Effect of process parameters on tensile strength and morphology of friction stir spot welds of aluminium and copper

[a*]Mukuna Patrick Mubiayi., [a]Esther titilayo Akinlabi and [b]Mamookho Elizabeth Makhatha
[a]Department of Mechanical Engineering Science,
[b]Department of metallurgy
University of Johannesburg
Johannesburg, South Africa
patrickmubiayi@gmail.com

***Abstract*— Friction stir spot welding (FSSW) is a solid-state welding process used for joining similar and dissimilar materials. AA1060 and C11000 sheets were joined using different process parameters and tool geometries. The presence of a copper rings also called hooks were observed in all the produced spot welds and their length increases with the tool shoulder plunge depth; whereas the spot welds produced at 1200 rpm for the two tool geometries exhibited a decrease and a slight increment in the length of the copper ring using a flat pin/flat shoulder and conical pin/ concave shoulder, respectively. Furthermore, the mapping of the produced spot weld using energy dispersive spectroscopy (EDS) exhibited different microstructures with the presence of copper fragments and particles in the aluminium matrix. It was also observed that, the shoulder plunge depth had an effect on the shear tensile results, except for the weld produced at 800 rpm when using a conical pin and a concave shoulder.**

Keywords- Aluminium, Copper, Copper ring, FSSW, Shear tensile test

I. INTRODUCTION

Recently many researchers have shown interest in joining dissimilar materials include aluminium and copper since the produced Al/Cu components are utilised in heat exchanger, power plants, radiators and electrical power transmission (i.e : busbars). Nevertheless, joining of dissimilar materials is a challenging task due to their differences in their mechanical, thermal and electrical properties. Friction stir spot welding (FSSW) is a variant of friction stir welding (FSW) process for spot joining. Friction stir welding (FSW) was experimentally proven and patented by The Welding Institute (TWI) in 1991 [1]. FSW has been employed by researchers to successfully join Al to Cu [2-11], whereas few efforts have been made to produce friction stir spot welds between aluminium and copper [12-16]. Ozdemir et al. [14], Heideman et al [15]and Shiraly et al. [16] have both successfully friction stir spot welded a 3 mm thick AA1050 to pure copper, 1.5 mm thick AA6061 – T6 to oxygen free pure copper and AA1050 foil, 500µm thick to pure copper, 100 µm to produce a 2.3 mm thick multilayer sample, respectively. Recently Mubiayi and Akinlabi [12, 13] friction stir spot welded 3 mm thick AA1060 to commercially pure copper sheets.

According to Ozdemir et al. [14], the tensile shear test results showed that 2.8 mm plunge depth produced poor results; whereas a 4mm plunge depth showed the highest values of shear tensile test compared to the 5mm. This was suspected to be due to the penetration of Cu into Al in a more diffused way [14].

On the other hand, Heideman et al. [15] conducted a metallurgical analysis of AA 6061-T6 to oxygen-free Cu using the friction stir spot welding process. The tool used was a threaded pin design using a pre-hardened H13 tool steel with a shoulder of 10 mm, pin diameter of 4 mm and a thread pitch of 0.7mm. Two different plunge depths were used: 0.0 and 0.13 mm; and two different weld times of 3 and 6 seconds were utilised [15]. Rotational speeds varying from 1000 to 2000 rpm were used. Additionally, they indicated that, the rotation speed, the plunge depth and the tool length were the primary factors affecting the welds strength.

Shiraly et al. [16] used FSSW process to join Al/Cu composite produced by accumulative roll-bonding process, using a triangular pin with no features. They found that the weld made at a lower tool rotation speed was not bonded; this was due to no intermixing between the upper and lower sheets. Moreover, the maximum shear failure load increased with the increasing tool rotation rate, which can be attributed to the increasing area and effective length of the stir zone (SZ).

The present study aimed to investigate the effect of process parameters on the shear tensile and the morphology of the produced friction stir spot weld using AA1060 and C11000 as parent materials.

