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Research Article

Mechanical Properties and Electrical Resistivity of the Friction Stir Spot-Welded Dissimilar Al–Cu Joints

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Alternative methods for dissimilar metal joining particularly aluminium and copper have gain interest in manufacturing sectors. Friction stir spot welding was carried out on the AA6061 and C11000 wires of 2 mm diameter. This research paper reported the results on microstructures and mechanical properties of the spot-welded joints, and also special attention is provided for electrical resistivity of the welds. The microstructures reveal the information of grain structure and bonding. The width of diffusion layer significantly reduced with low dwell times. For a plunge depth of 1 mm, the maximum tensile strength (294 MPa) is achieved during the higher rotational speed (1400 rpm). For the same plunge depth, lower tensile strength values are exhibited by the joint produced using the lower rotational speed (800 rpm). Hardness of the weld region recorded 70 HV which is less than Cu (115 HV) and greater than Al (40 HV). FSSW joints (0.30 to 0.34 $\mu\Omega$) offered higher range of electrical resistivity than that of base metal (0.02 $\mu\Omega$). The results highlighted in this paper might be helpful for both academic researchers and industrialists.

1. Introduction

The application range of aluminium in automotive industries is expanding due to its many inherent characteristics like low weight, high ductility, and excellent thermal and electrical conductivity. Joining of aluminium with the other metals is still a challenge for many researchers. With advances in welding processes, interest has become more on solid-state welding processes as an alternative for dissimilar metal joining. Friction stir spot welding (FSSW) is a newer technique under solid-state welding processes, which shows the greater efficiency than the existing methods of dissimilar joining of aluminium. Extensive feasibility studies are performed on FSSW of dissimilar metals (aluminium and copper) from manufacturers of aeroplanes, trucks, trains, motor vehicles, and appliances.

FSSW is a modified version of friction stir welding (FSW) originally developed for joining Al-alloys [1–6], with similar working mechanism used for special applications (spot welding process) [7, 8]. A rotating tool (nonconsumable) is positioned perpendicular to the workpiece and pushed towards the workpiece with the application of axial force for a specific duration also called as dwell time. After the formation of weld, the tool retracts from the workpiece. In FSSW, the heat input and material plasticization are determined through the two significant parameters such as dwell time and tool penetration speed. Based on the material plasticization and heat input, the mechanical properties of the joint are determined [8]. The schematic of FSSW process [9] is shown in Figure 1.

Spot welding techniques are mainly concentrated in the joining of dissimilar wires, sheets, terminals, and contacts to retain its intrinsic metallic properties which are not possible in conventional fusion welding techniques, brazing, and soldering. Solid-state welding processes help avoid the intermetallic compounds formation, whereas conventional welding leads to produce them [10]. Several researchers attempted the dissimilar welding [1] of aluminium and copper through FSW [11–19]. Akinlabi et al. investigated the electrical resistivities of the Al to Cu joints. The authors found the relationship between the resistivity and the heat input, and higher heat inputs lead to the increased electrical resistance. The higher resistivity of joints is about 9.8% more than that of the parent metal resistivity [20]. Similar studies have been performed by the other researchers. Savolainen found that the joint resistivity is 2.5% times more than the average value of both parent materials [21]. Most of the work carried out on FSSW of aluminium to copper deals with mechanical and microstructural properties of the welds. Dissimilar metal joint (aluminium-copper) could be beneficial in electrical connections, wiring circuits in automobiles, and electronic board assemblies. All these applications require the knowledge about weld joint electrical performance. Hence, the present study has been conducted to address the friction stir spot-welded joint electrical performance parameters. The present paper investigates the effect of the FSSW process parameters on electrical resistivity of the weld joints and its relationships. Mechanical and metallurgical properties of the weld joints are reported. This research deals with the dissimilar aluminium-copper spot joint produced by friction stir spot welding. The mechanical properties reveal the joint strength of the weld, and the microstructure highlights the various defects in the joint. The electrical resistivity is also measured to find the resistivity.

