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Original Research

Investigating Mechanical and Physical Properties of Stir Casted Al6061/Nano Al_2O_3/Quartz Hybrid Composite

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Abstract

Aluminum alloys are widely used in different engineering application areas, such as aerospace, automotive, and marine industries. However, their properties need some improvement in order to enlarge their application area. Thus, the objective of the study was to improve the physical and mechanical properties of Al6061 aluminum alloy by reinforcing it with nano-Al_2O_3 and micro-quartz particles. The investigation primarily was focused on studying the impact of quartz particles on the mechanical and physical properties of an Al6061/nano-Al_2O_3/quartz hybrid composite. The hybrid composite was developed using a stir casting technique, by varying the weight percentage of quartz particles at 3%, 6%, and 9%, while maintaining a constant weight percentage of nano-Al_2O_3 at 3.5%. To evaluate the composite's properties, test samples were prepared according to ASTM E9-09 and ASTM E23 standards for hardness, compressive strength, creep, and impact energy absorption, respectively. The results of the investigation demonstrate that, with the addition of 9 wt.% of micro-quartz particles and 3.5 wt.% of nano-Al_2O_3 nanoparticles, all mechanical and physical properties of the matrix were improved, except for the impact strength. Based on these results, the developed hybrid composite material can be recommended for light weight automotive spare parts such as brakes and clutch discs.

Keywords: Al6061 aluminium alloy, hybrid aluminium matrix composite, nano-Al_2O_3, quartz (SiO_2), stir casting

1. Introduction

The evolution of materials has played a pivotal role in advancing human civilization from the Stone Age to the modern era. Materials are indispensable in our day-to-day activities, and without them, our current way of life would be nearly impossible to imagine. Researchers continuously strive to develop new materials that meet the evolving needs of society and industry, ensuring safety and comfort in our world. Industries such as automobile, defense, marine, and aerospace demand materials with higher resistance, strength, weldability, and corrosion resistance (Virinchy et al., 2019; Yang et al., 2004).

One class of materials that has shown significant promise in meeting these requirements is the third generation of aluminum metal matrix composites (AMMCs). These composites offer an excellent strength-to-weight ratio, low thermal expansion coefficients, and improved mechanical properties, making them ideal for various applications (Parhiban et al., 2017; Sun et al., 2014). Aluminum composites, including AMMCs, have found widespread use in the manufacturing of automotive components, electronics, defense systems, and aerospace components (Baradeswaran et al., 2013).

To fabricate composite materials, several methods such as stir casting, compo-casting, and powder metallurgy are available. Among these techniques, stir casting stands out as a cost-effective and versatile process for composite manufacturing (Chen & Hoshi, 1992; Poornachandiran et al., 2020). The process involves blending the matrix alloy with reinforcement materials using a friction stir casting setup. Stir casting allows for easy fabrication of large quantities of composite materials, and it ensures a minimal chemical reaction between the matrix alloy and reinforcements, resulting in low porosity (Caracostas et al., 1997; Pugazhenthi et al., 2019). The uniform distribution of reinforcement particles within the composite is achieved through the optimization of the process parameters (Baradeswaran & Perumal, 2013). Considering its cost-effectiveness and favorable outcomes, stir casting has become a preferred method for producing composite materials (Jino et al., 2017).

In the quest to enhance the hardness and strength of aluminum alloys, researchers have incorporated various reinforcement particles, such as silicon carbide (SiC) and boron carbide (B_4C), through the stir casting process (Das et al., 2014; Sankarlal & Kuppusamy, 2018). These additions significantly improve the mechanical properties of the composite materials, particularly hardness and tensile strength (Mishra et al., 2019a). The chemical analysis of the composite materials confirms the composition of the aluminum alloy, such as Al6061, using techniques like optical emission spectrometry.

Aluminum alloys, including Al6061, have demonstrated their suitability across a wide range of applications, including automobiles, aircraft, spacecraft, ships, biomedical devices, household appliances, industrial equipment, electrical components, and electronic instruments (Mishra et al., 2019b). The advantages of Al6061 alloy include high strength-to-weight ratio, resilience under static and dynamic loading, excellent corrosion resistance, and durability at low temperatures. To further enhance the mechanical properties, researchers have developed and formulated composite materials based on alloy matrices. Composites consist of a matrix in the continuous phase and reinforcements in the discontinuous phase, where the matrix can be metallic, ceramic, or polymer, and the reinforcement can be particulate fillers or fibrous materials (Marques et al., 2021; Nieberle et al., 2021).

Composite materials, such as metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer matrix composites (PMCs), exhibit superior properties compared to their individual constituents. By formulating the composition, specific properties can be modified or improved (Gangwar et al., 2013; Mehara et al., 2021; Singh et al., 2012; Singh et al., 2013). Aluminum matrix composites (AMCs), comprising aluminum or its alloys as the matrix and fillers or fibers as reinforcements, are widely used due to their remarkable mechanical and wear properties (Bodunrin et al., 2015; Manigandan et al., 2015; Singh et al., 2011). Among them, Al6061 alloy-based composites have gained attention in automotive, aircraft, and ship components due to their lightweight nature, strength, formability, corrosion resistance, and weldability (Breval, 1995; Kamat et al., 1989). The addition of alumina ceramic fillers to Al6061 alloy composites has been observed to increase the ultimate tensile strength and yield strength (Kumar et al. 2016). Additionally, the size, shape, and surface treatment of the filler materials influences the performance of the composite materials (Arif et al., 2018; Ezatpour et al., 2014).

