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Effect of squeeze casting pressure on the interdiffusion zone characteristics of the aluminum-copper bimetallic layer

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ABSTRACT

Bimetals are composite materials created by combining two different metals with metallurgical bonding at their interface. Squeeze casting is a promising method for bimetal manufacturing; however, the optimal pressure required to achieve desirable mechanical properties remains under investigation. This study aims to determine the casting pressure required to achieve an optimal interdiffusion bond at the aluminium–copper interface. In this work, aluminum and copper alloys were used, with aluminum melted at 750 °C and copper at 1150 °C. The process involved sequentially pouring molten metals into the mould. Copper was poured first, and once partial solidification occurred, aluminum was subsequently poured, forming an Al–Cu bimetal bushing. Pressure was applied during the first frozen-layer stage at 60, 70, 80, and 90 MPa. Results revealed that applying greater pressure promotes the development of a thicker interdiffusion layer. The interface region exhibited the highest hardness and wear resistance due to the in-situ formation of Al_2Cu and Al_4Cu_9 compounds. Therefore, Al–Cu bimetal can be effectively produced by squeeze casting at 90 MPa, resulting in an optimal interdiffusion zone at the interface.

Keywords: Bimetal, Aluminum-copper, Squeeze casting, Interdiffusion

INTRODUCTION

Bimetals are defined as composite materials created by joining two different metal alloys into separate layers, forming a microstructure bond that improves the material's mechanical characteristics [1–4]. One of the most widely developed examples of bimetals is the aluminum–copper bimetal (Al–Cu bimetal). Recently, Al–Cu bimetals have gained significant interest due to their advantageous combination of properties. Aluminum and copper bimetals combine the good corrosion resistance, low density, and lightweight nature with excellent electrical and thermal conductivity [5]. Because of this synergy, Al–Cu bimetals are widely used in products such as yoke coils, armoured cables, air-cooling fins, and bus-bar connections [6]. Research has also indicated that using Al–Cu bimetals rather than conventional Al–Cu alloys can reduce weight by up to 40% and production costs by up to 60% [6].

Various methods have been employed to manufacture Al–Cu bimetals, such as friction welding [7], friction stir welding [8], cold rolling [9], rod extrusion [10], and ultrasonic welding [11]. These processes are typically performed under solid–solid conditions. Alternatively, Al–Cu bimetals can also be manufactured under solid–liquid conditions through methods such as gravity casting, compound casting [7], squeeze casting [12], and centrifugal casting [13]. However, most welding-based approaches are generally confined to plate-shaped workpieces [14].

Among these techniques, squeeze casting has emerged as an advanced forming process [15]. This modern hybrid technique integrates the dimensional accuracy of die casting with the mechanical advantages of forging [16,17]. Squeeze casting offers several notable benefits: (1) the decrease of gas and shrinkage porosity in the final product; (2) the elimination of the need for feeders or risers, which reduces metal waste; and (3) its suitability for both traditional casting alloys and wrought alloys, as applied pressure facilitates near-net shape forming regardless of alloy fluidity [18,19]. This casting procedure is essential to the production of large, complex, and high-performance Al–Cu bimetals structural components [20,21]. Nonetheless, when cast components exhibit significant variations in wall thickness, defects such as porosity and shrinkage often occur in the thicker regions. To prevent such issues, key process parameters—such as pressing time, pressure duration, mold temperature, and applied pressure—must be precisely controlled. Therefore, accurate prediction of these defects is essential to ensure casting quality. A practical approach to minimizing defects in squeeze casting involves allowing the liquid metal to have sufficient time to fully occupy the mold before pressure is applied by the punch [13]. This step is crucial because casting quality is significantly affected by factors such as pouring temperature, applied pressure, mould preheating temperature, and metal superheat [22]. Furthermore, increasing the applied pressure can raise the melting point of most metals, thereby altering the phase diagram and influencing the solidification behavior [22]. The application of pressure also activates feeding mechanisms in the molten metal, thereby reducing shrinkage porosity and improving the mechanical properties of the final product [23]. In addition, higher pressure levels have been shown to enhance both the strength and ductility of the casting [24]. To achieve optimal results, it is recommended to apply pressures within the range of 50–140 MPa and maintain pressing durations between 30–120 seconds [15].