2. Experimental Setup

Aluminium, AA6061, and copper, C11000, wires of 2 mm diameter are employed for joining process (friction stir spot welding). Tables 1 and 2 show the elemental composition and mechanical properties of both the metallic wires adopted for experimentation. Before producing weldments, surfaces of the workpiece are cleaned with acetone for the removal of surface contaminants. Welds are produced by placing Cu on the top side of Al. Experimental trials are carried out by different combinations of the process parameters of FSSW process. The FSSW tool is produced with H13 steel tool hardened to 46-48 HRC (with a pin length of 4 mm, shoulder diameter of 10 mm, and diameter of 5 mm). The tool plunge depths of 0.5 and 1 mm with a constant dwell time of 5 s are employed. FSSW rotational speeds are varied from 800 rpm to 1400 rpm. The FSSW torque and axial load values are analyzed through a load cell of six axis attached to the data acquisition system for continuous monitoring. The dimensional indication of workpiece is provided in Figure 2.

For metallographic examination of the weld cross sections, Keller's reagent is used as an etchant for Al side and a solution comprising of HCI (6 ml) + FeCI3 (10 g) + ethanol (C2H50H) (20 ml) + deaerated water (80 ml) was utilized to etch the Cu side. (Morphology and qualitative analysis of the weldments are performed using SEM and EDAS analysis. The electrical resistivity values of the samples are determined using four-point probe meter. Simple device employed for gauging the resistivity of semiconductor specimens is known as four-point probe meter. The substrate resistivity is measured by applying the current through two outer probes and assessed the voltage through the inner probes. Further, weld specimens for tensile tests are machined as per the standard (ASTM A-931). The tensile tests are carried out at the standard room temperature. Vickers hardness apparatus (with a load of 0.98 N) is employed to measure the hardness in the weld region and base metal. An average of five values is taken in each region. Scanning electron microscopy (SEM) is equipped to observe the microstructures of weld joints. Energy-dispersive X-ray spectroscopy is employed to assess the elemental compositions of the weld joints.

3. Results and Discussion

Dissimilar joints (Al and Cu) were successfully obtained through friction stir spot welding according to the experimental design. The cross sections of the joints exhibit the five distinct regions such as base metal (BM), stir zone (SZ), thermo-mechanically affected zone (TMAZ), the heat affected zone (HAZ), and hook region [8].

3.1. Microstructures. Figures 3(a) and 3(b) depict the micrographs of the spot weldments. It is observed that the six intermetallic phases exist below 500°C which are likely some of many metastable intermetallic phases existing in the Al-Cu phase diagram [22–24]. Sound welds are obtained for the selected process parametric range. The width of diffusion layer at the interface is significantly decreased with the decrease in dwell time. The diffusion layer is noticed in Figure 3 for rotational speed of 1400 rpm with dwell time of 5 s. In Figure 4 (rotational speed: 1400 rpm and dwell time: 1 s), the diffusion layer is lower than the Figure 3. The micrographs reveal the negligible pores and defect free weldments. Microstructural studies are performed in all the five distinct zones of weld. The TMAZ constitutes smaller and equiaxed grains because of the mechanical deformation and thermal cycles during stirring action. Stir zone has fully crystallized small and fine grains along the boundaries. Longer grains are observed in the HAZ than that of TMAZ and SZ. Typically, with the increase in distance from weld center, evolution of grain structures takes place. Further, grains in HAZ are randomly distributed in the region.

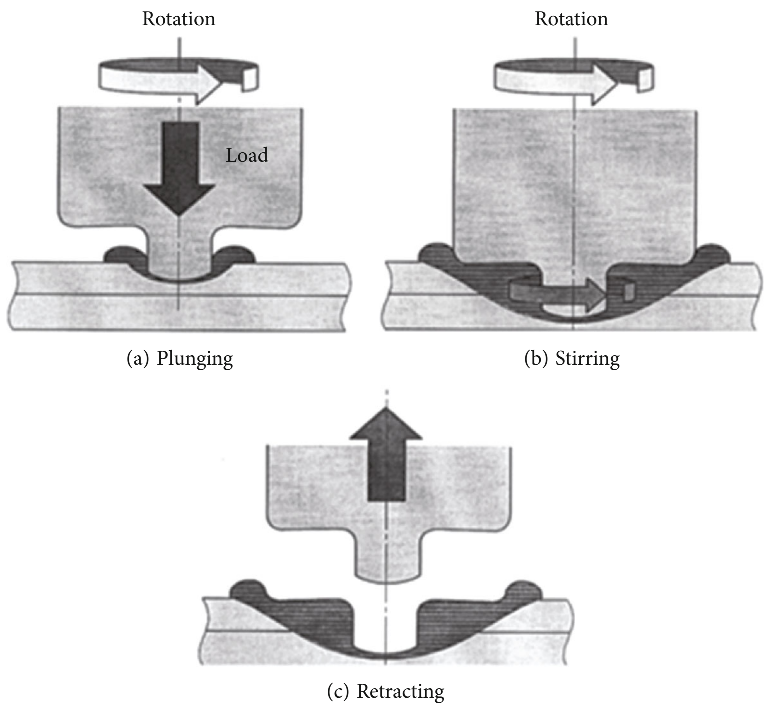


Figure 1: Graphic representation of friction stir spot welding process.

