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Mechanical Properties of Al6061 Composites Reinforced with Electroless-Coated and Uncoated Sea Sand with Magnesium Addition

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Abstract. This study, Al6061 composite reinforced with sea sand were produced using the stir casting method at a stirring speed of 600 rpm for ten minutes. Sea sand particles were applied in both uncoated and electroless coated conditions with a constant 4 wt% fraction. Magnesium (Mg) was added with variations of 0 wt%, 1 wt%, 1.5 wt%, and 2 wt% to improve wettability. Density, tensile, and hardness tests were used to assess the final composites. The results showed that the electroless coated sea sand composite with 2 wt% Mg achieved the highest tensile strength and highest hardness, respectively, of 191.81 MPa and 67.12 BHN.

1 Introduction

Metal matrix composites (MMCs) are consisted of two or more constituent materials that have distinct physical and chemical properties. Composites have superior properties compared to their constituent materials [1]. One type of metal composites is aluminum matrix composites (AMCs), where aluminum plays the role as the matrix. The superior properties of AMC include corrosion resistance, superior weight to strength ratio and lightweight [1]. Traditional ceramic particles are commonly used as reinforcement particles in AMC, such as Al_2O_3, SiO_2, SiC, TiO_2, & graphite. The use of conventional ceramics in AMC manufacture has been extensively researched, but it has the disadvantage of being expensive to produce. It is necessary to innovate AMC reinforcements that are easy to obtain and cheap. One way to mitigate this is to use natural materials, such as sea sand. Because sea sand is rich in oxides like Al_2O_3 and SiO_2, it may be utilized as reinforcement in AMC [2].

In AMC manufacturing, the distribution of reinforcement particles is a key factor in determining the final mechanical properties of the material. Therefore, an appropriate method is needed to produce aluminum composites with the desired properties. Among the available techniques, stir casting is one of the commonly used methods due to its easy to use, low cost, and suitable for large-scale production [3]. When compared to other manufacturing techniques, the stir casting method is the simplest and least expensive. To obtain AMC that has the desired properties, it is necessary to carefully evaluate a number of stir casting parameters, including temperature, stirring speed, stirring time, and stirrer type [4]. Despite its advantages, stir casting has a major problem with particle distribution. This is due to the low wettability between the liquid metal interface and the surface of the reinforcement particles [5]. Modifications are required, such as adding magnesium (Mg) as a wetting agent or surface treatment of the reinforcement particles, which are typically employed to enhance wettability. One method to enhance wettability is to apply an electroless coating on reinforcement particles [1]. The purpose of adding magnesium wetting agent to the liquid metal during the stir casting process is to lower the liquid metal's surface tension. A strong interfacial bond forms when the surface tension of the liquid metal decreases, making it easier for the metal to spread on the surface of the reinforcement particles [6].

The existing literature is limited to aluminum composites reinforced with conventional ceramic particles or agricultural waste-based reinforcers. The use of sea sand as a reinforcing material in the creation of aluminum composites has only been the subject of a few research. Therefore, it is important to determine the optimal parameters for Mg addition and particle treatment in order to develop aluminum composites reinforced with sea sand to achieve better mechanical properties. In this study, Al6061 alloy was chosen as the matrix material for composite fabrication due to its superior mechanical properties and its ability to be further enhanced through reinforcement [7]. Sea sand was chosen as a reinforcement particle because of its low cost, wide availability, and high intrinsic content of ceramic oxides. However, systematic investigations of the combined effects of sea sand surface modification

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through electroless coating and the addition of Magnesium as a wetting agent for the stir casting fabrication of Al6061 composite reinforced with sea sand are still limited. This article aims to address this gap. Therefore, this study focused on the analysis and comparison of the combined effects of various Mg contents (0, 1, 1.5, and 2 Wt%) and electroless coating treatments on the properties of Al6061 composite reinforced with sea sand. The resulting material is subjected to physical, mechanical, and metallographic characterization to determine the optimal processing combination.

