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Original Article

Mechanical and Tribological Insights Coupled with SEM Analysis of Al-Cu Bimetals Produced via Centrifugal Casting

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Abstract *- Metals have been around for a long time, and we have developed many ways to shape them for different uses in engineering. Nowadays, high-tech applications need strong, long-lasting materials. Bimetal cylinders are important for industries, and one effective way to make them is through centrifugal casting. This paper focuses on Al-Cu bimetal combinations that may be combined to study bimetal cylinders by varying the speed of rotation of mould and insulating the rotating mould with asbestos as process parameters. The investigation involves analyzing the mechanical, tribological properties, and microstructure features of Al-Cu bimetallic materials produced through centrifugal casting.*

Keywords *- Bimetal, Horizontal centrifugal casting, Interface, Al-Cu, Insulation.*

1. Introduction

Various manufacturing processes exist to transform raw materials into finished products. Among these methods, casting remains significant and distinct. In casting, liquid material is poured into a prepared mould with the desired shape. As the molten metal fills the cavity and solidifies, it takes on the intended form. Centrifugal casting, based on the principle of using forces generated by a rotating mould's centripetal acceleration[1], produces accurately dimensioned products with minimal gas porosity.

Though casting is an older manufacturing method, its development in casting technology still faces several challenges compared to other manufacturing techniques. Casting poses complexities due to phase changes, extreme temperature variations, dynamic conditions, rapid solidification, impurities, void formation, irregularities, grain formation, and microstructures. Among these complexities, grain structure formation during solidification is crucial yet intricate [9]. This involves grain and nucleus formation, along with potential structure defects and phase changes in solid metal.

1.1. Principle of Centrifugal Casting

Prospective Centrifugal casting is a casting technique that is typically used to cast thin-walled cylinders. It is typically used to cast materials such as metals, glass, and concrete. A high quality is attainable by control of metallurgy and crystal structure.

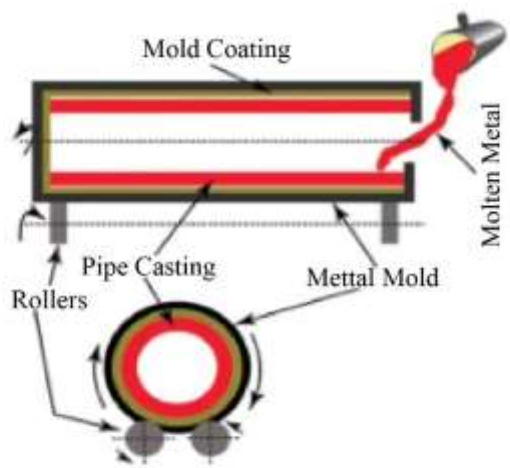

Fig. 1 Horizontal centrifugal casting machine

Molten metal is poured into a casting chamber, which is connected to the mould cavity. A piston here plays an important role by pressing liquid metal into a part called the channel. Die casting with a series of moulds contains a series of channels connected to them. At this point, casting solidifies under high pressure and is removed.

1.2. Bimetal Production and Applications

In certain applications, combining different metals in the form of bimetals offers advantages by leveraging the unique properties of each metal. Bimetals, a simple type of metal composite, consist of two metals layered together instead of being mixed like alloys. Metallurgical bonding [18] between these metals occurs due to atomic forces at their interface [3]. The production of Bimetal Cylinders using the Horizontal Centrifugal Casting method is shown in Fig. 2. This bonding enables the creation of components that harness the individual strengths of both metals. Bimetallic components find widespread use in fields like space exploration, wind power, petrochemicals, and marine vessels.

