between ~0.24 μm to ~4.07 μm. The thickness of the intermetallics layer increased with the tool rotational speed. The X-ray diffraction patterns of the AlA—Cu FSWed joint at the SZ and interface at variable tool rotational speed are shown in Fig. 3. At all tool rotational speed the characteristic peaks of Al_4Cu_9, Al_2Cu_3, AlCu, and Al_2Cu IMCs phases were observed. It confirms that the required temperatures were generated

Table 1 Residual stress values for AlA—AlA and Cu—Cu FSWed joint.

Rotational speed	AlA—AlA		Cu—Cu	
	Longitudinal (MPa)	Transverse (MPa)	Longitudinal (MPa)	Transverse (MPa)
300	108.7 ± 11.6	84.3 ± 8.9	64.1 ± 10.6	34.6 ± 13.8
600	88.6 ± 8.4	62.7 ± 10	56.2 ± 10.0	15.8 ± 11.9
900	76.5 ± 7.8	50.8 ± 8.9	30.7 ± 13.9	−13.7 ± 18.8

Table 2 Residual stress values for AlA—Cu FSWed joint.

Rotational speed	Aluminium side		Copper side	
	Longitudinal (MPa)	Transverse (MPa)	Longitudinal (MPa)	Transverse (MPa)
300	−135.0 ± 5.9	−96.7 ± 3.3	8.0 ± 5.3	−106.2 ± 10.6
600	41.2 ± 6.9	71.9 ± 7.4	88.1 ± 5.0	130.4 ± 7.0
900	36.3 ± 14	76.4 ± 4.9	69.8 ± 9.8	112.8 ± 7.6

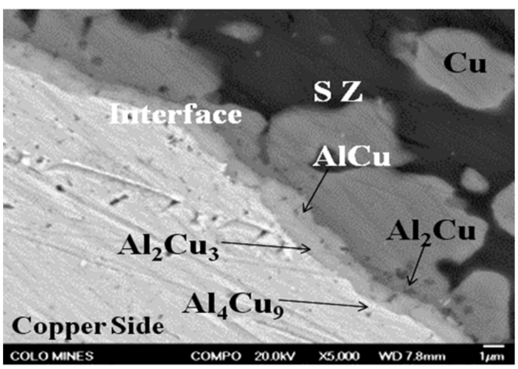

Figure 2 SEM-BSE image showing interface region in AlA—Cu FSWed joints at 600 rpm.

during the welding process. X-ray diffraction pattern of all AlA—Cu FSWed joints have shown the good volume fraction of intermetallics at the interface and stir zone region.

The mechanical properties of the tensile samples were carried out in Instron 4900R tensile testing machine. For AlA—AlA at tool rotating speed of 150 rpm, UTS, YS and elongation was lower due to the void present in the stir zone, however at 750 rpm tool rotational speed maximum UTS and YS of ~186.72 MPa (~75% of AlA strength) and ~151.16 MPa was obtained along with ~20.16% elongation at fracture. For Cu—Cu FSWed joints the maximum UTS and YS of ~281.2 MPa (~104% of Cu strength) and ~253.7 MPa, and ~15.93% elongation were obtained at tool rotational speed 300 rpm. However maximum elongation of ~34% was observed at 900 rpm with UTS and YS of ~223.87 MPa and ~126.57 MPa. In case of AlA—Cu FSWed joints, maximum UTS and YS of ~189.16 MPa (~77% of AlA strength) and ~167 MPa

