This study investigated the effect of pouring temperature, Al-RHA composition and pattern thickness on fluidity length, surface roughness at Al-RHA composition (85:15, 80:20, 75:25) %, pouring temperature (650, 700, 750) °C, and pattern thickness (1, 2, 3, 4, 5, 6, 10) mm. The challenge in this study is to optimize the fluidity length and hardness but minimize the surface roughness and porosity of the composite. The results showed that raising the pouring temperature increased the fluidity length, surface roughness, hardness, and porosity. Higher pouring temperature caused an increase in fluidity length by 13.51–54.17 % when the temperature raised from 650 °C to 750 °C. This was accompanied by an increase in hardness by 1.96–10.69 %. However, higher temperature also resulted in increased surface roughness by 3.9–7.92 % and increased porosity by 1.3–3 %. The composition ratio of Al-RHA plays an important role in determining the physical and mechanical properties of the composites. Increasing RHA content tends to increase the fluidity length but increases the surface roughness, hardness, and porosity. The higher RHA content increases the fluidity length by 2.44–11.9 % and the hardness also increases by 1.26–12.87 %. However, the higher RHA composition also increases the surface roughness by 1.2–30.95 % and the porosity increases by 2–2.7 %. The larger pattern thickness increases the fluidity length by 10.53–60.42 %. Controlling the RHA content and pouring temperature is very important to improve the physical-mechanical properties of Al-RHA composites. The results have potential applications in industries that require special composite materials such as automotive, aerospace, machinery and agricultural equipment

Keywords: evaporative casting, Al-RHA composites, pouring temperature, physical-mechanical properties, pattern thickness

UDC 669.715:621.746.5
DOI: 10.15587/1729-4061.2024.310274

IDENTIFYING THE INFLUENCE OF POURING TEMPERATURE, Al-RHA COMPOSITION, AND PATTERN THICKNESS ON THE PROPERTIES OF Al-RHA COMPOSITES PRODUCED BY EVAPORATIVE CASTING

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Received date 16.07.2024
Accepted date 23.09.2024
Published date 30.10.2024

How to Cite: *Siswanto, R., Subagyo, R., Tamjidillah, M., Mahmud, Setiawan, M. S. I. (2024). Identifying the influence of pouring temperature, Al-RHA composition, and pattern thickness on the properties of Al-RHA composites produced by evaporative casting. Eastern-European Journal of Enterprise Technologies, 5 (12 (131)), 39–49. https://doi.org/10.15587/1729-4061.2024.310274*

1. Introduction

The incorporation of agricultural waste into metal matrices has gained significant attention in recent years, driven by the dual need to enhance material properties and promote environmental sustainability. Among various agricultural wastes, Rice Husk Ash (RHA) is well-known for its high silica content, making it a promising reinforcing material in metal matrix composites. Aluminum (Al), recognized for its excellent mechanical properties and low density, is widely used in various industries, including automotive and aerospace. The combination of Al with RHA aims to improve the material properties of composites while utilizing waste by-products, thus contributing to resource efficiency and waste reduction.

Recent studies have shown that the inclusion of rice husk ash in the Al matrix can significantly affect the mechanical and physical properties of the composite. RHA has been extensively studied as a reinforcing material in various composite systems to enhance mechanical properties, including hardness and wear resistance. Incorporating RHA into aluminum composites has shown promising results in improving hardness and wear resistance [1]. The addition of RHA has been reported to have a positive impact on the mechanical properties, wear resistance, and corrosion resistance of composite materials, demonstrating its potential to enhance the performance of aluminum composites [2]. Research has shown that the inclusion of RHA as a reinforcement in the aluminum matrix leads to increased hardness, density, and wear resistance in the resulting composite [3, 4].

The mechanical properties of RHA-reinforced composites have attracted considerable attention. Studies indicate that the incorporation of RHA fillers can enhance the flexural modulus of composites [5]. Additionally, the wettability behavior, thermo-mechanical and electrical properties of composites have been improved with the addition of RHA, contributing to the overall enhancement of their mechanical performance [6]. Aluminum Matrix Composites (AMC) reinforced with RHA have shown improved mechanical properties such as compressive strength, hardness, ductility, and tensile strength [7]. Specifically, composites such as AA7075-RHA have demonstrated superior mechanical properties compared to the base aluminum matrix [8].

The relevance of incorporating agricultural waste into metal matrices has grown significantly due to the need to enhance material properties while promoting environmental sustainability. Rice Husk Ash (RHA), with its high silica content, is a promising reinforcing material for metal matrix composites, particularly aluminum (Al), known for its excellent mechanical properties and low density. The combination of Al with RHA not only improves the material properties of composites but also contributes to resource efficiency and waste reduction, making it highly relevant in the context of current environmental and industrial needs.

2. Literature review and problem statement

Lost foam casting (LFC), also known as evaporative casting, is a process that offers several advantages, particularly in producing complex shapes with high dimensional accuracy and superior surface finish. Despite these advantages, several factors, such as the type and thickness of the refractory layer, the grain size of the molding sand, and various process parameters significantly affect the quality of the final product [9]. However, the control of surface roughness and overall casting quality in LFC remains inconsistent [10]. Achieving optimal microstructure and mechanical properties is also a challenge, as factors such as the nature of the refractory layer, the grain size of the sand, and parameters such as pouring temperature often lead to defects, including porosity and poor surface finish. The LFC process uses expanded polystyrene (EPS) patterns coated with a refractory material and surrounded by unbound sand, which contributes to the excellent dimensional accuracy and high-quality castings achieved [11]. However, the use of EPS patterns can lead to carbon buildup during casting, which compromises the quality of the final metal product. This problem arises due to the decomposition of EPS, which produces carbon-rich byproducts that are absorbed by the molten metal, leading to defects. Pouring temperature is an important factor affecting the fluidity of molten metal and the occurrence of casting defects.

Higher pouring temperatures generally increase the flowability of molten metal, improving shape replication and surface finish [12]. Studies have shown that as the pouring temperature raises, the fluidity of aluminum alloys and composites increases, facilitating better shape replication [13]. However, achieving optimal surface roughness and replication in aluminum alloy casting using LFC remains limited by the variation of pouring temperature, which directly affects the fluidity of molten metal, surface finish, and overall casting quality. According to [14], the fluidity length of aluminum alloys increases linearly with pouring temperature within a certain range. However, the balance between increased fluidity and potential quality issues, such as larger grain size and reduced mechanical properties at higher temperatures, remains elusive. While raising pouring temperature improves fluidity, it can also coarsen the microstructure of the material, reduce mechanical performance, and increase susceptibility to defects. In addition, higher pouring temperatures increase the risk of oxidation and gas porosity if not properly controlled [15]. This is because increased fluidity can lead to turbulent flow and overheating, which can lead to defects such as porosity and oxidation. These challenges can be overcome by carefully controlling the pouring temperature and using techniques such as degassing or protective atmospheres to minimize oxidation and gas entrapment.

