SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V13I7P110

Volume 13 Issue 7, 122-131, July 2026

Original Article

Mechanical and Microstructural Analysis of Al 6061 Hybrid Composite Reinforced with SiC, TiC and Marble Dust

Aditya Balkrishna Kale[1], Sachin Ganpatrao Ghalme[2]

[1]*Department of Mechanical Engineering, Pravara Rural Engineering College, Savitribai Phule Pune University, Maharashtra, India.*
[2]*Sandip Institute of Technology and Research Centre, Nashik, Maharashtra, India.*

[1]*Corresponding Author : adikale2603@gmail.com*

Received: 09 May 2026 Revised: 23 June 2026 Accepted: 13 July 2026 Published: 30 July 2026

Abstract *- In the present study, hybrid aluminum metal matrix composites containing Silicon Carbide (SiC), Titanium Carbide (TiC), and Marble Dust is fabricated using the stir casting technique and systematically investigated. A Taguchi L9 orthogonal array is employed to optimize the reinforcement combinations and to evaluate their effect on mechanical performance. Hardness and compression tests were conducted to assess deformation resistance and compressive load-bearing capability. The experimental data show improvement in both hardness and compressive strength with an increase in the amount of reinforcement, with a hardness increase from 29.83 HRA to 51.3 HRA and the compressive strength reaching to 412 MPa, while maintaining acceptable density levels from 2.78 g/cm^3 to 2.9 g/cm^3. Compression testing using 0.2% offset method showed improvement in resistance to yielding under compressive loading. Microstructural analysis performed by scanning electron microscopy indicated a homogeneous distribution of reinforcement particles and a higher density of the matrix phase with an increase in the amount of reinforcement, and energy-dispersive spectroscopy confirmed a homogeneous distribution of elements. The X-ray diffraction analysis showed the stable phases of aluminum, SiC, TiC, and marble dust without the presence of harmful intermetallic compounds. The data demonstrate the potential of marble dust as a sustainable reinforcement material for aluminum matrix composites, as well as the synergistic effect of strengthening.*

Keywords *- Hybrid composite, Stir casting, Microstructure, Mechanical properties, Sustainable reinforcement material.*

1. Introduction

Aluminum Metal Matrix Composites (AMMCs) are getting a lot important in metal casting because like low density, high strength. Aluminum alloys often use AA6061 as a matrix material since it is easy to cast, does not corrode, and will give higher mechanical properties with the right reinforcement procedures [4, 23]. The mechanical performance of AMMCs is greatly affected by the kind, size, and arrangement of the reinforcing particles in the aluminum matrix [1, 3]. Silicon carbide (SiC) and titanium carbide (TiC) are two types of ceramic reinforcements added to aluminum matrices to make them harder, stiffer, and stronger when they are squeezed. While SiC restricts plastic deformation and TiC improves compressive strength, the cost and processing challenges of Al-TiC systems have driven interest toward hybrid AMMCs that balance mechanical performance with manufacturability [4, 5, 7]. In this scenario, marble dust, which is a sort of industrial waste made from calcium carbonate that originates from cutting and polishing stone, has been suggested as a viable secondary reinforcement. It is cheap, easy to find, and stable mechanically, making marble dust an ideal choice for making long-lasting composites [9, 19]. Stir casting is still one of the best techniques to create AMMC because it uses classic foundry methods and does not cost too much. But composites can perform less well when they have a lot of reinforcement because of difficulties, including particle agglomeration, porosity, and weak interfacial bonding [2, 3]. To acquire uniform microstructures and dependable mechanical properties, it is vital to systematically improve the combinations of reinforcements [5, 9, 14]. This study included making multi-reinforce aluminum matrix composites based on AA6061 and SiC, TiC, and marble dust using the stir casting method. A Taguchi L9 orthogonal array is utilized to discover the optimal combinations of reinforcements. Recently, hybrid composites reinforced by ceramic particles and elements in the AA6061 matrix were investigated. The synergistic effect of SiC, TiC and marble dust on the physical, microstructural and mechanical properties of AA6061 composites remains mostly unexplored. The novelty of this work is the development of a sustainable AA6061 hybrid composite reinforced with SiC, TiC and marble dust. The selection of marble dust as a sustainable reinforcement is due to its abundance, low cost, ability to enhance mechanical properties and the ease of using industrial waste. This work examines the influence of reinforcement content on hardness, compressive strength, density, microstructure, and phase constitution to identify optimal compositions for metal casting.

2. Literature Review

2.1. Recent Developments in AMMCs

AMMCs have received significant interest owing to their low density and specific strength, outstanding corrosion resistance and exceptional wear performance, which make them most suitable for aerospace, automotive and structural applications. The use of different reinforcements such as Aluminum Oxide (Al_2O_3), Silicon Carbide (SiC), Boron carbide (B_4C), Titanium diboride (TiB_2), Tungsten Carbide (WC), Titanium Carbide (TiC), Graphite, Graphene, Molybdenum disulfide (MoS_2) and other ceramic or carbon-based materials has improved the overall tribological and mechanical properties of aluminium alloys. The reinforcements enhance the composite performance by grain refinement, effective load transmission and resistance to dislocation movement [5, 6, 9, 13]. Ceramics are frequently employed because of their high hardness, excellent thermal stability and strengthening capability. Significant increases in hardness, compressive strength, wear resistance and overall performance of aluminum alloys reinforced with hard ceramic materials have been reported in studies [1-4, 11, 12, 15]. However, most of the documented examinations were on traditional ceramic reinforcing systems, and there are limited studies on hybrid composites utilizing sustainable industrial waste materials without sacrificing mechanical performance.

2.2. Sustainable Reinforcements and Multi-Response Optimization

The Recent studies on the utilization of agricultural and industrial waste materials as reinforcements in aluminium matrix composites for sustainability and economic and environmental effect reductions. Considerable potential to improve mechanical performance while encouraging effective waste usage has been proven by reinforcements such as red mud, fly ash, rice husk ash, bagasse ash and other industrial waste products [7, 9, 15, 19]. Furthermore, statistical optimization methods, especially the Taguchi method, are generally widely used to improve the reinforcement composition and processing parameters for AMMCs [5, 9, 10]. The multi-response optimization allows the simultaneous consideration of several performance aspects, which results in a more reliable selection of materials. However, the use of sustainable hybrid reinforcements with complete multi-response optimization is still very few.