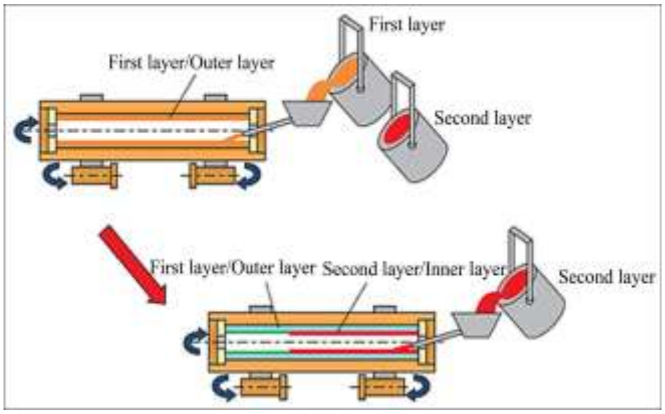

Fig. 2 Bimetal cylinder casting using horizontal centrifugal casting method

The interface morphology and bonding characteristics are key factors defining the performance of bimetallic components, owing to differences in structure and properties between the metals. After years of research, achieving centrifugal casting of bimetallic composite rollers and pipes is a notable advancement. The process involves creating both layers of bimetallic cylinders using the horizontal centrifugal casting method by pouring one molten metal after the other into the rotating mould. The bonding interface morphology is influenced by factors like pouring temperature [7] for the outer layer, time intervals between inner and outer layers, and the rotational speed of the casting mould. The thickness of the bonding is primarily affected by pouring temperature and solidification methods [9]. The mechanical properties of these bimetal components heavily rely on the quality of the bonding interface. The composited mechanism of centrifugal casting is mainly characterized by metallurgical bonding [2].

These Bimetals are formed through a crucial process of creating a strong metal bond at the interface between two metals or metal alloys, effectively merging them into a single composite unit. The presence of this metallic bond contributes to the fusion of the two materials. These combined metals offer advantages by complementing each other in mechanical, chemical, physical, or economic aspects.

Creating this bond relies on the ability of atoms near the interface to generate both repulsive and attractive forces between the metals. Not all metals can be combined to form bimetals due to variations in their chemical, physical, and metallurgical properties, which limit the compatibility of certain metal pairings.

The applications of such bimetal products are in chemical industries, petrochemicals, power plants, nuclear power plants and metals mining industries (Copper, Iron, and Steel). It is also widely used in the fields of deep space exploration, wind power, petrochemicals, ocean-going ships, etc. Bimetal cylinders are the most common type of components used in industries for their usage as bimetal pipes, which are produced with centrifugal casting. In these industries, bimetal pipes are widely used for heat converters, reformers, heat exchangers, reactors, condensers, pumps, radiation tubes, etc. In applications, multilayer metals may be divided into corrosion-resistant, wear-resistant, or tool materials, thermal bimetals, electrical engineering, wire, contact, or anti-frictional materials, materials for deep extrusion, for heat exchangers, or domestic appliances, and so on. Bimetals significantly improve the production efficiency of components in various branches of industry.[4]

2. Experimentation

2.1. Materials and Bimetal Fabrication

Given the wide array of available materials suitable for diverse applications, the production of bimetals offers options involving both Ferrous and Non-Ferrous metals. Researchers have explored specific combinations of metals, conducting various studies in this domain. However, limitations exist when it comes to pairing certain metals due to their reactivity or inability to form a cohesive metallic bond. Some metal combinations may undergo reactions that prevent the formation of a strong bond, leading to the separation of the two metal pieces. These limitations stem from the inability of certain metals to effectively amalgamate or form a durable bond when combined, necessitating careful consideration and selection of compatible metal pairings for successful bimetal production.

The focus of this paper centers around the bimetal combination of Aluminum and Copper. These two metals possess distinct properties that make their combination valuable for various applications. Aluminum is known for its lightweight nature, corrosion resistance, and conductivity, making it useful in aerospace, electrical, and construction industries. On the other hand, Copper offers excellent electrical conductivity, high thermal conductivity, and superior strength, making it widely used in electrical wiring, heat exchangers, and plumbing.

Combining Aluminum and Copper in a bimetallic structure leverages the strengths of both metals, resulting in a composite material with improved mechanical, electrical, and thermal properties. However, achieving a strong metallurgical bond between these metals is crucial for the success of bimetallic components [5], ensuring that the unique properties of each metal contribute to the overall performance of the composite. The paper likely deals with the manufacturing techniques and properties of Aluminum-Copper bimetals, emphasizing the significance of their interface and bonding [6] characteristics in enhancing the quality and performance of the final product.

3. Materials and Methods

The properties highlight some of the distinguishing characteristics of Aluminum and Copper, showcasing differences in density, melting point, electrical and thermal conductivity, strength, and corrosion resistance. Copper has a higher melting point and higher thermal conductivity than Aluminum metal. These differences make each metal suitable for various applications across industries, and when combined in a bimetallic structure, their properties can complement each other to achieve specific desired outcomes.

