



Effect of Nano-SiO₂ on the Mechanical Properties of AA6061 Stir-cast Composites

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ABSTRACT

Aluminum metal matrix composites (AMMCs), which are promising lightweight engineering materials, possess exceptional properties. Several industries make use of AMMCs, especially in sectors such as automotive, aerospace, marine, and defense, where lightweight structures with enhanced mechanical performance are essential. Innovative technological developments have enabled the incorporation of nanoscale reinforcements into aluminum alloy matrices. Compared with microscale reinforcements, nanoscale reinforcements provide superior enhancements to the properties of the base matrix. This study focuses on AA6061 composites synthesized using the stir-casting technique and reinforced with nano-silicon dioxide (nano-SiO₂) particulates. The weight fraction of nano-SiO₂ was varied at 0, 2, 4, 8, and 12 wt.%. Mechanical properties, including tensile, compressive, and impact strengths, as well as micro-Vickers hardness, were measured for both the composites and the fabricated plain alloy. The results indicated that increasing the reinforcement content enhanced the mechanical properties of the base matrix up to an optimal level.

Keywords: AA6061; Nano-SiO₂; Mechanical properties; Liquid metallurgy; Stir casting.

1. INTRODUCTION

The superior characteristics of aluminium and its composites subjected to rubbing or abrasive environments make them suitable for applications including transportation, aviation, and defense, as their value lies mainly in durability and low friction (Sharma *et al.* 2024; Wu *et al.* 2024; Sivamaran *et al.* 2021). Engine parts, durable lightweight structures, aircraft components, and mechanical linkages are all manufactured using AMMCs because of their greater strength and dimensional stability under varied temperatures. Additionally, their resilience makes them ideal for armors, casings, and vehicle components (Ramesh *et al.* 2025a; Ramesh *et al.* 2025b). Many researchers have demonstrated that AMMCs with reinforcements exhibit better features and can be ideal for multiple engineering applications. The main problems that arise when reinforcing AMMCs are the reaction between the matrix and reinforcement material, the amount of reinforcement to use, and the distribution of the reinforcement (Sundar *et al.* 2019; Kar *et al.* 2024).

Powder metallurgy, stir casting, and other methods are used for synthesizing AMMCs and to enhance their base characteristics. Secondary treatments

are analyzed for their roles in improving the microstructure and overall functionality of as-fabricated composites (Orhadahwe *et al.* 2020; Pooja *et al.* 2025). The significance of strategies to improve the characteristics of AMMCs and the detailed essential elements of diverse synthesis methods and their subsequent post-processing approaches have been discussed in many earlier works. Stir casting technology (SCT) is a cost-effective and widely used method for producing AMMCs, enhancing the mechanical strength of the composites. Multiple research studies have investigated the methodology, the mechanics of agitation, and the variables influencing the dispersion of reinforcements. The interaction of ceramic particles with molten aluminum has been well investigated regarding aggregation, porosity, and poor wettability (Kumar, 2017; Sankhla *et al.* 2022). Owing to its many uses, advantageous characteristics, and adaptability, AA 6061 is a commonly used material for the fabrication of AMMCs. With various ceramic reinforcements such as carbides, oxides, and nitrides, the most popular and inexpensive method for producing AA 6061 composites is SCT. Increasing the number of reinforcements usually improves the properties. The possibility of using

agricultural and industrial waste as reinforcements has also been studied. The potential usage of nanocomposites with AA 6061 has universal applications, suggesting that it will be the focus of future studies (Kareem *et al.* 2021).

Bonding action between the ceramic and aluminum at the interface on grain movement allows AMMCs to endure higher external stresses. According to the experimental findings, the addition of zirconium silicate (ZrSiO_4) and titanium diboride (TiB_2) significantly improves the properties, showing increases of 52% and 125%, respectively (Vargas *et al.* 2024). Extensive trials were conducted to study the characteristics of the material, and found that the addition of SiC made it much harder than the base AA6061. Bhat and Kakandikar (2019) used pin-on-disc tribometry to determine how resistant the SiC-reinforced metal was to wear. Different loads and speeds were used in the tests. An analysis was conducted to examine how load and RPM affected the wear rate. The new Al6061 + SiC mix wore out much more slowly than the pure aluminum. The beneficial results of the study show that focused strengthening with SiC improves the alloy's surface qualities while keeping its general strength. Ravi *et al.* (2015) fabricated AA6061/ B_4C using varying reinforcement weight percentages through stir casting. The presence of B_4C particles was found in the composite and distributed uniformly with reduced grain size. Microhardness increased from 62 to 68 HV as the wt.% increased.

