Research article

Fabrication of AA6061-sea sand composite and analysis of its properties

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ABSTRACT

Aluminium matrix composites (AMCs) are widely used in various applications because of their excellent properties; however, their lightweightness limits their broad application scope. Various ceramic compounds are used as reinforcements in AMCs such as Al₂O₃, SiC, ZrO₂, and TiO₂. However, the use of ceramic compounds results in high production costs in AMC manufacturing. Thus, the substitution of reinforcement particles with various organic and industrial waste reinforcements is required. In line with the research trend of using industrial waste materials such as rice husk ash, red mud, and fly ash, this study uses sea sand as an AMC reinforcement. Sea sand is used because it primarily contains SiO₂ and Fe₃O₄ ceramic compounds and, thus, can be used as a reinforcement. This study aims to determine the physical and mechanical properties of an AA6061–sea sand composite. Sea sand was subjected to electroless coating to increase its wettability before the stir-casting process. The as-prepared composite was manufactured by the stir-casting method upon the addition of 2–6 wt% sea sand. Composite characterisation was carried out through Brinell hardness and tensile tests. The results showed that the electroless-coated composites possessed lower porosity and, therefore, higher hardness and ultimate tensile strength than the non-electroless-coated composites.

1. Introduction

1.1. Background

Metal matrix composites have been widely used in various fields such as automotive and aerospace manufacturing. Such composites are widely used because of their excellent physicochemical properties compared to those of conventional materials (such as strong structure [1, 2, 3, 4], stiffness, high strength, and good thermal conductivity and wear resistance [5, 6]). Aluminium matrix composites (AMCs) have been widely used in the manufacturing of various automotive components and structures such as pistons, connecting rods, and brake discs [7, 8]. In recent years, casting methods have been used for manufacturing composites. The casting methods are advantageous because of their ease of processing, large-scale production capability, and low cost [9, 10]. However, the use of conventional ceramic reinforcements (Al₂O₃, SiC, carbon nanotubes) in AMCs leads to significantly high production costs [11, 12]. This has prompted the researchers to use various ceramic and oxide materials as substitutes for conventional ceramic compounds. The applicability of various organic materials such as fly ash and red mud as well as various agricultural wastes as reinforcement particles in AMCs has been studied [13, 14]. Sea sand, an oxide-rich material, is a promising candidate as a reinforcement in AMCs. Sea sand contains various ceramic and oxide compounds such as Fe₂O₃, SiO₂, Al₂O₃, which can induce a strengthening effect on AMCs [6, 15, 16].

Several types of composite fabrication methods such as solid-phase processing, liquid-phase processing, infiltration, and powder metallurgy have been widely used [14]. However, liquid-phase processing is the easiest technique with low production cost and is suitable for mass production [17]. One of liquid-phase processing in manufacturing of metal matrix composite is stir casting. Stir casting is an AMC manufacturing process that utilises vortex flow in the molten metal to obtain homogeneous particle distribution in the cast. Over the years, the non-uniform distribution of particles has primarily limited the manufacturing of AMCs by the stir-casting method [18, 19]. Various methods for increasing particle homogeneity have been investigated, including addition of wetting agents, chemical treatment of reinforcements, and various modifications of the stir-casting method [20, 21]. Prasad and Jayadevan [22] studied stirring simulations for overcoming the limitation of stir casting. The simulation was performed with three blade and four-blade impellers. The impeller angle was set at 90°, the impeller height was fixed at 20 mm from the base of the crucible, and
the stirring speed was varied from 100 to 300 rpm. The simulation results showed that the shear rate increases with the increase in the stirring speed, which lowers the dispersion time of the particles. The simulation results showed a positive correlation with the experimental results. Moreover, the stir-casting method that applied in Al–SiC manufacturing was investigated. A total of 3 wt% micro SiC was added to molten aluminium at various casting temperatures (680 and 850 °C) and agitation times (2 and 6 min). The results showed that it takes a minimum time for SiC particles to be homogeneously distributed when stirred for 2 min, which causes the formation of a weak bond at the interface. Casting at higher temperatures indicated the enhancement of ceramic incorporation and the formation of shrinkage defects [23].