Using a horizontal centrifugal casting machine differs significantly from other casting methods. The rotational force is transmitted to the shaft assembly through the coupling, driving both the driven shaft and the main shaft. This rotation causes the mould to spin on its axis at speeds of up to 2000 RPM. Molten metal was poured into the spinning mould through the sprue, and the spinning action of the mould generated centrifugal force on the molten metal, distributing and shaping it within the mould as cylinders. As the casting solidifies from the outside, the inner surface supplies additional molten metal to complete the casting as needed [10].

3.1. Melting the Metals

During the high-temperature melting process of molten metals, there is a risk of atmospheric interaction, leading to the formation of dissolved gasses, primarily hydrogen and oxides [5]. This can result in poor surface finish and low-quality casts. Additionally, the bonding of two metals may be hindered by the formation of oxide layers [5] on the inner surface of the first cast cylinder. To mitigate such oxidation and enhance the quality of produced casts, it is crucial to employ specific chemicals acting as degassing agents. Figure 3 (a), (b), and (c) illustrate the degassing agents utilized for aluminum, and Figure 4 (a) and (b) illustrate the degassing agents utilized for copper, respectively.

Fig. 3 (a) Alflux-1 (b) Degasal 200 (c) Nuclan-2

The Alflux-1 used for Aluminum cast acts as a Covering flux to protect the molten metal from atmospheric contamination and oxidation. It forms a protective layer on the surface of the molten metal, preventing exposure to air and other reactive elements. While the Degasal 200 tab removes the hydrogen, Nuclan-2 will enhance the grain refinement of the metal during solidification.

Fig. 4 (a) Degaxon tablet (b) Cover flux cuprit -44

3.2. Development of Bimetal Cylinders

The metals Aluminum and Copper were melted using two different Electric furnaces set at a temperature of 800 degrees Celcius and 1150 degrees Celcius, respectively.

The metals, once melted were poured into the rotating mould at different speeds of rotations like 600rpm, 800rpm, 1000 rpm and 1200 rpm.

Fig. 5 (a) Bimetal Cylinder casted in Horizontal centrifugal casting machine at 600rpm (b) Bimetal Cylinder Cut in half.

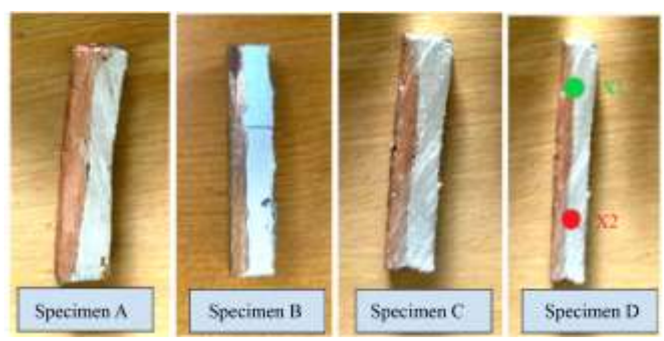

Fig. 6 Bimetal Specimens cut from cast cylinders at different speeds of rotations without mould Insulation (a)600rpm (b)800rpm (c) 1000rpm (d) 1200rpm

To prepare the rotating mould for casting, it was preheated to 250 degrees Celsius using a Benzene flame torch. Following preheating, the mould was insulated with an asbestos rope wound around its surface. This insulation served to decrease the rate of heat flow and improve the solidification rate of the casting material.

Subsequently, aluminum and copper were sequentially poured into the rotating mould to produce Al-Cu bimetal casts. This step-by-step pouring process ensured proper distribution and bonding of the two metals within the mould, resulting in the desired bimetallic structure.

