STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 2, 2026
DOI (Journal): 10.37591/JoPC

Research JoPC

Enhancement of Mechanical Properties in Eutectic Al-Si Alloy Matrix Composites Reinforced with Kyanite and Graphite via Stir Casting

Rahul A Patil[1,]*, E.R. Deore[2]

Abstract

The purpose of this work is to enhance the mechanical performance of a eutectic Al–Si alloy by incorporating hard ceramic (kyanite) and soft solid lubricant (graphite) reinforcements using a liquid-state stir casting route. Metal matrix composites were fabricated with kyanite contents of 2, 4, and 6 wt.% and a constant 2.5 wt.% graphite. Their microstructures and mechanical properties were systematically evaluated. The microstructure was examined using optical microscopy and energy dispersive spectroscopy (EDS), which revealed that the reinforcement was evenly distributed and that the integration was successful. Vickers microhardness and ultimate tensile strength (UTS) tests revealed that increasing the kyanite content significantly improved both hardness and tensile properties. The optimum hybrid composition containing 6 wt.% kyanite and 2.5 wt.% graphite exhibited a Vickers microhardness of 107 HV which corresponding to a 16% increase over the base Al–Si alloy having microhardness of 92 HV and an ultimate tensile strength of 195 MPa i.e. an 18.2% improvement relative to the unreinforced matrix of 165 MPa. These results establish kyanite as a cost-effective ceramic reinforcement and demonstrate that stir-cast kyanite–graphite hybrid aluminum matrix composites offer a viable and economical route for developing lightweight, high-performance materials for structural engineering applications.

Keywords: Al-Si alloy, metal matrix composites, stir casting, kyanite reinforcement, mechanical properties

INTRODUCTION

Modern engineering applications increasingly demand lightweight, high-strength materials that can improve fuel efficiency and performance while remaining cost-effective [1, 2]. Metal matrix composites (MMCs) have emerged as promising candidates because they offer higher strength-to-weight ratios, improved thermal conductivity and better fatigue and wear resistance compared to monolithic metals and alloys [3–5]. Recent research has focused on hybrid aluminum matrix composites that incorporate two or more distinct reinforcement phases to exploit synergistic combinations of hard ceramics for load-bearing and soft solid lubricants for improved machinability and tribological performance. This is in contrast to traditional reinforcements like silicon carbide and alumina which have been explored a lot [6]. Hybrid aluminum matrix composites (HAMCs) incorporating two or more distinct reinforcement phases within a single metal matrix represent the second-generation evolution of composite

***Author for Correspondence**
Rahul A Patil
E-mail: rahul.patil@nmiet.edu.in

[1]Research Scholar, Department of Mechanical Engineering, SSVPS's BSD College of Engineering, Dhule, Maharashtra, India
[1]Assistant Professor, `Department of Mechanical Engineering, Nutan Maharashtra Institute of Engineering and Technology, Talegaon Dabhade, Maharashtra, India
[2]Professor, Department of Mechanical Engineering, SSVPS's BSD College of Engineering, Dhule, Maharashtra, India

Received Date: February 21, 2026
Accepted Date: March 02, 2026
Published Date: March 12, 2026

Citation: Rahul A Patil, E.R. Deore. Enhancement of Mechanical Properties in Eutectic Al-Si Alloy Matrix Composites Reinforced with Kyanite and Graphite via Stir Casting. Journal of Polymer & Composites. 2026; 14(2): 90–100p.

technology. Unlike single-reinforced systems hybrid composites exploit synergistic interactions between complementary reinforcement materials as hard ceramics for strength and wear resistance and soft lubricants for machinability and tribological performance to overcome individual phase limitations [7–11]. Key fabrication challenges include porosity control and reinforcement wettability management. Especially when constituent phases exhibit significant density differences [12, 13]. Among composite categories of polymer, ceramic and metal matrix systems, MMCs demonstrate superior thermal conductivity and mechanical performance driving their adoption in demanding structural applications. MMCs have been successfully commercialized across a wide range of high-performance applications. In the automotive industry they are now used in the manufacturing of components such as brake calipers, rotors, pistons, connecting rods, camshafts, tappets and cylinder liners. To reduce production costs, several approaches have been explored including single-step fabrication methods careful selection of reinforcement materials and the incorporation of cost-effective reinforcements [14]. Aluminum alloys serve as the preferred matrix material for MMC fabrication by offering multiple advantages as low density 2.7 g/cm³, high thermal conductivity 150-200 W/m·K, cost-effectiveness and excellent castability [12, 15]. Eutectic aluminum-silicon alloys offer specific advantages over unalloyed aluminum with enhanced mechanical strength i.e. the yield strength ~170 MPa compare to 70 MPa for pure Al. improved thermal conductivity, reduced coefficient of thermal expansion ($\sim 23 \times 10^{-6}$ K^{-1} vs. 23.1×10^{-6} K^{-1} for pure Al) and superior fluidity during casting. The incorporation of ceramic reinforcements further amplifies these properties through load transfer mechanisms and geometric dislocation constraint yielding composites with 20-40% property enhancement over unreinforced matrices. For practical uses particularly under tough conditions composites need to be stronger than regular metals and alloys at both room temperature and higher temperatures. They also need to have better tribological qualities. These qualities make metal matrix composites great replacements for traditional materials in a wide range of engineering and industrial uses [16].

