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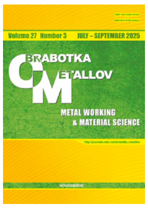

Investigation on the mechanical properties of stir-cast Al7075-T6-based nanocomposites with microstructural and fractographic surface analysis

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ABSTRACT

Introduction. Aluminum-based metal matrix composites (*MMCs*) have garnered considerable attention recently due to their enhanced mechanical properties, making them suitable for a wide range of industrial applications. While other methods exist for incorporating reinforcements into the base metal, stir casting is a particularly efficient process as it promotes a more uniform distribution of reinforcement particles throughout the matrix. *The purpose of this work.* It has been demonstrated that adding silicon carbide (*SiC*) reinforcements to alloys from the *7XXX* series enhances their fatigue strength. The impact of *SiC* reinforcements on the mechanical properties of *A356* composites, such as elongation, compressive strength, tensile strength, and hardness, has also been investigated. However, there is a need for more research on how hybrid reinforcement particles affect the mechanical properties of *Al7075-T6* alloy. **Methods.** Considering the broad application spectrum of aluminum matrix composites (*AMCs*) in the automotive and aerospace sectors, this study examines the influence of varying ratios of nano-sized *SiC* and graphene reinforcements on the hardness and tensile strength of stir-cast *Al7075-T6* aluminum alloy. The scanning electron microscopy — energy-dispersive X-ray spectroscopy (*SEM-EDS*) analysis of the composites' microstructural and fractographic surfaces is also included. The objectives of this work are to develop lightweight, high-performance hybrid metal matrix nanocomposite materials and to explore the feasibility of integrating graphene and *SiC* nanoparticles into *Al7075* alloy. Particular emphasis is placed on the discussion of the mechanical characteristics of these hybrid materials. **Results and discussion.** This study found that mechanical stirring improved the bonding, wetting, and cohesion between the reinforcements and matrix while reducing porosity. Compared to composites produced without stirring, stirred composites exhibited improved strength and toughness due to microstructural changes. The study suggests that appropriate mixing strategies can significantly impact the mechanical properties and surface morphology of *Al7075* nanocomposites. The results indicated that the hybrid reinforcement nanoparticles significantly improved both the hardness and tensile strength of the *Al7075-T6* alloy. Moreover, a distinct correlation between the ratio of silicon carbide to graphene nanoparticles and the mechanical properties of the specimens was observed. Specifically, an *Al7075* specimen reinforced with 0.5 wt.% graphene and 3 wt.% silicon carbide nanoparticles demonstrated superior hardness and tensile strength compared to unreinforced *Al7075* and other combinations of silicon carbide and graphene nanoparticles considered in this study. With a 0.5 wt.% graphene content and 1–3 wt.% *SiC* content, the *Al7075*-based nanocomposites consistently exhibited a well-defined grain structure with distinct, continuous grain boundaries. The resulting finely dispersed nanoparticles, ranging in size from 62.57 to 91.54 nm, facilitated effective load transfer, grain refinement, and impeded dislocation motion, leading to enhanced mechanical properties. An *Al7075*-based nanocomposite exhibited superior mechanical performance characterized by a dense, dimpled surface featuring uniform microvoids and minimal particle pull-out. This behavior was attributed to ductile fracture resulting from strong matrix-reinforcement bonding and efficient load transfer. Consistent with these observations, the study indicates that the mechanical behavior of hybrid *Al7075*-based nanocomposites is significantly influenced by the reinforcement ratio, particle size, and dispersion quality. This information is valuable for advanced industrial applications. The study further demonstrates that a balanced combination of graphene and silicon carbide nanoparticle reinforcements can enhance the mechanical properties of *Al7075*, emphasizing the need for further investigation into these synergistic effects.

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Introduction

Hybrid metal matrix composites (*HMMCs*) are increasingly being utilized in the automotive and aerospace industries due to their exceptional properties, including low density, high stiffness, high specific strength, and a low coefficient of thermal expansion. Composite materials are categorized into two main

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groups: matrix-based (metal, polymer, or ceramic) and reinforcement-based (particulate, fiber, or whisker). Currently, particulate metal matrix composites are widely adopted. These composites consist of a base metal (such as aluminum or magnesium) and reinforcement particles (such as silicon carbide (*SiC*), graphene (*C*), or boron carbide (B_4C), as well as natural materials like rock dust, eggshell, or jute).

Various methods are employed to incorporate reinforcements into the base metal; however, stir casting stands out as an effective technique, ensuring a uniform distribution of reinforcement particles throughout the base metal. Aluminum-based metal matrix composites (*Al-MMCs*) have garnered significant attention in recent years due to their improved mechanical properties, making them suitable for various industrial applications. The incorporation of reinforcement particles, such as silicon carbide (*SiC*) and graphene, has been shown to enhance the mechanical properties of metal matrix composites (*MMCs*). These *MMCs* have gained significant attention in recent years due to their improved mechanical and thermal properties [1].

A substantial enhancement in the material's mechanical properties is achieved by the addition of components such as graphene nanoplates (*GNPs*), boron nitride (*BN*), and vanadium carbide (*VC*), among others. For example, the hybrid *AA7075*/*GNPs*+*BN*+*VC* material exhibited superior hardness and compression strength due to the effective use of particle reinforcement [2]. Enhanced mechanical strength can also be achieved through the utilization of boride nanocrystals, such as hafnium diboride (HfB_2), which improve hardness and facilitate grain refinement [3].