The ratio of aluminum to rice husk ash (RHA) composition is another important factor affecting the properties of the composites. RHA, known for its high silica content, serves as a valuable reinforcing material in various matrices [16]. The amorphous silica in RHA, combined with other elements such as Al_2O_3, CaO, Fe_2O_3, MgO, Na_2O, and K_2O, contributes to its reinforcing properties. However, optimizing the mechanical properties of Al-RHA composites, especially in terms of balancing hardness, tensile strength, and ductility, remains unresolved. Issues such as porosity, agglomeration, and inconsistent reinforcement distribution negatively affect the mechanical properties of these composites, making it essential to find the optimal RHA ratio. Excessive RHA can lead to agglomeration, while insufficient RHA fails to provide the desired reinforcing effect. Optimization of process parameters, including pouring temperature, stirring speed, and pouring rate, is essential to improve the mechanical properties and machinability of metal matrix composites [17]. However, achieving the desired mechanical properties and machinability of Al6061-Cu-SiCp composites remains unresolved due to the high sensitivity of these properties to casting parameter variations, which often result in uneven SiCp distribution, porosity, and inconsistent material removal rates. Although extensive research on Al-RHA composites has been conducted, there is still a significant gap in understanding how multiple casting parameters interact to affect the final properties. Most studies have focused on individual variables such as composition ratio or pouring temperature, ignoring their combined effects.

In addition, the impact of pattern thickness on the evaporative casting properties of Al-RHA composites is rarely reported. One study found that although raising the pouring temperature increased the fluidity, it also increased the porosity level unless optimized simultaneously with the composition ratio and pattern thickness [18]. The importance of multivariable optimization is emphasized to achieve desired composite properties. However, optimizing the mechanical properties of Al/SiC/Mg/Cu composites through the stir casting process remains a challenge, mainly due to the varying pouring temperature. The mechanical properties are highly dependent on the microstructure, which is affected by the pouring temperature. Improper temperature control can lead to defects such as SiC particle clustering, weak bonding, and increased porosity. By optimizing multivariable parameters such as pouring temperature control, uniform distribution of reinforcement particles and reduction of defects can be achieved.

3. The aim and objectives of the study

The aim of this study is to identify the formation features of the physical and mechanical properties of Al-RHA composites using evaporative casting. This will allow optimizing the production process parameters, which is expected to improve the quality and efficiency in practical applications, especially in the automotive, aerospace, agricultural machinery and construction industries, where composite materials with superior physical and mechanical properties are in great demand.

To achieve this aim, the following objectives are set:

– to investigate the effect of pouring temperature on the fluidity length, surface roughness, hardness, and porosity of Al-RHA composites;

– to analyze the impact of the Al-RHA composition ratio on the fluidity length, surface roughness, hardness, and porosity of the composites.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study focuses on the evaporative casting process and the development of aluminum composites with rice husk ash (RHA) reinforcement. The three main factors studied are pouring temperature, RHA composition, and EPS pattern thickness, and their effects on composite quality such as fluidity length, surface roughness, hardness and porosity.

The hypothesis states that optimization of pouring temperature, proper RHA ratio, and Styrofoam pattern thickness can improve casting quality and mechanical properties of aluminum-RHA composites. The proper pouring temperature will increase metal fluidity, a balanced RHA ratio will improve reinforcement, and optimal Styrofoam pattern thickness will produce accurate casting shapes.

In this study, it is assumed that:

1) Styrofoam decomposition is controlled without significant carbonization if the pouring temperature and pattern thickness are controlled;

2) RHA will be evenly distributed in aluminum if the pouring and stirring temperatures are optimized;

3) high pouring temperature increases metal fluidity without reducing mechanical properties if within safe limits.

Research simplifications include:

1) external environmental influences such as humidity are ignored;

2) the thickness of the Styrofoam pattern is assumed to be uniform;

3) the research uses a small-scale laboratory model, which is expected to identify relevant trends.

4. 2. Scrap Al and rice husk ash composite materials

The object of the research is scrap aluminum (Al) material as a matrix and rice husk ash (RHA) as a reinforcement. Aluminum is obtained in the form of electrical cable scrap. Fig. 1 shows the main raw material, namely Al electrical cable scrap. Fig. 1, *a* is Al electrical cable scrap that is still obtained from scrap collectors, with irregular shapes and still many impurities. Fig. 1, *b* is Al scrap that has been cleaned from impurities and cut to a length of 20 cm, then ready to be melted in a furnace.

Fig. 2 shows the stages of making rice husk ash (RHA), which is used as a filler or strengthener in making this composite material.

Fig. 2, *a*, rice plant (Oryza sativa): is a plant that is cultivated to produce grain rice. Rice is a staple food for many people in the world, especially in Asia. Dried grain rice that is then milled will produce rice, bran and rice husks.

Fig. 2, *b*, rice husk: the outer protective layer of rice grain is called rice skin or rice husk. Husk has a high fiber content, but cannot be consumed by humans. However, rice husk is widely used as fuel, animal feed or as a raw material for making rice husk ash, which contains high silica.

Fig. 2, *c*, RHA from burning at 400 °C: rice husk (golden yellow color) that has been dried and cleaned from impurities is burned in an open combustion drum with a combustion temperature of around 400 °C for 1.5 hours, so that it becomes black and partly white charcoal-ash. This contains a number of organic materials and carbon, so that the color looks darker. The combustion temperature is measured with an infrared thermometer, Benetech brand, type GM1850, temperature range (200–1,850) °C.

a *b*

Fig. 1. Raw material for Al electrical cable scrap: *a* – Al scrap from collectors; *b* – Al scrap that has been cleaned and cut