Among available fabrication routes, liquid-state stir casting dominates commercial MMC production due to its cost-effectiveness, scalability and ability to produce components with complex geometries [17]. In stir casting, ceramic particles are mechanically suspended in molten metal, and process effectiveness depends critically on parameters such as stirring speed, duration, impeller design, and controlled melt temperature to ensure good wettability, homogeneous particle distribution, and minimal casting defects [18]. Conventional reinforcements such as SiC, Al_2O_3, ZrO_2 and B_4C provide excellent mechanical properties but are relatively expensive, which limits their use in cost-sensitive applications despite advances that enable defect-free, uniformly reinforced composites [19, 20]. Industrial waste and minerals that are found in nature are good options for lowering costs. Kyanite (Al_2SiO_5) is a naturally occurring aluminosilicate mineral with a Mohs hardness of 6.5–7 and a density of 3500 kg/m³. It has been shown to work well in polymer matrix systems and as a refractory material [21–24]. It has been successfully used in polymer matrices and refractory materials to improve mechanical properties and thermal stability at significantly lower cost than synthetic ceramic reinforcements. However, systematic studies of kyanite in aluminum metal matrix systems are still limited, particularly for eutectic Al–Si alloys processed by stir casting. In this work, a hybrid reinforcement strategy is adopted by combining kyanite as a hard ceramic phase with graphite as a soft solid lubricant to simultaneously enhance strength and machinability. The aim is to (i) fabricate eutectic Al–Si/kyanite/graphite composites by stir casting, (ii) examine the effects of kyanite content on microstructure, hardness, and tensile properties, and (iii) elucidate the processing–structure–property relationships and evaluate kyanite as a cost-effective alternative to conventional ceramic reinforcements.

MATERIALS & METHODS

Metal matrix composites can be fabricated by several routes including in-situ synthesis, vapor deposition and solid- semi-solid or liquid-state processing. Among these stir casting is widely recognized as a cost-effective and practical method for producing discontinuously reinforced MMCs. In this process, ceramic particles or short fibers are mechanically stirred into molten metal to achieve uniform dispersion before the melt is cast using conventional foundry techniques [25–29]. Proper control of process parameters such as melt temperature, stirring speed and time impeller design and mold preheating is essential to minimize porosity, avoid particle clustering and ensure reproducible mechanical properties [30, 31].

Material

The matrix material was a commercial eutectic Al–Si alloy with a nominal composition of Al–12.5 wt.% Si, procured from Fenmet (Bangalore, India); its detailed chemical composition is given in Table 1. Kyanite (Al_2SiO_5) powder was sourced from a mineral and gemstone supplier in Kolkata, and its oxide composition range is listed in Table 2. Artificial graphite powder with medium crystallinity, a particle size of 250 ± 50 μm, and a density of 2200 ± 30 kg/m³ was used as the secondary soft-phase reinforcement [32].

Synthesis Process

Composite synthesis employed the liquid-state stir casting technique represented in Figure 1. Eutectic Al-Si ingots mass of 500gm were melted in a graphite crucible within an electric resistance furnace shown in Figure 1a) at 850±10°C. Before reinforcement addition, the molten alloy was degassed using 2 gm of C_2Cl_6 for injection duration of 5 minutes to minimize dissolved hydrogen and reduce casting porosity. Kyanite and graphite powders were separately preheated to 200±10°C for 30 minutes in a laboratory oven immediately prior to composite addition. This pre-treatment improved particle wettability and reduced thermal shock upon contact with molten matrix. The preheated reinforcements were subsequently transferred into the molten alloy at 850±10°C (Figure 1b shows stirring apparatus). Following reinforcement addition mechanical stirring commenced at range: 450-500 RPM using a stainless steel curved-blade stirrer blade diameter of 40 mm, 45° angle for 5 minutes. maintaining melt temperature at 850±10°C by continuous furnace temperature control. Figure 1c shows complete stir casting setup. The stirring duration and speed were optimized through preliminary trials and literature recommendations to ensure uniform reinforcement distribution without excessive vortex formation or particle agglomeration. After homogenization the molten composite was transferred via pouring funnel into a preheated 150±10°C cast iron mold. Controlled cooling in the ambient 22–25°C laboratory environment provided a natural cooling rate of approximately 8–12°C/minute. Solidified composites were extracted after 24 hours and allowed to reach room temperature before further processing [33–36]. The reinforcement preheating to 200 ± 10 °C and mould preheating to 150 ± 10 °C were selected to enhance particle wettability and reduce thermal shock and porosity, respectively. The composite samples were fabricated as shown in Figure 2 in accordance with relevant ASTM standards for various mechanical and microstructural evaluations. Specifically, tensile test specimens were prepared following the ASTM E8/E8M:2016a standard [37]. These samples were used to assess the microstructure and mechanical properties of the developed composites. The details of the fabricated materials along with their corresponding sample numbers are presented in Table 3.

Table 1. Chemical composition of Eutectic Al-Si alloy (in wt. %).

Matrix	Si	Fe	Al
Al-12.5% Si	12.6	0.18	87.22

Table 2. Chemical composition of Al_2SiO_5 (In wt.%).

Al_2O_3	SiO_2	TiO_2	Fe_2O_3	CaO	LoI
48.0 - 55.0	39.0 - 45.0	0.5 -0.6	0.8-1.75	0.52	1.65

Table 3. Material fabricated with sample name and wt.% of kyanite and graphite.

