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Metallurgical Review of Al–Cu Friction Welded Joints

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ABSTRACT

Friction welding of aluminum and copper is a solid-state joining technique widely used in electrical and industrial applications. Significant differences in physical and thermal properties between these metals create challenges at the joint interface. This review focuses on the metallurgical characterization of Al–Cu friction welded joints, emphasizing intermetallic compound (IMC) formation and growth, and the influence of process parameters such as temperature, pressure, friction time, and rotational speed on microstructure and mechanical performance. Excessive IMC layers can cause embrittlement, interfacial cracking, porosity, and reduced thermal stability. Recent advances in process optimization, active cooling, and interface engineering have improved joint strength, ductility, and conductivity. Controlling IMC growth and understanding intermetallic diffusion are crucial for producing reliable Al-Cu joints. This review summarizes current strategies for enhancing the mechanical performance of Al–Cu friction welded joints.

KEYWORDS: *Al-Cu; Friction Welding; Intermetallic Compounds; Joint Strength; Metallurgical Characterization.*

1. INTRODUCTION

Aluminum and copper are widely used in modern manufacturing industries, particularly in the electrical, automotive, and aerospace sectors, due to their excellent electrical and thermal conductivity [1],[2],[3]. Copper offers superior electrical conductivity; however, it is relatively expensive and its availability in the market is limited. In contrast, aluminum provides several advantages, including a lower melting point, low density, good corrosion resistance, and more economical material costs [4],[5],[6],[7],[8],[9].

In electrical applications, copper is typically employed in regions with high current density, whereas aluminum is more commonly used in areas with lower current density [10]. In the automotive industry, the use of aluminum–copper joints are considered an effective approach to reducing vehicle weight, thereby improving energy efficiency and supporting environmental sustainability at a lower cost [11].

However, significant differences in the physical and thermal properties of aluminum and copper, such as melting temperature, thermal conductivity, and coefficients of thermal expansion, pose substantial challenges in producing high quality joints [4]. Conventional fusion welding of aluminum and copper often leads to various defects, including cracking and porosity, which adversely affect mechanical strength and joint reliability [1],[12]. Moreover, the large disparity in melting temperatures between aluminum and copper promotes the formation of thick and brittle intermetallic layers, further degrading the mechanical performance of the joint. Consequently, friction welding has emerged as a promising alternative because it is a solid-state process that avoids melting of the base materials. This process enhances joint mechanical properties, eliminates the need for filler materials, simplifies production procedures, and reduces manufacturing costs [12],[13]. In friction welding, heat is generated through friction between two rotating metal surfaces, enabling atomic bonding to occur without exceeding the melting temperatures of the base metals. Owing to its solid-state nature and absence of melting, friction welding represents an effective and reliable approach for joining aluminum and copper [14].

Research on the metallurgical characterization of aluminum copper joints produced by friction welding remains a complex and continuously evolving topic. Process parameters such as friction time, friction pressure, and rotational speed strongly influence the interfacial temperature and the metallurgical phenomena occurring across the joint zone, which ultimately determine the mechanical properties of the welded joint [15]. A comprehensive understanding of the relationship between process parameters, microstructural evolution, and mechanical behavior is therefore essential for optimizing joint quality. Accordingly, this review aims to provide a comprehensive overview of the metallurgical phenomena occurring in aluminum copper friction welded joints, highlight recent research developments, and identify existing research gaps in the field of friction welding of these dissimilar metals.

2. LITERATURE REVIEW

Friction welding is a solid-state joining process that is widely used for joining dissimilar metals [15]. The process utilizes heat generated by friction and plastic deformation at the metal interface without causing melting of the base materials. The frictional heat softens the material in the interfacial region, thereby enabling atomic diffusion and the formation of metallurgical bonds between the joining surfaces. In general, friction welding can be classified into three main categories, namely rotary friction welding, friction stir welding, and linear friction welding [12]. Although these methods share the same fundamental principle of using frictional energy to generate heat at the joint interface, they differ in terms of processing mechanisms and application areas.

Rotary friction welding is employed to join components of various geometries, including plates, rods, and pipes, whereas friction stir welding and linear friction welding are primarily applied to plate joining. In friction stir welding, the joining process is achieved through friction generated by a rotating tool [16], while linear friction welding relies on direct oscillatory friction between the mating surfaces [17],[18]. The basic principle of rotary friction welding involves clamping one component and rotating it at a prescribed speed, while the other component is axially pressed against it to generate friction at the interface. The heat produced by friction and plastic deformation softens the interfacial material, enabling metallurgical bonding to occur when rotation is stopped and axial pressure is maintained during the forging stage [4]. In general, rotary friction welding can be classified into two types, namely continuous drive friction welding and inertia friction welding. In this process, the primary source of welding energy is derived from heat generated by friction and plastic deformation at the interface of the two base metals, which has a significant influence on the microstructure and mechanical properties of the joint [12]. A schematic illustration of the rotary friction welding process, consisting of four main stages, is presented in Figure 1.

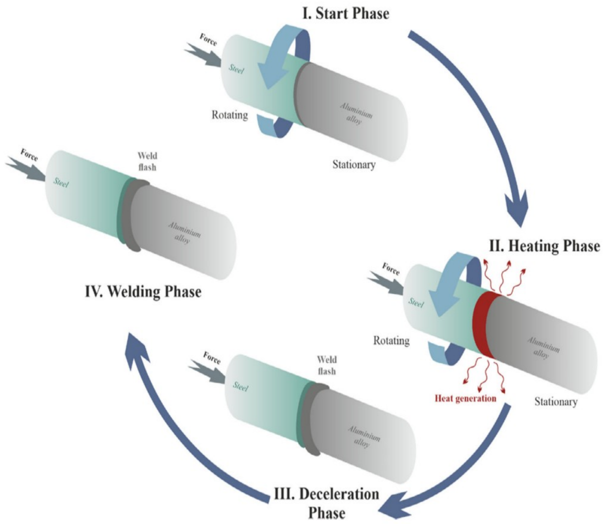

Figure 1: Schematic illustration of the rotary friction welding process for bulk materials, highlighting the individual stages: (I) initial, (II) heating, (III) deceleration, and (IV) forging [6]