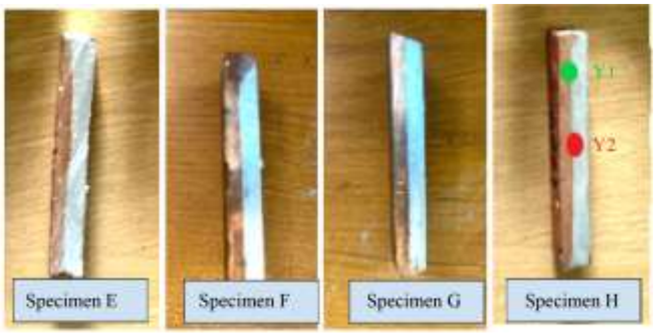

Fig. 7 Bimetal Specimens cut from cast cylinders at different speeds of rotations with mould Insulation (a)600rpm (b)800rpm (c) 1000rpm (d) 1200rpm

4. Results and Discussion

The bimetal specimens underwent cross-sectional cutting along the length of the cast cylinder for testing purposes. These specimens remained untouched by polishing, etching, or any additional finishing procedures. This approach aimed to assess the raw state of the cast bimetals from the casting machine, avoiding alterations in properties caused by cutting or shear forces. Subsequent tests focused on hardness, wear resistance, and microstructure examination of the specimens that exhibited the most promising results.

Microstructural investigation was conducted using a Scanning Electron Microscope (SEM), specifically a field emission gun scanning electron microscope, to analyze the Al/Cu bimetallic composites. Hardness tests were performed at the bimetal interface [6] using Rockwell Hardness testing, and Izod Impact tests were carried out to evaluate the impact strength of the bimetal specimens. These tests aimed to provide comprehensive insights into the structural integrity, hardness [17], and durability of the bimetal components without altering their initial state post-casting.

4.1. Hardness Tests

The Rockwell hardness test, outlined in ASTM E-18, stands as the most widely used method due to its simplicity and accuracy. It involves applying a preliminary force with an indenter to penetrate the surface, followed by measuring the initial indentation depth. Then, an additional load is applied, and after a dwell period, the final indentation depth is measured. The difference between these depths yields the Rockwell hardness value, representing the material's resistance to indentation.

The bimetal was produced using two different metals, melted and poured into the rotating mould to form bimetal cylinders. Considering the same parameters of producing bimetal cylinders like the speed of rotation, pouring temperature and thickness of insulation [6], the casts were prepared with individual metals as well to compare the bimetal cylinder's quality and strength. The Rockwell hardness tests were carried out on Specimen A, Specimen B, Specimen C and Specimen D for different loads 100 N, 150N, 200N and 250N with a constant indent of 1/8 inch at four different positions. The hardness values thus obtained are presented in the bar chart below.

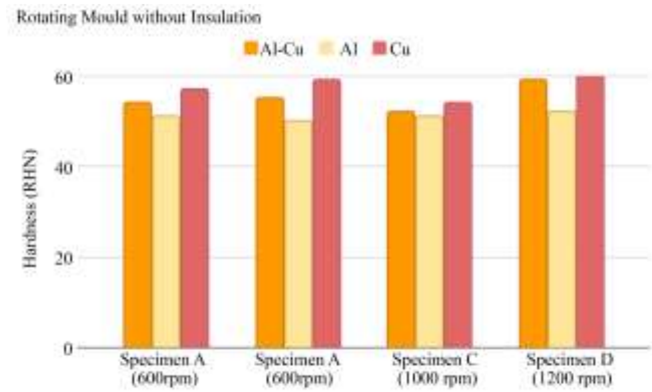

Fig. 8 Comparison of rockwell hardness number for different specimens produced without insulating the rotating mould

As depicted in Figure 8, the hardness of the bimetals is closely matching with the hardness of the individual metal castings. The hardness number is increasing as the speed of rotation is increasing. This is due to the fact that the higher speed of rotation will make the molten metal settle down around the inner surface of the rotating mould at the required shape with enough solidification time [10] for the metals to solidify, leading to a better microstructure and surface finish.

