DOI: 10.31276/VJSTE.65(4).25-28

Tensile behaviour of the dissimilar friction stir welding between pure copper and aluminium 1050

Hoai Nam Quach[1], Dinh Hao Duong[1], Thanh Nhut Pham[2], Huu Huy Ho[1], Hong Chuong Pham[3], Van Hao Pham[4], Hung Tra Tran[1*]

[1]*Mechanics Department, Nha Trang University, 2 Nguyen Dinh Chieu Street, Vinh Tho Ward, Nha Trang City, Khanh Hoa Province, Vietnam*
[2]*Department of Naval Architecture, Nha Trang University, 2 Nguyen Dinh Chieu Street, Vinh Tho Ward, Nha Trang City, Khanh Hoa Province, Vietnam*
[3]*Quang Nam College, 224 Huynh Thuc Khang Street, An Xuan Ward, Tam Ky City, Quang Nam Province, Vietnam*
[4]*Institute of Scientific Research Application, Hanoi Pedagogical University, 136 Xuan Thuy Street, Dich Vong Hau Ward, Cau Giay District, Hanoi, Vietnam*

Received 12 May 2022; revised 18 June 2022; accepted 20 June 2022

Abstract:

Copper-aluminum hybrid connectors play a crucial role in electric vehicles, but welding these metals together poses a significant challenge due to their distinct physical and mechanical properties. Friction stir welding, a solid-state welding technique, proves to be suitable for joining dissimilar metals. In this study, friction stir welding was employed to create a joint between pure copper 1100 and aluminum 1050 plates, each with a thickness of 5 mm. The fabricated results showed that a significant amount of copper was dispersed into the aluminum side to establish the bonding. The bonding strength was evaluated through tensile testing, while the macrostructure and fracture paths of the joints were monitored using an optical microscope. Despite efforts, eliminating defects in the joint proved challenging, with most defects attributed to vacancies. Increasing the tool rotation speed resulted in greater mixing intensity between the aluminum and copper. The interface between the copper and aluminum was found to be prone to crack propagation. The tensile strength of the joint improved with higher tool rotation, reaching up to 88 MPa. For further analysis, stress within the joint under tensile loading was simulated.

Keywords: **dissimilar Cu/Al joint, friction stir welding, interface stress, tensile failure.**

Classification numbers: **2.1, 2.3**

1. Introduction

To reduce emissions of greenhouse gases, electric vehicles have been the most interesting option in recent years. By increasing the number of electric vehicles on the road, the dependency on fossil fuels will reduce. Regarding hybrid connectors, some studies have addressed dissimilar welding of copper to aluminium as one of the main electrical connections in electric vehicles [1, 2]. It is well known that copper and aluminium are key materials in the field of electronics. In comparison with aluminium, copper possesses excellent electric conductivity, but this metal is remarkably more expensive and heavier. Thus, both copper and aluminium are used to optimize the cost. Unfortunately, since there is a significant difference in the potential energy between copper and aluminium, contact between them leads to galvanic phenomena in the joints, resulting in a short lifespan. Thus, several efforts have been made toward welding copper to aluminium. However, the large difference in properties of the two alloys is a big challenge in the joining process. Traditional fusion welding methods seem to be an ineffective solution for this dissimilar joint. So, some methods of solid-state welding such as cold rolling, brazing, explosive welding, among others, have been used to join them.

Recently, FSW technology has emerged as a key method to join copper to aluminium with high strength and long life [3-9]. However, upon mixing copper and aluminium with their remarkable differences in physical and mechanical properties, a non-uniform flow can form during the FSW technique and an unstable welding process seems to be inevitable. Thus, welding parameters sensitively affected the microstructure and mechanical properties of this type of joint. The high demand on the welding machine and instability in the welding process are the challenges in FSW of dissimilar joints. In this study, a joint between aluminium 1050 and pure copper C1100 was manufactured by FSW technology in the Friction Welding Laboratory of Nha Trang University. The tensile behaviour of the joints fabricated with various tool rotation speeds was

*Corresponding author: Email: tra@ntu.edu.vn

investigated. Attention was placed on defect morphology and crack paths. The results in this work provide a view to enhance the possibility of fabrication of hybrid Cu/Al connectors by the FSW technique in Vietnam.