While previous research has focused on the incorporation of nanoparticles, such as nano-alumina, nano-silica, and SiC, into Al alloy-based materials, however, there is a scarcity of published articles on the effect of adding micro quartz particles on the mechanical and physical properties of Al6061/nano-Al_2O_3 (Kareem et al., 2021). While previous research has focused on the incorporation of nanoparticles, such as nano-alumina, nano-silica, and SiC, into Al alloy-based materials, there is a lack of comprehensive studies on their physical and detailed mechanical properties (Kareem et al., 2021). Therefore, this research aims to investigate the effects of micro quartz particles on the physical and mechanical properties of Al6061-based composite materials. By exploring the behavior of these hybrid composites, valuable insights can be gained for further optimization and applications. The novelty of the current research work is that no one has ever developed this hybrid composite material. Furthermore, there might be some research that tries to study different mechanical properties and physical properties of hybrid aluminum alloy-based metal matrix composites, but there is no published study that is conducted on studying the creep properties of Al6061/nano Al_2O_3/quartz hybrid composites, so this also makes this research novel.

In summary, the present study focuses on the investigation of the mechanical and physical properties of Al6061/nano Al_2O_3/quartz hybrid composite. By examining the effects of micro-quartz particles combined with nano-Al_2O_3 on the composite, valuable insights can be gained to enhance the performance and durability of these materials.

2. Materials and methods

2.1. Materials

For the current research work, aluminum alloy 6061 is selected as a matrix material as it has better wear resistance and mechanical properties than other aluminum alloys because Si and Mg are the main alloying elements in this alloy (Alnaqi et al., 2016; Arif et al., 2018) as shown in Table 1. The reason behind selecting aluminum as a matrix is due to its light weight from other metals. Various companies use different aluminum alloys in automotive parts such as clutches and brake rotors, especially for light duty vehicles (Alnaqi et al., 2016). Aluminum alloy 6061 has better wear resistance properties than the other aluminum alloy groups (Sabry et al., 2001).

Table 1. Nominal chemical composition (in wt.%) of the matrix Al6061 alloy used in the study in the ASTM standard (Sabry et al., 2001).

Elements of Al6061	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	other
Content	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	94.0	0.15

In order to identify the major and minor oxides which are present within the quartz particle, a complete silicate analysis was performed in Ethiopian Geological survey laboratory, and the report was presented in the appendix section of this article. Furthermore, Table 2 presents the report of complete silicate analysis of the micro quartz particles.

Table 2: Major and minor oxides which are present with in quartz particles.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Percentage	96.68	<0.01	0.74	0.36	0.16	0.54	<0.01	<0.01	<0.01	0.02	0.22	0.31

Micro quartz and nano-Al_2O_3 (aluminum oxide) were used as reinforcement particles. Al_2O_3 is the second wear-resistance material next to silicon carbide. Due to the oxide it has the highest corrosion resistance properties than any other ceramic reinforcement agent. Furthermore, it has better thermal conductivity which is 20–30 W/mK. If the material has good thermal conductivity, then heat will be easily removed from it (Kala et al., 2014). Furthermore, quartz is the second material that has the highest impact resistance (toughness), whenever any material becomes tough it improves the wear resistance and high temperature performance of the composite (Sayuti et al., 2012). Particle sizes of 45 μm quartz particles are prepared by ball milling and 50 μm of Al_2O_3 reinforcing particles are bought from the shelf to develop the composite. Table 3 shows the details of the mixture design during casting.

Table 3. Mixture proportion design of matrix and reinforcement materials in one sample composite material.

Exp. run	% mass of Al6061	% mass of nano-Al_2O_3	% mass of quartz
1	100% = 1382 g	0% = 0 g	0% = 0 g
2	96.5%= 1333.63 g	3.5%= 48.37 g	0% = 0 g
3	93.5% = 1292.17 g	3.5% = 48.37 g	3% = 41.46 g
4	90.5% = 1250.71 g	3.5% = 48.37 g	6% = 82.92 g
5	87.5% = 1209.25 g	3.5% = 48.37 g	9% = 124.38 g

2.2. Methods

2.2.1. Experimental design for sample preparation

The mass amount of the matrix required for a single run of casting was determined by calculating the volume of each test sample using simple formulas based on density times volume. For all samples, it is calculated in similar ways. For this study, 6.5 kilograms of Al6061 alloy matrix, 300 grams of quartz, and 320 grams of nano aluminum oxide were used to prepare the hybrid composite specimen. Overall, the passage effectively explains the methodology used to determine the mass amount of the components for the hybrid composite specimen, providing clarity and context for the study.

2.2.2. Sample preparation

The stir casting method of fabrication was utilized to develop the hybrid metal matrix composite. Due to the fact that whenever ceramic particles are added to melted metals, since the density of the ceramic is higher than that of aluminum, the ceramic particles will segregate at the bottom of the melt

(Arunachalam et al., 2019; Kumar, 2017). In order to prevent this scenario, stir casting is used. The four-blade stirrer was made from chrome-plated stainless steel in order to prevent the melting of the stirrer blade and was powered by a Nama 21 steeper motor, the stirring speed and time of which were controlled by the Arduino Mega microcontroller.