2.3. Research Gap and Motivation

Recent studies showed that the performance of AMMCs was drastically improved by ceramic and hybrid reinforcements; despite this, most studies focused on traditional reinforcement systems or the optimization of particular features. There is little research on the combined use of ceramic reinforcements with sustainable industrial waste materials and their systematic multi-response optimization.

Hence, the present work aims to fabricate aluminum alloy 6061 hybrid composites reinforced with SiC, TiC and marble dust by stir casting technique and to optimize the density, hardness and compressive strength using Taguchi L9 orthogonal array. The work also links the microstructural features with the observed mechanical performance and provides a sustainable pathway to build lightweight engineering composites.

3. Material

3.1. Matrix Material

Aluminum alloy 6061 (AA6061) is selected as the matrix material for the fabrication of hybrid composites. AA6061 is a heat-treatable aluminum alloy extensively used in structural and automotive applications owing to its balanced combination of adequate strength, good corrosion resistance, and excellent castability. In addition, its chemical stability and favorable interfacial compatibility with ceramic reinforcements make it well-suited for the development of particle-reinforced aluminum matrix composites.

3.2. Reinforcement Material

Silicon carbide (SiC) was selected due to its high intrinsic hardness and its proven effectiveness in enhancing resistance to localized plastic deformation in aluminum-based composites [18, 21]. Titanium Carbide (TiC) is distinguished by its high hardness, high melting point, and excellent thermal stability, which together contribute to improved load transfer, enhanced compressive strength capacity, and overall mechanical performance of the composite [4, 7]. Marble dust obtained as an industrial waste by-product from stone processing operations is used as a reinforcement material in the composite system. The addition of marble dust promotes sustainable material utilization while contributing to improved particle packing and reduced porosity within the aluminum matrix.

Table 1. Taguchi L9 orthogonal array showing the reinforcement compositions used for fabricating hybrid composites

Material	Particle Size	Density	Purity	Impurities
SiC	<30 microns	3.20 g/cm^3	99%	SiO_2, , Al_2O_3, Free Carbon
TiC	<20 microns	4.93 g/cm^3	99%	TiO_2 , Al_2O_3, Free Carbon
Marble Dust	20-50 microns	2.7-2.9 g/cm^3	92-99%	SiO_2, Al_2O_3, Fe_2O_3, MgO

4. Experimental Methods

The stir casting method is used to prepare hybrid aluminum matrix composites, where aluminum alloy AA 6061 is used as the base material, which is reinforced with SiC, TiC, and marble dust particles. A Taguchi L9 orthogonal array is utilized to systematically change the level of reinforcement. The aluminum alloy was heated to 700-800 ^{O}C to melt it. After that, reinforcement particles preheated to 200 ^{O}C were added to the molten metal with steady feed rate manually. Mechanical stirring is done at 500 rpm for 5-6 minutes to evenly mixed reinforcement particles by creating a stable vortex. The mixtures pour into a preheated metallic mold of 2L capacity and allowed to solidify under normal environment condition.

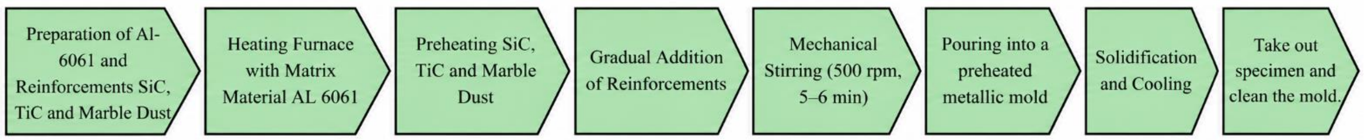


Fig. 1 Flow chart of stir casting process and reinforcement addition sequence for the fabrication of AA6061 hybrid composites

Table 2. Taguchi L9 orthogonal array showing the reinforcement compositions used for fabricating hybrid composites (Experiment Result)

Experiment	Silicon Carbide	Titanium Carbide	Marble Dust
1	Level 1 (5%)	Level 1 (4%)	Level 1 (2%)
2	Level 1 (5%)	Level 2 (6%)	Level 2 (4%)
3	Level 1 (5%)	Level 3 (8%)	Level 3 (6%)
4	Level 2 (10%)	Level 1 (4%)	Level 2 (4%)
5	Level 2 (10%)	Level 2 (6%)	Level 3 (6%)
6	Level 2 (10%)	Level 3 (8%)	Level 1 (2%)
7	Level 3 (15%)	Level 1 (4%)	Level 3 (6%)
8	Level 3 (15%)	Level 2 (6%)	Level 1 (2%)
9	Level 3 (15%)	Level 3 (8%)	Level 2 (4%)

5. Results and Discussion

Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD) investigations were performed to investigate the microstructural properties, elemental composition and phase constitution of the produced AA6061 hybrid composites. For the dependability and repeatability of the experimental results, the tests of density, hardness and compressive strength are repeated three times under the same testing conditions and the average values are shown.

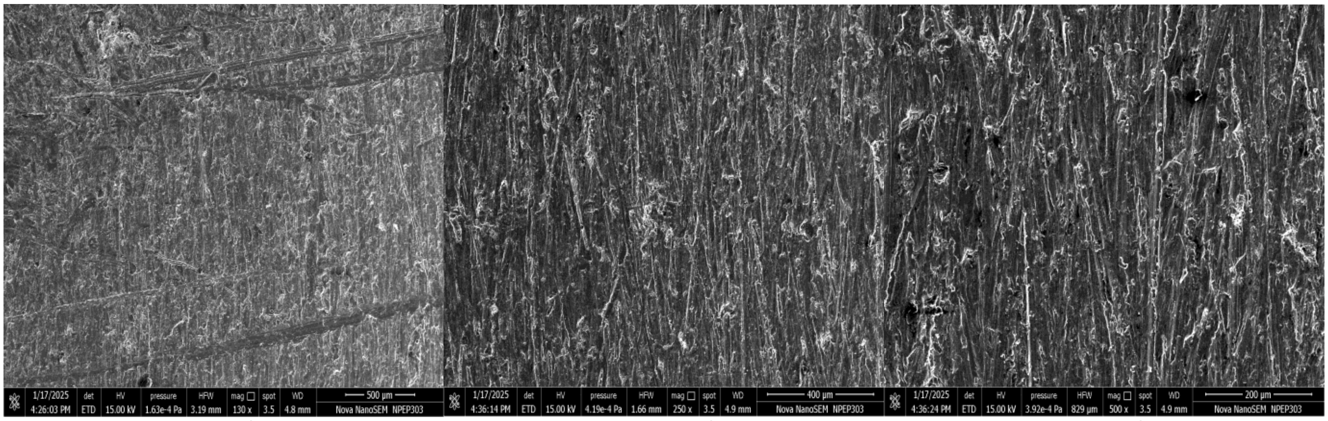
5.1. SEM and EDS Analysis of AA6061-SiC-TiC-Marble Dust Composites

SEM and EDS were used to analyze the microstructural characteristics, reinforcement distribution, and elemental composition of AA6061 hybrid metal matrix composites. All nine Taguchi L9 experimental experiments were analysed to determine how SiC, TiC, and marble dust contents affected microstructural integrity.