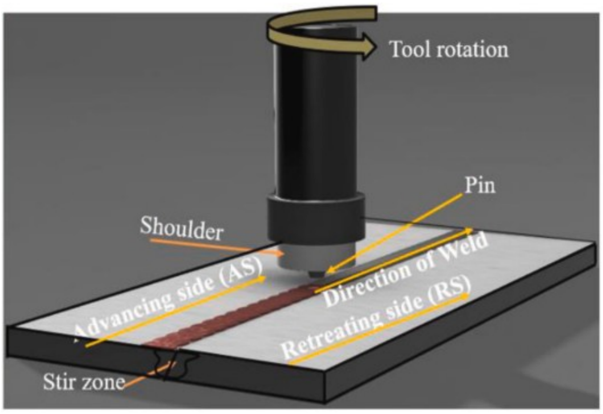

Figure 2: Schematic illustration of the friction stir welding process [21]

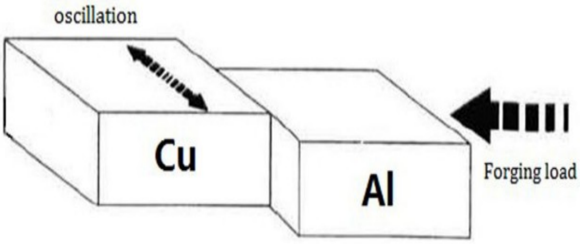

Figure 3: Schematic illustration of the linear friction welding process [22]

In friction stir welding, a rotating tool consisting of a pin and a shoulder is pressed against the joint surface, generating sufficient frictional heat to soften the material without causing melting. The softened material then undergoes intense plastic mixing along the welding path, resulting in a strong and homogeneous joint [19],[20]. Friction stir welding is well known for producing high quality welds with minimal defects, such as porosity and solidification cracking [19]. Linear friction welding operates on a principle similar to that of rotary friction welding; however, the relative motion between the two materials is achieved through high frequency linear reciprocating movement. The friction generated by this motion produces heat and plastic deformation at the interface, leading to the formation of a solid-state bond. A schematic representation of the linear friction welding process is shown in Figures 2 and 3. This method offers several advantages, including cost efficiency, high reliability, and the ability to produce joints with minimal defects [17],[18].

The intense frictional heat and applied mechanical pressure during the friction welding process raise the interfacial temperature, thereby promoting the diffusion of aluminum and copper atoms. Aluminum atoms tend to diffuse more rapidly into copper due to their smaller atomic size and higher diffusivity. As diffusion proceeds, atomic interactions and reactions occur, leading to the formation of intermetallic compounds at specific compositional ratios and temperatures [23],[24]. The diffusion rate plays a critical role in intermetallic compound formation, as represented by the diffusion coefficient D, as defined in Equation (1). Higher values of the diffusion coefficient correspond to increased diffusion rates, resulting in the formation of thicker intermetallic layers [4]. These intermetallic compounds are phases that form and can be identified based on the binary aluminum copper phase diagram.

Figure 4 presents the Al Cu binary phase diagram at atmospheric pressure for various compositions [25]. The intermetallic compounds most commonly formed during aluminum copper friction welding include Al_2Cu (θ), Al_4Cu_9 (γ), and AlCu (η). The θ phase (Al_2Cu), which is copper rich with a copper content exceeding 53 percent, exhibits brittle behavior and has an atomic ratio of n(Al) to n(Cu) of approximately 2 to 1 [23]. This phase is frequently reported as a crack initiation site. The γ phase (Al_4Cu_9) tends to develop closer to the copper rich side, possesses a complex crystal structure, and is generally characterized by high hardness and brittleness [26],[25],[27]. The η phase (AlCu) is a metastable intermetallic compound with an orthorhombic crystal structure, formed under stable thermal conditions and compositional gradients during the friction welding process. Owing to its relative stability, this phase can contribute to optimal strength and hardness. In addition, the η phase exhibits distinct structural characteristics associated with its orthorhombic crystal structure [24]. Intermetallic compounds continue to grow during the diffusion process. A controlled intermetallic layer thickness enhances joint quality, whereas excessive or overly thick intermetallic layers tend to be hard and brittle, thereby reducing joint toughness and strength [2].

The formation of inter-metallic compounds during the friction welding process is strongly influenced by process parameters; therefore, controlling their growth is essential to achieve optimal joint quality [24]. The primary process parameters in friction welding include friction time, friction pressure, upset time, upset pressure, rotational speed, and component geometry [15]. A major limitation of this method is that effective metallurgical bonding can only be achieved within a relatively narrow processing window. Outside this range, excessive formation of intermetallic compounds may occur, which in turn adversely affects joint strength and electrical conductivity [28]. Several previous studies have investigated the influence of friction welding parameters on joint quality using both experimental approaches and statistical analyses [6],[28].

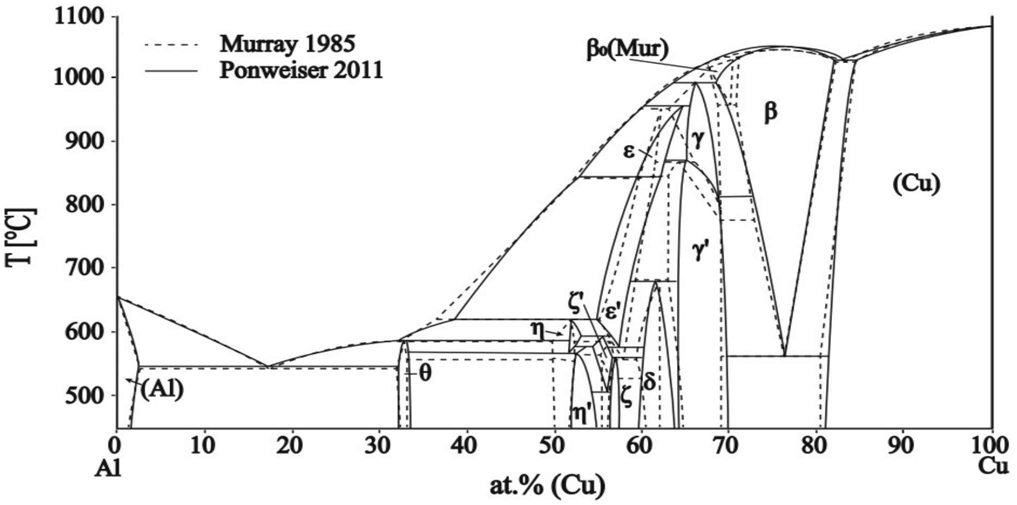

Figure 4: Binary Al–Cu phase diagram [25]