The preheated Al_2O_3 particles were first sintered at 500°C for activation and to remove any moisture if present in the particles in order to prevent porosity and added to the molten metal at a constant feed rate in the order of 5% in each cast, and after the addition of nano aluminum oxide, the 45 μm particle size quartz powderwas added to the aluminum and aluminum oxide mixture at a constant feed rate in the order of 3%, 6%, and 9% by weight of the Al alloy matrix. The molten aluminum alloy matrix composite was stirred continuously for 5 minutes at a stirring speed of 400 rpm to distribute the reinforcements uniformly inside the matrix phase using a especially speed-controlled stirrer. Then the molten metal is poured immediately into the metallic mold. After solidification, the mold is splinted and the specimen is taken out. finally different machining operations such as turning, milling and drilling were performed to produce ASTM standard sample for testing. The procedure was repeated three times in the same manner to get a different percentage of the reinforcement. Figure 1 depicts fabrication of the composite starting from preheating the reinforcement to machining of the sample to standard ASTM samples.

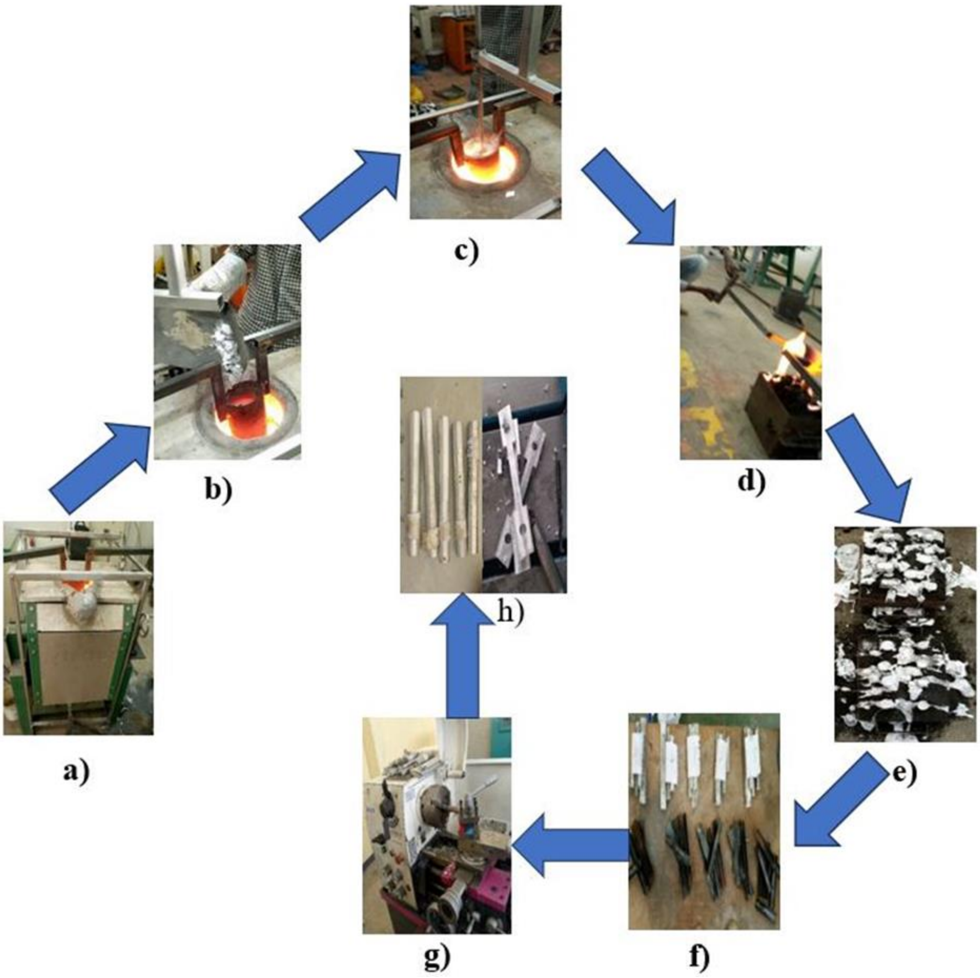


Fig. 1. Fabrication of the metal matrix composite: a) heating the empty crucible in the furnace at 500˚C, b) adding the aluminum matrix in the crucible, c) after adding the reinforcement on molten Al 6061 alloy then stirring of the melt, d) pouring of the melt in to the mold, e) cooling of the melt in the mold, f) removing the cast from the mold, g) machining, h) machined samples.

Both physical and mechanical property characterizations are performed to investigate the effect of the reinforcing ceramic particles on the developed hybrid metal matrix composite, which is presented below.

2.2.3. Physical property characterization

The physical property test includes density (theoretical and experimental) and porosity calculation.

1. Theoretical density

The theoretical density of composite can be calculated from the rule of mixture (Kala et al., 2014) as given in equation (1).

$$\rho_c = \rho_r \times V_r + \rho_m \times V_m \tag{1}$$

For hybrid reinforced composite the theoretical density can be re written as in equation (2).

$$\rho_c = (\rho_{r1} \times V_{r1} + \rho_{r2} \times V_{r2}) + (\rho_m \times V_m) \tag{2}$$

where: ρ_c is density of the composite, ρ_r is density of the reinforcement, ρ_m is density of the matrix, V_{r1} is volume fraction of the first reinforcement, V_{r2} is volume fraction of the second reinforcement, V_m is volume fraction of the matrix.