Sample Designation	Material Composition	Kyanite Content (wt%)	Graphite Content (wt%)
S1	Eutectic Al–Si	0	0
S2	Al–Si + Kyanite + Graphite	2	2.5
S3	Al–Si + Kyanite + Graphite	4	2.5
S4	Al–Si + Kyanite + Graphite	6	2.5

(a)

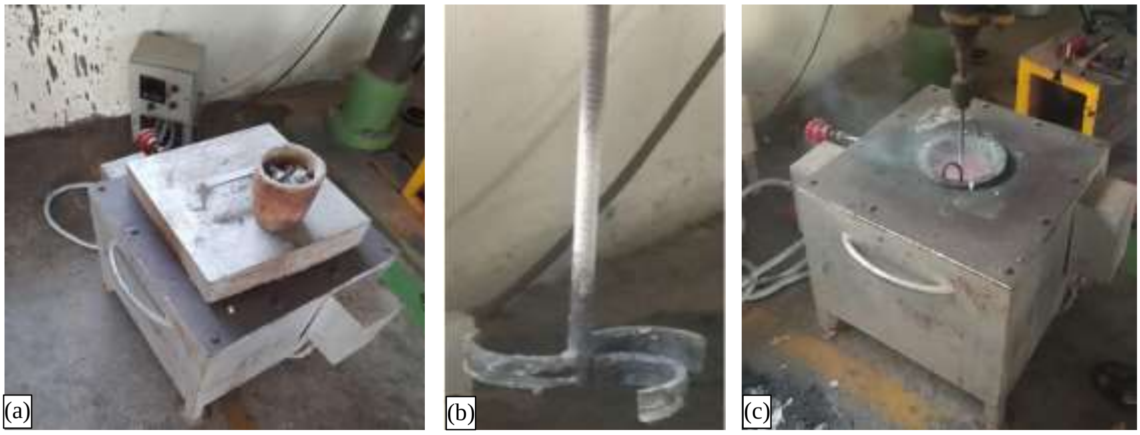


Figure 1. Experimental stir casting apparatus shown in (a) Stir casting furnace. (b) Stirrer rod. (c) stir casting setup

Figure 2. (a) Composite samples after synthesis; (b) Composite samples after surface finishing.

Testing of specimen

All mechanical tests followed ASTM standards with calibrated equipment. The consistent standard deviations across all compositions reflect both the inherent precision of the test methods and the excellent reproducibility of the composite fabrication process under rigorously controlled conditions.

Microstructural Characterization

Composite samples were mechanically sectioned into 15 × 15 × 5 mm^3 specimens and subjected to standard metallographic preparation with progressive abrasive grinding using SiC paper of grid size 400, 600, 1000, 1200, 2000 followed by polishing with 1 μm alumina suspension on felt pads. Etching was performed using Keller's reagent with content 2.5 mL HF, 1.5 mL HCl, 1 mL HNO_3, 95 mL H_2O for 15±2 seconds to reveal microstructural features. Optical microscopy with Magnification of 200× captured micrographs at five random locations per sample for representative microstructural documentation. Energy Dispersive X-ray Spectroscopy performed qualitative and semi-quantitative elemental analysis confirming reinforcement integration and identifying interfacial reactions [2, 3, 38, 39].

Hardness Testing

Vickers microhardness measurements were performed in accordance with ASTM E92-17 using specimens prepared for microstructural analysis. The samples were polished to an optical finish and five indentations were made on each specimen using a 0.5 kgf (4.9 N) load, a dwell time of 15 ± 1 s and a minimum spacing of 0.5 mm between adjacent indents to avoid interaction. Diagonal lengths were measured using an optical microscope, and hardness values (HV) were calculated following ASTM E92; results are reported as mean ± standard deviation.

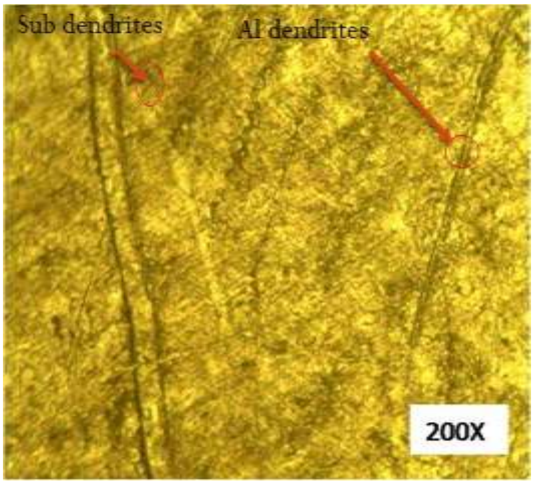
Ultimate Tensile Test

Cylindrical tensile specimens with gauge length: 25 mm, gauge diameter: 5 mm were fabricated as per ASTM E8M-21 using precision CNC machining (tolerances: ±0.05 mm). Three specimens per composition were tested using a servo-hydraulic universal testing machine with Capacity of 600kN. Stress-strain curves were recorded at 100 Hz sampling rate. Ultimate Tensile Strength (UTS) were calculated per ASTM E8M. Results reported as mean ± SD from three replicates.

