https://doi.org/10.56452/2022-12-021

ISSN: 0974-5823 Vol. 7 No. 07 December, 2022

International Journal of Mechanical Engineering

Horizontal Axis friction stir welding process for joining Al6063 and pure Copper

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Submitted: 18th December 2022, Accepted: 27th December 2022, Published: 25th February 2023

Abstract

In this research paper, the feasibility of using nonpolluting horizontal axis friction stir welding (HAFSW) to join Al6063 with copper plates to create lightweight and cost-effective electrical and structural components was investigated. The tool's rotation rate and traverse speed were kept constant at 1200 rpm and 20 mm/min, respectively. Two specimens were prepared, one with the tool pin centered on the abutting plates and another with a 10% offset towards the Al6063 side. The results were analyzed and compared for mechanical behavior viz tensile strength, toughness and percentage elongation. Fractographs of the fractured specimen were analyzed under scanning electron microscope (SEM) to draw important conclusions. It was found that a stronger and more reliable weld was produced when the tool was offset towards the Al6063 side.

Index terms: Horizontal axis FSW (HAFSW), Tensile strength, Toughness, SEM, Electronic dispersion analysis.

INTRODUCTION

In 1991, The Welding Institute (TWI) of the United Kingdom developed the friction stir welding (FSW) method as a solid-state joining technique [1-7]. Aluminum and copper possess adequate mechanical, thermal, and electrical properties that make them appropriate for use in structural applications [8,9]. These materials are also eco-friendly and recyclable [10]. To produce lightweight and cost-effective electrical and structural components without compromising their essential properties, copper must be combined with other lightweight materials like aluminum [11]. Nevertheless, when these dissimilar materials are fused together, various defects and hard intermetallic compounds (IMCs) can form, leading to poor weld quality [12]. As a solution, several solid-state joining processes like explosive welding, friction welding, and roll welding have been utilized effectively to join dissimilar materials [13]. Friction stir welding (FSW), on the other hand, eliminates joint defects such as porosities, alloy segregations, and grain boundary cracks, making it an ideal technique for joining dissimilar alloys [14,15]. The process employs a revolving, non-consumable tool with a specially constructed pin/probe and shoulder.

The literature has reported that the presence of hard and brittle intermetallic compounds (IMCs) in the thermo-mechanically affected zone (TMAZ) is a common cause of joint failures in FSW of Al-Cu, with such joints often failing through the nugget or TMAZ. [16,17] Various FSW parameters, including tool geometry and design, tool tilt angle, base plate position, rotational speed, welding speed, plunge force, etc., have been identified as influential factors in the quality of FSW joints. [18,19] However, the research on the effect of FSW tool geometry and design for joining Al to Cu is limited. Similarly, while there is literature available on the effect of different pin profiles on material movement and joint quality during FSW of some ferrous and non-ferrous materials, there is a lack of similar studies for FSW of dissimilar nonferrous materials. [20,21] The FSW process for joining Al to Cu is still evolving, as Al and Cu have good thermal conductivities but their joining is difficult due to significant differences in their strength, softening temperatures, and flow characteristics.

MATERIALS AND METHODS

This paper introduces a new method for friction stir welding (FSW) of Al 6063 with pure copper using a lathe machine, which is a cost-effective alternative to using a dedicated FSW machine. 5.5 mm thickness plates of Al6063 and pure copper were used in butt configuration to perform HAFSW operation. A cylindrical threaded pin (CTP), H-13 hot-work tool steel was used with shoulder to pin diameter ratio (D/d) of 3.2 :1. The results are evaluated based on joint quality, tensile strength, percentage elongation, and toughness, demonstrating the feasibility of this approach. Abstraction of experimental methods is shown in figure 1. Composition of base metal plates are given in table 1. Process parameters of the HAFSW process is given in table 2.