Longer friction times increase both the duration of thermal exposure and the intensity of mechanical stirring at the interface. This condition promotes more extensive atomic diffusion, thereby accelerating the growth of the intermetallic compound layer [13]. Several studies have reported that the optimal friction time for aluminum copper friction welding lies in the range of 30 to 45 seconds [29],[30]. In addition, increasing friction pressure generally tends to reduce the thickness of the intermetallic compound layer [10]. Based on reported findings, the optimal friction pressure for aluminum copper friction welding ranges from 3 to 10 MPa per second [11],[15],[31]. Higher rotational speeds increase frictional heat generation and enhance plastic flow, thereby expanding the weld zone and accelerating diffusion at the interface. As a result, thicker intermetallic layers may form due to elevated temperatures and intensified material mixing. Component geometry also plays a significant role in heat generation and material flow behavior. Larger contact areas or specific tool geometries, such as conical angles or pin shapes, can alter temperature distribution and plastic deformation, thereby influencing local diffusion conditions [13]. In addition, the condition of the faying surfaces is critical to joint quality; therefore, proper surface preparation prior to welding is essential. Cleaning of aluminum and copper surfaces is mandatory, as both metals tend to form oxide layers when exposed to air [28].

In friction welding of dissimilar metals, several common challenges are frequently encountered, including interfacial cracking, brittleness of the intermetallic compound layer, porosity, and thermal instability of the joint. Interfacial cracks typically arise from the formation of highly brittle intermetallic layers, which act as stress concentration sites within the joint region [1],[32]. The brittle nature of these layers restricts plastic deformation, thereby increasing the likelihood of joint failure under tensile or shear loading conditions [32]. In addition, porosity or internal voids may form when the combination of frictional heat generation and material flow is not optimal, ultimately reducing structural continuity and joint strength [32],[33]. Differences in thermophysical properties, such as thermal conductivity, coefficients of thermal expansion, and cooling rates between the joined metals, also contribute to thermal instability of the joint. These conditions may induce residual stresses, distortion, and post weld microstructural changes, which adversely affect the long-term performance of the joint. Therefore, careful control of process parameters, appropriate joint geometry design, and a comprehensive understanding of interfacial characteristics are critical factors for minimizing these issues and ensuring the formation of strong and reliable joints.

3. DISCUSSION

3.1 Process Parameters and Microstructural Evolution

Table 1 presents a selection of aluminum copper friction welding studies published over the past ten years. Based on the welding method employed, eleven articles utilized Rotary Friction Welding (RFW) or Continuous Drive Friction Welding (CDFW), thirteen employed Frictions Stir Welding (FSW) or Friction Stir Spot Welding (FSSW), and one study applied Linear Friction Welding (LFW). Table 2 summarizes the mode values of the corresponding process parameters, while Figure 5 illustrates the distribution of these parameter modes for aluminum copper friction welding. The mode of each parameter was calculated using Equation (1), where amount represents the number of selected parameter values and N denotes the total number of aluminum copper friction welding articles considered in the analysis [34].

$$\text{Modus} = (\text{Amount} / N) \times 100\% \qquad (1)$$

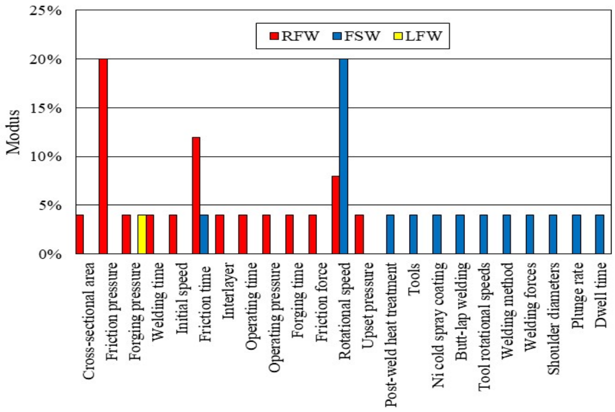

Figure 5: Modus plot of aluminum copper friction welding parameters

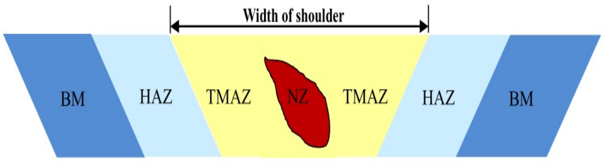

Figure 6: Friction stir welding zones [46]