5.1.1. SEM Microstructural Observations

These micrographs Figure 1 show the aluminum matrix is solid and has ceramic particles that reinforce it. The reinforcing particles look as brighter, angled features, while the aluminum matrix looks like darker sections. This is because they have different surfaces and compositions. Within the matrix, it can be clearly see silicon carbide and titanium carbide particles. Marble dust particles, on the other hand, are mostly made up of calcium carbonate and have finer, more evenly distributed properties. The SEM images indicate that in composites with reduced reinforcement concentrations experiments 1 - 3, the reinforcement particles are uniformly distributed throughout the aluminum matrix, exhibiting minimal porosity.

Occasionally, minor surface defects and micro-voids occur. These are probably due to localized solidification shrinkage during the stir-casting process. At medium reinforcement levels, experiments 4 - 6, the particle distribution becomes more uniform, indicating effective vortex-assisted mixing and optimal integration of the ceramic reinforcements. The interfaces between the reinforcement and the matrix appear satisfactory, exhibiting minimal signs of interfacial discontinuities. In experiments 7 - 9, increased reinforcement results in SEM micrographs revealing a greater density of reinforcement particles within the matrix, with notable clustering of particles, particularly in composites containing higher amounts of TiC. Overall dispersion is good; SEM investigation shows that the particles of SiC, TiC, and marble dust have been well mixed and spread throughout the aluminum matrix.



(a) 130x magnification **(b) 250x magnification** **(c) 500x magnification**

Fig. 2(a-c) SEM micrographs of the fabricated hybrid composites at different magnifications, illustrating the distribution of reinforcement particles and microstructural features

5.1.2. EDS Point Analysis

EDS spectra Figure 3 from certain areas of each sample confirm the presence of the matrix and reinforcement constituents. Aluminum (Al) always has the highest peak (1.5 keV), which shows that it is the matrix material in all compositions. The peaks for Silicon (Si) and Titanium (Ti) show that SiC and TiC reinforcements are successfully added. Carbon (C) peaks come from carbide reinforcements (SiC and TiC), while Oxygen (O) peaks come from marble dust and some surface oxidation. Few samples show small peaks of iron (Fe), which probably came from processing equipment, but concentrations are still quite low. Changes in reinforcement content are closely related to changes in peak intensities throughout experiments. This shows that the designed compositions and produced samples are consistent with each other.

5.1.3. SEM-EDS Elemental Mapping

Elemental mapping Figure 4 (a)-(i) provides additional evidence for the SEM and EDS results, and is used for visually assessing the spatial distribution of the elements that play a major role. Aluminum maps show the continuous and uniform matrix phase in the samples. Silicon and Titanium maps are confirming the fact that SiC and TiC reinforcements are thus generally well dispersed throughout the matrix, and only slight clustering is noticed at higher levels of reinforcement. Carbon maps match with Si and Ti distributions, thus confirming the carbide origin. Oxygen mapping reveals a scattered distribution, which is consistent with the addition of marble dust and minor oxidation effects. The oxygen signals intensity becomes lower in the samples containing less marble dust, thus proving compositional control during the manufacturing process.

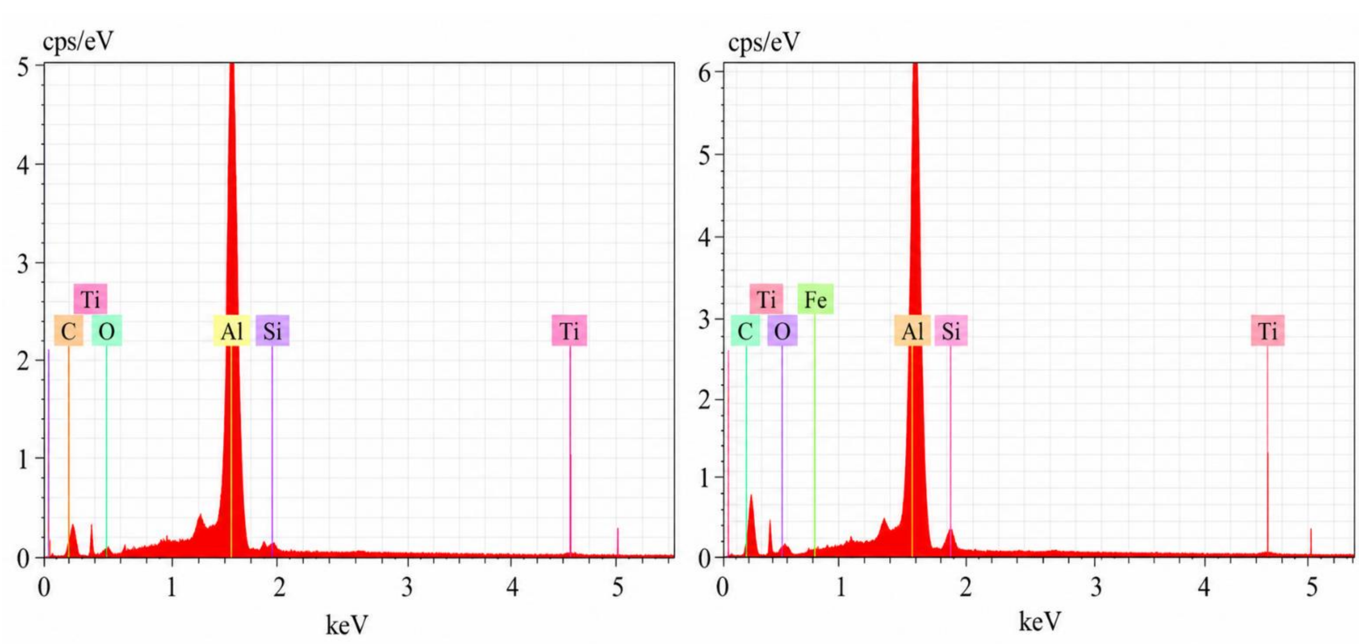


Fig. 3 EDS spectrum of the fabricated hybrid composite confirming the presence of Al, Si, Ti, C, and O elements, with trace Fe as a minor impurity

