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Investigating the Impact of Mould Insulation on Aluminium-Zinc Bimetallic Interfaces Produced by Centrifugal Casting

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Abstract

As the demand for bimetals in engineering, household, and commercial applications grows, advanced techniques like centrifugal casting are increasingly utilised to combine the strengths of two metals. This study investigates the influence of mould insulation and varying rotation speeds on Al-Zn bimetals' heat dissipation and quality produced by centrifugal casting. Al-Zn bimetallic specimens were created using a horizontal centrifugal casting machine under varying process parameters, including mould rotation speed and the presence or absence of insulation. The effects on solidification rates, mechanical properties (evaluated through hardness testing), and bimetal interface quality (analysed using SEM and microscopic imaging) were assessed. Results show that mould insulation significantly reduces heat loss, enhancing solidification control, improving mechanical properties, and minimising defects in the castings. Furthermore, higher rotation speeds were found to influence the bonding quality at the bimetal interface. This study underscores the importance of optimising both mould insulation and rotation speed for achieving superior Al-Zn bimetal performance and casting quality.

Major Findings: *The presence of thermal insulation around the rotating mould in the centrifugal casting process reduces the solidification rate of the melt and enhances the properties and surface finish of the cast produced.*

Keywords: *Aluminium-Zinc, Bimetals, Horizontal Centrifugal Casting, Interface, Mould Insulation*

1.0 Introduction

Casting has been a fundamental manufacturing process for centuries, evolving from traditional methods to advanced precision techniques. Among these, centrifugal casting is widely utilised for producing high-integrity cylindrical components with minimal defects. This process relies on centrifugal forces to distribute molten metal evenly within a rotating mould, ensuring uniform solidification and superior mechanical properties compared to conventional gravity casting.

In recent years, the demand for high-performance materials has driven the development of bimetal composites—materials that combine two distinct metals to enhance mechanical strength, wear resistance, and corrosion protection. These composites leverage the benefits of different metals, such as the toughness of steel combined with the thermal conductivity of copper, making them ideal for aerospace, automotive, and industrial applications. Another such promising combination is Aluminium-Zinc (Al-Zn) bimetal composites. Aluminium, known for its lightweight nature,

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high thermal conductivity, and corrosion resistance, is extensively used in aerospace, automotive, and structural applications. Zinc, on the other hand, provides excellent wear resistance, anti-corrosive properties, and self-healing capabilities due to its sacrificial anodic behaviour. By integrating aluminium and zinc, Al-Zn bimetal composites offer an ideal balance of lightweight design, strength, and durability, making them suitable for applications[1] such as heat exchangers, engine components, bearings, and marine structures.

Out of many casting processes that exist, the centrifugal casting is based on the principle of centrifugal forces generated by a rotating mould's centripetal acceleration, producing accurate cylindrical components with minimal defects compared to gravity casting. Horizontal centrifugal casting plays a crucial role in manufacturing Al-Zn bimetal composites, ensuring strong metallurgical bonding and precise control over layer distribution. This method is particularly beneficial for producing tubular and cylindrical components where distinct inner and outer material properties are required for enhanced performance and longevity.

Though casting is one of the early manufacturing practices, it still faces several challenges compared to other manufacturing methods. Casting usually involves complexities due to phase change of the material and high temperature variations, quick solidification, and also defects like impurities, void formation, irregularities, and poor grain formation are quite common. Among these complexities, the formation of grain structure during solidification is crucial yet complicated.

Centrifugal casting is a casting technique that is typically used to cast cylinder components. It is typically used to cast metals and non-metals, such as metals, glass, and concrete. A high quality is attainable by control of metallurgy and crystal structure. Out of the many centrifugal casting methods, the one in which casting method involves rotating the mould on a horizontal axis is called horizontal centrifugal casting process, as shown in Figure 1. It is preferred for geometry in the form of tubes, especially the ones in which the diameter of such geometry is less than its length.

