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The Effect of Magnesium Variation on the Hardness Characteristics of Aluminium/SiC/Rice Husk Ash Composites

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Abstract: The reutilization of aluminum scrap as a composite matrix is an effective strategy to reduce import dependence and environmental impact, yet recycled aluminum typically exhibits inferior mechanical properties, requiring additional reinforcement. This study investigates the effect of varying weight fractions of the wetting agent magnesium (Mg) on the hardness characteristics of Aluminum Matrix Composites (AMCs) reinforced with sustainable Silicon Carbide (SiC) and Rice Husk Ash (RHA). The composites were fabricated using the stir casting method with fixed reinforcement contents of 2 wt% SiC and 2 wt% RHA, while Mg was varied at 0 g (control), 1.0 g (1 wt%), and 1.5 g (1.5 wt%). Hardness testing was performed using the Rockwell method (HRF scale). The results show that Mg addition significantly improves hardness compared to pure aluminum. The average hardness increased from 65.5 HRF for pure aluminum to 64.4 HRF with 1.0 wt% Mg and reached an optimum value of 69.1 HRF at 1.5 wt% Mg. The improvement is attributed to Mg enhancing wettability and strengthening interfacial bonding between the aluminum matrix and reinforcement particles, effectively impeding dislocation movement. It is concluded that 1.5 wt% Mg provides the optimal hardness enhancement for Aluminum/SiC/RHA composites produced via stir casting.

Keywords: Magnesium, Aluminium Matrix Composites, Rice Husk Ash, Silicon Carbide, Stir Casting, Rockwell Hardness.

1. Introduction

The advancement of the global manufacturing industry, particularly within the automotive and aerospace sectors, has persistently intensified the demand for lightweight, high-performance materials capable of meeting stringent requirements related to fuel efficiency, structural integrity, and environmental sustainability. Aluminum alloys have emerged as a dominant class of materials in these industries due to their favorable strength-to-weight ratio, excellent corrosion resistance, and good formability. The continuous push toward vehicle lightweighting to reduce fuel consumption and greenhouse gas emissions has further accelerated the adoption of aluminum-based components, replacing traditional ferrous materials in various structural and semi-structural applications. Consequently, global aluminum consumption has experienced steady growth over the past decades, reflecting its strategic importance in modern manufacturing systems. In the

Indonesian context, aluminum plays a vital role in supporting industrial development, particularly in transportation, construction, packaging, and consumer goods sectors. Recent data indicate that Indonesia's aluminum consumption has reached approximately 1.2 million tons per year, with nearly 56% of this demand still being fulfilled through imports. This high level of import dependency highlights structural challenges within the domestic aluminum supply chain, including limited primary aluminum production capacity, high capital investment requirements, and dependence on imported raw materials and energy sources. These challenges not only exert pressure on the national trade balance but also increase vulnerability to fluctuations in global aluminum prices and supply disruptions. As a result, there is a growing need to explore alternative strategies that can strengthen domestic material availability while simultaneously supporting sustainable industrial development.

Beyond supply constraints, aluminum production and consumption are associated with significant environmental concerns. Primary aluminum production from bauxite ore is an energy-intensive process, involving mining, refining through the Bayer process, and smelting via the Hall–Héroult process. These stages collectively consume large amounts of electrical energy and generate substantial greenhouse gas emissions, particularly carbon dioxide and perfluorocarbons. In addition, aluminum-related industrial activities produce various forms of waste, including red mud, spent pot lining, and post-consumer aluminum scrap. Improper management of aluminum waste can contribute to air, soil, and water pollution, posing risks to ecosystems and human health. Therefore, addressing aluminum waste management has become an integral component of broader environmental sustainability initiatives.

Recycling aluminum scrap has emerged as one of the most effective strategies to mitigate both supply and environmental challenges. From an energy perspective, recycling aluminum requires only about 5–10% of the energy needed for primary aluminum production, leading to significant reductions in energy consumption and greenhouse gas emissions. Economically, recycling offers cost advantages by lowering raw material and energy expenses, while strategically, it reduces reliance on imported primary aluminum. For Indonesia, which generates increasing volumes of aluminum waste from industrial activities and end-of-life products, aluminum recycling represents a promising pathway toward circular economy implementation. By transforming waste into value-added materials, recycling not only conserves natural resources but also supports sustainable industrial growth.

Despite its advantages, recycled aluminum often suffers from inferior mechanical properties when compared to primary aluminum alloys. This degradation is primarily attributed to contamination, oxidation, and compositional heterogeneity introduced during service life and recycling processes. Impurities such as iron, silicon, and other residual elements can adversely affect microstructure evolution, leading to reduced ductility, strength, and fatigue resistance. Consequently, the direct reuse of recycled aluminum in high-performance applications is frequently limited, necessitating strategies to enhance its mechanical and tribological properties. One widely adopted approach to address these limitations is the development of aluminum matrix composites (AMCs).