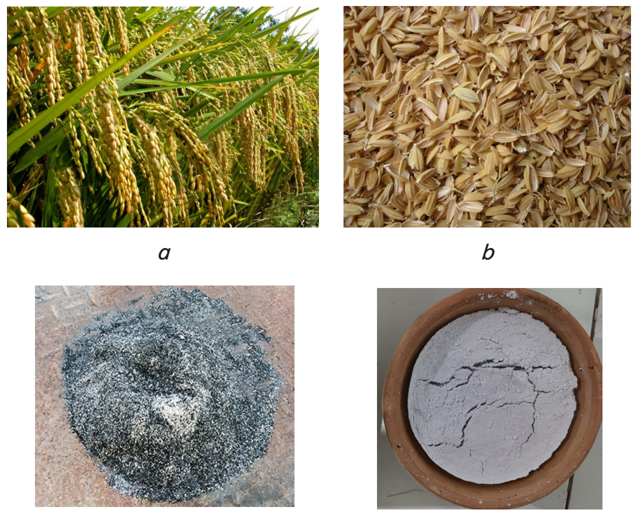
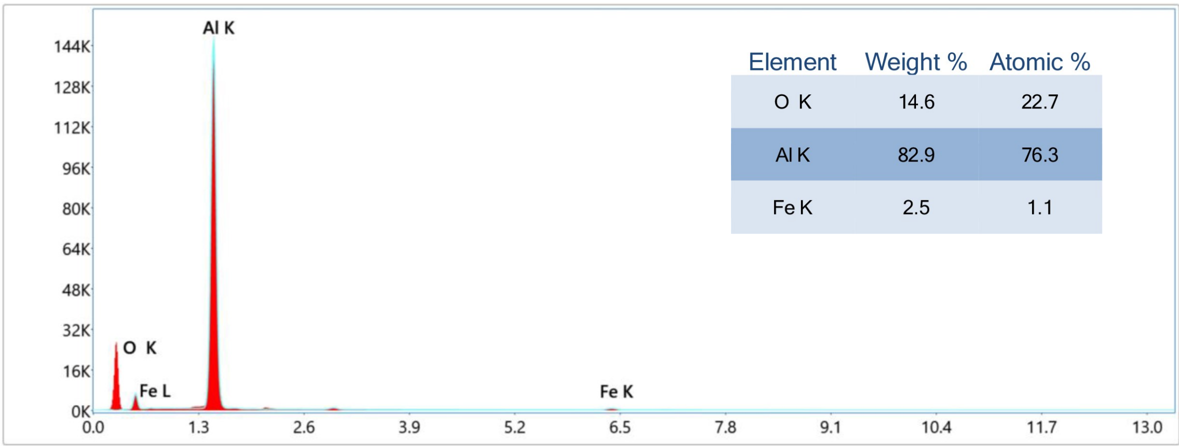


Fig. 2. Stages of making rice husk ash: *a* – rice plants; *b* – rice husks; *c* – rice husk ash from burning at a temperature of 400 °C; *d* – rice husk ash from burning at 900 °C for 2 hours

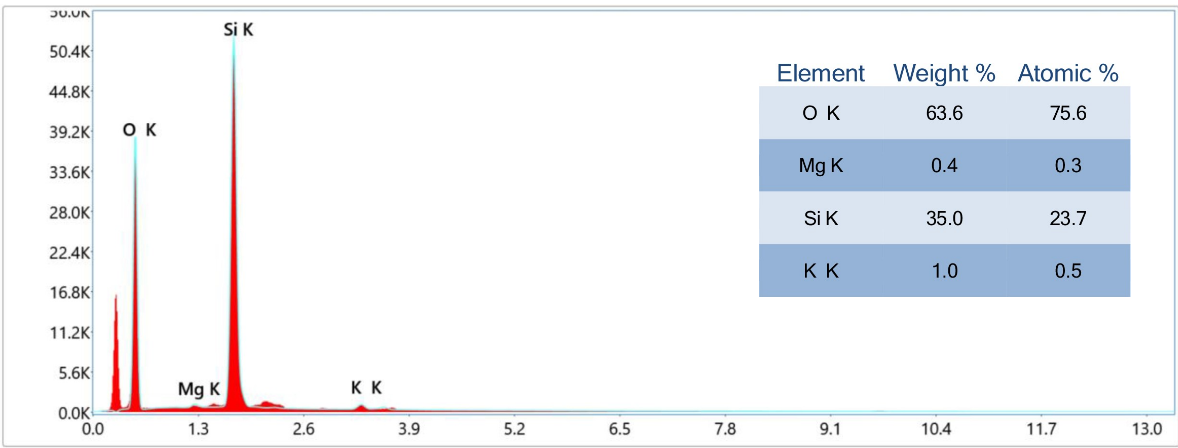
Fig. 2, *d*, RHA from 900 °C combustion (2 hours): the black and partly white rice husk ash is then ground and sieved with a 200 mesh sieve and then heated in a furnace at a temperature of 900 °C for 2 hours to produce ash with a lighter color (white) due to the perfect combustion of organic materials and carbon. Combustion at this higher temperature produces ash with a higher silica content. The furnace tool used is the B-ONE brand, Model BFNC-2012, temperature range (300–1,200) °C.

4. 3. Energy dispersive X-ray spectroscopy (EDX) testing of scrap aluminum and rice husk ash

Fig. 3, *a* shows the EDX test results, displaying the X-ray intensity spectrum generated by each element in the sample. The highest intensity peak corresponds to energy associated with aluminum (AlK=82.9 % by weight), indicating that aluminum is the primary element in this sample. Smaller peaks indicate the presence of oxygen (OK=14.6 % by weight), and a very small peak suggests the presence of iron (FeK=2.5 % by weight).



a

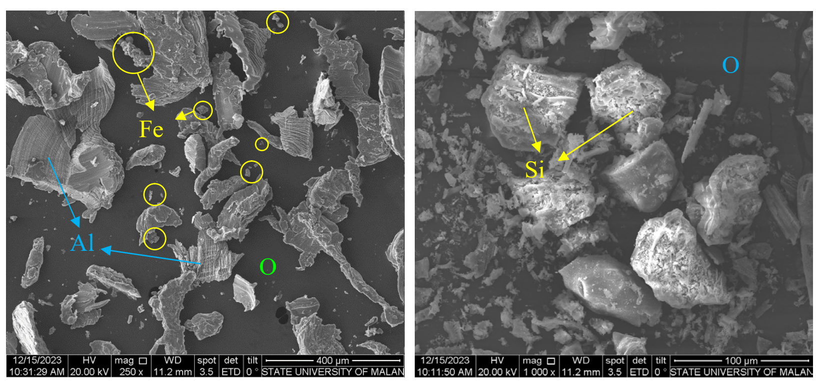


b

Fig. 3. Energy Dispersive X-ray Spectroscopy (EDX) test on raw materials: *a* — scrap aluminum electrical cable; *b* — Rice Husk Ash (RHA)

Fig. 3, *b* shows the EDX test results, displaying the X-ray intensity spectrum generated by each element in the sample. The highest intensity peaks correspond to energy associated with oxygen (OK=63.6 % by weight) and silicon (SiK=35 % by weight), indicating that these two elements are the main components in the material. Smaller peaks are seen for magnesium (MgK=0.4 % by weight) and potassium (KK=1.0 % by weight), indicating their presence in smaller amounts.

