Dissimilar Metal Joining of Pure Copper and Al 6061 by using Friction Stir Spot Welding

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ABSTRACT

Dissimilar metal joints with good electrical conductivity and high mechanical strength are generally required in electrical industry. In this work joining of Al 6061 and pure copper sheets by FSSW process was studied. Friction stir spot welding (FSSW) is a solid-state welding technology; it is energy efficient, environment friendly and versatile. FSSW is derived from Friction-Stir Welding (FSW). FSSW process is proving to be a better alternative to Resistance Spot Welding (RSW). In this work feasibility of joining Al 6061 and pure copper sheets by FSSW process was studied using a cylindrical pin tool. Tool rotation speed, plunge depth and dwell time were varied to determine the optimum process parameter so as to achieve high values of lap shear separation force and cross tension force. For process parameters optimization Taguchi technique based on L16 orthogonal array was used. Joints were made by altering the top-bottom position of copper and aluminium alloy sheets. For joints with pure copper top-Al 6061 bottom, the optimum values for processing parameters were 1600 rpm rotational speed, 1.9 mm plunge depth and 8 sec dwell time. For joints with Al 6061 top –pure copper bottom the optimum values were 1200 rpm rotational speed, 1.9 mm plunge depth and 12 sec dwell time. Their respective lap sheet forces were 4638N and 4235 N. Nugget pullout failure was observed in either type of joints. The electrical resistivity for copper-top joints was in the range of 0.15×10^{-4} Ω-m to 0.30×10^{-4} Ω-m and for copper-bottom joints, it was changing from 0.25×10^{-4} Ω-m to 0.45×10^{-4} Ω-m.

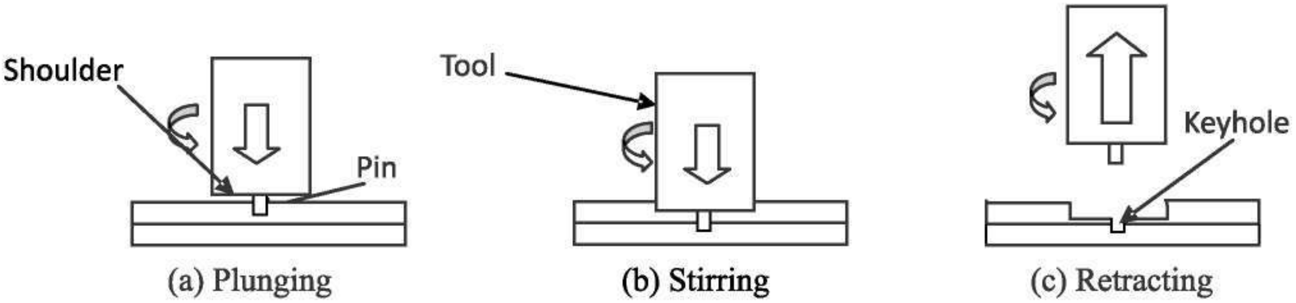
Key Words : Friction stir spot welding, Electrical resistivity, Lap shear strength, Fracture morphology

1.0 INTRODUCTION

Aluminium alloy has been one of the most promising lightweight materials because of its properties such as good electrical conductivity, low density, considerable corrosion resistance and high strength to weight ratio [1]. Copper is widely used for its high thermal and electrical conductivity. Therefore, assembling both aluminium alloys and copper is necessary to develop joints for electrical conduction. There are many joining methods such as pressure welding, diffusion bonding, vacuum brazing, laser welding-brazing, liquid phase diffusion welding and friction welding used to join copper and aluminium [1, 2]. These processes have many disadvantages such as high-energy consumption, large current requirement, severe deformation during welding and low production efficiency. Literature study shows that the key issue is dissimilar welding of alumnium alloy to copper alloy is formation of interfacial intermetallic compounds (IMC) such as AlCu, Al_2Cu_4 and Al_4Cu_9 as observed on the C-Al phase diagram. The strength of these dissimilar joints depends on process related heating and cooling cycles, which significantly deteriorate the joint performance. Therefore, to overcome these issues Friction Stir Welding (FSW) is becoming the focus of study [3]. The process was developed by The Welding Institute (TWI) of UK in 1991. FSW was improvised to weld sheet metals, which is nearly similar configuration of spot welding; the process is called 'Friction Stir Spot Welding'