Table 1: Aluminum copper friction welding studies

Type of Friction Welding	Research Parameters	Testing	Ref.
RFW (CDFW)	Cross-sectional area	SEM-EDX, tensile, hardness	[35]
RFW	Friction pressure	Microstructure, tensile, hardness	[4]
RFW (CDFW)	Friction pressure and forging pressure	Analysis of thermal images, SEM-EDS, microstructure, hardness, tensile	[10]
RFW	Welding time	Microstructure, tensile, hardness	[36]
RFW	Friction pressure	Tensile, bend	[37]
RFW	Initial speed	Microstructure, Tensile	[32]
RFW (CDFW)	Friction time	SEM-EDS, XRD	[38]
RFW	Interlayer	Bend, SEM-EDS, and hardness.	[2]
RFW	Operating Time, Operating Pressure, Forging Time, and Forging Pressure.	SEM-EDS	[28]
RFW	Friction force, rotational speed, friction pressure, and friction time.	Response surface method (RSM)	[39]
RFW	Friction Pressure, Upset Pressure, Rotational Speed, and Friction Time.	Tensile and bend.	[40]
FSW	Friction time	Microstructure, hardness, numerical simulation	[13]
FSW	Post-weld heat treatment	Microstructure, SEM-EDS, XRD, hardness, and tensile.	[1]
FSW	Rotational speed	Microstructure, hardness, tensile, SEM, and fatigue cracks growth	[19]
FSW	Tools	Microstructure, tensile, hardness, and XRD.	[41]
FSW	Rotational speed	Microstructure, SEM-EDS, XRD, EBSD, hardness, and tensile.	[42]
FSW	Ni cold spray coating	SEM-EDS, TEM, tensile, hardness, and XRD.	[43]
FSW	Butt-lap welding	FE-SEM, EDS	[44]
FSW	Rotational speed	Microstructure and hardness.	[45]
FSW	Tool rotational speeds	Heat generation, microstructure, XRD, hardness, and tensile.	[46]
FSW	Welding method	XRD and SEM-EDS	[47]
FSSW	Rotational speed	Tensile	[48]
FSSW	Welding forces and shoulder diameters	Microstructure, tensile	[49]
FSSW	Rotational speed, Plunge rate, and dwell time.	SEM, hardness, and bend.	[50]
LFW	Forging pressure	Microstructure, SEM-EDX, hardness, and tensile	[22]

Table 2: Modus of aluminum copper friction welding parameters

Research	RFW		FSW		LFW	
parameters	Amount	Modus	Amount	Modus	Amount	Modus
Cross-sectional area	1	4%	0	0%	0	0%
Friction pressure	5	20%	0	0%	0	0%
Forging pressure	1	4%	0	0%	1	4%
Welding time	1	4%	0	0%	0	0%
Initial speed	1	4%	0	0%	0	0%
Friction time	3	12%	1	4%	0	0%
Interlayer	1	4%	0	0%	0	0%
Operating time	1	4%	0	0%	0	0%
Operating pressure	1	4%	0	0%	0	0%
Forging time	1	4%	0	0%	0	0%
Friction force	1	4%	0	0%	0	0%
Rotational speed	2	8%	5	20%	0	0%
Upset pressure	1	4%	0	0%	0	0%
Post-weld heat treatment	0	0%	1	4%	0	0%
Tools	0	0%	1	4%	0	0%
Ni cold spray coating	0	0%	1	4%	0	0%
Butt-lap welding	0	0%	1	4%	0	0%
Tool rotational speeds	0	0%	1	4%	0	0%
Welding method	0	0%	1	4%	0	0%
Welding forces	0	0%	1	4%	0	0%
Shoulder diameters	0	0%	1	4%	0	0%
Plunge rate	0	0%	1	4%	0	0%
Dwell time	0	0%	1	4%	0	0%

Process parameters in friction welding, such as friction pressure, friction time, upset time, and rotational speed, play a critical role in heat generation, plastic deformation, and microstructural evolution, including diffusion, intermetallic compound growth, recrystallization, and the formation of potential defects in aluminum copper joints [13],[51]. Based on Table 2 and Figure 5, the most extensively investigated parameters in aluminum copper of the friction welding are friction pressure and rotational speed, both of which strongly influence microstructural evolution in the weld region. The microstructure produced by rotary friction welding consists of the center weld zone, the thermo mechanically affected zone, the heat affected zone, and the base metal [4],[7],[19]. In friction stir welding, the microstructural regions include the weld nugget zone, the thermo mechanically affected zone, the heat affected zone, and the base material, as illustrated in Figure 6 [19],[46]. In linear friction welding, the joint typically comprises the friction interface zone or center weld zone, the thermo mechanically affected zone, the heat affected zone, and the base material [17],[22],[52]. Figures 7 to 9 present representative joint morphologies obtained using rotary friction welding, friction stir welding, and linear friction welding, respectively.

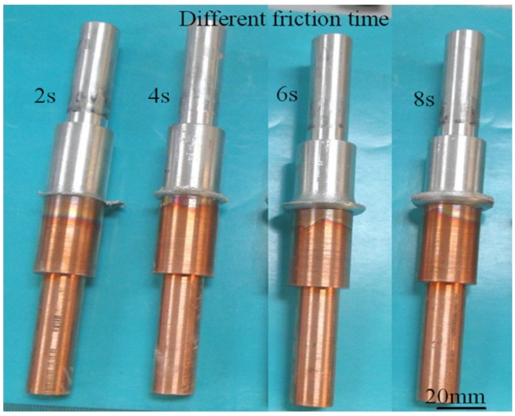

Figure 7: Macrostructure of aluminum copper welded joints under different process parameters [38]

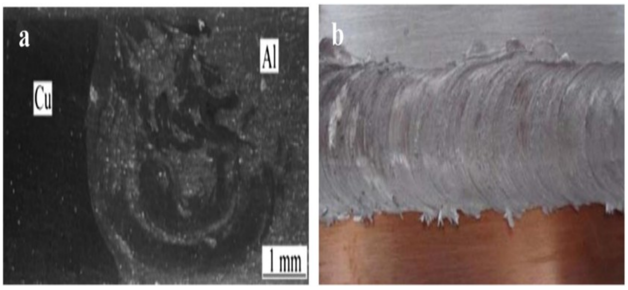

Figure 8: (a) Macroscopic view of an Al–Cu joint without intermetallic compounds and (b) surface appearance of the joint [32]

Figure 9: Macroscopic features of joints produced by linear friction welding [53]

An increase in friction pressure during rotary friction welding generally leads to a reduction in intermetallic compound thickness [10]. However, excessively high friction pressure can significantly raise the interfacial temperature, resulting in nonuniform intermetallic compound distribution at the interface and ultimately reducing joint strength [54]. Although intermetallic compounds are inherently brittle, a uniform distribution and fine microstructure within the center weld zone can still enhance joint strength [9]. Within the center weld zone, intermetallic compounds such as AlCu, Al_2Cu, and Al_4Cu_9 are typically formed, particularly on the copper rich side, as a result of thermally driven reactions between the two metals. These compounds exhibit brittle behavior [32],[55] and significantly influence the mechanical strength and stability of aluminum copper joints [23]. Consequently, intermetallic compound thickness is considered a key parameter in determining overall joint quality [44].

