Microstructure and electrical resistivity properties of copper and aluminium friction stir spot welds

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***Abstract*— Dissimilar metal joining methods are essential for the manufacturing of a various structures and parts in the industries. Friction stir spot welding process was performed on 3 mm thick AA1060 and C11000. This paper presents the results on the microstructure, chemical analysis and electrical resistivities of the produced joints. The microstructure showed a contrast between the two different materials namely copper and aluminium and the presence of a copper ring (hook) in all the produced spot welds. The presence of copper particles in the aluminium matrix was observed in most of the welds. The conducted energy dispersive spectroscopy (EDS) analysis confirmed the presence intermetallic compounds. It was observed that, the spot weld produced using 800 rpm and 1 mm shoulder plunge depth exhibited a low electrical resistivity value of 0.009 µΩ, which shows an appreciation of 0.011 µΩ (55 %), compared to the average of the parent materials (0.020 µΩ). This could be an attractive option for electrical applications.**

Keywords- Aluminium, Copper, Electrical resistivity, FSSW, Intermetallics, Microstructure

I. INTRODUCTION

The joining of dissimilar materials is becoming progressively significant in industrial applications due to their numerous advantages [1]. Friction stir welding (FSW) is a solid-state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non-ferrous metals and plastics [2] Friction stir spot welding (FSSW) is a variant of friction stir welding (FSW) process for spot welding applications [3]. A non-consumable rotating tool is plunged into the workpieces to be joined. Upon reaching the selected plunge depth, the rotating tool is held in that position for a fixed time which is sometimes referred to as dwell period. Afterward, the rotating tool is retracted from the welded joint leaving behind a friction stir spot weld. During friction stir spot welding, tool penetration and the dwell period fundamentally determine the heat generation, material plasticization around the pin, weld geometry and therefore the mechanical properties of the welded joint [3]. A schematic illustration of the FSSW process is shown in Fig.1.

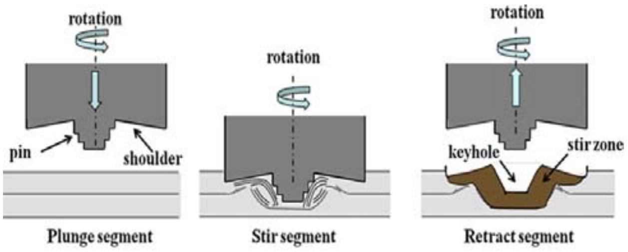

Figure 1. A schematic illustration of the friction-stir spot welding process [4].

FSSW process uses a tool, similar to the FSW tool [5]. The shoulder generates bulk of the frictional or deformational heat whereas; the pin assists in material flow between the work pieces [3]. Besides the tool, the other parameters involved in FSSW are, the tool rotation speed; tool plunge depth and the dwell period. These parameters determine the strength and the surface finish of the welded joints [3]. A nomenclature is required to accurately describe the different microstructural regions present after FSSW.

The cross section of the spot weld shows the five distinct characteristics include the parent material (PM), the heat affected zone (HAZ), thermomechanically affected zone (TMAZ), the stir zone (SZ) and the hook [3]. Friction stir welding between aluminium and copper is well researched [6-14] however; there are few published papers on friction stir spot welding between aluminium and copper [15-19].

The electrical resistivities of aluminium to copper joints have been investigated by Akinlabi et al. [20] and Savolainen [21]. Akinlabi et al [20] used AA 5754 to C11000 friction stir welds of 3.175 mm thick, whereas Savolainen used Cu-OF to extruded aluminium alloy EN-AW 6060 T6 of 10mm thick. Akinlabi et al [20] found that the electrical resistivities of the produced joints increased as the heat input to the welds increases. The maximum percentage increase in resistivity compared to the average joint resistivity of the parent material was found to be 9.8% [20]. On the other hand, Savolainen [21] found that the resistivity of the welded joint (29 nΩm) is 2.5 % higher than the average resistivity of both base materials which was 28.3 nΩm. In the open literature, there is no research work reporting on the electrical resistivity of friction stir spot welds between aluminium and copper. Therefore, this research work reports on the electrical resistivity measurement of FSS Welds between AA1060 and C11000 using different tool geometries and process parameters. Additionally the microstructure and the chemical analysis of the produced spot welds are reported.

