Research Article

Journal of Environmental Nanotechnology

Evaluation of the Mechanical Properties of Aluminium Hybrid Nano Composites Using Ultrasonic-assisted Stir Casting Method and Reinforced with Nano-scale SiC and MoS_2 Particles

D. Sudarsan[1*], A. Bovas Herbert Bejaxhin[1], S. Raj Kumar[2], A. S. Anitha[3] and Venkat Prasat Sridhar[4]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Thandalam, Chennai, TN, India

[2]Institute of Technology, Hawassa University, Department of Mechanical Engineering, Ethiopia

[3]Department of Biotechnology, Karpaga Vinayaga College of Engineering and Technology, Chengalpattu, TN, India

[4]Department of Mechanical Engineering, Rajalakshmi Engineering College, Thandalam, Chennai, TN, India

Received: 28.05.2024 Accepted: 25.08.2024 Published: 30.09.2024

*dssudersun1976@gmail.com

ABSTRACT

The purpose of this research is to investigate the effects of adding large quantities of reinforcing agents specifically, 3% MoS_2 along with different SiC concentrations 5%, 10%, and 15% to LM25 aluminium alloys. The goal of producing these composites was to improve the material characteristics of hybrid metal matrix composites by the use of ultrasonic-assisted stir casting. The study looks at the possible benefits of using particulate materials to improve the mechanical properties of metallic composites, such as SiC and MoS_2. The study investigated the effect of nano-scale additions of SiC and MoS_2 on the mechanical and structural properties of LM25 composites through experimental analysis. The results of mechanical testing showed notable improvements, particularly with the addition of 15% nano-scale SiC. This improvement was mainly attributed to the uniform distribution of nano-SiC within the matrix material.

Keywords: Metal matrix composite; Ultrasonic stir casting; Nano SiC reinforcements; Tensile strength; Nano composite.

1. INTRODUCTION

Metals are used as matrix materials and can be reinforced with ceramics, metals, or organic compounds to develop metal matrix composites (MMCs). Since metals alone cannot satisfy all application requirements, their properties are enhanced through reinforcement with suitable materials. In this context, aluminium MMCs help meet the demands of various applications, including automotive, aerospace, and related industries. To improve the properties of base alloys, reinforcements such as SiC, Al_2O_3, boron carbide, zircon, and fly ash are commonly used. These reinforcements are generally classified into three types: particulate, discontinuous fibres, and continuous fibres.

Sulaiman *et al.* (2017) examined how different weight percentages of strontium affect the mechanical and microstructural characteristics of Al-12Si (LM6) alloy and Al-SiC composites. The effect of strontium as a modifier on the microstructure was investigated using an electron microscope equipped with an EDS scanning system. Using the vortex process, the Al-SiC composite was created using 10 weight percent silicon carbide and various Al-10Sr fractions (0.02, 0.5 weight percent). The inclusion of SiC and Sr enhanced the ultimate tensile strength, but any increases in tensile characteristics were limited by the weak contact between the particles and the matrix. Mohan *et al.* (2015) reported that silicon carbide-reinforced aluminium matrix composites are widely used in the automotive and aerospace industries due to their enhanced strength and stiffness. Many studies have been conducted on the production of AMCs using the stir casting method with different weight percent of SiC. Studies show that as the SiC content increases, so do the yield strength and modulus of elasticity of Al/SiC composites. However, the inclusion of SiC particles causes a shift in fracture behavior from ductile to brittle, as shown by SEM fractographs, indicating a balance between strength and fracture toughness.