Sadanand *et al.* (2023) studied AA6061 with the combined effects of age hardening, low-temperature thermomechanical treatment, and copper reinforcements. The age-hardened and treated composites demonstrated superior properties compared to the as-cast composites. The research revealed an improvement in the composite's hardness and strength with increasing deformation, as well as a decrease in the time required to reach peak hardness. Prabhu *et al.* (2019) found that the mechanical characteristics improved by increasing the amount of rutile particles. However, the ductility was negatively affected. Adding 1, 2, 3, and 4% rutile particles to the matrix made them 15%, 24%, 36%, and 44% harder than the base material. Increased content of rutile particles, relative to the base material, increased the composite's UTS by 5%, 10%, 14% and 7%, respectively. At concentrations more than 3 wt.%, rutile particles showed a tendency to clump together and exhibited uneven distribution, reducing the composite's tensile strength.

Wubieneh *et al.* (2022) examined the bonding of AA 6061 to glass particles. The produced composite, which is made up of 80% AA 6061 and 20% glass powder, has a hardness increase of 23.94% and a UTS increase of 56.6% relative to the base material, owing to the strong harmonic bonding interactions and favorable density difference.

Glass powder is inexpensive and can act as a reinforcement for AMMCs, enhancing their mechanical properties. At 1 wt.% selenium, the mechanical properties of Al 6061 were enhanced by 32%, 29.5%, and 25% in tensile, flexural, and compressive strengths, and 25% in Brinell hardness. The mechanical qualities were found to be diminished at 1.5 wt.% selenium, suggesting that the ideal range for selenium content is between 1 and 1.5 wt.%. (Tirumala *et al.* 2024).

Hariharan *et al.* (2023) reported that composites made of Al 6061, SiC, and MgO had a higher Brinell hardness than the parent material. The tensile strength increased with reinforcement additions up to 6% and then decreased. At 6% SiC and MgO reinforcement, the compressive and impact strengths increased compared to those of the monolithic alloy. Reinforced AMMCs have superior characteristics (improved properties and lower thermal expansion coefficients) because the reinforced components are dispersed throughout the matrix, and the material is not homogeneous. Sharma *et al.* (2021) suggested that by careful choice of production procedures, economically viable AMMCs can be synthesized.

Yuvaraj *et al.* (2023) synthesized two variants of AA6061 composites (one with SiC reinforcements and the other with SiC and aloe vera particles). Aloe vera particulates increased the composite's wear performance by creating a thin lubricating layer, while the dense SiC ceramic particles provided load support. Many characteristics of aloe vera-reinforced composites were determined to be compatible with those of SiC.

Composites with nano-reinforcements have an exceptionally high aspect ratio. Proper utilization of nano-sized strengthening substances may enable AMMCs to circumvent several deficiencies, including suboptimal machinability, structural inconsistency, limited wear resistance, and insufficient mechanical stability (Malaki *et al.* 2021). The stir-casting process has only been employed in a limited number of experiments to generate AA6061 nano-MMCs. A stir-casting technique was used in this work to manufacture composites that had varying weight percentages of nano- SiO_2 particles. A comparison was made between the pure matrix and the nano- SiO_2 -reinforced matrix in terms of their mechanical properties using experimental methods.

2. EXPERIMENTATION

The primary alloying components of AA 6061 are silicon and magnesium. This material is selected owing to its excellent mechanical features and exceptional welding ability. The formation of Mg_2Si in the aluminum alloy contributes to the strengthening of AA 6061, which belongs to the Al-Si-Mg alloy system (Mohanavel *et al.* 2018). Table 1 presents the elemental composition of AA6061. This study examined AA6061

and its composites reinforced with nano-SiO₂ particles (0, 2, 4, 8, and 12 wt.%) produced through the conventional stir-casting process.

Table 1. Chemical constituents of AA6061

Element	Symbol	Percentage
Silicon	Si	0.80
Iron	Fe	0.67
Copper	Cu	0.15
Magnesium	Mg	0.95
Chromium	Cr	0.32
Zinc	Zn	0.23
Aluminium	Al	Balance

Nano-silica, an inexpensive and readily available reinforcement (Fig. 1), retains its strength even at elevated temperatures and exhibits excellent structural and abrasion-resistant characteristics. Figures 1 and 2 display the SEM and EDAX images, whereas Tables 2 and 3 present the chemical elements and properties of nano-SiO₂, respectively. Silica, widely used as a filler in composites, also serves in engineering applications for producing porous ceramics that function as thermal barriers and high-temperature dielectrics. Silica enhances the strength and hardness of ceramics. Composite insulation, water and fire resistance, and ultraviolet shielding are some additional applications enabled by nanostructured materials. When chemically modified from a hydrophilic to a hydrophobic state, silica nanoparticles can achieve super-hydrophobic characteristics, enabling their use in a wide range of engineering applications (Dayanand *et al.* 2024).