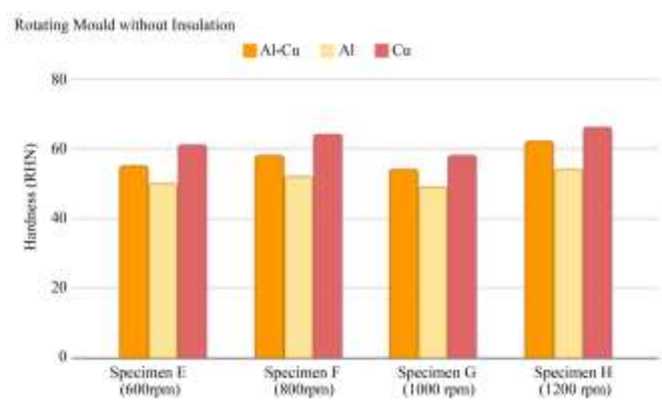

Fig. 9 Comparison of Rockwell Hardness Number for different specimens produced insulating the rotating mould

Figure 9 reveals a significant trend: specimen H exhibits marginally superior hardness [16] compared to Specimen D, as depicted in Figures 3 and 4 showcases the hardness values of Aluminum, Copper, and Aluminum-Copper Bimetal specimens, all produced with the insulation of the rotating mould using asbestos rope.

4.2. Impact Tests

Impact testing of metals is made to assess their resistance to fracture and toughness by measuring the energy absorbed during fracture. The ISO 148-1 standard outlines the Charpy impact test, employing both U-notch and V-notch configurations, to determine impact strength in metals. This characteristic holds significant relevance in industries such as pipeline construction and shipbuilding, where materials must withstand sudden loads and harsh environments. Additionally, ASTM E23 provides detailed guidelines for conducting and interpreting the results of impact tests, ensuring standardized and reliable assessment of material properties.

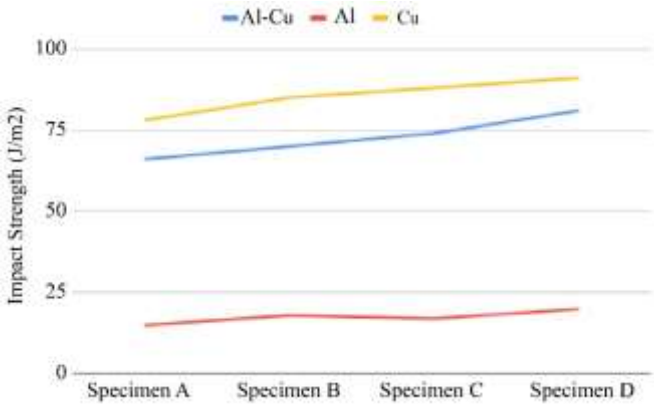

Fig. 10 Impact strength of different specimens (Without mould insulation)

Figure 10 reveals that the impact strength of pure copper metal surpasses that of pure aluminum and aluminum-copper bimetal. However, the combination of aluminum and copper in the bimetal configuration notably enhances its impact strength compared to pure aluminum, albeit still falling short of pure copper. Moreover, there is a discernible trend of increasing impact strength values with higher rotation speeds, as depicted in Figure 10.

Employing identical parameters as previously mentioned, including the addition of insulation around the rotating mould using asbestos rope, castings were manufactured, and subsequent Charpy Impact tests were conducted. The impact strength values for both individual metals and bimetallic compositions are depicted in Figure 11.

Despite minimal alterations, notable changes in impact strength values are observable, attributed to the introduction of insulation. Insulation assumes a pivotal role in regulating the cooling rate [6] during casting solidification by affording additional time for molten metal to flow around the rotating mould[13]. Thicker insulation, in particular, leads to decelerated cooling rates, yielding various effects on the resulting casting. This includes the promotion of superior grain structures, resulting in enhanced surface finish and improved strength compared to non-insulated rotating mould[15].

4.3. Wear Tests

The wear test procedure involved placing the pin against the counter face of a rotating disc made of EN31 steel with a wear track diameter of 60 mm. The pin was subjected to loading against the disc using a dead-weight loading system. The wear tests were conducted under varying normal loads of 40N and 50N, with sliding velocities set at 1 m/s and 2 m/s. Each specimen underwent wear testing for a total sliding distance of approximately 1000 m, maintaining consistent testing conditions throughout the experiment.