Aluminum matrix composites are engineered materials in which ceramic or other reinforcing phases are embedded within an aluminum matrix to improve specific properties such as hardness, strength, stiffness, and wear resistance. Through appropriate selection and distribution of reinforcement materials, AMCs can be tailored to meet the demands of advanced engineering applications. Among the various reinforcement options, silicon carbide (SiC) has been extensively studied and utilized due to its high hardness, high elastic modulus, thermal stability, and excellent wear resistance. The incorporation of SiC particles into aluminum matrices has been shown to significantly enhance load-bearing capacity and resistance to abrasive and erosive wear, making SiC-reinforced AMCs suitable for automotive brake components, pistons, and aerospace structural elements.

In parallel with the development of conventional ceramic-reinforced composites, increasing attention has been directed toward the use of agro-industrial waste materials as alternative or complementary reinforcements. Rice husk ash (RHA) has attracted particular interest due to its high silica (SiO_2) content, low density, and wide availability. As an agricultural by-product generated from rice milling and combustion processes, RHA is produced in large quantities in rice-producing countries such as Indonesia. It is estimated that Indonesia generates approximately 11.69 million tons of rice husks annually, yet their utilization remains relatively limited, with a significant portion being disposed of or underutilized. Improper disposal of rice husks and ash can lead to environmental issues, including air pollution and land degradation.

The incorporation of RHA into aluminum matrix composites offers multiple benefits from both material performance and sustainability perspectives. From a materials standpoint, the silica-rich composition of RHA enables it to act as a reinforcing phase, contributing to improved hardness and strength through load transfer mechanisms and grain refinement effects. From an environmental standpoint, the utilization of RHA promotes waste valorization by converting agricultural residues into value-added engineering materials. This approach aligns with circular economic principles by integrating industrial and agricultural waste streams into a unified resource-efficient system. Moreover, RHA-based reinforcements are generally more cost-effective than conventional ceramic particles, providing economic incentives for large-scale implementation.

While numerous studies have investigated the effects of SiC or RHA as individual reinforcements in aluminum matrix composites, research on hybrid reinforcement systems combining both materials remains limited. Hybrid aluminum matrix composites, which incorporate two or more distinct reinforcement phases, have the potential to exploit synergistic effects that cannot be achieved by single reinforcements alone. In the case of SiC–RHA hybrid composites, SiC can provide high hardness and stiffness, while RHA can contribute to reduced density, improved sustainability, and potential cost reduction. The combined use of these reinforcements may result in a balanced enhancement of mechanical properties, including strength, hardness, and wear resistance, while mitigating some of the drawbacks associated with each reinforcement when used individually.

The effectiveness of hybrid reinforcement systems is strongly influenced by processing methods, reinforcement content, particle size, and interfacial bonding between the matrix and reinforcements. Among various fabrication techniques available for aluminum matrix composites, stir casting is one of the most widely employed methods due to its simplicity, cost efficiency, and suitability for mass production. Stir casting involves the mechanical stirring of molten aluminum to facilitate the uniform distribution of reinforcement particles before casting. When properly controlled, this technique can produce composites with relatively homogeneous microstructures and acceptable interfacial bonding. Additionally, stir casting is compatible with recycled aluminum feedstock, further enhancing its attractiveness for sustainable composite manufacturing.

However, stir casting also presents challenges, particularly related to particle agglomeration, poor wettability, and porosity formation. These issues can be exacerbated when multiple reinforcement phases are introduced into the melt. Therefore, systematic investigation of processing parameters and reinforcement weight fractions is essential to achieve optimal composite performance. Understanding the relationship between reinforcement content, microstructural evolution, and mechanical behavior is critical for the successful development of hybrid aluminum matrix composites.

In light of these considerations, the present study aims to investigate the effect of varying weight fractions of silicon carbide (SiC) and rice husk ash (RHA) on the mechanical performance of recycled aluminum matrix composites fabricated through the stir casting method. Particular emphasis is placed on evaluating key mechanical properties, including hardness and strength, as well as analyzing microstructural characteristics to elucidate reinforcement distribution, interfacial bonding, and potential defect formation. By systematically varying the reinforcement content, this study seeks to establish clear correlations between hybrid reinforcement composition and composite performance, thereby providing a more comprehensive understanding of material behavior under different reinforcement configurations.

Research Gap and Novelty, although previous studies have demonstrated that the individual addition of SiC or RHA can enhance the hardness and strength of aluminum matrix composites [18], [2], investigations focusing on their combined use as hybrid reinforcements remain scarce. In particular, limited attention has been given to recycled aluminum matrices, where compositional heterogeneity and impurity pose additional challenges to achieving consistent mechanical performance. Furthermore, existing studies often emphasize either mechanical properties or microstructural observations in isolation, without establishing an integrated understanding of how hybrid reinforcement systems influence both aspects simultaneously. This lack of comprehensive investigation represents a critical research gap in the development of sustainable aluminum matrix composites.