In certain applications, combining two different metals in the form of bimetals is advantageous 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[2] between these metals occurs due to atomic forces at their interface[3]. This bonding enables the creation of components that harness the individual strengths of both 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 horizontal CCM by pouring one molten metal after the other into the rotating mould. The bonding interface morphology is influenced by factors like pouring temperature[4] for the outer layer, time intervals between inner and outer layers, and rotational speed of the casting mould. The thickness of the bonding is primarily affected by pouring temperature and solidification methods[5]. The properties of these bimetal components heavily rely on the class of the bonding at the interface[6]. The composited mechanism of centrifugal casting is mainly characterised by metallurgical bonding[7]. 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

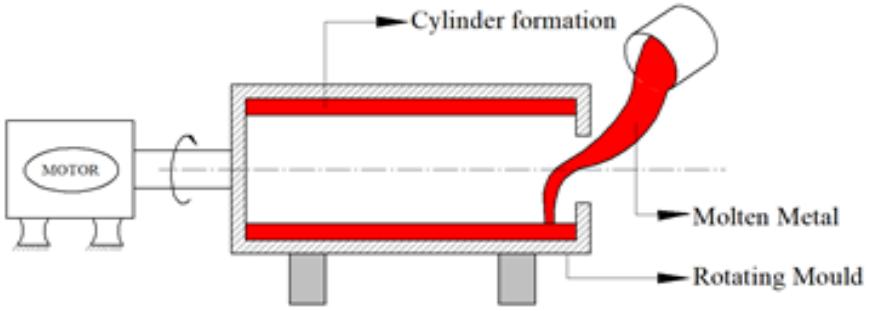


Figure 2. Schematic diagram of the principle of the horizontal centrifugal casting process.

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. The extensive use of metals in engineering applications has led to the rise of bimetallic materials, valued for combining the strengths of two distinct metals to achieve superior performance. Among fabrication methods, centrifugal casting stands out for its efficiency, particularly in producing bimetal castings. A key factor in this process is understanding heat dissipation within the rotating mould, as it directly affects solidification rates[8], which directly impacts the flow of melt[9] and the resulting properties of the castings.

This study investigates the production of Al-Zn bimetal castings, focusing on heat transfer mechanisms with and without mould insulation to optimise the process for improved casting quality. The effects of rotation speed, mould length, and insulation are analysed alongside hardness evaluations at the bimetallic interface. Scanning Electron Microscope (SEM) and macroscopic imaging are employed to assess interface integrity and mechanical properties, providing insights into the structural and performance characteristics of the castings. This comprehensive approach aims to enhance the quality and applicability of Al-Zn bimetal castings in engineering.

2.0 Materials and Methods

With the wide variety of materials available for different applications, producing bimetals involves selecting combinations of both ferrous and non-ferrous metals. Researchers have investigated various metal pairings and conducted numerous studies in this area. Though some boundaries arise due to the reactivity of certain metals or their inability to form a stable metallic bond. Certain metal combinations may react in ways that hinder the creation of a strong bond, leading to the separation of the two metals. These challenges result from the difficulty of some metals in merging effectively or forming a lasting bond, making it essential to carefully choose compatible metal pairings for successful bimetal production. The main materials used in this study are pure aluminium, pure zinc for the production of bimetallic cylinders. Other materials of concern are mould material made of mild steel and insulation material, which is asbestos. The main properties of these materials are mentioned in Table 1.

These two metals possess distinct properties that make their combination valuable for various applications[10]. Aluminium is recognised for its less weight, corrosion resistance, and conductivity, making it useful in aerospace, electrical, and construction industries while, Zinc offers exceptional resistance to corrosion, low friction, self-lubricating, cost-effectiveness, good machinability, heat dissipation, durability and is used as protective coating in a variety of applications.

Aluminium-zinc bimetallic cylinders were produced by using horizontal centrifugal casting. Both metals were melted in two different electric furnaces simultaneously, to pour the molten metal one after the other with minimum time delay into the rotating mould for the formation of cylindrical casts. The first metal, aluminium, was melted with the furnace temperature set at 800^{0}C, while the second metal, zinc, was melted with the furnace temperature set at 600^{0}C. During the centrifugal casting process for Al-Zn bimetal composites, aluminium is

Table 1. Material properties

Particulars	Mold	Insulation	Metal-1	Metal-2
Material	Mild Steel	Asbestos	Aluminum	Zinc
Thermal Conductivity (W/mK)	55	0.08	237	125
Specific heat (J/kgK)	500	810	900	387
Thickness (mm)	10	25	5	5
Melting Point (^{0}C)	1450	1400	660	420



Figure 2. **(a)** Mould without Insulation



Figure 2. **(b)** Mould with asbestos insulation.

poured first, followed immediately by zinc. This sequence is critical to achieving a strong metallurgical bond between the two metals. Since aluminum has a higher melting point than zinc, pouring it first ensures that the mould reaches a high enough temperature to prevent premature solidification. The immediate introduction of molten zinc then allows it to fuse with the aluminium while both metals are still in a semi-solid state, promoting a more uniform interface and enhancing adhesion. Additionally, the use of insulation around the mould minimises heat loss, allowing for a gradual cooling process that prevents thermal stresses and promotes controlled solidification. This precise thermal management ensures a defect-free microstructure, improving the mechanical integrity and longevity of the final component[11]. Both the melts were poured into a rotating mould with a constant filling speed of about 0.20 kg/s. Figures 2 (a) and (b) below show the experimental set-up of the rotating mould with and without insulation, respectively.