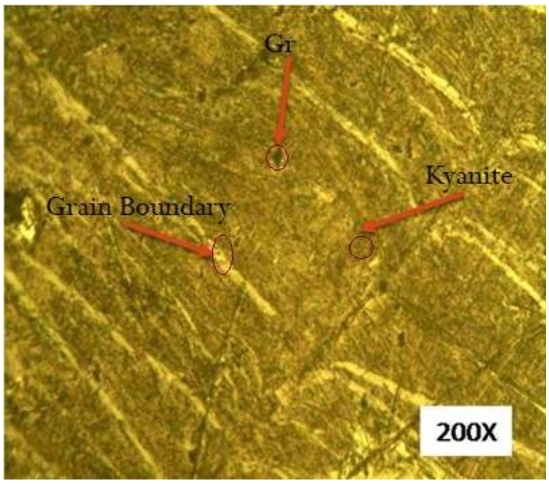
RESULT & DISCUSSION

Microstructure Study

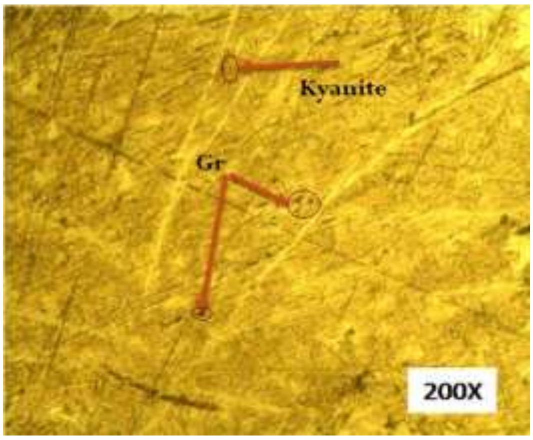
Figure 3(a) shows the unreinforced eutectic Al-Si baseline microstructure, characterized by primary aluminium dendrites (light gray) interspersed with coarse eutectic silicon particles, typical of as-cast eutectic Al-12.5Si. Secondary dendritic arm spacing averaged 35±5 µm, consistent with the natural cooling rate of 8–12°C/min employed. Figures 3(b-d) document systematic microstructural evolution in composites with increasing kyanite content 2%, 4%, 6% wt%. Preheating reinforcements to 200°C before incorporation substantially enhanced wettability, as evidenced by the lack of particle aggregation and void formation frequently seen in non-preheated systems.



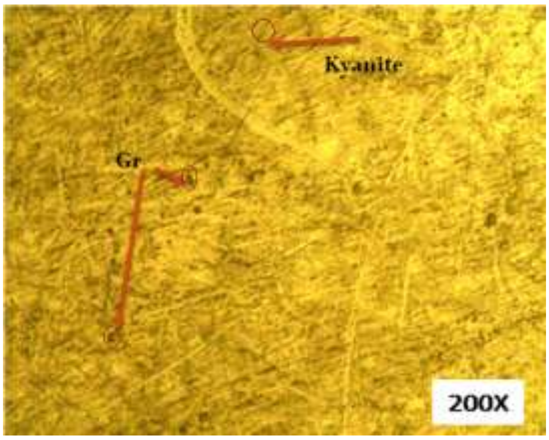
(a) Sample 1



(b) Sample (b)



(c) Sample 3



(d) Sample 4

Figure 3. Optical micrographs (200×) showing (a) unmodified needle-like eutectic Si in Sample S1 (base alloy) and modified fibrous Si morphology in (b) Sample S2 (c) Sample 3 and (d) Sample 4.

Particles are equally distributed throughout the matrix verifying the specifications of stir casting [33, 40–42]. In contrast with graphite powder, which maintains its distinctive plate-like or acicular morphology observable in optical micrographs. kyanite does not manifest as a separate secondary phase in optical pictures. During solidification kyanite likely experiences partial dissolution and a chemical reaction with the aluminum and silicon matrix resulting in the formation of integrated interfacial phases instead of staying as immiscible particles. This result significantly distinct from SiC or Al_2O_3, which maintain particle identity suggests strong interfacial interaction between kyanite and the matrix.

This integration enhances load transfer in weakly bound particle systems demonstrating superior mechanical properties. Figures 3 (c-d) demonstrate modified eutectic silicon morphology with elevated kyanite content. The unreinforced alloy (Figure 3a) exhibits coarse, needle-like plate-like eutectic Si particles characteristic of unmodified eutectic Al–Si alloys. In contrast, the reinforced composites show modified Si morphology, transitioning to irregular, fibrous particles with increasing kyanite content (Figures 3b–d). This refinement is likely due to chemical modification from kyanite–matrix interfacial reactions during solidification, analogous to Sr/Na modification effects reported in the literature [39–41, 43].

Figures 4 a–c show the results of energy dispersive X-ray spectroscopy (EDS) for Samples 2, 3 and 4 respectively. The EDS analysis verifies the effective integration of both kyanite and graphite into the Al-Si eutectic matrix. The EDS spectra show peaks for oxygen (O), aluminum (Al) and silicon (Si) which means that kyanite (Al_2SiO_5) is present. The elemental presence in wt.% given in table 4. The presence of graphite validated by its formation of a unique carbon (C) peak. The compositional gradients observed at interfacial regions with progressive Al and Si enrichment compared to bulk kyanite composition provide evidence of inter diffusion and chemical integration at the matrix-reinforcement interface. These results confirm the elemental makeup of the reinforcements and show that both phases are mixed together in the composite matrix (Figure 4).

Hardness

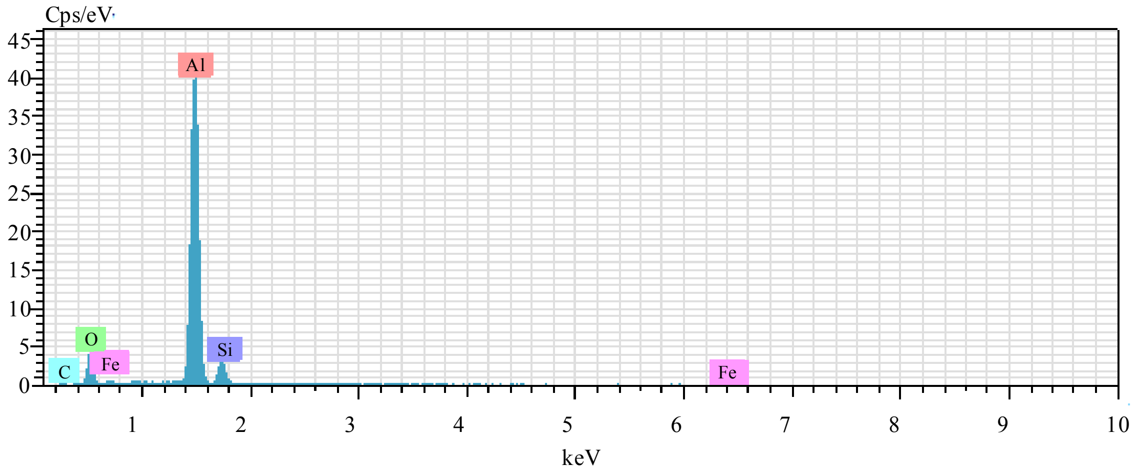
Sample 4 of Al-Si + 6 wt% Al_2SiO_5 + 2.5 wt% graphite exhibits the highest hardness value of 107 ± 3 HV as represented graphically in Figure 5, representing a 16.3% increase compared to the unreinforced base alloy of Vickers hardness of 92 ± 3 HV. The hardness progression shows a non-monotonic relationship with kyanite content for Sample 2 (2 wt% kyanite) achieves 99 ± 3 HV i.e.+7.6% improvement, Sample 3 (4 wt% kyanite) shows decrease to 94 ± 3 HV, before maximum hardness at Sample 4 (6 wt% kyanite) shown in Table 5. The hardness improvement for Sample S4 (107 ± 3 HV) relative to the unreinforced alloy (92 ± 3 HV) is statistically significant (two-sample t-test assuming equal variances, $p < 0.001$).