Singh *et al.* (2020) extensively studied the mechanical and microstructural properties of aluminium–silicon carbide composites fabricated using powder metallurgy and stir casting techniques. Research indicates that the effective transmission of stress and strengthening of dislocations are the reasons why adding more SiC to Al/SiC composites increases their hardness. Analyses using SEM show how SiC particles are distributed and affect the composites. Furthermore, the SiC concentration has a major impact on the densification behavior, which in turn affects the composites' overall

density and mechanical performance. Ashebir *et al*. (2022) reported that hybrid aluminium matrix composites, which incorporate multiple reinforcing elements, exhibit superior properties compared to single-reinforcement composites. The study reviewed various synthesis techniques, including powder metallurgy and stir casting, and evaluated the effects of reinforcements such as graphite, silicon carbide, and aluminium oxide on mechanical and metallurgical properties. It also provided detailed insights into testing methods, including hardness, tensile, compressive, and tribological tests, as well as characterization techniques such as X-ray diffraction and optical microscopy, highlighting a comprehensive understanding of the physicomechanical behaviour and processing of HAMCs. The increased mechanical characteristics of aluminium Nano composites supplemented with B_4C, SiC, and CNT particles are attracting growing attention in research (Nirala *et al*. 2023). The SEM and XRD tests validated that the reinforcing distribution is uniform throughout the fabrication process of squeeze stir casting. The production of intermetallic compounds and dislocation structures, which increase composite strength, was confirmed by TEM examinations. Comparative analyses showed that B_4C-reinforced composites outperform SiC-reinforced composites in terms of hardness, Young's modulus, and wear resistance, underscoring the important influence of reinforcing type on the performance of the nanocomposites. Sharifi, E *et al*. (2011) reported that Al–B_4C nanocomposites have attracted significant attention due to their enhanced mechanical properties. In their study, bulk composites with varying B_4C contents were fabricated by combining pure aluminium powder and B_4C nanoparticles through ball milling followed by hot pressing. The results indicated that an increase in B_4C content, particularly at 15 wt%, led to a substantial improvement in wear resistance, compressive strength, and hardness compared to pure aluminium. The improved wear performance was primarily attributed to the formation of a mechanically mixed layer on the composite surface, which acts as a protective barrier during sliding.

Arif *et al*. (2019) extensively investigated the wear behaviour of hybrid Al–SiC nanocomposites reinforced with micro-SiC and varying concentrations of nano-SiC. The study revealed that wear resistance is strongly influenced by factors such as nano-SiC content, sliding distance, and applied load, with 5 wt% nano-SiC providing optimal performance. Microstructural analysis of worn surfaces and wear debris using SEM and EDS confirmed the significant role of nano-SiC reinforcement in enhancing tribological properties. Furthermore, regression models employed to predict wear behaviour demonstrated high accuracy, highlighting their effectiveness in estimating tribological performance under specific operating conditions. Vinayaka. N *et al*. (2023) highlighted that aluminium metal matrix composites, particularly those reinforced with nanoscale particles, play a crucial role in automotive, aerospace, and defence applications due to their superior mechanical properties. In their study, stir-cast AA8011 aluminium alloy reinforced with 15 wt% nano boron carbide exhibited significant improvements in tribological behaviour. Detailed analysis of worn surfaces using scanning electron microscopy under varying sliding velocities, temperatures, and applied loads demonstrated enhanced wear performance. Furthermore, multi-objective optimisation using the grey relational analysis approach confirmed the effectiveness of these composites in achieving desirable tribological characteristics. Ma M *et al*. (2015) reported that nano-multilayered films, characterized by their nanoscale layered architecture, exhibit exceptional hardness, superior high-temperature oxidation resistance, and reduced wear rates. These properties make them highly suitable for surface protection applications across a wide range of engineering fields.

