

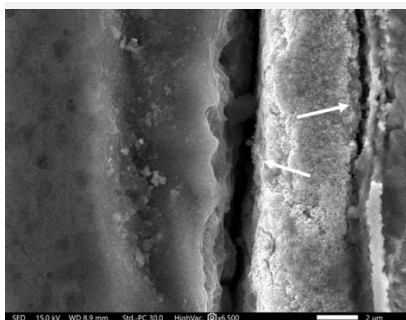
Effect of forging pressure and rotational speed on the quality of rotary friction welding of Al 6063 and copper joints

Yeni Muriani Zulaida¹, Muhammad Anis^{1,*}, Mahfudz Al Huda², Kirman²,
Hermawan Agus Suhartono²

¹ Department of Metallurgical and Materials Engineering, Universitas Indonesia, Depok 16424, **Indonesia**

² Research Center for Structural Strength Technology (PR TKS), National Research and Innovation Agency (BRIN), South of Tangerang 15314, **Indonesia**

✉ anis2657@gmail.com



Highlights:

- The optimal forging pressure can improve joint strength.
- The optimal forging pressure minimizes excessive flash formation.
- Low-temperature operation reduces intermetallic compound formation.

Abstract

This study investigates the effect of forging/upset pressure and high rotational speed on the quality of dissimilar metal joints between aluminum 6063 (Al6063) and copper (Cu). The method uses solid-state rotary friction welding (RFW) method. Joining dissimilar metals poses challenges due to significant differences in thermal conductivity, melting point, and mechanical properties. At high rotational speeds, the increased heating rate and higher frictional pressure result in greater deformation of the aluminum component. A novel aspect of this research lies in its systematic evaluation of the combined effects of forging pressure and rotational speed in an area that has received limited attention in prior RFW studies. Despite not achieving full joint efficiency, the results demonstrate that increasing forging pressure significantly enhanced joint strength up to an optimum level. Consequently, higher rotational speeds led to larger and more irregular flash due to rapid heat generation. However, a well-balanced combination between pressure and speed produced stronger joints with less flash. Excessive pressure was found to widen flash formation, while the heat generation from high rotational speeds diminished after material deformation. The RFW process in this study reached temperatures approaching 300 °C; a very few intermetallic phases were detected at the Al/Cu interface. These findings contribute valuable insights into improving the weldability and mechanical performance of dissimilar Al-Cu through parameter optimization in RFW parameters.

Keywords: Rotary friction welding; Dissimilar metal welding; Al 6063; Forging pressure; Rotational speed

Article info

Submitted:
2025-08-06

Revised:
2025-11-14

Accepted:
2025-12-28



This work is licensed under
a Creative Commons
Attribution-NonCommercial 4.0
International License

Publisher

Universitas
Muhammadiyah
Magelang

1. Introduction

The welding of dissimilar materials, particularly aluminum (Al) and copper (Cu), plays a crucial role in various industrial applications, especially in the electrical and chemical engineering sectors. Al-Cu joints are highly valued for their unique combination of properties, such as excellent electrical and thermal conductivity, outstanding corrosion resistance, and desirable mechanical strength. Among the various welding methods available, rotary friction welding (RFW) has emerged as a promising technique due to its efficiency in both material usage and energy consumption [1].

Aluminum alloy 6063 (Al 6063) is widely used in construction, architecture, transportation, and electrical systems due to its lightweight characteristics, excellent formability and weldability, and high electrical conductivity among aluminum alloys [2], [3]. The type of aluminum from the AA6000 series is a type of aluminum alloyed with magnesium and silicon. Some members of this series have good conductivity and are typically used for electrical applications; for example as conductors for transmission lines. They have high strength compared to pure aluminum, making it suitable for electrical applications that experience mechanical loads [4]. The characteristics of lightweight metals with good conductivity can be combined by combining high-conductivity materials, such as Al/Cu. However, welding aluminum to copper presents considerable challenges due to the marked differences in their physical, thermal, and chemical properties. Dissimilar metal joining often encounters problems such as poor metallurgical bonding and the formation of brittle intermetallic compounds (IMCs). To address these issues, solid-state welding techniques that minimize melting are preferred to reduce elemental intermixing and suppress the formation of IMCs [5], [6].

Rotary friction welding (RFW) is a solid-state welding process that does not involve melting the base metals. Compared to fusion welding, it offers numerous advantages, including the absence of smoke and spatter, no need for filler metals or shielding gases, reduced energy consumption, and shorter welding times [7], [8]. The RFW process involves applying a compressive force at the interface of the materials while one component rotates relative to the other, generating friction heat that raises the temperature into the plastic deformation range [9]. However, despite these advantages, RFW has limitations such as the necessity for precise axial alignment, flash formation that must be removed after welding, and difficulties in welding dissimilar metals with significantly different forging temperatures [9], [10]. The RFW process consists of three main stages [11]:

- Heating stage, where relative motion combined with axial pressure generates frictional heat that results in softening the interface.
- Burn-off stage, during which plastic deformation forms flash and expels oxides and contaminants.
- Forging/upset stage, where rotation the joint is consolidated and metallurgical bonding is achieved by stopping the rotation and applying a high axial force.

Weld quality in RFW is governed by several parameters, including axial force, rotational speed, and welding time [12], [13], [14]. These parameters directly affect the heat input and interface bonding characteristics. The axial force consists of two components: friction force and forging force, which correspond to friction pressure and forging/upset pressure at the interface. Inappropriate friction pressure can affect peak torque during welding [15], [16], [17]. Kimura [17] reported that higher upset pressure enhances joint efficiency, causing failure on the aluminum component side. At pressures below 80 MPa, interfacial cracking tends to occur, whereas pressures above 120 MPa lead to crack propagation into the aluminum component [18]. Maintaining constant upset pressure improves tensile strength with increasing energy input up to a peak, beyond which it declines [19], [20].

Temperature friction analysis is essential to optimize and qualify the welding of parameters [21]. Rotational speed directly affects the peak temperature (T_p); for example, with speeds between 1700 and 2500 rpm, reaching T_p values range from around 451 to 466 °C [22]. In aluminum welding, the relationship between rotational speed and burn-off time forms a "V-shaped" curve, with the shortest burn-off time observed around 900 rpm [23]. Heat input is a function of frictional torque and rotational speed [24]. At a constant rotational speed, increasing friction time causes more deformation and higher material loss (burn-off length) [25]. During the friction time, shortening of the aluminum and copper components is monitored due to the formation and size of the characteristic mushroom-shaped flash [26].