(FSSW) [4]. Friction-Stir Spot Welding may become an alternative to other welding processes. FSSW is considered as 'green technology', due to excellent mechanical properties, low distortion, low cost and clean working environment. It can be easily applied to weld aluminium alloy sheets due to their ductility. The schematic diagram with stages in FSSW is shown in **Fig.1**. The two sheets to be joined are clamped in overlapping manner and a specially designed tool with pin is rotated and plunged into the top surface of the upper plate **(Fig.1 (a))**. Plunging of the tool slightly induces compression of material. This causes intimate mixing and closing of the flaws if present. Rotating tool develops frictional heat in the sheets, due which they are softened. This lead to deform the material plastically and stirring of the material starts in the direction of tool rotation **(Fig.1 (b))**. The plastic flow reaches the interface of the two sheets. On withdrawal or retracting of the tool **(Fig.1 (c))**, a solid-state bond is developed between the sheets at the interface of the upper and lower sheets as the joint cools to room temperature. There is a characteristic dent formation at the center of the joint due to the pin provided on the tool. As the projected area cools down, it produces a high quality weld joint in solid state without melting of the sheets [1].

The present work aims to apply the process of friction stir spot welding for joining of sheets of aluminium alloy Al6061 and pure copper to achieve optimum properties - both mechanical and electrical - in the joints by changing the process parameters such as tool rotation speed, plunge depth and dwell time after plunging of the tool.



(a) Plunging (b) Stirring (c) Retracting

Fig.1: Schematic sequence in Friction Stir Spot Welding

2.0 EXPERIMENTAL PROCEDURE

Sheets aluminium alloy Al6061 and pure copper of 2 mm and 1 mm thickness respectively have been used for the present study. Al6061 is a heat treatable alloy with magnesium and silicon alloying elements. The chemical compositions of these sheets are listed in **Table 1.**

In this study, the tool shoulder diameter of 12 mm with flat configuration was used. A straight cylindrical pin of diameter 4 mm and height 0.7 mm was provided. Tool material was tungsten carbide. The FSSW welding experiments were conducted on a Premium make vertical milling machine PVM40 with FANUC controller machine. A fixture was assembled on the milling machine to clamp the firmly during welding. FSSW

Table 1 : Mineral Composition of the sheets used for FSSW

Mineral	Composition								
	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
AA 6061 (2 mm thick)	0.62	0.32	0.21	0.054	0.99	0.024	0.15	0.014	Balance
Copper (1 mm thick)	–	0.008	99.96	–	–	–	–	–	--

welding was made by changing the positions of Al6061 and copper sheets in the lap joint - namely 'copper top' and 'copper bottom'.

The aim of Taguchi method of Design of Experiments is to analyze the statistical data using the input parameters to produce optimum result [5]. This method was used for understanding the effect of various parameters on the joint properties. Taguchi's L16 orthogonal array was used for experimentation. Variation in tool rotational speed, plunge depth and dwell time were made as shown in **Table 2.** Four levels were decided for each process parameters. During FSSW welding, the plunge rate was 5 mm/min. The sheets were cut to size of 100×30 mm each. They were joined with overlap of 40×30 mm.

After FSSW welding, the joints were tested for finding lap shear separation load, for which a UTM machine TUECN- 100 was used. The specimens were cut at the center to observe their macrostructures and microstructures and mounted in epoxy resin. They were prepared metallographically and etched in two steps. Firstly, polished specimens were etched to reveal copper side microstructures and then re-etched to reveal alumnium side microstructures. Etchant for copper side was 25ml Methanol+ 1.3 $FeCl_3$ and for alumnium side Keller's reagent with 2% HF. The micro-hardness traverse was determined by using Vickers micro-hardness tester using a constant load of 100 g for a dwell time of 10 s with 50μm pitch distance from center of the joint to the base metal. For each specimen, two hardness traverses were measured on alumnium side and copper side with 0.5 mm away from the interface. Resistance values of the weld joints were measured on Auto-compute LCR-Q-METER-Sorter, and then by using resistivity formula, resistivity was calculated. The fractured surfaces of lap shear tested specimens were examined under SEM. The chemical composition variation across the weld joint of two specimens was measured by using the energy dispersive spectroscopy (EDS). The two specimen were of 'copper top' and 'copper bottom' positions each.