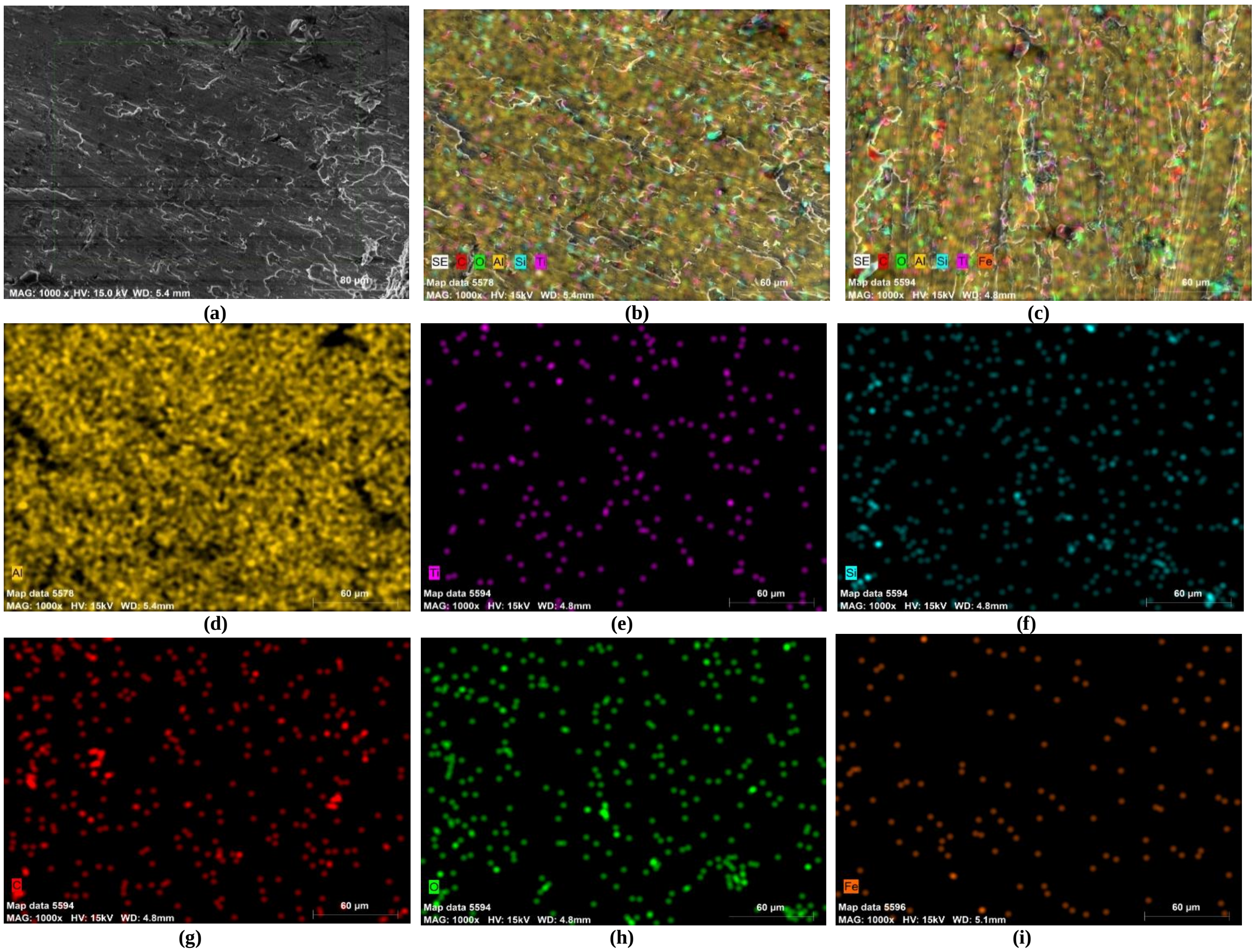


Fig. 4 SEM image and corresponding EDS elemental maps of the as-fabricated Al-SiC-TiC-marble dust composite: (a) SEM micrograph of the analyzed region, (b) combined elemental overlay (C, O, Al, Si, Ti), (c) combined elemental overlay including Fe, (d) Al, (e) Ti, (f) Si, (g) C, (h) O, and (i) Fe elemental distributions.

5.1.4. Microstructural Implications

The SEM-EDS results together show that the stir casting method works well for making AA6061 hybrid composites containing SiC, TiC, and marble dust. At low to moderate levels of reinforcement, the particles are evenly spread out, and the bonds between them are strong. But when more ceramics are added, the particles tend to clump together, and micro-cracks start to form.

5.2. XRD Results and Discussion

X-ray diffraction (XRD) analysis is carried out to identify the crystalline phases present in the AA 6061-SiC-TiC-Marble dust hybrid composites and to examine phase stability after stir casting. The diffraction patterns confirm the formation of a stable multiphase composite system without the appearance of undesirable reaction products.

5.2.1. Phase Identification and Matrix Integrity

All of the XRD patterns show strong diffraction peaks at about $2\Theta=38.7^{O}-38.9^{O}$ and $44.9^{O}-45.1^{O}$. These peaks correspond to the (111) and (200) planes of Face-Centred Cubic (FCC) aluminum, respectively. The peaks are quite sharp and strong, which means that the aluminum matrix keeps its crystalline structure even after adding reinforcement and solidifying. There is no peak splitting or unusual peak shifts, which means that the aluminum matrix is not forming solid solutions or severely distorting its lattice.

5.2.2. Reinforcement Phase Confirmation

Additional diffraction peaks observed at $2\Theta = 65^{O}$ and 78^{O} are attributed to the (220) and (311) planes of silicon carbide and titanium carbide. These peaks look the same in different experiments shows that carbide reinforcements were successfully added and kept throughout stir casting. There are no new intermetallic phase’s means that there were no harmful chemical interactions between the aluminum matrix and the reinforcements during processing. This is important because such kinds of reaction products can damage mechanical characteristics and long-term stability. The low-angle diffraction peaks seen at $2\Theta = 8.3^{O}$-8.8^{O} match those of calcite ($CaCO_3$), which shows that there is marble dust in crystalline form. This peak appeared in all of the samples that were looked at shows that marble dust kept its structural identity after being cast. Even though $CaCO_3$ peaks are weak because they have less content and a lower scattering factor, finding them shows that marble dust is a stable secondary phase that does not breakdown or react with the aluminum matrix.