The novelty of the present study lies in its systematic evaluation of hybrid SiC–RHA reinforcement in recycled aluminum using a cost-effective and scalable stir casting technique [25], [1]. By maintaining the advantages of conventional ceramic reinforcement (SiC) while incorporating an environmentally friendly agricultural waste material (RHA), this research offers a dual benefit of performance enhancement and sustainability improvement. The findings are expected to provide new insights into the synergistic interaction between SiC and RHA reinforcements, contributing to the advancement of high-performance, low-cost, and environmentally sustainable recycled aluminum-based composites. Such insights are particularly relevant for reducing import dependency, improving waste utilization, and supporting the long-term development of Indonesia's manufacturing sector.

2. Methods

This study was designed using an experimental approach to quantitatively investigate the effect of varying doses of the wetting agent magnesium (Mg) on the hardness and microstructural characteristics of Aluminum Matrix Composites (AMCs) reinforced with silicon carbide (SiC) and rice husk ash (RHA). The materials used consisted of aluminum scrap as the matrix, SiC and RHA as the reinforcement phases, and magnesium (Mg) as the wetting agent. To isolate the effect of Mg, the weight fractions of SiC and RHA were kept constant at predetermined levels (e.g., 2% SiC and 2% RHA of the total matrix weight), while Mg was varied into three groups: 0 g (control), 1.0 g, and 1.5 g. All composite fabrication processes were carried out using the stir casting method.

The fabrication process began with material preparation, including accurate weighing of all components. The reinforcement particles (SiC and RHA) were preheated at a temperature of approximately 250° C to remove moisture and enhance adhesion with the molten metal. Subsequently, the aluminum scrap was melted in a furnace at 700 °C and purified from slag using flux.

The melt temperature was then reduced to a semi-solid condition 650°C, at which point the specified amount of magnesium was introduced. The addition of Mg aimed to form a thin layer on the surface of the ceramic particles, reduce interfacial tension, and effectively improve particle dispersion. A mechanical stirrer was then operated at a speed of 350 rpm to create a vortex, into which the SiC and RHA particles were gradually added. The stirring process was maintained for 10 minutes to ensure homogeneous distribution of the reinforcement phases. The prepared composite melt was immediately poured into preheated molds.

Figure 1. *Aluminium temperature melted*

After cooling, the specimens were cut according to standard testing dimensions, followed by characterization tests. Hardness testing was performed using the Rockwell method (HRF scale), with each sample tested at a minimum of three to five random points to obtain a representative average value. This test provided the primary quantitative data on the improvement of mechanical properties. The hardness data obtained were then analyzed and compared with results from aluminum scrap without the addition of magnesium, SiC, and RHA to determine the influence of magnesium on the hardness of the AMCs.

Table 1. *Input parameters of a*

Weight Fraction	Mixing Speed (Rpm)	Mixing Time (Minute)	Casting Temprature (ºC)
Pure Aluminium	350	10	700
Rha 2 wt %- SiC 2 wt %- Mg 1 wt %	350	10	700
Rha 2 wt %- SiC 2 wt %- Mg 1,5 wt %	350	10	700

3. Result and Discussions

3.1. The Result of Rockwell Hardness Test

For comparison purposes, a recycled aluminum (scrap) specimen originating from a previous casting process was used as a reference. This material served as the baseline in the compositional analysis to evaluate the influence of magnesium variation on the composite. The specimen used is shown in Figure 3

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Figure 3. *The aluminum scrap used in this study*

The hardness test results of the cast aluminum specimen are presented in Figure **4.**

Figure 4. *The result of Rockwell test process*

The Rockwell hardness (HRF) test results are presented in Table 3.

Table 3. *Hardness Values*

Item	Rockwell Hardness (HRF)					Ave. Hardness (HRF)
	1	2	3	4	5	
Pure Aluminium	64	60	65	55	65.5	61
Rha 2 wt % - SiC 2 wt % - Mg 1 wt %.	66	61	63.5	69	62	64.4
Rha 2 wt % - SiC 2 wt % - Mg 1,5 wt %.	71	67	70.5	70	69.1	69.1

The average rockwell hardness (HRF) test result are presented in Figure 5.