The chemical composition of both materials used for welding plays an important role in determining the properties of the weld. In Al/Cu joints, a major concern is the formation of the intermetallic compounds (IMCs) that can affect joint performance. In the dissimilar metal joining between Al and Cu, it is possible that an intermetallic compound will be formed. The IMC that may be formed are phases such as η -phase (AlCu), δ -phase (Al_3Cu_4), ζ -phase (Al_4Cu_3), and γ -phase (Al_4Cu_9) [27]. They tend to form and grow at a temperature range of 480–540 °C [28], where rapid interdiffusion occurs, with a reported diffusion coefficient of $7.8 \times 10^{-12} \text{ m}^2/\text{s}$ at 375–450 K [29]. However, Kimura [15] found that at RFW temperatures up to 379 °C, IMC formation may be minimal or absent. Among the common IMCs, the growth of the Al_2Cu phase is more sensitive to

changes in rotational speed compared to AlCu and Al₂Cu₃ [30]. Excessive IMC layer thickness can degrade both electrical conductivity and mechanical strength of the joint [31], [32].

This study investigates the characteristics of Al 6063 and Copper joint produced by RFW, with focus on heat generation, deformation behavior, and joint performance under various forging and high rotational speeds. The novelty of this study lies in its investigation of the RFW process at high rotational speeds combined with varied forging pressures. Unlike most previous study have focused on rotational speeds below 1700 rpm, this work extends the range to higher rotational speeds. The findings provide valuable insights for optimizing solid-state RFW parameters to enhance joint strength, suppress excess deformation, and the formation of intermetallic compounds in dissimilar Al-Cu systems.

2. Method

This research was designed to analyze the joint characteristics of aluminum and copper by varying the forging pressure (P2). The chemical composition of the base materials is presented in

Table 1.
Chemical composition
of base metal

Base Metal	Composition (wt%)					
Aluminium	Si	Mg	Fe	Ti	Zn	Al
	0.53	0.53	0.29	0.01	0.04	Bal
Copper	Sn	Ni	Cu			
	0.02	0.02	Bal			

Table 1. Based on its composition and mechanical properties, the aluminum used in this research is classified as AA 6063 [2]. The microstructure of both materials are shown in **Figure 1**.

Figure 1.
Microstructure of base
metal:
(a) Aluminium alloy;
(b) Copper

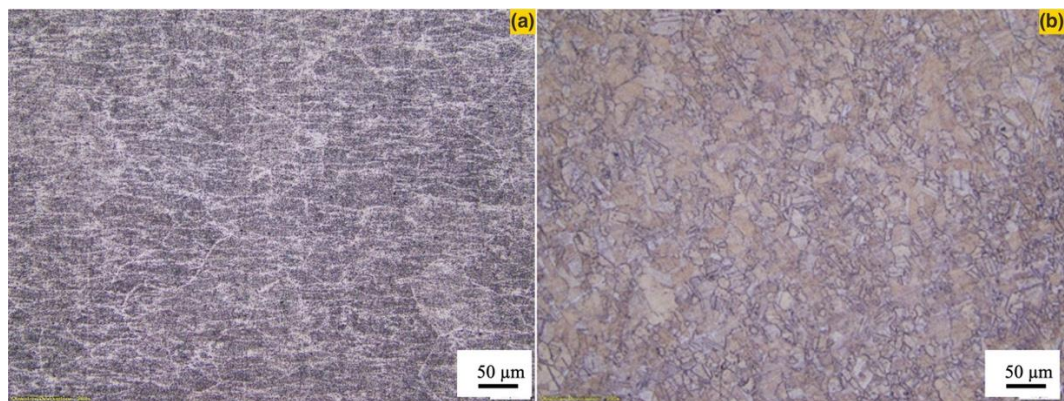
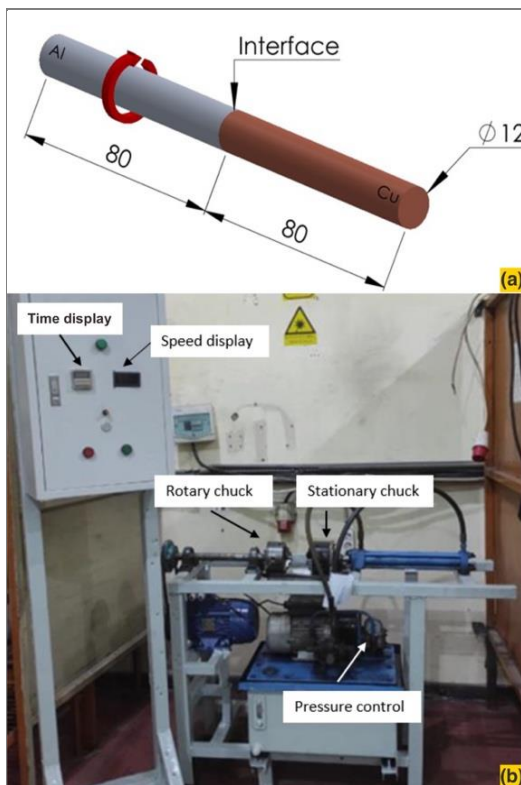


Figure 2.
(a) Dimension and principal
setup of rotary friction
welding specimens;
(b) Friction welding
machine schematic



The welding process was carried out using the rotary friction welding method with a continuous drive system. The specimens were cylindrical rods, each with a diameter of 12 mm and a length of 80 mm. The base metals—aluminum and copper—have relatively similar tensile strengths: aluminum exhibits a tensile strength at 135 MPa, and copper shows a tensile strength at 215 MPa.

Friction welding was performed by placing the copper on the stationary side (hydraulic side) and the aluminum on the rotating side (motor side), as illustrated in **Figure 2a** and **Figure 2b**. The method used was continuous drive friction welding without a braking system. During the welding process, both the stationary and rotating specimens were subjected to a friction pressure (P1) of 18 MPa. Once the desired friction time (t1) was reached and visible deformation occurred, the motor was stopped, and an upset pressure (P2) was applied for a specific duration (t2). In this study, the forging pressure was maintained for 3 seconds.

To achieve the research objectives, rotational speeds of 1900 rpm to 2300 rpm were selected, according to a preliminary experiment. Earlier trials conducted at rotational speeds exceeding 2300 rpm yielded suboptimal results, including decreased joint strength and excessive aluminum loss. Some of the specimens in excess rotation speed start to bend. The value of friction pressure (P1), friction time (t1), and forging pressure/upset time (t2) on preliminary results was reported in previous conference proceedings and prior research [22]. All of the values were selected according to the optimum joint strength of the weld. The experimental variables used in this study are summarized in Table 2.