Cheng *et al.* (2023) reported that nano-multilayered films, composed of layers structured at the nanoscale, are widely employed for surface protection due to their low wear rates, high-temperature oxidation resistance, and superior hardness. Recent studies have extensively examined their various types, fabrication techniques, microstructural features, mechanical properties, and corrosion resistance. Nagavelly *et al*. (2024) reported that the development of lightweight materials, particularly aluminium alloys, plays a vital role in reducing CO_2 emissions and enhancing fuel efficiency. Their study demonstrated that reinforcing aluminium 7075 alloy with various nanoparticles leads to the formation of metal matrix composites with improved mechanical and tribological properties. Kumar *et al*. (2020) conducted studies on the high-temperature wear behaviour of Al2219-based composites, such as Al2219+2%n-B_4C (mono) and Al2219+2%n-B_4C+2%MoS_2 (hybrid). These composites were prepared by stir casting, and wear experiments showed that temperature, load, and sliding velocity had a major impact on wear rates. Owing to the production of oxide layers and the lubricating properties of MoS_2, the Al2219/2%n-B_4C/2%MoS_2 hybrid composite exhibited decreased wear at higher temperatures, while the specific wear rate of Al2219 and Al2219/2%n-B_4C increased with temperature. At higher temperatures, SEM analysis verified that the hybrid composite has shallower and narrower wear tracks. Wu *et al*. (2022) used an *in-situ* reaction between KBF_4 and K_2ZrF_6 fluoride powders to form ZrB_2/Al7085 nanocomposites, which were subjected to heat treatment and hot deformation. ZrB_2 nanoparticles and second phases were redistributed during hot rolling, which enhanced the microstructure. ZrB_2 particles and α-Al interfaced semi-coherently, according to TEM examination. By minimizing anisotropy, reducing residual stress, and refining grain size, ZrB_2 particles improved the mechanical properties. To increase the strength of the composite, the

strengthening methods comprised load transfer, Orowan strengthening, thermal expansion coefficient, and grain refining. Gao *et al*. (2023) reported that the incorporation of dispersed nanoparticles is an effective approach to enhance both the strength and ductility of metals and alloys. In their study, ZrB_2/AA7085 nanocomposites fabricated through an *in situ* melt process exhibited significant improvements in mechanical properties. The presence of ZrB_2 nanoparticles, with an average size of approximately 95 nm, facilitated dynamic recrystallization and modified precipitation behaviour, leading to improved particle distribution and refined α-Al grains. As a result, both ultimate tensile strength and elongation were markedly enhanced, highlighting the potential of nanoparticle reinforcement in the development of high-performance nanocomposites. Fang *et al*. (2020) investigated the *in situ* reinforced AA6016 matrix composite with ZrB_2 and Al_2O_3 nanoparticles. The study demonstrated that temperature and strain rate have a major impact on the behaviour of hot deformation, with flow stress quickly rising with true strain and falling with temperature. The behaviour of the material was well described by the constitutive model based on the Arrhenius equation. Two stable deformation zones were found by processing maps: Domain B (410–430 °C/0.37–1 s^{-1}), which is characterized by dynamic recrystallization, and Domain A (300–360 °C/0.08–0.01 s^{-1}), which was regulated by dynamic recovery. According to microstructural study, these nanoparticles improved the nucleation of recrystallization at high temperatures, which makes Domain B the ideal hot processing window. Zhao *et al*. (2018) reported *in situ* synthesized 2 vol. % nano ZrB_2/AA6111 composites. The authors showed that flow stress reduces with increasing temperature and decreasing strain rates, with notable post-stability variation in the flow curves. Constitutive modeling based on predicted material constants accurately characterized the behaviour of the composite. Processing maps revealed the best hot deformation domains, with Domain B (430 °C–460 °C/0.13–1.1 s^{-1}) being the most advantageous because particle clusters promote dynamic recrystallization. By lowering recrystallization grain size, these clusters improved high-temperature performance by enhancing DRX while restricting grain growth. Kai *et al*. (2015) investigated the hot deformation behaviour of an *in situ* 5 wt% nano ZrB_2/2024Al composite and reported that both temperature and strain rate significantly influence flow stress. The study showed that the presence of nanoparticles led to noticeable strain hardening, particularly at higher temperatures and strain rates. Microstructural observations supported the kinetic analysis, confirming dynamic recrystallization as the dominant deformation mechanism governing the material response. Two primary domains were found by processing maps: domain 1 (380–410°C/0.018–0.032 s^{-1}) and domain 2 (440–460 °C/0.075–0.56 s^{-1}). Domain 2 was best suited for hot processing because of its finely equiaxed grain structure and better power dissipation efficiency. The results highlighted domain 2 as the ideal window for effective and secure hot deformation. Tao *et al*. (2022) reported that particle-reinforced aluminium matrix composites (PRAMCs) often exhibit poor forming stability due to particle–matrix separation; however, in situ PRAMCs such as ZrB_2-reinforced AA6111 demonstrate improved interfacial bonding and enhanced mechanical properties. The study showed that increasing the ZrB_2 content in AA6111 composites significantly refines grain size, increases geometrically necessary dislocation density, and promotes continuous dynamic recrystallization. This microstructural refinement and increased dislocation density collectively improve tensile performance, with the 2 vol% ZrB_2/AA6111 composite exhibiting notable ultimate tensile strength, yield strength, and elongation. Qian *et al*. (2023) reported that *in situ* ZrB_2 nanoparticle-reinforced AA6111 composites exhibit significantly improved high-temperature creep resistance compared to the base alloy, with a threshold stress of 28 MPa at 573 K, compared to 15 MPa for the unreinforced matrix. The ZrB_2 nanoparticles enhance creep performance by impeding dislocation motion and pinning grain boundaries, thereby maintaining grain size stability during deformation. The study further indicated that the creep mechanism in both the composite and the matrix alloy is dominated by high-temperature dislocation climb, as evidenced by a stress exponent of 5. Yang *et al*. (2016) fabricated ZrB_2/6061Al hierarchical nanocomposites using a direct melt reaction with halide salts, resulting in a two-level composite microstructure. This unique microstructural architecture led to significant improvements in mechanical properties compared to the unreinforced matrix, including increased hardness, strength, and ductility. In particular, the 2 vol% ZrB_2/6061Al composite exhibited notable enhancements in yield strength and elongation. These improvements were primarily attributed to quench strengthening and the presence of toughened particle clusters, which facilitated plastic deformation.