Table 1: Chemical composition of AA6061 and C11000 wires.

Materials (wt%)	Cu	Fe	Si	Zn	Pb	Ni	Al
AA6061	0.005	0.3	0.07	0.005	0.003	<0.001	Balance
C11000	Balance	0.05	0.009	4.69	0.03	0.03	0.02

Table 2: Mechanical properties of AA6061 and C11000 used for the experimentation.

Properties	AA6061	C11000
Tensile strength (MPa)	290	455
Elongation (%)	15	33
Hardness (HV)	41	115

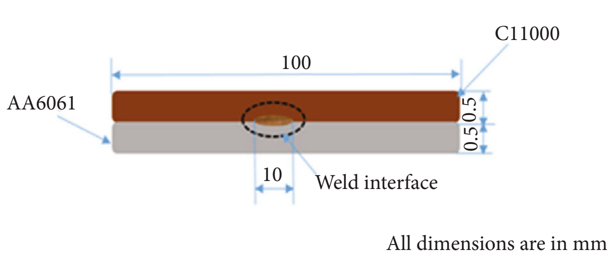
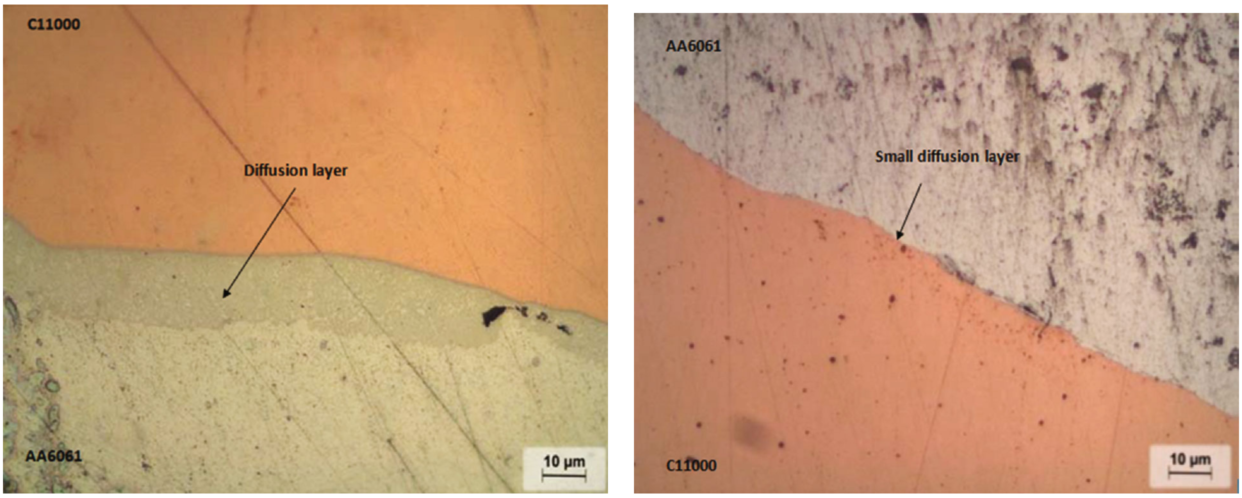


Figure 2: Workpiece dimensions for experimentation.

SEM images are shown in Figures 4(a) and 4(b). The images depict the Cu rings and keyhole of the spot-welded joints by varying process parameter range. Scanning electron microscopy (SEM) analysis performed to find the disparity between two base metals such as Al and Cu. The micrographs clearly reveal the presence of Cu on the Al side and disparity between the base metals. The large variation between the melting points of Al and Cu combined with FSSW tool stirring action and dwell time produce the brittle and hard intermetallic compounds.