II. EXPERIMENTAL PROCEDURE

Aluminium 1060 Alloy and copper C11000 sheets (600 x 120 x 3 mm^3) were used in this investigation. A lap joint weld configuration was used and the sheets were friction stir spot welded in a 30 mm overlap configuration. The chemical composition of the two base materials was determined using a Q4 TASMAN spectrometer. The 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.

Two different tool geometry were used to produce the spot welds namely a flat pin / flat shoulder and a conical pin / concave shoulder coded as FPS and CCS respectively. The tools were machined to fit the FSW machine (MTS PDS I-Stir) at the Nelson Mandela Metropolitan University (NMMU), as shown in Fig. 1 (a). The tool material is H13 tool steel hardened to 50-52 HRC. The tool pin length and the diameter were kept constant at 4 mm and 5mm respectively whereas the tool shoulder diameter was 15 mm.

The spot welds were named as X1_X2_X3, the first part (X1) depicts the tool geometry, the second part (X2) the rotational speed and the third part (X3) the shoulder plunge depth. Two rotational speeds namely 800 and 1200 rpm were used. Moreover, the tool shoulder plunge depths employed were 0.5 and 1 mm using a constant dwell time of 10 seconds.

A wire electrical discharge machining (WEDM) was used to cut the produced spot weld samples. Moreover, the samples were grinded and polished, mounted and prepared, using ASTM Standard E3-11 [17]. 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; whereas the aluminium side was etched with H_2O (190 ml) + HNO_3 (5 ml) + HCl (10 ml) + HF (2 ml). The morphology and mapping of the produced spot welds were done using scanning electron microscopy combined with energy dispersive spectroscopy (SEM/EDS) respectively. A TESCAN equipped with an Oxford instrument was used to analyse the samples.

Lap shear tensile tests were conducted in order to determine the shear tension strength of the spot welds. The shear tensile specimens used in the current research can be seen in Fig. 1 (b). The lap shear testing was performed, using a Model 1195, 5500R Instron screw-driven tensile machine with 100 kN load cell and with a crosshead speed of 3 mm /min.

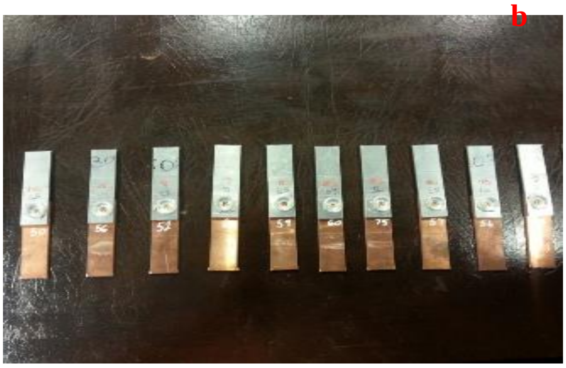


Figure 1. Depicts the I-STIR friction-stir welding machine (a) and geometry of the lap shear tensile sample (b).

III. RESULTS AND DISCUSSION

It was observed in Fig. 2 (a and b) , that the shapes of the pin and the shoulder in the cross sections of the produced spot welds, namely flat pin/flat shoulder and conical pin/concave shoulder could be clearly seen.

Furthermore, the colour contrast between the two sheets welded, namely: aluminium and copper could be seen; and the copper sheet has a lighter colour than the aluminium. The presence of a keyhole was also observed; and on both sides of the welds, there was a presence of copper rings [15] also known as hooks, which are a deformed part of the copper material (lower sheet) penetrating into the aluminium (top sheet). Fig.2 shows the copper rings and the corresponding lengths of FPS_1200_1 and CCS_1200_1, which were measured using the scanning electron microscope measuring tool. Furthermore, Fig.3 present the variation of copper ring length of the friction stir spot welds produced using different process parameters and tool geometries.