An increase in rotational speed generally promotes grain coarsening as a result of higher heat input and reduced cooling rates [12]. Mattie et al. reported that rotational speed does not significantly affect the overall welding process but has a pronounced influence on total deformation [56]. Increased deformation enhances diffusion rates, thereby promoting the growth of intermetallic compounds such as AlCu, Al_2Cu, and Al_4Cu_9 at the interface [13],[35]. In addition, longer friction times increase heat input and plastic deformation, leading to an increase in intermetallic compound thickness [13],[37],[57]. However, excessively long friction times may result in overly thick intermetallic layers and cause joint embrittlement [10]. Figure 10 illustrates the microstructure of aluminum copper joints produced by rotary friction welding.

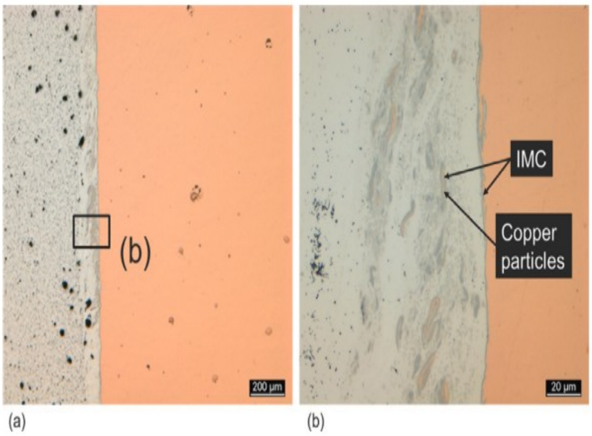

Figure 10: Optical micrographs of the central Al–Cu interface at different magnifications [35]

In friction stir welding, higher rotational speeds increase heat input and promote more intense material flow, resulting in thicker and more continuous intermetallic compound layers along both the stirred zone and the interface [58]. In contrast, lower rotational speeds lead to insufficient stirring, which may cause void defects and produce thinner, discontinuous intermetallic layers [59]. Other parameters influencing the friction stir welding process include axial force, welding depth, and pin and shoulder geometry. Higher axial forces and greater welding depths can expand the stirred zone, thereby increasing intermetallic compound layer thickness [24],[60].

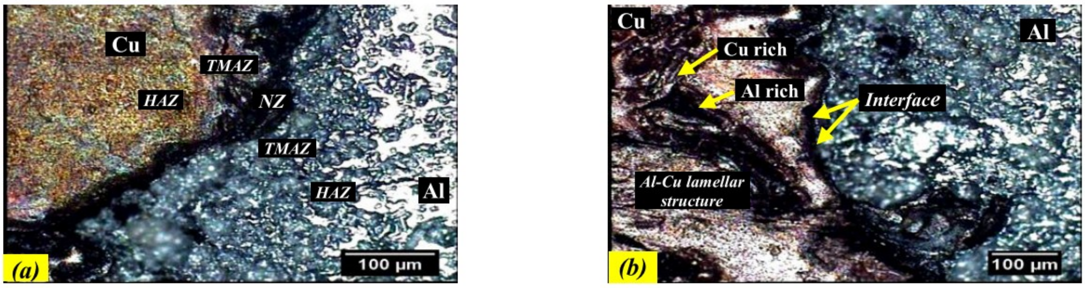

Figure 11: Microstructural analysis of dissimilar aluminum copper joints produced by friction stir welding at (a) 1750 RPM and (b) 2000 RPM [46]

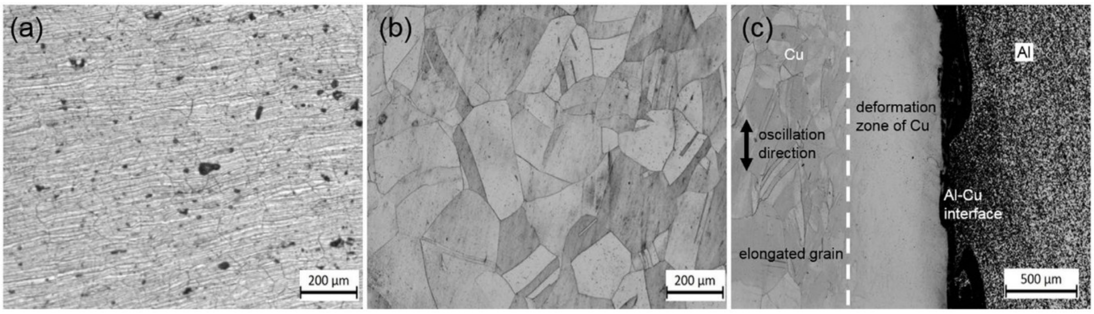

Figure 12: Microstructure of the Al–Cu joint produced by linear friction welding: (a) aluminum base metal; (b) copper base metal; and (c) Al–Cu interface showing the weld region [22]

Pin geometry also plays a significant role in heat input during friction stir welding, which in turn affects grain coarsening and the dissolution of precipitate phases [61]. Square pin geometries have been reported to produce superior joint morphology and mechanical properties due to the generation of a distinctive stirring pattern. This pattern arises from pulsating motion at the sharp pin edges, which enhances material transport within the stirred zone during tool rotation and welding progression [61]. Figure 11 presents the microstructure of aluminum copper joints produced by friction stir welding.