2 Material and Methods

2.1 Electroless Coating Sea Sand Particles

Sea sand particle was collected from Samas Beach, Yogyakarta. The analysis of the sea sand revealed the presence of silicon dioxide (SiO_2) at 42.2%, diopside at 38.9%, Fe_2MgO_4 at 14.1% and Fe_3O_4 at 4.7%. The coating of sea sand particles was performed using the electroless wet-chemical deposition technique. In this method, Mg and Al fine powders (Merck KGaA brand) acted as the deposition precursors, while a nitric acid (HNO_3) solution served as an electrolyte to facilitate the chemical adhesion of the coating to the surface of the particle. The first step in the electroless coating process is to mix 40 ml of HNO_3 with 20 g of 150 mesh (88–100 microns) sea sand particles. The mixture is then heated to 70℃. 0.1 g Mg and 0.5 g Al fine powders are added at the same time once the temperature is reached and the mixture is agitated with a magnetic stirrer. The stirring process was carried out for 40 minutes at a solution temperature of 100℃. Once finished, the coated sea sand particles are put into the mortar and subsequently dried in a furnace at 200℃ for 1 hour. The drying process is then continued at 400℃ for 2 hours to increase oxidation and improve coating adhesion, followed by cooling to room temperature.

2.2 Preparation of Composites

The Al6061 composite reinforced with sea sand were fabricated through stir casting method, as shown in Figure 1. This process used Al6061 alloy as the matrix, sea sand particles (electroless coated and untreated) as reinforcement at a constant weight fraction (4%), and magnesium (Mg) as a wetting agent with varying amounts from 0 wt% to 2 wt%. Table 1 presented the specifics of the composite sample codification. During the fabrication process, 1 kg of Al6061 alloy was melted in a crucible at a temperature of 750℃ utilizing an electric resistance heater. After the alloy reached a fully liquid, a four-blade impeller stirrer was submerged to half the depth of the molten metal and maintained a constant speed of 600 rpm for a duration of ten minutes. To guarantee even distribution of the reinforcements, sea sand particles and the specified quantity of magnesium were progressively added throughout the stirring phase. The composites was well mixed before being placed into a warmed steel mold at 500℃ to manage solidification and reduce thermal shock. The mold dimensions employed in this study were 132 x 132 x 40 mm, with an open permanent mold, and the cooling rate was air-cooled. The sample preparation process was carried out using a CNC milling machine.

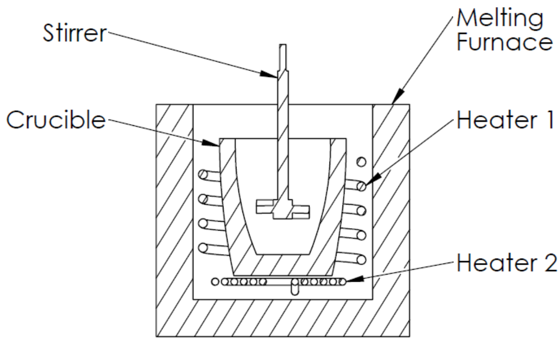


Fig. 1. Stir casting apparatus.

Table 1. Tabulation of specimens.

Magnesium (Wt%)	Particles treatment	Specimen code
0	Untreated	NE-0
	Electroless coating	EC-0
1	Untreated	NE-1
	Electroless coating	EC-1
1.5	Untreated	NE-1.5
	Electroless coating	EC-1.5
2	Untreated	NE-2
	Electroless coating	EC-2

2.3 Characterization

Tensile tests were carried out using a SANS SHT 4106 Universal Testing Machine in accordance with the ASTM E8 standard. The specimens were loaded under a constant crosshead speed of 1.0 mm/minutes until fracture occurred. The resulting stress-strain curves were analyzed to determine the ultimate tensile strength (UTS) and elongation at failure.

Brinell Hardness Number (BHN) testing was conducted in accordance with ASTM E10 standards. The Brinell hardness testing apparatus (Controlab Serial No. 6767) was used to test the specimens, with five indentations per sample. This was done to minimize errors in each test and obtain accurate results. A steel ball with a diameter of 2.5 mm, an indentation load of 62.5 kgf, and 30 seconds were used for the indentations.

Microstructural observations were conducted using an optical metallographic microscope. Specimens were prepared following metallographic procedures. The polished surfaces were etched for 20-25 seconds following ASTM E407 utilizing Keller's Reagent (2 ml HF, 3 ml HCl, 5 ml HNO_3, and 190 ml H_2O), just before examination.