First, aluminium melt was poured into the mould, and then immediately, the zinc melt was poured into the mould to form aluminium-zinc bimetallic cylinders. There was a successive pouring of melts in this production process. The rotational speed of the centrifugal casting mould was varied to 600, 800, 1000 and 1200rpm. Mould rotational speed significantly influences the mechanical properties of Al-Zn bimetal composites[12] heat transfer, flow characteristics. Optimised rotational speeds ensure better heat dissipation control, reducing thermal stresses and promoting fine-grain structures. They also facilitate stable molten metal flow, resulting in defect-free layers with improved metallurgical bonding. Additionally, a well-balanced speed contributes to uniform hardness distribution, enhancing wear resistance and overall mechanical reliability. However, excessively low or high speeds can lead to defects such as porosity, non-uniform layer formation, and brittle intermetallic phases, ultimately compromising the composite's performance. Therefore, maintaining an optimal balance between cooling rate, interface bonding[13], and mechanical properties[14] is essential for producing high-quality Al-Zn bimetal components. The schematic diagram of the casts produced is shown in Figure 3. The cast bimetal cylinders had 80mm and 100mm diameters for inner and outer, respectively, with a length of 45mm. The thickness of each metal, aluminium and zinc, is 5mm.

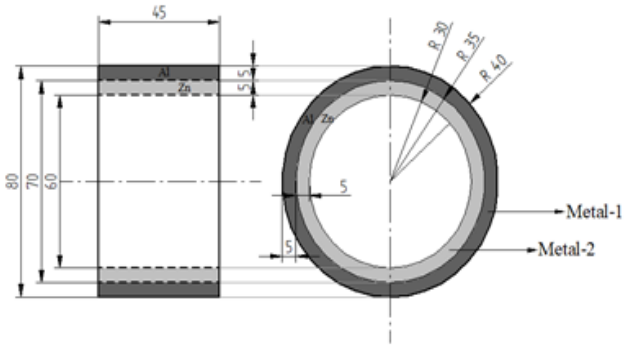


Figure 3. The schematic diagram of cast cylinders.



Figure 3. **(a)** Specimens produced without insulation.



Figure 3. **(b)** Specimens produced without insulation.

The cast Aluminium-Zinc Bimetal Cylinders are taken out from the rotating mould after it solidifies in a few seconds, and are water quenched for cooling. The Bimetal cylinders are as shown in Figures 4 (a) and (b).

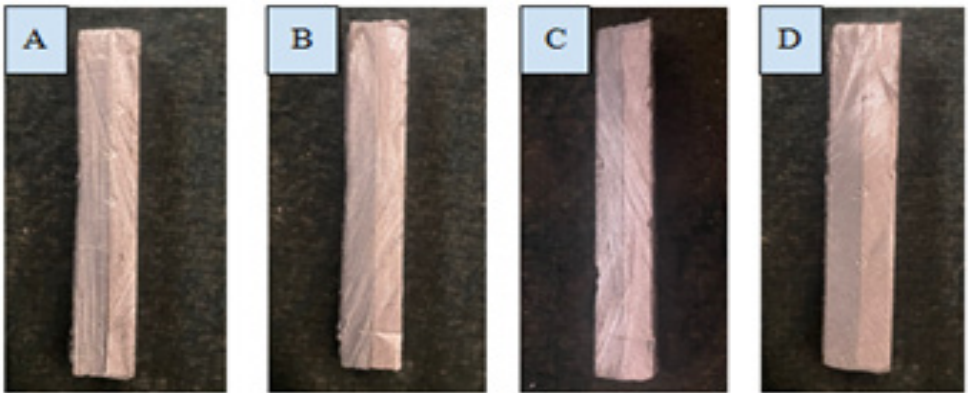


Figure 5. **(a)** Cut specimens from cast cylinders without insulation produced 600rpm, 800rpm, 1000rpm and 1200 rpm respectively.