Optimizing the microstructure of a material can be achieved by employing methods such as equal channel angular pressing (*ECAP*) and spark plasma sintering (*SPS*). This optimization, in turn, affects the yield strength and hardness of the material [4]. To attain optimal outcomes, it is necessary to refine grain size through hybridization and processing techniques. The enhanced grain boundary strengthening resulting from smaller grain sizes contributes to the improvement of the material's mechanical properties. Strong interfacial bonding between the matrix and reinforcements is crucial for efficient load transfer, directly influencing the mechanical performance of the composites.

Aluminum matrix composites (*AMCs*) have become increasingly popular due to the advantages they offer compared to monolithic aluminum alloys [5]. The mechanical and tribological properties of *AMCs* are influenced by several factors, including the processing methods, the type of reinforcement, the size, and the composition of the material [6]. Stir casting, friction stir processing, powder metallurgy, and spark plasma sintering are a few examples of the various manufacturing techniques available for *AMCs* [7].

Techniques such as stir casting, powder metallurgy, and friction stir processing are particularly significant in establishing a homogeneous distribution of reinforcements throughout the material. Friction stir processing effectively reduces grain size, with reductions of up to 10.3 times compared to the base alloy. This technique utilizes friction to stir the material, enhancing its mechanical properties. During friction stir processing, the uniform distribution of hybrid reinforcement particles contributes to an increase in both the hardness and compression strength of the resulting composites [2].

Powder metallurgy techniques, such as mechanical alloying and hot pressing, are used to enhance the compressive strength, elongation to failure, and microhardness of composites. Researchers have found that hot pressing yields superior mechanical properties for *AA2024*/multi-walled carbon nanotube (*MWCNT*) composites compared to other techniques, as it facilitates uniform *MWCNT* dispersion and improved connectivity across interfacial surfaces [8].

Stir casting is a cost-effective method but faces challenges with agglomeration during production. Powder metallurgy is also considered a successful approach for creating hybrid aluminum nanocomposites [5]. Nanocomposites produced via stir casting exhibit enhanced hardness and a lower wear rate. This technique enables the creation of a dense microstructure with minimal porosity, leading to improved mechanical properties in the composite [9].

Silicon carbide (*SiC*) and boron carbide (B_4C) are two examples of established materials used as reinforcements. Powders derived from agricultural waste, such as rice husk ash and coconut shell ash, can also be effectively employed. The use of these reinforcements enhances characteristics such as compressive strength, hardness, and wear resistance [10]. The incorporation of B_4C and *SiC* reinforcements into *Al6061* composites has been shown to affect mechanical properties, including hardness, tensile strength, and impact energy [11].

The addition of *SiC* reinforcements to *7XXX* series alloys has been shown to improve fatigue strength [12]. The incorporation of Al_2O_3 reinforcements into scrap aluminum alloy wheels affects porosity, hardness, ultimate tensile strength, and ultimate compressive strength [13-15]. Researchers have reviewed the effect of mixed nanoparticles in base fluids on the properties of nanofluids and machining characteristics, suggesting that nanoparticle size and concentration significantly influence nanofluid effectiveness [16-19]. Research has also explored the effect of *SiC* reinforcements on the mechanical properties of *A356* composites, including hardness, tensile strength, compressive strength, and elongation [20]. However, the effects of hybrid reinforcement particles on *Al7075-T6* alloy remain largely unexplored.

Silicon carbide and graphene offer varying benefits as reinforcement materials: *SiC* is ideal for enhancing hardness and tensile strength, while graphene excels in lightweight, high-strength applications. This study aims to investigate the influence of varying proportions of nanosized *SiC* and graphene (*Gr*) on the hardness and tensile strength of *Al7075-T6* alloy, prepared using the stir casting method. The study also examines the microstructural and fracture surface analysis of the composites using scanning electron microscopy (*SEM*) and energy-dispersive X-ray spectroscopy (*EDX*).

This research aims to create lightweight, high-performance hybrid metal matrix nanocomposite materials and explore the potential of combining *SiC* and *Gr* nanoparticles with *Al7075*, with a focus on characterizing the mechanical properties of these hybrid materials.

Materials and Design

Aluminum matrix composites (*AMCs*) reinforced with silicon carbide (*SiC*) and graphene are favored for aerospace and automotive applications due to their enhanced mechanical and tribological properties [21]. Graphene's high strength-to-weight ratio can improve property enhancement, although its poor wettability and tendency to aggregate can be limiting factors [22]. Stir casting and other methods are employed to achieve a homogeneous reinforcement distribution, which enhances the mechanical properties of *Al7075* composites [23]. In this study, *Al7075-T6* serves as the matrix material, while silicon carbide (30-50 nm) and graphene (5-10 nm) are used as reinforcements. Reinforcement materials influence the mechanical and physical properties of composites. *SiC* and graphene are preferred reinforcements for engineering applications due to their distinctive characteristics.

Silicon carbide, known for its hardness, thermal conductivity, and resistance to corrosion and chemical attack, is well-suited for high-temperature environments and enhances durability. With a density of 3.22 g/cm³ and a hardness of 2450 BHN, silicon carbide is a rigid, robust material ideal for wear-resistant applications. Graphene, with a low density of 2.2 g/cm³ and a hardness of 110 BHN, is well-suited for strong, lightweight components. Despite its lower hardness compared to SiC, graphene can be used to create flexible, high-strength composites. Graphene's tensile strength of 130 GPa surpasses that of most materials, benefiting advanced composites that require a high strength-to-weight ratio.