Based on Table 2, the primary process parameter applied in linear friction welding is forging pressure, which has a significant influence on heat input, deformation level, and diffusion rate at the joint interface [22]. An increase in forging pressure has been shown to promote the growth of intermetallic compounds along the joint interface [22],[62]. In addition, higher forging pressure can induce dynamic recrystallization, resulting in finer grain sizes and a tendency toward increased hardness in the vicinity of the intermetallic compound layer [22],[63]. Although other parameters, such as friction pressure and friction time, may also affect the quality of linear friction welded joints, limited studies have specifically investigated the influence of these parameters on the welding of dissimilar aluminum and copper materials. Figure 12 presents the microstructure of aluminum copper joints produced by linear friction welding.

3.2 Characterization of Friction-Welded Joints and Their Mechanical Properties

Material characterization techniques are used to investigate the metallurgical phenomena in friction welded Al–Cu joints. The following methods are commonly employed for this purpose.

SEM-EDS

Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM–EDS) analyses reported in the literature consistently indicate that the interfacial microstructure of Al–Cu friction-welded joints is predominantly composed of intermetallic compounds, particularly Al_2Cu and Al_4Cu_9. [13]. Increases in friction pressure, rotational speed, and friction time can expand the diffusion zone, resulting in thicker IMC layers [13],[35]. Optimal process conditions produce thin and uniform IMC layers, thereby enhancing the mechanical properties of the joint [64], [65]. According to various studies, the optimal friction pressure ranges from 80 to 150 MPa, ensuring full interfacial contact while minimizing unbonded areas. Excessively high friction pressures (>150 MPa) tend to produce thick and brittle IMC layers [13],[66]. The optimal rotational speed lies between 1000 and 2000 rpm, providing sufficient heat input to form strong joints [13],[67]. Friction times of 5 to 8 seconds are generally sufficient to control the width of the diffusion zone and the thickness of the IMC layer, ultimately improving joint strength. Longer friction times may result in excessive heat and reduced joint quality [13],[56]. Figures 13 and 14 present SEM–EDS analyses of aluminum–copper joints produced by conventional friction stir welding and underwater friction stir welding [47].

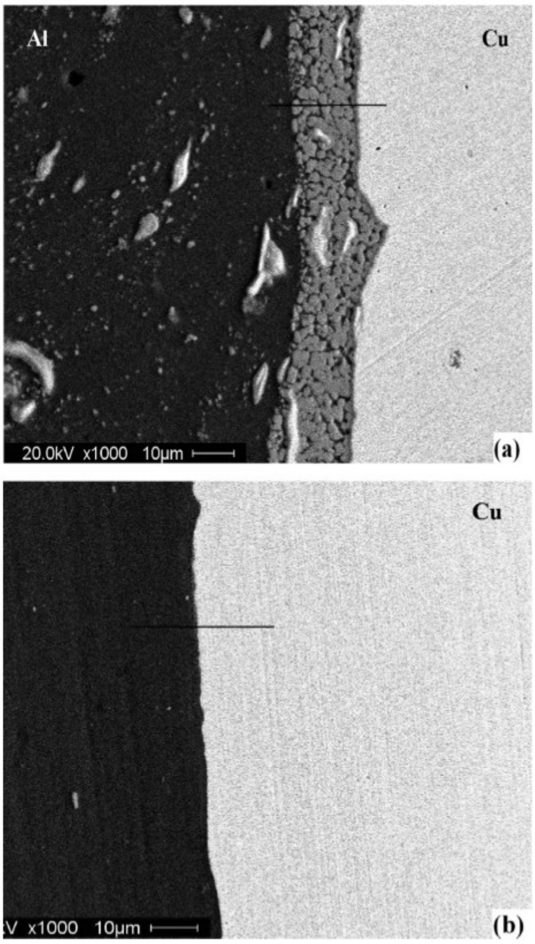

Figure 13: SEM images of (a) a localized region in conventional FSW and (b) a localized region in underwater FSW [47]

XRD

X-ray diffraction (XRD) characterization in aluminum–copper friction welding is used to identify crystalline phases at the weld interface, particularly intermetallic compounds (IMCs) formed through Al–Cu interdiffusion, by matching diffraction patterns with standard databases [13],[56]. Figure 15 presents XRD analyses of FSW joints at different rotational speeds, showing variations in diffraction peak positions under each condition.

According to Dawood et al [46], intermetallic compounds were detected at a rotational speed of 2000 rpm (Figure 15a) as a result of chemical reactions occurring during the welding process. In contrast, at rotational speeds of 1750 and 1000 rpm (Figures 15b and 15c), no intermetallic compounds were detected, indicating that chemical reactions at the interface had not yet occurred during welding. XRD analyses were conducted along the weld zone. On the aluminum side, the α-Al phase dominates, while moving toward the center, the intensity of α-Al decreases as the θ-Al_2Cu phase begins to appear [13]. On the copper side, the Cu phase is predominant, with the possible presence of copper-rich intermetallic compounds, indicating the extent of diffusion [50],[68].