Innovative chemical treatments of particles with the aim of increasing wettability have been studied; one of these methods is electroless coating. A previous study [24] investigated the effect of electroless coating treatment on Al2O3 particles with varying amounts of Mg powder; the addition of 0.004 mol Mg powder and 0.018 mol Al powder produced a thin layer of the MgAl2O4 spinel phase, which enhanced the wettability of the manufactured AMC, thereby increasing its mechanical properties. A similar phenomenon occurred to SiC when Mg powder varied on the electroless coating treatment. This addition facilitated the formation of MgO and MgAl2O4 spinel phases. The addition of 0.02 wt% Mg powder is the optimal addition because it allowed the formation of the spinel phase and imparted a higher modulus of elasticity than the addition of 0.25 wt% Mg powder [20].

Thus far, the performance of sea sand as a reinforcement material in AMCs has not been investigated. The physical and mechanical properties of AMCs reinforced with sea sand have not yet been determined. This paper aims to study the fabrication and development of AA6061–sea sand composites and investigate their properties.

1.2. Profile of sea sand

The characterisation of sea sand was carried out to determine the applicability of sea sand for engineering purposes. Several studies have stated that the size, composition, and shape of sea sand particles affect the physical and mechanical properties of sea sand [25]. Di et al. [26] investigated marine sand from the Zhoushan Seas and determined 2652 and 1370.3 kg/m³ apparent and bulk densities of marine sand with shell and mud contents of 0.23 % and 0.27 %, respectively. A study of the physical properties of sea sand from the Yantarny, Kaliningrad region, Russia, confirmed that the true and bulk densities of sea sand are 2612 and 1474 kg/m³, respectively [27]. The investigation of iron sand from the Syiah Kuala beach, Banda Aceh, Indonesia, showed that the dominant phase was magnetite (Fe3O4) with 85 %, while compounds such as TiO2, SiO2, and Al2O3 constituted the minor phase [15].

2. Materials and methods

2.1. Composite manufacturing

Sea sand was obtained from Samas, Yogyakarta (South Coast of Java), and the particles were processed through ball milling to obtain a 200 mesh particle size, followed by washing with alcohol to remove impurities. Next, 40 g of particles was subjected to electroless coating by using 40 ml HNO3 + 1 g Mg fine powder + 0.5 g Al fine powder. The electroless-coated AMC sample was melted in a graphite crucible at 720–750 °C, followed by stirring by a TiO2 coated four-blade impeller, as shown in Figure 1, for 5 min and at 400 rpm. The sea sand particles were added up to 6 wt% with a range of 2 wt% to the molten aluminium. After the first round of stirring, 1 wt% Mg powder was added to improve wettability, and the mixture was stirred again for 5 min. The melted composite was poured into a 130 × 130 × 60 mm steel mould and was heated at 500 °C. The stir-casting apparatus is shown in Figure 2. The AMC specimens were classified into two types, namely, non-electroless-coated (NE) and electroless-coated (EC) specimens. The NE composites are the specimens wherein sea sand particles were not electroless coated, while the EC composites are the specimens containing electroless-coated sea sand particles.

2.2. Testing method

a) Density and porosity measurement

The mechanical and physical properties of the composites were evaluated. The density of the composites was calculated by Archimedes’ method using Eq. (1) and Eq. (2), where \( \rho_M \) stands for the theoretical density of the composite, \( \rho_M \) and \( \rho_P \) are the densities of the matrix and the reinforcement particle, respectively; \( V_m \) and \( V_p \) are the volume fractions of the matrix and the reinforcement particle, respectively; \( \rho_m \) is the actual density of the composite; and \( m_s \) and \( m_r \) are the specimen mass on the air and water, respectively. Porosity (P) was calculated using Eq. (3). The weight of the specimen was measured using Vibra AJ-620E Precision...
Balance Analytical Scales (Shinko Denshi Co., Ltd., Tokyo, Japan). The measurement scheme is shown in Figure 3.