The mechanical properties of the cast specimens were characterized using hardness tests (*ASTM* E10) and tensile tests (*ASTM-B557*). Hardness was measured using a *Brinell* hardness tester. Tensile tests were performed on a universal testing machine (*UTM*). Scanning electron microscopy (*SEM*) was used to analyze the particle distribution patterns in the composites. Energy dispersive X-ray spectroscopy (*EDS*) was used to identify the elements present in the specimens. *SEM* and *EDS* were performed using a *JEOL JSM-IT200* model.

The experimental setup for preparing *Al7075*-based nanocomposites with varying reinforcements is depicted in Fig. 1. Initially, *Al7075-T6* ingots weighing 1.5 kg each were obtained. These ingots were then placed in a crucible within the stir casting furnace. The molten metal was heated to 750 °C and maintained at that temperature for 120 minutes. Magnesium powder (1 wt.%) was added to the molten metal to prevent oxidation. Varying combinations of graphene and silicon carbide reinforcements were then introduced into the molten metal. Before introduction, these reinforcements were preheated for 5-7 minutes.

A mechanical stirrer was used to ensure uniform dispersion of reinforcements in the molten metal for fifteen minutes. The slurry that formed on the surface of the molten metal was gradually removed to

Fig. 1. Preparation of *Al7075* specimens with varying reinforcements by stir casting

ensure sound cast specimens. Specimens with a diameter of 20 mm and a length of 250 mm were obtained. The mold was preheated for 5-7 minutes prior to pouring the molten metal to facilitate deoxidation. The chemical composition of *Al7075* is presented in Table 1. Table 2 describes the different specimens prepared with varying reinforcements using stir casting.

Hardness was measured using a *Brinell* hardness tester according to *ASTM E10*. A load of 187.50 kg was applied to the specimen using a 2.5 mm steel ball indenter for a dwell time of 20 seconds. To assess the uniform distribution of hybrid reinforcements, hardness values were measured at two different locations on the cast specimen. Tensile behavior of the nanocomposites was investigated by manufacturing and testing specimens in accordance with *ASTM B557*. Before testing in the *UTM*, the test specimen was machined according to the standard.

Table 1

Chemical composition of *Al7075-T6* alloy

Element	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	*Cr*	*Ni*	*Zn*	*Ti*	*Zr*	*Al*
wt.%	0.10	0.23	1.48	0.07	2.11	0.22	0.01	5.29	0.07	0.02	Balance

Table 2

***Al7075* nanocomposites prepared with varying reinforcements**

Specimen	Reinforcement
S1	Unreinforced *Al7075* alloy
S2	*Al7075* + 0.5% *SiC* + 0.1 % graphene
S3	*Al7075* + 0.5% *SiC* + 0.2 % graphene
S4	*Al7075* + 0.5% *SiC* + 0.3 % graphene
S5	*Al7075* + 0.5% graphene + 1 % *SiC*
S6	*Al7075* + 0.5% graphene + 2 % *SiC*
S7	*Al7075* + 0.5% graphene + 3 % *SiC*
S8	*Al7075* + 1 % graphene + 2 % *SiC*
S9	*Al7075* + 1 % graphene + 4 % *SiC*

Results and Discussion

This section presents the effects of varying ratios of nanosized *SiC* and graphene reinforcements on the hardness and tensile strength of *Al7075-T6* aluminum alloy produced via stir casting, considering the widespread use of aluminum matrix composites (*AMCs*) in aerospace and automotive applications. The microstructural and fracture surface analysis of the composites, conducted using *SEM-EDX* analysis, is also presented.

This research aims to develop lightweight, high-performance hybrid metal matrix nanocomposite materials and explore the potential of combining *SiC* and graphene nanoparticles with *Al7075* alloy, focusing on characterizing the mechanical properties of these hybrid materials.

The following aspects will be addressed:

– The influence of varying proportions of nanosized *SiC* and graphene on the hardness and tensile strength of *Al7075-T6* alloy;

– The microstructure and fracture surface morphology of *Al7075-T6* nanocomposites, investigated using *SEM-EDX* analysis;

– Key findings of the study and directions for further research.

Mechanical properties of Al7075-T6 nanocomposites

This subsection discusses the mechanical properties - hardness and tensile strength – of both unreinforced and reinforced *Al7075-T6* nanocomposite specimens prepared using stir casting. As shown in Table 2, a total of eight different *Al7075-T6* nanocomposite specimens were fabricated via stir casting, with varying silicon carbide (*SiC*) and graphene nanoparticle reinforcements. The mechanical properties – hardness and tensile strength – were measured and compared between the unreinforced and differently reinforced *Al7075-T6* nanocomposites. Fig. 2 illustrates the hardness and tensile strength of both unreinforced and reinforced *Al7075-T6* nanocomposites.