The effect of forging pressure and rotational speed on the joint tensile strength was also investigated. Tensile tests were performed on the specimens. Tensile test specimens were

Table 2.
Friction welding
parameters

Parameters	Variation
Rotation Speed (N), rpm	1900, 2100, 2300
Friction Time (t1), s	7
Friction Pressure (P1), MPa	18
Forging Time (t2), s	3
Forging Pressure (P2), MPa	51, 68, 85, 130

machined to remove excess metal (flash) protruding from the joint surface. Tensile testing was performed at a diameter equal to the base metal diameter. Furthermore, the chemical composition distribution of the joint area was analyzed using EDS.

3. Results and Discussion

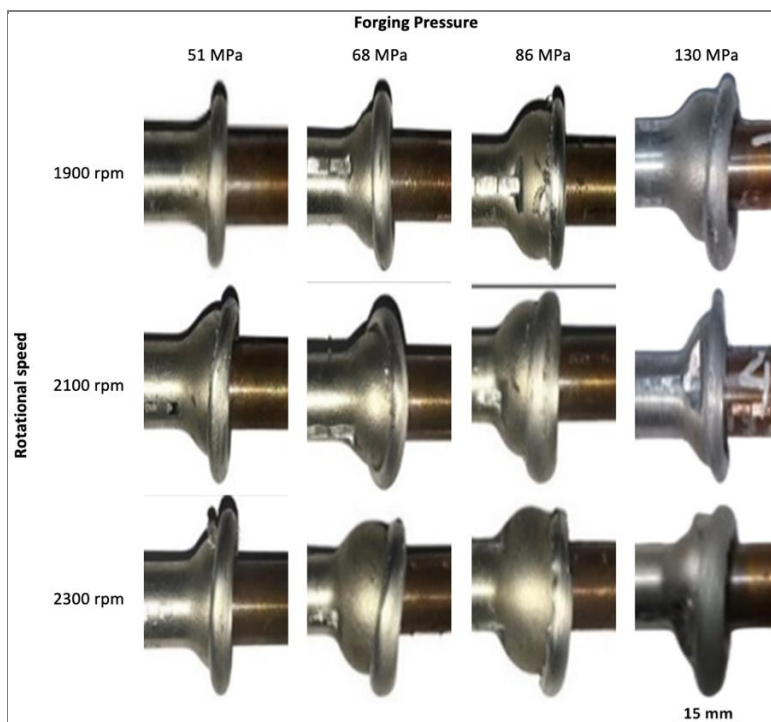
3.1. Relationship between Rotational Speed and Axial Pressure

The initial stage of the rotary friction welding (RFW) process involves heat generation at the interface between the aluminum and copper surfaces due to frictional contact. In this stage, both materials are subjected to a moderate axial friction pressure of approximately 18 MPa while rotation is maintained for 7 seconds at varying rotational speeds. As the interface temperature rises, aluminum—due to its lower flow stress—undergoes plastic deformation earlier than copper. As plastic deformation progresses, aluminum begins to extrude outward from the contact interface, forming a characteristic flash, concurrently a reduction in the original specimen length—referred to as the burn-off length (BoL) is observed, Figure. This marks the transition to the second stage of the rotary friction welding process, known as the burn-off stage. Once sufficient burn-off has occurred, the rotation is stopped, and the axial pressure is increased to initiate the forging stage, resulting in further deformation of the base metals, promoting solid-state bonding and enhancing consolidation at the joint interface.

Rotational speed has a direct influence on the amount of flash generated during the friction stage. As shown in Figure 3, increasing the rotational speeds result in greater flash formation due

to higher heat input and more extensive plastic deformation. In this study, after 7 seconds of rotation, the motor was stopped, and the axial pressure was increased to initiate forging stage. The application of forging pressure further contributed to flash formation at the joint interface and additional reduction in specimen length. In general, excessive flash formation is undesirable, as it must be removed during post-weld processing. Therefore, although some flash is necessary

Figure 3.
The effect of rotational speed and forging pressure on flash formation. Excessive speed causes an irregular flash formation



for effective material mixing and oxide removal, controlling flash formation is essential not only to minimize secondary operation but also to enhance overall joint quality.

An increase in flash formation was also accompanied by a corresponding rise in burn-off length. At rotational speeds of 1900 and 2100 rpm, it was observed that higher upset pressures resulted in greater burn-off lengths, as shown in Figure 4. This finding is consistent with previous studies, which suggest that burn-off is a cumulative result of material deformation occurring during both the friction and forging/upset stages [33]. However, at excessively high rotational speeds, a decrease in deformation was observed. This reduction may be attributed to increased instability in the material flow, which can disrupt uniform plastic deformation and hinder the consolidation process at the joint interface.

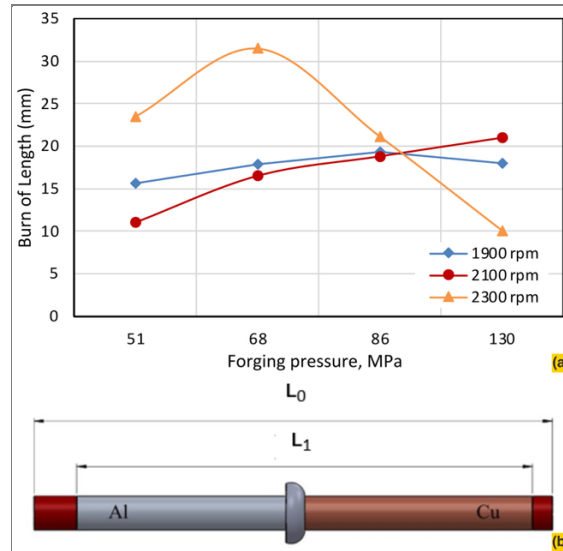


Figure 4.
(a) Reduction in base metal length (burn-off length) as a function of forging pressure;
(b) Measurement of burn of length (BoL): $L_0 - L_1$

These temperature variations may result from factors such as machine instability or inhomogeneities in the material properties (Figure 5). Compared to previous studies [15], [23], the measured temperatures in this experiment were lower, suggesting that the formation of intermetallic compounds is unlikely under the current process conditions. While higher rotational speeds can enhance the rate of heat generation, excessively high speeds may cause temperature instability, as illustrated in Figure 6. This thermal fluctuation can adversely affect the subsequent forging stage and compromise overall weld quality.