The quality of bimetal is determined by the bond at the interface between the constituent materials. Recent developments have shown that a strong microstructural bond at the interdiffusion layer significantly enhances the overall performance of metals, thereby complementing their mechanical, physical, and chemical properties [9]. The formation of a microstructure bond at the two-metal interface is significantly impacted by the different pressures and temperatures of the molten metals during the joining process. More specifically, the temperature of the first frozen, solidified aluminium layer significantly influences interface diffusion and hardness during the pouring of copper into the mould. Elevated pouring temperatures enhance intermetallic bonding and minimize the formation of metal oxides, thereby improving the interdiffusion bond [25]. Conversely, a delayed copper pour after aluminum solidification can result in interface defects, limiting diffusion and weakening the metallurgical connection [26, 27].

The interaction between solid copper and molten aluminum at the interface typically produces a reaction zone consisting of four separated layers: an Al_4Cu_9 intermetallic layer, an Al_2Cu layer, an Al–Cu eutectic structure, and a Cu-rich aluminum layer [15,28]. The thickness and uniformity of these layers are influenced by casting parameters, particularly applied pressure and pouring temperature. Excessive intermetallic growth and the presence of microstructural defects at the interface can decrease bond strength and increase the risk of crack initiation. Studies have shown that a pouring temperature of approximately 700 °C yields optimal mechanical and electrical performance for Al–Cu bimetallic structures [1]. The strength of the metallurgical bond at the Al–Cu interface increases significantly as the pressure and temperature of the initially solidified aluminium increase during pouring. This improvement is attributed to the formation of intermolecular and intermetallic compounds that securely bind the two metal alloys. However, excessively high temperatures may lead to the formation of brittle intermetallic phases, compromising mechanical performance [26]. Applying high pressure during the process further enhances interface bonding by improving contact and facilitating metallurgical fusion. The resulting interface structure consists of intermetallic and quasicrystalline phases embedded within the face-centered cubic (FCC) aluminum matrix. The quasicrystalline phases are known for their stability and have demonstrated mechanical strengths up to 4–7 times greater than their unalloyed counterparts [29]. Notably, intermetallic

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compounds exhibit unique physical, mechanical, and chemical characteristics distinct from those of the base metals. Despite ongoing advancements in the fabrication of Al–Cu bimetals through squeeze casting, optimal processing parameters—particularly the ideal applied pressure and the temperature of the first frozen solidified aluminum layer—remain undefined. To address this gap, research has evaluated the hardness, microstructure, and wear rate at the Al–Cu interface under various casting conditions. The study focuses on the effects of applied pouring temperature and pressure on the microstructural evolution of Al-Si aluminum alloy. The primary objective is to determine the optimal pressure and temperature for squeeze casting to achieve strong, defect-free bonding at the Al–Cu bimetallic interface.

MATERIALS AND METHODS

The primary materials used in this study were copper and an aluminium alloy. The elemental compositions of both metals were characterized using Optical Emission Spectrometers (Belec In-Spect). Detailed results of the elemental analysis are presented in **Table 1**.

Table 1 The composition of copper and aluminum alloy materials used

	Main Composition (wt.%)						
Alloy	**Al**	**Cu**	**Si**	**Fe**	**Ag**	**C**	**Zn**
Aluminum	94.01	0.44	2.85	0.69	0.76	0.31	0.94
Copper	0.11	99.42	0.03	0.02	0.02	0.28	0.13

The Al-Cu bimetallic component was fabricated by squeeze casting, using a solid–liquid compound casting method. Aluminum alloy was first melted at 750 °C, followed by copper at 1150 °C. The liquid metals were introduced into a preheated mold cavity at a controlled filling rate of about 0.2 kg/s. Initially, aluminum alloy was filled into the mold, and once it began to solidify, copper was gradually added to form a layered bimetallic bushing. During casting, different pressure levels (60, 70, 80, and 90 MPa) were applied. At the time of copper introduction, the temperature of the partially solidified aluminum alloy layer was maintained at 500 °C to ensure optimal bonding. **Fig. 1** describes a schematic representation of the bimetallic bushing of the Al-Cu bimetallic component. The final dimensions of the bushing for outer diameter, inner diameter, and height were 25 mm, 20mm, and 20 mm, respectively, with both the aluminum alloy and copper layers each measuring 2.5 mm in thickness.