\[ \rho_{th} = \rho_m V_m + \rho_p V_p \]  
\[ \rho_a = \frac{m_s}{m_s - m_g} \times \rho_{H_2O} \]  
\[ P = \left(1 - \frac{\rho_a}{\rho_{H_2O}}\right) \times 100\% \]

(b) X-Ray diffraction (XRD) analysis and scanning electron microscope (SEM) observation

The XRD analysis of the composites was performed using Shimadzu XRD-7000 (Shimadzu Corporation, Kyoto, Japan). The microstructural characteristics were observed through SEM (Zeiss Evo 10, Zeiss, Oberkochen, Germany) to evaluate particle distribution.

c) Hardness test

The hardness of the composites was measured using Contorlab Dia Testor 2RC (Controlab, Paris, France), according to ASTM E-10 [28], with a 2.5 mm steel ball indenter with 62.5 kg applied load. The Brinell hardness of the composites was calculated using Eq. (4), where \( P \) is the load used, \( D \) is the diameter of the indenter, and \( d \) is the width of indentation on the specimen. The hardness value reported is an average of nine values taken at various locations on the specimen and denoted in Brinell Hardness Number (BHN).

\[ \text{BHN} = \frac{2P}{\pi D \left(D - \sqrt{D^2 - d^2}\right)} \]  

d) Tensile test

The tensile strength and forging process were evaluated using SUNPOC WEW-300D Hydraulic Universal Testing Machine (Guizhou Sunpoc Tech Industry CO., LTD., Guiyang City, China). The tensile test was performed according to JIS Z 2201: 1998, No. 14a test piece [29] considering 6 mm specimen thickness and \( 10^{-1} \) mm/min strain rate. The dimension of the tensile test specimen is shown in Figure 4.
3. Results

3.1. Sea sand characterisation

The XRD analysis results show that sea sand mainly contains SiO$_2$ and Fe$_3$O$_4$; the XRD patterns are shown in Figure 5. The presence of SiO$_2$ and Fe$_3$O$_4$ ceramic compounds allows sea sand to form composites with superior properties [30, 31, 32]. This is because the presence of SiO$_2$ and Fe$_3$O$_4$ ceramic compounds increase the mechanical and physical properties of the composites. The compounds in sea sand are listed in Table 1. The XRD results of this study are in agreement with the findings of Rianna et al. [33], who characterised sea sand on the west coast of Sumatra. Elements such as C, O, Al, Si, Ca, Mn, and Fe were the dominant elements found in sea sand. Uniform characteristics can be observed in sea sand obtained from the west coast of Sumatra, the south coast of Java, to the south coast of Bali and Nusa Tenggara [34]. In addition to SiO$_2$ and Fe$_3$O$_4$, sea sand contains diopside which is a glass-ceramic compound. This compound is rich in Si, O, Ca, and Mg, and its presence imparts a strengthening effect on the Al matrix [35].

3.2. Density and porosity

The electroless and non-electroless coating treatments on sea sand particles affect the physical and mechanical properties of the AA 6061–sea sand composites. The density and porosity of the AA6061–sea sand composite are summarised in Figures 6 and 7, respectively. The highest density of the EC specimen was achieved upon the addition of 2 wt% sea sand and was found to be 2.63 g/cm$^3$. The density of the EC specimen decreased to 2.62 and 2.60 g/cm$^3$ upon the addition of 4 and 6 wt% sea sand, respectively. For the NE specimen, the density of composites tends to be stable upon the addition of sea sand of up to 6 wt% and was found to be 2.57, 2.58, and 2.58 g/cm$^3$. The total porosity shows a similar trend upon the addition of sea sand with or without the electroless coating treatment—the total porosity continues to increase with the increase in the sea sand content. Decreasing on number of porosity indicate the difference treatment that given to the particles. This confirms that the electroless coating treatment is effective in increasing the wettability of sea sand. The density of the sea sand composites decreases with the addition of the sea sand reinforcement. This is because the density of sea sand is lower than that of aluminium (2.5 g/cm$^3$) [36], which causes the density of the composite to decrease with the increase in the reinforcement content. In contrast, the porosity of the composite increases with the sea sand content. The higher porosity is attributed to the increase in the surface contact of the sea sand particles with molten aluminium. Larger the contact surface, higher is the porosity [8].