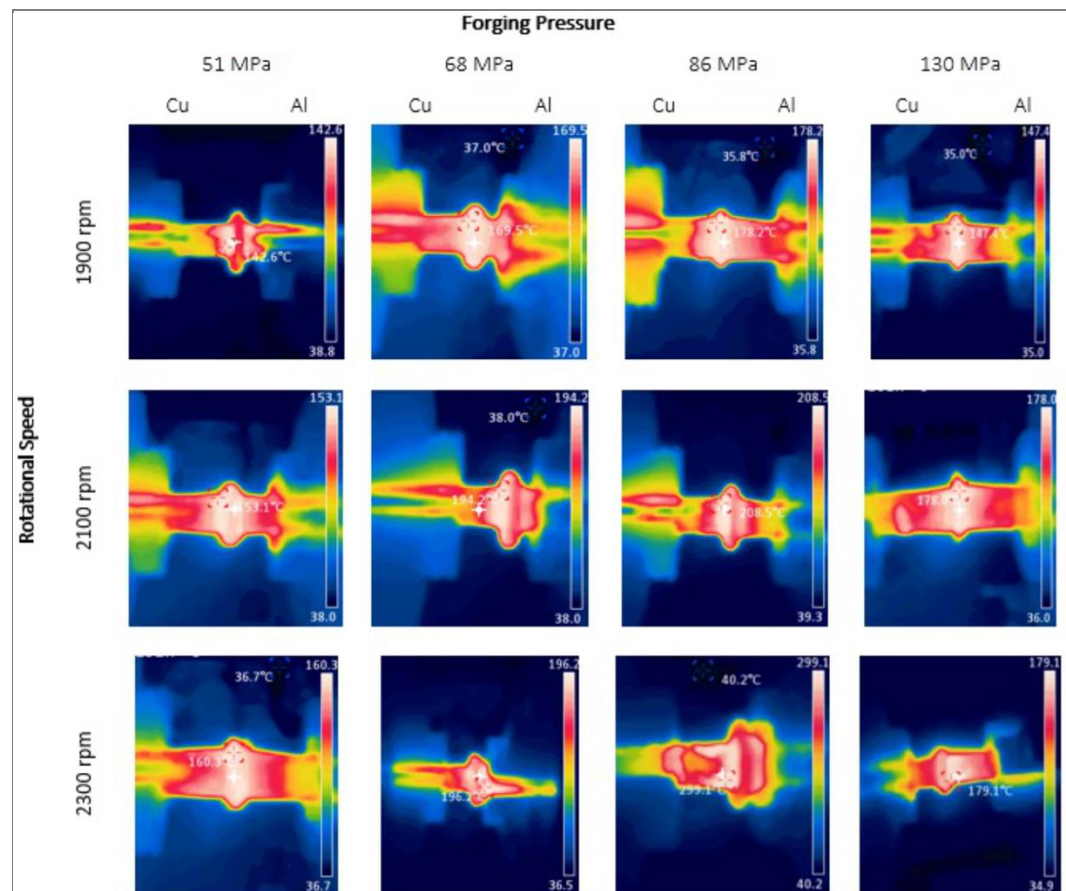


Figure 5.
Temperature distribution at different rotation speeds just before the forging pressure is applied (at the 7th second)

3.2. Reviewing Forging Temperature, Joint Strength and Joint Efficiency

The joint efficiency was calculated as the ratio of the ultimate tensile strength (UTS) of the joint to that of the base material, which in this case is aluminum [16], [34]. It expressed as a

percentage. A more consistent correlation between forging temperature and joint efficiency was observed at rotational speeds of 1900 rpm and 1200 rpm. In both cases, the higher forging temperatures generally resulted in increased joint efficiency, while lower forging temperature corresponded with reduced efficiency. At 2300 rpm—despite the unstable temperature fluctuations—the trend remained comparable, where higher forging temperatures still led to higher efficiency. However, the overall joint strength at 2300 rpm was lower than that achieved at the lower rotational speeds (Figure 7). This observation highlights the need for further investigation on the role of temperature in influencing joint performance.

Figure 6.
The relationship between rotational speed and forging temperature

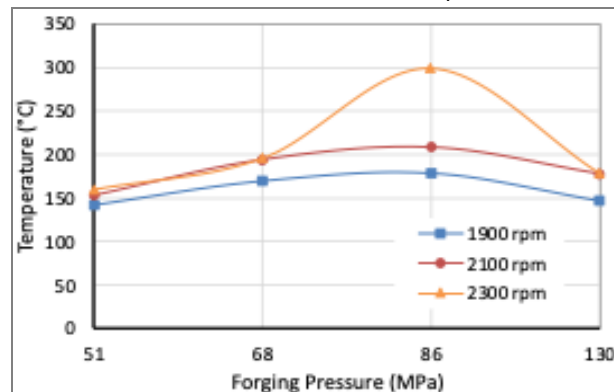


Figure 7.
The relationship between forging pressure and tensile strength

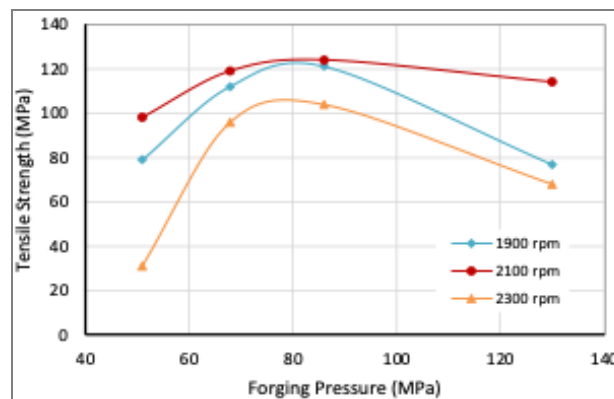
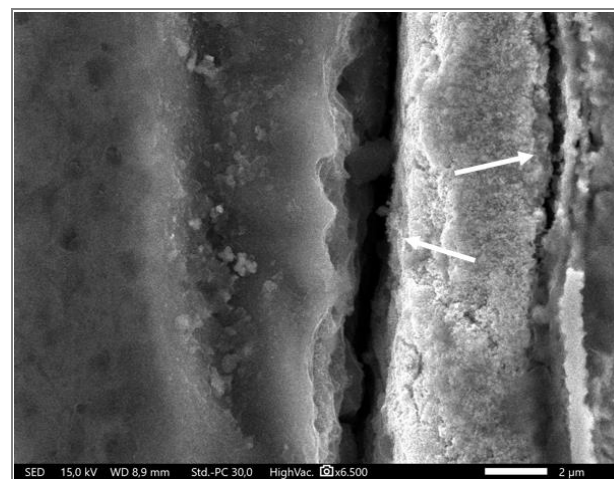


Figure 8.
The cracks near the contact area



3.3. Microstructure

An optical microscope and scanning electron microscope (SEM) were used to examine the microstructure of the joint. The thickness of the interface layer of the joint area can influence the joint's strength. The contact surface appeared slightly wavy and uneven, indicating that the pressure distribution across the interface was not uniform. Aluminum exhibited substantial plastic deformation, whereas copper remained relatively undeformed. Structural alterations near the contact surface revealed evidence of metal flow on the copper side, which may be the result of the force generated during rotation (Figure 9). The microstructure on the copper side near the joint appeared denser and smoother (area 1), suggesting localized plastic flow. In contrast, the aluminum side exhibits a higher density of precipitates near the interface. The accumulation of these precipitates in the joint area can reduce the joint's strength, as they may act as stress concentrators or weaken the bonding interface.