2. Experimental approach

The experimental approach to density computation was performed by using the Archimedes principle. According to the Archimedes principle, the density of the material will be determined by measuring the mass of the specimen in air and submerging the specimen in distilled water, and then the mass of the displaced fluid will be measured. The density of the material will be computed from the given formula (Kala et al., 2014; Singh & Chauhan, 2018). That is shown by equation (3).

$$\rho_c = \frac{M_a}{M_a - M_l} \times \rho_d \tag{3}$$

where ρ_c is density of the composite, M_a is mass of the specimen in air, M_l is mass of the displaced fluid and ρ_d is density of distilled water at 20°C (0.998 g/cm^3).

3. Percent porosity analysis

The basic objective of density computation is in order to investigate the porosity level in the manufactured compositespecimen. It can be estimated by comparing the experimental density with the theoretical density. Porosity in cast metal matrix composite play crucial role in controlling the mechanical properties of the fabricated composite material. Percent porosity (P) of a composite can be calculated by the help of equation (4) (Singh & Chauhan, 2018).

$$P = \frac{\rho_{\text{actual}} - \rho_{\text{theoretical}}}{\rho_{\text{theoretical}}} \times 100\% \tag{4}$$

2.2.4. Mechanical property characterization

The mechanical property test includes hardness test, impact test, compression test and high temperature creep test.

1. Hardness test

The hardness of a material is usually determined by pressing an indenter into its surface that is precisely dimensionedand loaded, and then the depth of the indentation gives the hardness of that specific material. But the depth of indentationis inversely proportional to the hardness of the material. For the current study, the hardness of the material is measuredusing Rockwell hardness testing machine as per scale B because the material is soft compared to other materials such as steel and cast iron (Prasad et al., 2014). To get a well-defined indentation, the aluminum matrix composite surface should be flat and smooth. Smooth cylindricalsamples are prepared as per the ASTM E23 standard with a specimen diameter of 15 mm and a 25 mm length. During the test, the load is kept constant for a specified time of 15 seconds. The prepared composite samples for the hardness test are shown in Fig. 2a.

2. Compression test

A compressive strength test is a method used for determining the behavior of the aluminum metal matrix composite material under a compressive load. It is one of the basic properties of a material, which is the ability to resist deformation by applied compressive load. In this experiment, the material specimen was subjected to a gradual increasing compressive loading that was applied uniaxial along the long axis of the specimen at a constant compressive strain rate until failure. The compressive specimen was made according to ASTM E9-09 standard. Theexperimental test was conducted on universal testing machine (UTM) at room temperature with a deformation rate of 2 mm/min. Square and circular cross-section specimens were used with different volume fractions of the reinforcement material. The specimen for the compressive test has a diameter of 13 mm and a height of 22 mm and has an aspect ratio of 1.7, which is machined from the cast specimen. The test samples are shown in Fig. 2b.

3. Impact test

The impact resistance of a material determines the ability of the material to absorb energy without cracking. This testis very important for automotive brake disc material because the brake disc should absorb the energy during the braking action by the brake pad without cracking. The impact test for the current experimental investigation is carriedout using a Charpy impact testing machine. The specimens were prepared from the casting materials and machined asper ASTM E-23 standard size. The specimens have a square cross section which is prepared as per ASTM E-23 standard size (Muraliraja et al., 2019). The dimension of the V-notch is 2 mm depth with angle of 45°. The prepared composite samples for impact test are shown in Fig. 2c.

4. High temperature creep test

Creep resistance of a material determines its ability to withstand the highest operating loads at elevated temperatures (Singh & Chauhan, 2018). The high temperature creep resistance property of a material is a significant index to determine the elevated temperature performance of the material or part (Prasad et al., 2014). Creep resistant materials are used in machine parts and facilities operated at higher temperatures, such as automotive engine parts and brake system components. A constant stress tensile creep technique was performed on the metal matrix composite sample to quantify the macro-creep behavior of the aluminum alloy on a SUST-D5 creep testing machine (SUST, Zhuhai, China) with an assisting furnace. The creep specimen was machined to a gauge length of 50 mm. The creep test samples were shown in Fig. 2d. The creep temperature was 360°C to obtain an aluminum alloy with high strength and fine precipitates.