The EDX test tool is used to determine the elemental content of the Al material of electrical cable scrap and rice husk ash, namely the FEI Brand, Type: Inspect-S50 (FEI Company-United States).



a *b*

Fig. 4. Scanning electron microscope (SEM) test results images of raw materials: *a* — scrap aluminum electrical cable; *b* — rice husk ash (RHA)

4. 4. Scanning electron microscopy (SEM) testing of scrap aluminum and rice husk ash

The SEM results of the raw materials, scrap aluminum, and RHA, are shown in Fig. 4.

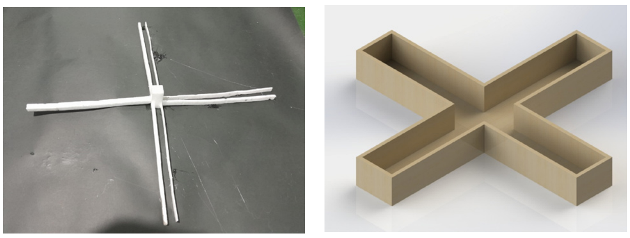
In Fig. 4, *a*, it can be observed that aluminum (Al) dominates the material structure, as seen from the large areas. Oxygen (O) is also relatively evenly distributed in significant amounts, indicating the possible presence of aluminum oxide (Al_2O_3) on the material's surface. Iron (Fe) appears in very small quantities, scattered in small areas.

In Fig. 4, *b*, it can be seen that silicon (Si) dominates the map with yellow color spreading widely, indicating that the material is rich in silicon. Oxygen is also evenly distributed in large amounts, indicating a strong likelihood of silicate compounds. Magnesium (Mg) and potassium (K) are present in very small amounts, visible in only a few small areas.

The SEM test tool used to study the surface morphological structure of the Al material of electrical cable scrap and rice husk ash is the FEI Brand, Type: Inspect-S50 (FEI Company-United States).

4. 5. Patterns and molds

Styrofoam is used from unused electronic equipment packaging. This Styrofoam functions as a pattern material for product specimens to be made. Styrofoam is cut according to the desired shape and size. The pieces of Styrofoam are assembled with glue to form the planned pattern (Fig. 5, *a*). The mold frame is made of plywood. The Styrofoam pattern and mold frame are shown in Fig. 5. The molding sand used is a local silica sand type with a sieve size that passes 60 mesh.



a *b*

Fig. 5. Pattern and mold frame: *a* – Styrofoam pattern; *b* – mold frame

Fig. 5, *a* is a Styrofoam pattern with the following dimensions (thickness x width x length):

1) size (1×10×40) mm;
2) size (2×10×40) mm;
3) size (3×10×40) mm;
4) size (4×10×40) mm;
5) size (5×10×40) mm;
6) size (6×10×40) mm;
7) size (10×10×40) mm.

In point (7), a measurement is made with a different range from points (1–6), this is to ensure the difference in the length of the fluidity flow is further from the thickness of the Styrofoam pattern, which is somewhat thicker. Fig. 5, *b* is a mold frame made of 1 cm thick plywood. The mold frame functions to hold the molding sand so that it does not scatter during pouring.

4. 6. Al-RHA composite manufacturing procedure

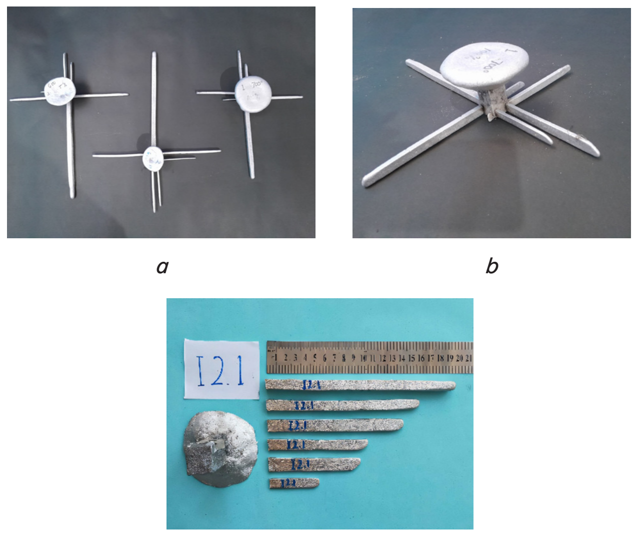
The experimental procedure involves melting aluminum in a crucible furnace at varying pouring temperatures (650 °C, 700 °C, and 750 °C). The molten aluminum is then mixed with RHA in proportions (85:15 %, 80:20 %, and 75:25 %). The mixture is stirred at 150 rpm for 20 minutes to ensure a homogeneous distribution of RHA particles in the aluminum matrix. The molten Al-RHA mixture is poured into a Styrofoam pattern embedded in silica sand. Pattern thickness varies (1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, and 10 mm). The shape and size of the Styrofoam pattern are shown in Fig. 5. The evaporation of the Styrofoam pattern facilitates the filling of the mold cavity by the molten metal, resulting in the desired shape. The casting is allowed to solidify in the mold for 30 minutes. Afterward, it is removed from the mold, cleaned, and specimens are prepared for further testing and analysis.

Fluidity length, surface roughness, Brinell hardness (HB), and porosity are measured using standard testing methods. Fluidity length is measured as the distance along which the molten metal fills the mold cavity (pattern) before solidifying. Surface roughness is evaluated using a surface profilometer (roughness tester), and hardness is measured using a Brinell hardness tester. Porosity is assessed by wet and dry weighing of specimens, and the percentage is calculated. Each experiment is conducted in triplicate to ensure reproducibility, and the results are averaged for analysis.

