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Effect of Liquid/Solid Volume Ratio on Interface Formation and Mechanical Properties of Aluminum – Copper Bimetal by Squeeze Casting

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Keywords:
Compound casting; Al-Cu bimetal; Intermetallic compound; Interface formation.

Highlights:
- *The possibility of producing Al-Cu bimetal by the squeeze casting method.*
- *The best metallurgical properties and good thickness of the transition point were obtained at a liquid-to-solids ratio of 17%.*

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Abstract: Many industrial applications require lightweight, low cost and high- performance materials. This work created a bimetal (Al-Cu) using the compound casting technique (Squeeze casting). Nickel-electro coating of copper substrates was used before casting; the copper inserted was a cylindrical rod into a carbon steel die, then melted aluminum at (700˚C). The liquid to-solid ratio influenced the formation of the interface (transition region between the two metals). Also the mechanical characteristics of the bimetal (Al-Cu) were studied. The intermetallic compounds were discovered as (Al_2Cu, $AlCu_4$, $AlCu$, Al_4Cu_9, and Cu_4Al_3). The nickel coating significantly enhanced and strengthened the bimetal (Al-Cu) interconnection by percentages (17% and 3.5%). Many tests and examinations were conducted, such as examining the microstructure with an optical microscope, scanning electron microscope and X-ray diffraction, hardness and interconnection strength examinations due to restricting the formation of intermetallic compounds. The results also showed that the interface had a thickness and good properties at a ratio of liquid to solids of 17% because the large thermal content increased the interface thickness between the two metals. The effect of this ratio was evident through the tests' results, as the interconnection strength reached 15.5 MPa. The copper and aluminum interfaces' hardness were is 168, 92, and 38 HV, respectively. While the intermetallic compounds were more diverse at a liquid to- solid ratio of 17%.

تأثير نسبة حجم السائل الى الصلب على تكوين السطح البيني والخصائص الميكانيكية للمعدن الثنائي (المنيوم – نحاس) المنتج بتقنية السباكة بالعصر

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الخلاصة
تحتاج الكثير من التطبيقات الصناعية الى مواد خفيفة الوزن قليلة الكلفة وذات اداء عالي، تم في هذا البحث انتاج المعدن الثنائي (Al-Cu) بطريقة السباكة المركبة واستخدام تقنية السباكة بالعصر، تم استخدام الطلاء الكهربائي بالنيكل لركائز النحاس قبل القيام بعملية السباكة، ادخل النحاس بشكل قضيب اسطواني في قالب من الصلب الكاربوني بعدها صب الالمنيوم عند (700 °C)، تم دراسة تأثير نسبة السائل الى الصلب على خصائص البنية المجهرية للسطح البيني (المنطقة الانتقالية بين المعدنين) وعلى الخصائص الميكانيكية للمعدن الثنائي (Al-Cu) بنسب (17% and 3.5%)، تم اجراء عدة اختبارات وفحوصات مثل فحص البنية المجهرية بالمجهر الضوئي والمجهر الماسح الالكتروني وفحص حيود الاشعة السينية وفحص الصلادة وفحص قوة الترابط البيني، من خلال النتائج تم تحديد المركبات البينية المعدنية في المنطقة الانتقالية بين المعدنين (transition zone) على انها ($Al_2Cu, AlCu_4, AlCu, Al_4Cu_9, Cu_4Al_3$)، كان لطـــلاء النيـــكل تأثيـــر كبير في تعزيز وتقوية الترابـــط البينـــي للمعدنيـــن من خلال تقييد تشكـــيل المركبـات البينية المعدنيـة (intermetallic compound)، كما اظهرت النتائج بأن السطح البيني (interface) يكون بمواصفات ميكانيكية فائقة عند نسبة سائل الى صلب ١٧ % بسبب المحتوى الحراري الكبير مما يزيد من سمك السطح البيني بين المعدنين وأن تأثير هذه النسبة كان واضحاً من خلال نتائج الفحوصات اذ بلغت قوة الترابط البيني 15.5 Mpa وكانت قيمة الصلادة لكل من السطح البيني والنحاس والالمنيوم على التوالي هي 168 ,92 and 38 HV، اما المركبات البينية المعدنية فكانت اكثر تنوعاً عند نسبة سائل الى صلب ١٧٪.

الكلمات الدالة: السباكة المركبة، المعدن الثنائي (المنيوم –نحاس)، المركبات البينية المعدنية، تكوين السطح البيني.