2. Materials and methods

A dissimilar joint between 5.0-mm-thick pure copper 1100 and aluminium 1050 plates was friction stir welded in Nha Trang University's Friction Welding Laboratory as demonstrated in Fig. 1. The properties of the two metal alloys aluminium 1050 and copper 1100 are presented in Tables 1 and 2 [10]. Before welding, the base metals were cut to 150×60 mm (length × width) and then cleaned with air pressure. A pin tool used for fabricating the joints was 8.0 mm in diameter and 4.8 mm in length. The tilt angle was set to 2.0 degrees off the perpendicular direction to the work pieces. Regarding the welding parameters, the welding speed was a constant value of 100 mm/min while the rotational speed was varied from 600 to 1000 rpm. The cross sections of the welded joints were sliced by a specimen cutting machine (MA-CU250M) to examine the macro- and microstructure. The specimens' surfaces were polished by a polishing machine (MA-PO250M). An Olympus microscope was used to examine the macrostructure and microstructure. The geometry of the tensile specimens was fabricated via ASTM E08 standard as seen in Fig. 2. The loading direction of the tensile specimen was perpendicular to the welding line. The tensile test was carried out by employing an Instron machine 3366 with a speed of 2 mm/min.

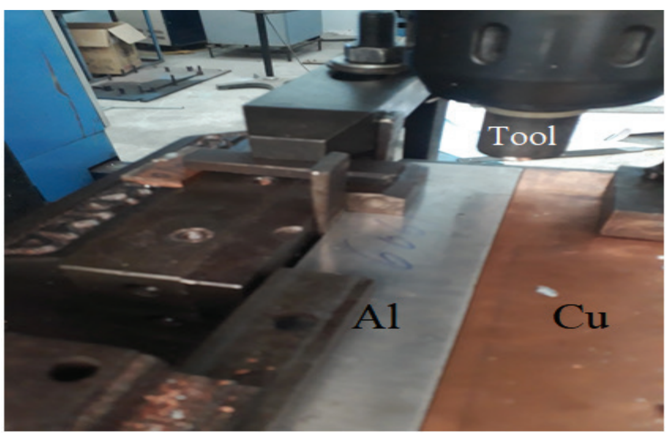


Fig. 1. Welding process setup.

Table 1. The chemical composition of aluminium 1050 and copper 1100 (% wt).

Element	Al	Cu	Fe	Mg	Mn	Si	Ti	V	Zn	Other
Aluminium 1050	≥99.50%	≤0.05%	≤0.40%	≤0.05%	≤0.05%	≤0.25%	≤0.03%	≤0.05%	≤0.05%	≤0.03%
Pure copper 1100		≥99.9%								<0.1%

Table 2. The mechanical properties of aluminium 1050 and copper 1100.

Mechanical properties	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (HV)	Elastic module (GPa)	Poisson ratio
Aluminium 1050	118.0	127.0	9.1	38.0	69.0	0.33
Copper 1100	230.0	245.0	26.0	87.0	115.0	0.33

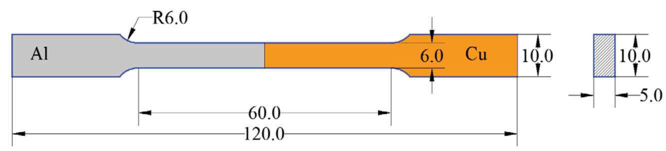


Fig. 2. The geometry of the tensile specimens.

3. Results and discussion

The tensile strengths of the joints produced by various rotational speeds are shown in Fig. 3. It seems that the joint strength improved owing to an increase in tool rotational speed. Here, the tensile stress of the joint gradually increased with increasing the rotational speed. The joint's strength reaches about 88 MPa corresponding to 1000 rpm.