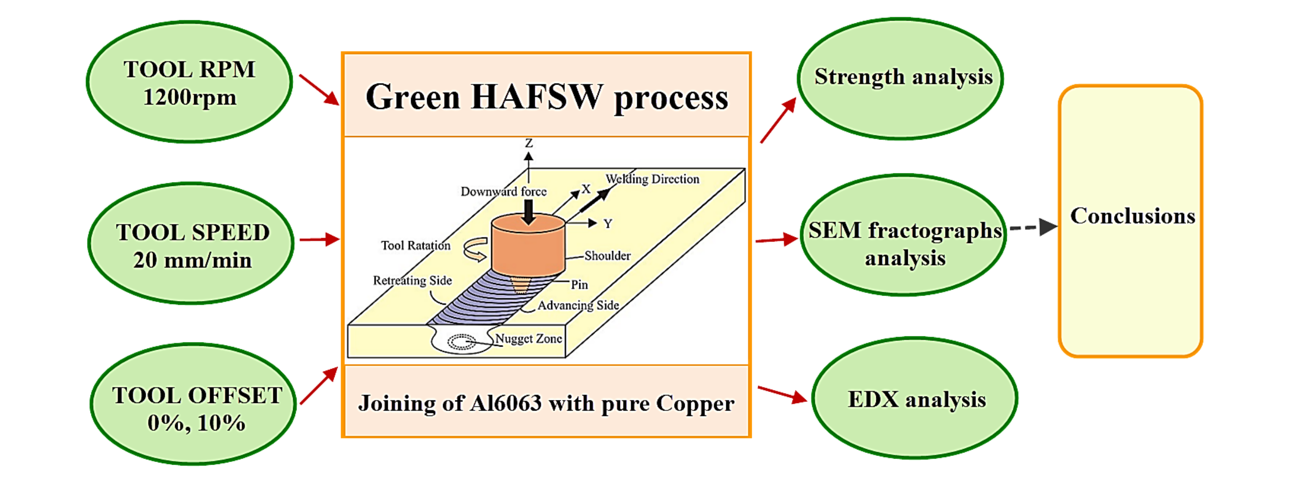

Figure 1. Experimental methods

Table 1: Composition of base metal plates, tool and mechanical properties of base material

Composition of Al6063 (wt %)									
Mn	**Fe**	**Mg**	**Si**	**Cu**	**Zn**	**Ti**	**Cr**	**others**	**Al**
0.15	0.50	0.8	0.4	0.2	0.3	0.15	0.04	0.15	Rest
Composition of pure copper (wt %)									
Sn	**Fe**	**P**	**Ni**	**Co**	**Ag**	**Zn**	**Pb**	**Others**	**Cu**
0.04	0.001	0.043	0.24	0.001	0.018	0.012	0.003	<001	99.65
Composition of H-13 hot worked steel (wt %)									
C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**V**	**Cu**	**P**	**S**
0.32-0.45	0.20-0.50	4.75-5.50	0.3	1.10-1.75	0.80-1.20	0.25	0.03	0.03	Rest

Mechanical properties of base material plates			
	Tensile strength	**% Elongation**	**Brinell Hardness**
Al6063	230 MPa	23%	71
Pure copper	252 MPa	28%	90

Table 2: Process parameters and their values

Process parameters	values
Tool pin type	Cylindrical threaded pin
Tool rotational speed	1200 rpm
Traverse speed of the plates	20 mm/min
Tool pin offset	0, 10%
Tool shoulder diameter	16 mm
Tool pin diameter	05 mm
Tool pin length	4.0 mm

A patented, easily-attachable portable fixture designed for friction stir welding (FSW) on a lathe machine. The fixture secured a copper plate on the bottom and an Al6063 plate on top. The arrangement of the fixture and tool is depicted in figure 2 (a), CTP tool is shown in figure 2 (b) and welded plates are shown in figure 3.