5.2.3. Peak Characteristics and Microstructural Implications

The XRD peaks in all of the samples are sharp and well-defined, which means that the crystals are well-formed. There is no considerable peak broadening, which means that grain refinement and micro-strain effects are restricted. This also means that the reinforcements are mostly present as separate phases and do not cause lattice deformation. The Taguchi-based compositional design works because small differences in peak intensity across experiments are linked to changes in reinforcement content. From a microstructural point of view, the XRD data enhance SEM-EDS observations by validating that the reinforcements exist as physically embedded phases with stable interfaces, rather than as reaction-induced phases. This phase's stability is important for getting constant hardness and compressive strength. Further, the qualitative SEM observations were validated by the XRD phase identification and density measurements. The XRD data indicated the successful incorporation of the reinforcement phases. The density measurements were indicative of the effect of reinforcement content and porosity on the microstructural features of the produced composites.

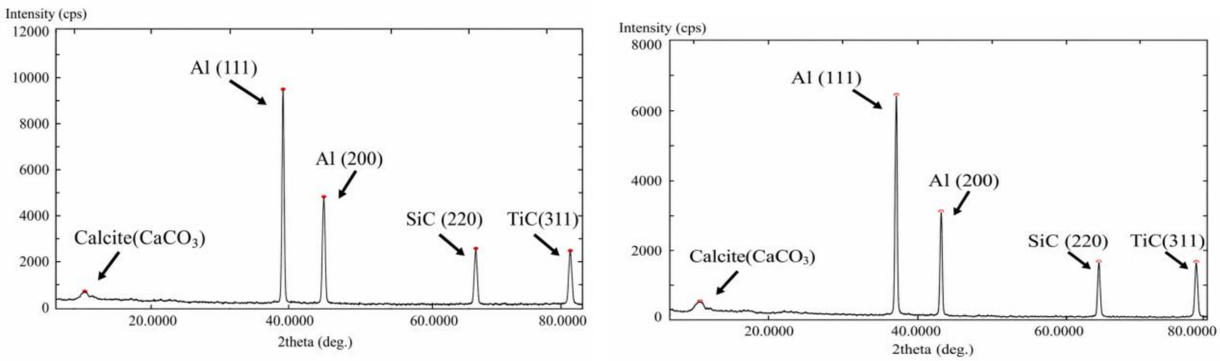


Fig. 5 (a-b) XRD patterns of the fabricated AA6061-SiC-TiC-Marble Dust hybrid composites showing the dominant Al matrix peaks together with SiC, TiC, and $CaCO_3$ reinforcement phases

5.2.4. Correlation with Mechanical Performance

The confirmed presence of hard ceramic phases SiC and TiC, along with a stable aluminium matrix and intact marble dust phase, explains the observed enhancement in hardness and compressive resistance. The lack of brittle reaction products supports the enhanced load transfer efficiency noted in mechanical testing. The XRD results strongly suggest that the way the materials are processed and the choice of reinforcements are good for making AA6061 hybrid composites that are stable in terms of mechanics.

5.3. Compression Test

The compressive strength of unreinforced AA6061 is 278 MPa, whereas the developed hybrid composites exhibited values ranging from 302 MPa to 412 MPa, indicating a significant improvement due to the combined reinforcement of SiC, TiC, and marble dust. Compression testing is performed to evaluate the elastic stability and compressive load-bearing capacity of the AA6061-SiC-TiC-marble dust composites. The compressive stress at a 15 mm displacement is selected to indicate the compressive strength, as all specimens are experienced stable elastic and plastic deformation without failure and gives strain hardening. The 0.2% offset yield stress and compressive stress at 15 mm displacement provide accurate elastic limit and compressive strength comparison of the effects of reinforcement combinations in the taguchi experiments. The Al with SiC, TiC, and marble dust composites' response clearly depends on the amount of reinforcement. In lower reinforcement levels up to experiment 3, compressive strength increases from 302 MPa to 326 MPa, with corresponding elastic limit increases from 36.7 MPa to 39 MPa. This trend reflects the increasing reinforcement of ceramic particles, enhancing load transfer. Composites of experiments 4 to 6 presented more stable and balanced compressive behaviour. Experiment 4 SiC 10%, TiC 4%, and marble dust 4% achieved a compressive strength of 337 MPa with an elastic limit of 39 MPa, highlighting the contribution of reinforcement to compressive strength. A similar response is observed for Experiment 6 SiC 10%, TiC 8%, and marble dust 2%, indicating that higher SiC, TiC and marble dust content improves particle matrix interaction and load-sharing efficiency. These compositions achieve an effective balance between reinforcement and matrix continuity. At higher reinforcement levels from Experiments 7 to 9, compressive strength increased further with ceramic content. Experiment 9: SiC 15%, TiC 8%, and marble dust 4%, compressive strength 412 MPa, with an elastic limit of 51.9 MPa achieved. Overall, the results show that intermediate compositions, Experiments 4 and 6, offer a more balanced compressive strength and structural stability, even though maximum compressive strength is attained at higher reinforcement levels.

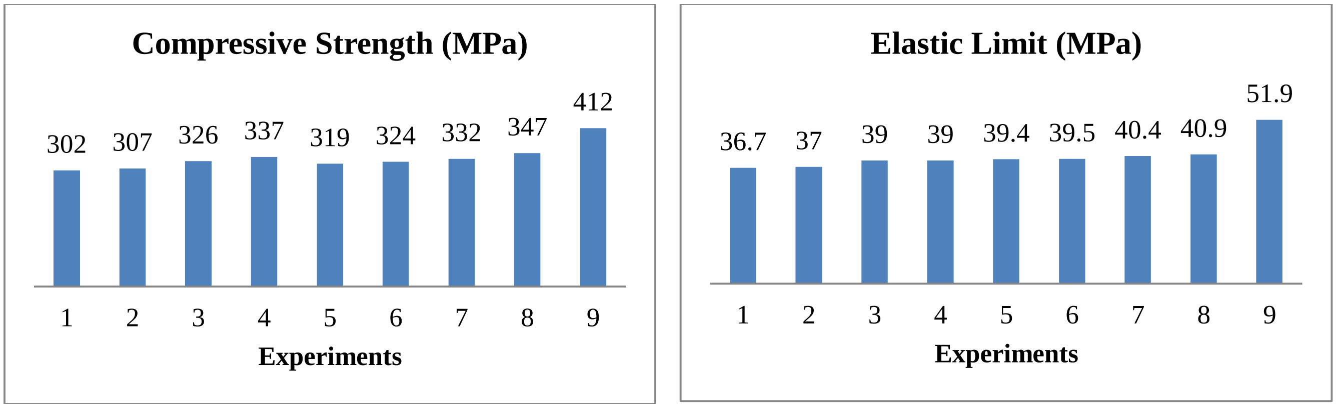


Fig. 6 Experimental results of compressive strength and elastic limit for the fabricated AA6061-SiC-TiC-Marble Dust hybrid composites.