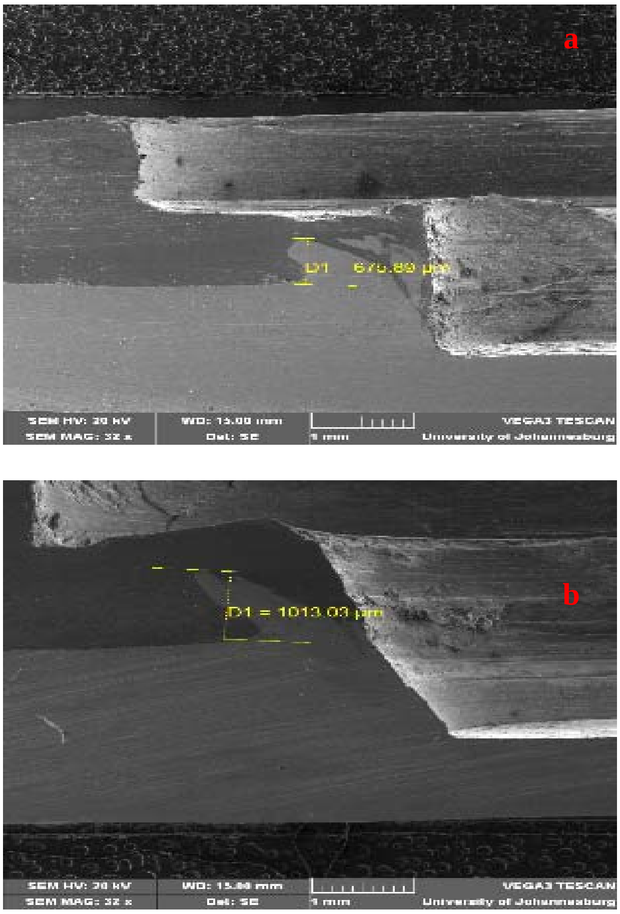


Figure 2. Depicts the copper ring length of the spot weld produced using 1200 rpm rotational speed and 1 mm shoulder plunge depth (a) flat pin/flat shoulder tool and (b) conical pin/concave shoulder tool.

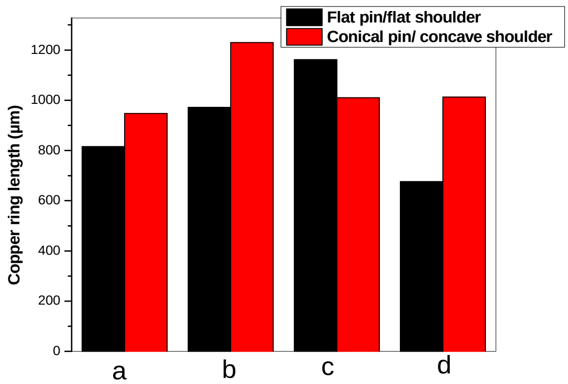


Figure 3. The copper ring lengths obtained using a flat pin and concave shoulder tool at different process parameters, 800 rpm, 0.5 mm (a), 800 rpm, 1mm (b), 1200 rpm, 0.5 mm(c), 1200 rpm, 1 mm (d).

The formation of the copper rings, which consists of the copper parent material extruded in the aluminium plate, was observed in all the produced spot welds. This suggests that while the copper material was moving and diffusing into the aluminium, the aluminium was not diffusing or being pushed into the copper ring [15]. There was also a reduction in the thicknesses of the workpieces in all the produced spot welds. It was seen that the copper ring length increases with the increase of the shoulder plunge depth, expect for the spot welds produced at 1200 rpm, using a flat pin and shoulder, where a decrease was seen. The copper ring lengths of the welds produced at 1200 rpm using a conical pin and concave shoulder also display a slight difference in the copper ring length. This demonstrates that the welds produced at high rotational speed display either a decrease or a slight increase.

The EDS mapping of the spot weld produced using conical pin/concave shoulder tool at 800 rpm and 0.5 mm shoulder plunge depth is depicted in Fig.4.