3.3. Hardness testing

The results of the composite hardness tests are shown in Figure 8. The highest hardness was achieved upon the addition of 6 wt% sea sand for the NE specimens, whereas in the EC specimens, the highest hardness was achieved with the addition of 2 wt% sea sand. The hardness of the ceramic compounds in sea sand affects the hardness of the composites. The higher the number of the dispersed sea sand particles, the higher the hardness of the composites [37]. The dispersion of the sea sand particles in the matrix causes slip disruption, which prevents dislocations [38]. In addition, the ceramic compounds in sea sand increase the hardness of the composites [39]. In the EC specimens, the highest hardness was achieved when a lower content of sea sand was added. This is because the addition of >2 wt% sea sand reinforces the agglomeration
of the composite castings. The greater the number of particles added, the higher is the chance of agglomeration, which decreases the mechanical properties of the composites [13]. The results of the hardness test showed that the electroless coating treatment was effective in improving the mechanical properties of the AA6061–sea sand composites. This is because the electroless coating treatment provides a coarse particle surface, as shown in Figure 9. The coarsening effect on the particle surface facilitates the interfacial bonding between the matrix and the particles [24]. Strong interfacial bonding is caused by mechanical interlocking that occurs because of the coarsening of the particles resulting from the electroless coating treatment.

3.4. Tensile test

The tensile strength of the AA6061–sea sand composite is shown in Figure 10. The UTS increased with the increase in the sea sand content. The highest tensile strength in NE specimen was achieved upon the addition of 6 wt% sea sand, while the lowest tensile strength was obtained upon the addition of 2 wt% sea sand. Moreover, in the EC specimens, the highest UTS was achieved upon the addition of 2 wt% sea sand and then decreased upon the addition of the sea sand particles. The increase in the tensile strength is related to the presence of ceramic compounds (Al₂O₃, SiO₂, Fe₂O₃) in sea sand [40]. Previous research has stated that in composites, there are several strengthening mechanisms, including grain refinement, particle strengthening, and strengthening due to thermal differences [41]. In the AA6061–sea sand composite, the strengthening mechanism was particle strengthening. This phenomenon is related to the limited movement of dislocation due to the presence of sea sand particles, thereby increasing the strength of the material. This is in accordance with the Orowan mechanism [42, 43]. Differences in mechanical properties were also observed in the EC specimens. The increase in strength in the EC specimens is due to the bonding between the matrix and the sea sand particles, as shown in Figure 11. However, in the NE specimens, there is no interface bonding between the matrix and the particles, as shown in Figure 12. Debonding that occurs between the matrix and the particles results in a lower strength of the composite. This shows that the electroless coating treatment of sea sand is effective for strengthening the interfacial bonding of the matrix and the sea sand particles, thereby increasing the mechanical properties of the composites.

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**Figure 9.** (a) EC and (b) NE specimens of sea sand particles.

**Figure 10.** Ultimate tensile strength of the AA6061–sea sand composite.

**Figure 11.** SEM image of 2 wt% EC specimen.

**Figure 12.** SEM image of 2 wt% NE specimen.
4. Discussions

The addition of sea sand to AA6061 resulted in increase in the hardness and tensile strength of the NE specimen. This is caused by the presence of ceramic compounds (SiO2 and Fe3O4) in sea sand. The presence of ceramic compounds that have higher mechanical properties than the aluminium matrix induces a positive effect on the composites [44]. In addition, the enhancement of the mechanical properties of the composites was caused by indirect strengthening. The presence of sea sand particles causes thermal mismatch during the manufacturing process, thereby increasing the dislocation density of the composites [45, 46]. This strengthening mechanism can occur at the atomic scale. Sea sand dispersion results in the propagation of the dislocation path in the matrix, thereby enhancing the mechanical properties of the composites [47]. However, the mechanical properties resulting from the addition of NE particles were not higher than those from the addition of EC particles to the aluminium matrix. This is indicated by the higher porosity of the NE specimens compared to that of the EC specimens.