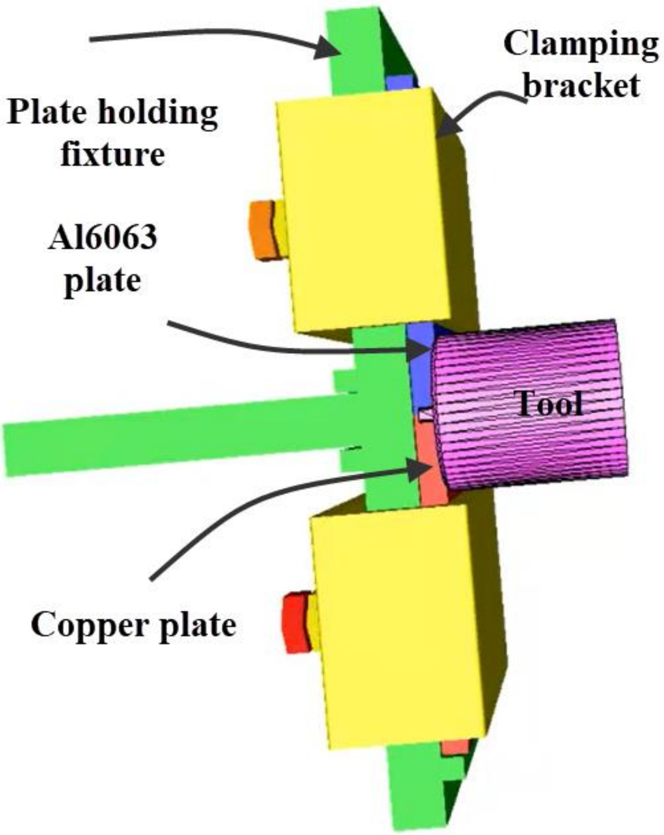

Figure 2 (a). Arrangement of Fixture and tool

Figure 2(b). Cylindrical threaded pin tool

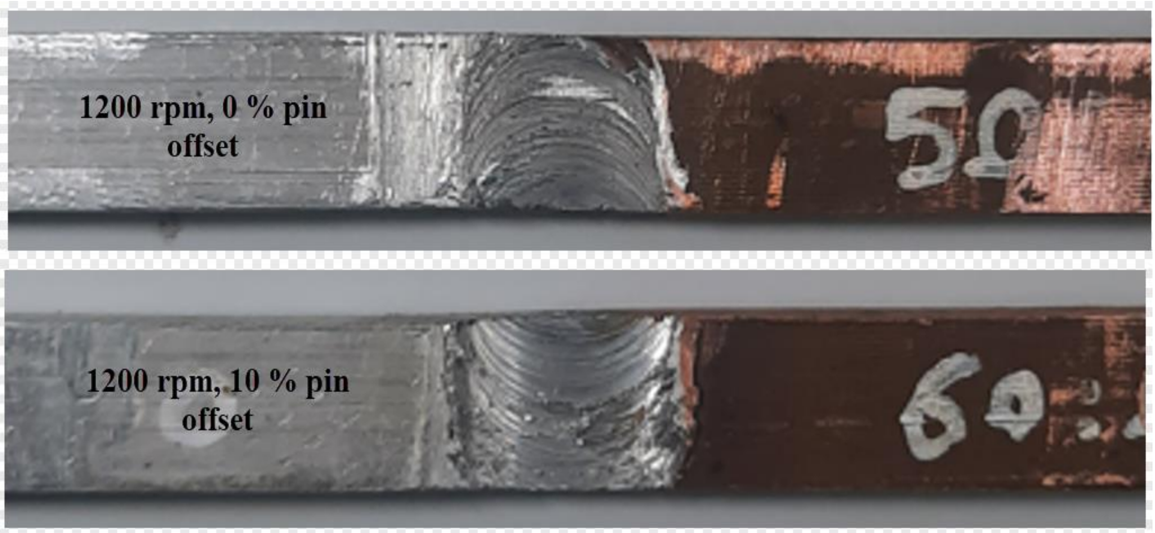

Figure 3. Straight threaded pin (STP) tool

RESULTS AND DISCUSSIONS

Specimen number 01was welded at 1200 rpm with zero pin offset and specimen 02 was welded at 1200 rpm and 10 % of tool pin offset the offset of the tool pin was considered on Al6063 side have the larger volume of material of Al6063 in contact with the rotating pin and hence reducing the temperature per unit volume on Al6063 side. The results of these welds and necessary discussion are presented below:

(a) Inspection on transverse surface of the weld

On visual inspection, it was found that the top plane of the welded surfaces showed no visible differences, regardless of the RPM and tool offset values used. However, defects were observed on the transverse plane in specimen 01, which had zero tool offset. This specimen exhibited tunnel and unfilled material defects in the nugget zone. Conversely, specimen 2, which was welded at 1200 RPM with a 10% tool offset, showed no defects. The weld line on this specimen displayed properly filled material. Figure 4 shows the transverse plane of the welded plates.