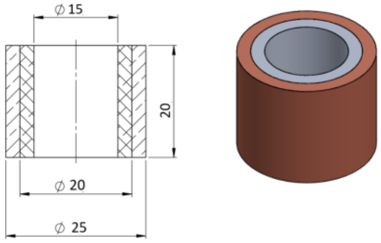

Fig. 1 Illustration of the schematic components of Al–Cu bimetal

This present study proposed to find the optimal force and initial aluminum alloy layer temperature in the squeeze casting process to produce a strong, defect-free bond at the aluminum alloy–copper bimetallic interface. Metallurgical characterization was done using a scanning electron microscope, energy dispersive spectroscopy, and an inverted metallurgical microscope (Olympus). The bimetallic product was transversely sectioned to reveal the interface in both copper and aluminum alloy. The samples were then mounted in resin to facilitate grinding and observation of the interface. Sample preparation involved sequential grinding with silicon carbide sandpapers ranging from #80 to #1500, followed by surface polishing with Autosol. During the etching process, 65% nitric acid was used on the copper surface, while 80% hydrofluoric acid was applied to etch the aluminum alloy surface.

The experimental procedures in this study included both hardness and wear observation. Oghosi's universal wear (Japan) was conducted to test wear specifically at the aluminium alloy–copper interface under a constant 62.3 N load over a 30 m sliding distance. Hardness was measured using a micro-Vickers tester (Shimadzu) focused on the interdiffusion zone between the two metals. Indentations were made at 50 µm intervals, with a 10 N load applied for 15 seconds at each point.

RESULTS AND DISCUSSION

Results

The microstructural observations of the interdiffusion zone within variation applied pressure are presented in **Fig. 2**.

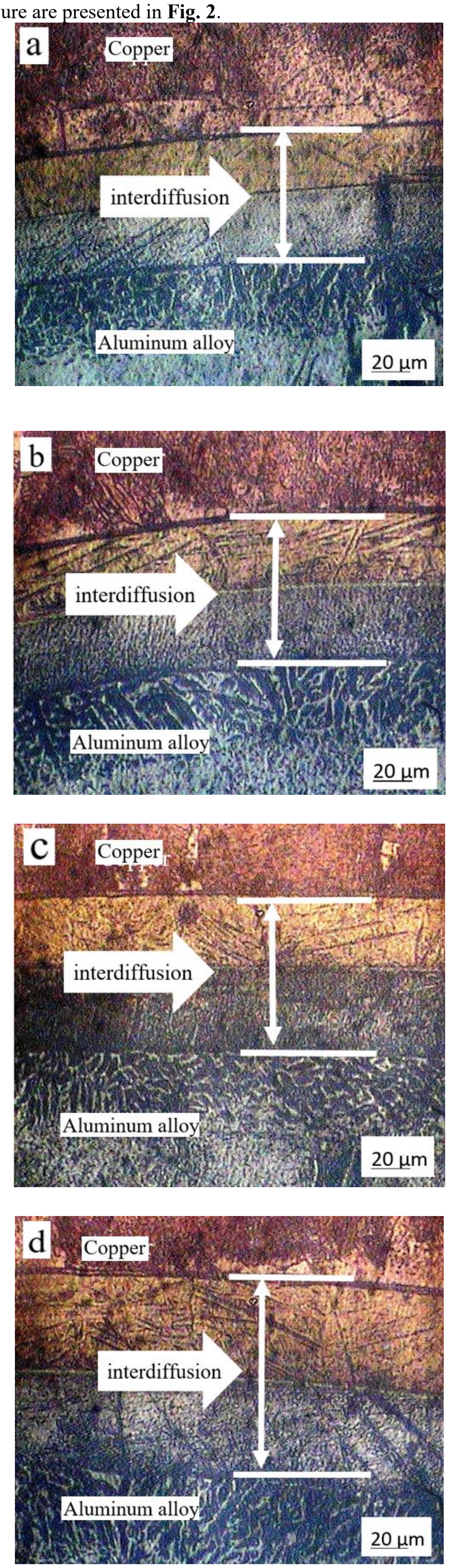

Fig. 2 Microstructural observations of the aluminum alloy–copper interdiffusion zone formed by squeeze casting under different pressures: (a) 60 MPa, (b) 70 MPa, (c) 80 MPa, and (d) 90 MPa