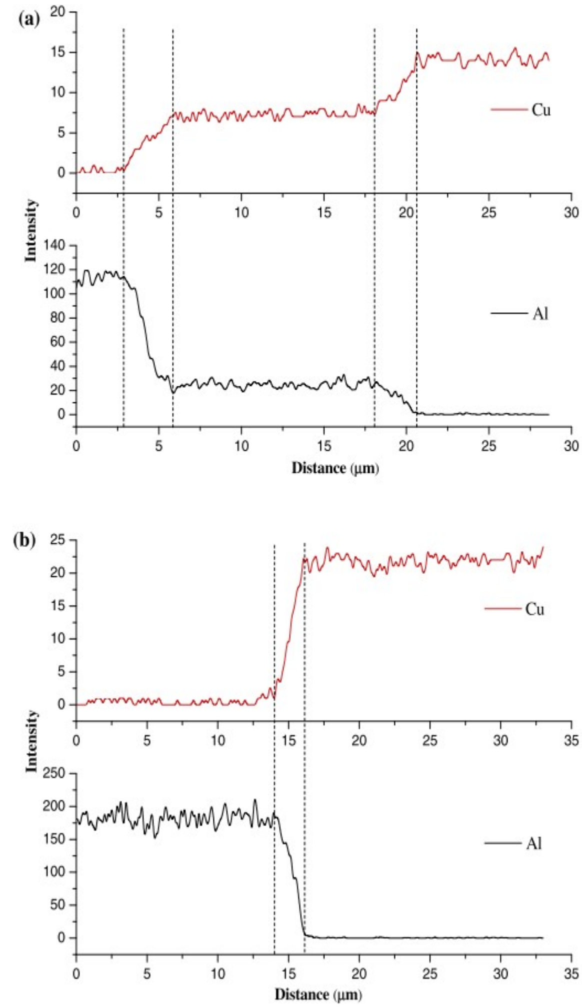

Figure 14: Major elemental profiles obtained from EDS line scans corresponding to (a) Figure 13a and (b) Figure 13b [47]

Vickers Micro-hardness

Friction welding process parameters significantly influence hardness distribution across the different joint zones. Hardness in the heat-affected zone (HAZ) is generally lower than in the base metal (BM) due to grain growth induced by thermal cycling in this region [42], [44]. In contrast, intense plastic deformation and dynamic recrystallization at the center weld zone (CWZ) produce very fine grains, resulting in higher hardness values compared to the other zones [42]. Furthermore, increased friction pressure and rotational speed generate higher heat input, which enhances diffusion rates and promotes the formation of brittle intermetallic compound (IMC) layers with high hardness characteristics [69]. Figure 16 illustrates the Vickers microhardness distribution, showing that increasing rotational speed gradually leads to more pronounced grain recovery and growth due to elevated heat input [42].

Tensile Strength

The tensile strength of aluminum–copper friction welded joints is strongly influenced by the characteristics of the intermetallic compound (IMC) layer. Thin and continuous IMC layers can form stable, non-brittle bonds, causing joint failure to typically shift to the heat affected zone (HAZ) [13]. An optimal combination of process parameters, including moderate rotational speed, moderate friction pressure, and short friction time, helps control heat input, limit excessive IMC growth, and maintain joint ductility. A comparison of tensile strengths at different rotational speeds shows that 1750 rpm yields the highest tensile strength compared to 1000 and 2000 rpm. At excessively high rotational speeds, increased heat input results in thicker, non-uniform IMC layers accompanied by microcracks, reducing joint strength. Overall, the tensile strength of the welded joint remains lower than that of the base metals, with fractures predominantly occurring on the aluminum side near the weld nugget zone (WNZ). This behavior is associated with intense plastic deformation and ultrafine grain formation, which reduce local deformation resistance [46].

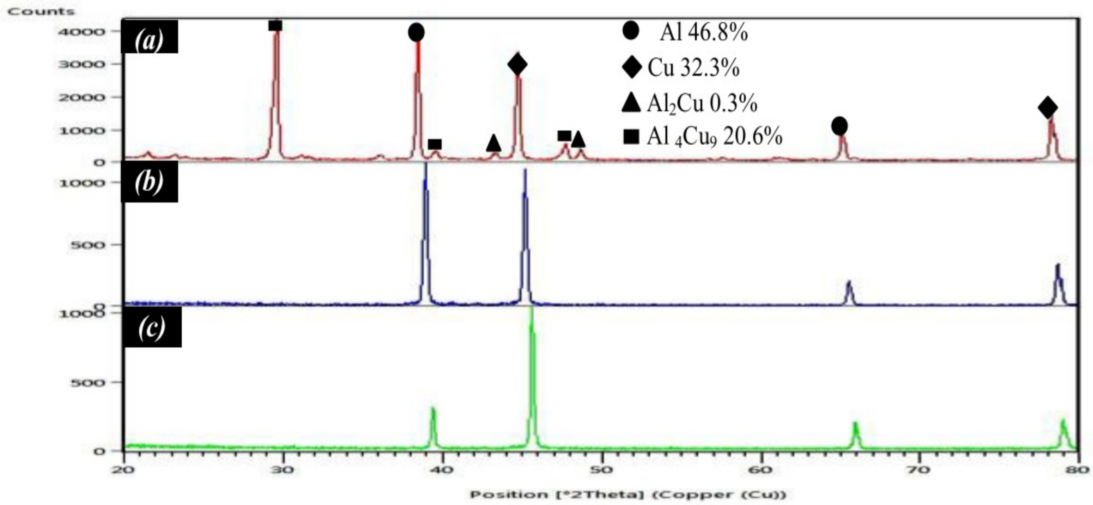

Figure 15: XRD analysis of FSW joints at rotational speeds of (a) 2000 RPM, (b) 1750 RPM, and (c) 1000 RPM [46]

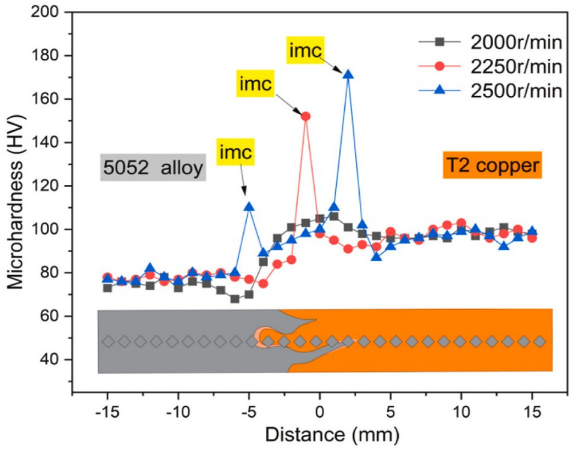

Figure 16: Microhardness distribution at different rotational speeds [42]