Table 2 : Process Parameters used for FSSW of Al6061 and copper sheets

Condition	Rotational Speed (RPM)	Dwell Time (sec)	Plunge Depth (mm)	
			Copper Top-Aluminium Bottom	Copper Bottom-Aluminium Top
1	1000	4	1.5	1.8
2	1200	8	1.7	1.9
3	1400	12	1.9	2.0
4	1600	16	2.0	2.1

3.0 RESULT AND DISCUSSION

3.1 Optimization of copper top-Al 6061 bottom joints

The effect of tool rotation speed, plunge depth and dwell time were studied on the lap separation load as output. The signal to noise ratio (S/N ratio) was calculated for individual process parameters. **Table 3** and **Table 4** show the response tables for S/N ratio and for mean lap separation load respectively when copper top position is used. The effect of individual parameters on the lap separation load is shown in **Fig.2** for copper top position. It shows the optimized parameters as tool rotational speed 1600 RPM, plunge depth 1.9mm, dwell time 8 s.

Table 3 : Response table of S/N ratios (%) for tool rotation speed, plunge depth and dwell time when copper top position is used

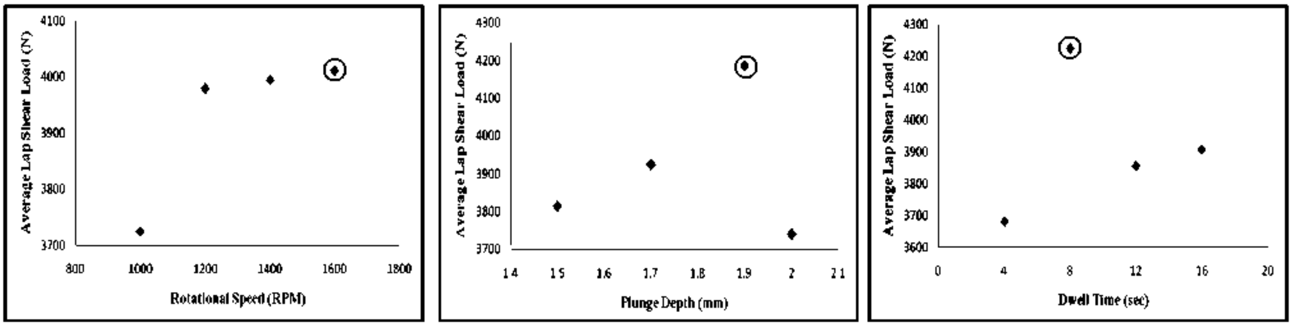
Level	S/N ratio for Tool Rotation Speed	S/N ratio for Plunge Depth	S/N ratio for Dwell Time
1	71.40	71.58	71.23
2	71.99	72.62	72.50
3	71.97	72.42	72.45
4	72.65	71.39	71.83

Table 4 : Response table of mean lap shear load in N for tool rotation speed, plunge depth and dwell time when copper top position is used

Level	Tool Rotation Speed	Plunge Depth	Dwell Time
1	3725	3814	3681
2	3979	3925	4225
3	3995	4186	3854
4	4011	3740	3906

3.2 Optimization of copper bottom-Al 6061 top joints

Table 5 and **Table 6** show the response tables for S/N ratio and for mean lap separation load respectively when copper bottom position is used. The effect of individual parameters on



(a) Tool rotational speed, rpm (b) Plunge depth, mm (c) Dwell time, s

Fig.2 : Effect of Process Parameters on Lap Shear Load, showing optimized parameters when copper top position is used: Tool rotational speed 1600 RPM, Plunge depth 1.9mm, Dwell time 8 s

the lap separation load is shown in **Fig.3** for copper bottom position. It shows the optimized parameters as tool rotational speed 1200 RPM, plunge depth 1.9mm, dwell time 12 s.