As illustrated in Fig. 2, the addition of graphene and *SiC* reinforcements to *Al7075* significantly increases the material's tensile strength and hardness, resulting in a considerable improvement in overall strength. Specimen **1**, representing the unreinforced *Al7075* material, exhibits a tensile strength of 89.47 MPa and a *Brinell* hardness number (BHN) of 84.3. Increasing the graphene percentage from 0.1% to 0.3% in Specimens **2** through **4**, while maintaining a constant 0.5% *SiC* reinforcement, results in a gradual increase in hardness (101.40-107.5 BHN) and tensile strength (117.68-141.82 MPa). Furthermore, increasing the *SiC* percentage from 1% to 3% in Specimens **5** through **7**, while maintaining a constant 0.5% graphene reinforcement, leads to a significant improvement in tensile strength (151.55-156.62 MPa) and hardness (132.60-163.40 BHN).

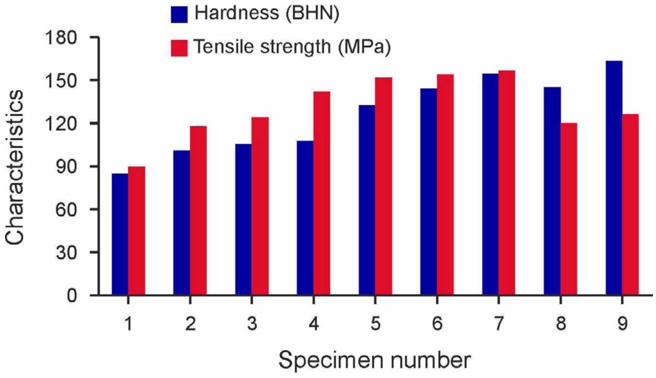


Fig. 2. Hardness and tensile strength of *Al7075-T6* nanocomposites

Fig. 2 demonstrates that reinforced *Al7075-T6* nanocomposites exhibit greater hardness and tensile strength compared to the unreinforced *Al7075* specimen. Furthermore, these properties increase with higher concentrations of *SiC* and graphene nanoparticle reinforcements. However, the increase in these properties, particularly hardness, appears more pronounced with *SiC* reinforcement compared to graphene reinforcement in the *Al7075-T6* alloy. With a constant 1% graphene reinforcement, tensile strength decreases when *SiC* reinforcement exceeds 2%.

Increasing the *SiC* percentage from 2% to 4% in *Al7075*-based nanocomposites, while maintaining a constant 1% graphene reinforcement (Specimens **8** and **9**), results in a significant decrease in tensile strength (120.24-126.16 MPa) compared to the increase in hardness (145.16-163.40 BHN). The decrease in tensile strength for the *Al7075* nanocomposite when reinforced beyond 2% *SiC* with a constant 1% graphene proportion may be attributed to increased brittleness in the nanocomposite, resulting from stress concentrations caused by the *SiC* particles. This study underscores the importance of balancing hardness and tensile strength in nanocomposites to achieve the desired properties, highlighting the need for careful consideration of reinforcement material selection. It is crucial for researchers to carefully optimize reinforcement percentages to balance strength and hardness in *Al7075*-based nanocomposites.

When properly combined, graphene and silicon carbide reinforcements can synergistically enhance mechanical properties. This study indicates that Specimen **7**, composed of *Al7075*, 0.5% graphene, and 3% *SiC*, exhibits an excellent balance between tensile strength (156.62 MPa) and hardness (155.52 BHN), representing an optimal combination of these characteristics. The enhanced mechanical strength resulting from the addition of *SiC* and graphene to the *Al7075-T6* nanocomposite may be attributed to *SiC's* hardness and modulus, which facilitate load transfer, grain refinement, and dislocation impediment. Furthermore, graphene's high tensile strength and large surface area improve interfacial bonding and inhibit cracking. Differential thermal expansion between the reinforcements and the matrix generates dislocation networks that impede plastic deformation. Consequently, *SiC* and graphene enhance the composite's tensile strength, hardness, and wear resistance.

The test results demonstrate that the hybrid nanocomposites possess higher tensile strength and hardness than the unreinforced *Al7075* alloy, and these properties increase with the hybrid reinforcement ratio. The correlation between mechanical properties and the homogeneous dispersion of nano reinforcements, which inhibits dislocation movement, reduces porosity, and minimizes nanoparticle agglomeration, is explored in the subsequent subsection focusing on the microstructural and fracture surface analysis of *Al7075*-based nanocomposites.