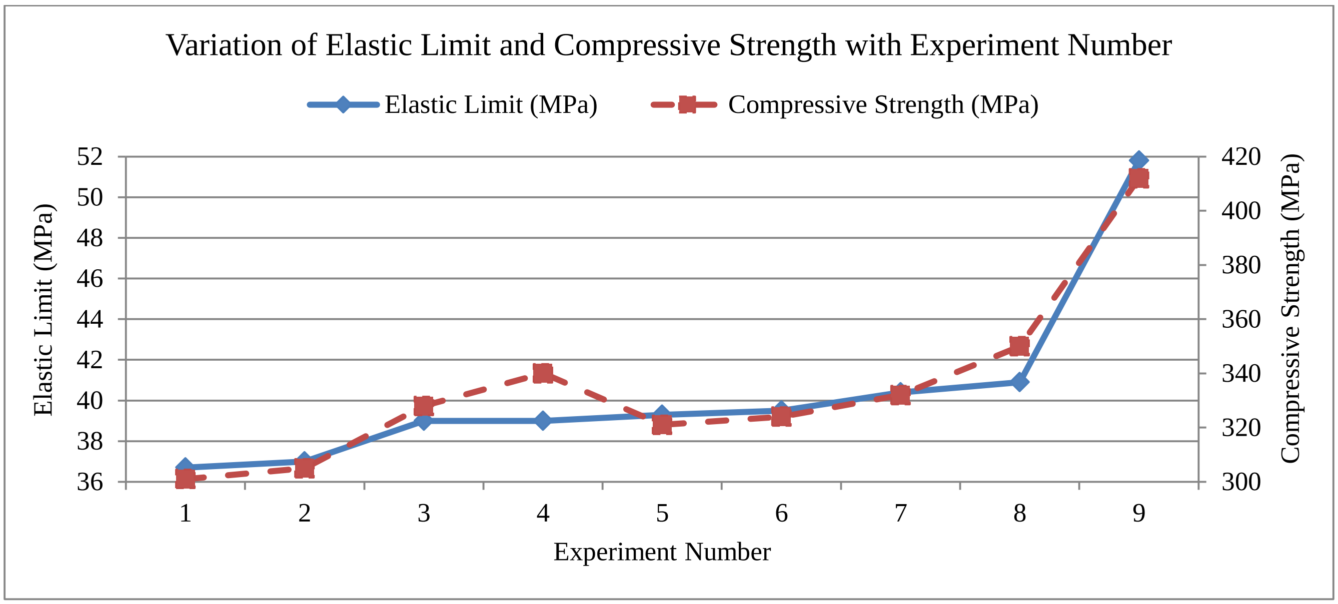


Fig. 7 Variation in compressive strength and elastic limit of the fabricated hybrid composites with different reinforcement compositions

5.4. Hardness Test

Al-SiC-TiC-Marble Dust hybrid reinforced composite specimen hardness tests are carried out on a Rockwell hardness tester machine conforming to IS 1586 (Part 1): 2018, at room temperature. The hardness of unreinforced AA6061 is 27.6 HRA, while the fabricated hybrid composites exhibited hardness values ranging from 29.83 HRA to 51.3 HRA, demonstrating the strengthening effect of the ceramic reinforcements.

As the amount of reinforcement increases, the hardness also increases. This was especially true for larger amounts of SiC and TiC, which showed that they are effective as hard ceramic reinforcements. Experiment 1, which is the lowest level of all three reinforcements, 5% SiC, 4% TiC, and 2% marble dust, has the lowest hardness value, 29.83 HRA. Experiment 9, on the other hand, has the highest hardness rating of 51.3 HRA. This is because it has the highest levels of SiC 15% and TiC 8%, along with a reasonable amount of marble dust 4%.

5.5. Density Test

The density of unreinforced AA6061 is 2.70 g/cm³, whereas the hybrid composites increased steadily from 2.78 g/cm^3 to 2.90 g/cm^3 as the amount of reinforcement increased. The density measurements showed the composite density. It shows the reinforcing particles were effectively added, and the composite became more compact. The composite with the lowest amount of reinforcement has the lowest density, whereas with 15% SiC, 8% TiC, and 4% marble dust has the highest density. The higher SiC and TiC content makes the material denser since these materials have higher intrinsic densities than the matrix. Marble dust changed the density due act as a micro filler. The intermediate substance helped fill in the gaps and make the material denser. However, because the particles are insufficiently moist and adhered to one another, an excessive amount of marble dust caused the density to significantly decrease. The fact that the optimal density and hardness conditions are very close to each other shows that better densification and less porosity are important for making the composites work better mechanically.

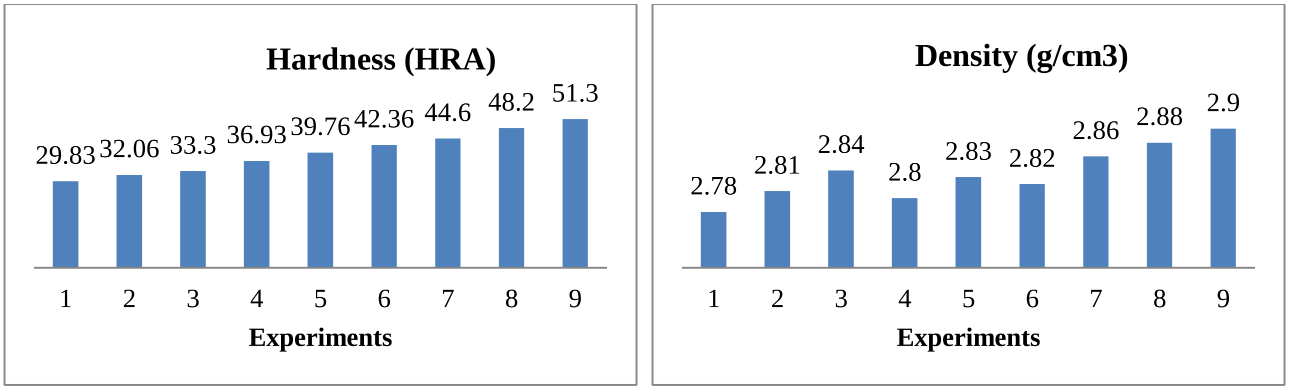


Fig. 8 Experimental results of hardness and density for the fabricated AA6061-SiC-TiC-Marble Dust hybrid composites.