1.INTRODUCTION

Bimetal combines properties of the metals, i.e., physical, chemical, and mechanical, with different bonding methods [1]. It has been used since the 1960 to produce copper-clad aluminum rods [2]. The advancement of modern industries has become arduous to meet the cheap price and good performance work requirements of one metal material [3]. Development in the automotive industry has focused on lightweight materials to meet-modern industry requirements. For example, when trying to reduce the emission of carbon oxide (CO_2), one substance is often unable to meet this matter's requirements [4]. Despite the success of the method, it has limitations. One of these limitations is the inability to bond all metals, each having a huge difference in the melting temperature. Therefore, the bond between them is weak, as in the bonding of aluminum and iron (Al-Fe), due to many defects, including cracks and high porosity [5]. In the last few decades, the two metals (Al-Cu) bonding with each other has received great attention due to the advantages enjoyed by metals and the great affinity of diffusion with each other at high temperatures [6]. Aluminum is characterized by its abundance, low cost, low density, and high corrosion resistance in all conditions; however, it has determinants including high ductility, which determines its use in certain fields, and density, which is prone to oxidation. So, binding the two metals reduces weight by (40%) and cost by (60%). It combines the properties of two metals in thermal and electrical conductivities [7]. Al-Cu Bimetal is widely applicable in heat transfer and electrical industries, heat exchanger systems, and mechanical parts with special requirements [1, 2, 8, 9]. The methods of producing bimetal are mainly divided into three methods [10-12]:

1- Solid-Solid: including Extrusion, diffusion bonding, friction welding, and rolling with all other types and welding methods.
2- Solid-Liquid: such as the compound casting process.
3- Liquid-Liquid: such as centrifugal casting and continuous vertical casting methods.