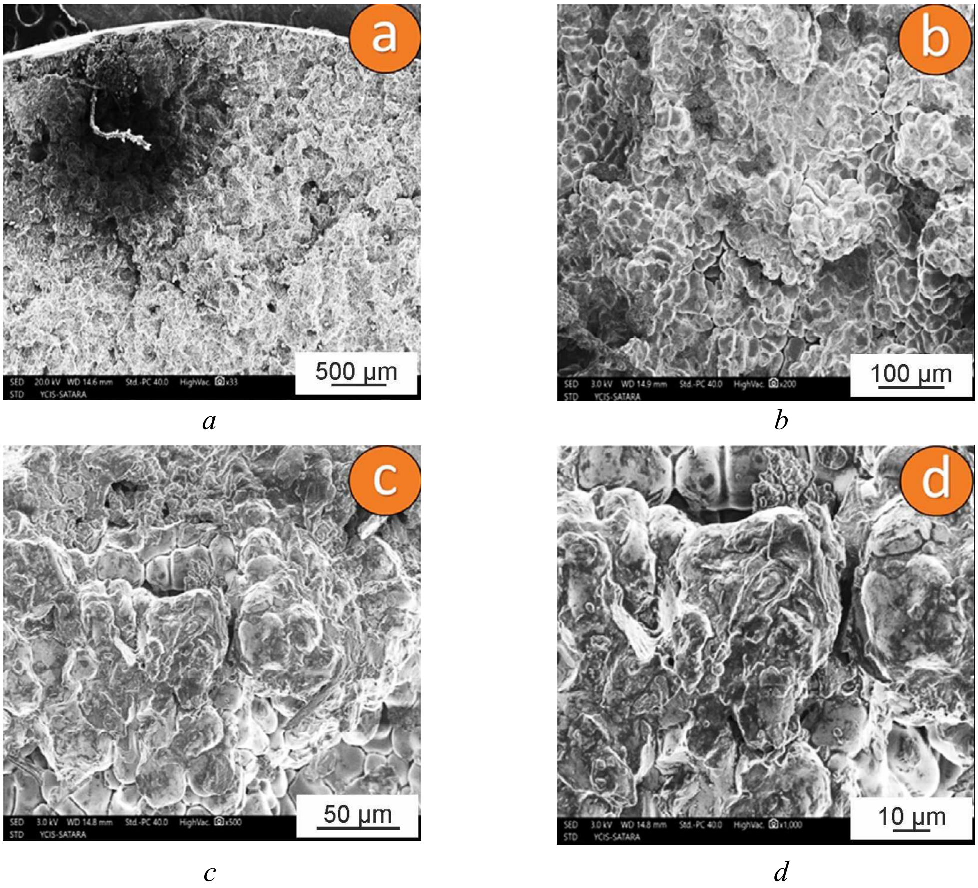
The microstructural and fracture surface analysis of nanocomposites

The superior tensile strength (156.62 MPa) and hardness (155.52 BHN) observed for Specimen **7** among the prepared nanocomposites can be elucidated through microstructural and fracture surface analysis. Fig. 3 presents *SEM* images of the fracture surfaces of Specimen **7** (*Al7075* + 0.5% *Gr* + 3% *SiC*) after tensile testing. Figs. 3, *a* through 3, *d* display *SEM* images of the fracture surfaces at increasing magnification levels. These images reveal the microstructural traits and features of the fracture surfaces at various scales.

The *SEM* analysis provides valuable insights into the material's failure mechanisms and fracture propagation characteristics. A dense, dimpled surface with homogeneous microvoids and minimal particle pull-out is observed, indicative of ductile fracture with strong matrix-reinforcement bonding and efficient load transfer. The presence of fine, uniformly distributed dimples suggests that *SiC* particles served as solidification nucleation sites, while graphene blunted crack tips and impeded dislocation movement.

SEM images of the fracture surfaces of Specimen **8** (*Al7075* + 1% *Gr* + 2% *SiC*) are shown in Figs. 4, *a* through 4, *d* at increasing magnification levels. The fracture surfaces exhibit non-uniform dimples with mixed-mode characteristics, indicating interfacial decohesion and reinforcement particle pull-out. Increased graphene concentration may weaken matrix-reinforcement bonding due to graphene agglomeration and reduced wettability. Stress concentrations caused by microstructural discontinuities can lead to premature cracking, potentially explaining why Specimen **8** exhibits lower tensile strength and hardness compared to Specimen **7** despite having a higher overall reinforcement content.

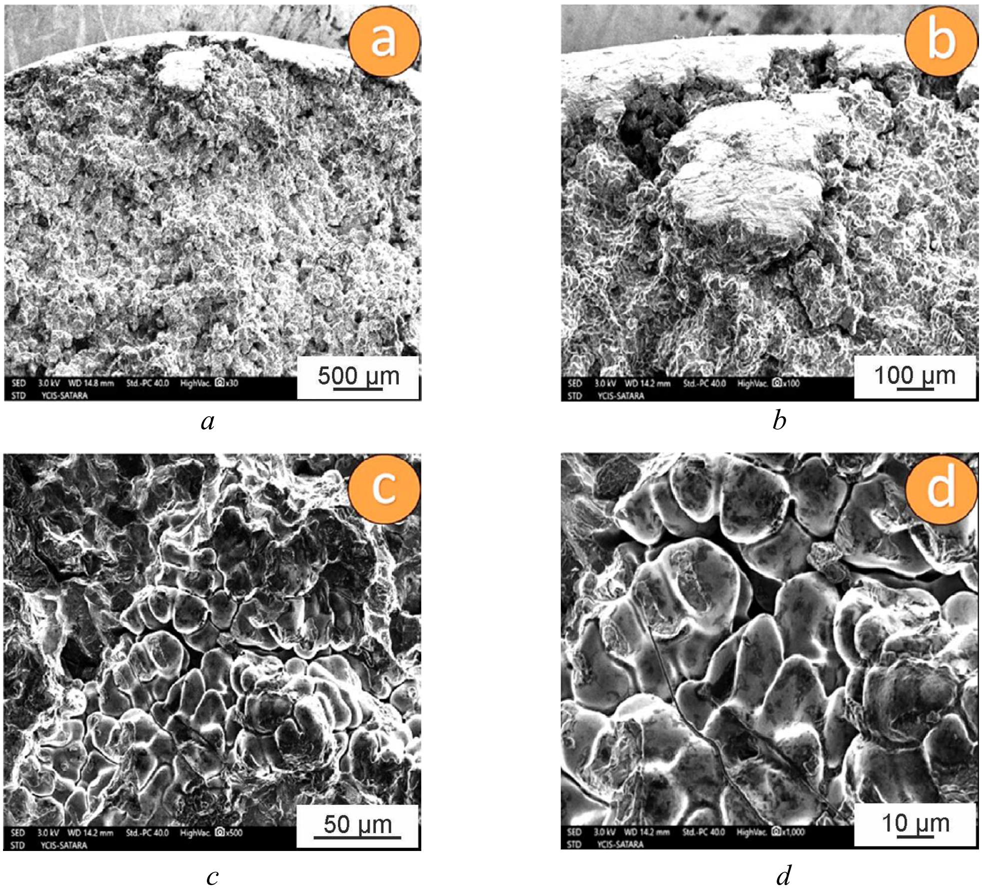
This study observed that *Al7075* nanocomposites prepared with stirring exhibit a more uniform and homogeneous surface compared to those prepared without stirring. Scanning electron micrographs reveal distinct surface morphologies for composites prepared with and without stirring. Fig. 5, *a* depicts the unstirred composite's flat, featureless surface characterized by scattered particles, non-uniform reinforcement distribution, and agglomerates. This non-uniformity indicates inadequate matrix-reinforcement particle dispersion resulting from insufficient mechanical mixing during fabrication. Visible voids and poor interfacial bonding suggest weak matrix-reinforcement interaction, which can negatively impact composite mechanical performance. Fig. 5, *b* displays the stirred composite's smooth, homogeneous surface. Visible striations and consistent fine particle dispersion suggest that stirring enhances mixing and reinforcement