3.3 Macrostructures

Both types of FSSW joints with copper top and copper bottom were observed for macrostructure. The typical macro-structures are shown in **Fig.4**. The extent of deformation of the sheets at the joint can be very well observed. There is considerable reduction in thickness of the sheets placed at top. However, severe deformation is seen just below the pin compared to that below the shoulder location. The inward bending of copper sheet in the copper top joint **(Fig.4 (a))** indicates that there considerable residual stress relaxing by spring back elasticity when tool retreats and cooling takes place. Different zones of the welded joint have been marked A-D, in the increasing degree of temperature during FSSW. Zone A is the base metal, B is heat affected zone, C is thermo-mechanically affected zone and D is stirred zone. Zones C is subjected to lesser severity of plastic deformation compared to zone D.

3.4 Microstructures

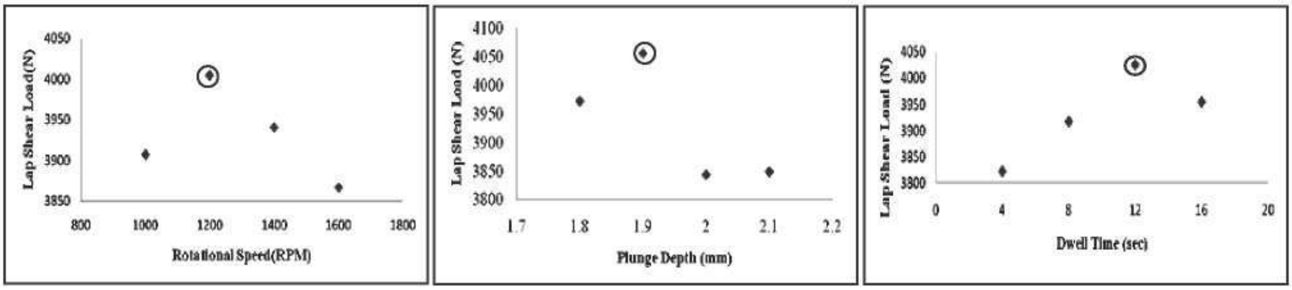
The series microstructures on copper side and Al6061 side have been shown in **Fig.5**, for the FSSW conditions of copper top position and rotation speed1600 rpm, plunge depth 1.9 mm, dwell time 8 s. Both copper and alumnium microstructure show significant changes. There is some grain growth in HAZ and elongation of grains in the TMAZ. The stirred zone shows very fine recrystallized equiaxed grains. This may be attributed to the conditions of severe plastic deformation along with high temperature, resulting in dynamic recrystallization.

Table 5 : Response table of S/N ratios (%) for tool rotation speed, plunge depth and dwell time when copper bottom position is used

Level	S/N ratio for Tool Rotation Speed	S/N ratio for Plunge Depth	S/N ratio for Dwell Time
1	71.83	71.98	71.65
2	72.05	72.16	71.85
3	72.65	71.69	72.09
4	71.75	71.69	71.93

Table 6 : Response table of mean lap shear load in N for tool rotation speed, plunge depth and dwell time when copper bottom position is used

Level	Tool Rotation Speed	Plunge Depth	Dwell Time
1	3907	3972	3822
2	4005	4056	3917
3	3941	3843	4026
4	3867	3849	3955