Table 4. Elements wt. percentage in each sample through EDS.

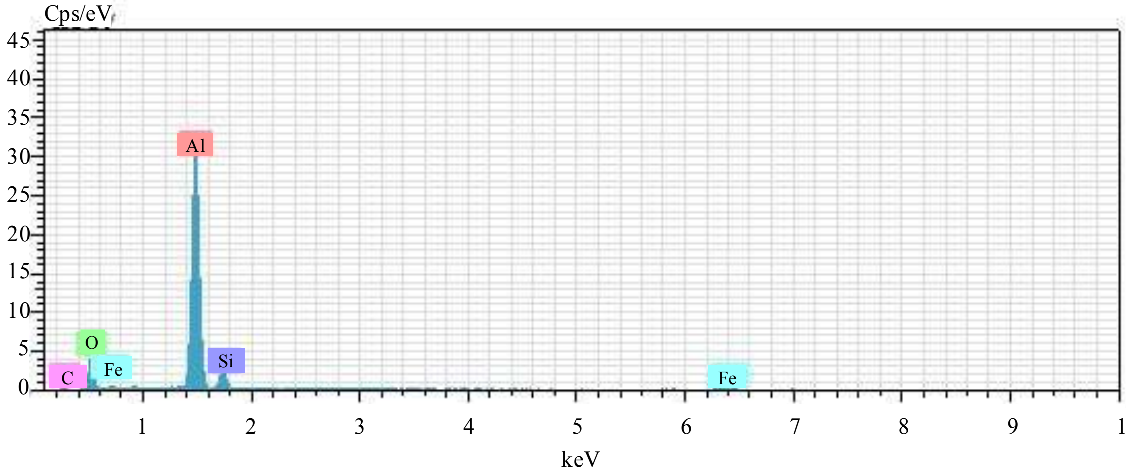
Sr. No.	Sample	Elements normal wt. percentage present in Samples				
		Al(wt.%)	***Si (wt.%)***	***O(wt.%)***	***C(wt.%)***	***Fe(wt.%)***
1	Sample 1	44.61	11.20	27.34	4.18	12.67
2	Sample 2	63.10	8.10	21.16	5.16	2.47
3	Sample 3	57.92	6.99	23.66	5.01	6.43
4	Sample 4	61.16	6.98	19.93	4.59	7.34

Table 5. Vickers microhardness results for samples as per wt.% of kyanite and graphite.

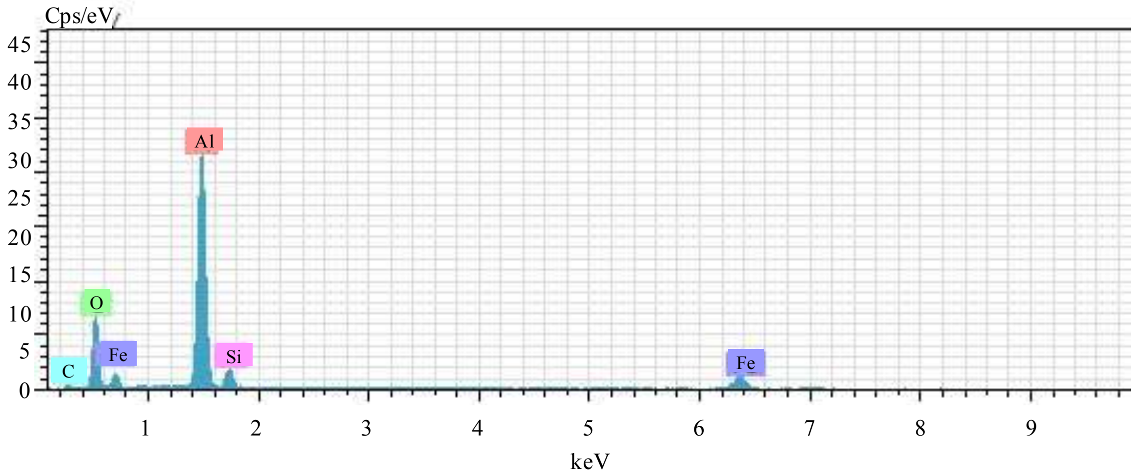
Sample	Composition	Hardness (HV)	± SD	% Change vs. S1
S1	Base Al–Si (0 wt.% kyanite)	92	±3	Baseline
S2	Al–Si + 2 wt.% kyanite + 2.5 wt.% graphite	99	±3	+7.6
S3	Al–Si + 4 wt.% kyanite + 2.5 wt.% graphite	94	±3	+2.2
S4	Al–Si + 6 wt.% kyanite + 2.5 wt.% graphite	107	±3	+16



Sample 2



Sample 3



Sample 4

Figure 4. EDS for a) sample 2 (b) sample 3 and (c) sample 4.