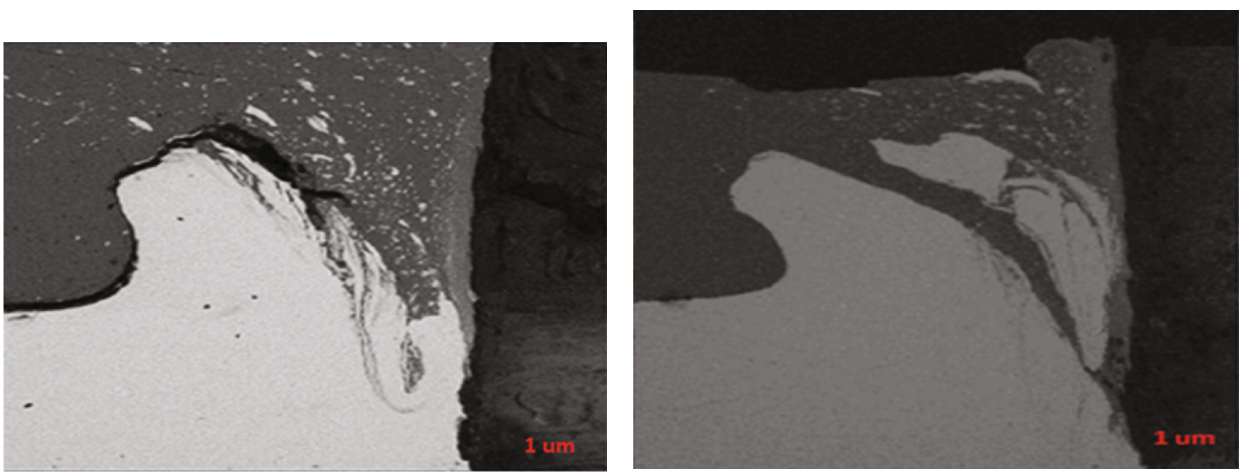
The intermetallic compounds in the specimens are analyzed using an electron dispersed X-ray spectroscopy (EDS). Previous literature reports suggested the increased resistivity of the joints due to the presence of long-range–ordered alloys [25, 26]. The long-range–ordered alloys in the weld region of weldment produced with tool rotational speed of 1000 rpm and dwell time of 1 s are noticed in Figure 4(a). Three major intermetallic compounds, namely, Al_2Cu, AlCu, and Al_4Cu_9, are noticed in the SZ of the joints for dwell time of 1 s and rotational speed of 1000 rpm, whereas the joint produced with dwell time of 1 s and 1400 rpm showed only two intermetallic compounds, namely, Al_3Cu_4 and Al_2Cu.

In most of the welded samples, it is observed the accumulation of aluminium particles or aluminium-rich content on the Cu side, particularly in the upper side of keyhole with small percentages of copper. This may be attributed to FSSW tool stirring action which takes bottom side of aluminium particles to the top region. This action promotes the formation of intermetallic compounds or aluminium-rich contents on Cu side.



(a) (b)

Figure 3: Microstructures of friction stir spot-welded Al-Cu wires (a) rotational speed: 1400 rpm, dwell time, and 5 s (b) rotational speed: 1400 rpm, dwell time: 1 s.



(a) (b)

Figure 4: (a) Microstructure of the spot weld using SEM (1000 rpm, 1 s and 0.5 mm plunge depth). (b) Microstructure of the spot weld using SEM (1400 rpm, 1 s, and 0.5 mm plunge depth).

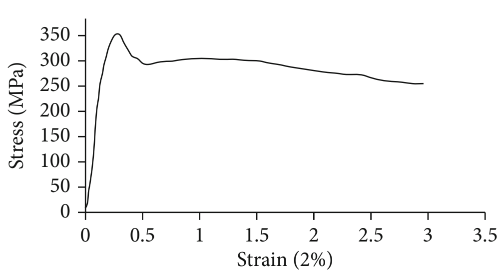


Figure 5: Stress vs. strain curve of spot-welded wire joints (rotational speed: 1400 rpm and plunge depth: 1 mm).