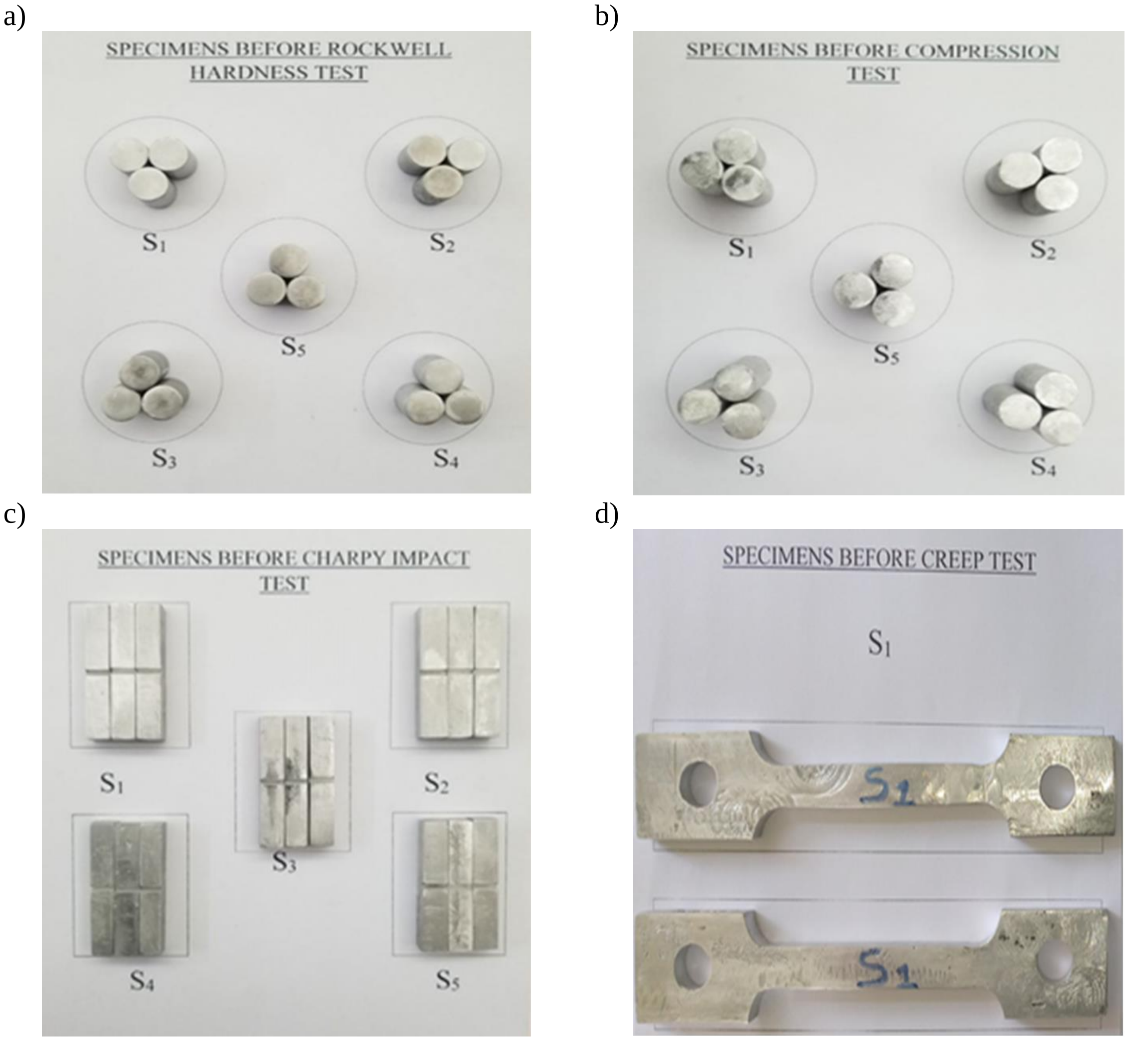


Fig. 2. Composite samples for: a) hardness test, b) compression test, c) impact test, d) creep test.

3. Results and discussion

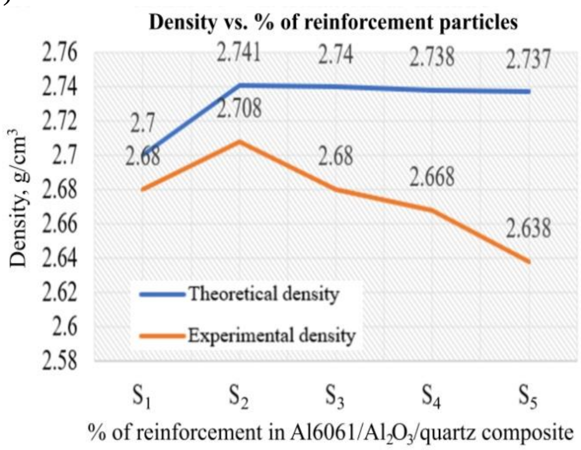
This section of the study presents the result obtained from the different mechanical and physical tests as well as the discussion behind each test result in separate sections.

3.1. Results

3.1.1. Physical property test

The results of the physical tests, such as density and porosity, are shown in Fig. 3. The percentage porosity demonstrates an increase as the weight percentage of the reinforcement rises. This increase in porosity can be attributed to several factors, including the presence of reinforcing powder in molten aluminum and poor nucleation at Al_2O_3 particulate sizes. These factors are primarily responsible for the increment in porosity. The minimum porosity was obtained for the 0% reinforcing composite, i.e., the unreinforced aluminum alloy.

a)



b)

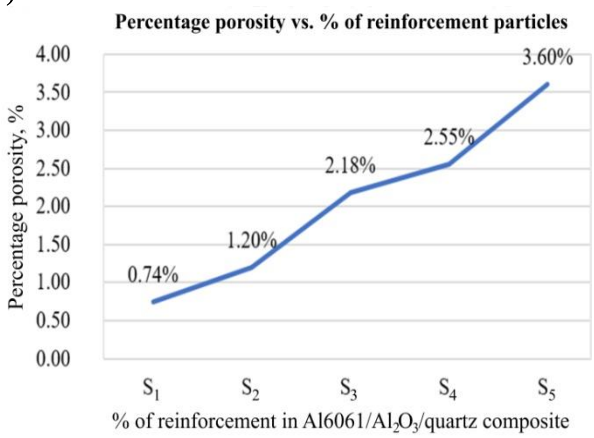


Fig. 3. a) density vs. % of reinforcement, b) percentage porosity vs. % of reinforcement.