II. EXPERIMETAL SET UP

A. *Materials and welding parameters*

AA1060 (aluminium) and C11000 (copper) sheets, each with 3 mm thickness, 600 mm length and 120 mm in width were spot lap welded. The chemical composition of the two parent materials was determined using a spectrometer (Q4 TASMAN). The nominal chemical composition of the aluminium plate is as follow: 0.058 wt. % Si, 0.481 wt. % Fe, 0.011 wt. % Ga, 0.05 wt. % others and the balance was Al. whereas, the chemical composition of the copper sheet is, 0.137 wt. % Zn, <0.1 wt. % Pb, 0.02 wt. % Ni, 0.023 wt. % Al, 0.012 wt. % Co, 0.077 wt. % B, 0.036 wt. % Sb, 0.043 wt. % Nb, <0.492 wt. % others and the balance was Cu. The sheets were friction stir spot welded in a 30 mm overlap configuration. An MTS PDS I-Stir at the eNtsa of Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa was used to produce the spot welds. The tool material is H13 steel tool hardened to 50-52 HRC. The tool pin length and the diameter were kept constant at 4 mm and 5 mm respectively; whereas the shoulder diameter was 15 mm. Rotational speeds of 800 and 1200 rpm were used. Furthermore, the tool shoulder plunge depths employed were 0.5 and 1 mm using a constant dwell time of 10 seconds. The produced spot welds were coded as FPS and CCS for the samples produced using a Flat pin/ Flat shoulder and Conical pin/ Concave shoulder tool respectively.

B. *Microstructure and electrical resistivity measurement*

The produced spot weld samples were cut by using the wire electrical discharge machining (WEDM), grinded and polished, mounted and prepared, using ASTM Standard E3-11 [22]. A solution of $FeCl_3$ (10g) + HCl (6 ml) + Ethanol (C_2H_5OH) (20 ml) + H_2O (80 ml) was used to etch the copper side of the spot welds; while the aluminium side was etched with H_2O (190 ml) + HNO_3 (5 ml) + HCl (10 ml) + HF (2 ml). Morphological and qualitative analyses of the spot welds were performed using SEM/EDS. A TESCAN equipped with Oxford instrument X-Max was used for the SEM/EDS analyses of the produced spot weld samples. On the other hand, the electrical resistance of the samples was measured, in accordance with the ASTM standard cited by Akinlabi [23]. The Four-Point probe meter consists of two probes carrying the current, with the other two probes sensing the voltage, as shown in Fig.2.

Figure 2. Experimental set-up for electrical resistance measurement

III. RESULTS AND DISCUSSION

Fig. 3 and 4 depict the SEM secondary electron (SE) (a) and a backscattered electron (BSE) (b) micrographs of the copper ring and part of the keyhole of the welds produced using different process parameters and tool geometries, namely, a Flat pin/ Flat Shoulder and Conical pin/ Concave Shoulder tools. This was conducted to show the contrast between the two different materials, namely copper and aluminium. The contrast between the two materials and the presence of Cu particles in the aluminium matrix can be clearly seen. This difference could lead to the formation of hard and brittle intermetallic compounds.

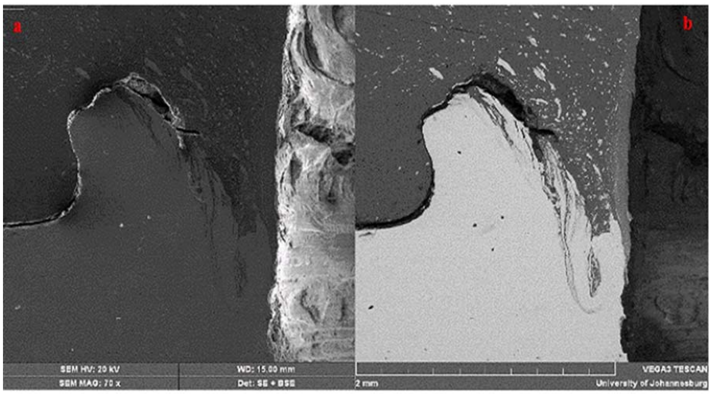

Figure 3. Showing a secondary electron (a) and a backscattered electron (b) images of the spot weld produced at 800 rpm and 0.5 mm plunge depth using a flat pin and a flat shoulder tool.