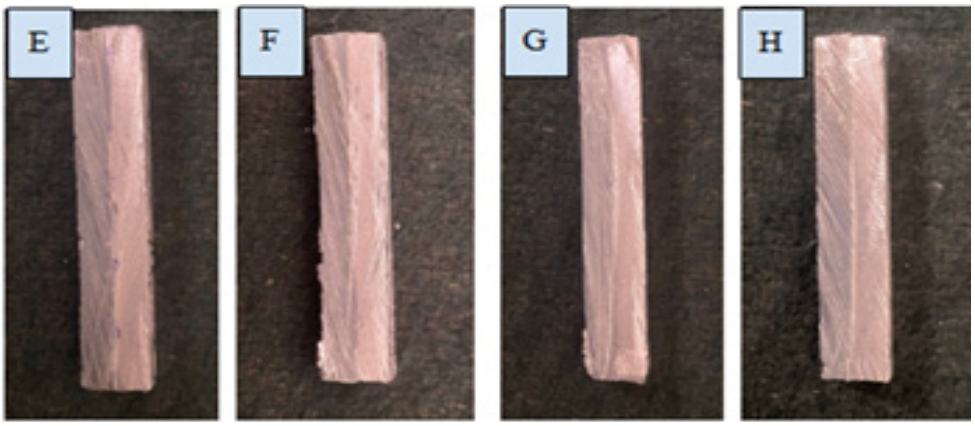


Figure 5. **(b)** Cut specimens from cast cylinders with insulation produced 600rpm, 800rpm, 1000rpm and 1200 rpm, respectively.

The casts obtained from the centrifugal casting mould are bimetal cylinders. For this study, the casts produced are cut along their length of casts. The cut specimens are as shown in Figure 5 (a) and (b).

The investigations carried out in this study include microstructures and microscopic images at the bimetallic interface. The microstructure characterisation was analysed using a metallurgical microscope and SEM. The tests done in this study include hardness tests and wear tests. The hardness no was obtained at the interface between aluminium and zinc specimens cut from the centrifugally cast cylinders, using a Rockwell Hardness test machine.

The Bimetal was manufactured using two different metals, melted and poured into the rotating mould to form bimetal cylinders. Considering the same parameters of producing bimetal cylinders, like, pouring temperature, thickness of insulation, speed of rotation[15], the casts were prepared with individual metals as well to compare the bimetal cylinder's quality and strength. The Rockwell hardness tests were done 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.

3.0 Results and Discussion

The hardness values of each specimen were found using the Rockwell hardness setup at four different locations along the length of the specimen.

The Rockwell hardness values near the interface along the length of the cut specimens and Specimen H can be seen in Figure 6 (c) and Figure 7 (c), respectively. Figure 6 (a) shows the picture of a cut specimen-D from a cast bimetal cylinder produced at 1200 rpm without insulation of the rotating mould, while Figure 7 (a) shows the picture of a cut specimen-H from a cast bimetal cylinder produced at 1200 rpm without insulation of the rotating mould. Figure 6 (b) and Figure 7 (b) correspond to the microscopic image of the bimetallic interface at four different positions in specimen D and specimen H, respectively. The four positions where the microscopic images were captured are shown with red circles along the length of the specimen. The reason why four locations were opted is because the solidification of the melt occurs within few seconds of pouring it into the rotating mould, during which the molten metal has to flow along the length of the mould as well as due to the centrifugal force of the mould rotation the melt forms a cylinder, by which the molten metal would be solidified.

The flow would be quick and the formation of uniform thickness of cylinder is appropriate at the entrance of the molten metal than at the other end (i.e from left to right in both Figures 6 (a) and 7 (a)). It can be observed from the microscopic images that the bonding is much better at the left end of the specimen than at the right. This is due to the reason aforesaid.

The hardness at the interface shows considerably equal values compared to the hardness of the base metal. The hardness value of the bimetal depends on the