Based on the analysis of Fig. 3, it can be concluded that the porosity level of the composite specimen increases as the volume fraction of the reinforcement particulates increases.

3.1.2. Mechanical property

In this section, hardness, compressive strength, impact, and creep tests were discussed.

1. Hardness

The results of the Rockwell hardness test are presented in Table 4 and Figure 4a. During the test, a minor load is applied to overcome the film thickness on the material's surface.

Table 4. Hardness result of the fabricated composite as a function of reinforcement.

Designation	Composite description	Rockwell hardness (HRB)			Average Rockwell hardness (HRB)
		Test 1	Test 2	Test 3	
S1	Al6061 alloy	40.5	39.2	41.4	40.36
S2	Al6061 + 3.6% Al_2O_3	47.6	48.4	46.9	47.63
S3	Al6061 + 3.6% Al_2O_3 + 5% quartz	54.7	53.2	52.7	53.6
S4	Al6061 + 3.6% Al_2O_3 + 10% quartz	57.2	57.9	58.4	57.83
S5	Al6061 + 3.6% Al_2O_3 + 15% quartz	60.7	59.1	61.5	60.43

As observed in Fig. 4a, the hardness of the composite improves with increasing weight fraction of reinforcing particles. The addition of 3.5% nano-Al_2O_3 to the Al6061 alloy enhances the hardness from 40.36 HRB to 47.63 HRB, a 18.01% increase. Further, the inclusion of quartz particles in the Al6061/nano-Al_2O_3 composite boosts the hardness from 47.63 HRB (sample S_2) to 60.43 HRB (sample S_5). Similar results were reported by Bhat et al. (2021), where the addition of 10% and 15% Al_2O_3 in the Al6061 matrix improved hardness from 90 HV to 140 HV, attributed to the incorporation of very hard Al_2O_3 particles into the soft aluminum alloy.

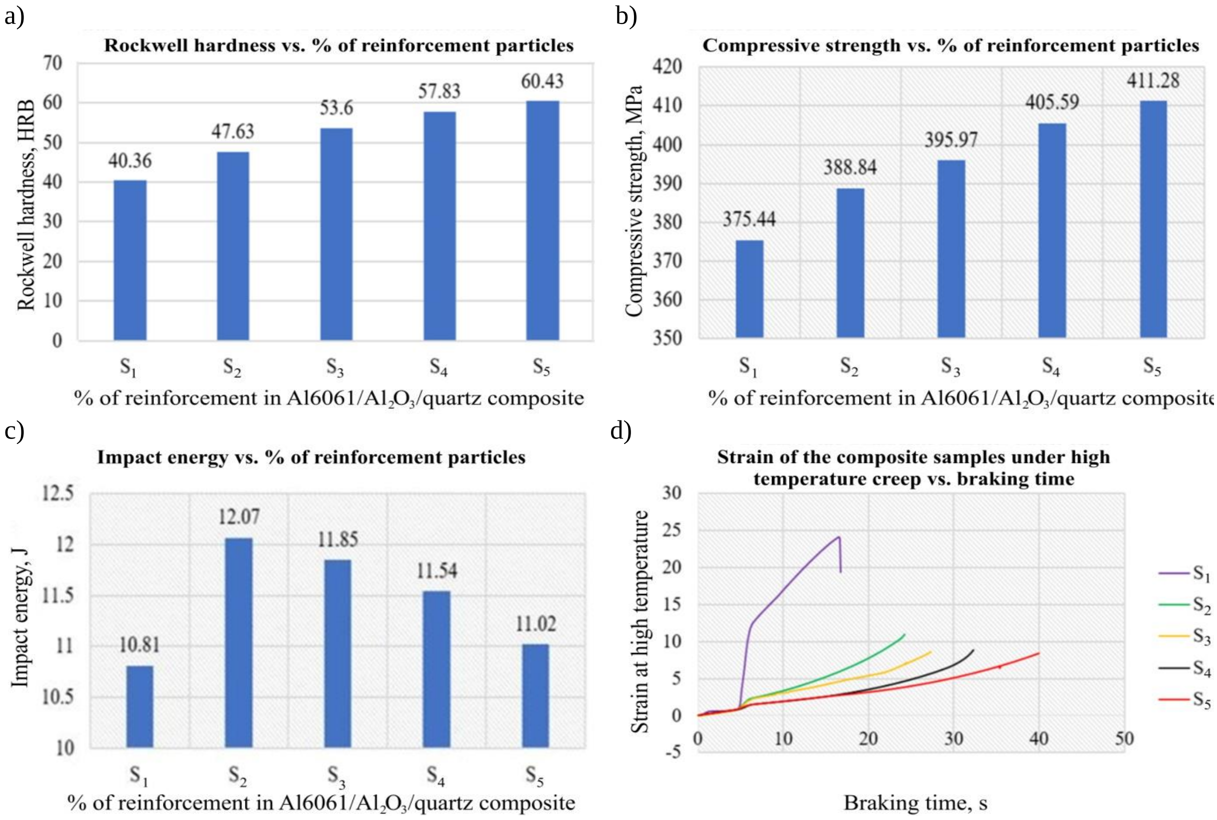


Fig. 4. The effect of percentage weight fraction of the reinforcement on: a) hardness, b) compressive strength, c) impact energy and d) high temperature strain of the hybrid composite sample.