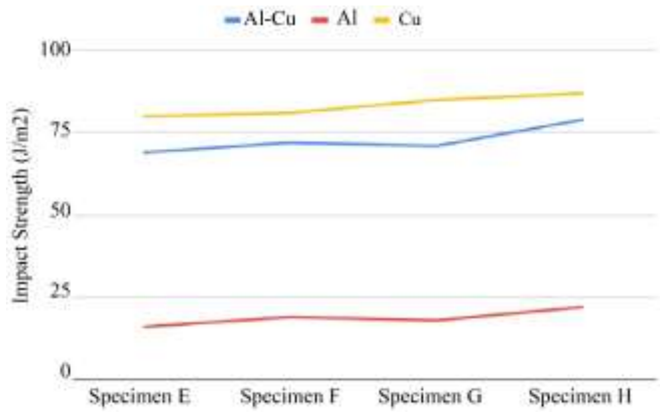

Fig. 11 Impact strength of different specimens (With mould insulation)

4.3.1. Wear Rate

Figures 12(a) and 12(b) illustrate the relationship between the speed of rotation of the mould and the resulting wear rate of specimens with sliding speeds of 1m/s and 2m/s, respectively. Notably, the specimen subjected to the highest speed of rotation exhibits a lower wear rate compared to others within the batch. Additionally, there is a slight reduction in wear rate for the specimen prepared at 1200 rpm with the rotating mould insulated. This phenomenon can be attributed to the mitigated heat loss and enhanced solidification of the molten metal.

4.3.2. Specific Wear Rate

Figures 13(a) and 13(b) present a comparative analysis of the specific wear rates of specimens, highlighting the notable observations regarding copper and aluminum materials. Both metals demonstrate relatively high specific wear rates initially. However, as the speed of rotation of the mould increases and insulation is applied, there is a discernible decrease in the specific wear rate.

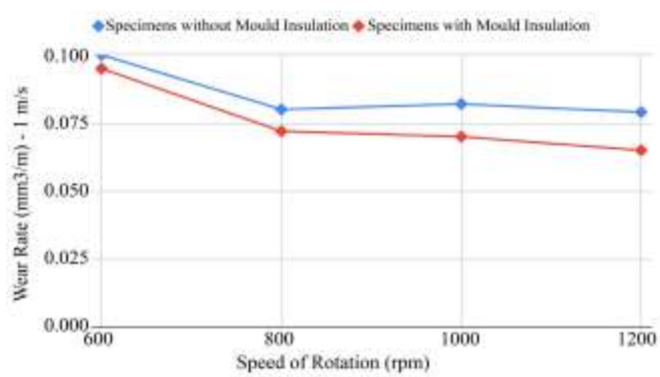

Fig. 12(a) Speed of Rotation vs Wear rate at 1m/s(cubic mm/m)

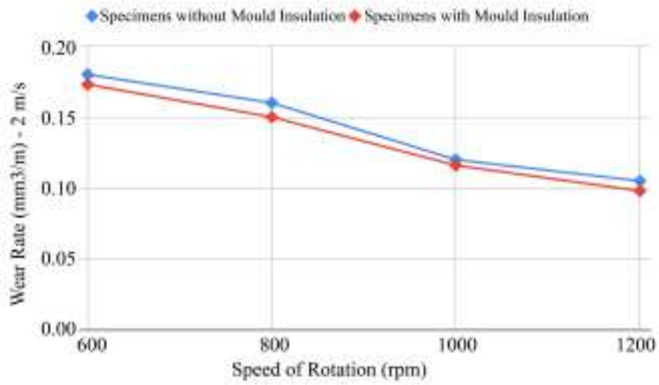

Fig. 12(b) Speed of rotation vs Wear rate at 2m/s(cubic mm/m)

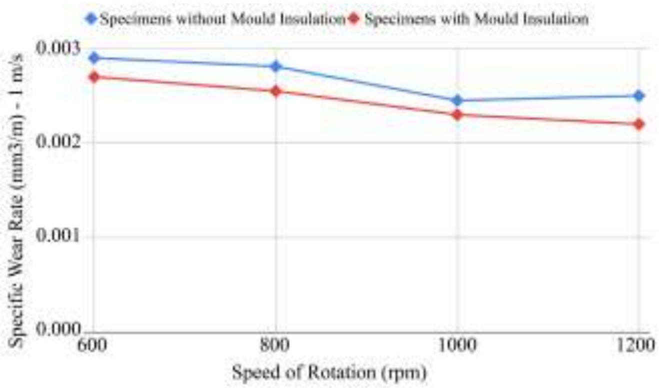

Fig. 13(a) Speed of rotation vs Specific wear rate at 1m/s(cubic mm/m)

These figures distinctly indicate that the addition of insulation to the rotating mould plays a significant role in reducing the specific wear rate, thereby enhancing the material's wear resistance under sliding conditions. Consequently, it is clear that the concentration of aluminum is a major factor influencing the specific wear rate of the specimens.