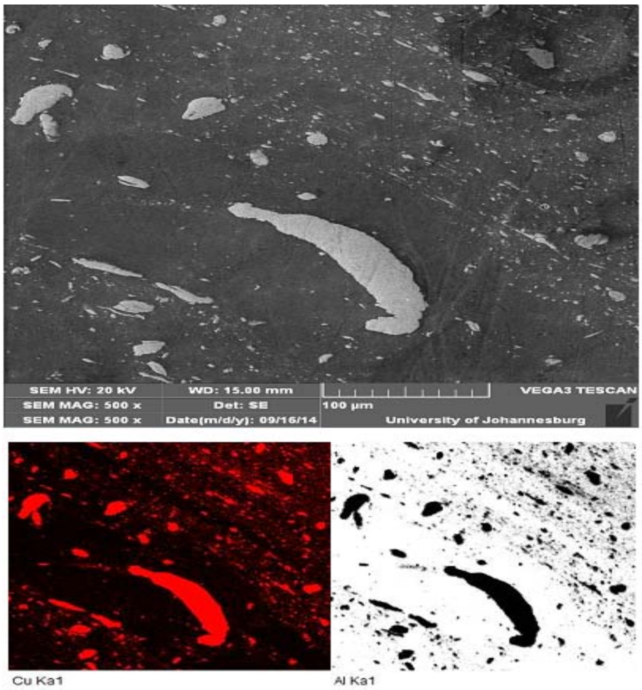


Figure 4. Mapping of the stir zone (SZ) for the spot weld produced using a conical pin and a concave shoulder tool at 800 rpm and 0.5 mm shoulder plunge depth, copper (red), aluminium (black).

It can be observed that the element distribution shows a mixing of copper and aluminium, which was expected; since the stir zone is in the vicinity of the keyhole, where the material is expected to move around the tool pin to produce good mixing of the materials. A large number of copper particles can be seen in the aluminium matrix compared with the number of copper particles found in the aluminium matrix. The presence of the copper particles and fragments mixed in the aluminium matrix, and the aluminium particles mixed in the copper matrix could possibly favour the formation of hard and brittle intermetallic compounds.

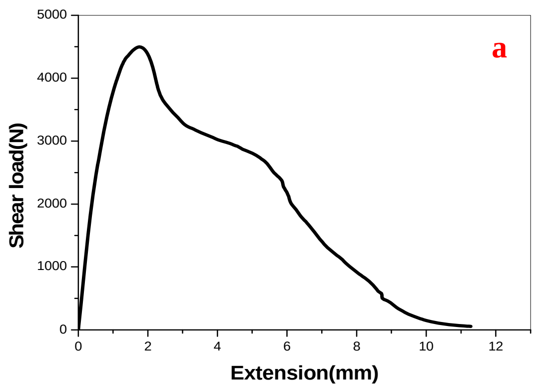
It was further observed in Fig.4, the presence of large copper particles surrounded by small copper particles in the aluminium matrix, that the large copper particle has a curved like microstructure.

On the other hand, the mapping of the weld produced using 1200 rpm and 1 mm shoulder plunge depth showed fewer copper particles in the aluminium matrix. Whereas, the mapping of the spot weld produced using 800 rpm, 1 mm shoulder plunge depth shows the presence of a number of larger particles of copper mixed with small copper particles in the aluminium matrix.

Furthermore, the mapping of the welds produced at 1200 rpm and 0.5 mm shoulder plunge depth, where the presence of more uniform copper particles of more or less same size in the aluminium matrix and a mixture structure could also be seen.

It has been reported in the literature that, the copper ring caused interlocking between the two plates and help the plates stick to each other through the tensile test and this will result in reaching a high strength before failure [15].

Fig.5 depicts the shear tensile behaviour of the spot welds produced at 800 rpm and 1 mm shoulder plunge depth using a flat pin/ flat shoulder tool (a) and conical pin/concave shoulder tool (b). Additionally Fig.6 shows the effect of process parameters on the maximum shear failure loads of the produced spot welds.



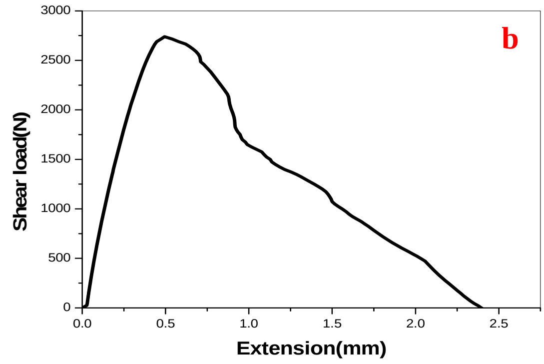


Figure 5. Shear tensile behaviour of weld produced at 800 rpm and 1mm shoulder plunge depth using a flat pin/flat shoulder (a) and conical pin/concave shoulder (b).