2. MATERIALS AND METHODS

2.1 Selection of Matrix and Reinforcement Materials

Aluminium (purity 98%) was used as the matrix material in this study, while SiC (5%, 10%, and 15%) and molybdenum (IV) sulphide (MoS_2)-3% were used as reinforcing materials to fabricate aluminium hybrid metal matrix composites using ultrasonic aided stir casting. The particle sizes of the SiC and MoS_2 particles were assessed using the Zetasizer particle size analyzer. During the synthesis process, MoS_2 powder with a particle size of 2 µm was employed and SiC particles with a purity of 40–50 nm were used. The size and surface appearance of the composite with SiC nanoparticles serving as reinforcement are shown in Fig 1.

Table 1. LM25 aluminium alloy chemical composition

Chemical composition	Ti	Sn	Pb	Zn	Ni	Mn	Fe	Si	Mg	Cu
LM25	0.2	0.1	0	0.1	0.1	0.3	0.5	6.5-7.5	0.2-0.6	0.1

Table 2. Mechanical properties of pure LM25 and LM25-MoS_2-SiC composites

Samples Composition	LM25-MoS_2-SiC/Nano Composites			
	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	% of Elongation	Hardness (BHN)
Pure LM25	205.60±0.5	132.24 ±2.5	11.23±0.5	70.26
LM25-3% MoS_2	242.25±0.7	165.29±0.6	10.56±0.6	87.28
LM25-3% MoS_2-5% SiC	251.58±2.0	182.34±1.5	8.25±1.3	90.43
LM25-3% MoS_2-10% SiC	261.79±2.2	194.21±2.2	6.54±1.5	94.16
LM25-3% MoS_2-15% SiC	280.71±2.3	220.56±0.8	3.3±2.1	103.16

