An investigation on microstructure and mechanical characterization of high performance magnesium hybrid nanocomposites with $Al_2 0_3$ and MoS_2 nanoparticles

Senthilkumar V *1, Nagadeepan A[2], Senthilkumar S[3] and Raja K[4]

[1] 1Associate Professor, Department of Mechanical Engineering, SRM TRP Engineering College, Trichy, Tamilnadu

[2,3]Assistant Professor, Department of Mechanical Engineering, SRM TRP Engineering College, Trichy, Tamilnadu

[4] Research Scholar, Department of Mechanical Engineering, SRM TRP Engineering College, Trichy, Tamilnadu

*Corresponding Author mail id – trpvsk12@gmail.com

Abstract. This study investigates the microstructure and mechanical behavior of high-performance magnesium hybrid nanocomposites reinforced with aluminum oxide (Al_2O_3) and molybdenum disulfide (MoS_2) nanoparticles. Magnesum, recognized for its lightweight nature and high strength-to-weight ratio, is further enhanced by the inclusion of these nanofillers to improve mechanical properties such as tensile strength, hardness, and wear resistance. A stir casting method was employed to ensure uniform dispersion of the nanoparticles within the magnesium matrix, followed by a sol-gel coating process to enhance surface characteristics. Detailed microstructural analysis revealed effective grain refinement attributed to Al_2O_3, while MoS_2 contributed to improved tribological performance by reducing friction. The hybrid nanocomposites exhibited superior mechanical properties compared to unreinforced magnesium and those reinforced with a single type of nanoparticle. These findings underscore the potential of Mg-based hybrid nanocomposites in various applications, including automotive, aerospace, and biomedical sectors, providing an optimal combination of strength, wear resistance, and lightweight properties.

Keywords: Magnesium hybrid nanocomposites, Al_2O_3 nanoparticles, MoS_2 nanoparticles, Mcrostructure characterization, Mechanical properties.

© The Author(s) 2025
R. K. Ramachandra et al. (eds.), *Proceedings of the International Conference on Bio-Based Environment for Sustainable Territory (IC-BEST 2024)*, Advances in Biological Sciences Research 44,
https://doi.org/10.2991/978-94-6463-648-2_11

1. Introduction

Magnesium and its alloys, when reinforced with nano-sized particles, offer a viable solution for lightweight structural applications. These reinforcements increase the mechanical properties however retaining ductility, which is often compromised when using more significant micron-sized reinforcements. Magnesium-based hybrid composites has superior mechanical and tribological properties over their lightweight counterparts [1]. Using single type of nanoparticle in lubricants constrains the heat transfer capability and hence affects the performance in specific applications during optimization. The addition of numerous nanoparticles creates combined results, which improves overall properties. Nanoparticles made from ceramic oxides have a tendency to lower thermal conductivity than those from metals and carbon compounds. However, combining two or more types of nanoparticles can create a synergistic effect, resulting in a hybrid nanolubricant with enhanced thermal conductivity and stability [2,3].

Composite production is primarily classified into three groups - liquid-state, semi-solid-state and solid-state technologies. A liquid-state process called stir casting mechanically mixes a dispersed phase into a molten matrix metal to generate composite materials. Ceramic particles are included in the melt during this process, which has many benefits over solid-state techniques. These include near-net form accomplishment, easier matrix structure management and enhanced particle-matrix bonding, lower processing costs, and compatibility with different materials [4, 5].

Metal matrix composites (MMCs) are valuable because they combines the strengths of metals and ceramics that improves their tensile strength, fatigue resistance, wear resistance and stiffness than single-metal alloy. MMCs with particle reinforcement are versatile and well-suited for many applications. Metal alone often needs to meet the diverse requirements of various applications, so its properties are enhanced by including the other materials. Several methods have been developed to produce Metal Matrix Composites (MMCs), such as powder metallurgy (P/M), stir casting and pressure infiltration. Aluminum-based MMCs (Al MMCs) are highly effective in industries like automotive and aerospace due to their enhanced strength, wear resistance, thermal conductivity and lower thermal expansion. Common reinforcements used to boost the properties of base alloys include silicon carbide (SiC), aluminum oxide (Al_2O_3), boron carbide, zircon and fly ash that can be added as particles or fibers. These composites are produced mainly through stir casting, where particles are mixed into molten aluminum, or by using powder metallurgy process which involves mixing and compacting aluminum powder with reinforcements. Their flexibility makes Aluminium composites a valuable solution for a wide range of applications.