The highest joint strength among rotational speeds is achieved at 2100 rpm, as indicated by the tensile strength curve. At this speed, a forging pressure of 86 MPa resulted in the maximum joint strength at that speed. In comparison to other forging pressures, the microstructure at this

condition exhibited a highly dense interface. At a lower forging pressure, voids and discontinuities at the joint interface were still present in the microstructure. However, these defects were significantly reduced at a forging pressure of 68 MPa, which leads to an increase in joint strength. Nevertheless, further increases in forging pressure cause excessive deformation in the interface zone, as evidenced by the formation of multilayer structures indicating the development of flash and material extrusion formed in the joint zone (Figure 10).

Figure 9.
Characteristics of joints
at 2300 rpm speed at
68 MPa

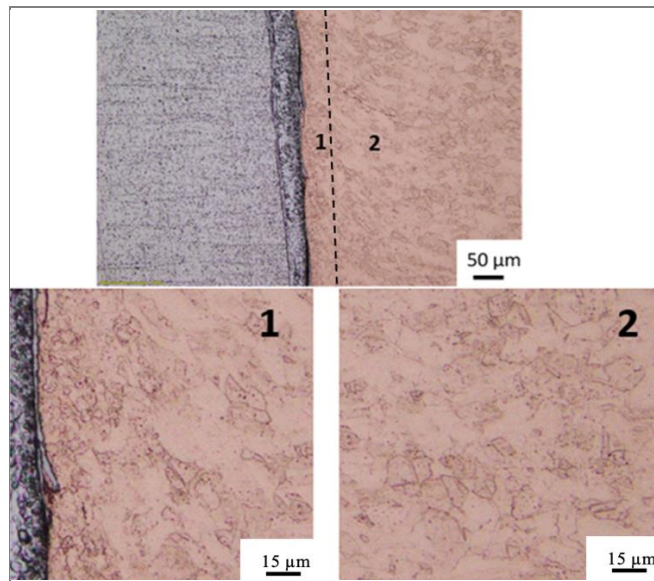
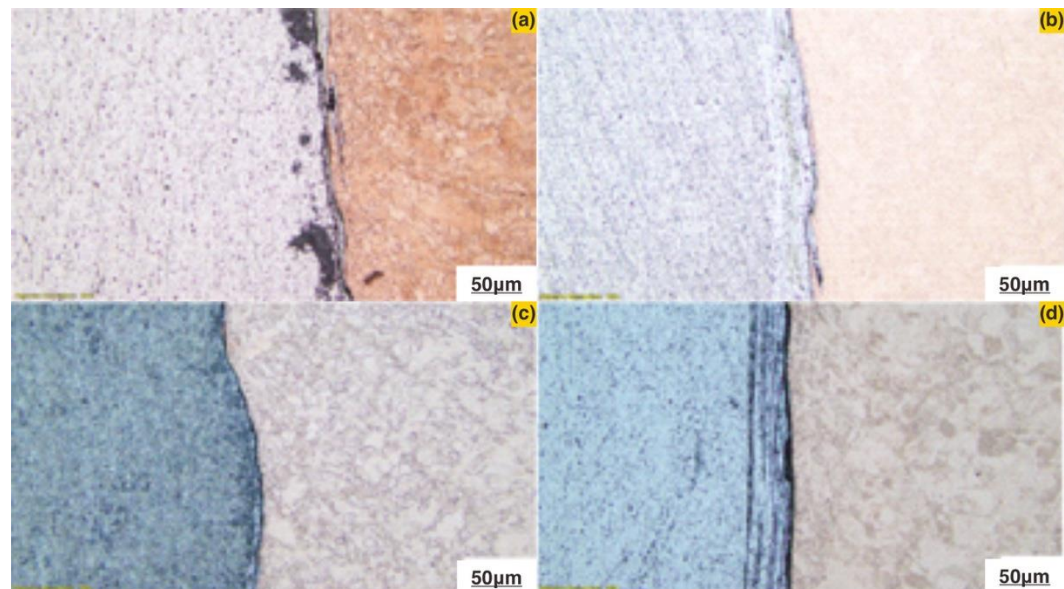


Figure 10.
Characteristics of joints
in 2100 rpm speed at
various forging
pressures:
(a) 51 MPa;
(b) 68 MPa;
(c) 86 MPa;
(d) 130 MPa



Insufficient forging pressure fails to induce adequate plastic deformation, leading to suboptimal material bonding and poorly formed metallurgical bonds. Increasing the forging pressure enhances metal penetration at the contact surface. Optimal forging pressure promotes adequate plastic deformation and high interface temperature, both of which contribute to enhance joint strength. However, excessive forging pressure can result in over-deformation, which may reduce local mechanical properties.

Composition distribution analysis in and near the joint can be used to observe the diffusion behavior of aluminum and copper elements. SEM-EDX analysis confirmed the diffusion of aluminum and copper elements into the joint area (Figure 11) as indicated by the compositional gradient observed in spectrum. Both aluminum and copper were detected within the joint region, with their concentrations varying along the scan line. Toward the copper side, the copper content gradually increases while the aluminum content decreases. Indicating a diffusion-driven gradient between the two base metals.

3.4. Hardness Distribution in Joint Area

The composition data shown in Figure 12 is supported by the corresponding hardness test results. The increased hardness in the joint area may be due to the presence of a copper element that possesses a higher hardness than aluminum. In general, higher forging pressure tends to

correlate with increased hardness in the joint zone. Point 0 at Figure 12 corresponds to the joint area. The optimal forging pressure is observed within the range of 86 MPa. The transition from Al to Cu is marked by a sharp and uniform increase in hardness that is consistent across all rotational speed variations.

The highest hardness in the joint area is consistently achieved at a rotational speed of 1900 rpm, as shown in Figure 12, suggesting that the frictional energy and heat input at this speed are adequate to establish a strong joint. The combination of 1900 rpm and a forging pressure of 86 MPa not only produce the greatest hardness but also the most uniform hardness distribution across the joint. In contrast, the majority of the joints produced at a rotational speed of 2300 rpm exhibit a lower hardness. This decline suggests that excessive speed may negatively affect joint quality by hindering the metal bonding process or introducing thermal defects.