Compound casting is a technique that combines dual metals, one in a liquid condition and the other in a solid state with each other, as a bonding and diffusion zone arises between them [13]. By reviewing previous studies, the success of the method of bonding the two metals depends largely on the characteristics of the bonding zone (interface). Therefore, the previous research studied the bonding of the two metals (Al-Cu) in different ways and found the optimal conditions for the variables of each method [14]. The appropriate way to bond (Al-Cu) with each other is the compound casting method duo to its high efficiency, low cost, and the possibility of producing any part without dimensions restrictions. However, research on compound casting is still severely constrained because the copper oxidizes easily at high temperatures, causing imperfections like cracks in the fastening interface [15]. The squeezing casting process is one of the Hybrid forming processes in which the mold is filled quickly to reduce the turbulence of a liquid metal. It is a sophisticated procedure for strengthening the metal under pressure [8]. The applied pressure on the molten metal is in the region of the pasty state (Mushy Zone), which is the area where the molten consists of the liquid and solid phases; they are in approximately equal proportions Pressing the metal until it is completely frozen [16]. Applied pressure leads to many positive effects, including reducing the gap caused by freezing between the cast and the inner mold surface and gas porosity and shrinkage by strengthening the mechanism of nutrition between the arboreal arms (Interdenderitic feeding) and changing the solidification rate (an increase in the cooling rate) and changing the phasing scheme. Therefore the castings produced in this way are characterized by their high density and fine grains and show superior mechanical properties, as the cast pressure and casting temperature significantly influence the mechanical properties, microstructure and thermal [17]. Despite the advantages offered by this type of bonding (Compound Casting) there are many problems when bonding the two metals (Al-Cu) with each other by the composite casting method [18]. One of these problems is the presence of intermetallic Compounds at the interface, which are of high hardness and high resistance to electrical conductivity. Their presence significantly affected the bimetallic properties. Copper is prone to oxidation, so many studies investigated using different coatings to protect copper and improve the interface properties [19]. Yuan et al. [20] studied non-electroplated (Ni-P) coating. It was found that the microstructure significantly improved with the (Ni) layer, and a greater shear resistance distinguished the samples than without it within the same experimental setting. Zhao et al. [21] studied the nickel immersion coating effect on the mechanical characteristics and the interface's microstructure of the AL-Cu bimetal produced by the diffusion method. The researchers concluded that the interlayer formed during immersion with the coating effectively reduces the synthesis of Al-Cu compounds, but this caused the synthesis of Al-Ni compounds. However, Al-Ni compound growth was significantly slower than Al-Cu compound. Bakke et al. [22] studied the Flux Coating impact on The bimetal's (Al_7SiMg/Cu) created by the composite method, mechanical characteristics and microstructure. The coating was a mixture of ($K_{1-3}AlF_{3-6}$ and $CsAl_4$) with alcohol. The authors concluded that the melting range of the coating was (558-566 ˚C). Also, they found that this coating solvent for copper pipes effectively prevented the forming of oxides and increased wettability. Guan et al. [23] studied the casting temperature effects on the mechanical and microstructural characteristics of the AL-Cu bilayer that the lost foam (LFC) casting produced. The studied temperatures were (680,720,760, and 800 ˚C). The authors concluded that casting the size and form of the object were influenced by the temperature of intermetallic compounds, and the shear resistance increased with the casting temperature reported pouring temperature at 800 ℃ with 81 MPa. Akbarifar and Divandari [24] studied the influence of casting temperature and the volume ratio of liquid-to-solid on the interfacial characteristics of the AL-Brass bilayer produced by the composite casting method. The authors concluded that increasing the casting temperature or the proportion of liquid-to-solid increased the interlayers thickness duo to enthalpy rise. Su et al. [25] studied the method of copper Cladding aluminum rods (CCA rods) produced by the method of continuous horizontal core fillin continuous casting (HCFC). The authors used pure copper and pure aluminum (CCA rods) were manufactured with a diameter of (30mm), a copper casing thickness of (3mm) and a length of more than (10m). The authors concluded that the value of the interconnection strength of (CCA rods) reached (40.5-67.9 MPa) equal to or greater than the shear strength of pure aluminum, and the thickness of the interlayers significantly affected the interconnection's strength, i.e., its value decreased with layers' thickness. The optimal state to produce (CCA rods) by (HCFC) method was (T_{Cu} =1230 ˚C), (T_{Al} =790 ˚C) (Q_1=600L/H), (Q_2=700L/h), and (V=87mm/Min). Under these conditions, the interlayer's thickness decreased to (75 µm). Zare et al. [26] studied the microstructure and mechanical properties of the Al-Cu bimetal produced by the composite casting method. The authors used pure copper and pure aluminum. The casting process was conducted in a sand mold. Copper was inserted in the form of (rod) with a diameter of (5.12 mm) after casting aluminum at a temperature of (700 ˚C). It was found through the results of microscopic examination that the interface consisted of several layers, including ($Cu_9Al_4, AlCu$ and Al_2Cu). Through the results of the hardness test by the Vickers method the interface area was characterized by the highest hardness, as its value reached (300 HV) while the hardness value of the base metal was (<50 HV). The hardness decreased from copper toward aluminum because of this gradient in concentration between the substrate (copper) and the base metal (aluminum) formed the reaction zone, which included the various layers mentioned. Fu et al. [27] studied the aluminum casting temperature impact and the copper preheating temperature to form the interface by the gravity plumbing method. The authors used an alloy (Al-7%si) and a pure copper rod with the preheating process of copper before casting to a temperature of (250 ˚C). The authors used different temperatures for casting, i.e.,(700,750, and 800 ˚C). The authors found through the microscopic examination that at a casting temperature of (800 ˚C), copper deformed significantly because of the melting part of it due to the high casting temperature. Many Al-Cu intermetallic compounds (IMCs) were observed at the interface when the casting temperature dropped to (750 ˚C). Good bonding was obtained when there was no melting of copper or defects in casting, and rarely there is any (IMCs). The interface was completely clear between the two metals. At a casting temperature of (700 ˚C), there were cracks and cavities due to insufficient interaction near the interface, damaging the bonding between the two metals. A review of previous studies, found that the ratio of liquid-to-solid impact on the bimetal's (Al-Cu) properties produced by the squeeze casting technique has yet to be studied. Also commercial copper and aluminum are used in the present study with copper-nickel plating by electroplating method, fixing the casting temperature and preheating copper metal and die and the pressure applied. The only variable is the liquid-to-solid ratio.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials

The first materials applied on the practical side were commercial aluminum and commercial copper, i.e., copper was a cylindrical rod. Chemical analysis conducted for models of these materials, as shown in Table 1. Commercial copper was processed from the domestic markets in solid cylindrical rods with diameters of 10 mm and 20 mm and a length of 50 mm. The copper metal was cleaned to remove oxides and grease using a softening paper until (p 1500). The samples were placed in a diluted hydrochloric acid (HCl) solution and washed with distilled water. Then, they were dried to conduct nickel electro-coating. The components of the coating electrolyte consisted of 250 g of nickel sulfate, 15 g of nickel chloride, and 15 g of boric acid dissolved in one liter of distilled water at 50 °C. Fig. 1 shows the copper rod before and after coating.