The graphite crucible melts the AA6061 ingot at 820 °C for 35 min in a muffle furnace under an inert argon atmosphere (Fig. 3). Nano-SiO₂ particles were dehydrated in a muffle furnace for 45 min at 900 °C. This heat treatment removes moisture and facilitates better bonding between the reinforcement and the matrix. Additionally, the addition of 2 wt.% pure magnesium reduced oxygen on the dispersoid surface, thinning the gas layer and improving wetting of the reinforcement.

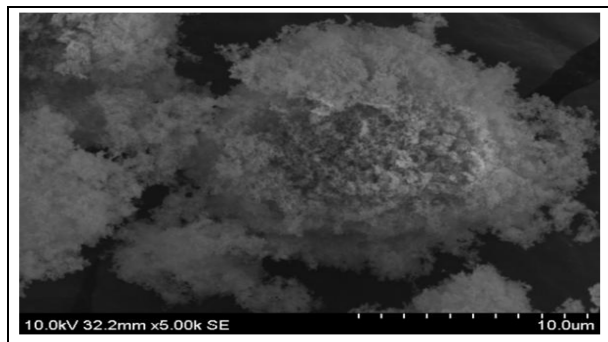


Fig. 1: SEM image of nano-SiO₂ particles

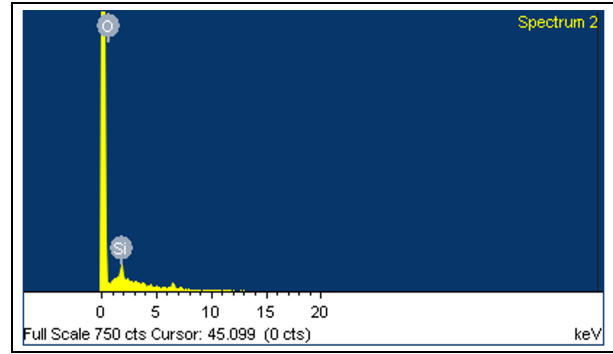


Fig. 2: EDAX image of nano-SiO₂

Table 2. Chemical elements of nano-SiO₂

Element	Weight %	Atomic %
O K	72.40	82.16
Si K	27.60	17.84

Stir casting (15 min at 400 rpm) ensured uniform dispersion of nano-SiO₂ in the composites, as the multi-blade stirrer remained in continuous motion within the furnace. The molten mixture was then poured into a preheated metal mold at 600 °C. The cooled composite samples removed from the mold are shown in Fig. 4.



Fig. 3: Muffle furnace and stirrer blade for SCT



Fig. 4: Synthesized composites of AA6061 with nano-SiO₂

2.1 Experimental Testing

Universal testing equipment was used to conduct tensile and compression tests. Samples are cut and shaped in accordance with ASTM E8 and ASTM E9 standards using a CNC machine. In tensile testing of composites, all samples were extracted from the core of the cast billets. Testing was performed on two samples of each composite, and the average outcomes were documented. Securing the specimen in a Universal Testing Machine is a crucial step in obtaining accurate and reliable measurements of the material's properties. Effective clamping stabilizes the specimen and results in accurate outcomes

Table 3. Physical and mechanical properties of nano-SiO₂

Properties	Units	Value
Density	g/cm ³	2.65
Melting Point	°C	1710
Modulus of Rupture	MPa	Up to 200
Youngs Modulus	GPa	Up to 74.8
Poisson's Ratio	-	Up to 0.19
Thermal conductivity	W/mK	Up to 1.5

Impact specimen sizes for the Izod impact test were 10 × 10 × 55 mm. According to ASTM E-23 standards, specimens were machined precisely to the required length, breadth, and thickness with a single V-notch. Materials with varying degrees of hardness were measured using the Vickers hardness test. A diamond-shaped indenter was pressed into the surface of the material under a specific force of 100 kgf in order to conduct a Vickers hardness test. All hardness test specimens were precisely proportioned according to the standards set forth by ASTM E384, with a 45-second dwell time for every sample. The hardness value reported is the average of three measurements taken at different locations.