5. Results of the study of fluidity length, surface roughness, hardness and porosity of Al-RHA composites

5. 1. Investigation of the effect of pouring temperature on fluidity length, surface roughness, hardness, and porosity of Al-RHA composites

Fig. 6 shows the specimen shape for the fluidity length testing method of aluminum and rice husk ash composites produced through the evaporative casting method. The measured fluidity length is the maximum result that can be achieved by the flow of molten metal filling the Styrofoam pattern. The fluidity length is measured using a vernier caliper length measuring tool from the channel boundary to the maximum length of the perfect product as shown in Fig. 6, *b, c*. Variations in the results of fluidity length measurements indicate the importance of controlling the material composition and evaporative casting process parameters to achieve optimal results.



a *b* *c*

Fig. 6. Results of evaporative casting of Al-RHA composites: *a* – 3× repetition sample (top view); *b* – sample (perspective view); *c* – measurement of the length of the sample fluidity

Fig. 6, *a* is a sample of a composite specimen in 1 treatment repeated 3 times (viewed from above). Fig. 6, *b* is the results of the composite product (perspective view). Fig. 6, *c*, is a measurement of the length of the composite fluidity, after cutting the channel system.

Fig. 7 shows the graph of the fluidity length of aluminum (Al) and rice husk ash (RHA) composites at mixture compositions (85:15, 80:20, 75:25) % and pouring temperatures (650 °C, 700 °C, 750 °C).

From the three graphs in Fig. 7, it can be seen that the higher the pouring temperature (650 °C, 700 °C, 750 °C), the fluidity length tends to increase for all Al-RHA compositions. This indicates that higher pouring temperatures allow the molten metal to flow further before solidifying. Because the viscosity of the metal decreases with raising temperature, it extends the flow time before solidification occurs. Therefore, raising the pouring temperature will increase the fluidity length, allowing the molten metal to fill longer and more complex molds.

Fig. 8 shows the graph of the surface roughness of aluminum (Al) and Rice Husk Ash (RHA) composites at the mixture composition (85:15, 80:20, 75:25) % and pouring temperature (650 °C, 700 °C, 750 °C).

Based on the graph in Fig. 8, the effect of pouring temperature on surface roughness for each composition shows that raising the pouring temperature from 650 °C to 750 °C tends to increase surface roughness. The higher pouring temperature (750 °C) results in the highest roughness values in each composition. For example, in the Al-RHA 75:25 % composition, surface roughness increases from 9.48 µm at 650 °C to 10.63 µm at 750 °C. This indicates that at higher pouring temperatures, material flow is smoother but may cause segregation or agglomeration of reinforcing particles (RHA), resulting in a rougher surface after cooling.

Fig. 9 shows the hardness graph of aluminum (Al) and Rice Husk Ash (RHA) composites at mixture compositions of (85:15, 80:20, 75:25) % and pouring temperatures of (650 °C, 700 °C, 750 °C). Based on the graph in Fig. 9 regarding the Brinell hardness (HB) test results, the Al-RHA composition and pouring temperature affect the composite's hardness.

Based on the graph in Fig. 9, the effect of pouring temperature on the composite's hardness for each composition shows that raising the pouring temperature from 650 °C to 750 °C tends to increase the Brinell hardness (HB) values. The higher pouring temperature (750 °C) results in the highest hardness values in each composition. For example, in the (75:25) % composition, the hardness increases from 34.11 HB at 650 °C to 35.33 HB at 750 °C. This indicates that higher pouring temperatures allow for more uniform particle distribution in the matrix and increase the composite's density, all contributing to increased hardness.

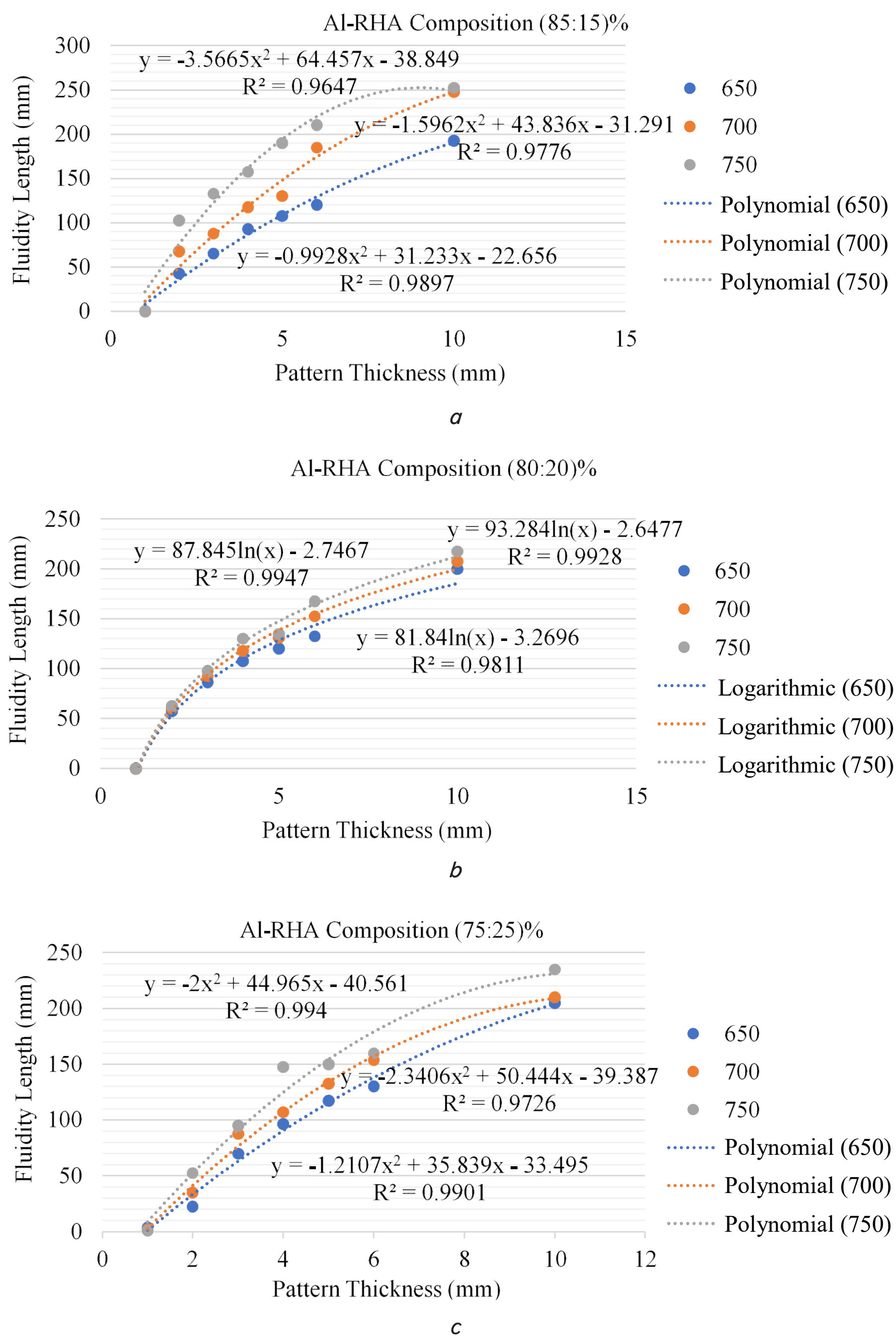
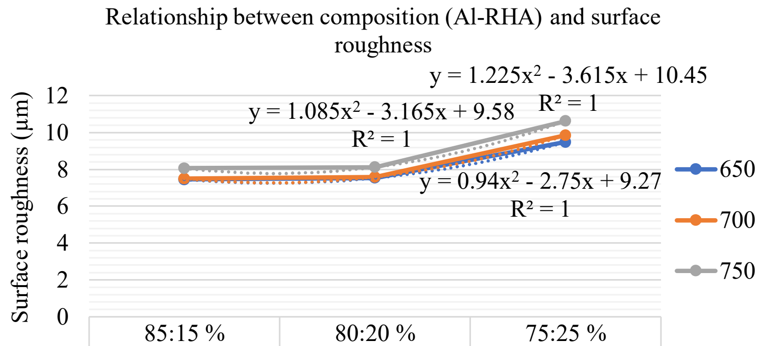