(a) Specimen 1 (b) Specimen 2

Figure 04. Visual inspection of transvrse surface of HAFSW specimen

(b) Tensile test

In the course of the investigation, a Hounsfield tensiometer was employed to conduct a tensile test. This mechanical apparatus was capable of measuring load versus deformation for the test specimen, with a capacity of 2000 kg-f and a least count of 10 kg-f. Load and deformation data were documented on graph paper wrapped around a drum. To determine the tensile strength of the specimen in MPa, the maximum load at failure was divided by its cross-sectional area. Strain was obtained by dividing elongation by the distance between the grips. The area beneath the load deformation curve was measured using a special apparatus called planimeter to compute toughness. Figure 5 shows the arrangement of tensiometer for performing the tensile test. Table 03 shows the test results in terms of tensile strength, percentage elongation and toughness.

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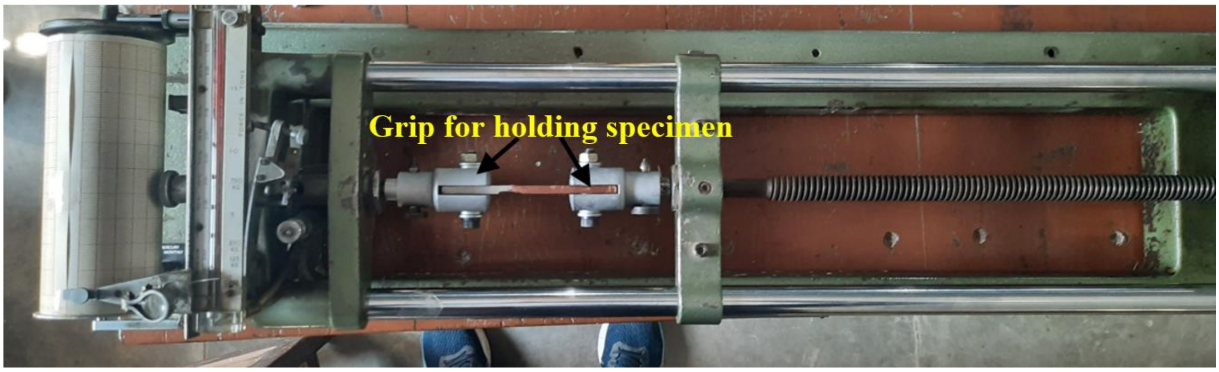


Figure 5. Hounsfield Tensiometer setup for performing tensile test

It can be seen from table 03 and figure 6, that specimen 01 which showed larger defects on its transverse face viz tunnel and unfilled material gives very poor strength under tensile test. The tensile strength of specimen 01 was observed to be 43.9 MPa which is only 19 % of Al6063 strength and 17.5% of pure copper strength. On the other hand, specimen 02 prepared by 10% offset on the weld line showed no defects along its transverse face through visual inspection performs very well under tensile test. The strength of the specimen was found to be 211.9 MPa which was 92% of Al6063 and 85% of virgin pure copper specimen. A Percentage elongation of 12% was observed for specimen 02 against the elongation of only 2.7% for specimen 01. The toughness results of specimen 02 were 12 time more than specimen 01.

Table 03: Tensile test results of Al6063-Cu specimen

Specimen	Rpm	offset	Max load (Kg-f)	Area (mm^2)	Tensile strength MPa (Kg-f* 9.81/area)	% Elongation	Toughness (N-m)
01	1200	Zero	280	62.75	43.9	2.7	10
02	1200	10%	1350	62.5	211.9	12	121

