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INTERDIFFUSION ZONE CHARACTERISTICS OF INTERFACE BIMETAL ALUMINUM-COPPER PRODUCED BY SQUEEZE CASTING

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ABSTRACT

Bimetals are metallurgical bonds formed by the mixing of two materials. One method of producing bimetal is through squeeze casting. However, no optimal pressure reference exists for the pressing during bimetal production. This research aims to determine the optimal pressure in the form of bushings to achieve an optimal interdiffusion bond at the interface. The study uses copper and aluminum alloys. The aluminum is heated to a melting temperature of 770°C, whereas the copper reaches 1150°C. The process begins with alternately poured molten metals into a mold. In the first stage, aluminum is poured into the mold, followed by copper in the second stage, gradually forming an aluminum-copper bimetal bushing. In the third stage, pressure is applied. The squeeze pressure variations are 30, 40, 50, and 60 MPa. The results show that increasing the squeeze casting pressure increases the thickness of the interdiffusion layer. The highest hardness is found at the interface because of the formation of AlCu compounds. The increase in hardness also enhances wear resistance in the interface. Therefore, squeeze casting with a pressure of 60 MPa is recommended for producing Al-Cu bimetal to achieve optimal interdiffusion at the interface.

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

INTRODUCTION

Bimetal is a composite material that combines two different metals or metal alloys. These metals form distinct layers, creating a metallurgical bond that enhances the product's mechanical properties [1,2,3,4]. The production of bimetal is aimed at developing integrated components where each metal retains its distinct characteristics [5]. Aluminum-copper (Al/Cu) bimetal is particularly popular due to aluminum's low density, lightweight, and high corrosion resistance, and copper's superior electrical and thermal conductivity. This combination can reduce weight by 40% and cost by 60%, while maintaining comparable electrical and thermal performance [6, 7]. Al/Cu bimetals are widely utilized in applications such as armored cables, air conditioning fins, electronic packaging, and bus bar conductor connections [7,8]. Light bimetal constructions including Al/Cu and Al/Mg have been developed currently [9, 10]. Bimetal manufacturing methods are gravity casting, compound casting [8] and squeeze casting [11]. The process is carried out in solid-liquid conditions to form a metallurgical transition zone at the interface [1, 2, 8, 12].

Squeeze casting is considered as one method to overcome casting defects at the bimetal composite interface [11,13]. Parameters to be considered in squeeze casting of bimetal Al-Cu to ensure that the casting is defect free include mold temperature, mold pressure, pressing time and pressure duration. Aging treatment increases the yield strength, strain and hardness at the Al-Cu bimetal interface. Optimal metallurgical bonding at the interface based on metallographic analysis is produced in products with a melt of 800°C, insert preheat of 250°C, squeeze pressure of 100 MPa, pressure duration of 150 seconds and time delay of 10 seconds [11]. Increasing the thickness of the metallurgical bond at the interface increases the tensile strength of the resulting bimetal [14]. Defects often arising at the interface include gas porosity, micro-cracks, shrinkage voids, pinholes, and hot tearing [11].

One effective method for reducing porosity in metal casting is to ensure that the molten metal has adequate time to fill the mold cavity before the punch applies pressure to the surface. Complex mold shapes require longer filling times compared to simpler designs. For optimal results, the punch temperature should be approximately 30°C lower than the mold temperature. The recommended pressure range is 50-140 MPa, with a pressing duration of 30-120 seconds.

In its development, bimetal manufacturing technology constantly evolves to achieve enhanced bimetal properties. A composite that merges two metals through a metallurgical bond can be bimetal [14]. In this work, the goal of producing bimetal components is to create materials with mechanical properties distinct from their individual metal constituents while preserving the unique characteristics of each metal [15]. Bimetal casting was introduced to offer an affordable and efficient production method. Additionally, ongoing efforts focus on enhancing the interfacial bonding between the combined metals to bridge the gap between bimetal casting and traditional casting methods [16]. The robust metallurgical bond between the two metals enhances the properties of the final product, enabling the alloyed metals to complement one another in their mechanical, physical, and chemical attributes [17].