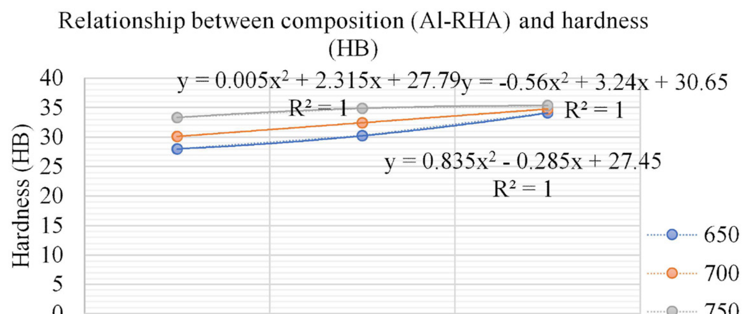
Fig. 7. Fluidity length of Al-RHA composites at mixture compositions: *a* – (85:15) %; *b* – (80:20) %; *c* – (75:25) %



	85:15 %	80:20 %	75:25 %
650	7.46	7.53	9.48
700	7.5	7.59	9.85
750	8.06	8.12	10.63

Al-RHA Composition (%)

Fig. 8. Surface roughness of Al-RHA composites

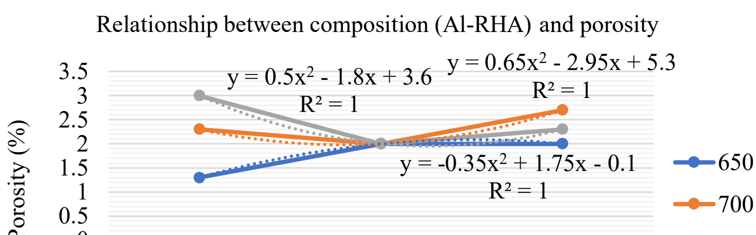


	85:15 %	80:20 %	75:25 %
650	28	30.22	34.11
700	30.11	32.44	34.78
750	33.33	34.89	35.33

Al-RHA Composition (%)

Fig. 9. Hardness (HB) of Al-RHA composites

Fig. 10 shows the porosity graph of aluminum (Al) and Rice Husk Ash (RHA) composites at mixture compositions of (85:15, 80:20, 75:25) % and pouring temperatures of (650 °C, 700 °C, 750 °C). Based on the graph in Fig. 10 regarding the porosity test results, the Al-RHA composition and pouring temperature affect the composite's porosity.



	85:15 %	80:20 %	75:25 %
650	1.3	2	2
700	2.3	2	2.7
750	3	2	2.3

Al-RHA Composition (%)

Fig. 10. Porosity of Al-RHA composites

Based on the graph in Fig. 10, at a pouring temperature of 650 °C, the lowest porosity occurs in the 85:15 % composition (1.3 %) and the highest in the 75:25 % composition (2 %). This indicates that at lower pouring temperatures, higher RHA content tends to increase porosity. At a pouring temperature of 700 °C, porosity is around 2 % for the 80:20 % composition and increases for the 85:15 % and 75:25 % compositions. This temperature seems to provide a balance in the 80:20 % composition but is less optimal for other compositions. At a pouring temperature of 750 °C, the highest porosity occurs in the 85:15 % composition (3 %), while the 80:20 % and 75:25 % compositions have lower values (2 % and 2.3 %). The increase in temperature seems to decrease porosity in compositions with higher RHA content, but porosity increases in compositions with lower RHA content.

5. 2. Analysis of the impact of Al-RHA composition ratio on fluidity length, surface roughness, hardness, and porosity of composites

Based on the graph in Fig. 7, the three different Al-RHA compositions are shown: (85:15) %, (80:20) %, and (75:25) %. From the three graphs, it can be observed that at the same pattern thickness and temperature, the Al-RHA composition with a higher RHA percentage (e. g., 75:25) tends to have a shorter fluidity length compared to compositions with a lower RHA percentage (e .g., 85:15). This may be due to the increased viscosity and flow resistance caused by the higher RHA addition, reducing the metal's ability to flow further.

Based on the graph in Fig. 8 regarding the surface roughness test results, the Al-RHA composition and pouring temperature affect the surface roughness of the composite. The (85:15) % composition has the lowest surface roughness at all pouring temperatures, with values ranging from 7.46 μm to 8.06 μm. The (80:20) % composition shows a slight increase in surface roughness compared to the (85:15) % composition, with values ranging from 7.53 μm to 8.12 μm. Meanwhile, the (75:25) % composition has the highest surface roughness values, ranging from 9.48 μm to 10.63 μm. These results indicate that increasing the RHA content in the aluminum alloy leads to increased surface roughness. This may be due to the higher distribution of rice husk ash particles in the aluminum matrix, increasing surface heterogeneity and causing the surface to become rougher.

Based on the graph in Fig. 9, the (85:15) % composition shows the lowest hardness values at all pouring temperatures, with hardness values ranging from 28 HB to 33.33 HB. The (80:20) % composition shows an increase in hardness compared to the (85:15) % composition, with hardness values ranging from 30.22 HB to 34.89 HB. The (75:25) % composition shows the highest hardness values among the three compositions, with hardness values ranging from 34.11 HB to 35.33 HB. These results indicate that adding more rice husk ash (RHA) to the aluminum alloy increases the composite's hardness. This may be due to the more even distribution of rice husk ash particles and the increased number of hard particles (RHA) in the aluminum matrix, which adds resistance to deformation.