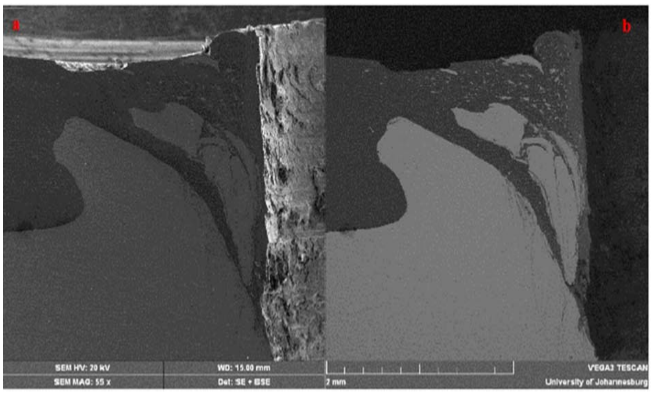

Figure 4. Showing a secondary electron (a) and a backscattered electron (b) images of the spot weld produced at 1200 rpm and 1 mm plunge depth using a flat pin and a flat shoulder tool.

The presence of hard and brittle intermetallic compounds in the produced samples using energy dispersive spectroscopy (EDS) technique was observed. It has been reported that intermetallic compounds at the joint interface of aluminium and copper are known to exhibit high electrical resistivity [24]. Fig. 5 depict the presence of intermetallic compounds in the SZ of the spot sample produced using a flat/pin and flat shoulder tool at 1200 rpm, 1 mm shoulder plunge depth.

Three intermetallic compounds, namely AlCu, Al_4Cu_9 and Al_2Cu were found in the stir zone of the weld produced at 800 rpm, 0.5 mm shoulder plunge depth, whereas the weld produced at 1200 rpm and 0.5 mm shoulder plunge depth contained Al_2Cu and Al_3Cu_4 intermetallic compounds. On the other hand, the Al_4Cu_9 and AlCu intermetallics were found in the weld produced at 1200 rpm and 1 mm shoulder plunge depth. These were obtained using a flat pin and flat shoulder.

On the other hand, the EDS results of the stir zone for the spot welds produced when using a conical pin and a concave shoulder tool showed only Al_4Cu_9 intermetallic was found in the weld produced at 800 rpm and 0.5 shoulder depth; whereas Al_4Cu_9 and AlCu were present in the weld produced at the same rotational speed, but with a 1 mm shoulder plunge depth. Three intermetallics, namely: Al_2Cu, AlCu and $AlCu_3$ were present in the weld produced at 1200 rpm and 0.5 shoulder plunge depth; while only AlCu was found in the weld produced at 1200 rpm and 1 mm shoulder plunge depth.

In various samples, it was noticed that there was region rich in aluminium, especially in the upper zone (aluminium sheet) of the keyhole, with a lower percentage of copper. This could have been caused by the stirring of the tool pin, which took the copper particles from the bottom plate upward, and favoured the presence of either rich aluminium regions or the presence of intermetallics.