Bimetals can be manufactured using centrifugal casting [5] or gravity casting techniques [18]. During the casting process, a metallurgical bond is formed at the interface as the two metals diffuse while being poured, creating a strong bond [19]. Currently, the bimetallic applications technology is focused in developing manufacture of bushing products. However, bushings manufactured through gravity casting tend to have low density due to casting defects [18]. In contrast, using squeeze casting to produce bushings results in products with faster solidification, reduced porosity, smoother surfaces, and more precise dimensions [20].

For the purpose of determining the freezing time of the first layer at the aluminum-copper interface in bimetal casting, the chornief equation can be used [21]. The metallurgical bond at the interface is influenced by the temperature of the liquid metal when it is joined. When copper is injected into the mold, the temperature of the initial frozen aluminum layer affects the diffusion and hardness of the interface. Higher pouring temperatures promote stronger intermetallic bonds and reduce metal oxide formation [21]. On the other hand, delaying the copper pour after the first layer has solidified can lead to defects at the interface, hindering proper diffusion and the formation of a strong metallurgical bond [5, 13].

Metallurgical bonding at the bimetal interface can be accomplished by implementing a zinc coating on copper, followed by careful pressure application. The interfacial reaction between molten aluminum and solid copper leads to the formation of a interfacial zone comprising four distinct layers: the Al_4Cu_9 layer, the Al_2Cu layer, the Al–Cu eutectic layer, and a Cu-rich Aluminum solid solution layer [12]. Variations in pressure and pouring temperature influence the thickness of these layers. The presence of inherent defects and thickening of intermetallic compounds may weaken the bond strength and potentially initiate cracks. Pouring at 700°C has been shown to result in optimal mechanical and electrical properties [1].

The bending strength at the aluminum-copper interface improves as the temperature of the initial frozen aluminum layer rises during pouring. This strength is the product of intermetallic and intermolecular compounds that hold the two metals together. Fortunately, a brittle phase can develop if the pouring temperature is very high [5]. The high pressure exerted improves bonding at the contact, increasing bond quality. Bonds produced at the contact comprise intermetallic and quasicrystalline phases in the Aluminum-FCC matrix. The quasicrystalline phase is stable and exhibits mechanical strength 4-7 times greater

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than before [22]. The intermetallic phase possesses distinct physical, mechanical, and chemical properties compared to the original metals.

Although the technology, process, and methods for producing bimetallic bushings via squeeze casting are continuously evolving, there is still no established recommendation for the optimal pressure and the first frozen layer of temperature. To address this, research has analysed the microstructure, hardness, and wear resistance at the aluminum-copper interface. This research aims to identify the ideal pressure and first frozen layer temperature in squeeze casting to achieve effective bonding at the aluminum-copper bimetal interface.

MATERIALS AND METHODS

Copper and aluminum were the materials used in this research. **Table 1** provides the elements of aluminum and copper, as analyzed by SEM-EDS using the JEOL Neoscope JCM-7000 Series.

Table 1. The main chemical elements of materials (wt.%)

Alloy	Main Composition (wt.%)						
	Al	Si	Cu	Fe	Mn	Ni	Zn
Cu	0.09	0.03	99.61	0.02	0.01	0.06	0.13
Al	91.25	5.95	0.53	0.69	0.21	0.06	0.96

The aluminum-copper bimetallic was produced using the squeeze casting method with a solid-liquid process. Copper melted at 1150ºC, while aluminum was melted at 725ºC. The liquid metal was poured into a cavity of mold at a filling rate of approximately 0.3 kg/s. Aluminum was poured into the mold first, followed by a gradual pouring of copper to form a bimetallic bushing. The applied pressures varied between 30, 40, 50, and 60 MPa, with the first solidified aluminum layer at 300ºC when the copper was introduced. The schematic of the bimetallic bushing is shown in **Fig. 1**. The bushing dimensions were an outer diameter of 30 mm, an inner diameter of 20 mm, and 35 mm height, with each layer of aluminium and copper having a thickness of 2.5 mm.