At 60 MPa (**Fig. 2a**), an interdiffusion zone is formed between copper and aluminum alloy, where elemental mixing occurs at the interface during squeeze casting. The distinct transition region at this pressure indicates metallurgical bonding between the two metals. At 70 MPa (**Fig. 2b**), the interdiffusion layer becomes wider compared to that observed at 60 MPa. Increasing the pressure to 80 MPa (Fig. 2c) further enhances elemental diffusion, resulting in a more pronounced bonding interface. The thickest and most distinct transition zone is observed at 90 MPa (Fig. 2d), signifying intensified diffusion and stronger metallurgical bonding. Microstructural observations at the interdiffusion interface reveal the initiation of new compounds between aluminum alloy and copper, with thicknesses varying under different applied pressures. The in-situ formation of these compounds is clearly observed at the Al–Cu interface, in agreement with previous reports on bimetals [15, 23, 24]. Moreover, higher applied pressure during squeeze casting promotes the formation of a stronger and thicker interdiffusion zone at the interface. The observed interdiffusion layer thicknesses at pressures of 60, 70, 80, and 90 MPa were 60 µm, 70 µm, 75 µm, and 96 µm, respectively.

Based on the observed microstructures, distinct characteristics were identified at the interdiffusion interface between aluminum alloy and copper. Figure 3(a) indicates the microstructure of the interdiffusion region with an interface layer between the two metals. Two layers of different thicknesses can be distinguished: the aluminum alloy interface (layer 1), the boundary of aluminum alloy–copper, and the copper interface (layer 2). The formation of these layers is consistent with previous findings [13, 15, 22, 24]. The thicknesses of the aluminum alloy and copper interface layers were nearly identical, ranging from 30 to 48 µm depending on the applied squeeze casting pressure, while the aluminum alloy–copper boundary layer measured only about 5 µm. Normal cooling was applied during solidification, resulting in an Al–Cu alloy microstructure consisting of dark grains and white grains (α phase). The formation of the grains is attributed to the phase transformation of β during slow cooling (<10 °C/min). Lamellar structure is formed when aluminum at the eutectoid reaction at a temperature of more than 565 °C [25]. The initial formation of various microstructural phases, especially lamellar and α, highlights the significant role of cooling rate in determining the interfacial characteristics of aluminium alloy–copper bimetal (Al-Cu bimetal).

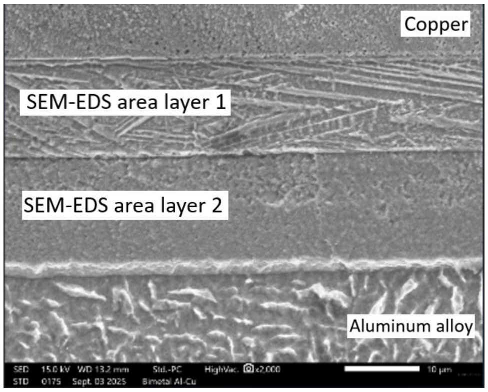

Fig. 3 SEM-EDS of the aluminum alloy–copper interdiffusion zone

Tabel 2 The composition by SEM-EDS of the Al-Cu interdiffusion zone

Element	SEM-EDS Layer 1	SEM-EDS Layer 2
	Atomic mass (wt. %)	**Atomic mass (wt. %)**
C	10.14±0.16	9.23±0.17
O	1.83±0.10	1.89±0.10
Al	27.12±0.11	59.16±0.15
Cu	60.91±0.83	29.72±0.82