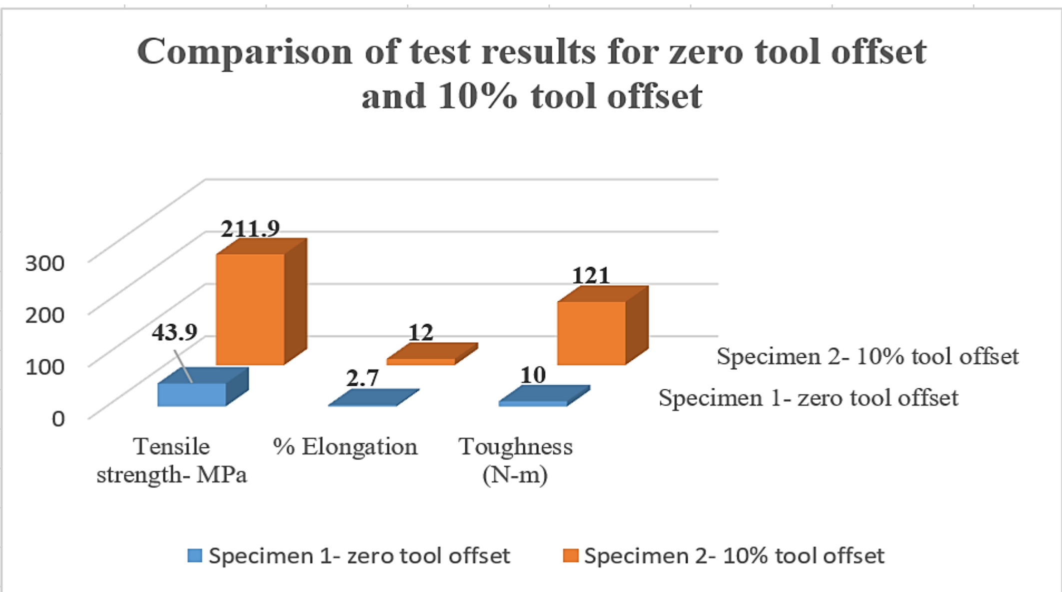
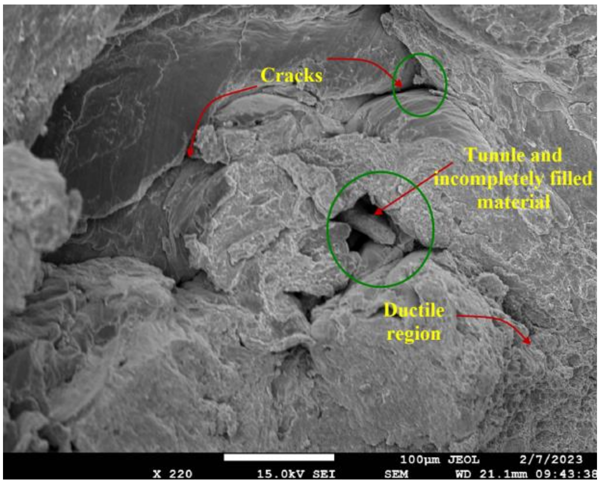


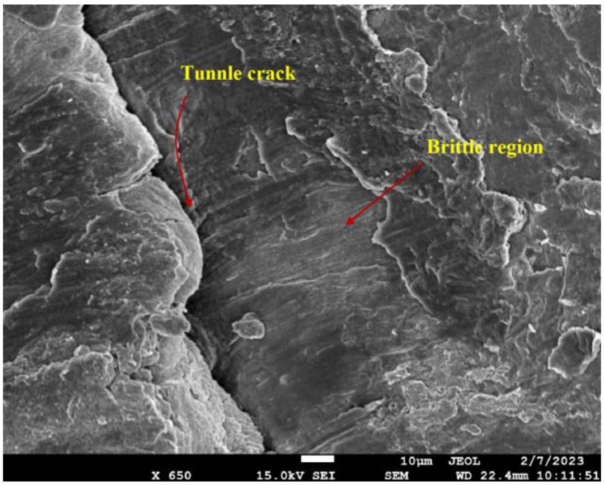
Figure 6. Comparison of test results for specimen 1 (zero tool offset) and specimen 2 (10% tool offset)

(c) Scanning Electron Microscopy (SEM) of fractured specimen

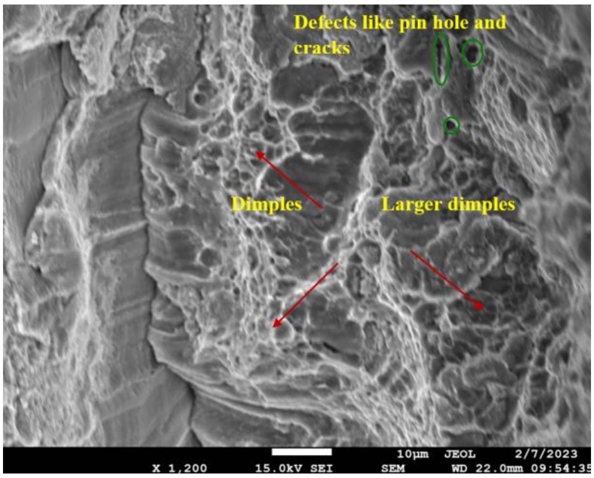
A fractographic analysis was performed using SEM on both specimens that had different tool offsets. Figure 07 displays the fractographs of specimen 01 and 02 on both the Al6063 and copper sides. Specimen 01, processed at 1200 rpm with 0% pin offset, exhibited brittle failure on both the aluminium and copper sides. The Al6063 side revealed large cavities and unfilled tunnel regions, while the copper side displayed a continuous crack along the length of the weld on the fractured surface. The copper side also exhibited a brittle region with no discernible dimples. On the other hand, specimen 02 with a 10% pin offset showed ductile fracture on both the Al6063 and copper sides, as evidenced by the uniformly distributed dimples. This indicated proper intermixing of Al6063 and Cu, resulting in high tensile strength and deformation at fracture. Minimal defects, such as pinholes and minor cracks, were observed on the Al6063 side of specimen 02.