The actual density value of the sample is determined using Archimedes method. Each sample is weighed in air and immersed in distilled water, which is then calculated based on the mass of the sample under two different conditions. The theoretical density of a composite is calculated by referring to the rule of mixture, which is based on the density value and volume fraction of each composite constituent material. By comparing the actual density of the composite with its theoretical density, the percentage of porosity is ascertained. The percentage of porosity indicates the number of voids present in the sample.

3 Result and Discussion

3.1 Density and Porosity

The density of the Al6061 sea sand composites is shown in Figure 2. Density was clearly raised by applying the electroless coating and adding the magnesium. The measured density of the NE-0 specimen is 2.638 g/cm^3, while the EC-0 specimen exhibits a slightly higher value of 2.644 g/cm^3. For the NE-1 and EC-1 specimens, the densities increase to 2.649 g/cm^3 and 2.654 g/cm^3, respectively. Similarly, the NE-1.5 and EC-1.5 specimens show density of 2.656 g/cm^3 and 2.660 g/cm^3. The highest values were recorded for NE-2 (2.663 g/cm^3) and EC-2 (2.670 g/cm^3). This trend indicates that the electroless coating treatment successfully increases the density of the reinforcement particles, thereby increasing the bulk density of the final composite.

Composites reinforced with electroless coated sea sand showed a clear density improvement. The development of a spinel layer on the substrate surface, which increases the particles' wettability by the molten metal matrix, is responsible for this improvement [8]. The existence of this spinel layer reduces the matrix surface tension, thereby promoting better interfacial bonding and consequently decreasing porosity at the particle-matrix interface [9].

The addition of Mg during the stir casting process has been shown to increase wettability [2]. While in the molten state of aluminum, Mg acts as a surface-active agent that can reduce the surface tension of the matrix, resulting in better contact within the interface matrix and reinforcement particles. Furthermore, magnesium reacts with oxygen on the particle surfaces, functioning as an efficient oxygen scavenger. By lowering the adsorbed gas layer, this reaction increases wettability and considerably lessens the propensity for particle agglomeration [10].

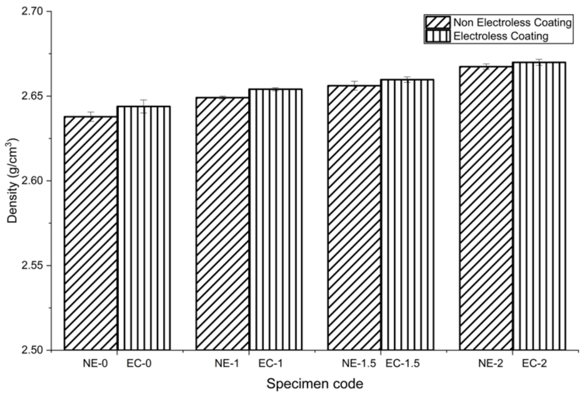


Fig. 2. Average density of the specimens.

The porosity of the Al6061 composite reinforced with sea sand decreases when the sea sand reinforcement particles undergo electroless coating treatment, as shown in Figure 3. The figure further demonstrates that porosity continues to decrease with increasing Mg weight fraction during the fabrication of the Al6061–sea sand composites. In cast composites, porosity generally originates from three primary mechanisms: hydrogen evolution, gas entrapment during stirring, and shrinkage during solidification [1]. The combined application of electroless coating and magnesium addition has been shown to reduce the overall porosity levels in the composites effectively.

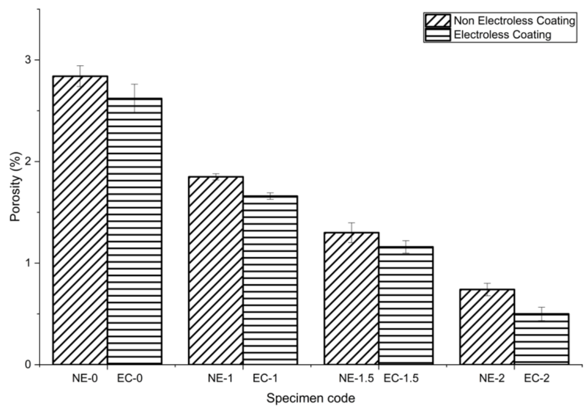


Fig. 3. Average porosity of the specimens.