Fig. 3 and **Table 2** present SEM-EDS observations, combining surface morphology analysis (SEM) and elemental composition analysis (EDS). The interdiffusion zone (Layer 1 and Layer 2) exhibits a uniform, clean, and well-bonded interface, indicating the formation of a strong metallurgical bond. SEM-EDS analysis of layer 1 revealed an atomic mass of 27.12 ± 0.11 wt.% Al and 60.91 ± 0.83 wt.% Cu. This composition suggests the in-situ formation of the intermetallic compound Al_4Cu_9 within the interdiffusion region. Layer 1 represents the boundary adjacent to the copper base, resulting in a higher Cu an atomic mass. In contrast, SEM-EDS analysis of layer 2, located at the boundary between the aluminum alloy base and the interface, revealed an atomic mass of 59.16 ± 0.15 wt.% Al and 29.72 ± 0.82 wt.% Cu, indicating the in-situ formation of Al_2Cu during the casting process. These observations confirm the presence of a gradual transition in both composition and metallurgical structure across the interface. Such a phenomenon plays a crucial role in determining the mechanical properties of the Al–Cu bimetal. Furthermore, the observed interfacial bonding and diffusion characteristics demonstrate the effectiveness of the squeeze casting process in producing a strong metallurgical joint.

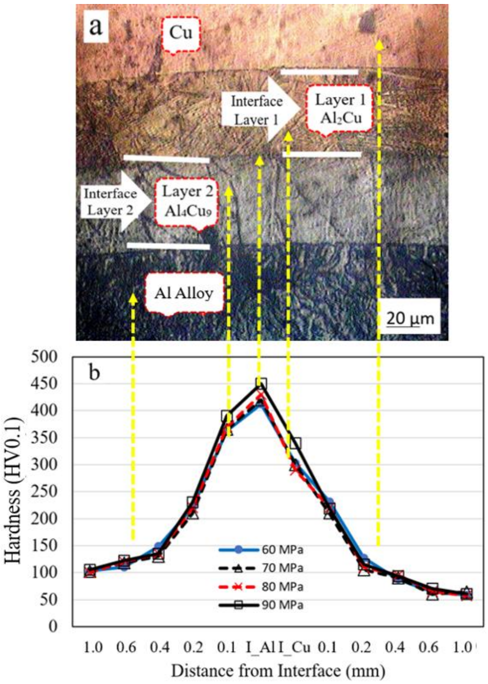

Fig. 4 Interface microstructure of copper and aluminum alloy (a) together with hardness values measured for each layer (b).

Fig. 4(a) and (b) illustrate the relationship between microstructure and hardness across each layer of the Al–Cu bimetal interface diffusion. The hardness values at the interface diffusion are higher than those of the base metals, owing to the formation of new in-situ compounds between the aluminum alloy and copper. Despite variations in casting pressure, a similar hardness trend was observed across all specimens. As shown in Fig. 4(b), the average hardness of the base Al alloy and Cu was 100 HV0.1 and 60 HV0.1, respectively. In contrast, the average hardness values at the Al alloy interface (layer 1), the Al-Cu boundary, and the Cu interface (layer 2) were 370, 430, and 310 HV0.1, respectively. The increased hardness at the interface is attributed to the formation of Al_4Cu_9 and Al_2Cu compounds during squeeze casting at high temperatures. The combined effect of high pressure and temperature-induced microstructural transformations further strengthens the interface. The maximum boundary hardness of 450 HV0.1 was found in the specimen processed at 90 MPa. Overall, the hardness profile shows that the aluminum alloy maintains a relatively stable value of 100 HV0.1, increases sharply to 371 HV0.1 in the Al_4Cu_9 layer, gradually decreases to 310 HV0.1 in the Al_2Cu layer, and finally stabilizes at 60 HV0.1 in the copper base metal.

Fig. 5 illustrates the wear rate at each interdiffusion layer of the Al–Cu bimetal. A clear variation in wear rates is observed across the layers, due to differences in hardness. The measured wear rates for aluminum alloy, the aluminum alloy interface (interdiffusion layer 1), the copper interface (interdiffusion layer 2), and copper are 1.6×10^{-8}, 0.9×10^{-8}, 1.1×10^{-8}, and 3.2×10^{-8} mm^3/N.m, respectively. The wear rate at the Al interface decreases by 43% compared to the Al base metal due to the formation of the Al_4Cu_9 phase. In comparison, the copper interface exhibits a 78% reduction in wear rate compared to copper base metal, attributed to the formation of the Al_2Cu phase. This improvement in wear rate is primarily associated with the in-situ initiation of Al–Cu carbides at the interdiffusion, which exhibit high hardness. **Fig. 2** clearly illustrates the interdiffusion at the interface. Furthermore, a direct correlation between hardness and wear rate is observed. Copper, with the lowest hardness (60 HV0.1), reveals the highest wear rate (5.2×10^{-8} mm³/N.m), while the aluminum alloy interdiffusion interface, which has the highest hardness (450 HV0.1), shows the lowest wear rate (0.9×10^{-8} mm³/N.m).