Figure 11.
Distribution of
aluminum and copper
elements in the area
around the joint at a
speed at 2100 rpm
with a forging pressure
at 86 MPa

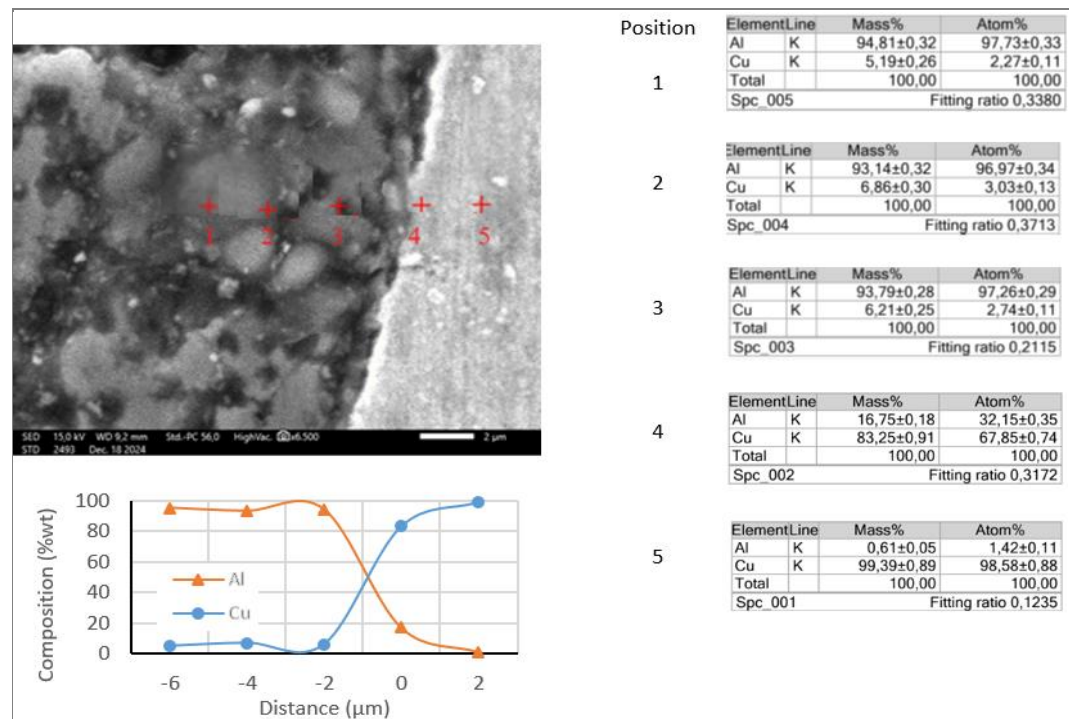
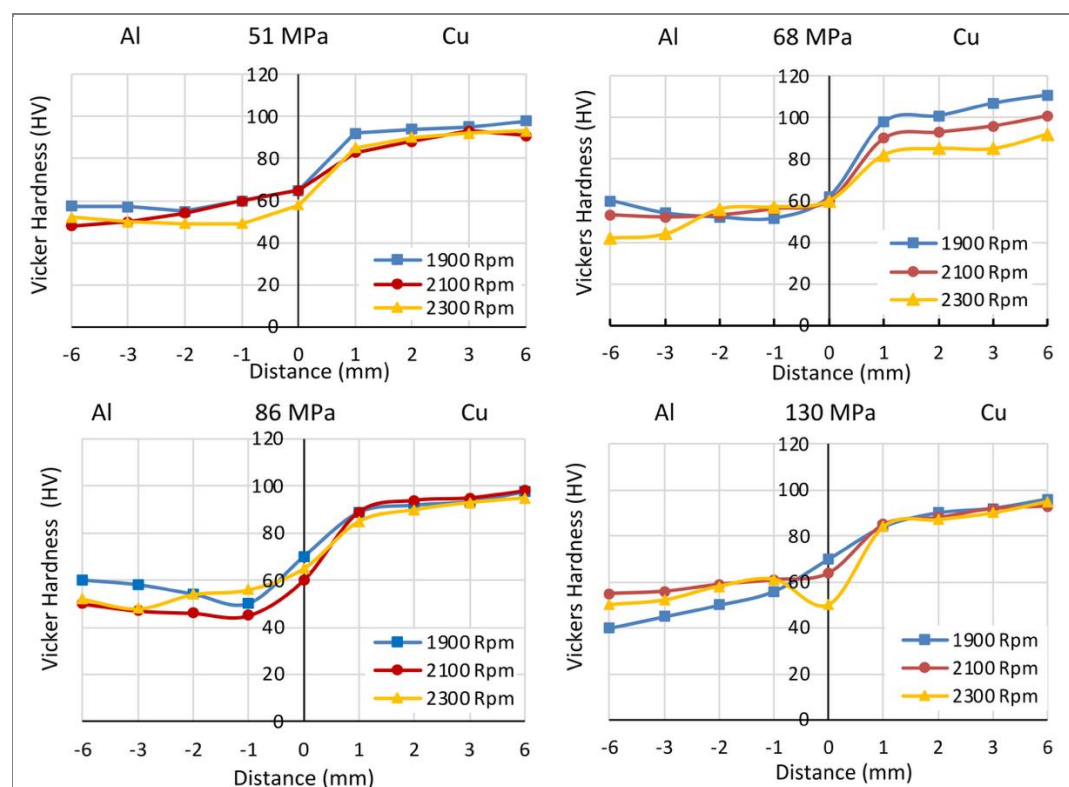


Figure 12.
The distribution of
hardness around the
joint area



A comprehensive examination of the joint area was performed utilizing XRD to observe the phase transformation occurring during the friction welding process. The observations were performed at the maximum process temperature. It can be seen from **Figure 13**, the XRD diffractogram reveals the crystalline phases developed in the joint region. The diffraction peaks in the image have detected multiple crystal phases, including aluminum, copper, and intermetallic compounds. Notably, the Al_4Cu_9 compound was detected at 73° (2θ) in small quantities (ref code ICSD 98-005-7669), possibly related to the very thin layer near the interface. The formation of the compound indicates a metallurgical reaction between Al and Cu resulting from thermal exposure during frictional heating. This compound exhibits high hardness and inherent brittleness, the formation of Al_4Cu_9 may significantly influence the mechanical behavior of the joint, potentially contributing to increased hardness while reducing ductility.