a *b*

c *d*

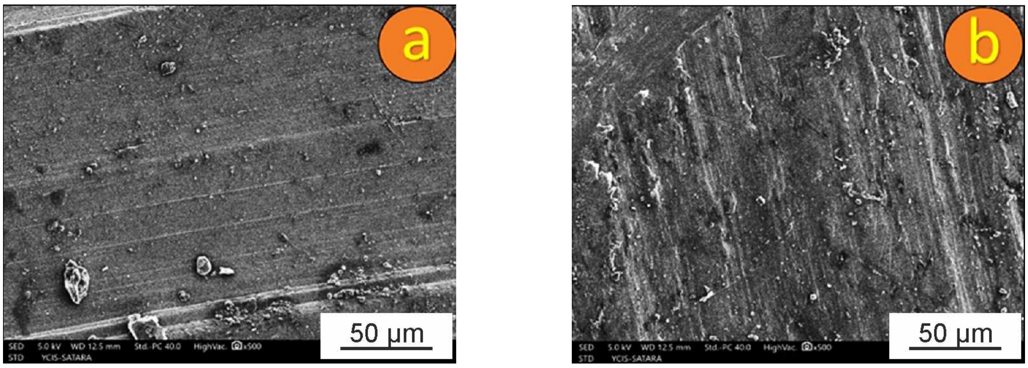
Fig. 3. SEM images of fractured surfaces after tensile testing for Specimen 7



a *b*

c *d*

Fig. 4. SEM images of fractured surfaces after tensile testing for Specimen 8



a *b*

Fig. 5. Surface images without (*a*) and with (*b*) stirring for Specimen 7

distribution. Mechanical stirring reduces porosity and improves bonding, wetting, and cohesion between the matrix and reinforcements. These microstructural alterations likely contribute to the superior strength and toughness of stirred composites compared to unstirred ones. The study highlights that the implementation of appropriate mixing techniques can significantly influence the surface morphology and mechanical properties of *Al7075* nanocomposites.

Energy dispersive X-ray spectroscopy (*EDX*) analysis in this study confirms the homogeneous distribution of *SiC* and graphene nanoparticles within the aluminum matrix. Figs. 6 and 7 present the elemental analyses of Specimens **7** (*Al7075* + 0.5% graphene + 3% *SiC*) and **8** (*Al7075* + 1% graphene + + 2% *SiC*), respectively. The *EDX* analysis confirms the presence of *SiC* nanoparticles within the aluminum

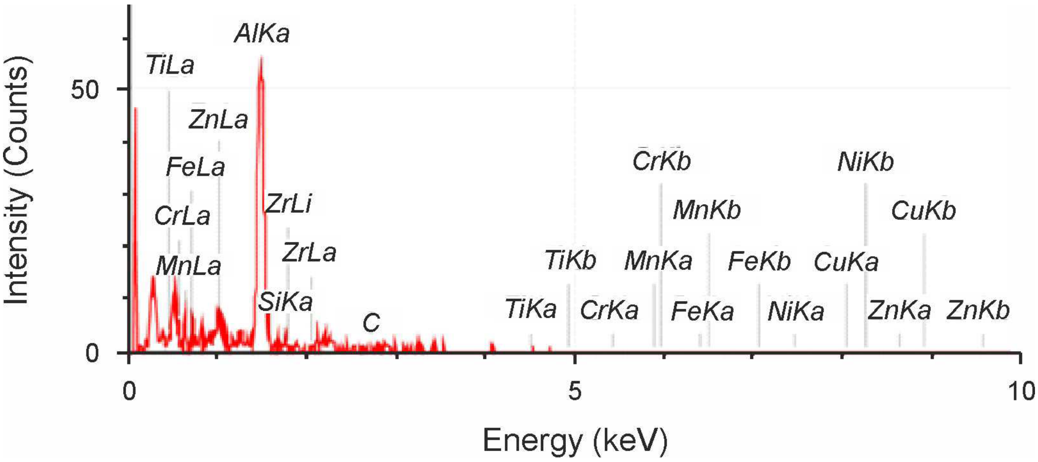


Fig. 6. Elemental analysis of Specimen 7 (*Al7075* + 0.5 % graphene + 3 % *SiC*)