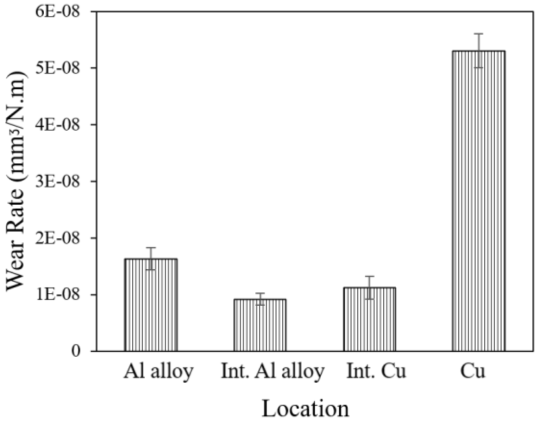

Fig. 5 Wear characteristics of the aluminum alloy–copper bimetal interface.

Discussion

The manufacture of Al–Cu bimetal was successfully achieved by squeeze casting at 60–90 MPa. The success of the process is evidenced by the formation of interdiffusion and metallurgical bonding at the interface. This bonding provides strong adhesion between the two metals across all applied pressure variations. The width of the interdiffusion zone increases with increasing pressure. Observations show that the interdiffusion layer thicknesses at 60, 70, 80, and 90 MPa are 60, 70, 75, and 96 µm, respectively.

The application of pressure during the squeeze casting process induces forced diffusion of the molten metal as it is poured into the mold [26,30]. The applied driving force enhances diffusion during solidification, resulting in a thicker and stronger interface bond. The results show that diffusion caused by pressure during casting from 60 - 90 MPa produces an interface with a thickness of 60 -96 µm. Metallurgical bonding is attributed to atomic interactions during interdiffusion, without the formation of new phases [31].

Based on SEM-EDS observations, the intermetallic compounds formed are Al_4Cu_9 at the aluminum alloy layer interface and Al_2Cu at the copper layer interface. Irregular formation of intermetallic compounds during diffusion and solidification is attributed to insufficient interfacial energy [32]. The emergence of new phases can be observed as distinct layers, particularly at the interface when the metals come into contact at high temperatures. The formation of these new phases is affected by factors such as nucleation at the onset of diffusion, chemical potential, and the mobility of the constituent elements [33].

Under 60-90 MPa pressure, the bimetal interface layer is clearly visible, free of oxidation or impurities. These bond conditions produce a strong bond between the two metals. The relationship between mechanical strength and the interdiffusion microstructure has also been reported in previous research [34]. During casting, the applied pressure suppresses oxide formation at the interface, thereby promoting a clean metallurgical bond free of oxides or contaminants. The presence of oxides can hinder diffusion bonding and cause interface gaps. Uniform pressure distribution within the mold is critical to ensuring consistent interface thickness [2]. A uniform distribution minimizes the formation of gaps and defects, including interface oxide inclusions [35].

The interdiffusion region between aluminum alloy and copper reveals significantly higher hardness compared to their respective base metals. When it reaches the distance of 0.4 mm from the interface, the hardness approaches the base metals. The aluminum alloy interface layer (layer 1) shows a remarkable increase to 370 HV0.1, which is at least 3.6 times higher than the aluminum alloy base metal. Similarly, the copper interface (layer 2) reaches 310 HV0.1 (5.1 times the base copper value). The highest hardness is observed at the boundary layer, with a thickness of approximately 4–6 µm, reaching 430 HV0.1. This value is about 4.3 times higher than aluminum alloy and 7.1 times higher than copper.