Table 1 Chemical Structure of Materials (Al-Cu).

Composition (wt.%)							
Alloy	**Al**	**Cu**	**Si**	**Fe**	**Zn**	**Ni**	**Mn**
Al	99.5	-	0.41	0.006	-	0.01	0.02
Cu	0.29	99.6	0.04	0.03	0.02	-	0.01

Fig. 1 Copper Rod before and after Coating.

2.2. Experimental Procedure

The die was made of carbon steel with a 70 mm outer diameter, 40 mm in diameter inside, and a height of 55 mm with a base to fix the die. The copper inside the die was a cylindrical shaft of 39.5 mm and a length of 100 mm. The pressing pressure was fixed at 45 MPa; the casting temperature was 700 °C , the preheating temperature of the die was 300 °C and the copper was 350 °C, Fig. 2 shows the complete casting system. The experiment procedure was as follows: melting aluminum in an electric furnace using a crucible of graphite, install the copper in the base's center, install the die on the base so that the copper is in the die's center, install the base and die under the piston, pour molten aluminum and wait until the metal reaches the dough state, apply the pressure on the metal and maintaining the pressure for (100 sec) until the metal freezes under pressure, remove the cast from the die, and leave it for a sufficient period (refrigerate at room temperature). After the casting process, the samples were cut and Prepared (smoothing and polishing) conduct the tests. Figures 3- 8 show the oven used, the hydraulic press, the temperature measuring device (SD Logger), the die heating device, the sample cutting device and the smoothing and polishing device.

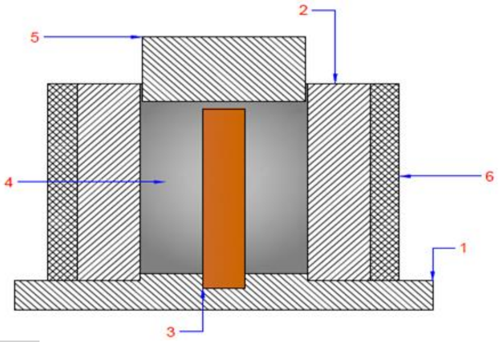

Fig. 2 Schematic Showing the Squeeze Casting System: 1-Plate, 2- Die, 3- Copper Rod, 4- Aluminum Melting, 5- Punch, 6- Heater.

Fig. 3 Electric Resistance Furnace.

Fig. 4 Hydraulic Press.

Fig. 5 (SD Logger).

Fig. 6 Die Heating Device.

Fig. 7 Sample Cutting Device.

Fig. 8 Smoothing and Polishing Device.

2.2.1.Experimental Sets

Two sets of experiments were conducted. In the first set, the liquid-to-solid ratio were (17%), the copper diameter was (10mm), the pressing pressure was fixed at (45 MPa), the casting temperature was (700˚C), and the die and copper's preheating temperatures were (300˚C) and (350˚C), respectively. In the second set, the same previous values were applied with a difference in the ratio of liquid-to-solid (3.5%), and the copper diameter was (20mm). Fig. 9 shows samples at different liquid-to-solid ratios.

(a)

(b)

Fig. 9 (a) at the Liquid-to-Solid Ratio 17% (b) at the Liquid-to-Solid Ratio 3.5%.

3.EVALUATION

To evaluate the microstructure(interface) and the bimetal mechanical properties, several tests and examinations were conducted to determine the optimal variables and show this method's efficiency in connecting the two metals (squeeze casting); among such examinations, microscopic, hardness, and interconnection strength.

3.1.Optical and Scanning Electron Microscopy Test

Optical microscopy (OM), Olympus Japan, and scanning electron microscopy (SEM), Axia, equipped with an energy dispersive X-ray spectrometer (EDS), were used to determine the microstructure nature and the bimetal interface properties. Figures 10 and 11 show the optical microscope and scanning electron microscopy, respectively.

Fig. 10 Optical Microscope.

Fig.11 Scanning Electron Microscope.

3.2.X-ray Diffraction Test

This test determined the compound's intermetallic type between the two metals. These compounds in diverse forms indicate the success of the linkage and achieved good diffusion. Fig. 12 shows the X-ray diffraction device.

Fig.12 X-ray Diffraction Device.

3.3.Micro Hardness Test

The hardness was checked using a Vickers hardness tester of the type (REF.D0029. 8) applied load of 300 g for 5 sec. The hardness of copper, aluminum and all samples' interfaces were measured with different variables of the practical side. Fig. 13 shows the Vickers hardness device.