Based on the graph in Fig. 10, the (85:15) % composition shows an increase in porosity with raising pouring temperature. Porosity starts from 1.3 % at 650 °C, increases to 2.3 % at 700 °C, and reaches 3 % at 750 °C. The (85:15) % alloy composition indicates that with lower ASP content, increased pouring temperature may lead to higher porosity, possibly due to gas formation or void expansion caused by the faster solidification process. In the (80:20) % composition, porosity remains constant at 2 % at all pouring temperatures. The stability of porosity in the (80:20) % alloy composition may indicate that at 80:20 % composition, there is a balance between RHA distribution and molten metal flow behavior, keeping porosity at the same level despite temperature variations. In the (75:25) % composition, porosity starts from 2 % at 650 °C, increases to 2.7 % at 700 °C, and then slightly decreases to 2.3 % at 750 °C. The initial increase in porosity at 700 °C may be due to increased interaction between RHA particles and molten metal, raising the potential for void formation. The decrease at 750 °C may indicate better mold filling at higher temperatures, despite the risk of oxidation.

6. Discussion of the results of the study of fluidity length, surface roughness, hardness and porosity of Al-RHA composites

Pouring temperature is one of the main factors affecting fluidity length. Fig. 7 shows the graph of the relationship between pouring temperature and fluidity length, indicating that higher pouring temperatures increase fluidity length. This is because at higher temperatures, the molten metal has lower viscosity, allowing it to flow further before solidifying. The results of the study [15] also reported that the fluidity of alloy casting increases with raising pouring temperature. Additionally, the fluidity length of aluminum alloys was found to increase linearly with pouring temperature within a certain temperature range [14]. However, if the pouring temperature is too high, oxidation or material degradation may occur, which might reduce fluidity length due to the formation of oxide layers that hinder the flow of the metal.

Pouring temperature plays an important role in surface roughness, as it affects the flow behavior of the molten alloy and the formation of the Al-RHA composite. As shown in Fig. 8, the higher the pouring temperature, the more the surface roughness of the composite tends to increase across all compositions. Higher pouring temperatures cause the molten metal to have lower viscosity, making it easier to flow into the mold cavity. However, too fast and fluid flow can cause turbulence when the molten metal enters the mold cavity. This turbulence can disrupt smooth filling, resulting in a rough surface after cooling. The findings [19] also show that pouring temperature can affect the rate of solidification, which in turn can influence the surface roughness of the final composite. Thus, too high a pouring temperature during casting can affect the surface quality of the casting product, making it rougher and negatively impacting the casting product. The combination of composition and pouring temperature needs to be considered in applications where a smooth or rough surface is required, depending on specific needs.

Pouring temperature affects the hardness of Al-RHA composites resulting from evaporative casting. Fig. 9 shows the relationship between pouring temperature and hardness. The graph indicates that an increase in pouring temperature leads to an increase in composite hardness. This is because higher pouring temperatures tend to create conditions that produce a finer, more homogeneous microstructure and phase distribution that can enhance the hardness of the casting. The study [14] shows that variations in pouring temperature can affect particle distribution and the mechanical properties of the composite. Research by [20] shows that raising the pouring temperature can slightly increase hardness due to changes in microstructure characteristics.

The pouring temperature of the molten metal has an effect on the porosity of the casting results. As seen in Fig. 10, the test results show that pouring temperature has an effect on porosity, especially at higher Al-RHA composition ratios (85:15) %. The higher the pouring temperature, the greater the tendency for porosity to increase, most likely due to the increased solubility of gas in the molten metal that then becomes trapped during cooling. This is in line with the findings of [15], which state that higher pouring temperatures can present challenges such as increased oxidation and gas porosity if not properly controlled. Excessive heat causes porosity, solidification shrinkage, and waste formation into the microstructure of alloys melted at temperatures above 760 °C [15]. At a composition of (80:20) %, porosity is more stable and is not affected by variations in pouring temperature, which may indicate a better balance between fluidity and mold filling. The (75:25) % composition shows an increase in porosity at higher pouring temperatures but not as high as at the (85:15) % composition. Improper pouring temperature (too high or too low) can increase the risk of porosity in castings. Too high a temperature can cause dissolved gases and oxide formation, while too low a temperature can hinder molten metal flow, causing air entrapment and shrinkage porosity. Therefore, proper control of pouring temperature is crucial to minimize porosity and improve casting quality. The optimum condition for achieving the lowest porosity is at an Al-RHA composition of 85:15 % with a pouring temperature of 650 °C. This combination results in a material with a denser structure and less porosity.

The addition of RHA as a filler in the aluminum matrix through the evaporative casting process can affect fluidity length. As shown in Fig. 7, increasing the RHA composition tends to reduce the fluidity length of the composite. This is due to increased viscosity, reduced thermal conductivity, and the potential for uneven particle distribution. This is in line with the findings of [21], which state that the presence of ceramic reinforcement particles in the aluminum matrix has been shown to reduce total solidification time, which affects the fluidity and solidification behavior of aluminum composites. Various factors such as solidification mode, metal composition, silicon content, rare earth elements, and pouring temperature have been identified as significant parameters affecting the fluidity of aluminum alloys [14, 22]. Increasing the content of SiC particulates tends to form Al_4C_3 at the interface; as a result, viscosity increases, and the fluidity of the melt composite decreases [21]. RHA in Al alloys can act as a flow barrier if too much is added, reducing fluidity length due to increased viscosity and reduced material flowability. However, in the right proportions, RHA can enhance fluidity length by improving metal flow characteristics by increasing resistance to early solidification.

The Al-RHA alloy composition affects the surface roughness of evaporative cast composites. As shown in Fig. 8, increasing the RHA content in the Al matrix tends to increase surface roughness, indicating that RHA contributes to the formation of a more irregular or rough surface. The addition of RHA into the aluminum matrix can cause particle agglomeration, especially if the distribution is uneven. This agglomeration creates areas with high RHA concentration, which can result in uneven surfaces and increased surface roughness. The same was reported by [3] that the coarse nature of RHA ash causes an increase in composite grain size. The findings of [23, 24] show that silica from rice husk ash has been used in various applications, including as a reinforcement in aluminum alloys. The silica composition of rice husk ash can affect the properties of aluminum alloys, influencing their mechanical properties and surface characteristics. The silica-aluminum rice husk ash alloy composition can affect the fluidity and solidification behavior of the material, which in turn affects the composite surface quality [25].