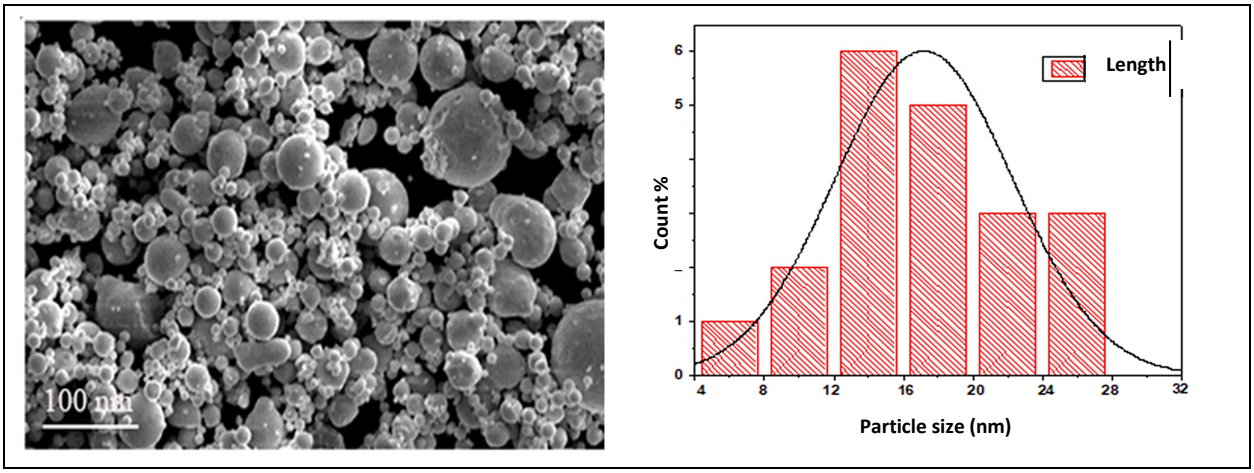


Fig. 1: (a) Microstructure of SiC particle (b) SiC nanoparticle size (20-21nm)

2.2 Hybrid Composite Slurry Formation by Stirring Operation

Al-LM25 was heated and filled with all possible combinations of composite samples into a graphite crucible furnace that measured 150 × 150 mm in height and diameter. The addition of a fixed 5-wt% of MoS_2 for reinforcement to the molten metal was accomplished by using an external device running at 900 ℃. To get a uniform dispersion of the reinforcing particles inside the aluminium melt, a standardized mixing procedure was used, which included a 10-minute duration and 460 rpm. To reduce the amount of gas trapped within the aluminium, a tablet containing hexachloroethane (C_2C_{l6}) was added to the mixture in order to degas it. Then, the SiC nanoparticles were added to the molten aluminium after being heated to 2000 ℃ for 30 minutes. An automatic mixer was then used to thoroughly mix this mixture for a further 20 minutes at a speed of 350 to 400 rpm. Magnesium powder was mixed into the melt during the mixing phase to enhance the wetting connection between the reinforcements and the matrix. An argon gas shield was used throughout the stir-casting process to stop the reinforcements and matrix from oxidizing.

2.4 Mechanical Testing

Using the Archimedes principle, the density was calculated both theoretically and empirically. The purpose of the hardness test (ASTM E384-16) was to determine how the nano-scale SiC/MoS_2 reinforcement affected the hardness characteristics of the LM25 aluminium matrix. With a dwell period of three seconds and a load of 25 N, the hardness profile was measured. The assessment energy was sustained for 10-15 seconds and exposed to a range of applied loads, from 1 to 120 kgf. The initial energy application interval was specified as 2-8 seconds. The study was conducted under ambient settings, and the data that was collected was the average of each specimen's five consecutive impressions. Using the ASTM E8 standard as a guide, the tensile strength was calculated parallel to the extrusion direction. A

universal testing machine (UTM) was used to perform a tensile test at room temperature and a cross-head speed of one mm per minute.