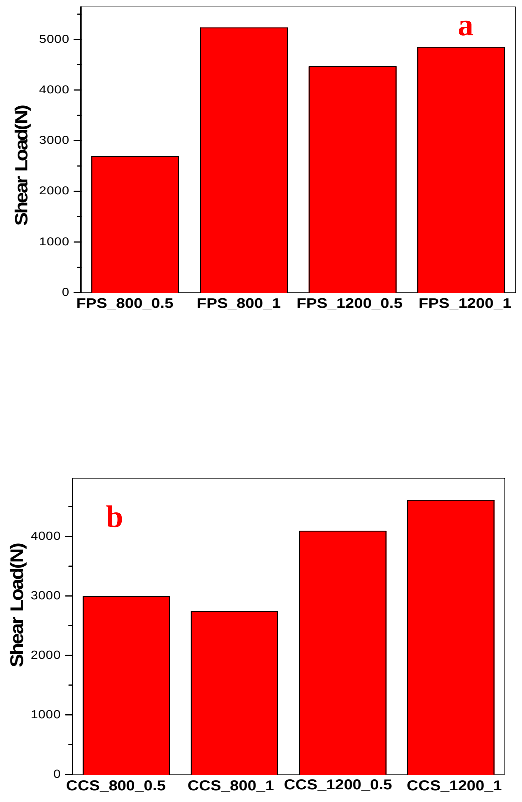
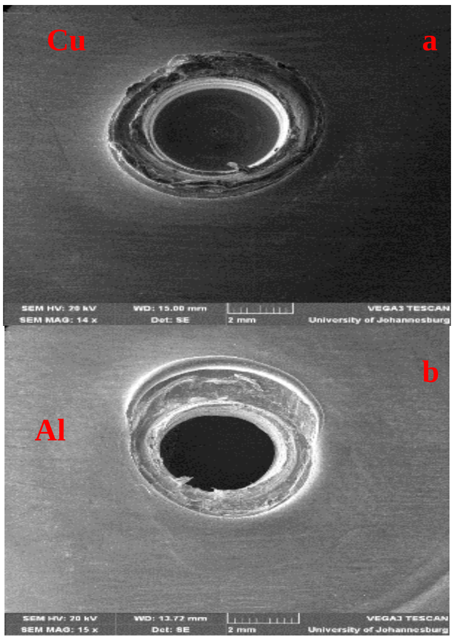


Figure 6. Showing the effect of process parameters on the maximum failure load of the welds produced using a flat pin/flat shoulder tool (a) and a conical pin and a concave shoulder tool (b).

The effect of the process parameters on the maximum failure load shown in Fig.6 for the welds produced when using a flat pin/ flat shoulder and conical pin and concave shoulder. It was observed that as the shoulder plunge depth increases, the failure load increases, except for the weld produced at 800 rpm when using a conical pin and a concave shoulder. High failure loads of 5225 N and 4844 N were achieved using a flat pin/flat shoulder produced at 800 rpm, 1 mm shoulder plunge depth and 1200 rpm, and 1 mm shoulder plunge depth, respectively. It was observed that by increasing the shoulder plunge depth, high strength welds were obtained. Additionally, the two highest failure loads obtained using a conical pin/concave shoulder were 2991 N and 4606 N, respectively; where the parameters used were 800 rpm, 0.5 mm pin plunge depth and 1200 rpm, and 1 mm shoulder plunge depth, respectively.