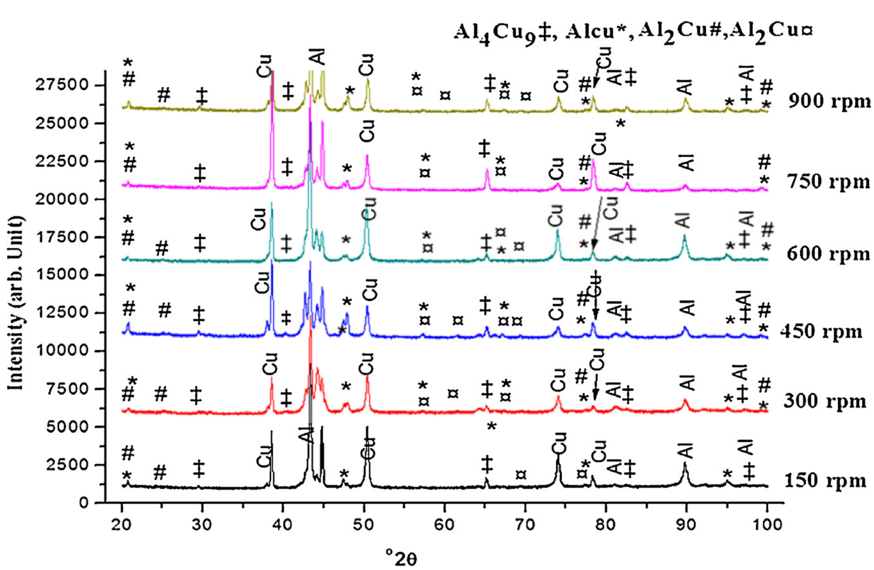

Figure 3 X-ray diffraction pattern of FSWed joint of AlA—Cu at variable tool rotational speed.

along with ~6.92% elongation at fracture was obtained at 600 rpm. With an increase in the tool rotational speed up to 600 rpm, the weld strength increased, while above this strength decreased.

Normal residual stresses in the longitudinal and transverse direction for AlA—AlA, Cu—Cu, and AlA—Cu at the stir zone have shown mostly tensile in nature is given in Tables 1 and 2 respectively. The compressive type residual stress (RS) was obtained for transverse direction at 900 rpm for Cu—Cu. For AlA—Cu FSWed joints at 300 rpm, compressive type residual stress were obtained for both in transverse and longitudinal direction on aluminium side, while on copper side only compressive type RS was obtained in the transverse direction. Normal RS value has shown decreasing tendency for AlA—AlA, and Cu—Cu with the increase in tool rotational speed, while in AlA—Cu decreasing tendency was observed after 300 rpm. Machine data values have shown decreasing trend of axial force, traverse force, and torque value with increased rotational speed.

Conclusions

In the present study, the microstructure and mechanical properties of similar and dissimilar FSWed joints of AlA and Cu were evaluated at tool rotational speeds from 150 to 900 rpm in steps of 150 rpm at 60 mm/min travel speed. In the optical microstructure, the SZ, HAZ and TMAZ were clearly observed for all the FSW joints. The grain size of SZ, TMAZ and HAZ for all the joints increased with the increase in tool rotational speeds. The Al_4Cu_9, AlCu, Al_2Cu and Al_2Cu_3 intermetallic phases have been observed at the interface and stir zone region of dissimilar Al/Cu FSWed joints.

Conflicts of interest

Authors have a primary interest as well as their results, patient applications/registrations, and grants or other funding.

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References

Chen, Y.C., Nakata, K., 2009. Microstructural characterization and mechanical properties in friction stir welding of aluminum and titanium dissimilar alloys. Mater. Des. 30 (3), 469—474.

Liu, P., Shi, Y.Q., Wang, W., Wang, X., Zhang, Z.L., 2008. Microstructure and XRD analysis of FSW joints for copper T2/aluminium 5A06 dissimilar materials. Mater. Lett. 62, 4106—4108.

Nandan, R., Debroy, T., Bhadeshia, H., 2008. Recent advances in friction-stir welding — process, weldment structure and properties. Prog. Mater. Sci. 53, 980—1023.

Somasekharan, A.C., Murr, L.E., 2006. Microstructures in friction-stir welded dissimilar magnesium alloys and magnesium alloys to 6061-T6 aluminum alloy. J. Mater. Sci. 41, 5365—5370.

Tsutomu, T., Taiki, M., Tomotake, H., 2009. Comprehensive analysis of joint strength for dissimilar friction stir welds of mild steel to aluminum alloys. Scr. Mater. 61, 756—759.

Watanabe, T., Takayama, H., Yanagisawa, A., 2006. Joining of aluminum alloy to steel by friction stir welding. J. Mater. Process. Technol. 178, 342—349.

Wig, M., Albert, F., Schmidt, M., 2011. Enhancing the ductility of laser-welded copper-aluminum connections by using adapted filler materials. Phys. Procedia 12, 335—341.

Xie, G.M., Ma, Z.Y., Geng, L., 2007. Development of a fine grained microstructure and the properties of a nugget zone in friction stir welded pure copper. Scr. Mater. 57 (2), 73—76.

Xue, P., Ni, D.R., Wang, D., Xiao, B.L., Ma, Z.Y., 2011. Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al-Cu joints. Mater. Sci. Eng. 528, 4683—4689.