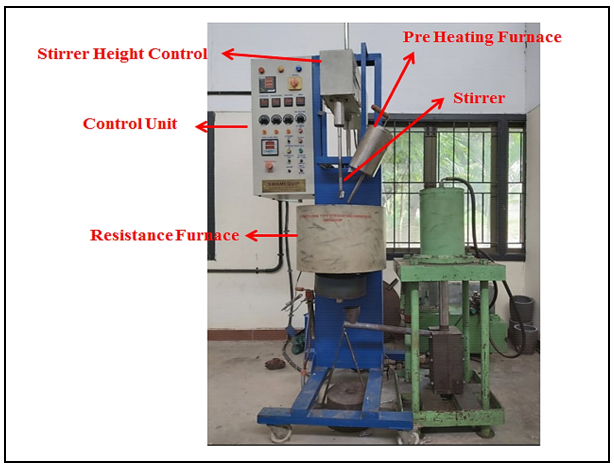


Fig. 2: Experimental setup of ultrasonic assisted stir casting process

3. RESULTS AND DISCUSSION

3.1 Density Measurement

The calculated density values for novel hybrid nanocomposites, consisting of varying ratios of nano-sized silicon carbide and molybdenum disulphide within a monolithic aluminum alloy matrix, show that the experimental densities are consistently lower than the theoretical values. The alloying element proportions by weight were converted to their respective volume fractions to determine the theoretical density using the rule of mixtures. The experimental density ($e_{xperimental}$) was calculated using the formula:

$$\rho_{Experimental} = \left[\frac{m_{air}}{m_{air-}m_{water}}\right] x\rho_{water} \quad \ldots (1)$$

Density of water (0.998 g/cm^3 at 20 °C).

$$\rho_{Theoretical} = \rho_{Al\ alloy} + W_{Al\ alloy} + \rho_{SiC} * W_{SiC} + \rho_{MoS_2} - W_{MoS_2} \quad \ldots (2)$$

Where the weight fraction and density are W and ρ

$$\%porosity = \left(1 - \frac{\rho_{Experimental}}{\rho_{Theoretical}}\right) \times 100$$

The 3 wt% of MoS_2 reinforced on LM_{25} aluminium composite density (2.74 g/cm^3) is 5.3% higher than pre-aluminium alloy. Pure LM25 alloy demonstrated the smallest density value due to differences in the densities of the reinforcing material and the matrix, as shown in Fig. 3. As previously indicated, the density of the 3 wt%MoS_2-5wt% SiC particles was 2.589 g/cm^3, a value that increases above the density of Aluminium LM_{25} matrix alloy. Metal matrix composite can be linked to the inclusion of ceramic particles, which are less dense. Therefore, the sample with the reduced density is predicted to be the more delicate. When SiC particles are added to the Al matrix, the porosity levels in hybrid composites different from those in previous aluminium alloys. It leads to an increase in the density of the composite material.