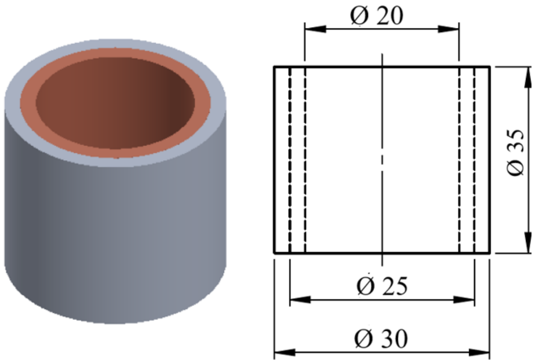


Fig. 1 The bimetal bushing schematic of product

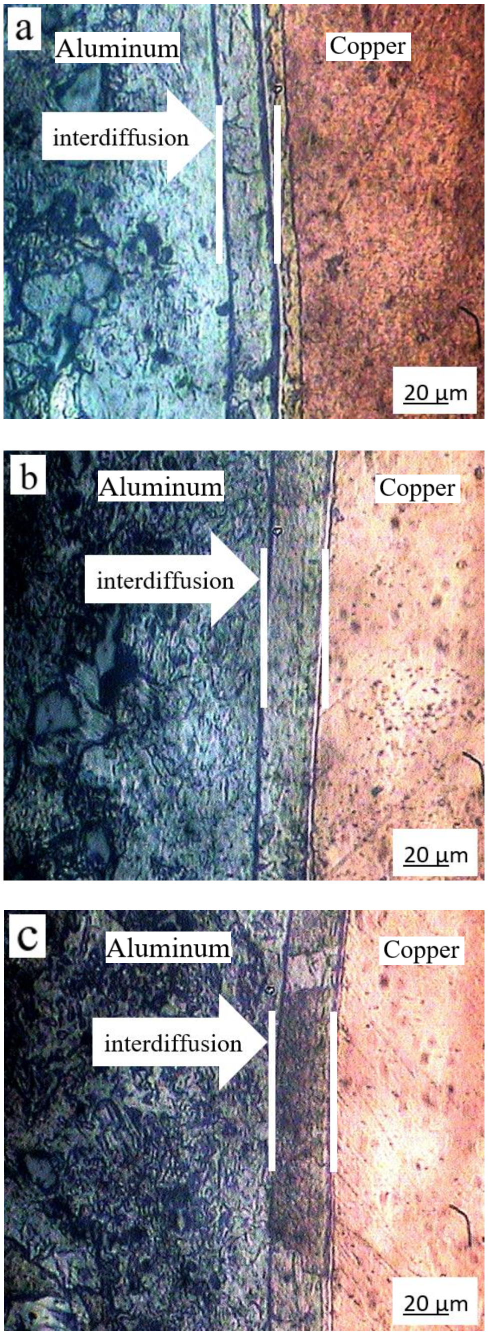
This research aimed to examine the microstructures present at the bonding interface of the bimetal. The microstructure analysis was performed using SEM-EDS (JEOL Neoscope JCM-7000 series) along with a metallurgical microscope with inverted (Olympus, Japan). Sample preparation involved grinding the surface with sandpapers ranging from #180 to #1500 grit, followed by polishing with autosol. For the etching process, 60% HNO_3 was applied to the copper, while 65% hydrofluoric acid (HF) was used on the aluminum to etching.

The experiments in this research involved wear and hardness evaluations. The wear test was performed at the bond interfacial/interface using an oghosi's universal wear (Japan), applying a load of 6.36 kgf over a distance of 15 meters. A micro Vickers hardness tester (HMV-M3, Shimadzu) was utilized to assess the hardness at the interdiffusion between copper and aluminum samples. The hardness measurement points were placed 50 µm apart, with a 200 gf load applied for 15 seconds.

RESULTS AND DISCUSSION

Results

Fig. 2 illustrates the microstructure observations at the interdiffusion under different pressure variations.