Fig. 13 Vickers Hardness Device.

3.4.Interfacial Shear Strength Test

The shear test was conducted using a machine of type (identity). The samples used had a height of 10 mm and a diameter of 40 mm. From Eq. (1), the shear resistance can be calculated. This type of test is considered an important one that determines the mechanical properties, i.e., the metal's interconnection strength, which directly depends on the diffusion. Figures 14 and 15 show the shear device and the schematics of the shear test, respectively.

$$\tau = \frac{F_{max}}{A} = \frac{F_{max}}{\pi dh} \qquad (1)$$

Fig. 14 Shear Test Device.

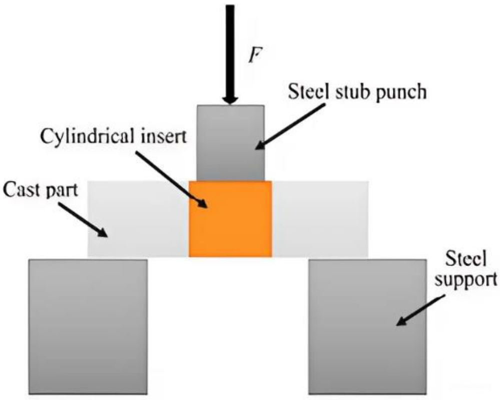

Fig. 15 Schematics of the Shear Test.

4.RESULTS AND DISCUSSION

4.1.Optical and Scanning Electron Microscopy Result

The microstructure in the transition zone varies with the difference in the liquid-to-solid ratios. The transition zone mainly comprises intermetallic compounds (IMCs) with different thicknesses and shapes. The type of layers at the interface is determined by the distribution of copper atoms across the transition zone. The primary influencing parameters are temperature and diffusion time, affecting the distribution of copper atoms across the interface, as the diffusion of copper in the molten aluminum increased with diffusion time due to the solid at the interface. Increasing the number of copper atoms dissolved in the proportion of liquid-to-solid significantly influenced the bonding between the two metals. The higher the aluminum enthalpy, the greater the amount of copper atoms dissolved; therefore, the intermetallic compound thickness will increase and decrease, positively reflecting on the rest of the properties, including the bonding strength, as shown Fig. 16. The Ni layer influenced the intermetallic region (Al-Cu) microstructure because it acts as a protective membrane that can prevent development of oxides on the copper surface, which it helps a continuous metal transition from molten aluminum to solid copper. Also the Ni interlayer prevented the copper atoms from passing through the interlayer (Ni), i.e., diffusing in the molten aluminum, which is evident by the presence of phases in the interlayer. The (Ni) atoms diffused in copper and aluminum and were uniformly distributed in copper and (IMCs) adjacent to the interlayer of the bimetal (Al-Cu) at the interface using a scanning electron microscope (SEM), as shown in Fig. 17. It was found through the analysis of (EDS) shown in Fig. 18 that except for the interface the aluminum content in copper or the copper content in molten aluminum was very small, indicating that the interaction or diffusion between the two metals occurred only in the interface area. The in the of both Al and Cu concentration gradient differed by different Interface areas [28]. The dominant process of the interaction is copper melting in molten aluminum duo to the diffusion factor of a solid in liquid metal. There are five to six metal atoms times greater than the diffusion inside solid metal. The higher the temperature [18]. The longer the reaction time, i.e., increase the diffusion of copper atoms in the molten aluminum.

4.2.X-ray Diffraction Result

From the XRD test, shown in the Figs. 19 and 20, the correlation between bimetallic was successful duo to vehicles' interlayer minerals (IMCs). Also those figures show the access of the interdependence and interaction between bimetallic (Al-Cu) at the interface; however, they did not note the presence of vehicles interfacial metal brittle between aluminum and nickel (brittle Al-Ni intermetallic compounds) because the growth rate of vehicle interface metal between (Al and Cu) was much faster than (Al-Ni) and the power interface (Ni) was not enough to deal with molten aluminum.

Each layer interaction from the side of the aluminum to the copper was compatible with the vehicle interface metal ($Al_2Cu, AlCu_4, AlCu, Al_4Cu_9, Cu_4Al_3$). The (Ni) layer effectively assessed the vehicle configuration interface of the metal. The increase in the liquid-to-solid ratio increased the bonding and emerged new compounds duo to the adult enthalpy, melting the coating and consisting of new vehicles. The vehicles were even more versatile when the largest proportion of liquid-to- solid was 17%.