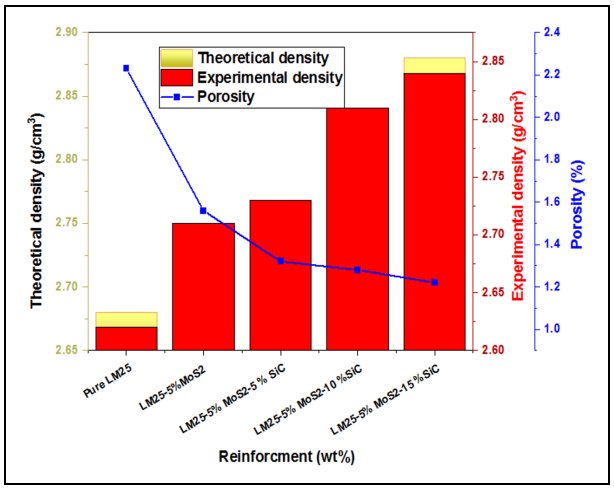


Fig. 3: Density prediction for prepared composites

3.3 Effect of SiC Nanoparticles on Tensile Strength of LM25 Hybrid Composites

The tensile properties, Ultimate Tensile Strength Yield Strength and Elongation (E), were measured for the newly developed hybrid metal matrix composites at ambient temperature with the aid of a universal testing machine. To ensure accuracy, the tensile strength readings for the composite specimens were averaged from three individual tests. The composite comprising LM25 alloy, with 3wt% MoS_2 and 15wt% SiC nanoparticles, exhibited a maximum tensile strength of 280.71 MPa. This represents a significant increase in strength 36.23% in UTS and 40.93% in YS compared to the unaltered base alloy. When LM25 alloy was combined with 3% MoS_2, without SiC, it demonstrated a tensile strength of 251.2 MPa and a YS of 165.29 MPa. The inclusion of up to 15 wt% SiC nanoparticles was proven to substantially enhance the mechanical characteristics of Al-SiC Nano composites. Furthermore, the uniform dispersion of SiC nanoparticles within the aluminium matrix enhances interparticle bonding. A clear increasing trend in hardness was observed in the nanocomposites with the rise in SiC content from 5 wt% to 15 wt%. The incorporation of 15 vol% nano-SiC particles resulted in the highest hardness, significantly exceeding that of the base LM25 alloy.

4. CONCLUSION

Through the use of ultrasonic-assisted stir casting, the aluminium composite was fabricated using nano SiC particles and MoS_2. The main goal of the study was to determine how changing the weight percentages

of SiC would affect the composite's mechanical properties, tensile strength, and hardness. Several findings were drawn from the study. The incorporation of 15 wt% SiC and 3 wt% MoS_2 particles significantly enhanced the hardness and ultimate tensile strength (UTS) of the synthesized composite compared to pure LM25 aluminium alloy. This improvement can be attributed to the increased reinforcement provided by the stiff particles, which also contributed to higher Brinell hardness number (BHN), ultimate strength, and yield strength. The composite achieved a maximum tensile strength of 280.71 MPa upon reinforcement with 3 wt% MoS_2 and 15 wt% SiC nanoparticles, indicating a notable improvement in both UTS and YS relative to the base alloy. Additionally, an increasing trend in hardness was observed with the rise in SiC content from 5 wt% to 15 wt%. The highest hardness of 103.16 BHN was recorded for the composite containing 15 wt% nano-SiC, compared to 70.26 BHN for pure LM25 alloy.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).



REFERENCES

Arif, S., Alam, T., Ansari, A. H. and Shaikh, M. B. N., Morphological characterization, statistical modelling and tribological behaviour of aluminum hybrid nanocomposites reinforced with micro-nano-silicon carbide, *J. Asian Ceram. Soc.*, 7 (4), 434–448 (2019). https://doi.org/10.1080/21870764.2019.1665765

Ashebir, D. A., Mengesha, G. A. and Sinha, D. K., An Insight into Mechanical and Metallurgical Behavior of Hybrid Reinforced Aluminum Metal Matrix Composite, *Adv. Mater. Sci. Eng.*, 2022, 1–31 (2022). https://doi.org/10.1155/2022/7843981

Cheng, W., Wang, J., Ma, X., Liu, P., Liaw, P.K. and Li, W., A review on microstructures and mechanical properties of protective nano-multilayered films or coatings, *J. Mater. Res. Technol.*, 27 2413–2442 (2023). https://doi.org/10.1016/j.jmrt.2023.10.012

Gao, X., Kai, X., Qian, W., Guan, C., Huang, L., Sun, K., Wang, T., Peng, Q. and Zhao, Y., Microstructure and mechanical property evolution of in-situ ZrB_2/AA7085 nanocomposites during hot rolling, *Mater. Charact.*, 195 112503 (2023). https://doi.org/10.1016/j.matchar.2022.112503