3.2. Mechanical Properties. Figure 5 reveals the weld strength profile of the spot-welded Al-Cu wires for different process parametric range. The results revealed that the weld strength is influenced by many factors such as tool pin length, tool rotational speed, and plunge depth [27]. The least affected parameter in joint strength is weld time and remains to be insignificant. Weld strength is majorly influenced by the tool rotational speed. As the rotational speed increases, weld strength increases. The maximum tensile strength (294 MPa) is achieved during the higher rotational speed (1400 rpm). The minimum tensile strength is yielded during the lower rotational speed (800 rpm). Weld strength remains to be unaffected even for rotational speed more than 1400 rpm. The linear relationship between weld strength and rotational speed exists only for the limited range. All the specimens observed

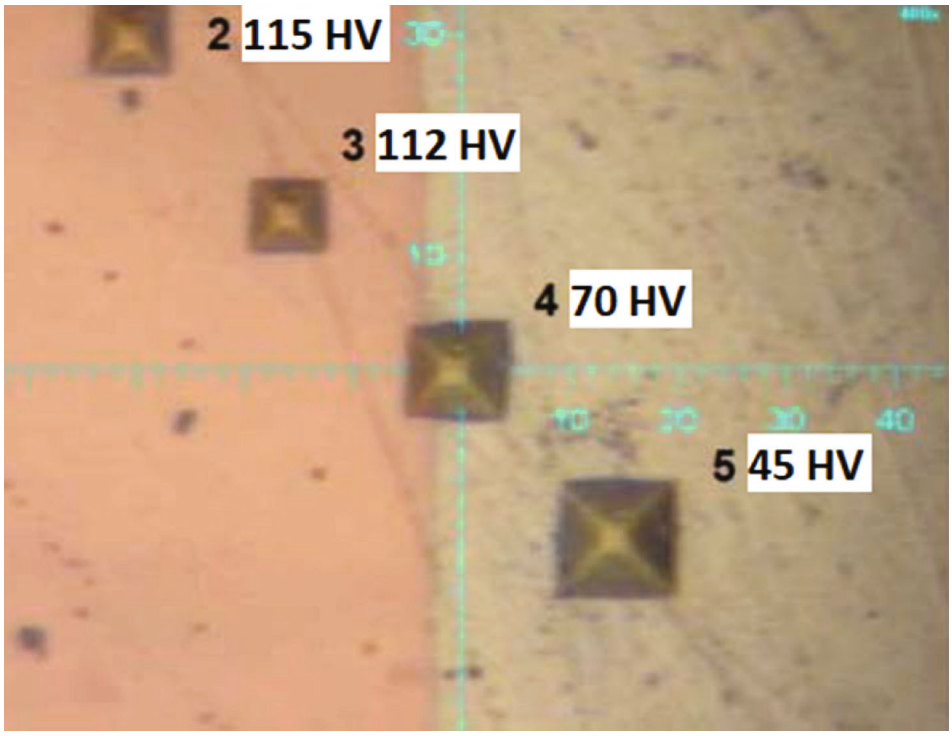


Figure 6: Hardness profile of Al-Cu spot welds (rotational speed: 1200 rpm and plunge depth: 0.5 mm).

Table 3: Electrical resistivities of the base metals and the spot welds of various process parameters (TRS: tool rotational speed; PD: plunge depth).

Material	*Resistivity ($\mu\Omega$)*
Base metal, Al	0.018
Base metal, Cu	0.026
Average value	0.022
Spot welds	*Resistivity ($\mu\Omega$)*
TRS: 800 rpm; PD: 0.5 mm	0.061
TRS: 800 rpm; PD: 1 mm	0.038
TRS: 1000 rpm; PD: 0.5 mm	0.047
TRS: 1000 rpm; PD: 1 mm	0.032
TRS: 1200 rpm; PD: 0.5 mm	0.036
TRS: 1200 rpm; PD: 1 mm	0.030
TRS: 1400 rpm; PD: 0.5 mm	0.029
TRS: 1400 rpm; PD: 1 mm	0.024

failure in the weld region during tensile testing. Weldments are achieved with the average tensile strength of 293.48 MPa and the maximum load of 40.45 kN by using 1400 rpm rotational speed and plunge depth of 1 mm.

Vickers hardness measurements are performed across the weld region and base metal region of the welded specimens (Figure 6). Figure 6 shows the hardness profile of spot-welded specimen with plunge depth of 0.5 mm and rotational speed of 1200 rpm. At the center of the weldment, hardness value observed is 70 HV which is less than Cu and greater than Al. Slight decrease in hardness values on Cu is observed to the contrast in plasticization and thermal cycles during welding process. The increase in hardness value of joint when compared to Al is because of the grain recrystallization in the stir zone.

3.3. Electrical Resistivity. The electrical resistivity at the joint interface of spot-welded dissimilar Al-Cu wires is measured using four-wire probe meter. Similar studies are performed by the authors for ultrasonic spot welding of Al-Cu wires [28, 29]. The electrical resistivity values of joints for process parameters of welding are presented (Table 3).