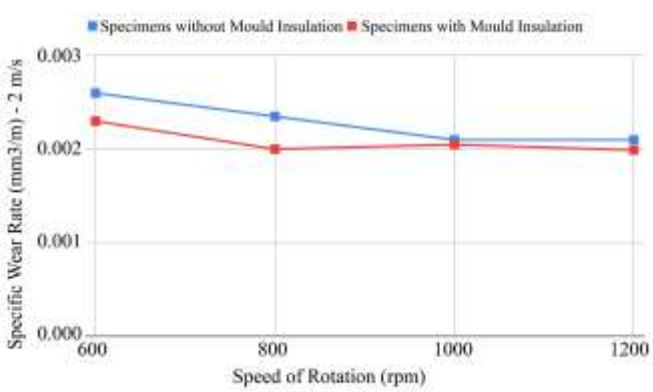

Fig. 13(b) Speed of rotation vs Specific wear rate at 2m/s(cubic mm/m)

4.3.2. Wear Resistance

Figure 14 clearly indicates that the wear resistance of the specimens is influenced by the higher speed of rotation, with insulation of rotating mould having a great impact on the wear resistance.

As the speed of rotation increases, the wear resistance of the bimetal also increases. It can also be observed that there is slightly increased wear resistance offered by the bimetal produced at 1200 rpm with insulated mould.

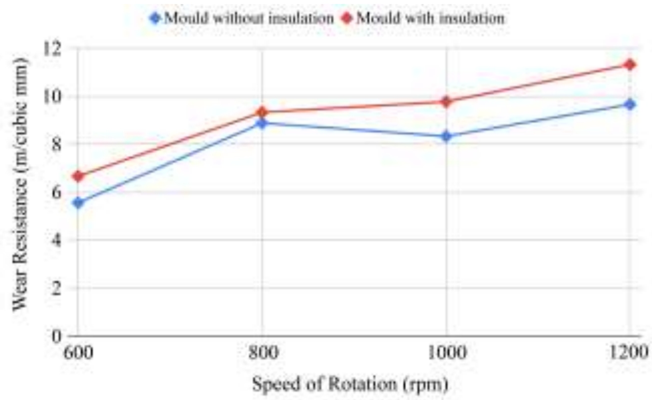

Fig. 14 Speed of rotation vs Wear resistance

Through careful examination of the above results, it can be inferred that optimizing the composition of copper and aluminum, along with specific process parameters such as increased speed of rotation and insulation of the rotating mould, can substantially strengthen the wear resistance of the bimetal and consequently improve its overall durability.

4.4. SEM Analysis

SEM provides unparalleled detail of material surfaces at a microscopic scale, far beyond optical microscopes, by using a focused electron beam instead of visible light. Specimens yielding the best mechanical test results were selected for SEM analysis. Specimen-D from Figures 3 and 5, without insulation, and Specimen-H from Figures 4 and 6, with insulation, were chosen for their respective groups.

The selection of these specimens for SEM analysis underscores the significance of understanding the surface morphology, composition, and structure of bimetals at a microscopic level.

By delving into these intricate details, we can glean valuable insights into the factors influencing the mechanical properties and overall performance of the bimetallic materials under investigation. Such insights are pivotal for informing further optimization efforts and enhancing the quality and functionality of the materials for diverse applications.