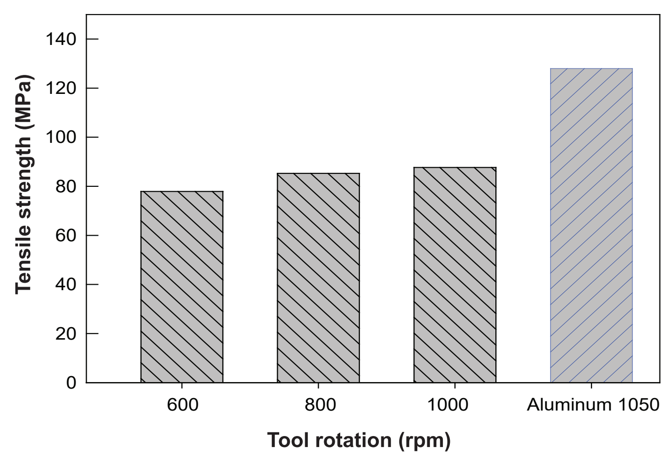
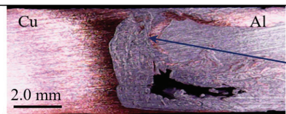
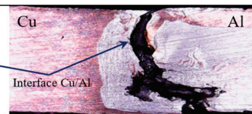
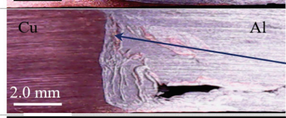
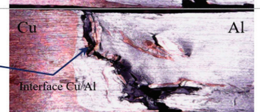
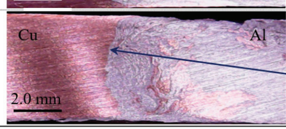
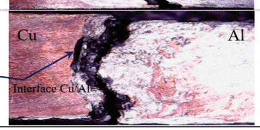


Fig. 3. The tensile strengths of the joints at various rotational speeds.

The macrostructure and the tensile fracture of the joints were monitored. Table 3 summarises the cross sections of the dissimilar joints between copper 1100 and aluminium 1050 at various welding regimes. The macrostructures of the joints are shown in the second column of Table 3. The third column represents the bonding's fracture location under tensile loadings. The FSW process could be used to achieve an advantageous bond between copper 1100 and aluminium 1050. The welded zone was formed in the inhomogeneous features. The copper metal was stirred and dispersed dramatically into the aluminium in all welding regimes, as shown in Table 3 and Fig. 4. Tunnel defects formed on the bottom side of the joints and appeared to be dominant at low rotation speeds (600 and 800 rpm) as shown in Table 3. The tunnel seems to be eliminated when the rotation speed reaches 1000 rpm.

Table 3. The cross sectional macrostructure of the joint at three welding regimes (copper on the left and aluminium on the right).

Tool rotation speed, rpm.	Macrostructure	Fracture location
600		
800		
1000		

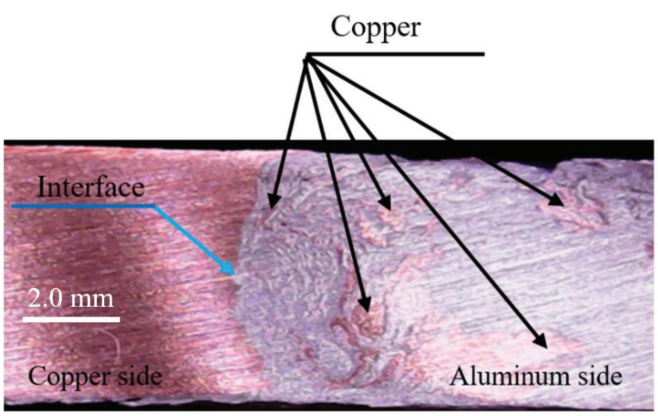


Fig. 4. The cross section of the joint fabricated at a tool rotation speed of 1000 rpm.

The cracks initiated from the tunnels and propagated to the copper/aluminium interface when the joints were subjected to tensile loading. However, in the case without a tunnel defect (at 1000 rpm welding regime), the crack also initiated and propagated mostly at the interface (Table 3).