This trend suggests particle clustering or secondary phase formation effects at intermediate compositions. The hardness improvement is attributable to the higher content of kyanite a hard ceramic reinforcement with Mohs hardness 6.5–7 compared to aluminum's ~2.5–3, which enhances overall resistance of the matrix to indentation.

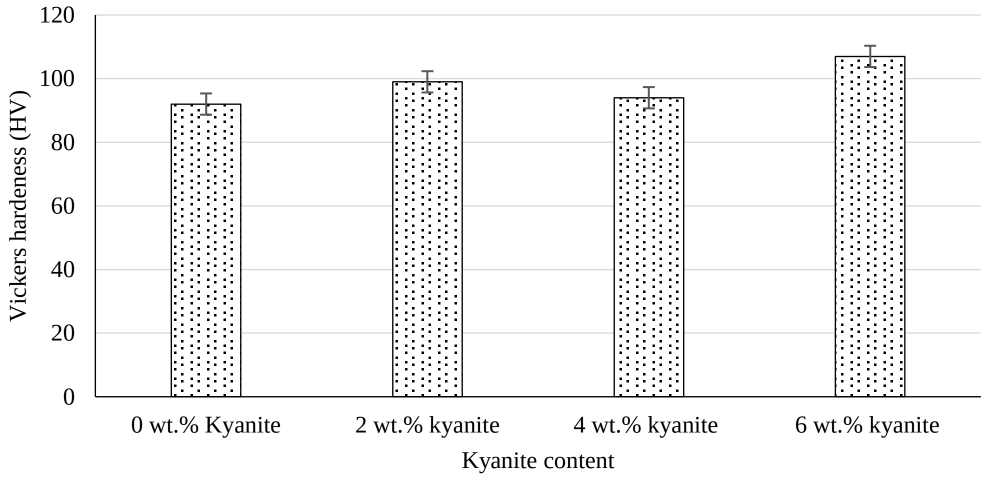


Figure 5. Comparison of vickers hardness of samples.

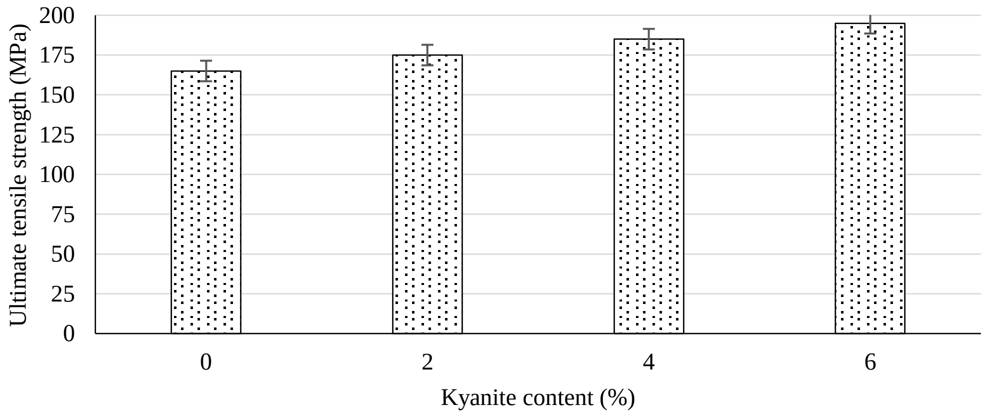


Figure 6. Comparison of tensile strength of Samples.

Table 6. Ultimate tensile strength results.

Sample	Composition	UTS (MPa)	± SD	% Change vs. S1
S1	Base Al–Si (0 wt.% kyanite)	165	±3	Baseline
S2	Al–Si + 2 wt.% kyanite + 2.5 wt.% graphite	175	±3	+6.1
S3	Al–Si + 4 wt.% kyanite + 2.5 wt.% graphite	185	±3	+12.1
S4	Al–Si + 6 wt.% kyanite + 2.5 wt.% graphite	195	±3	+18.2

While the incorporation of hard particles such as kyanite increases microhardness. The presence of graphite being a soft solid lubricant has minimal influence on final hardness due to its lower volume fraction 2.5 wt% and its role as a secondary reinforcement phase. The addition of graphite helps in improving machinability and tribological properties without significantly compromising hardness as reported by other researchers [33, 40–42].

Tensile Testing Result

Ultimate tensile strength shows a steady linear increase as the amount of kyanite in the composition range studied (2, 4, and 6 wt%) goes up as shown in Figure 6. The base alloy sample S1 has a strength of 165 MPa while the 6 wt% kyanite composite sample S4 has a strength of 195 MPa which is an 18.2% improvement. The percentage change in UTS of sample S2, S3 and S4 as compare to sample 1 represented in tabular form in Table 6.