3.2 Hardness Test

Figure 4 shows the hardness result of the Al6061 composite reinforced with sea sand. The hardness increases along with the increase in Mg content. The Brinell hardness of Al6061 alloy is 47.56 BHN. While the hardness of the Al6061 composite reinforced with sea sand is as follows, the NE-0 specimen is 50.05 BHN, the EC-0 specimen is 52.03 BHN, the NE-1 specimen is 55.05 BHN, the EC-1 specimen is 57.00 BHN, the NE-1.5 specimen is 59.99 BHN, the EC-1.5 specimen is 62.23 BHN, the NE-2 specimen is 65.82 BHN, and the EC-2 specimen is 67.12 BHN.

In comparison to the untreated version, the Al6061 composite reinforced with sea sand hardness increased after the electroless coating procedure. It has been shown that electroless coating of the sea sand particles improves wettability. This enhancement is related to the increased wetting of the reinforcing particles with the matrix, thus causes the composite's hardness to rise. Poor wettability can lead to the agglomeration of reinforcement particles, resulting in high porosity, as illustrated in Figure 3.

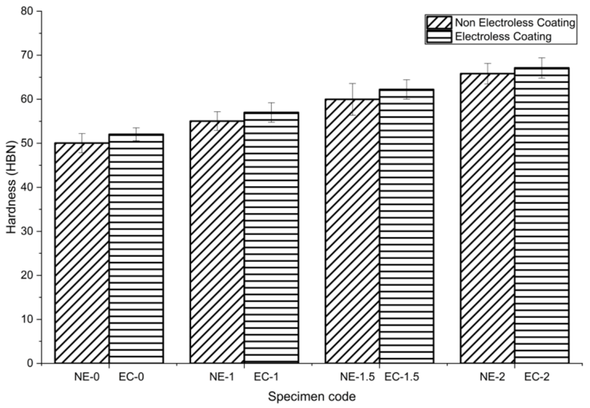


Fig. 4. Average hardness of the specimens.

It has been reported that adding magnesium to the stir casting process reduces the aluminum matrix's surface tension [11]. This phenomenon allows the reinforcement particles to form stronger bonds with the aluminum matrix. Therefore, as shown in Figure 4, creating a strong interface bounding between the aluminum matrix and the reinforcing particles is essential to raising the composite's hardness value.

3.3 Tensile Test

Figure 5 shows the tensile strength results for composites with different Mg fractions. Tensile strength gradually rises with increasing magnesium concentration, according to a trend. The Al6061 alloy exhibits a tensile strength of 155 MPa. The tensile strength for composites without Mg addition are 159.17 MPa (NE-0) and 161.62 MPa (EC-0). After the addition of 1% Mg, the strengths increase to 170.01 MPa (NE-1) and 172.25 MPa (EC-1). The values further increased to 180.42 MPa (NE-1.5) and 182.65 MPa (EC-1.5) for the composite with the addition of 1.5 % Mg. The highest strengths are obtained at 2% Mg, reaching 189.98 MPa (NE-2) and 191.81 MPa (EC-2). The results indicate that the addition of Mg and applying an electroless coating treatment enhance the composites tensile characteristics.

The improvement in ultimate tensile strength after electroless coating treatment and the addition of Mg mass fraction can be associated with the interfacial properties between the matrix and reinforcement. A particle that undergoes electroless coating treatment will possess a rough surface, which consequently leads to an augmentation in the area of the reinforcing particle. As a result, the bounding between the reinforcing particle and the matrix is strengthened [12]. Electroless coating treatment enhances wettability, resulting in a more uniform dispersion of reinforcing particles [8]. The addition of Mg to the stir casting process reduces the surface tension of the aluminum matrix, thereby promoting adequate wetting [5]. Therefore, the reinforcement particles exhibit a stronger bonding interface to the aluminum matrix, resulting in an increase in tensile strength.

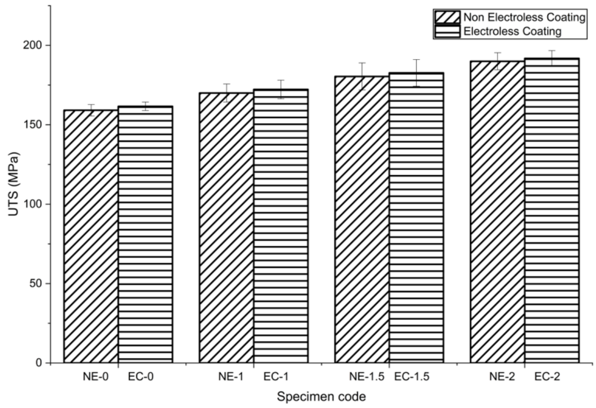


Fig. 5. Average ultimate tensile strength of the specimens.