Kai, X., Zhao, Y., Wang, A., Wang, C. and Mao, Z., Hot deformation behavior of in situ nano ZrB_2 reinforced 2024Al matrix composite, *Compos. Sci. Technol.*, 116 1–8 (2015). https://doi.org/10.1016/j.compscitech.2015.05.006

Ma, M., Huo, P., Liu, W.C., Wang, G.J. and Wang, D.M., Microstructure and mechanical properties of Al/Ti/Al laminated composites prepared by roll bonding, *Mater. Sci. Eng. A*, 636 301–310 (2015). https://doi.org/10.1016/j.msea.2015.03.086

Mohammad Sharifi, E., Karimzadeh, F. and Enayati, M. H., Fabrication and evaluation of mechanical and tribological properties of boron carbide reinforced aluminum matrix nanocomposites, *Mater. Des.*, 32 (6), 3263–3271 (2011). https://doi.org/10.1016/j.matdes.2011.02.033

Nirala, A., Soren, S., Kumar, N., Khan, M. A., Islam, S. and Khan, N. A., Micro-mechanical and tribological behavior of Al/SiC/B_4C/CNT hybrid nanocomposite, *Sci. Rep.*, 13 (1), 13147 (2023). https://doi.org/10.1038/s41598-023-39713-2

Qian, W., Kai, X., Tao, R., Cao, R., Guan, C. and Zhao, Y., Investigation on high-temperature creep property and mechanism of AA6111 matrix composites reinforced by in-situ ZrB_2 nanoparticles, *Mater. Charact.*, 196, 112620 (2023). https://doi.org/10.1016/j.matchar.2022.112620

Siddesh Kumar, N. G., Suresh, R. and Shiva Shankar, G. S., High temperature wear behavior of Al2219/n-B_4C/MoS_2 hybrid metal matrix composites, *Compos. Commun.*, 19, 61–73 (2020). https://doi.org/10.1016/j.coco.2020.02.011

Sulaiman, S., Marjom, Z., Ismail, M. I. S., Ariffin, M. K. A. and Ashrafi, N., Effect of Modifier on Mechanical Properties of Aluminium Silicon Carbide (Al-SiC) Composites, *Procedia Eng.*, 184, 773–777 (2017). https://doi.org/10.1016/j.proeng.2017.04.156

Tao, R., Zhao, Y., Chen, G. and Kai, X., Effects of ZrB_2 Nanoparticles on the Microstructures and Tensile Properties of a Hot Extruded in Situ AA6111 Composite, *Met. Mater. Int.*, 28 (12), 3145–3159 (2022). https://doi.org/10.1007/s12540-022-01192-x

Vinayaka, N., Christiyan, K. G. J., Shreepad, S., Padhi, S. N., Dambhare, S. G., Puse, R. kumar., Gayathri, K., Kolekar, A. B. and Nagarajan, S., Tribological Behavior on Stir-Casted Metal Matrix Composites of Al8011 and Nano Boron Carbide Particles, *J. Nanomater.*, 2023, 1–9 (2023). https://doi.org/10.1155/2023/6453166

Wu, J., Kai, X., Guan, C., Xu, Z., Miao, C., Cao, R. and Zhao, Y., Microstructure evolution and mechanical properties of in-situ ZrB_2/Al7085 nanocomposites during hot rolling deformation, *Mater. Today Commun.*, 32, 103921 (2022). https://doi.org/10.1016/j.mtcomm.2022.103921

Yang, R., Zhang, Z., Zhao, Y., Chen, G., Liu, M., Jiao, L. and Chen, L., Microstructure-property analysis of ZrB_2 /6061Al hierarchical nanocomposites fabricated by direct melt reaction, *Mater. Charact.*, 112, 51–59 (2016). https://doi.org/10.1016/j.matchar.2015.12.012