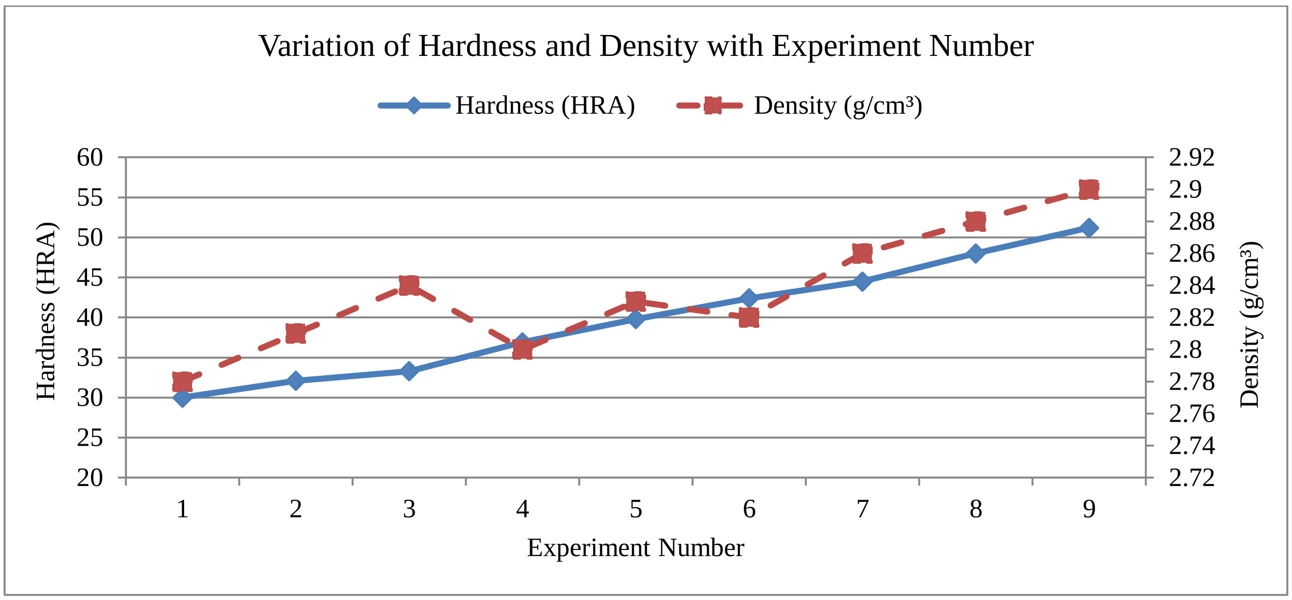


Fig. 9 Variation in hardness and density of the fabricated hybrid composite with different reinforcement compositions

5.6. Comparative Analysis with Published Literature

The experimental results reported in the present work are in line with the prior studies on aluminum matrix composites reinforced with ceramic particles.

Previous researches have shown that ceramic reinforcements improve the hardness and compressive strength of aluminum alloys through effective load transmission, grain refinement and resistance to plastic deformation.

The microstructural investigation showed that the improved characteristics achieved in this work are due to the synergistic effect of the hybrid reinforcements and their rather uniform distribution in the AA6061 matrix.

In addition, the mechanical properties were improved at a relatively low density due to the optimal combinations of reinforcements obtained via the Taguchi L9 design. The study shows the promise of the created hybrid composite for lightweight engineering applications and also encourages the sustainable use of industrial marble waste.

5.7. Strengthening and Failure Mechanism

The failure behavior of the developed AA6061-SiC-TiC-Marble Dust hybrid composites was evaluated based on the results of microstructural characterization and compressive strength. SEM micrographs showed a rather homogeneous distribution of the reinforcement particles in the aluminum matrix. EDS and XRD investigations validated the successful inclusion of SiC, TiC and marble dust without noticeable adverse reaction products. Such microstructural characteristics enable an efficient load transfer from the matrix to the reinforcements and increase resistance to localized plastic deformation under compressive loading. The ceramic particles are obstacles for dislocation motion, whilst the marble dust provides particle filling, a decrease in porosity and stabilization of the matrix. These properties are intended to enhance resistance to crack initiation and propagation and, therefore, to enhance the compressive strength of the composite. The overall improved mechanical performance of the produced hybrid composites is attributed to the improved interfacial bonding, homogeneous reinforcement distribution and reduced porosity.

5.8. Multi-Response Optimization Results

Experiment 1 is lowest hardness, 29.83 HRA and compressive strength 302 Mpa and Experiment 9 is the hardest, 51.3 HRA and compression strength 412 MPa of experiments. In general, increasing the levels of SiC and TiC makes things harder and stronger. But this experiment also has the highest density and cost index, which decreases its overall optimization score. The experimental results and the corresponding multi-response optimization using the closeness coefficient (Ci), Experiment 4 has the highest closeness coefficient Ci = 0.781 and is most optimal. This means that it had the best balance of cost, density, and mechanical performance. Experiment 6 is the next closeness coefficient Ci = 0.704 and was a little more expensive, but it was harder and has almost the same compressive strength. The results suggest that Experiments 4 and 6 are the best combinations of reinforcements for casting because they achieve an optimal balance. The optimized AA6061-SiC-TiC-Marble Dust hybrid composite offers potential for lightweight engineering applications requiring improved compressive strength, hardness, and low density. In addition, the use of marble dust as a waste-derived reinforcement supports sustainable material development through the effective utilization of industrial waste, making the developed composite suitable for automotive and structural applications.

Table 3. Taguchi L9 experimental runs and corresponding multi-response optimization results.