The tensile strength shows a clear linear relationship with the amount of kyanite in the material.

$$\text{UTS (MPa)} = 165 + 5.0 \times (\text{wt\% kyanite}) \quad (1)$$

with $R^2 = 1.0$, indicating well describe linear fit to experimental data. This relationship demonstrates that each 1 wt% kyanite addition contributes approximately 5 MPa to the composite tensile strength The 18.2% increase in tensile strength is significant since it shows that the improvement is ongoing and doesn't stop at the 6 wt% kyanite composition that was studied [33, 41, 42, 44]. The observed increased hardness from 92 HV of sample S1 to 107 HV sample S4 and the improvement in linear tensile strength from 165 MPa to 195 MPa i.e., +18.2% improvement show that the strengthening mechanisms work together in ways that are much stronger than what basic rule-of-mixture calculations would suggest. The UTS enhancement for Sample S4 (195 ± 3 MPa) compared to S1 (165 ± 3 MPa) is statistically significant (two-sample t-test assuming equal variances, $p < 0.001$), confirming the reinforcing effect of kyanite addition. The main reason for the rise in strength getting stronger because kyanite particles are stopping dislocation motion during plastic deformation. When plastic flows dislocations, have to bend or climb around particles which means that more stress has to be applied based on the density of the particles and the space between them. All mechanical tests followed ASTM standards with calibrated equipment. The consistent standard deviations across all fabricated compositions reflect both the inherent precision of the test methods and the excellent reproducibility of the composite fabrication process under rigorously controlled conditions.

CONCLUSION

Hybrid-reinforced eutectic Al–Si composites were successfully fabricated by liquid-state stir casting using kyanite contents of 2, 4, and 6 wt.% and a fixed graphite content of 2.5 wt.%. Microstructural analysis confirmed generally uniform dispersion of reinforcements and indicated partial chemical interaction of kyanite with the matrix, whereas graphite largely retained its morphology and is expected to provide solid-lubrication benefits. Compared with the unreinforced alloy, the composite containing 6 wt.% kyanite and 2.5 wt.% graphite exhibited a 16% increase in Vickers hardness (from 92 to 107 HV) and an 18.2% increase in UTS (from 165 to 195 MPa), demonstrating the effectiveness of kyanite as a low-cost ceramic reinforcement in eutectic Al–Si. While hardness shows a non-monotonic variation with kyanite content and tensile strength increases nearly linearly within the examined range. This indicating that further optimization of processing and composition could yield additional property gains. These findings highlight the potential of kyanite and graphite reinforcement. The hybrid aluminum matrix composites consider as cost-effective, lightweight materials for structural engineering applications.

Future Scope

Future research should focus on: (i) optimizing T6 heat treatment parameters to exploit precipitation hardening and improve ductility (ii) implementing advanced casting routes such as vacuum stir casting or squeeze casting to reduce porosity and enable higher kyanite contents (8–10 wt.%) and (iii) evaluating mechanical and tribological performance at elevated temperatures (150–250 °C) representative of automotive service conditions.

Author Contributions

The first author was responsible for Conceptualization, experimental design, composite synthesis via stir casting, sample preparation, microstructural characterization (optical microscopy and EDS analysis), hardness testing, tensile testing, data collection and analysis, manuscript writing and original draft preparation. The second author supervised the research design and ensured methodological accuracy. Both authors contributed equally to the critical revision and final approval of the manuscript. The first author prepared the tables and figures.

REFERENCES

1. Chen G, Zhang W and Iizuka T 2019 The fatigue fracture characteristics of the bond zone of aluminum matrix composites (Al-12Si/ABOw) with Al-12Si alloys Mater. Sci. Eng. A 755 181–9

2. Gururaja M N and Rao H 2012 A Review on Recent Applications and Future Prospectus of Hybrid Composites Int. J. Soft Comput. Eng. 2231–307
3. Prasad T, Chinna Srinivasa Rao P, Raja Narender B and Ameresh H 2018 A study on mechanical behaviour of hybrid composites Int. J. Mech. Prod. Eng. Res. Dev. 8 661–6
4. Kala H, Mer K K S and Kumar S 2014 A Review on Mechanical and Tribological Behaviors of Stir Cast Aluminum Matrix Composites. Procedia Mater. Sci. 6 1951–60
5. Sahoo S K, Majhi J, Pattnaik A B, Sahoo J K and Das S 2018 Mechanical properties enhancement and microstructure study of Al-Si-TiB2 in situ composites IOP Conf. Ser. Mater. Sci. Eng. 338
6. Suresh N, Venkateswaran S and Seetharamu S 2011 Studies on eutectic Al-Si alloy-flyash composites Int. J. Cast Met. Res. 24 118–23
7. Singh J and Chauhan A 2016 Characterization of hybrid aluminum matrix composites for advanced applications - A review J. Mater. Res. Technol. 5 159–69
8. Rajkeerthi E, Satyanarayan C P, Jaivignesh M, Pradeep N and Hariharan P 2019 Effect of heat treatment on strength of aluminium matrix composites Materials Today: Proceedings vol 46 (Elsevier Ltd) pp 4419–25
9. Surappa M K 2003 Aluminium matrix composites: Challenges and opportunities Sadhana - Acad. Proc. Eng. Sci. 28 319–34
10. Khond A, Charkha P and Tiwari H 2024 Synthesis and characterization of Al-AlN composite Mater. Today Proc. 98 160–5
11. Khond A, Charkha P and Tiwari H 2025 Synthesis of Al−AlN metal matrix composites by powder metallurgy route Eng. Res. Express 7 25505
12. Krishnan P K, Christy J V, Arunachalam R, Mourad A H I, Muraliraja R, Al-Maharbi M, Murali V and Chandra M M 2019 Production of aluminum alloy-based metal matrix composites using scrap aluminum alloy and waste materials: Influence on microstructure and mechanical properties J. Alloys Compd. 784 1047–61
13. Rohatgi P K, Weiss D and Gupta N 2006 Applications of fly ash in synthesizing low-cost MMCs for automotive and other applications Jom 58 71–6
14. Suthar J and Patel K 2018 Identification, screening and optimization of significant parameters for stir cast hybrid aluminium metal matrix composite Heliyon 4 e00988
15. Gupta P K and Srivastava R K 2018 Fabrication of ceramic reinforcement aluminium and its alloys metal matrix composite materials: A review Mater. Today Proc. 5 18761–75
16. Bandil K, Vashisth H, Kumar S, Verma L, Jamwal A, Kumar D, Singh N, Sadasivuni K K and Gupta P 2019 Microstructural, mechanical and corrosion behaviour of Al–Si alloy reinforced with SiC metal matrix composite J. Compos. Mater. 53 4215–23
17. Ramanathan A, Krishnan P K and Muraliraja R 2019 A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities J. Manuf. Process. 42 213–45
18. Kumar M, Gupta R K and Pandey A 2018 A Review on Fabrication and Characteristics of Metal Matrix Composites Fabricated by Stir Casting IOP Conf. Ser. Mater. Sci. Eng. 377
19. Panwar N and Chauhan A 2018 Fabrication methods of particulate reinforced Aluminium metal matrix composite-A review Mater. Today Proc. 5 5933–9
20. Patil R A and Deore E R 2020 Eutectic Al-Si alloy metal matrix composite : Solid State Technol. 63 11029–39
21. Zhang W, Meng Q and Dai W 2013 Research on application of kyanite in plastic refractory Chinese J. Geochemistry 32 326–30
22. Oliwa R 2020 The mechanical properties of kevlar fabric/epoxy composites containing aluminosilicates modified with quaternary ammonium and phosphonium salts Materials (Basel). 13
23. Nemaleu Deutou J G, Kaze R C, Kamseu E and Sglavo V M 2021 Controlling the thermal stability of kyanite-based refractory geopolymers Materials (Basel). 14 1–23
24. Kamseu E, Deutou N J G, Nzeukou N A, Melo U C, Magdalena L G, Sglavo V M, Beda T and Lionelli C 2018 The role of kyanite in the crystallization and densification of the high strength mullite matrix composites J. Therm. Anal. Calorim. 131 969–82