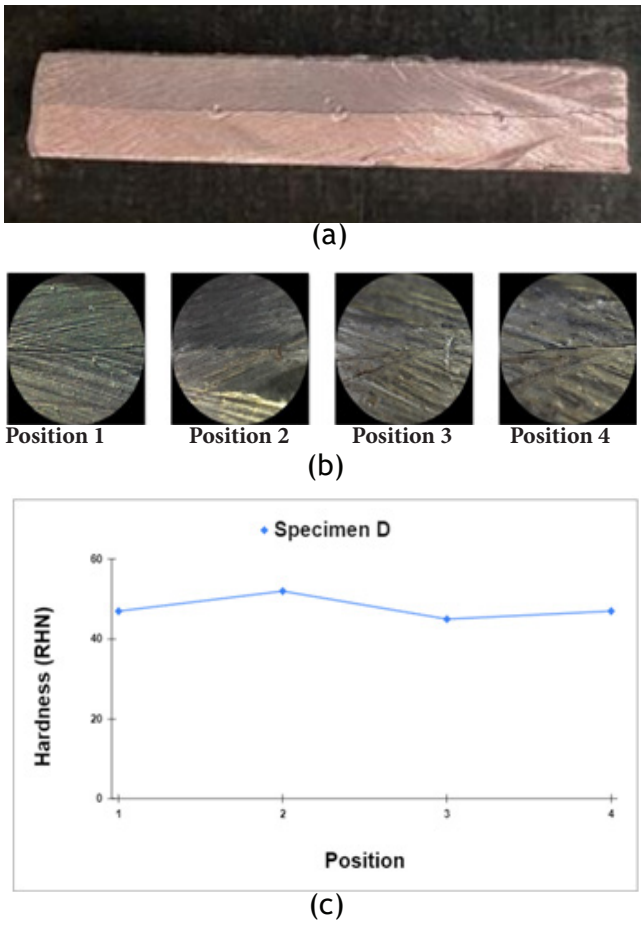


Figure 6. **(a)** Cut Specimen D. **(b)** Microscopic images at 30x in four different locations along the length of the specimen. **(c)** Graph of hardness v/s position on cut specimen D.

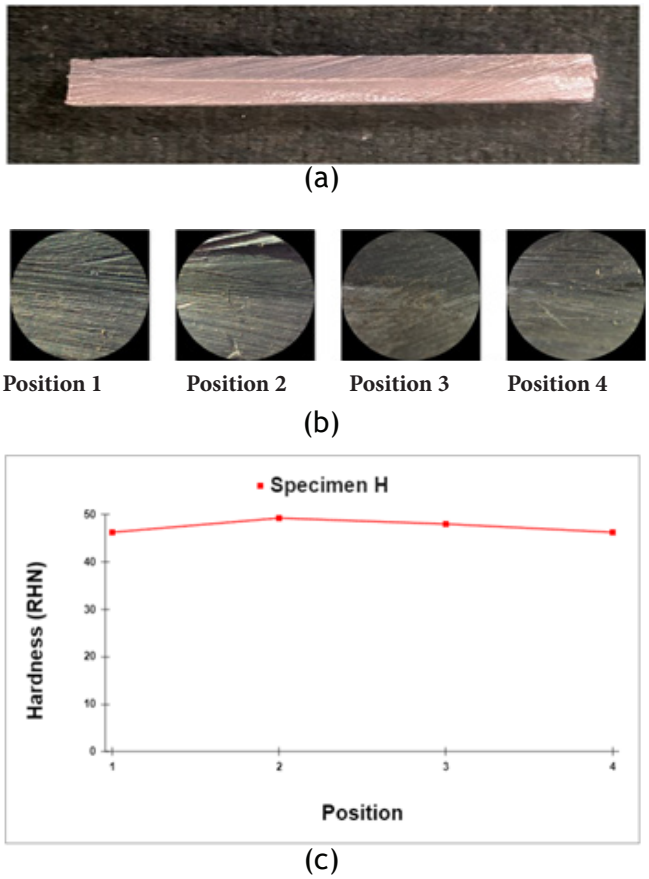


Figure 7. **(a)** Cut Specimen H, **(b)** Microscopic images at 30x in four different locations along the length of the specimen. **(c)** Graph of Hardness v/s Position on cut Specimen H.

formation of the microstructure during solidification. The insulation plays a major role in reducing the heat loss from inside of the mould and hence the molten metal will be able to flow more smoothly with low viscosity for the first few seconds of the solidification which leads to better microstructure and marginally better surface finish and hardness as it can be observed from Figures 7 (a) and (b).

Comparing Figures 6 (b) and 7 (b), it can be seen that the interface bonding[16] is much better when there is insulation of the rotating mould. In Figure 6 (b), there is a slight gap that is visible in the microscopic images, while this gap is very minimal in the case of Figure 7 (b), due to insulation. It is also to be noted that as the speed of rotation of the mould increases, the formation

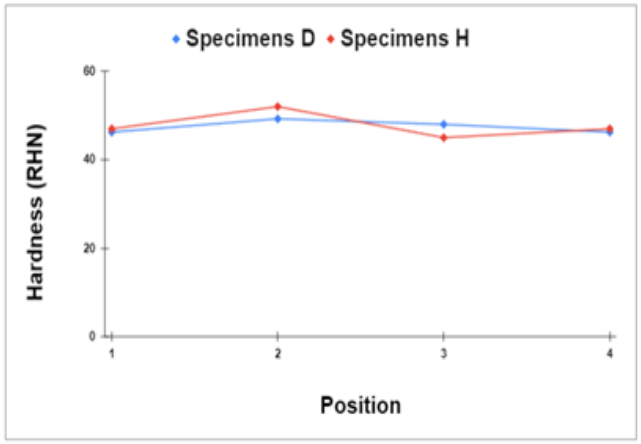


Figure 8. Hardness v/s position along the length of the specimens D and H.