Focusing on the failure of the joint without defects fabricated at 1000 rpm, various copper particles were mixed into aluminium in the welded zone, as seen in Fig. 4. This means that the tensile strength of the welded zone (on the aluminium side) might be enhanced by copper particles since the tensile strength of the base copper C1100 is twice as high as that of base aluminium 1050. This view also implies that the tensile strength of the stirred zone might be higher than that of the heat-affected zone on the aluminium side. From this point of view, the joint fractured near the interface in the aluminium side as seen in the 4th row of Table 3 could not be explained by the microstructure view. Instead, the failure might be associated with the intermetallic compounds (IMCs) mentioned in [10].

One of the factors suspected to enhance failure at the interface zone is the stress concentration at the interface induced by the dissimilar properties between the two metals. To clarify the role of the dissimilar effect in the stress state at the interface, the stress and strain in the copper/aluminium joint were numerically simulated using Ansys software. The stress state in the joint under tensile loading was simulated using an elastic analysis model. Copper has a Young's modulus of 115 GPa and a Poisson's ratio of 0.33. Aluminium 1050 has a Young's modulus of 69 GPa and a Poisson's ratio of 0.33, respectively. The welded zone's Young's modulus and Poisson's ratio are assumed to be the same as the base aluminium 1050. Fig. 5 depicts a finite element model of the joint. Figs. 6 and 7 show the equivalent stresses in the joints. There was a significant stress concentration at the interface and on the copper side. Because of the dissimilar effect, the stress at the interface on the aluminium side was significantly reduced. From this point of view, it is obvious that the stress induced by the dissimilar base metals has no role in the failure of the joint where the fracture took place, which is near the interface and on the aluminium side (as seen in the 4th row of Table 3).

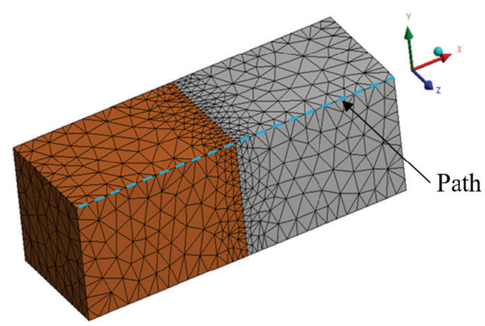


Fig. 5. FEM model of the dissimilar copper/aluminium joint. Cu on the left side, Al on the right side.

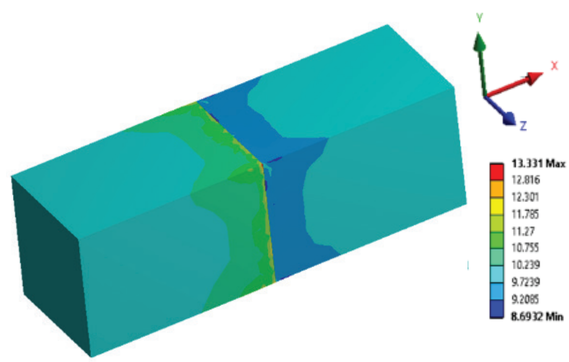


Fig. 6. Von Mises equivalent stress distribution in the joint with 10 MPa axial loading. In the direction of the x-axis, Cu is on the left side and Al on the right side.

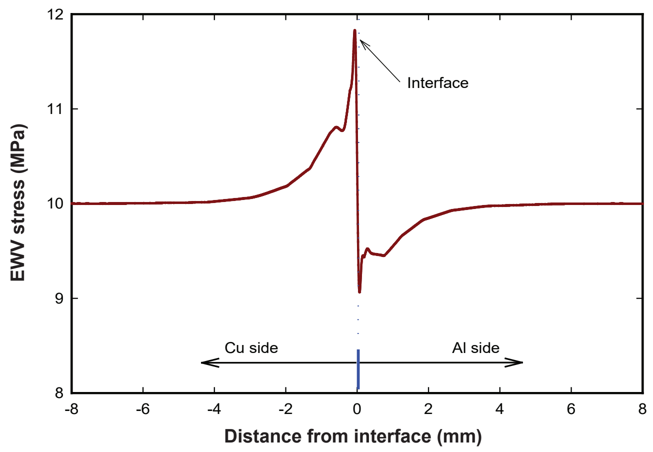


Fig. 7. Von Mises equivalent stress distribution along the path shown in Fig. 4 (with axial loading of 10 MPa).