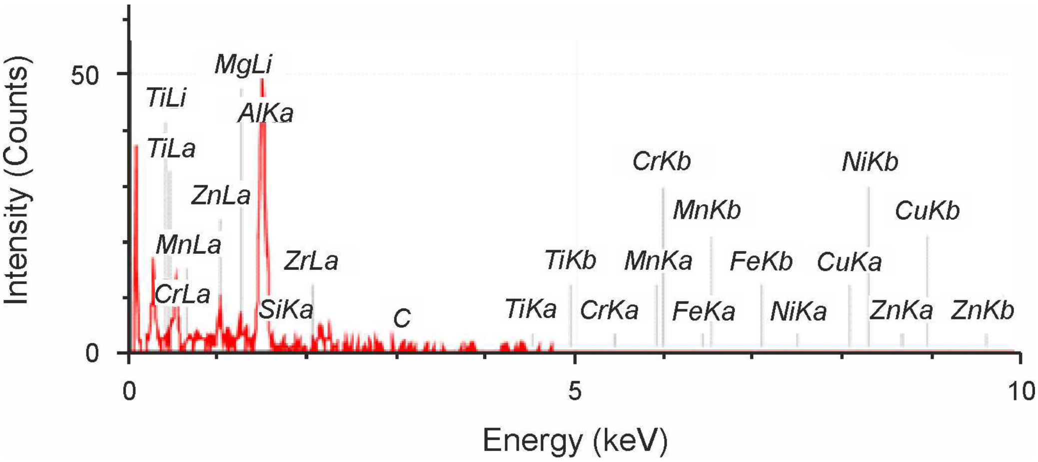


Fig. 7. Elemental analysis of Specimen 8 (*Al7075* + 1% graphene + 2% *SiC*)

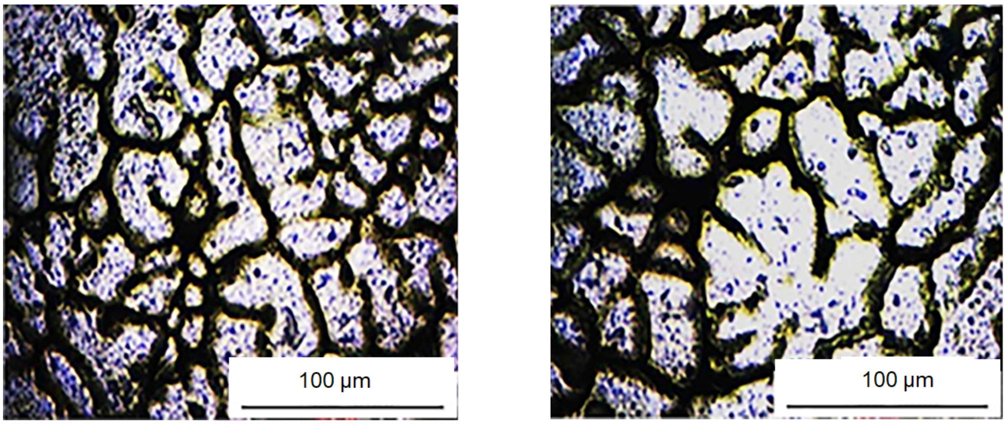
matrix, indicated by the detection of carbon, silicon, and aluminum. Furthermore, the *EDX* results clearly demonstrate the presence of graphene nanoparticles in the aluminum matrix, with carbon peaks observed in both specimens. The dispersion of *SiC* and graphene nanoparticles throughout the aluminum matrix highlights their potential to enhance the mechanical properties of the composite material.

Energy dispersive X-ray spectroscopy (*EDX*) analyzes the elemental composition of the *Al7075*-based nanocomposites. Figs. 6 and 7 show a dominant aluminum signal in the *EDX* spectra, confirming that the matrix material is primarily aluminum. The presence of titanium (*Ti*) and zirconium (*Zr*) peaks suggests their role in mechanical optimization as reinforcing elements. Silicon (*Si*) may be present as intermetallic compounds or ceramics. Trace peaks of iron (*Fe*), manganese (*Mn*), chromium (*Cr*), nickel (*Ni*), copper (*Cu*), and zinc (*Zn*) indicate the presence of a multi-elemental alloying system designed to improve strength, wear resistance, and corrosion resistance. While *EDX* has limited sensitivity to light elements like carbon, a minor carbon peak near 2 keV suggests the presence of graphene or graphitic carbon structures. Even at low concentrations, graphene's high tensile strength and large surface area contribute to enhanced structural and functional performance of the composite. Overall, the *EDX* results demonstrate the successful incorporation of both micro- and nano-scale reinforcements into the aluminum matrix, highlighting its suitability for advanced structural applications.