of the cylinder is uniform and with better surface finish, the bonding also seems better in the case of mould rotational speed of 1200rpm and with insulation. The trend of hardness looks similar between specimens with variations in rpm. The hardness is particularly affected by the kind of phase of the microstructure[24]. Figure 8 shows the comparison of Hardness values in four different positions along the length of the specimens D and H. It can be observed that the hardness values are slightly better at the left end of the specimen, that is, positions 1 and 2, compared to positions 3 and 4.

Figures 9 (a) and (b) show the SEM images of the Al-Zn bimetal at the interface for mould rotational speed with and without insulation. The SEM micrographs depicted in Figures 9 (a) and (b) illustrate the surface morphology at magnifications of 500x, 1000x, and 2000x, corresponding to observed contours at 100μm, 50μm, and 20μm, respectively. Figure 9 (a) represents images of Specimen-D extracted from the bimetal interface, while Figure 9 (b) depicts images of Specimen-H. Specimen D was prepared from the bimetal cylinder cast at a speed of 1200 rpm without insulation, while Specimen H was prepared from the bimetal cylinder cast at a speed of 1200rpm with insulation. These two specimens, D and H, were selected for SEM analysis because the hardness value and impact strength values of these two specimens show considerably higher values out of the four specimens without and with insulation, respectively.

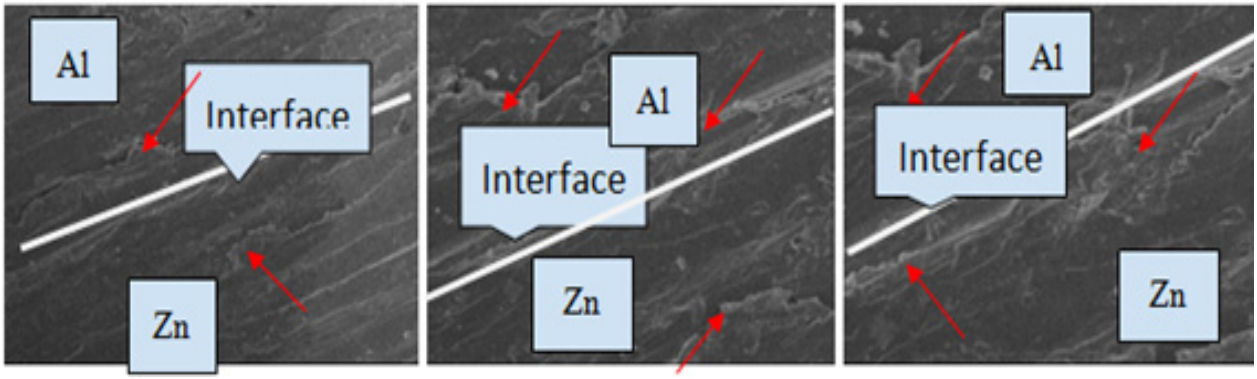


Figure 9. (a) SEM images of bimetal specimen D (without insulation).

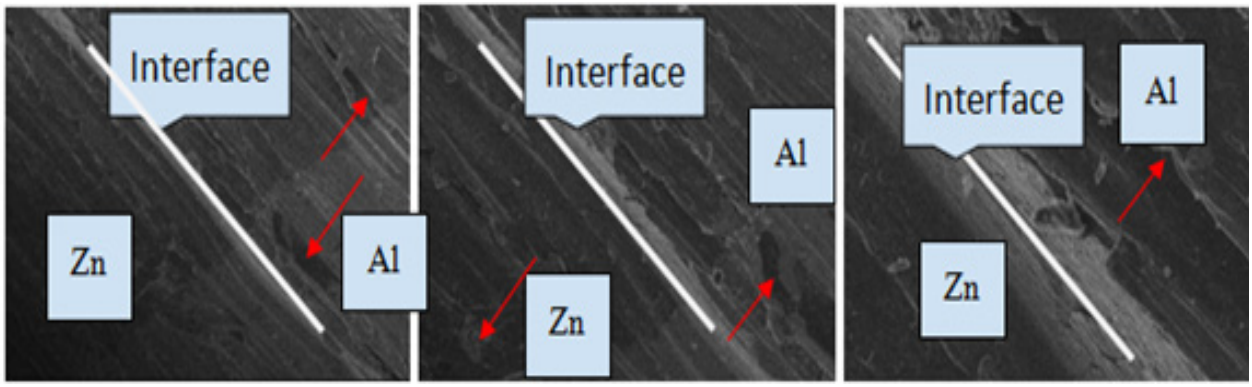


Figure 59. (b) SEM images of bimetal specimen H (with insulation).