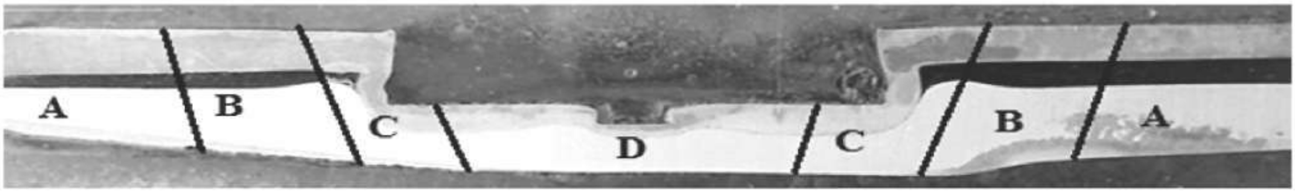


(a) Tool rotational speed

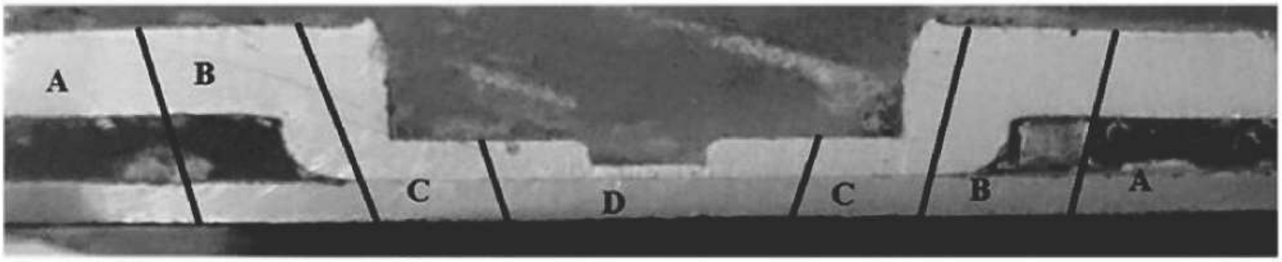
(b) Plunge depth

(c) Dwell time

Fig.3 : Effect of Process Parameters on Lap Shear Load, showing optimized parameters when copper bottom position is used: Tool rotational speed 1200 RPM, Plunge depth 1.9mm, Dwell time 12 s

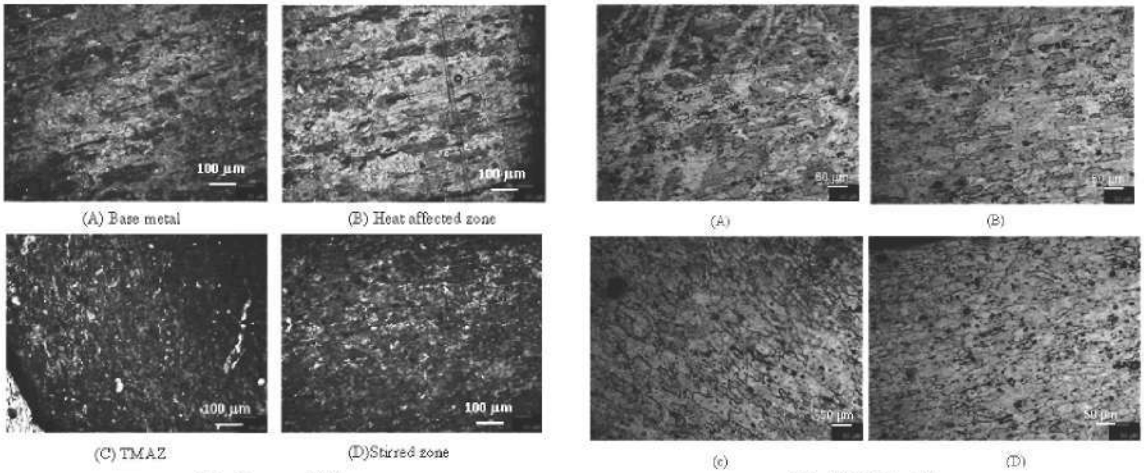


(a) Copper top joint : Rotation speed 1600 rpm, plunge depth 1.9 mm, dwell time 8 s



(b) Copper bottom joint : Rotation speed 1400 rpm, plunge depth 1.9 mm, dwell time 16 s