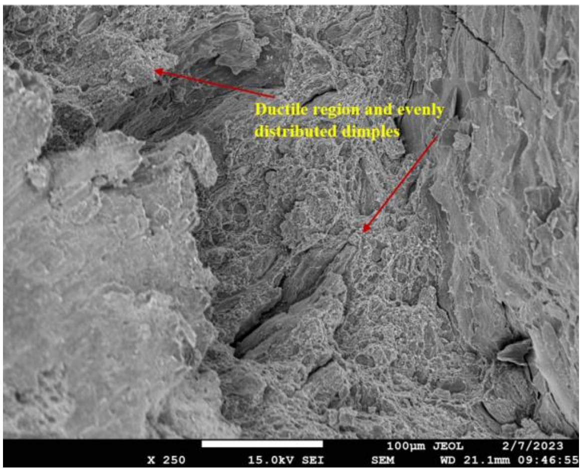
Specimen 01- Al6063 side (1200 rpm and 0% pin offset) at 220 x magnification



Specimen 01- Copper side (1200 rpm and 0% pin offset) at 650 x magnification



Specimen 02- Al6063 side (800 rpm and 10% pin offset) at 1200 x magnification



Specimen 02- Copper side (800 rpm and 10% pin offset) at 250 x magnification

Figure 7. Fractographic images of fractured specimens with 0% tool offset and 10% tool offset.

(d) Energy Dispersive X-ray (EDX) analysis of fractured surface

Figure 7 displays an EDX image of Specimen 02, which was produced with a 10% offset of the tool during the fracture of Al6063. The image reveals that the proportion of both aluminium and copper present on the fractured surface is comparable. This suggests that Al6063 and pure copper were effectively intermixed during the Friction Stir Welding (FSW) process, resulting in a robust joint between these two dissimilar materials, despite their significantly different softening temperatures. In contrast, Specimen 01, which was produced with a zero offset of the tool pin, exhibited poor intermixing.