In summary, from the above-mentioned facts, joints were established by mixing copper with aluminium. The interfaces between copper and aluminium were believed to be suitable places for cracking and intermetallic compounds at the interface may be the prevailing mechanism behind the failure behaviour of the joints.

4. Conclusions

A joint between copper 1100 and aluminium 1050 was produced by FSW at Nha Trang University. A joint free of defects and with a tensile strength of about 88 MPa was reached. At low rotation speeds (below 1000 rpm), tunnel defects formed on the joint's bottom side. The copper/aluminium interface appeared to be the preferred place for cracks to propagate and the IMCs formed at the interface were believed to be an important factor in the failure path in the joints. The interface stress induced by the dissimilar properties between copper and aluminium has a minor role in the failure of the joint. The results of this work encourage the possibility of fabricating dissimilar copper and aluminium connections for advanced performance in electronic applications.

CRediT author statement

Hoai Nam Quach: Writing original draft preparation; Dinh Hao Duong: Methodology and Formal analysis; Thanh Nhut Pham: Methodology; Huu Huy Ho: Formal analysis; Hong Chuong Pham: Formal analysis; Van Hao Pham: Editing; Hung Tra Tran: Conceptualisation and Methodology.

ACKNOWLEDGEMENTS

This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 13/2020/TN.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] P. Kah, C. Vimalraj, J. Martikainen, et al. (2015), "Factors influencing Al-Cu weld properties by intermetallic compound formation", *Int. J. Mech. Mater. Eng.*, **10(1)**, DOI: 10.1186/s40712-015-0037-8.

[2] J. Feng, S. Xue, J. Lou, et al. (2012), "Microstructure and properties of Cu/Al joints brazed with Zn-Al filler metals", *Trans. Nonferrous Met. Soc. China*, **22(2)**, pp.281-287, DOI: 10.1016/S1003-6326(11)61172-2.

[3] S. Shankar, P. Vilaça, P. Dash, et al. (2019), "Joint strength evaluation of friction stir welded Al-Cu dissimilar alloys", *Measurement*, **146**, pp.892-902, DOI: 10.1016/j.measurement.2019.07.019

[4] F.B. Argesi, A. Shamsipur, S.E. Mirsalehi (2018), "Dissimilar joining of pure copper to aluminium alloy via friction stir welding", *Acta. Metall. Sin. (Engl. Lett.)*, **31**, pp.1183-1196, DOI: 10.1007/s40195-018-0741-5.

[5] R. Anbukkarasi, S.V. Kailas (2020), "Influences of shape of the new interfaces and morphology of the intermetallics on mechanical properties of aluminium AA2024-pure copper joints by friction stir welding", *Int. J. Adv. Manuf. Technol.*, **106**, pp.5071-5083, DOI: 10.1007/s00170-019-04911-8.

[6] D. Parningotan, M. Tarrant, Z.W. Chen, et al. (2017), "Influence of stir flow on joint quality during friction stir lap Al-to-Cu welding", *Friction Stir Welding and Processing IX*, **2**, pp.157-166, DOI: 10.1007/978-3-319-52383-5_17.

[7] R. Rzaev, A. Chularis, V. Smirnov, et al. (2019), "The influence of the friction stir welding parameters on the formation of welded joint of aluminium and copper alloys", *Mater. Today Commun.*, **11(1)**, pp.534-542, DOI: 10.1016/j.matpr.2019.01.025.

[8] M.P. Mubiayi, E.T. Akinlabi, M.E. Makhatha, et al. (2018), "Current state of friction stir spot welding between aluminium and copper", *Mater. Today Commun.*, **5(9)**, pp.18633-18640, DOI: 10.1016/j.matpr.2018.06.208.

[9] K.P. Mehta, V.J. Badheka (2015), "A review on dissimilar friction stir welding of copper to aluminium: Process, properties, and variants", *Mat. Manuf. Process.*, **31(3)**, pp.233-254, DOI: 10.1080/10426914.2015.1025971.

[10] ASM International (1990), *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, https://www.asminternational.org/search/-/journal_content/56/10192/06182G/publication, accessed 10 July 2019.