It was observed that all the fractures were ductile and this was assumed to influence the fracture mode. Only one fracture mode was observed in all the analysed samples which was a pull nugget failure mode. An example is shown in Fig.7 (a and b) for fracture mode (a and b) and a fractured surface (c and d) for the spot weld produced at 1200 rpm, 0.5 mm shoulder plunge depth using a flat pin/flat shoulder tool. And this was due to the difference in properties of the parent materials. The fracture surface of the spot welds revealed a ductile morphology (Fig.7 (c and d). The dimples were in different sizes, which can be attributed to the different process parameters and the tool geometries used. The presence of a cavity defect in some of the fractured samples was observed; this could be the cause of the low shear tensile load results obtained for some spot welds. This was in agreement with the results obtained by Tan *et al.* [18].



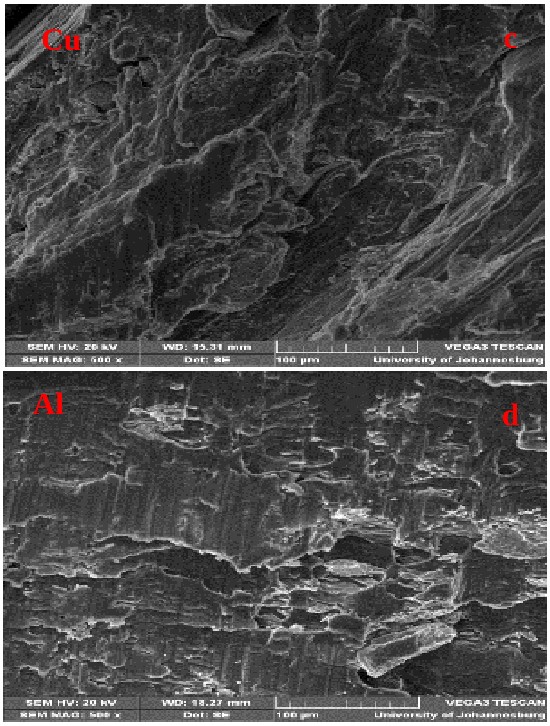


Figure 7. SEM images of spot weld produced using a flat pin and a flat shoulder tool; the rotation speed was 1200 rpm and the shoulder plunge depth of 0.5mm, (a) failed nugget upper sheet (Cu), (b) the lower sheet (Al), (c) and (d) fractured surface on the copper and aluminium side, respectively.

IV. CONCLUSIONS

The present research study has shown that pure AA 1060 and commercially pure copper C11000 can be successfully joined with friction stir spot welding technique.

A copper ring (hook) was present in all the spot welds; and it was found that the length increases with the shoulder plunge depth; while the spot welds produced at 1200 rpm for the two tool geometries exhibited a decrease and a slight increase in the length of the copper ring obtained using a flat pin/flat shoulder and conical pin/ concave shoulder, respectively. The mapping of the spot weld showed different microstructures with copper particles and fragments in the aluminium matrix. A good material mixing was achieved in most of the spot welds produced. Furthermore, the mapping of the stir zone of the welds showed the different distribution of the copper particles in the aluminium matrix. As the shoulder plunge depth increases, the failure load increases, except for the weld produced at 800 rpm when using a conical pin and a concave shoulder.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support of the University of Johannesburg and the assistance from Mr Riaan Brown (eNtsa at Nelson Mandela Metropolitan University).

REFERENCES

[1] W. M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith and C.J. Dawes,. 1991, International Patent No. PCT/GB92/02203, GB patent application No. 9125978.8.

[2] J. Ouyang, E. Yarrapareddy, R. Kovacevic, "Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper" Journal of Materials Processing Technology, 2006, 172, pp 110–122.

[3] A. Abdollah-Zadeh, T. Saeid, B. Sazgari , "Microstructural and mechanical properties of friction stir welded aluminum/copper lap joints" Journal of Alloys and Compounds, 2008, 460, pp. 535–538.

[4] I. Galvao, R. M. Leal, A. Loureiro and D. M. Rodrigues, "Material flow in heterogeneous friction stir welding of aluminium and copper thin sheets" Science and Technology of Welding and Joining, 2010, 15, No 8, pp. 654- 660.

[5] I. Galvao , J.C. Oliveira , A. Loureiro and D.M. Rodrigues, "Formation and distribution of brittle structures in friction stir welding of aluminium and copper: influence of process parameters" Science and Technology of Welding and Joining, (2011), 16, No 8, pp. 681- 689.