25. Chandra Kandpal B, Kumar J and Singh H 2018 Manufacturing and technological challenges in Stir casting of metal matrix composites- A Review Mater. Today Proc. 5 5–10
26. Baradeswaran A and Elaya Perumal A 2014 Study on mechanical and wear properties of Al 7075/Al2O 3/graphite hybrid composites Compos. Part B Eng. 56 464–71
27. Menargues S, Martín E, Baile M T and Picas J A 2015 New short T6 heat treatments for aluminium silicon alloys obtained by semisolid forming Mater. Sci. Eng. A 621 236–42
28. Gangil N, Siddiquee A N and Maheshwari S 2017 Aluminium based in-situ composite fabrication through friction stir processing: A review J. Alloys Compd. 715 91–104
29. Şenel M C, Gürbüz M and Koç E 2018 Fabrication and characterization of synergistic Al-SiC-GNPs hybrid composites Compos. Part B Eng. 154 1–9
30. Moustafa M A and Si A 2008 Effect of iron content on the formation of ␤ -Al 5 FeSi and porosity in Al – Si eutectic alloys 9 605–10
31. Tian W, Li S, Wang B, Chen X, Liu J and Yu M 2016 Graphene-reinforced aluminum matrix composites prepared by spark plasma sintering 23 723–9
32. Nagaral M, Shivananda B K, Auradi V, Parashivamurthy K I and Kori S A 2017 Mechanical Behavior of Al6061-Al2O3 and Al6061-Graphite Composites Mater. Today Proc. 4 10978–86
33. Imran M, Khan A R A, Megeri S and Sadik S 2016 Study of hardness and tensile strength of Aluminium-7075 percentage varying reinforced with graphite and bagasse-ash composites Resour. Technol. 2 81–8
34. Suthar J and Patel K M 2018 Processing issues, machining, and applications of aluminum metal matrix composites Mater. Manuf. Process. 33 499–527
35. Ravi K R, Pillai R M, Amaranathan K R, Pai B C and Chakraborty M 2008 Fluidity of aluminum alloys and composites: A review J. Alloys Compd. 456 201–10
36. Hashim J, Looney L and Hashmi M S J 1999 Metal matrix composites: production by the stir casting method J. Mater. Process. Technol. 92–93 1–7
37. Miracle D B, Donaldson S L, Chairs V, Henry S D, Editor P, Moosbrugger C, Editor T, Anton G J, Assistant E, Sanders B R, Production M, Hrivnak N, Terman C, Editors C, Kinson J, Editor P, Brown J and Kubel E J ASM Handbook 21
38. Ren S, Fang D, Liu J, Tao X, Ge J, Xu X, Guo A, Fan J and Liang J 2018 Preparation and characteristic of the fly ash cenospheres/mullite composite for high-temperature application Fuel 233 336–45
39. Vijaya M and Srinivas K Development and Mechanical Properties of SiC Reinforced Aluminium Metal Matrix Composites 3 1349–53
40. Saleem Pasha S, Imran M and Harish S N 2018 Mechanical properties and microstructure of Al-7075/Kyanite composites Int. Res. J. Eng. Technol.
41. Pasha S S, Imran M and Harish S N 2019 Wear rate and hardness characteristics of Al7075/kyanite (Al2SiO5) composites Mater. Today Proc. 26 922–8
42. Hemanth J 2011 Development and Wear Behavior of Al/Al 2 SiO 5 /C Chilled Hybrid Metal Matrix Composites by Both Experimental and Finite Element Modeling SAE 2011 World Congress & Exhibition (SAE International)
43. Mohanavel V, Rajan K, Suresh Kumar S, Vijayan G and Vijayanand M S 2018 Study on mechanical properties of graphite particulates reinforced aluminium matrix composite fabricated by stir casting technique Mater. Today Proc. 5 2945–50
44. Patil R and Khemraj Kale H 2024 Fabrication, Testing And Analysis Of Aluminium Composites With Base Alloy vol 12