Fig. 7 illustrates the elemental distribution within the eighth composite specimen. The prominent *AlK*α signal at 1.5 keV confirms aluminum as the primary matrix material. The presence of a strong *MgK*α peak indicates the addition of magnesium to enhance the strength-to-weight ratio and improve corrosion resistance. Peaks corresponding to titanium (*TiL*α, *TiK*α), zirconium (*ZrL*α), and silicon (*SiK*α) suggest the presence of reinforcing phases that contribute to mechanical and thermal stability. Transition metals such as chromium (*Cr*), manganese (*Mn*), iron (*Fe*), nickel (*Ni*), copper (*Cu*), and zinc (*Zn*) are detected across a wide energy range, particularly between 5 and 9 keV, suggesting their role as alloying elements or secondary reinforcements. These constituents can enhance the composite's hardness, wear resistance, and multifunctionality. Variations in magnesium content between spectra suggest a compositional design modification. Overall, the spectrum depicts a complex multi-phase aluminum-based composite system with tailored elemental additions for improved structural and functional performance.

Fig. 8 presents optical micrographs illustrating the microstructures of Specimen **7** (*Al7075* + 0.5% graphene + 3% *SiC*) and Specimen **8** (*Al7075* + 1% graphene + 2% *SiC*). Both specimens were fabricated with different combinations of graphene and *SiC*. Specimen **7** (Fig. 8, *a*) exhibits a consistently polished grain structure with well-defined, continuous grain boundaries. The absence of porosity or clustering suggests enhanced interfacial bonding, while the presence of fine grains indicates effective nucleation facilitated by properly dispersed *SiC* particles.

High-resolution *SEM* images reveal the nanoscale reinforcement particle size and dispersion within the composite matrix. The presence of fine particles ranging from 62.57 to 91.54 nm indicates a well-



a *b*

Fig. 8. Microstructure observed for (*a*) Specimen 7, (*b*) Specimen 8

distributed reinforcing phase in Fig. 8, *a*. Due to their higher surface area-to-volume ratio, these nanoscale particles exhibit strong bonding with the matrix, thereby improving mechanical properties. Effective load transfer, grain refinement, and impediment of dislocation motion contribute to increased hardness, tensile strength, and wear resistance. These microstructural observations corroborate the superior hardness (155.52 BHN) and tensile strength (156.62 MPa) observed for Specimen **7**.

Conversely, Fig. 8, *b* depicts a coarser particle distribution ranging from 90.49 to 116.9 nm for Specimen **8**. Coarser and irregular grains with less distinct grain boundaries are apparent. The clustered structure and larger particle size suggest agglomeration, often resulting from inadequate mixing or thermodynamic instability during processing. Agglomerated particles concentrate stress and degrade matrix-reinforcement interaction, limiting load transfer. The reduced grain boundary density and uniformity lead to decreased dislocation impediment, which correlates with the diminished mechanical properties observed for Specimen **8**.

This comparative microstructure analysis demonstrates that reinforcement percentage, particle size, and dispersion quality are key determinants of the mechanical behavior of hybrid *Al7075*-based nanocomposites. The study provides valuable insights for the development of advanced materials with enhanced performance for various industrial applications.

Conclusions

This research investigated the effects of varying ratios of nanosized *SiC* and graphene reinforcements on the hardness and tensile strength of *Al7075-T6* aluminum alloy produced via stir casting, considering the widespread use of aluminum matrix composites (*AMCs*) in aerospace and automotive applications. The microstructural and fracture surface analysis of the composites was also performed using *SEM-EDX*. This study aimed to develop lightweight, high-performance hybrid metal matrix nanocomposite materials and explore the potential of combining graphene and *SiC* nanoparticles with *Al7075* alloy, with particular attention given to characterizing the mechanical properties of these hybrid materials. The following conclusions can be drawn from this work:

– An *Al7075*-based nanocomposite with a 0.5 wt.% graphene and 3 wt.% *SiC* composition exhibited a tensile strength of 156.62 MPa and a hardness of 155.52 BHN. *SiC* nanoparticles were found to be most effective in hardening metal matrix composites, while graphene contributed to enhancing the tensile strength of the nanocomposites.

– Mechanical stirring effectively reduced porosity and improved bonding, wetting, and cohesion between the matrix and reinforcements. The resulting microstructural changes led to superior strength and toughness in stirred composites compared to unstirred composites. The use of appropriate mixing techniques significantly influenced the surface morphology and mechanical properties of *Al7075* nanocomposites.

– *Al7075*-based nanocomposites with 1 wt.% graphene and 2 wt.% *SiC* content exhibited decreased mechanical properties, which correlated with reduced dislocation obstruction due to decreased grain boundary density and uniformity.

– *Al7075*-based nanocomposites with 0.5 wt.% graphene and 1-3 wt.% *SiC* content displayed a uniformly polished grain structure with distinct and continuous grain boundaries. The fine-polished nanoparticles produced, ranging in size from 62.57 to 91.54 nm, demonstrated superior mechanical characteristics through efficient load transfer, grain refinement, and dislocation motion impediment.

– *Al7075*-based nanocomposites with a dense, dimpled surface, homogeneous microvoids, and minimal particle pull-out exhibited superior mechanical properties. This was attributed to ductile fracture with strong matrix-reinforcement bonding and effective load transfer.

– Reinforcement percentage, particle size, and dispersion quality significantly influence the mechanical behavior of hybrid *Al7075*-based nanocomposites, providing valuable insights for advanced industrial applications.

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Conflicts of Interest

The authors declare no conflict of interest.