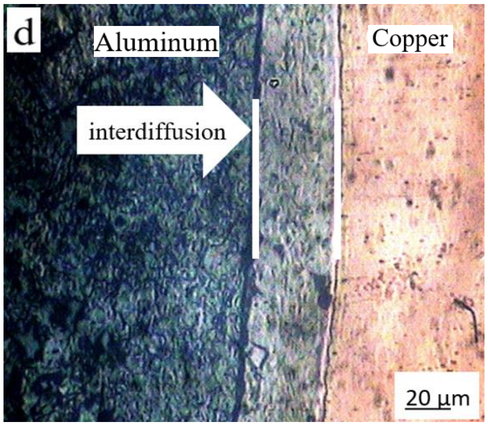


Fig. 2 illustrates the microstructure at the bimetal interdiffusion of aluminum alloy-copper, created through squeeze casting with pressure variations of 30 MPa (a), 40 MPa (b), 50 MPa (c), and 60 MPa (d).

Based on the microstructural analysis, compounds formed between aluminum and copper are observed in all products across various pressure levels. These compounds are visible at the interface between the two metals. The observations are consistent with previous studies on Al-Cu bimetal [15, 23, 24]. They are increasing the applied pressure results in a thicker interdiffusion layer at the interface between the two metals. The thickness of the interdiffusion layer for products with pressures of 30, 40, 50, and 60 MPa is 20 µm, 24 µm, 26 µm, and 30 µm, respectively.

According to the microstructural observations and analysis of the interdiffusion interface between the two metals, several characteristic differences were identified. **Fig. 3(a)** illustrates the interdiffusion microstructure, displaying the interface layer between copper and aluminum.

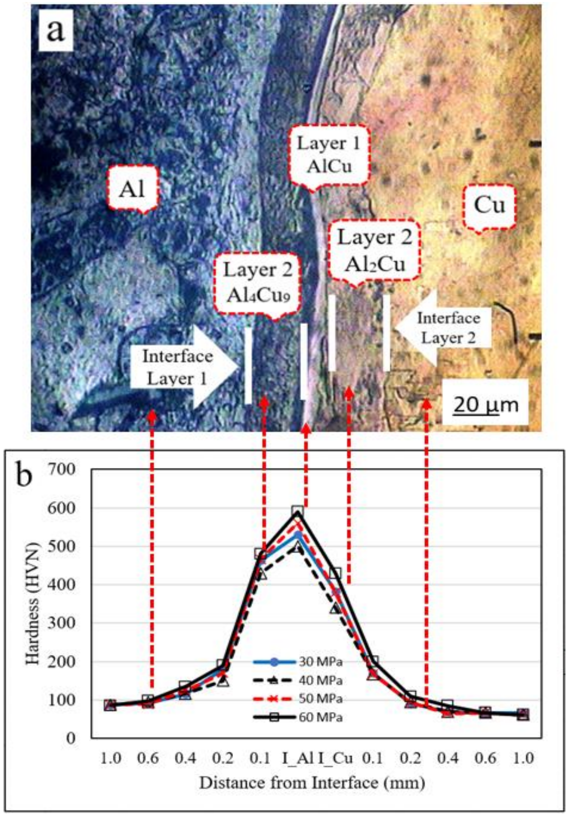


Fig. 3 shows the microstructure of the interface layer between aluminum and copper (a), along with the hardness measurements for each interface layer (b)

The analysis reveals the formation of three layers: the aluminum interface (layer 1), the aluminum-copper interface, and the copper interface (layer 2). The observed layer formation is similar to results from previous studies [22, 24]. The microstructure of the aluminum-copper alloy, under normal cooling conditions, displays bright grains (α phase) and dark grains. These grains' appearance results from the equilibrium β phase transition process at a cooling rate of less than 10°C/min, which transforms through a eutectoid reaction temperature at 565°C into a lamellar structure [25]. The presence of distinct microstructural phases, such as the α and lamellar structures, indicates that the cooling process plays a critical role in determining the properties of the bimetal interface.