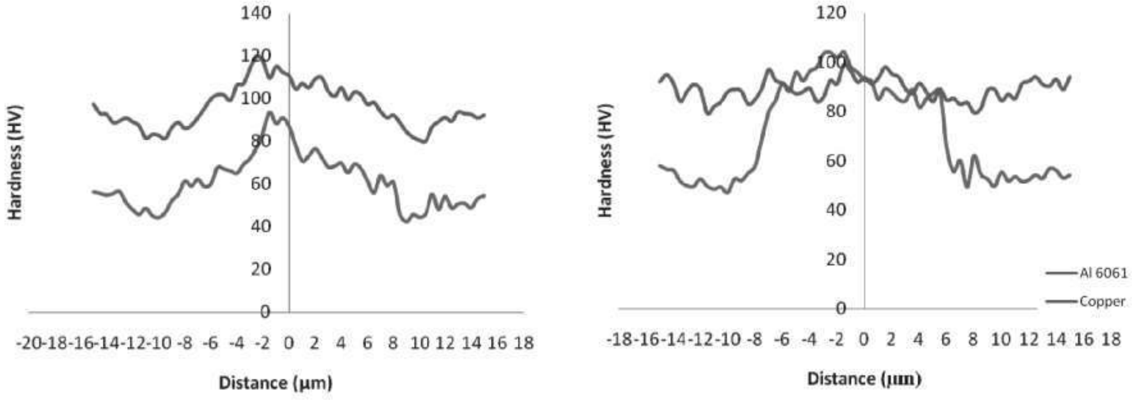
Fig. 4 : Macroscopic cross section of FSSW welded copper Ai6061 alloy steel



(a) Copper Slide

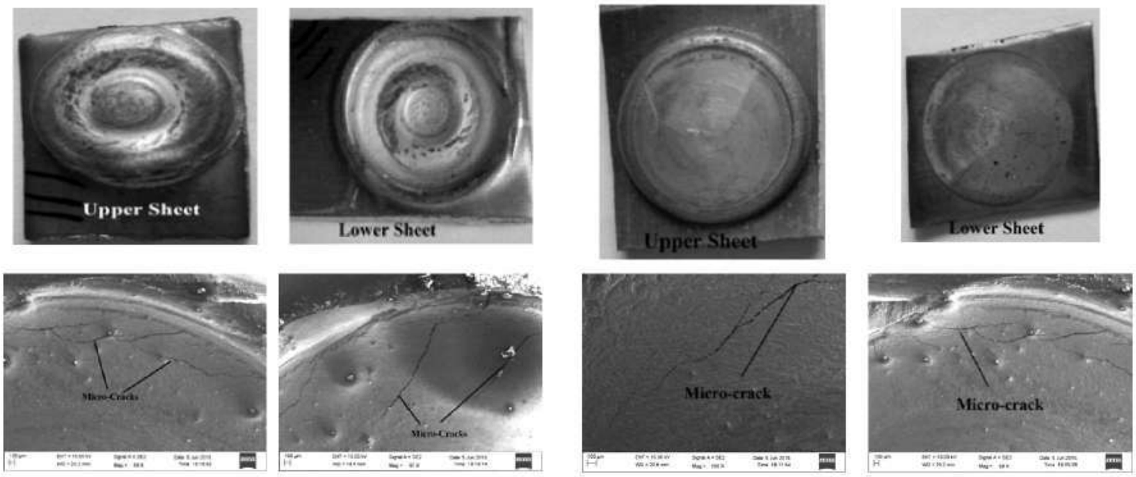
(a) AI 6061 side

Fig. 5 : Microstructural changes in (a) Copper side and (b) Ai6061 side of the FSSW joint when joined with copper top position and rotation speed 1600 rpm, plunge depth 1.9 mm, dwell time 8 s



(a) Copper Top (b) Copper bottom

Fig. 6 : hardness Distribution along the cross section of FSSW joints



(a) Copper top (b) Copper bottom

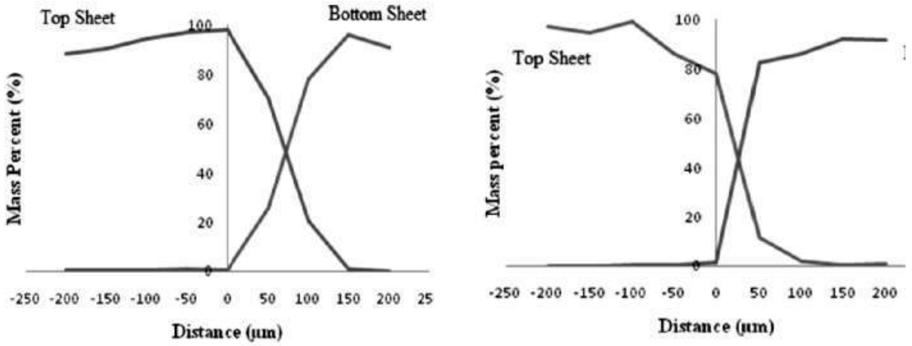
Fig. 7 : Appearance and SEM microphotographs of the nugget pullout failure observed in the joints made by FSSW with copper top and copper bottom positions