3. RESULTS AND DISCUSSION

3.1 Ultimate Tensile Strength and Elongation

Fig. 5 illustrates the tensile strength of AA6061 with different nano-SiO₂ particle combinations. The 8 wt.% nano-SiO₂ composite showed a maximum tensile strength of 219 MPa, which exceeded that of pure AA6061 by 90.43%. Composites reinforced by nano-SiO₂ also mitigated the degradation of AA6061. Nanoparticles reduced dislocation rates, thereby enhancing the composite's strength and stiffness. This interface facilitates effective load transfer between AA6061 and nano-SiO₂. The composite's tensile strength increased with nanoparticle addition up to 8 wt.%. However, in 12 wt.% composites, the aggregation of nanoparticles led to dislocation accumulation, reducing ductility and causing premature failure.

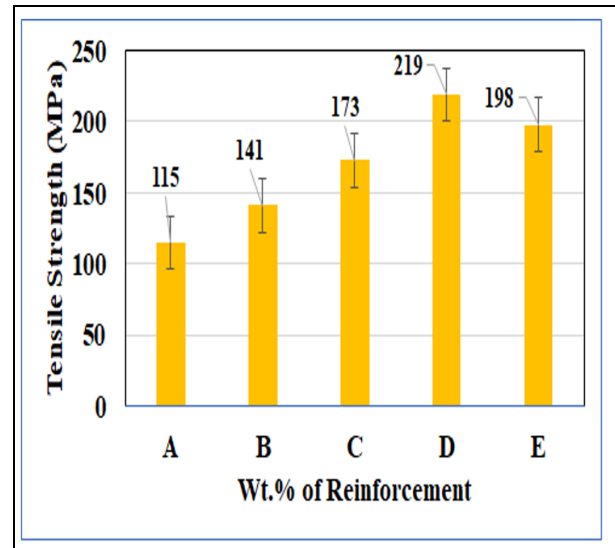


Fig. 5: Tensile strength of the composite samples

Fig. 6 illustrates the results of elongation obtained on as-cast AA6061 and composites made of nano-SiO₂. There is a linear relationship between the percentage of elongation and the concentration of nano-SiO₂ particles in the composite, with elongation decreasing as particle content increases. The incorporation of nano-SiO₂ particles into the composite reduces elongation due to their increased load-bearing capacity. When no nanoparticles were added, the elongation was 8.9%. Adding 8 wt.% nanoparticles decreased the elongation to a minimum of 4.1%, as the nanoparticles restrict dislocation motion. The transparent interface between AA6061 and nano-SiO₂ allows for the effective load transmission from the matrix to the reinforcement.

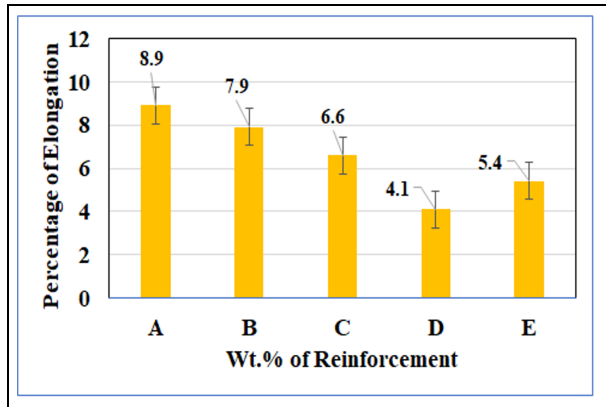


Fig. 6: Elongation test results of the composite samples

3.2 Vickers Microhardness

According to Fig. 7, the addition of nano-SiO₂ to AA6061 increases its microhardness. With 8 wt.% nanoparticles, the microhardness reached 89 HV, representing a 41.26% increase over pure AA6061. The nanoparticles impede plastic deformation by restricting indentation, while their uniform distribution and interaction within the matrix further enhance hardness.