The SEM analysis of Specimen-D reveals unique features resembling hair cuticle-like structures on the surface, as highlighted by red arrows. The width of these cuticle-like structures varies across regions, with narrower cuticles associated with reduced debris formation. This observation suggests a potential relationship between the cuticle width and the debris generated while melt flows during solidification. Additionally, the surface of Specimen-D displays prominent vertical slits, voids, pores, micro-cracks, and fractured intermetallic regions, reflecting various structural imperfections and defects within the bimetal.

In contrast, Specimen-H exhibits a comparatively smooth surface at the microscopic level. While the debris found in these SEM images is very little compared to Specimen D, the surface morphology also includes straight lines indicative of directional grain formation, a phenomenon attributed to the high rotational speeds employed during the mould solidification process. Both Specimen-D and Specimen-H display localised plastic deformation of the metal in specific regions. However, solidification appears more pronounced in Specimen-D compared to Specimen-H. This disparity is attributed to the insulating layer applied to the rotating mould in Specimen-H, which reduces the heat transfer rate[17], thereby enabling more uniform and extensive solidification within the mould[16].

Scanning Electron Microscopy (SEM) analysis of Al-Zn bimetal composites reveals significant differences in microstructure between insulated and non-insulated specimens, particularly in terms of crack formation, grain alignment, and intermetallic bonding at the interface.

In insulated specimens, the SEM images show a significantly reduced presence of micro-cracks, indicating improved thermal stability during solidification. The insulation minimises rapid heat dissipation, preventing thermal gradients that can induce residual stresses and micro-crack formation. This controlled cooling leads to a more homogeneous solidification process, reducing the occurrence of defects[17] such as porosity and voids at the

interface[18]. Furthermore, the grain structure in insulated specimens exhibits improved alignment and uniformity, particularly in the transition region between aluminium and zinc. The slower cooling rate facilitated by insulation promotes directional solidification, allowing for a well-defined and refined grain structure with fewer disordered grain boundaries. This enhanced grain orientation contributes to higher mechanical strength and better load distribution across the bimetal interface.

The intermetallic bonding at the Al-Zn interface is also notably improved in the insulated specimen-H. SEM observations indicate a thinner, more uniform intermetallic layer, which enhances adhesion between the two metals while preventing excessive brittle Intermetallic[5] Compound (IMC) formation. In contrast, non-insulated specimens often exhibit an irregular and thicker IMC layer, leading to weaker bonding and potential delamination under mechanical stress. The insulation helps maintain a controlled diffusion process, ensuring a stronger and more cohesive metallurgical bond between aluminium and zinc.

In non-insulated specimens, SEM analysis reveals a slightly higher density of micro-cracks, particularly at the interface, due to rapid cooling and thermal contraction stresses, with signs of coarse and misoriented grains, which can negatively impact mechanical properties. Additionally, the intermetallic layer in non-insulated specimens is often inconsistent in thickness, increasing the likelihood of interface failure under cyclic loading conditions.

Overall, SEM analysis confirms that insulation plays a critical role in enhancing the microstructural integrity of Al-Zn bimetal composites by promoting controlled solidification, reducing defects, and ensuring a more robust intermetallic bond. These microstructural improvements directly contribute to superior mechanical properties, making insulated Al-Zn bimetal components more reliable for engineering applications requiring high strength, wear resistance, and durability.

4.0 Conclusion

The study demonstrates that mould insulation significantly influences the heat dissipation, solidification behaviour, and mechanical properties of Al-Zn bimetal castings produced through centrifugal casting. Hardness analysis along the specimen length reveals that interface bonding and surface quality improve with insulation due to reduced heat loss, allowing the molten metal to flow smoothly and solidify more uniformly. Microscopic examination further confirms that specimens cast with insulation exhibit minimal gaps at the interface, leading to superior bonding. The hardness trends remain consistent across different rotational speeds, with better bonding observed at higher speeds due to improved centrifugal force-induced metal flow.