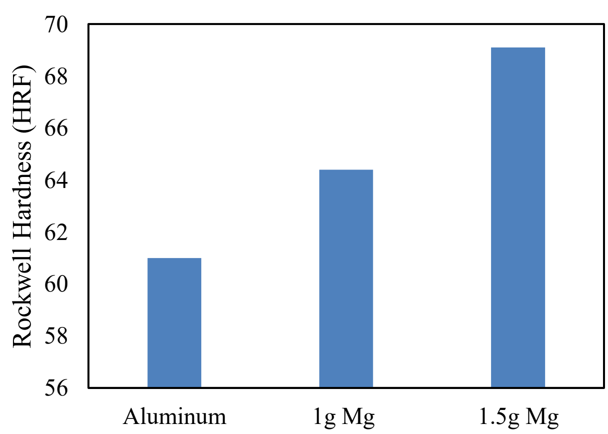

Figure 5. Average rockwell hardness test result graph

The Rockwell hardness test results presented in the graph show a significant trend related to the variation of Magnesium (Mg) addition in the Aluminium/SiC/Rice Husk Ash composite. It is evident that the addition of Mg, both at 1 g and 1.5 g, consistently increases the material's hardness compared to pure aluminum. Quantitatively, the hardness of pure aluminum is approximately 61 HRB (estimated from the graph), increasing to around 64 HRB with the addition of 1 g Mg, and reaching its peak at approximately 69 HRB with the addition of 1.5 g Mg. This improvement aligns with previous reports stating that the incorporation of RHA and SiC into an aluminum matrix generally enhances the hardness and mechanical properties of the composite [1–3, 5, 17].

This increase in hardness can be analyzed from a metallurgical perspective. Mg, as an alloying element, functions as a crucial wetting agent. In particulate-reinforced composites, Mg improves the wettability between the aluminum matrix and the reinforcing particles, namely SiC and Rice Husk Ash (RHA). The role of Mg in enhancing wettability and interfacial bonding strength is widely documented, including evidence that Mg reacts to form MgO or $MgAl_2O_4$ at the interface, thereby strengthening the adhesion between aluminum and ceramic reinforcements [39, 40, 41]. Improved wettability facilitates a more homogeneous distribution of reinforcement particles and stronger interfacial bonding between the matrix and the dispersed phases. Enhanced interfacial bonding as a major mechanism contributing to the increase in hardness has also been reported in earlier studies on Al–SiC and Al–RHA composites [24, 25, 32].

The improvement in interfacial bonding strength effectively impedes dislocation movement, which is the primary mechanism of plastic deformation, thus requiring greater energy for indenter penetration and resulting in higher hardness values. Furthermore, the 1.5 g Mg dosage produces the highest hardness value. This suggests that at this concentration, the role of Mg in facilitating interfacial reactions and forming strong metallurgical bonds— including potential intermetallic or reactive oxide phases at the interface, as also reported in the Al–Si–Mg–RHA system by Bahrami et al. [40]—reaches an optimal condition. Conversely, although 1 g Mg already significantly increases the hardness compared to pure aluminum, this concentration does not fully optimize the strengthening effect.

Therefore, it can be concluded that the addition of Magnesium is an effective strategy for controlling interfacial microstructure and directly improving the material's resistance to localized plastic deformation, which is the essence of hardness. This finding is consistent with various aluminum-based composite studies, which state that interfacial bonding quality, reinforcement particle distribution, and improved wettability are dominant factors determining the final hardness of the composite [1–3, 5, 17, 24, 27, 32]. Future analysis should integrate these results with microstructural studies to validate the proposed strengthening mechanisms. Furthermore, detailed compositional analysis using instruments such as EDS or XRF is required to verify the actual reacted Mg content and confirm the formation of specific intermetallic phases at the interface, as recommended by previous studies on Al–SiC–RHA and Al–RHA systems [1, 40].

4. Conclusion

This study successfully investigated the effect of varying weight fractions of the wetting agent magnesium (Mg) on the hardness characteristics of Aluminum Matrix Composites (AMCs) reinforced with 2 wt% Silicon Carbide (SiC) and 2 wt% Rice Husk Ash (RHA), fabricated using the stir casting method. The main findings from the Rockwell hardness (HRF) tests are as follows. Optimal Hardness Improvement, The addition of 1.5 wt% magnesium produced the highest average hardness value of the composite, reaching 69.1 HRF. Role of Mg Variation, The results show that increasing the amount of magnesium wetting agent from 1.0 wt% (64.4 HRF) to 1.5 wt% significantly enhanced the hardness of the composite. The hardness value of 69.1 HRF obtained at 1.5 wt% Mg even exceeded the hardness of pure aluminum, which was measured at 65.5 HRF.

Strengthening Mechanism, The increase in hardness is interpreted as resulting from the role of Mg in forming a thin layer on the surface of the ceramic particles, reducing interfacial tension, and effectively improving the dispersion of the reinforcing particles (SiC and RHA) within the aluminum matrix, thereby strengthening the material.

Overall, this study concludes that the addition of 1.5 wt% magnesium is the most optimal for maximizing the hardness properties of recycled Aluminum Matrix Composites (Aluminum–SiC–RHA) fabricated using the stir casting method.

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