Fig. 15 SEM images of bimetal specimen D (without insulation) at marked position X1 as shown in Fig. 6(d)

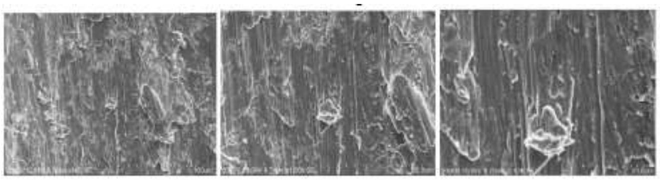

Fig. 16 SEM images of bimetal specimen D (without insulation) at marked position X2 as shown in Fig. 6(d)

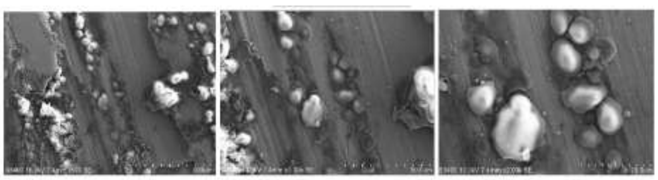

Fig. 17 SEM images of bimetal specimen H (with insulation) at marked position Y1 as shown in Fig. 7(d)

Fig. 18 SEM images of bimetal specimen H (with insulation) at marked position Y2 as shown in Fig. 7(d)

The three images shown in each of the SEM images, Figures 15, 16, 17, and 18, represent the magnification levels at 500x, 1000x and 2000x, which shows us the contours at 100µm, 50µm and 20µm respectively. While Figures 15 and 16 are SEM images extracted from Specimen-D at two different positions, X1 and X2, and shown in Figure 6(d), Figure 17 and Figure 18 are SEM images extracted from Specimen-H at two different positions, Y1 and Y2 and shown in Figure 7(d).

The SEM images obtained from Specimen-D unveil distinctive features resembling hair cuticles on the fractured zone or surface of the bimetals, as indicated by red arrows. Notably, the width of these cuticle-like structures varies across different regions.

Interestingly, regions with narrower cuticle widths tend to produce less debris, suggesting a potential correlation between debris formation and the width of the cuticle structures. Furthermore, the fractured areas exhibit vertical slits, voids, pores, micro-cracks, and fractured intermetallic areas, highlighting various irregularities and flaws within the bimetal structure.

On the other hand, SEM images from Specimen-H showcase a smooth surface finish at the micron level. However, white spherical structures observed in Specimen-H are identified as covering flux powder particles settled on the bimetal surface, potentially due to excessive flux powder usage. The surface also displays straight lines, indicating directional grain formation attributable to the high-speed rotation of the mould during solidification.

Both microstructures of Specimen-D and Specimen-H exhibit plastic deformation of the metal in certain areas. Additionally, the solidification of the molten metal during flow is more pronounced in Specimen-D compared to Specimen-H. This discrepancy is attributed to the addition of insulation to the rotating mould, reducing the rate of heat transfer [14] and allowing for more extensive solidification within the mould[13].

Overall, the SEM images offered insights into the distinctive morphology of the fractured zones, indicating the presence of hair cuticle-like structures and debris formation alongside other notable features such as voids, cracks, and intermetallic fractures. These findings provide valuable information about the structural integrity and potential failure modes of the Al/Cu bimetallic samples produced through centrifugal casting.

5. Conclusion

In conclusion, the introduction of insulation around the rotating mould in centrifugal casting resulted in notable improvements in impact strength values, as demonstrated by the Charpy Impact tests. The specimen D, produced with insulation at 1200 rpm, exhibited superior hardness compared to other specimens, indicating enhanced bonding strength between the two bimetal components. This improvement can be attributed to reduced heat flow and optimized solidification conditions, leading to improved microstructure and surface finish.

The experimental results from Figures 12(a), 12(b), 13(a), 13(b), and 14 collectively demonstrate that higher speeds of rotation, combined with insulation of the rotating mould, notably reduce wear rates and enhance wear resistance in bimetal specimens. This effect is particularly pronounced, showing a critical influence on wear resistance. Optimizing the process alongside specific process parameters such as rotational speed and insulation leads to substantial improvements in wear resistance and overall durability of bimetal materials.

The SEM analysis provides valuable insights into the morphology and structural characteristics of the Al/Cu bimetallic samples produced through centrifugal casting. Distinctive features such as hair cuticle-like structures, debris formation, voids, cracks, and intermetallic fractures were observed, shedding light on the structural integrity and potential failure modes of the specimens.

Overall, these findings underscore the importance of process parameters, such as rotation speed and insulation, in optimizing the mechanical properties and quality of bimetallic castings. Further research and optimization efforts in centrifugal casting processes hold promise for enhancing the performance and reliability of bimetallic components in various applications.

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