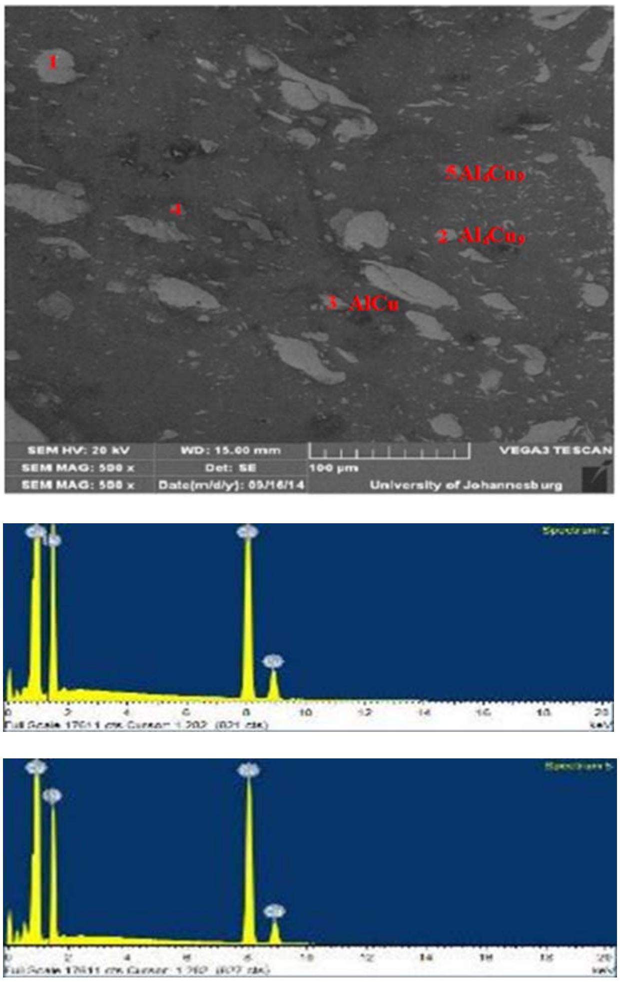

Figure 5. Scanning electron microscopy image and energy dispersive spectroscopy spectrums and intermetallic compounds of the weld produced at 1200 rpm, 1 mm shoulder plunge depth using a flat pin and a flat shoulder of the stir zone.

The electrical resistivity of the aluminium/ copper dissimilar material friction stir spot welds was measured at the joint interface and then studied. The electrical resistivity measurement results are shown in Tables 1 and 2 for the flat pin and the flat shoulder, and for the conical pin and the concave shoulder, respectively.

TABLE I. ELECTRICAL RESISTIVITY RESULTS USING A FLAT PIN AND A FLAT SHOULDER TOOL.

Spot welds ID	Resistivity ρ(μΩ)
Parent material_Al	0.014
Parent material_Cu	0.025
Average ρ	0.02
FPS_800_0.5_1	0.064
FPS_800_0.5_2	0.064
FPS_800_0.5_3	0.063
FPS_800_1_1	0.035
FPS_800_1_2	0.033
FPS_800_1_3	0.033
FPS_1200_0.5_1	0.034
FPS_1200_0.5_2	0.032
FPS_1200_0.5_3	0.032
FPS_1200_1_1	0.032
FPS_1200_1_2	0.031
FPS_1200_1_3	0.03

TABLE II. ELECTRICAL RESISTIVITY RESULTS USING A CONICAL PIN AND A CONCAVE SHOULDER TOOL.

Spot welds ID	Resistivity ρ(μΩ)
Parent material_Al	0.014
Parent material_Cu	0.025
Average ρ	0.02
CCS_800_0.5_1	0.035
CCS_800_0.5_2	0.032
CCS_800_0.5_3	0.033
CCS_800_1_1	0.011
CCS_800_1_2	0.009
CCS_800_1_3	0.011
CCS_1200_0.5_1	0.033
CCS_1200_0.5_2	0.033
CCS_1200_0.5_3	0.034
CCS_1200_1_1	0.034
CCS_1200_1_2	0.032
CCS_1200_1_3	0.029

The results show that by increasing the rotational speed and the shoulder plunge depths, the electrical resistivity decreases when using the flat pin and a flat shoulder tool (Table.1). It was further noticed that there is a big difference between the values of the electrical resistivity of the parent materials compared to most of the spot welded samples. This could be due to the presence of defects in the SZ, such as micro cracks. The highest electrical resistivity value of 0.064 μΩ was found for the sample produced at 800 rpm, 0.5 mm shoulder plunge depth, using a flat pin and flat shoulder. It was also observed that most of the welds had an electrical resistivity of between 0.029 μΩ and 0.035 μΩ; but when compared with the average of the parent materials showed a depreciation between 0.009 μΩ (45 %) and 0.015 μΩ (75 %), respectively, for 0.029 μΩ and 0.035 μΩ. On the other hand, a depreciation of 220% was found for the sample produced at 800 rpm, 0.5 mm shoulder plunge depth using a flat pin and a flat shoulder tool.