SEM results also showed that the NE specimens did not exhibit interface bonding between the matrix and the particles. This shows that the increase in the mechanical properties of the NE specimens due to indirect strengthening is restricted because of the absence of a strong bonding interface between the sea sand particles and the matrix, whereas a different phenomenon was observed for the EC specimens. Overall, the addition of the EC specimen of sea sand improved the mechanical properties of the composites. In particular, the highest increase in the mechanical properties was obtained upon the addition of 2 % wt of sea sand, and then gradually decreased with the addition of 4 and 6 wt% sea sand. This is due to the particle size of sea sand—the large-sized particles tend to agglomerate when the number of particles increases [48].

The electroless coating treatment also increases the mechanical properties of the composites. The addition of Mg and Al2O3 during the electroless coating process leads to the formation of a spinel phase on the particle surface. The deposition of a passive film with the spinel phase on the particle surface makes it easier for the molten aluminium to disperse the particles, resulting in strong interface bonding [20, 24]. The strong interface bonding produced by the EC specimens provides a barrier for crack growth in the specimen; therefore, the EC specimens have higher mechanical properties than the NE specimens. Table 2 show the mechanical properties comparison of the AMCs with agro and industrial waste reinforcements with AA6061–sea sand composites.

As established in Table 1, the AA6061–2%wt sea sand (EC) composite has higher hardness than the Al–3Mg–5%wt fly ash and Al6082–7.5%wt SiC–7.5%wt fly ash composites. However, it has a lower strength than the hybrid Al 6061–5%wt Al2O3–8%wt bagasse ash composite. This shows that sea sand has a strong effect on the improvement of mechanical properties compared to fly ash when added as a low-content reinforcement.

The lower tensile strength of the AA6061–sea sand composite is attributed to the fact that the sea sand particles used have a larger size than the bagasse ash particles, which results in a larger contact area between the reinforcement and the matrix, thereby increasing the strength of the matrix–reinforcement interfacial bond that results in an improvement in the mechanical properties of the composite.

Thus, it can be considered that sea sand has potential as a reinforcement in aluminium-based composites. Ceramic compounds found in sea sand induce a positive effect when sea sand is added to the aluminium matrix, but further improvement of the mechanical properties can be achieved by various approaches, such as by optimising the particle size of the sea sand used. Thus, the feasibility of sea sand addition to the aluminium matrix can be explored in future research toward the development of high-strength composites.

5. Conclusions

AA6061–sea sand composites were successfully prepared by using the stir-casting method. Sea sand particles containing SiO2 and Fe3O4 ceramic compounds strengthened the composite. Particle treatment before stir casting was found to have a strong effect on the physical and mechanical properties of the composite. The EC specimens possessed higher density and lower porosity than the NE specimens. The hardness and strength of the NE specimens increased with the addition of sea sand, but in the EC specimens, the addition of >2 wt% sea sand decreased their hardness and strength. The physical and mechanical properties of the AMCs are closely related to the wettability of reinforcement particles; therefore, the effect of sea sand wettability on the composite performance can be studied further.

Declarations

Author contribution statement

Hammar Ilham Akbar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Eko Surojo: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Dody Ariawan: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Aditya Rio Prabowo: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Fahmi Imanullah: Performed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data included in article_supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Table 2. Comparison of AA6061–sea sand with other aluminium composite.

| Composite | Result |
|-----------|--------|
| AA6061–2%wt sea sand (EC) | 63.44 BHN and 128.57 MPa |
| Al–3Mg–5%wt fly ash [49] | 54.96 BHN |
| Al6061–5%wt Al2O3–8%wt bagasse ash [50] | 180 MPa |
| Al6082–7.5%wt SiC–7.5%wt fly ash [51] | 51.9 BHN |