The increase in hardness within the diffusion region compared to the base metals is caused by the diffusion of compositions from the base metal, including Al, Si, Cu, and Sn, through both interstitial and substitutional mechanisms. Higher applied pressure promotes more extensive diffusion at the interface, thereby enhancing hardness. This hardness improvement is further affected by the formation of Al and Cu carbides, which possess inherently high hardness. The enhanced interface layer contributes to reduced wear rates, ultimately extending the product service life. Elemental diffusion and carbide formation under applied pressure play a critical role in ensuring the mechanical properties obtained, underscoring the importance of optimizing casting pressure in bimetal fabrication.

The reduction in wear rate within the interdiffusion region is primarily associated with the appearance of Al_4Cu_9 and Al_2Cu compounds [27,28,31]. Aluminum incorporates into the copper crystal lattice as a substitutional solid solution, thereby contributing to the enhancement of mechanical properties. Nevertheless, an excessive aluminum concentration in Al–Cu alloys can result in the appearance of the brittle γ phase. Therefore, Cu–Al alloys with Al levels above 12 wt% are usually avoided in manufacturing [34]. It should also be noted that increased hardness does not always correlate directly with improved wear resistance, as wear behavior is influenced not only by hardness but also by toughness and microstructural characteristics, both of which play vital roles in determining wear resistance and product service life [36].

Melting at the interface due to the high temperature during molten metal pouring promotes metallurgical bonding, solid-state diffusion, and solidification. Wear resistance increases in the diffusion area compared to the aluminum alloy base material. The wear rate in the diffusion area decreased from 1.6×10^{-8} mm³/N·m to 0.9×10^{-8} mm³/N·m (43%). In fact, wear resistance in the diffusion zone increased by up to 78% compared to the copper base. Elemental diffusion leads to the formation of solid solutions and subsequently triggers the development of intermetallic compounds at the diffusion interface [28]. Al and Cu exhibit a strong affinity at temperatures above 120°C, which can reduce bond strength [37] due to the formation of brittle IMCs with non-metallic bonding. This brittleness arises from a reduction in free electron density and an increase in electrical resistivity.

The increased pressure immediately after pouring increases the thickness of the diffusion layer between the two metal alloys, resulting in a high-hardness alloy. In-situ reactions at the interface further promote the formation of hard carbides, which play a critical role in reducing wear rates. Hard and wear-resistant materials are crucial for components subjected to frictional loading. However, excessive hardness may increase brittleness and lead to crack formation [34]. Thus, while higher applied pressure improves both hardness and wear resistance, excessive hardness should be avoided, as it may cause brittleness and premature failure due to crack initiation.

CONCLUSIONS

Squeeze casting can be an effective method for producing an Al–Cu bimetal with a strong interfacial bond. Based on microstructural observations, casting pressures of 60, 70, 80, and 90 MPa successfully generated interdiffusion layers with thicknesses of approximately 60, 70, 75, and 96 µm, respectively. This indicates that the thickness of the interface layer increases proportionally with the applied casting pressure. The hardness of the aluminum alloy interface layer increased up to 370 HV0.1, representing a 360% improvement compared to the base aluminum alloy metal. Similarly, the copper interface hardness increased to 310 HV0.1, a 510% increase compared to the base copper metal. Differences in the wear rates of each interdiffusion layer were attributed to variations in hardness. The average wear rates of the aluminum alloy, aluminum alloy interface, copper interface, and copper were 1.6×10^{-8}, 0.9×10^{-8}, 1.1×10^{-8}, and 3.2×10^{-8} mm³/N·m, respectively. The enhancement in hardness (360%) and wear resistance (43%) of the aluminum alloy interface compared to the base aluminum alloy is primarily due to the formation of the Al_2Cu phase. Meanwhile, the improvement in hardness (510%) and wear resistance (78%) of the copper interface relative to the base copper metal is due to the formation of the Al_4Cu_9 phase. The presence of these intermetallic compounds was confirmed by SEM–EDS analysis. Based on these findings, squeeze casting at 90 MPa was identified as the optimal condition for producing Al–Cu bimetallic components. Therefore, further studies are recommended to include bending, tensile, and impact tests to evaluate the mechanical behavior of the interface region comprehensively.

Acknowledgments

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