Friction Stir Welding of Aluminium and Copper: Fracture Surface Characterizations

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***Abstract*— Butt welds of aluminium alloy and copper alloy were produced by Friction Stir Welding by varying the feed rate and keeping all other parameters constant. The final weld matrix was composed of welds produced by a constant rotational speed of 600 rpm and the feed rate varied between 50 and 300mm/min. The microstructure and fracture surfaces of the joint interfaces were investigated. The results revealed that the joint interface was characterised with mixed layers of both materials joined. The strongest weld was produced at the highest feed rate employed at 300 mm/min. The fracture surfaces were characterised with thin layers of intermetallic compounds and can be considered fit for practical applications.**

***Keywords*—** Aluminium, Copper, Friction Stir Welding, Fracture surfaces.

I. INTRODUCTION

Friction Stir Welding (FSW) is a joining process that was developed and patented in 1991 by The Welding Institute (TWI) of Cambridge in England [1]. FSW is a joining technology that employs plastic deformation to create solid-state joints between wide ranges of materials which are used in the manufacturing industry. It has different joining configurations such as lap joints, fillet joints, T joints and butt joints [2]. The process is capable of producing welds better than fusion welds in terms of joint efficiency, mechanical properties and environmental robustness [2]-[3]. The weld is created by clamping the two materials that need to be joined. This is then followed by plunging a rotating tool into the joint. The rotating tool travels down the joint line of the materials while generating frictional heat which leaves a welded zone behind which is characterized by a fine-grained, and recrystallized microstructure which results in the formation of a solid- phase joint [4]. The interfacial zone of the welds is usually characterised by four major microstructural zones viz; the nugget zone, the thermo-mechanically affected zone, the heat affected zone and the parent material which is a zone remote from the welded zone [5].

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The FSW technology is considered to be the most significant metal joining process due to its environmental friendliness, energy efficiency and its broadness and the process is currently used for many applications and employed in many industries such as aerospace, marine, railway and electrical. The benefits of FSW being that it generates no harmful fumes, no solidification cracking, results in reduced distortion and improved weld quality for the proper parameters, adaptable to all positions and is a relatively quiet process [4].

The joining of the two dissimilar materials such as Aluminium (Al) and Copper (Cu) is of great demand for industrial applications. The need to join these materials is due to the thermal and mechanical properties they possess, such as a high corrosion resistance and a high electric conductivity. However, aluminium and copper are difficult to weld using the conventional welding processes due to the thermal properties of both materials. The current conventional welding methods result in the formation of hard and brittle intermetallic phases at the interface of the joint [6]. These phases will eventually result in cracks.

The use of FSW to join these two materials will result in improved contact surface, improved current flow and less resistance. FSW consumes little energy and no gas or flux is used, therefore making the process environmentally friendly.

The improvements will lead to energy savings; this will lead to a global energy consumption decrease if the method is implemented on a global scale. The FSW technology produces high quality welds but to achieve all these, there are several parameters that need to be addressed during the welding process of materials. The welding process parameters, tool geometry, joint design and heat generation exert a significant effect on the material flow pattern and temperature distribution thus influencing the microstructural evolution and the properties of the materials being welded [7]. Several researchers have successfully joined aluminium to copper using the friction stir welding process [8-13].

Tool shoulders are designed in a way such that frictional heat is generated on the surface and subsurface of the specimens being welded. The shoulder and pin combination work hand in hand. In situations were thin sheets are to be welded, the shoulder produces the most deformational and frictional heat. During the welding of thick specimens, the most heating is produced by the pin. The most important parameter of the shoulder is the diameter because it has significant effect on the amount of frictional heat generated [14]. The larger the shoulder diameter, the larger the pressure

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force which causes changes in the weld shape. This occurrence decreases the mechanical properties of the welds. There are different types of tool shoulder shapes and the differences in the shape and the welding parameters always induce significant changes in the resulting material flow path.

In this research study, a small shoulder diameter of 15 mm was employed to produce friction stir welds of aluminium and copper by varying the only the feedrate while other parameters were kept constant.

II. EXPERIMENTAL PROCEDURE

5754 aluminium alloy and C11000 copper of dimensions 3 x 120 x 600 mm^3 were friction stir welded using the Product Development System (PDS) FSW machine at the eNtsa of Nelson Mandela Metropolitan University, Port Elizabeth, South Africa. The samples were cleaned with 320 grit Silicon Carbide paper and then degreased using acetone. A schematic of the process is shown in Fig. 1.

Fig. 1. Schematic of the FSW process

The welds were conducted at a fairly low rotational speed of 600 rpm while the feed rates considered were 50, 150 and 300 mm/min representing the low, medium and high settings. A dwell time of 2 seconds and tool tilt angle of 2^o was employed. The tool geometry was threaded pin and concave shoulder. The shoulder diameter was 15 mm and the pin diameter was 5 mm. Total weld lengths of 160 mm were produced for each setting and the welds were sectioned at 50 mm mark to examine the cross sections. The samples for microscopic examination were prepared according to the ASTM standard [15] and characterised using the Olympus BMX5 microscope. The aluminium side was etched with Keller's reagent while the copper was etched with the modified Poulton's reagent. The electron dispersive spectroscopy of the cross sections was conducted using the Scanning Electron Microscope (SEM) - the TESCAN instrument equipped with Vega TC software to run the analysis. The Vickers hardness indentation was conducted using the Zwick / Roell indenter machine with a load of 200 g and dwell time of 15 seconds. The tensile samples were tested on the Instron tensile testing machine.