3.5 Microhardness

A hardness traverse was taken along the cross section of the weld. Hardness traverse for copper top weld is shown in **Fig. 6 (a)** for both copper side and Al6061 side of the weld. Similarly, **Fig. 6 (b)** shows hardness traverse for copper bottom weld. The hardness distribution was found to be almost symmetric with respect to the center. There is typical W-shaped distribution on both aluminium and copper sides. The low hardness is attributed to the grain coarsening in the HAZ region. The peak hardness stand for the finely equiaxed stirred zone just below the tool pin. The hardness of TMAZ is intermediate in both copper and alumnium. For joints with copper top-Al 6061 bottom, maximum hardness of aluminium in stir zone was 94 HV and maximum hardness of copper was 120 HV in stir zone whereas for joints with Al 6061 top-copper bottom, maximum hardness of aluminium in stir zone was 104 HV and maximum hardness of copper was 99 HV in stir zone. In the joints made with copper bottom position, there is marginal change in copper hardness as there is negligible deformation of copper sheet. The nugget hardness of alumnium is increased considerably due to heavy plastic deformation caused by the tool.

3.6 Fracture Appearance

In both configurations - copper top and copper bottom, the FSSW joints failed in the nugget pull out manner after lap shear testing. **Fig.7** shows the appearance and SEM microphotographs of the fracture surfaces. Due to the micro-cracks at the nugget circumference, the failure has taken place at the



(a) Copper top

(b) Copper bottom

Fig. 8 : EDS analysis of FSSW joints across the interface

interface of the two sheets. This indicates that the sheets throughout the joint are stronger than the interface.

3.7 Electrical Resistivity

The values of electrical resistivity for the FSSW joints made with copper top positions were lesser than those joined with copper-bottom. The range of electrical resistivity for joints with copper top position is 0.15×10^{-4} - 0.30×10^{-4}-'Ω.m. Electrical Resistivity of FSSW joints with copper bottom were in the range of 0.25×10^{-4} - 0.45×10^{-4}-'Ω.m. Those joints made with high rotation speeds showed high electrical resistivity, indicating the effect large amount of defects like enormous grain boundary area, vacancy, solid solution formation, and presence of submicroscopic intermetallic compounds.

3.8 Composition Change across the Interface

The composition profiles across the joint interfaces are shown in **Fig.8**. There is considerable difference in the profiles for the copper top and copper bottom joint. The frictional heat generated with copper top increases its temperature due to higher hardness than with alumnium top position. Since alumnium is softer than copper, it undergoes more deformation compared to copper. The difference in the inter-diffusion coefficients of copper in alumnium and aluminum in copper, solubility limits variation with temperature will decide these profiles.

4.0 CONCLUSIONS

1. Friction stir spot welding of dissimilar metals Al6061 and pure copper by altering the top-bottom positions was successfully performed.
2. For achieving the optimum lap shear strength in the FSSW joints with pure copper top position, the optimum values for processing parameters were 1600 rpm rotational speed, 1.9 mm plunge depth and 8 sec dwell time. Whereas for copper bottom position FSSW joints, the optimum values of joining parameters were 1200 rpm rotational speed, 1.9 mm plunge depth and 12 sec dwell time. Their respective lap shear loads were 4638N and 4235 N.
3. The lap shear tested specimens with both positions of copper sheet, there was nugget pullout failure due to the micro-cracking on periphery of the nugget as seen in the SEM images.
4. The electrical resistivity for copper-top joints was in the range of 0.15×10^{-4} Ω-m to 0.30×10^{-4} Ω-m and for copper-bottom joints it was 0.25×10^{-4} Ω-m to 0.45×10^{-4} Ω-m .

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