SEM analysis provides deeper insights into the structural integrity of the cast specimens, highlighting key morphological differences between insulated and non-insulated mould conditions. Specimen-D, cast without insulation, exhibits structural imperfections such as voids, cracks, and intermetallic fractures, whereas Specimen-H, cast with insulation, presents a more uniform microstructure with reduced defects and directional grain formation. These findings confirm that insulation enhances the casting quality by promoting controlled solidification, thereby improving mechanical strength and durability. Overall, optimising mould insulation in centrifugal casting can lead to superior bimetallic components with enhanced bonding, surface finish, and structural integrity, making it a valuable parameter for industrial applications.

5.0 References

1. Ebhota WS, Karun AS, Inambao FL. Centrifugal casting technique baseline knowledge, applications, and processing parameters: overview. Int J Mater Res. 2016; 107(10):960-969. https://doi.org/10.3139/146.111423
2. Greß T, Mittler T, Volk W. Casting methods for the production of rotationally symmetric copper bimetals. Mater Sci Technol. 2020; 36(8):906-916. https://doi.org/10.1080/02670836.2018.1479946
3. Dongxue MP, Xianzhong MP. Research on a bimetal composite casting material (high Cr white cast iron - Medium C cast steel) and its production technology. 55 International Foundry Congress; 1988. p. 1-10. 4. Sarvari M, Divandari M. Effects of melt/solid volume ratio and rotational speed on the interface of Al/Mg bimetal in centrifugal casting. J Adv Mater Eng. 2016; 35(2):83-94. https://doi.org/10.18869/acadpub.jame.35.2.83
5. Nazari J, Yousefi M, Kerahroodi MSA, Mofrad NSB, Abhari SHA. Production of copper-aluminium bimetal

by using centrifugal casting and evaluation of metal interface.

6. Wang X *et al*., Influence of casting temperature and mold preheating temperature on centrifugal casting by numerical simulation. J Mater Eng Perform. 2023; 32(15):6786-6809. https://doi.org/10.1007/s11665-022-07608-4
7. Darmo S, Setyana LD, Tarmono N. Santoso: IOP Conf. series. Mater Sci Engin. 2018; 384:1-4. https://doi.org/10.1088/1757-899X/384/1/012017
8. Yang Y, Chen H, Zhou J, Hui-hui Nie H, Xu X, San-xiao XI, Chang Y. Study on interface behaviour and mechanical properties of Al/Cu laminated tubes fabricated by strong staggered spinning at room temperature J Mater Res Technol. 2023; 25:7307-7324. ISSN2238-7854. https://doi.org/10.1016/j.jmrt.2023.07.129
9. Prasad K, Murali KS, MS. Mukunda PG. Analysis of fluid flow in centrifugal casting. Front Mater Sci China. 2010; 4:103-110. https://doi.org/10.1007/s11706-010-0005-4
10. Bykov AA. Bimetal production and applications. Steel Transl. 2011; 41(9):778-786.
11. Pandey S, Jha SK, Kumar P, Bharat AK. Analysis of defects for aluminium-copper bimetal fabricated by centrifugal casting. Asia Pac J. 2017.
12. Santoso N, Suharnadi B, Tulung Prayoga B, Dwi Setyana L. Characteristic of interface bimetal aluminium-copper for bimetal bushing produced by centrifugal casting. Acta Metall Slovaca. 2021; 27(1):28-31. https://doi.org/10.36547/ams.27.1.756
13. Wang Y, Qin F, Qi H, Qi H, Meng Z. Interfacial bonding behavior and mechanical properties of a bimetallic ring blank subjected to centrifugal casting process. J Mater Eng Perform. 2022; 31(4):3249-3261. https://doi.org/10.1007/s11665-021-06377-w
14. Zheng Z, Shatrava AP, Likhoshva VP, Pelikan OA, Zheng K. Structure and properties of bimetallic centrifugally cast milling rollers. Mater Sci. 2020; 56(1):59-65. https://doi.org/10.1007/s11003-020-00397-y
15. El-Sayed MA. Effect of the mould rotational speed on the quality of centrifugal castings.
16. Setyana L, Santoso N, Suharnadi B, Tulung Prayoga B, Wiyadi W. Bonding of interface bimetal aluminium-bronze for bimetal bushing produced by solid liquid method. Acta Metall Slovaca. 2022; 28(2):80-84. https://doi.org/10.36547/ams.28.2.1253
17. Gholami M, Divandari M. Interfacial phases and defects characteristics of Al/Cu-Zn bimetal produced via centrifugal casting process.
18. Hiteh E, Divandari M, Gholami M. Interface characterization of aluminium-copper bimetal composite produced via centrifugal casting. J Sci Technol Compos. 2017; 3(4):343-350.