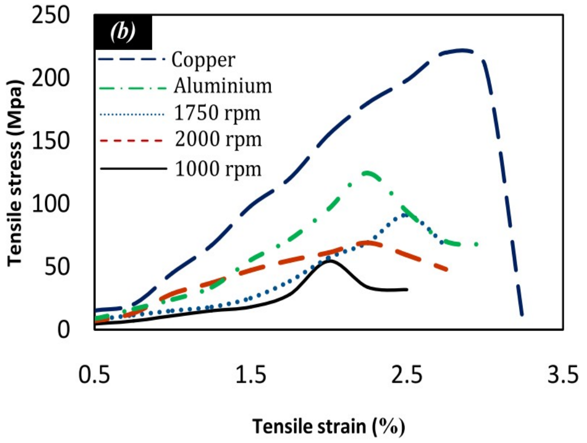

Figure 17: Tensile stress–strain curves of dissimilar Al-Cu FSW joints compared to the base metals [46]

Fractography analysis using field emission scanning electron microscopy (FESEM) (Figure 18) supports these findings. At a rotational speed of 1000 rpm, failure occurred on the aluminum side near the weld nugget zone (WNZ), with the presence of voids indicating incomplete bonding. Joints produced at 1750 rpm exhibited ductile fracture characteristics, whereas at 2000 rpm, brittle fracture dominated, featuring uneven fracture surfaces and the presence of copper particles on the aluminum side. These results confirm that the failure mechanism of Al–Cu FSW joints is governed by the thermomechanical conditions during welding, which dictate the microstructural evolution and morphology of the inter-metallic compound layers [46].

3.3 Recent Advances in Al–Cu Friction Welding

Recent advances in aluminum–copper friction welding have focused on controlling the formation of hard and brittle intermetallic compounds (IMCs). Numerous studies have investigated the optimization of process parameters, such as friction pressure, rotational speed, and friction time, which play a critical role in balancing heat input and plastic deformation. This optimization results in thinner, more homogeneous IMC layers and improved joint strength.

In addition, joint performance can be enhanced through the use of interlayers, such as nickel (Ni). Hou et al. reported that Al–Cu friction welded joints with a cold-sprayed Ni interlayer exhibited the formation of Al_2Cu, Al_4Cu_9, and Al_3Ni_3 phases in the center weld zone, reducing IMC thickness from approximately 1.2 µm to about 200 nm and increasing tensile strength by 10.5% [43]. Beyond experimental approaches, numerical modeling is increasingly employed to study microstructural evolution, predict joint feasibility, and accelerate process optimization. Ratković et al. reported numerical simulations of aluminum–copper friction welding that showed high agreement with experimental results [13]. Similarly, Li et al. used finite element methods to predict the microstructure and quality of inertia friction welded (IFW) joints [70].

Despite significant progress, major challenges remain in controlling IMC growth under high heat input conditions and the limited availability of long-term performance data, particularly under cyclic loading and complex service environments. Therefore, future research should focus on developing more precise IMC control strategies through the integration of process optimization, interface engineering, and numerical modeling to enable reliable and sustainable industrial applications of aluminum–copper friction welding.

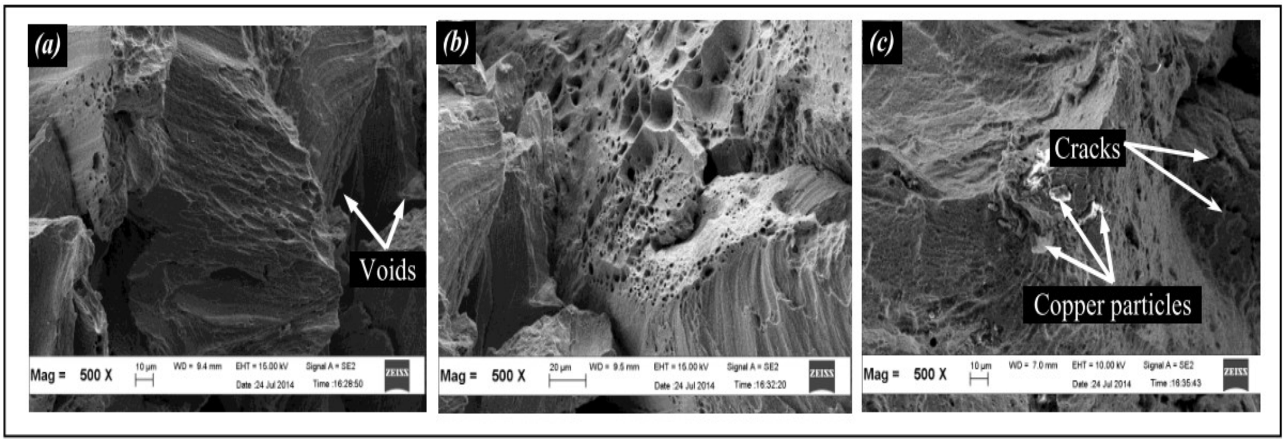

Figure 18: FESEM images showing the tensile fracture surface modes of dissimilar Al-Cu joints produced by friction stir welding (FSW): (a) 1000 RPM, (b) 1750 RPM and (c) 2000 RPM [46]

4. CONCLUSION

Metallurgical characterization of aluminum–copper friction welded joints indicates that the quality of the metallurgical bond is largely determined by the formation and control of intermetallic compound (IMC) layers at the interface, which are directly influenced by welding process parameters. Parameters such as friction pressure, rotational speed, friction time, and forging pressure govern heat input, plastic deformation, and the diffusion rate of Al–Cu atoms, thereby determining the thickness, homogeneity, and stability of the IMC layers. Although understanding of diffusion mechanisms, microstructural evolution, and mechanical behavior of the joints has advanced significantly, key challenges—such as excessive IMC growth, interfacial cracking, porosity, and thermal instability—still limit joint performance, especially under high heat input conditions and cyclic loading. Various approaches, including process parameter optimization, interface engineering through interlayers, and numerical modeling, have shown great potential in mitigating brittle IMC formation and enhancing joint strength and reliability. Therefore, future research should focus on developing innovative cooling strategies to produce aluminum–copper joints that are efficient, thermally stable, and reliable for high-performance industrial applications.

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