III. RESULTS AND DISCUSSION

This section presents the results obtained from the analysis of the weld cross sections and the fracture surface characterisations of the tensile samples.

A Tensile data

The tensile data and the fracture location of the tensile samples of the welds are presented in Table I. The parent materials – aluminium and copper had 266 and 244 MPa ultimate tensile strength [16].

TABLE I
TENSILE DATA [15]

Specimen	Rotational speed (rpm)	Feed rate (mm/min)	Average UTS (MPa)	Joint efficiency (%)	Fracture zone
1	600	50	134	55	TMAZ_CU
2	600	150	177	73	TMAZ_CU
3	600	300	192	79	TMAZ_AL

The study shows that the tensile samples fractured mostly in the Thermo-mechanically Affected Zone (TMAZ) of the copper specimens and portions of the welded aluminium material were present during the analysis of the weld.

The fracture of specimens 01 and 02 occurred at the TMAZ of copper on the advancing side of the weld while specimen 03, which was welded with a feed rate of 300 mm/min, fractured at the retreating side of the aluminium. This suggests that high feed rates with a fairly low rotational speed and a small shoulder diameter produce strong welds that do not fail at the stir zone. The mixing of the materials in specimen 03 was successfully accomplished and resulted in a strong weld. This suggests that the weld interface was stronger than the parent material. In comparing the joint efficiencies, the results indicated that specimens 01 and 02 which fractured at the TMAZ of copper had joint efficiencies lower than the acceptable weld efficiency of 75% [16]. Specimen 03 which fractured at the TMAZ of aluminium proved to be ductile with a joint efficiency of 79%.

B. Fracture Surface Characterisations

Energy dispersive spectroscopy analyses was conducted on the fracture surfaces of the tensile samples, the results are hereby presented and discussed in this section.

The SEM photo and the analysis on the weld conducted at 600 rpm and 50 mm/min is presented in Fig. 2(a) and (b).

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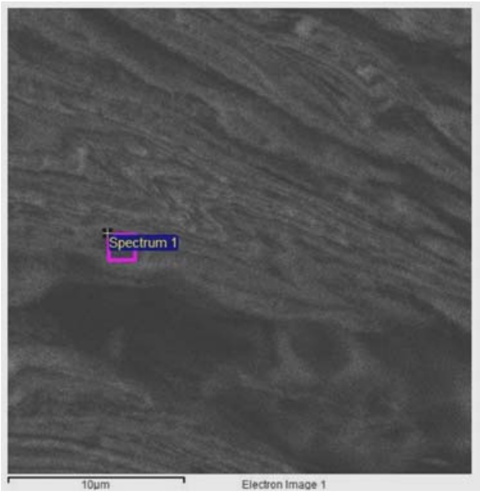

Fig. 2(a). SEM image of weld conducted at 600 rpm and 50 mm/min

The analysis on the point indicated as spectrum 1 in Fig. 2(a) is presented in Fig. 2 (b).

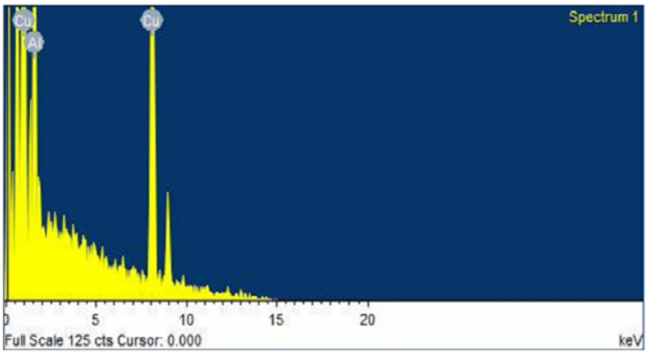

Fig. 2(b). Analysis of spectrum 1 for weld produced at 600 rpm and 50 mm/min

The SEM photo and the analysis on the weld conducted at 600 rpm and 150 mm/min is presented in Fig. 3(a) and (b).

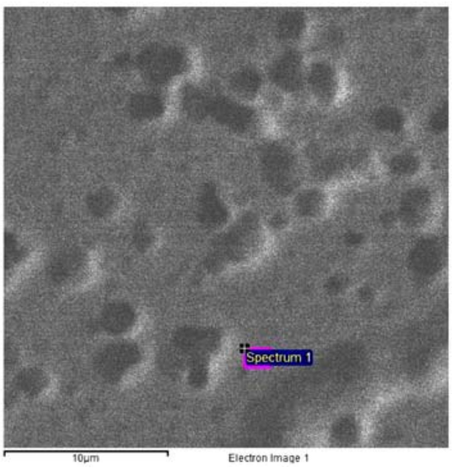

Fig. 3(a). SEM image of weld conducted at 600 rpm and 150 mm/min

The analysis on the point indicated as spectrum 1 in Fig. 3(a) is presented in Fig. 3(b).