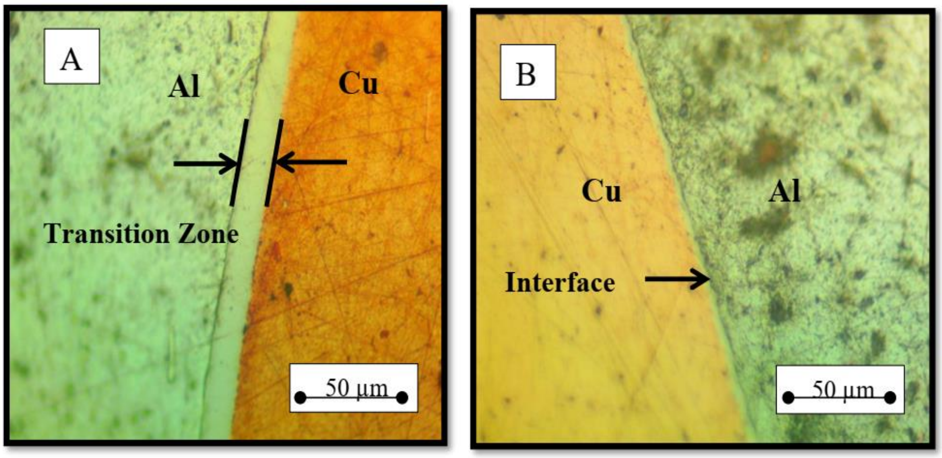

Fig. 16 Microstructure of Al-Cu Bimetal Interface Created Using Various Parameters at Liquid-to-Solid Ratio (a) 17% with 700 °C and 45 MPa, and (b) 3.5 %with 700 °C and 45 MPa.

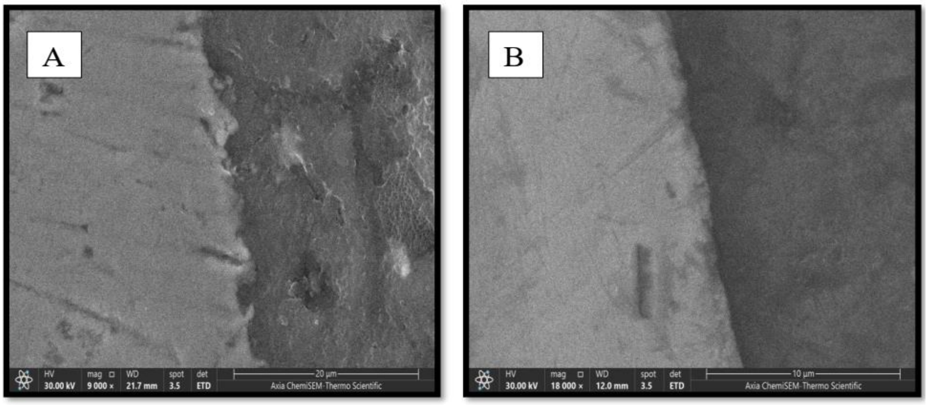

Fig. 17 SEM Image of the Al-Cu Contact at Liquid-to-Solid Ratio (a) 17% with 700 °C and 45 MPa, and (b) 3.5% with 700 °C and 45 MPa.