The electrical resistivity results for the welds produced with a conical pin and a concave shoulder (Table.2) showed different trends. A low resistivity value of 0.009 μΩ was found when using 800 rpm and 1 mm shoulder plunge depth, which shows an appreciation of 0.011 μΩ (55 %). However, the results obtained using the other parameters showed values varying from 0.029 to 0.035 μΩ. This result was obtained for the sample at 800 rpm, 1 mm shoulder plunge using a conical pin and a concave shoulder; and it has low electrical resistivity compared to the other spot welds and could be an attractive option for electrical conductivity applications purposes.

Fig.6 and 7 depict the effects of process parameters and tool geometry on the electrical resistivity of the produced spot welds.

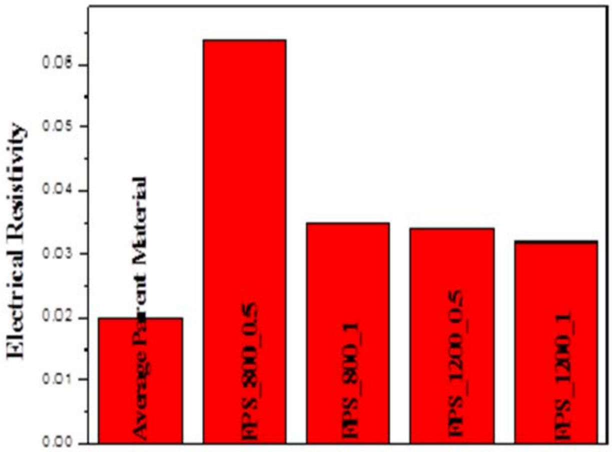

Figure 6. Effect of process parameters on the electrical resistivity of the spot welds when compared to the average resistivity of the parent materials produced using a flat pin and a flat shoulder tool.

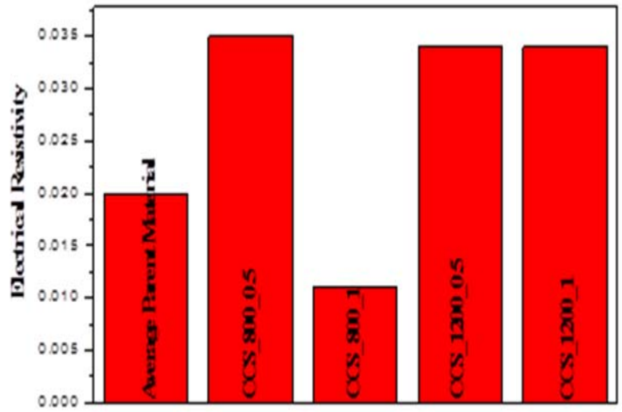

Figure 7. Effect of the process parameters on the electrical resistivity of the spot welds compared to the average resistivity of the parent materials produced when using a conical pin and a concave shoulder tool.

It can be seen that the electrical resistivity of all the welds is higher than those of the average parent materials except the spot weld produced at 800 rpm and 1 mm shoulder plunge depth using a conical pin /concave shoulder. Akinlabi [23] calculated the electrical resistivity of the friction stir welding between commercially pure copper to AA5754. She concluded that the presence of intermetallics affect the electrical resistivity. This was seen in the welds, where intermetallics were not found [23]. The high values of the electrical resistivity obtained except for the welds produced at 800 rpm and 1 mm shoulder plunge depth in the current research work could be due to the presence of intermetallics in the vicinity of the keyhole. This was confirmed with energy dispersive spectroscopy analyses.

IV. CONCLUSION

Friction stir spot welds between aluminium and copper were successfully produced using different tool geometries and process parameters. The results obtained can be summarized in the following ways:

- The microstructure shows a contrast between the two different materials (AA1060 and C11000). The contrast between the two materials and the presence of copper particles in the aluminium matrix was clearly seen and this difference leaded to the formation of hard and brittle intermetallic compounds.
- The energy dispersive spectroscopy (EDS) analysis confirmed the presence intermetallic compounds include AlCu, Al_4Cu_9 and Al_2Cu.
- A low resistivity value of 0.009 μΩ was found when using 800 rpm and 1 mm shoulder plunge depth, which shows an appreciation of 0.011 μΩ (55 %).

ACKNOWLEDGMENT

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