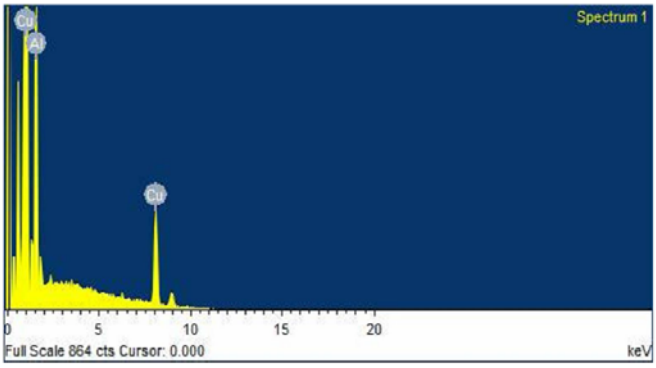

Fig. 3(b). Analysis of spectrum 1 for weld produced at 600 rpm and 150 mm/min

The SEM photo and the analysis on the weld conducted at 600 rpm and 300 mm/min is presented in Fig. 4(a) and (b).

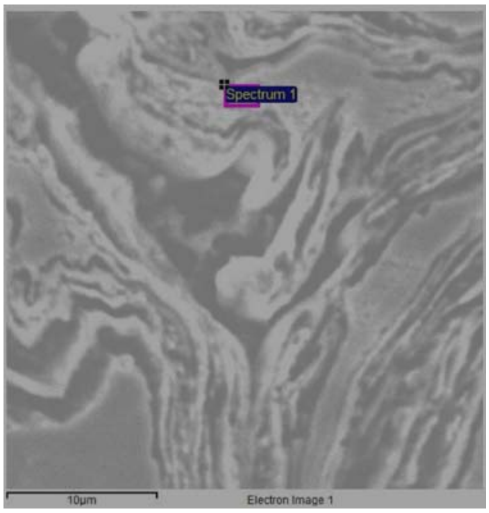

Fig. 4(a). SEM image of weld conducted at 600 rpm and 300 mm/min

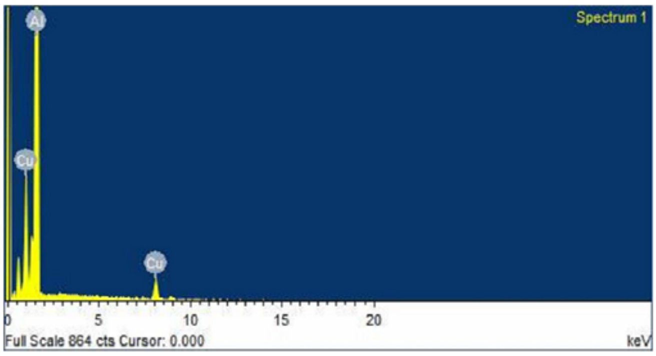

Fig. 4(b). Analysis of spectrum 1 for weld produced at 600 rpm and 300 mm/min

The evolving microstructures (Fig. 2(a), 3(a) and 4(a)) are characterised with mixture layers of both materials- aluminium and copper joined indicating soundness and good joint integrities in the welds.

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The results of the analyses viz; the percentage weight composition of aluminium and copper at the interfacial fracture regions are presented in Table II.

TABLE II
TENSILE DATA

Element	Percentage Weight (%) Sample 1	Percentage Weight (%) Sample 2	Percentage Weight (%) Sample 3
Al	24	30	45
Cu	76	70	55
Intermetallic	AlCu	AlCu	Al_2Cu

The percentage weight composition of the aluminium and copper present in the samples were correlated to the Aluminium-Copper (Al-Cu) Binary phase diagram [17] and the corresponding intermetallics are as presented in Table II. It was found that AlCu intermetallics were present in samples 1 and 2 produced at 50 and 150 mm/min which were produced at higher heat inputs, this is expected as these intermetallics are formed at about 590^o compared to sample 3 which has Al_2Cu intermetallic present, this intermetallic is usually formed at a lower temperature of about 550_o. Sample 3 was produced at 300 mm/min which was produced at a lower heat input due to the fast movement of the tool during the welding process. However, the thicknesses of the intermetallics were very thin.

IV. CONCLUSIONS

The fracture surfaces of friction stir welds of aluminium and copper have been successfully characterised and presented. It was found that the interfacial regions were characterised with mixed layers of both materials joined. The energy dispersive spectroscopy revealed the presence of thin layers of intermetallic compounds and the weld produced at highest feed rate of 300 mm/min can be considered optimum in this regard as it obtained the highest UTS. As such, from this study; it can be concluded that good joints can be achieved at a high feed rate when a small shoulder diameter of 15 mm as considered in this research work is employed and can be recommended.

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