4. Compressive strength

The compressive strength test results of the hybrid composites were displayed in Table 5 and Fig. 4b. As observed from both the table and the graphical representation, the compressive strength of the composite material improves with an increase in the percentage weight fraction of nano-Al_2O_3 and quartz particulates within the fabricated composite. Moreover, the compressive strength of the composite surpasses that of the unreinforced aluminum alloy.

Table 5. Compression test result of the fabricated composite as a function of reinforcements.

Designation	Composite description	Compressive strength, N/mm^2			Average strength, N/mm^2
		Test 1	Test 2	Test 3	
S1	Al6061 alloy	375.42	374.68	376.21	375.44
S2	Al6061 + 3.6% Al_2O_3	389.81	387.30	390.22	388.84
S3	Al6061 + 3.6% Al_2O_3 + 5% quartz	396.32	395.51	396.07	395.97
S4	Al6061 + 3.6% Al_2O_3 + 10% quartz	405.51	407.54	403.72	405.59
S5	Al6061 + 3.6% Al_2O_3 + 15% quartz	411.02	409.72	413.11	411.28

5. Impact energy

The values of impact energy absorbed by the individual specimens, along with their corresponding trials, are listed in Table 6 and Fig. 4c. The impact strengths, presented in the table below, were calculated as the impact energy per unit contact area of the specimens.

6. Creep properties

The addition of reinforcing ceramic particles enhances the composite's high-temperature strain, as seen in Fig. 4d. The applied stress during the creep test was 10 MPa, equivalent to 250 percent of the maximum compressive pressure that would be produced under difficult braking conditions in an automobile at a maximum temperature of 360°C. In comparison to the other composite samples tested, sample S_5 exhibits the optimum material properties for various automotive applications, such as clutch and brake discs. Furthermore, this sample shows the minimum high-temperature strain compared to other composite samples.

Table 6. Impact energy absorbed by the fabricated composite as a function of reinforcements.

Designation	Composite description	Impact energy, J			Average impact energy, J
		Test 1	Test 2	Test 3	
S1	Al6061 alloy	10.82	10.46	11.15	10.81
S2	Al6061 + 3.6% Al_2O_3	12.55	11.62	11.85	12.07
S3	Al6061 + 3.6% Al_2O_3 + 5% quartz	11.77	11.90	11.88	11.85
S4	Al6061 + 3.6% Al_2O_3 + 10% quartz	11.60	11.71	11.31	11.54
S5	Al6061 + 3.6% Al_2O_3 + 15% quartz	10.08	10.18	9.82	10.02

The same result was reported by Sivaram et al. (2015), who fabricated LM25 reinforced with zirconium dioxide particles to investigate the creep behavior of the composite. The test's results demonstrate that the addition of reinforcing ceramic particles improves the creep property of the composite, with the author concluding that this improvement was achieved due to the uniform distribution of the reinforcing particles in the matrix phase.

3.2. Discussion

The finding of the porosity study aligns with the results reported by Prasad et al. (2014), who observed a similar increase in porosity with an increase in the volume fraction of reinforcing particulates. Bhat et al. (2021) reported that the formation of porosity in aluminum metal matrix composites is mainly due to hydrogen gas in the melt, the higher amount of reinforcing particles in the melt, and the stirring process, which leads to an increment of air bubbles in the contact surface area between the matrix alloy and the reinforcement particulates. According to Shankar et al. (2018), the acceptable limit of porosity level in metal matrix composites is between 2% and 4%. As observed in the current study, the percentage porosity varies from 0.74% to 3.6%, which falls within the accepted limit. According to AnandhaKumar et al. (2021) the incorporation of a hard ceramic phase in an aluminum metal matrix composite always improves its hardness by hindering dislocation movement in the matrix. However, the current experimental investigation suggests that the addition of quartz particulate in the Al6061/nano Al_2O_3 composite initially improves hardness with a higher percentage increment. However, as more quartz particulate is added, the hardness value reaches a certain point and then declines due to the formation of brittle phase in the matrix as a result of the quartz reinforcement. Similar improvements in compressive strength were reported by Gnaneswaran et al. (2022) and Kumar et al. (2018), who stated that the addition of 9% Al_2O_3 to Al7075 improved the alloy's compressive strength by 70.61%. The author attributed this enhancement to the Al_2O_3 particles acting as barriers to dislocation in the microstructure of the composite, effectively resisting deforming stress and increasing the compressive strength. Likewise, Kaviyarasan et al. (2018) fabricated an aluminum metal matrix composite with an Al6061 matrix and Al_2O_3 as reinforcement. The author reported that adding 3% Al_2O_3 by mass to the matrix alloy enhanced the compressive strength from 554 N/mm^2 to 644 N/mm^2. This improvement indicates a transformation of the ductility behavior of the Al6061 matrix aluminum alloy to a more brittle nature, resulting from the incorporation of reinforcing hard ceramic Al_2O_3 particles into the soft ductile aluminum alloy. As observed from Table 6 and Figure 3(c), the impact energy absorbed by some of the fabricated composites (S_2, S_3, S_4, S_5) is slightly higher than that of the base alloy, but the improvement is marginal. Interestingly, sample S_5 exhibits the lowest impact energy among all the composite samples due to the fact that incorporation of more ceramic particles with in a matrix phase result in the formation of brittle phase. The maximum percentage improvement in impact energy is 11.65%, observed for sample S_2, attributed to the addition of 3.5% nano-Al_2O_3. The improvement is achieved due to uniformly distribution of small amount of reinforcing particles within the matrix phase. The high temperature creep strength of the developed composite show an increase with increase in reinforcing particles, same result was reported by Sivaram et al. (2015), who fabricated LM25 reinforced with zirconium dioxide particles to investigate the creep behavior of the composite. The test's results demonstrate that the addition of reinforcing ceramic particles improves the creep property of the composite, with the author concluding that this improvement was achieved due to the uniform distribution of the reinforcing particles in the matrix phase.