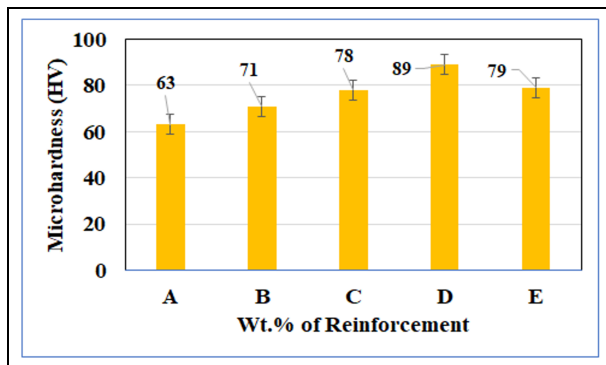


Fig. 7: Microhardness of the composite samples

3.3 Compression Strength

Fig. 8 shows that adding nano-SiO₂ has a major effect on the compressive strength of composites. Alloys with nanoparticles are stronger than the base AA6061. Adding 8 wt.% of nanoparticles to AA6061 increased its compressive strength to 289 MPa, which is 61.45% higher than that of pure AA6061. However, at higher nanoparticle contents, the mismatch in thermal expansion coefficients between AA6061 and nano-SiO₂ increases dislocation density within the composite, which can reduce its mechanical performance.

3.4 Impact Energy

Fig. 9 illustrates the effect of nano-SiO₂ addition on the impact energy of the composites. Pure AA6061 exhibited an impact energy of 12.28 J, while composites

with 2, 4, 8, and 12 wt.% nano-SiO₂ showed impact energies of 10.42, 8.82, 9.2, and 7 J, respectively. Composites devoid of nanoparticles exhibited 25% higher impact energy than those containing 8 wt.% nano-SiO₂. The presence of nanoparticles restricts matrix deformation under sudden loads, resulting in reduced impact energy with higher nanoparticle content.

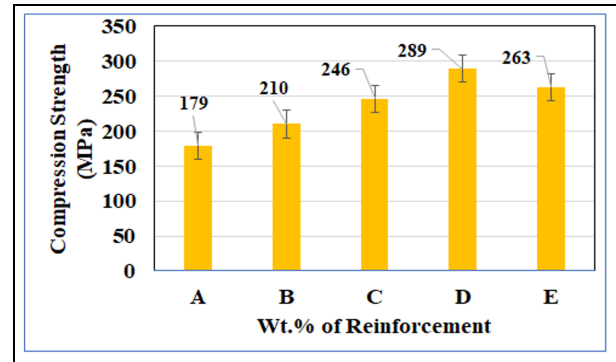


Fig. 8: Compressive strength of the composite samples

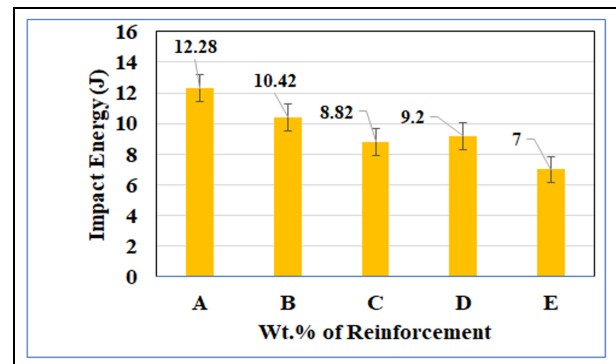


Fig. 9: Impact energy of the composite samples

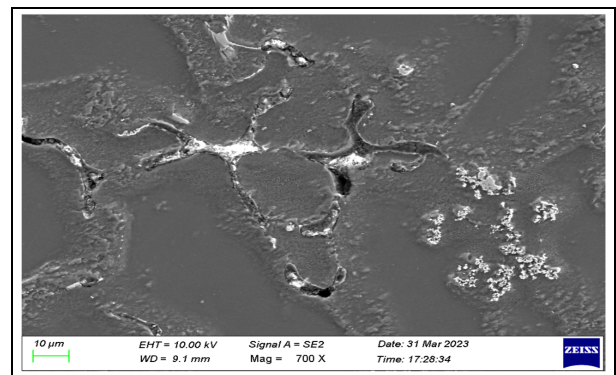


Fig. 10: SEM micrograph of AA6061 composite containing 12 wt.% nano-SiO₂

When nano-SiO₂ particles clump together in 12 wt.% composites, gaps (voids) form, increasing brittleness and reducing the material's ability to undergo plastic deformation (Fig. 10). This further lowers the impact energy.

4. CONCLUSION

The liquid metallurgy stir-casting technique was used to fabricate AA6061 composites, and their mechanical properties were evaluated. The results indicate that AA6061 reinforced with 8 wt.% nano-SiO₂ exhibits superior properties compared with other reinforcement levels. However, adding more than 8 wt.% nano-SiO₂ leads to a deterioration in properties, making the material less tough than unreinforced AA6061. This decline is attributed to increased nanoparticle agglomeration within the matrix at higher reinforcement levels.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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