The difference in hardness values at various temperatures for the same composition indicates that controlling the pouring temperature is an important factor in achieving the desired material hardness. Based on Fig. 9, increasing the RHA content in the alloy increases the material's hardness, indicating that RHA serves as an effective reinforcement in this composite. The Al-RHA alloy composition affects the mechanical properties (hardness) of the composite. This is consistent with the statements of [26, 27] that ceramic particles such as SiC, AlN, TiB2, and others have shown potential in enhancing the mechanical properties and wear resistance of aluminum alloys while maintaining their corrosion resistance. The inclusion of ceramic phases in the aluminum matrix has been found to improve the mechanical properties of the resulting composite [26].

RHA influences the porosity of the composite. As shown in Fig. 10, increasing the RHA content in the mixture tends to increase porosity, especially at lower pouring temperatures. This is because RHA is a non-metallic material that can cause the formation of porosity (voids) in the aluminum matrix. The higher the RHA content, as in the (75:25) % composition, the greater the likelihood of particle agglomeration, which leads to the formation of larger porosity. Compositions with lower RHA content (85:15) % show lower porosity because the reinforcement particles are more homogeneously distributed, and the aluminum matrix can better fill the voids during solidification. This research result is consistent with [28], which states that adding rice husk ash to aluminum can affect the porosity of the resulting composite material.

The thickness of the Styrofoam pattern plays an important role in determining fluidity length. As shown in Fig. 6, 7, the thicker the pattern, the greater the fluidity length. Thicker patterns allow for slower temperature drop during the pouring process, which can extend the time the molten metal remains in a flowing condition, thereby increasing fluidity length. Conversely, too thin a pattern will accelerate the solidification of the molten metal, reducing fluidity length because the material does not have enough time to flow fully before solidifying. In the fluidity of A356 aluminum alloy in the lost foam casting process [18], the study results show that thickness variations can affect the fluidity behavior of the alloy. Additionally, exploring the fluidity of A356 aluminum alloy under various conditions revealed variations in fluidity length based on material and measurement conditions [19]. Molds with strip thicknesses of less than 3 mm require preheating, where the molten metal does not reach the 3 mm strip [15].

The results of this study have broad applications in manufacturing industries that use aluminum and aluminum composites, such as automotive, aerospace, and electronics. Specifically, the use of scrap aluminum and rice husk ash in evaporative casting offers a sustainable and economical way to produce components with improved mechanical properties, which is especially valuable in mass production and specialty applications where durability and strength are priorities. The application of these results is optimal in conditions where high quality control is required to ensure the integrity and function of the manufactured components. Pouring temperature, material composition, and pattern thickness must be tightly adjusted based on the specific needs of the final product to avoid issues such as porosity or unwanted surface roughness. By adjusting variables such as pouring temperature and material composition, effects such as increased hardness and durability, as well as smoother surfaces that meet specific industry standards, are expected to be achieved. In addition, the use of rice husk ash as a reinforcing material not only reduces raw material costs but also helps in waste reduction, supporting sustainability efforts. On the other hand, increased production efficiency and potential cost reductions can be significant economic effects, allowing companies to produce more at a lower cost.

The optimal pattern thickness for achieving maximum fluidity length is specifically shown in Fig. 7. The thickness of the Styrofoam pattern also affects fluidity length. From the graph, it can be seen that at a pattern thickness of 1 mm in the Al-RHA composition (85:15) % and (80:20) % and pouring temperature (650 °C, 700 °C, 750 °C), the fluidity length is 0 mm. However, when the Al-RHA composition is (75:25) %, the fluidity length is formed for all pouring temperatures but only reaches (3.8 mm, 2 mm, 1 mm). As the pattern thickness increases (from 1 mm to 10 mm), the fluidity length tends to increase for all composition and temperature conditions. Thicker patterns, such as 10 mm, allow slower cooling, resulting in a 10.53–60.42 % increase in fluidity length compared to thinner patterns such as 1 mm. Thinner patterns, which cause faster solidification, reduce the fluidity length. This can be explained by the fact that greater pattern thickness provides more space for molten metal flow before cooling and solidifying. The larger pattern thickness slows the cooling rate, keeping the metal in a liquid state longer, allowing it to flow further before solidifying.

This research has limitations in terms of small scale, melting temperature control, cooling time and limited parameters, very specific material composition for aluminum-RHA composites. Lack of interaction between variables, long-term mechanical property tests, especially under extreme operating conditions such as corrosion, high temperature, or material fatigue, have not been explored in depth. However, this opens up the potential for further research development, especially in multivariable optimization, expanding the scope of long-term testing, computer simulation, stirring speed, pouring rate, resistance to corrosion, extreme temperature and wear, and environmental and economic impact evaluation are essential to improve practical applications.

7. Conclusions

1. The pouring temperature affects the fluidity length, surface roughness, hardness, and porosity of Al-RHA composites. Higher pouring temperature causes an increase in fluidity length by 13.51–54.17 % when the temperature raises from 650 °C to 750 °C. This is accompanied by an increase in hardness by 1.96–10.69 %. However, higher temperature also results in an increase in surface roughness by 3.9–7.92 % and an increase in porosity by 1.3–3 %, especially in composites with lower RHA content.

2. The composition ratio of Al-RHA plays an important role in determining the physical and mechanical properties of the composites. As the RHA content increases, the fluidity length increases by 2.44–11.9 % and the hardness also increases by 1.26–12.87 %. However, the higher RHA composition also increases the surface roughness by 1.2–30.95 % and the porosity increases by 2–2.7 %. The increased viscosity from excess RHA inhibits flow, but optimized RHA proportions can lead to significant increases in hardness and mechanical strength.

Conflict of interest

The authors declare that they have no conflicts of interest related to this research, whether financial, personal, authorial, or otherwise, that could have influenced the research and the results presented in this paper.

Financing

This research and paper are financially supported by the Directorate General of Higher Education, Ministry of Education and Culture, Research and Technology and Lambung Mangkurat University through the BOPTN Fund for the 2024 Fiscal Year with Master Contract Number 056/E5/PG.02.00.PL/2024 dated June 11, 2024 and Derivative Contract Number 1047/UN8.2/PG/2024 dated June 12, 2024.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

Our gratitude goes to the Team of the Advanced Mineral and Materials Laboratory-State University of Malang and Dr. Apip Amrullah, ST, M.Eng.

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