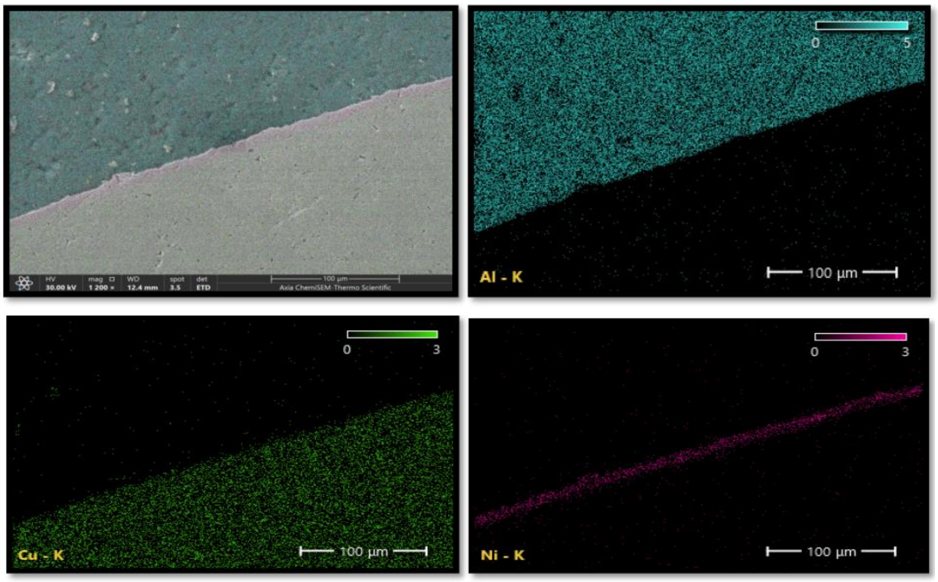

Fig. 18 Concentration Al, Ni, and Cu Mapping from Al-Cu Bimetal Produced at Pouring Temperature of 700 °C, Applied Pressure 45 MPa and Liquid-to-Solid Ratio 17%.

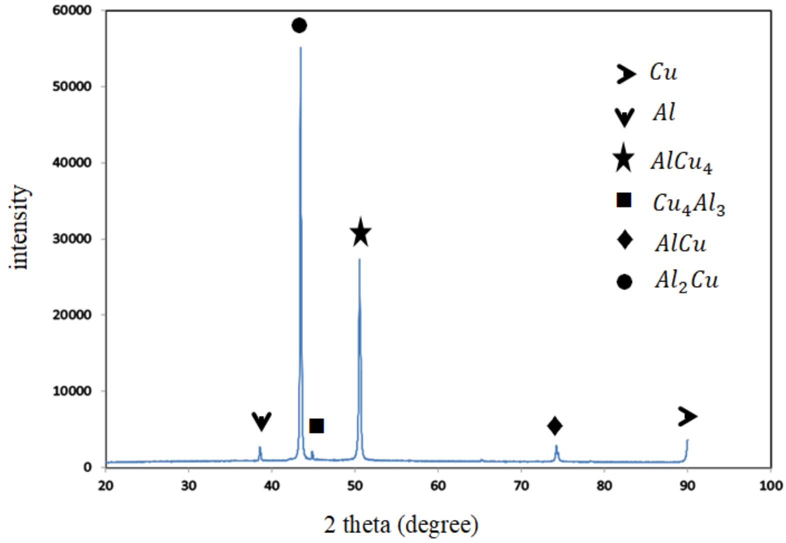

Fig. 19 XRD Interface Pattern of Al-Cu Bimetal at Liquid –to-Solid Ratio = 17%.

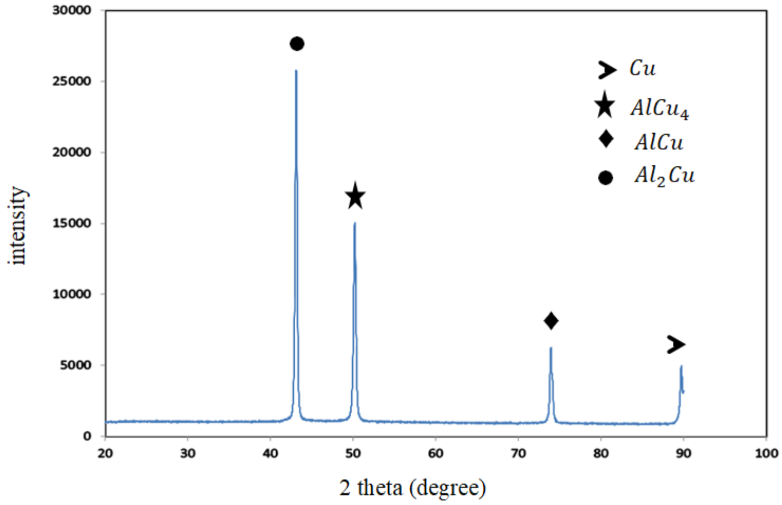

Fig. 20 XRD Interface Pattern of Al-Cu Bimetal at Liquid-to-Solid Ratio = 3.5%.

From the results mentioned above, it can be found that the liquid-to-solid ratio significantly affected controlling the transition zone's properties and thickness. The higher this ratio, the thicker the transition zone due to the large thermal content of molten aluminum, which melted copper atoms and thus increases the bonding strength between the two metals. The nickel coating significantly reduced the intermetallic compounds' thickness and produced good interface specifications and mechanical properties, i.e., protecting copper well from oxidation which was evident through mapping analysis, as the paint spread on the aluminum and copper was in completely dissolved.