From Table 3, the electrical resistivity values increased with the rise in magnitudes of plunge depth and tool rotational speed. The tool rotational speed has four values from 800 to 1400 rpm. The plunge depth with two values of 0.5 and 1 mm is used. The electrical resistivities of the spot-welded specimens are higher than the both metals. The difference in electrical resistivity values is huge between spot-welded joints and base metals. This pattern is attributed to the presence of pores and micro cracks at the stir zone of weldments [30–32]. The highest measured of resistivity is 0.061 $\mu\Omega$ for the plunge depth of 0.5 mm and tool rotational speed of 800 rpm. It is observed that the most values of the joint resistivities lies in the range of 0.30 to 0.34 $\mu\Omega$. The average of base metals is 0.022, and when comparing this value to the joint resistivities, a depreciation varies between 0.08 $\mu\Omega$ (42%) and 0.012 $\mu\Omega$ (60%). Along with these values, a maximum value of 0.061 $\mu\Omega$ is 200% rise of base metals average for plunge depth of 0.5 mm and tool rotational speed of 800 rpm. Figure 7 shows the comparison chart of electrical resistivities of the spot welds with various process parameters.

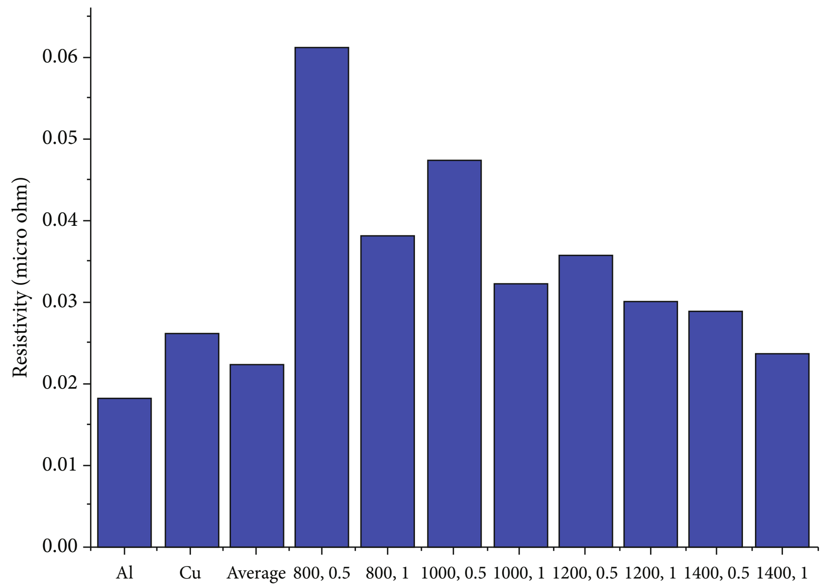


Figure 7: Influence of process parameters on the electrical resistivity of the spot welds when compared to the base metals and their average value.

It can be observed from the measurements that all the joint resistivity values are much more than the parent metal. In FSSW process, the presence of intermetallic compounds affects the electrical resistivity and therefore increases in magnitude. The higher electrical resistivities of the spot welds in the present work are because of the presence of long-range–ordered alloys (intermetallic phases) in the keyhole. This is validated from the energy-dispersive X-ray spectroscopy analysis.

4. Conclusions

Friction stir spot welding between 2 mm AA6061 wires and 2 mm C11000 wires was successfully performed using a hardened H13 steel tool. Within the taken process parametric range, the following important conclusions can be drawn.

(i) Width of diffusion layer is significantly decreased with the decrease in dwell time

(ii) The micrographs clearly reveal the presence of Cu on the Al side and disparity between the base metals which results in formation of harmful brittle and hard intermetallic compounds

(iii) The maximum tensile strength (294 MPa) is achieved during the higher rotational speed (1400 rpm) for a plunge depth of 1 mm. For the same plunge depth, lower tensile strength values are exhibited by the joint produced using the lower rotational speed (800 rpm)

(iv) Hardness of the weld region recorded 70 HV which is less than Cu (115 HV) and greater than Al (40 HV)

(v) The electrical resistivity of the spot welds lies in the range of 0.30 to 0.34 $\mu\Omega$ which is significantly more than the average value of base metals (0.022 $\mu\Omega$)

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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