Furthermore, there is a hardness trend across all interface levels. Figure 3 (b) presents the result of the hardness in the interdiffusion region, showing that the bond contact exhibits higher hardness than the base metal. Moreover, there is a consistent trend of hardness across all specimens despite variations in pressure and squeeze conditions. The average hardness in the aluminum and copper areas is 88 and 66 HVN. At this point, the aluminum interface (layer 1), interface, and copper interface (layer 2) have hardness values of 460, 545, and 383 HVN, respectively.The hardness is influenced mostly by the microstructure's phase and interference component. The hardest interface (590 HVN) occurred in goods with a pressure of 60 MPa. The hardness of the aluminum remained relatively stable at 88 HVN, then rose sharply to 545 HVN at the interface, before gradually declining to 66 HVN in the copper.

Fig. 4 illustrates the wear at the bimetal. The wear values for aluminum, the Al_4Cu_9 interface (interface layer 1), the Al_2Cu interface (interface layer 2), and copper are 2.5E-07, 1.2E-07, 1E-07, and 4.5E-07 mm³/kg.m, respectively. The wear rate of the Al_4Cu_9 interface is 2.1 times higher than that of aluminum, while the Al_2Cu interface experiences 4.5 times more wear compared to copper. The increased wear resistance is attributed to the in-situ formation of AlCu carbides at the interface, which possess high hardness. The occurrence of interdiffusion at the aluminum-copper interface is observed in **Fig. 3**. Hardness is directly proportional to wear resistance. Copper, which has the lowest hardness (66 HVN), exhibits the highest wear rate (4.5E-07 mm³/kg·m), whereas the Al_2Cu interface, with the highest hardness (545 HVN), demonstrates the lowest wear rate (1E-07 mm³/kg·m).

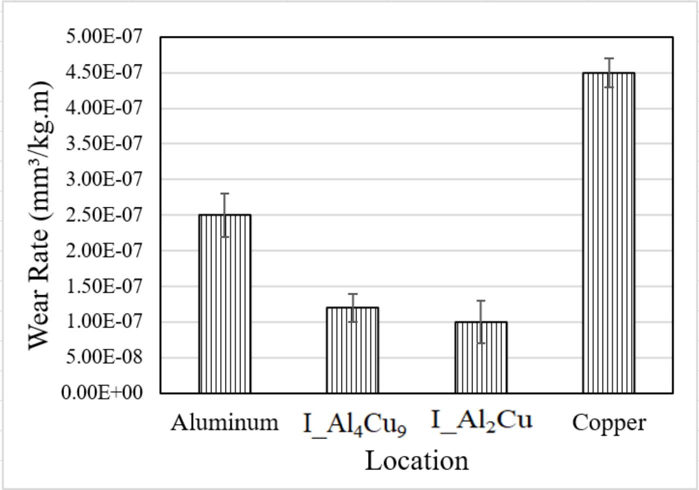


Fig. 4 shows the wear of a bimetallic contact.

Discussion

The interdiffusion bonding on interface of aluminum-copper bimetals produced by squeeze casting demonstrates strong adhesion across all applied pressure levels. As the pressure increases, the width of the interface also expands. Specifically, the interface widths at pressures of 30, 40, 50, and 60 MPa are 20 µm, 24 µm, 26 µm, and 30 µm, respectively.

The increase in pressure occurs as a result of the force exerted by the punch on the molten metal during its entry into the mold [5,26]. This driving force intensifies as solidification progresses during the pouring process, leading to improved bonding at the interface. The bonding occurs through atomic interactions at the interface without the formation of any new phases [15].

The growth of intermetallic compounds during the interdiffusion process is often irregular caused by a lack of interfacial energy related with the coherent character of the zone [27]. The formation of a new phase, observable as a distinct layer at the interface where hot metals meet, is influenced by several factors: nucleation conditions at the onset of interdiffusion, chemical potential, and the movement of constituent elements [28].

Based on microstructural observations, strong metallurgical interdiffusion bonding was evident, with no visible impurities, such as metal or protective oxides, at the interface. The correlation between mechanical properties and microstructure has been noted in previous studies [29]. The squeeze force pressure at the temperature of the first solidified layer effectively removes metal oxides, creating a metallurgical bond at the interface. The presence of impurities could prevent the formation of diffusion bonding by causing separation between the metal surfaces. The force of the mold during pouring further increases the pressure exerted on the liquid metal, enhancing its distribution within the mold [2]. This improved distribution reduces defect formation, including oxide impurities [20].