Experiment	Hardness (HRA)	Elastic Limit (MPa)	Compressive Strength (MPa)	Density (g/cm^3)	Cost Index	Ci (Closeness Coefficient)
1	29.83	36.7	302	2.78	11	0.446
2	32.06	37	307	2.81	15	0.492
3	33.3	39	326	2.84	19	0.668
4	36.93	39	337	2.8	18	0.781
5	39.76	39.4	319	2.83	22	0.561
6	42.36	39.5	324	2.82	20	0.704
7	44.6	40.4	332	2.86	25	0.604
8	48.2	40.9	347	2.88	23	0.632
9	51.3	51.9	412	2.9	27	0.548

6. Conclusion

Hybrid aluminum matrix composites reinforced with SiC, TiC, and marble dust are successfully fabricated by using stir casting. The composites exhibited interfacial bonding and stable microstructures. SEM-EDS and XRD analyses confirmed uniform reinforcement dispersion and phase stability, without any of the harmful reaction products, thereby demonstrating the effectiveness of the selected processing conditions. The mechanical tests showed that the hardness from 29.83 HRA to 51.3 HRA and compressive strength 302 MPa to 431 MPa improved in a systematic way as more ceramic reinforcement was added, while density remained within an acceptable range from 2.78 g/cm^3 to 2.90 g/cm^3 for lightweight applications. Multi-response optimization showed experiment 4 as the optimal composition for the best balance of mechanical properties, density control and cost efficiency. Experiment 6 showed slightly higher hardness and compressive strength suitable for applications where strength is important over cost. Overall, moderate reinforcement levels offer an effective balance between performances, making the developed composite suitable for metal casting applications. The developed hybrid composites showed potential for advanced lightweight engineering applications while supporting the sustainable utilization of industrial marble waste.

References

[1] Chitti Babu Golla et al., "Influence of TiC Particles on Mechanical and Tribological Characteristics of Advanced Aluminium Matrix Composites Fabricated through Ultrasonic-Assisted Stir Casting," *Crystals*, vol. 13, no. 9, pp. 1-20, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[2] Pardeep Sharma et al., "Microstructural and Mechanical Behavior of Microstructural and Mechanical Behavior of Aluminium Alloy Reinforced with TiC," *Materials Today Proceeding*, vol. 25, no. 4, pp. 934-937, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Pankaj Beldar, and Snehal Kadbhane, "Mechanical and Wear Analysis of AA6061-T6-SiC-TiC-Graphite Metal Matrix Composite," *Materials Letters*, vol. 382, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Manvendra Yadav et al., "Erosion Behavior of Al–SiC and Al–WC MMCs via Powder Metallurgy under Solid Particle Impingement," *Scientific Reports*, vol. 14, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Lucia Lattanzi, and Anders E. W. Jarfors, "Advances in Metal Matrix Composites: Structure, Properties and Applications," *Crystal*, vol. 15, no. 12, pp. 1-5, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[6] Jaswinder Singh, and Amit Chauhan, "Characterization of Hybrid Aluminum Matrix Composites for Advanced Applications – A Review," *Journals of Material Research and Technology*, vol. 5, no. 2, pp. 159-169, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[7] Chinmayee Kar, and B. Surekha, "Characterisation of Aluminium Metal Matrix Composites Reinforced with Titanium Carbide and Red Mud," *Materials Research Innovations*, 25, no. 2, pp. 67-75, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] P. Senthilkumar, R. Manimaran, and Y. Krishna Reddy, "Evaluation of Mechanical Properties of Hybrid Al7009 Nanocomposite," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 43, no. 2, pp. 216-224, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] N. Radhika et al., "Periodic Advancement of Aluminium Metal Matrix Composites: Tribo-Mechanical Performance, Corrosion Properties, Challenges and Future," *Advances in Materials and Processing Technologies*, vol. 10, no. 3, pp. 2397-2420, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] V.K. Parikh et al., "Fabrication and Processing of Aluminum Alloy Metal Matrix Composites," *Materials and Manufacturing Processes*, vol. 36, no. 14, pp. 1604-1617, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Chuan Tan et al., "Microstructure, Mechanical, and Machining Properties of 2024 Al Composites Reinforced with TiB_2, SiC, and Diamond Particles," *Metals*, vol. 16, no. 1, pp. 1-20, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[12] Hassan Raza Channar et al., "Mechanical Properties and Microstructural Investigation of AA2024-T6 Reinforced with Al_2O_3 and SiC Metal Matrix Composites," *Eng*, vol. 5, no. 4, pp. 3023-3032, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[13] Haitham Mohammed Ibrahim Al-Zuhairi, and Samir Ali Amin, "Manufacturing of Hybrid Aluminum Metal Matrix Composites Reinforced with SiC and Al_2O_3 : A Review," *Al-Rafidain Journal of Engineering Sciences*, vol. 3, no. 1, pp. 450-473, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[14] R. A. Oza, and Anand B. Dhruv, "Influence of Sic Reinforcement on Mechanical Properties of AA2024 Metal Matrix Composites (Ammc) Fabricated via Stir Casting Method: A Review," *Journal Propulsion of Technology*, vol. 25, no. 2, pp. 1434-1441, 2024. [CrossRef] [Publisher Link]

[15] Getachew Gashaw, Eyob Sisay Yeshanew, and Ramesh Babu Nallamothu, "Fabrication, Mechanical Properties and Microstructural Analysis of Al/SiC-Bagasse ash Hybrid Composite," *Discover Applied Science*, vol. 7, pp. 1-19, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[16] C.S. Ramesh et al., "Microstructure and Mechanical Properties of Ni–P Coated Si_3N_4 Reinforced Al6061 Composites," *Material Science and Engineering: A*, vol. 502, pp. 99-106, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[17] Y. Sahin, "Preparation and Some Properties of SiC Particle Reinforced Aluminium Alloy Composites," *Material & Design*, vol. 24, no. 8, pp. 671-679, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[18] A. Baradeswaran, and A. Elaya Perumal, "Influence of B_4C on the Tribological and Mechanical Properties of Al-7075-B_4C Composites," *Composite Part B: Engineering*, vol. 54, pp. 146-152 2013. [CrossRef] [Google Scholar] [Publisher Link]

[19] Sohan Lal, Rajeev Sehrawat, and Neeraj Sharma, "A Short Review on the Developments of Aluminium Matrix Composites," *Materials Today: Proceeding*, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[20] M.K. Surappa, "Aluminium Matrix Composites: Challenges and Opportunities," *Sadhana*, vol. 28, pp. 319-334, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[21] J. Hashim, L. Looney, and M.S.J Hashmi, "Metal Matrix Composites: Production by the Stir Casting Method," *Journal of Material Processing Technology*, vol. 92-93, pp. 1-7, 1999. [CrossRef] [Google Scholar] [Publisher Link]

[22] S. Balasivanandha Prabu et al., "Influence of Stirring Speed and Stirring Time on Distribution of Particles in Cast Metal Matrix Composites," *Journal of Material Processing Technology*, vol. 171, no. 2, pp. 268-273, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[23] Daniel B. Miracle, and Steven L. Donaldson, *Introduction to Composites*, ASM Handbook, ASM International, Materials Park, vol. 21. 2001. [CrossRef] [Google Scholar] [Publisher Link]