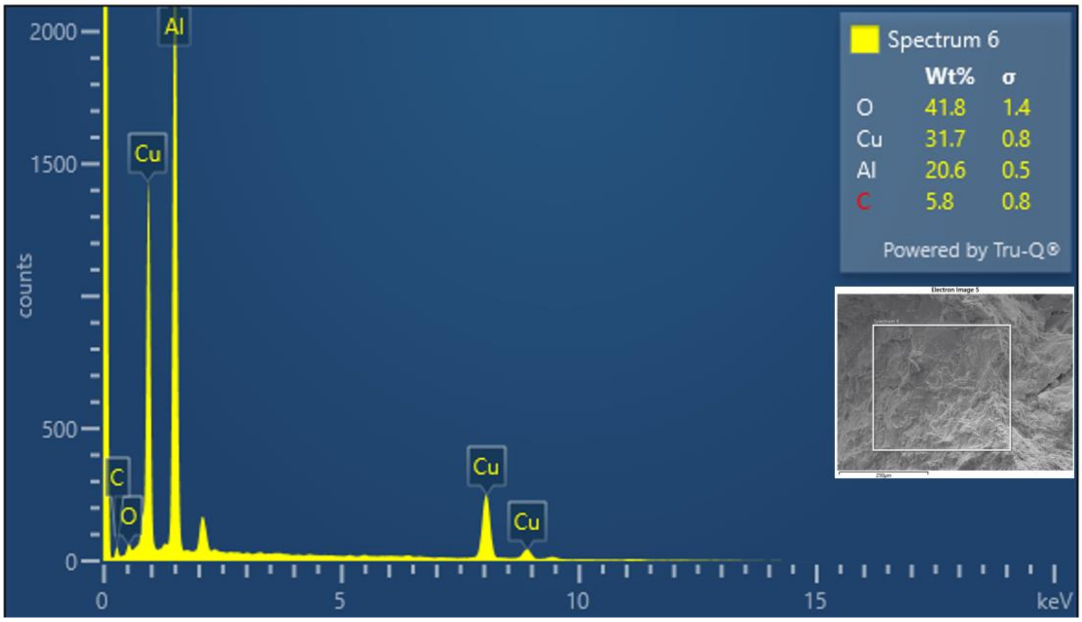


Figure 7. EDX analysis of fractured surface of specimen 02 on Al6063 side

CONCLUSIONS

Al6063 and pure copper plates, each with a thickness of 5.5 mm, were joined together using the HAFSW operation on a lathe machine. The copper plate was positioned at the bottom of the fixture, with the Al6063 plate resting on top and touching the copper plate. A straight threaded pin tool was utilized to perform the HAFSW operation on the lathe machine, with the plates fed against the rotating tool at a constant rate of 20 mm/min using the lathe cross slide's automatic feed. The resulting specimens were examined through visual inspection, tensile testing, and fractographic analysis using Scanning Electron Microscopy (SEM)

- Visual inspection of specimen number 1, produced by HAFSW at zero pin offset and 1200 rpm, revealed tunnel-like defects and improper material filling in the nugget zone. Conversely, specimen 02, produced with a 10% pin offset towards the Al6063 side and 1200 rpm, exhibited no such visual defects.
- Tensile testing revealed that specimen 02 achieved the highest strength of 211.9 MPa, which is 92% of the base Al6063 strength and 85% of the base copper plate strength. In comparison, specimen 01 with 0% tool offset exhibited only 22% of the strength achieved by specimen 02.
- Furthermore, the percentage elongation of specimen 2 with a 10% tool offset was 12%, which is 50% of the virgin Al6063 specimen. In contrast, specimen 01 had only 2.7% elongation due to the presence of defects in the welded region.
- Fracture morphology analysis was conducted on the broken specimens using a Jeol FE-SEM machine. Specimen 02 exhibited a uniform dimple region on the copper side and cavities with larger dimples on the Al6063 side, indicative of ductile failure. Conversely, specimen 1 with 0% tool offset exhibited a brittle region with various defects, including major cracks, tunnels, and unfilled material on

both the Al6063 and copper sides, resulting in poor mechanical performance.

- EDX of specimen 02 reveals a superior intermixing of aluminium with copper resulting in to a robust joint.

ACKNOWLEDGEMENTS

We are grateful to Head, Mechanical Engineering, Faculty of Engineering, DEI, Agra for his kind encouragement and providing necessary facilities. We are also thankful to DST-FIST sponsored department of Chemistry, Faculty of Science, DEI for providing FE-SEM and EDX facility.

REFERENCES

[1] Sindhuja, M; Neelakrishnan, S; Davidson, B. S; Effect of Welding Parameters on Mechanical Properties of Friction Stir Welding of Dissimilar Metals- A Review. *IOP Conf Ser Mater Sci Eng.* **2021** Sep 1;1185(1):012019

[2] Sharma, H.K; Bhatt, K; Shah, K; Joshi, U; Experimental Analysis of Friction Stir Welding of Dissimilar Alloys AA6061 and Mg AZ31 Using Circular Butt Joint Geometry. *Procedia Tech.* **2016**; 23: 566–572.

[3] Jesudoss, R; Hynes, N; Vivek Prabhu. M; Shenbaga Velu P; Kumar, R; Tharmaraj, R; Farooq, M.U; An experimental insight of friction stir welding of dissimilar AA 6061/Mg AZ 31 B joints. *Proc Inst Mech Engg*. **2022** May 1;236(6–7):787–797.

[4] Meyghani, B; Wu, C; Progress in Thermomechanical Analysis of Friction Stir Welding. Vol. 33, Chinese *J. Mech. Engg. Springer*; **2020**.

[5] Garware, M; Kridli, G.T; and Mallick, P.K; Tensile and Fatigue Behavior of Friction-Stir Welded Tailor-Welded Blank of Aluminum Alloy 5754, *J. Matr. Engg and Perf.* **2010**, 19(8), 1161-1171.