The hardness at the interdiffusion between the two metals is higher than the hardness of the base metals. Hardness at a location of 0.6 mm from the interface, the hardness closely matches that of the base metals. At the aluminum interface (layer 1), hardness increases significantly to 460 VHN, which is at least 5.2 times greater than the base aluminum. Similarly, at the copper interface (layer 2), hardness reaches 383 VHN, exceeding the base copper by at least 5.8 times. Notably, the interface layer—a narrow zone approximately 5-7 µm thick—achieves a hardness of 545 VHN, over 6.1 times higher than base aluminum and 8.2 times higher than base copper.

This increase in hardness at the interdiffusion area is attributed to the diffusion of other elements from the base metals, including Si, Cu, Sn, and others, which occurs through interstitial and substitutional mechanisms. Higher applied pressure facilitates diffusion, leading to greater hardness at the interface. The increased hardness is also influenced by the formation of hard aluminum and copper carbides. The significant rise in hardness at the interface can enhance wear resistance, making the material more suitable for applications that require high durability. The diffusion of other elements and the formation of carbides under higher pressure suggest that controlling pressure during the casting process is crucial for optimizing the mechanical properties of bimetal products.

The increase of wear at the interdiffusion zone is caused by the production of Al_2Cu, AlCu, and Al_4Cu_9 phases [12, 24]. Aluminum is a substitutional solid solution within the copper crystal lattice, enhancing mechanical properties such as wear rate. Additionally, corrosion resistance is improved by forming a thin alumina layer on the surface of the alloy. However, a high aluminum content in aluminum-copper alloys can lead to the formation of the brittle γ phase, making them unsuitable for industrial use. Consequently, Cu-Al alloys with aluminum content exceeding 12 wt% are typically avoided in manufacturing applications [25]. It's worth noting that increased hardness does not automatically translate to improved wear resistance, as wear resistance depends on multiple factors beyond hardness alone [30]. Properties like toughness and microstructure play significant roles in determining a material's ability to withstand wear. Although surface topography and wear behavior are related [30], when surface topography is comparable, wear resistance is largely influenced by hardness.

The increase in pressure during pouring onto the first solidified layer leads to a thicker and wider interdiffusion interface between the two metals, which exhibits high hardness. The in-situ reaction that triggers the formation of hard carbides at the interface reduces the wear rate. Materials with hard and wear-resistant properties are essential for various engineering components that experience friction. However, excessive hardness can make the material brittle and initiate crack formation [31]. While increased pressure enhances the hardness and wear resistance of the interface, care must be taken to avoid overly high hardness, which may lead to brittleness and potential failure due to crack formation.

The formation of metallurgical bonds at the interdiffusion is driven by local melting, resolidification, and solid-state diffusion. The diffusion of alloying elements leads to the development of solid solutions and initiates the formation of intermetallic compounds (IMCs) at the interface [12]. Aluminum (Al) and copper (Cu) exhibit an affinity at temperatures above 120°C, which promotes the formation of brittle IMCs characterized by non-metallic bonds and reduce bond strength [14]. The brittleness of these bonds arises from a reduction in the number of free electrons available, coupled with an increase in electrical resistance. Consequently, bond strength is diminished, and the material's flexibility is reduced.

CONCLUSIONS

This study provides an understanding of the use of squeeze casting to achieve effective interdiffusion bonding at the aluminum-copper bimetal interface. Several specific findings emerged from the observations. The interface width grows in proportion to the pressure applied during the pouring process, as higher pressure boosts the molten metal's driving force, resulting in better bonding at the interface. An improvement in hardness and wear resistance was observed at the interface equated to the base metals, caused by the formation of Al_2Cu, AlCu, and Al_4Cu_9 phases. The study suggests that squeeze casting of an aluminum at 60 MPa is optimal for aluminum-copper bimetal applications. For future research, it is recommended to perform tensile, bending, and impact strength tests to gain a more comprehensive understanding of the mechanical and physical properties at the interface.

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