3.4 Microstructure Observation

To illustrate the impact of electroless coating treatment on Al6061 matrix sea sand reinforcement particles, metallographic observations were performed on NE-0 and EC-0 samples. Figure 6 shows the findings from the microstructure observations.

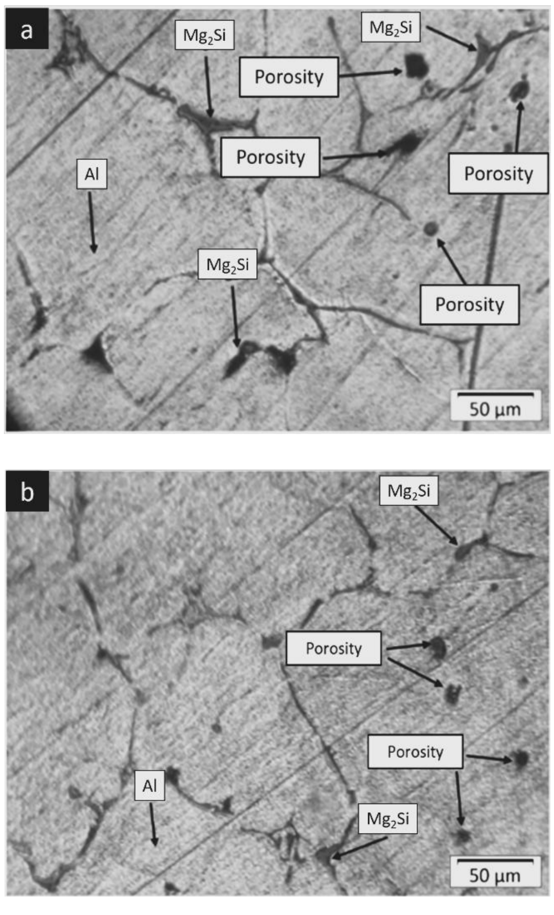
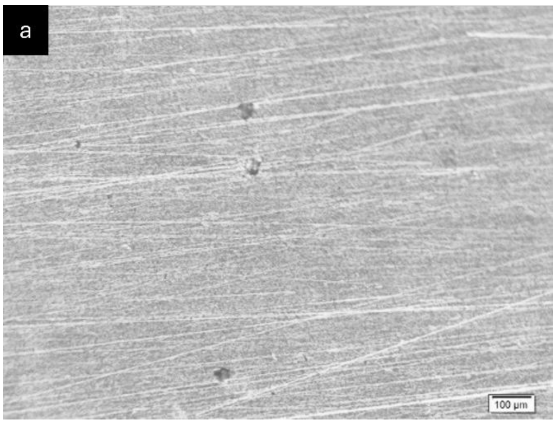


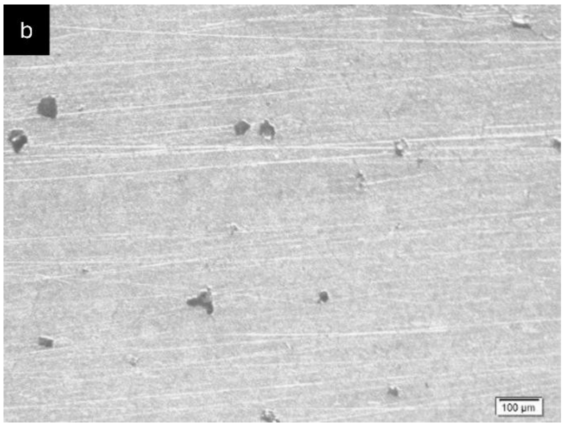
Fig. 6. Microstructure observations of Al6061 composite reinforced with sea sand without magnesium addition: (a) untreated, and (b) electroless coating treatment.