[6] Sahin, M;. Joining of Aluminium and Copper materials with Frictio. *Int. J. Adv. Manuf. Tech.*, **2009**, Vol. 49, 527-534.

[7] Adamowski, J; Szkodo, M; Friction Stir Welds (FSW) of aluminium alloy AW6082-T6, *J. Achi. in Mater. and Manuf. Engg* 20 **2007**, 403-406.

[8] Feng, J.; Xue, S. B.; Lou, J. Y.; Lou, Y. B.; Wang, S. Q. Microstructure and Properties of cu/al Joints Brazed with Zn–Al Filler Metals. *Trans. Nonferrous Met. Soc. China* **2012**, 22(2), 281–287. DOI: 10.1016/S1003-6326(11)61172-2

[9] Weigl, M.; Albert, F.; Schmidt, M. Enhancing the Ductility of Laser-Welded Copper- Aluminum Connections by Using Adapted Filler *Mater. Phys. Proc.* **2011**, 12, 332– 338. DOI: 10.1016/j.phpro.2011.03.141

[10] Copper Development Association. *CDA Publication*, 121, 1998.

[11] Miller, W.; Zhuang, L.; Bottema, J.; Wittebrood, A.; Smet, P. De.; Haszler, A.; Vieregge, A. Recent Development in Aluminium Alloys for the Automotive Industry. *Mater. Sci. Eng.* A **2000**, 280(1), 37–49. DOI: 10.1016/S0921-5093(99)00653-X

[12] Joseph, G.; Kundig, K. I. C. Association, Copper: Its Trade, Manufacture, Use, and Environmental Status. *ASM Int.* **1998**.

[13] Amancio-Filho, S.; Sheikhi, S.; dos Santos, J.; Bolfarini, C. Preliminary Study on the Microstructure and Mechanical Properties of Dissimilar Friction Stir Welds in Aircraft Aluminium Alloys 2024-t351 and 6056-t4. *J. Mater. Process. Technol.* **2008**, 206(1), 132–142. DOI: 10.1016/j.jmatprotec.2007.12.008

[14] Nandan, R.; DebRoy, T.; Bhadeshia, H. Recent Advances in Friction-Stir Welding–Process, Weldment Structure and Properties. *Prog. Mater. Sci.* **2008**, 53(6), 980–1023. DOI: 10.1016/j.pmatsci.2008.05.001

[15] Ghosh, M.; Kumar, K.; Kailas, S.; Ray, A. K. Optimization of Friction Stir Welding Parameters for Dissimilar Aluminum Alloys. *Mater. Des.* **2010**, 31(6), 3033–3037. DOI: 10.1016/j.matdes.2010.01.028

[16] Ouyang, J.; Kovacevic, R. Material Flow and Microstructure in the Friction Stir Butt Welds of the Same and Dissimilar Aluminum Alloys. *J. Mater. Eng. Perform.* **2002**, 11 (1), 51– 63. DOI: 10.1007/s11665-002-0008-0

[17] Murr, L.; Flores, R.; Flores, O.; McClure, J.; Liu, G.; Brown, D. Friction-Stir

Welding: Microstructural Characterization. *Mater. Res. Innovations* **1998**, 1(4), 211–223. DOI: 10.1007/s100190050043

[18] Cho, J. H.; Boyce, D. E.; Dawson, P. R. Modeling Strain Hardening and Texture Evolution in Friction Stir Welding of Stainless Steel. *Mater. Sci. Eng.* A **2005**, 398(1), 146–163. DOI: 10.1016/j.msea.2005.03.002

[19] Mehta, K. P.; Badheka, V. J. Effects of Tilt Angle on the Properties of Dissimilar Friction Stir Welding Copper to Aluminum. *Mater. Manufact. Processes* **2016**, 31(3), 255–263. DOI: 10.1080/10426914.2014.994754

[20] Zhao, Y. H.; Lin, S. B.; Wu, L.; Qu, F. X. The Influence of Pin Geometry on Bonding and Mechanical Properties in Friction Stir Weld 2014 Al Alloy. *Mater. Lett.* **2005**, 23, 2948– 2952. DOI: 10.1016/j.matlet.2005.04.048

[21] Kumar, A.; Suvarna Raju, L. Influence of Tool Pin Profiles on Friction Stir Welding of Copper. *Mater. Manufact. Processes* **2012**, 27 (12), 1414–1418. DOI: 10.1080/10426914.2012.689455