[6] LI Xia-wei, ZHANG Da-tong, QIU Cheng, ZHANG Wen "Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding" Trans. Nonferrous Met. Soc. China 22, 2012, pp. 1298-1306.

[7] E.T. Akinlabi, S.A. Akinlabi, "Effect of Heat Input on the Properties of Dissimilar Friction Stir Welds of Aluminium and Copper" American Journal of Materials Science, (2012), 2(5), pp. 147-152.

[8] A.S. Pratik, P. Nageswaran , N. Arivazhagan , K. Devendranath Ramkumar, "Development of Friction Stir Welded Butt Joints of AA 6063 Aluminium Alloy and Pure Copper" International Conference on Advanced Research in Mechanical Engineering, (2012), (ICARM), pp. 46-50.

[9] M.N. Avettand-Fenoel, R. Taillard, G. Ji and D. Goran, "Multiscale Study of Interfacial Intermetallic Compounds in a Dissimilar Al 6082-T6/Cu Friction-Stir Weld", 2012, Metallurgical and Materials Transactions A, pp 4655-4666.

[10] A.O. Al-Roubaiy, S.M. Nabat, A.D.L. Batako, "Experimental and theoretical analysis of friction stir welding of Al–Cu joints" Int J Adv Manuf Technol (2014) 71, pp 1631-1642.

[11] M.F.X. Muthu, V. Jayabalan, "Tool Travel Speed Effects on The Microstructure of Friction Stir Welded Aluminium - Copper Joints", Journal of Materials Processing Technology 217 (2015), pp 105-113.

[12] M.P. Mubiayi and E.T. Akinlabi," Evolving properties of friction stir spot welds between AA1060 and commercially pure copper C11000" Transactions of Nonferrous Metals Society of China, 26(2016) , pp.1852−1862.

[13] M.P. Mubiayi, E.T Akinlabi "Friction Stir Spot Welding between Copper and Aluminium: microstructural Evolution". Proceedings of the International Multi Conference of Engineers and Computer Scientists 2015 Vol II, IMECS 2015, March 18 - 20, 2015, Hong Kong (ISBN: 978-988-19253-9-8, ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)).

[14] U. Özdemir, S. Sayer, Ç. Yeni, Bornova-Izmir, 'Effect of Pin Penetration Depth on the Mechanical Properties of Friction Stir Spot Welded Aluminum and Copper' Materials Testing IN Joining Technology, 54(2012) 4, pp. 233-239.

[15] R. Heideman, C. Johnson, S. Kou, 'Metallurgical analysis of Al/Cu friction stir spot welding' Science and Technology of Welding and Joining Vol. 15 , No 7 (2010), pp. 597-604.

[16] M. Shiraly, M. Shamanian, M.R. Toroghinejad, and M. Ahmadi Jazani 'Effect of Tool Rotation Rate on Microstructure and Mechanical Behavior of Friction Stir Spot-Welded Al/Cu Composite' Journal of Materials Engineering and Performance, Volume 23(2) February 2014, pp 413-420.

[17] ASTM Standard E3-11, 2011 "Standard guide for preparation of metallographic specimens", ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/E0003-11, www.astm.org.

[18] C.W. Tan, Z.G. Jiang , L.Q. Li, Y.B. Chen, X.Y. Chen, "Microstructural evolution and mechanical properties of dissimilar Al–Cu joints produced by friction stir welding" Materials & Design , Vol. 51, (October 2013), pp. 466-473.

AUTHORS' BACKGROUND

Your Name	Title*	Research Field	Personal website
M.P Mubiayi	Doctor	Materials characterisation, Friction Stir Spot Welding (FSSW), Friction Stir Welding (FSW)	
E.T Akinlabi	Professor	Friction Stir welding, Laser Additive Manufacturing, Functionally graded material, Material Characterisation , Mechanical testing	
M.E Makhatha	Doctor	Polymer chemistry, Materials Chemistry, Coal Analysis, Extractive metallurgy, Analytical chemistry	