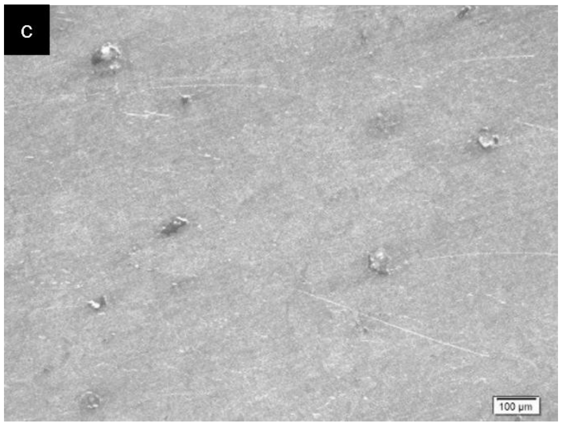
Metallographic observations confirmed that in the Al6061 composite reinforced with sea sand, electroless coating treatment on the reinforcement particles will reduce the percentage of porosity or voids. This is due to the presence of the spinel layer formed during the electroless coating treatment. This layer is known to enchourage interface adhesion by lowering the surface tension of the sea sand and the Al matrix. The spinel layer has been demonstrated to enhance wettability, thereby facilitating the wetting of sea sand by the Al matrix and produce stronger bonding with the aluminum matrix [9]. This statement is supported by Figure 3, where the composite reinforced with electroless coated sea sand particles has a lower porosity value.

Figure 7 shows a microstructure analysis without etching of AMC reinforced coated sea sand to determine the effect of Mg on bonding quality and distribution of reinforcement particles. Adding Magnesium serves as a wetting agent by reducing the oxide layer on the particle surface, thereby creating stronger bonds and greater contact areas between the matrix and the reinforcement. Figure 7 shows that the addition of Mg results in a more uniform particle distribution and reduced porosity at the interface compared to other samples. The high level of wettability allows the liquid matrix metal to properly fill the particle surface [13]. This aligns with the density and porosity measurements in Figures 2 and 3, where the addition of Mg results in lower porosity values and leads to an increase in AMC density. Strong interface quality can lead to enhancing the mechanical properties of AMC.

The capacity of the reinforcement particles to be sufficiently wetted by the matrix can be used to evaluate the quality of the interfacial bonding between particles and matrix in a composite. Because magnesium acts as a wetting agent to lower the surface tension of the molten metal, it must be added during the stir casting process [14]. The increasing of magnesium content also results in finer grains and reduced porosity. A finer grain structure contributes to improved mechanical strength [14]. This leads in the occurrence of the Hall-Petch mechanism, where the finer grain size creates more grain boundaries that can act as barrier to the movement of dislocation, thus increasing the yield strength of composites [15]. These findings are consistent with reported in Figures 4 and 5, indicating that an increase in the Mg fraction results in increase the mechanical strength of AMC.







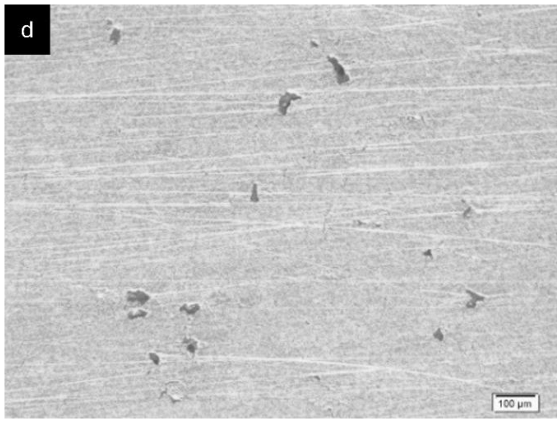


Fig. 7. Microstructure observations of (a) EC-0, (b) EC-1, (c) EC-1.5, and (d) EC-2 composites obtained without etching.

4 Conclusion

This study shows that electroless coating of sea sand reinforcement particles and the addition of magnesium are essential in improving the performance of Al6061 composite reinforced with sea sand. The electroless coating treatment results in lower porosity and higher density of the Al6061 composite reinforced with sea sand. The addition of Mg as a wetting agent improves particle distribution and reduces void formation. The electroless-coated composite with 2 wt% Mg exhibited the highest tensile strength of 191.81 MPa and highest hardness of 67.12 BHN. The findings confirm that the combination of electroless coating and Mg addition enhances the physical and mechanical properties of Al6061 composite reinforced with sea sand.

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