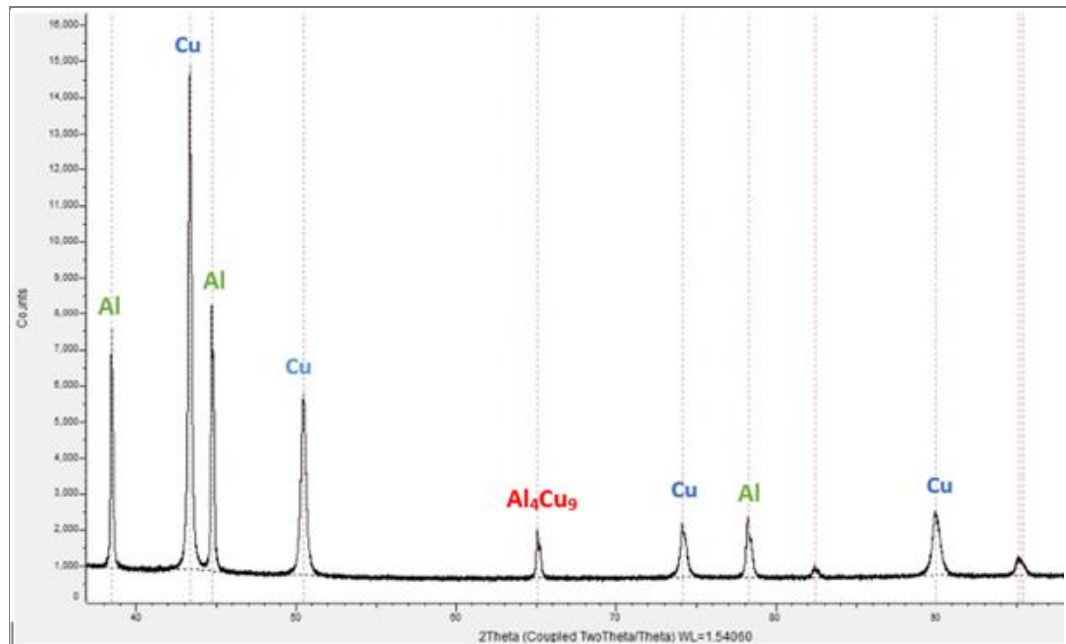


Figure 13.
XRD diffractogram at a
speed of 2300 rpm and
a forging pressure of 86
MPa

4. Conclusion

This recent study focuses on investigating forging/upset pressure and high rotation speed. Detailed findings have been developed regarding the influence of those parameters on joint performance and the formation of excess material produced by frictional pressure. The results of the experiment reveal a clear correlation between the forging pressure and rotation speed of the rotary friction welding, which includes the following:

1. Higher rotation speed can increase the heating rate in the contact area of the aluminum and copper interface. This can generate enough heat for plastic deformation and cause more excess material.
2. The forging pressure significantly influences the strength of the aluminum-copper joint; however, excessively high pressures, such as 130 MPa, can decrease joint strength. In higher rotation speed, suddenly stopped by pressure, it can increase the possibility induce crack formation near the interface.
3. Increasing hardness across the joint area indicates that Al and Cu elements have diffused into the joint area. According to XRD analysis on the contact area, only a small amount of intermetallic compounds were formed between the Al/Cu interfaces during this friction welding process. This intermetallic compound contributes to increasing the hardness. According to the microstructure photograph, increasing the hardness may occur due to the finer structure in the area near contact as well.

Acknowledgements

The author wishes to express the deepest gratitude to all parties who contributed to this research. This work was supported by the Research and Innovation for Advanced Indonesia (RIIM) Batch 4 of the National Research and Innovation Agency (BRIN) and the Education Fund

Management Institution (LPDP) through Contract Number 37/II.7/HK/2023. The author also extend appreciation for the invaluable technical assistance, resources, and financial support that made this research possible. Their contributions were crucial in the completion of this research.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding – This research was funded by the Research and Innovation for Advanced Indonesia (RIIM) Batch 4 of the National Research and Innovation Agency (BRIN) and the Education Fund Management Institution (LPDP).

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

References

- [1] M. Sahin, "Joining of aluminium and copper materials with friction welding," *The International Journal of Advanced Manufacturing Technology*, vol. 49, no. 5–8, pp. 527–534, Jul. 2010, doi: 10.1007/s00170-009-2443-7.
- [2] ASM Metal Handbook Vol.2, *Properties and Selection : Nonferrous Alloys and Special-Purpose Material*, vol. 2. 1992.
- [3] F. O. Edoziuno, C. C. Nwaeju, A. A. Adediran, B. U. Odoni, and V. R. Arun Prakash, "Mechanical and microstructural characteristics of Aluminium 6063 Alloy/Palm Kernel shell composites for lightweight applications," *Scientific African*, vol. 12, p. e00781, Jul. 2021, doi: 10.1016/j.sciaf.2021.e00781.
- [4] S. N. Mohtar, N. Jamal, and M. Sulaiman, "Analysis of all aluminum conductor (AAC) and all aluminum alloy conductor (AAAC)," in *2004 IEEE Region 10 Conference TENCON 2004.*, IEEE, 2004, pp. 409–412 Vol. 3. doi: 10.1109/TENCON.2004.1414794.
- [5] P. Kah and M. S. Jukka Martikainen, "Trends in joining dissimilar metals by welding," *Applied Mechanics and Materials*, vol. 440, no. 2014, pp. 269–276, 2013, doi: 10.4028/www.scientific.net/AMM.440.269.
- [6] G. B. Sathishkumar et al., "Friction welding of similar and dissimilar materials: A review," *Materials Today: Proceedings*, no. xxxx, 2021, doi: 10.1016/j.matpr.2021.03.089.
- [7] M. Aritoshi and K. Okita, "Friction welding of dissimilar metals," *Welding International*, vol. 17, no. 4, pp. 271–275, Jan. 2003, doi: 10.1533/wint.2003.3112.
- [8] J. P. Bergmann, F. Petzoldt, R. Schürer, and S. Schneider, "Solid-state welding of aluminum to copper - Case studies," *Welding in the World*, vol. 57, no. 4, pp. 541–550, 2013, doi: 10.1007/s40194-013-0049-z.
- [9] M. Uzkut, B. Ünlü, S. Yilmaz, and M. Akdağ, "Friction Welding And Its Applications In Today's World," *Sarajevo: International Symposium on Sustainable Development*, pp. 710–724, 2010.
- [10] E. oualid Bouarroudj, S. Chikh, S. Abdi, and D. Miroud, "Thermal analysis during a rotational friction welding," *Applied Thermal Engineering*, vol. 110, pp. 1543–1553, 2017, doi: 10.1016/j.applthermaleng.2016.09.067.
- [11] M. Maalekian, "Friction welding - Critical assessment of literature," *Science and Technology of Welding and Joining*, vol. 12, no. 8, pp. 738–759, 2007, doi: 10.1179/174329307X249333.
- [12] R. Ramesh Kumar et al., "Experimental and analytical investigation on friction welding dissimilar joints for aerospace applications," *Ain Shams Engineering Journal*, vol. 14, no. 2, p. 101853, 2023, doi: 10.1016/j.asej.2022.101853.
- [13] E. T. Akinlabi and R. M. Mahamood, *Solid-State Welding: Friction and Friction Stir Welding Processes*. in Mechanical Engineering Series. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-030-37015-2.
- [14] K. Faes, A. Dhooge, P. De Baets, E. Van Der Donckt, and W. De Waele, "Parameter