4.3.Microhardness Result

According to the hardness test, i.e., the Vickers method, the aluminum hardness was (30-40 HV), copper was (80-90 HV), and the interface was (100-200 HV). The copper and aluminum hardness were unaffected by the liquid-to-solid ratio, contrary to the hardness of the two metals. If the interface area's hardness increases with the of liquid-to-solid ratio because of the large thermal content, melting the copper surface and thus achieving diffusion. The formation of metal-structural compounds to increase their thickness increased with this ratio. Fig. 21 shows the samples' with different liquid-to-solid ratios.

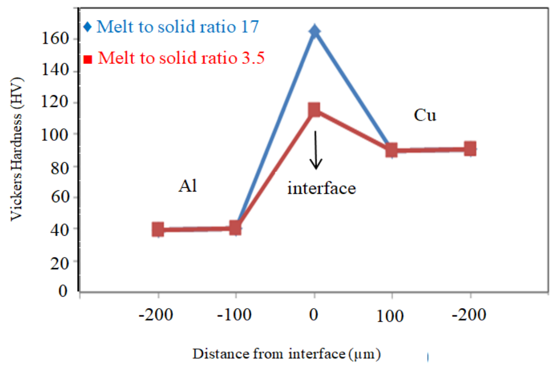

Fig. 21 Hardness Distributions in the Interface of Al-Cu Bimetal Made at Different Liquid-to- Solid Ratios and Fixed Applied Pressure at 45 MPa and Pouring Temperature at 700 °C.

4.4. Interfacial Shear Strength Result

The liquid-to-solid ratio is a significant influence on the shear strength of the bimetal (Al-Cu) because it directly affects the intermetallic compounds' thickness (IMCs). The thickness of these compounds decreased with increasing the liquid-to-solid ratios; therefore, the strength of the intermetallic bonding of the bimetal (Al-Cu) increased. The shear failure occurred mainly in rigid brittle interfacial intermetallic compounds area due to the high hardness and poor plasticity. The layer (Ni) substantially impacted the heart resistance of bimetallic (Al-Cu) because it improves the mechanical characteristics of bimetallic (Al-Cu). Fig. 22 displays the shear resistance of bimetallic with a different amount of liquid-to-solid due to the increase in enthalpy with the liquid-to-solid ratio. The shear strength also increased, and diffusion between the two metals occurred. When the liquid-to-solid ratio was 17%, the bimetal's shear resistance reached 15.5 MPa, and the liquid-to-solid was 3.5%. The large difference in the shear resistance, i.e., 8.3 MPa, showed the great effect of the liquid-to-solid in determining the bimetal's mechanical characteristics.

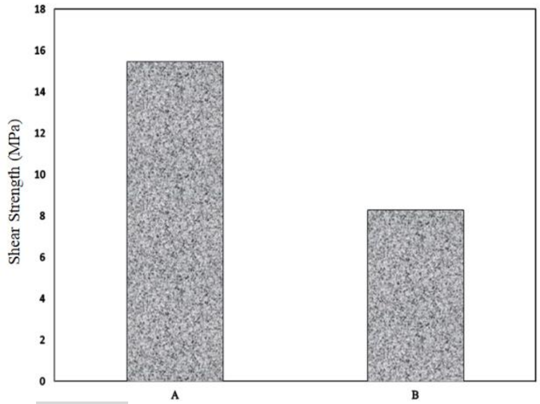

Fig. 22 Shear Strength of Al-Cu Bimetal Produced at a Liquid to Solid Ratio (A) at 17%, and (B) 3.5%.

5. CONCLUSIONS

The main conclusions of the present study could be summarized as follows:

- The possibility of producing Al-Cu bimetal by the squeeze casting method.
- The best metallurgical properties and good thickness of the transition point were obtained at a liquid-to-solids ratio of 17%.
- The hardness of the interface between Al-Cu bimetallic was affected by the liquid to-solid ratio, reaching (168 HV) at a liquid to-solid ratio of 17%, while the hardness of copper and aluminum was (80-90 and 30-40 HV) and was not affected by the ratio of liquid to solid.
- The shear strength of the Al-Cu bimetallic was affected by the liquid to-solid ratio, reaching its highest value, i.e., 15.5 MPa, at a liquid to-solid ratio of 17%, while this value at 8.3 MPa was at the of liquid to-solid ratio of 3.5%.
- According to the EDS analysis and from the mapping analysis, the nickel coating dispersed in aluminum and copper and incompletely dissolved, improving the mechanical properties.

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