4. Conclusions

Al6061/nano Al_2O_3/quartz hybrid composite materials samples were prepared using stir casting methods for the first time. Then, mechanical properties (hardness, compressive strength, creep, and impact energy absorption) and physical properties (porosity and density) were studied. From the study, the following points are concluded.

- The porosity level of the composite specimen increases as the volume fraction of the reinforcing particulates increases, due to the increment of air bubbles in the contact surface area between the matrix alloy and the reinforcement particulates.
- The Rockwell hardness of the hybrid composite was found to increase linearly with the addition of hard ceramic reinforcing particles. Furthermore, the results reveal that the addition of quartz particles improves the material's resistance to indentation, with the maximum hardness value of 60.43 HRB recorded for sample S_5 (3.5% nano-Al_2O_3 + 9% quartz).
- The compressive strength test of the hybrid composite shows that the addition of quartz particles linearly increases the compressive strength of the composite, similar to the hardness test. However, as the weight percentage of the reinforcing particles increases within the composite, the percentage increase in compressive strength decreases. The maximum compressive strength value of 411.283 N/mm^2 was recorded for sample S_5 (3.5% nano-Al_2O_3 + 9% quartz).
- Upon adding reinforcing quartz particles up to 6%, the impact energy absorption capacity of the hybrid composite improves. However, adding quartz above 6% drastically reduces the impact energy-absorbing capacity of the composite material. For 9% quartz particle addition, the impact energy of the composite is even lower than that of the base aluminum alloy matrix.
- The addition of reinforcing ceramic particles improves the high-temperature strain of the composite samples. Sample S_1 shows the minimum elongation with short braking or deformation time compared to the other samples. However, sample S_5 (3.5% nano-Al_2O_3 + 9% quartz) reveals the maximum long braking or deformation time. Based on the results of the mechanical property tests, the developed hybrid composite sample S_5 (3.5% nano-Al_2O_3 + 9% quartz) can replace the Al6061 matrix in different engineering applications with improved properties. The creep property of the developed new hybrid metal matrix composite (Al6061/nano Al_2O_3/quartz) was studied for the first time; there is no published research article on studying the high-temperature creep property of Al6061/nano Al_2O_3/quartz. This research provides new insight into studying the creep properties of hybrid metal matrix composites for different engineering applications.

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Badanie Właściwości Mechanicznych i Fizycznych Hybrydowego Kompozytu Al6061/Nano Al_2O_3/Kwarc Wytwarzanego Metodą Odlewania z Mieszaniem

Streszczenie

Stopy aluminium są szeroko stosowane w różnych obszarach zastosowań inżynieryjnych, takich jak przemysł lotniczy, motoryzacyjny i morski. Właściwości stopów aluminium wymagają udoskonaleń, aby zwiększyć zakres ich zastosowań. Celem badań była poprawa właściwości fizycznych i mechanicznych stopu aluminium Al6061 poprzez wzmocnienie nanocząstkami Al_2O_3 i cząstkami mikrokwarcu. Badania skupiały się przede wszystkim na badaniu wpływu cząstek kwarcu na właściwości mechaniczne i fizyczne kompozytu hybrydowego Al6061/nano Al_2O_3/kwarc. Kompozyt hybrydowy opracowano techniką odlewania z mieszaniem, zmieniając udział wagowy cząstek kwarcu na 3%, 6% i 9%, utrzymując natomiast stały udział wagowy nanocząstek Al_2O_3 (3,5%). Do oceny właściwości kompozytu, przygotowano próbki testowe zgodnie z normami ASTM E9-09 i ASTM E23 dotyczącymi odpowiednio twardości, wytrzymałości na ściskanie, pełzania i pochłaniania energii uderzenia. Wyniki badań wykazały, że dodatek 9% kwarcu i 3,5% nanocząstek Al_2O_3 spowodował poprawę wszystkich właściwości mechanicznych i fizycznych osnowy, z wyjątkiem udarności. Na podstawie uzyskanych wyników, opracowany hybrydowy materiał kompozytowy może być zalecany do lekkich części zamiennych do samochodów, takich jak tarcze hamulcowe i sprzęgła.

Słowa kluczowe: stop aluminium Al6061, kompozyt hybrydowy, nano Al_2O_3, kwarc (SiO_2), odlewanie z mieszaniem