- optimisation for automatic pipeline girth welding using a new friction welding method," *Materials and Design*, vol. 30, no. 3, pp. 581–589, 2009, doi: 10.1016/j.matdes.2008.05.073.
- [15] M. Kimura, I. Yuusuke, M. Kusaka, and K. Kaizu, "Effects of friction welding conditions on tensile strength of friction welded joint between 5052 Al alloy and pure copper," *Mechanical Engineering Journal*, vol. 5, no. 2, pp. 17-00398-17-00398, 2018, doi: 10.1299/mej.17-00398.
- [16] M. Kimura, Y. Inui, M. Kusaka, K. Kaizu, and A. Fuji, "Joining phenomena and tensile strength of friction welded joint between pure aluminum and pure copper," *Mechanical Engineering Journal*, vol. 2, no. 1, pp. 14-00328-14-00328, 2015, doi: 10.1299/mej.14-00328.
- [17] S. Senkathir and V. B. Siddharth, "Friction welding of dissimilar metals (aluminium AL 6061 T6 and stainless steel AISI 304)," *IOP Conference Series: Materials Science and Engineering*, vol. 912, no. 3, pp. 1–10, 2020, doi: 10.1088/1757-899X/912/3/032043.
- [18] M. Aritoshi, K. Okita, T. Enjo, K. Ikeuchi, and F. Matsuda, "Friction welding of oxygen free copper to pure aluminium," *Welding International*, vol. 6, no. 11, pp. 853–859, Jan. 1992, doi: 10.1080/09507119209548302.
- [19] G. Wang, J. Li, W. Wang, J. Xiong, and F. Zhang, "Study on the effect of energy-input on the joint mechanical properties of rotary friction-welding," *Metals*, vol. 8, no. 11, 2018, doi: 10.3390/met8110908.
- [20] V. Milašinović et al., "Continuous Drive Friction Welded Al/Cu Joints Produced Using Short Welding Time, Elevated Rotational Speed, and High Welding Pressures," *Materials*, vol. 17, no. 13, p. 3284, Jul. 2024, doi: 10.3390/ma17133284.
- [21] E. P. Alves, F. P. Neto, C. Y. An, and E. C. da Silva, "Experimental determination of temperature during rotary friction welding of AA1050 aluminum with AISI 304 stainless steel," *Journal of Aerospace Technology and Management*, vol. 4, no. 1, pp. 61–68, 2012, doi: 10.5028/jatm.2012.04013211.
- [22] A. Sasmito, M. N. Ilman, P. T. Iswanto, and R. Muslih, "Effect of Rotational Speed on Static and Fatigue Properties of Rotary Friction Welded Dissimilar AA7075/AA5083 Aluminium Alloy Joints," *Metals*, vol. 12, no. 1, 2022, doi: 10.3390/met12010099.
- [23] Xun Li, L. Jinglong, J. Feng, X. Jiangtao, and Z. Fusheng, "Effect of rotation speed on friction behavior of rotary friction welding of AA6061-T6 aluminum alloy," *Welding in the World*, vol. 62, no. 5, pp. 923–930, 2018, doi: 10.1007/s40194-018-0601-y.
- [24] T. Sawai, K. Ogawa, H. Yamaguchi, H. Ochi, Y. Yamamoto, and Y. Suga, "Evaluation of joint strength of friction welded carbon steel by heat input," *Welding International*, vol. 16, no. 6, pp. 432–441, 2002, doi: 10.1080/09507110209549556.
- [25] K. Katoh and H. Tokisue, "Friction welding of aluminium to copper," *Welding International*, vol. 20, no. 7, pp. 525–531, 2010, doi: 10.1533/wint.2006.3596.
- [26] N. Ratković et al., "Experimental and Numerical Analysis of Rotary Friction Welding for Al-Cu Joints: Effects of Friction Time on Plastic Deformation and Joint Integrity," *Materials*, vol. 18, no. 9, 2025, doi: 10.3390/ma18091932.
- [27] L. Sauter, "Journal of Advanced Joining Processes Continuous drive friction welding of commercial pure aluminum to copper : Metallographic and mechanical characterization of various cross-sections," *Journal of Advanced Joining Processes*, vol. 12, no. June, p. 100342, 2025, doi: 10.1016/j.jajp.2025.100342.
- [28] F. Cao, P. Zhang, J. Zou, and T. Wang, "The formation and growth of intermetallic compounds during interdiffusion of Al/Cu bimetals," *Materials Research Express*, vol. 9, no. 5, 2022, doi: 10.1088/2053-1591/ac69b4.
- [29] Y. Wei, J. Li, J. Xiong, and F. Zhang, "Investigation of interdiffusion and intermetallic compounds in Al–Cu joint produced by continuous drive friction welding," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 90–95, Mar. 2016, doi: 10.1016/j.jestch.2015.05.009.
- [30] W. Li, Q. Wen, X. Yang, Y. Wang, D. Gao, and W. Wang, "Interface microstructure evolution and mechanical properties of Al/Cu bimetallic tubes fabricated by a novel friction-based welding technology," *Materials and Design*, vol. 134, pp. 383–393, 2017, doi: 10.1016/j.matdes.2017.08.065.
- [31] W. B. Lee, K. S. Bang, and S. B. Jung, "Effects of intermetallic compound on the electrical and mechanical properties of friction welded Cu/Al bimetallic joints during annealing," *Journal of*

- Alloys and Compounds*, vol. 390, no. 1–2, pp. 212–219, 2005, doi: 10.1016/j.jallcom.2004.07.057.
- [32] W. S. Ebhota and T.-C. Jen, “Intermetallics Formation and Their Effect on Mechanical Properties of Al-Si-X Alloys,” *Intermetallic Compounds - Formation and Applications*, 2018, doi: 10.5772/intechopen.73188.
- [33] Mohammed Asif and Shri, “The impact of heat input on the strength, toughness, microhardness, microstructure and corrosion aspects of friction welded duplex stainless steel joints,” *Journal of Manufacturing Processes*, vol. 18, pp. 92–106, 2015, doi: 10.1016/j.jmapro.2015.01.004.
- [34] H. Ochi, K. Ogawa, Y. Yamamoto, G. Kawai, and T. Sawai, “The formation of intermetallic compounds in aluminium alloy to copper friction-welded joints and their effect on joint efficiency,” *Welding International*, vol. 18, no. 7, pp. 516–523, 2004, doi: 10.1533/wint.2004.3282.