Molybdenum Disulfide (MoS_2) is a layered transition metal dichalcogenide with a tunable bandgap which changes from an indirect (~1.2 eV) in bulk to a direct

(~1.8 eV) in monolayers and makes it perfect for optoelectronics and electronics. Applications in transistors, batteries, catalysis and lubrication are made possible by its strength, flexibility, thermal stability, and chemical resistance. MoS_2 can be synthesized using chemical vapor deposition (CVD), mechanical exfoliation and hydrothermal processes. Key challenges include large-scale production, maintaining quality and integration into current technologies. Research focuses on improving synthesis and exploring new applications, especially in energy storage and nanoelectronics. It is essential for materials science and engineering to precisely determine the relationship between atomic structure and material physical properties in order to develop novel materials with exceptional qualities [6]. This understanding is crucial as it sets the stage for developing advanced materials. Nanocomposites allow most components to achieve their maximum potential in modern applications. In structural and automotive applications, nanoparticle-reinforced lightweight aluminum-based nanocrystalline matrices exhibit remarkable properties [7]. With their exceptional mechanical and physical characteristics, these materials open up new avenues for materials science and engineering research. They are very well suited for usage in such demanding industries due to their improved performance [8].

MoS_2 nanospheres have not been extensively studied and using a solvothermal technique, Wu et al. [9] produced MoS_2 microspheres (~2 μm) and Wu et al. [10] produced MoS_2 nanospheres (100 nm) using HCl. Park et al. [11] used a solvothermal technique using L-cysteine to create stable MoS_2 nanospheres for lithium-ion batteries. Coating core particles or altering their surfaces creates core-shell formations. This study investigates how Al_2O_3 as a shell material enhances the photocatalytic activity of MoS_2 nanospheres under UV light, focusing on the degradation of rhodamine B (RhB) [12,13]. Khatkar et al. identified Al_2O_3 (20%) as a key reinforcing ceramic for hybrid magnesium composites, which, along with other ceramics like SiC and TiC, enhances wear resistance, creep resistance, and mechanical properties. Although there is less research on the impact, creep, flexural, and compressive strengths of ceramic-reinforced magnesium composites, their tribological performance has improved with the addition of solid lubricants like MoS_2 and graphene.

This research aims to investigate the microstructure and mechanical characterization of high-performance magnesium hybrid nanocomposites reinforced with aluminum oxide (Al_2O_3) and molybdenum disulfide (MoS_2) nanoparticles. This is an unique and significant project in the field of engineering and materials research. The study aims to improve the effects of all compositions on the mechanical properties, wear resistance and performance of magnesium-based composites. The issues of improving performance and integrating nanoparticles in metal matrix composites are the focus of this study. By understanding the combined impacts of these reinforcements, it also aims to develop lightweight materials appropriate for demanding applications in industries like aerospace and automotive.

2. Materials And Methods

2.1 Selection of Matrix and Reinforcement Materials

The stir casting technique was used to create magnesium hybrid nanocomposites reinforced with AlO_3 and MoS_2 nanoparticles. The nano-sized AlO_3 and MoS_2 reinforcements had average sizes of 75 nm and 60 nm, respectively, and a purity of roughly 99%. The base material was magnesium alloy (AZ61). A planetary ball milling machine was used to combine the magnesium alloy with the nanoparticles at different weight ratios of 2% and 3% for one hour in order to guarantee consistent dispersion. To get rid of volatile ingredients, the mixed powders were then preheated for two hours at 110°C. This pre-heated mixture was melted in a crucible furnace at 700°C under an ar-gon atmosphere to prevent oxidation. The Al_2O_3 and MoS_2 nanoparticles were preheated to 300°C and introduced gradually into the molten magnesium while stirring at 500 rpm for 10 minutes. The well blended molten substance was poured into a steel mold that had been heated beforehand, creating cylindrical billets that measured 15 mm in diameter and 30 mm in height. The billets were coated for additional processing using a sol-gel solution that contained 0.01 g of silicon carbide and 1 ml titanium dioxide and 10 ml bu-tane in a 1:10 ratioBy offering a protective layer that increases wear resistance and corrosion protection, this sol-gel coating is intended to improve surface qualities and increase the longevity and functionality of magnesium hybrid nano-composites. Applying this sol-gel mixture involved spin coating it for 30 seconds at 1000 rpm, then sintering it for 45 minutes at 450°C with a vacuum pressure of 450 ± 10 KPa. A compressive testing equipment was then used for compression testing, and SEM analysis revealed information about the microstructure and dispersion of the nanoparticles. The hardness values of both coated and untreated samples were evaluated using Vickers micro-hardness testing.

The study prepared five composites:
pure AZ61,
AZ61 with 2% Al_2O_3,
AZ61 with 2% MoS_2,
AZ61 with 2% Al_2O_3 and 2% MoS_2, and
AZ61 with 3% Al_2O_3 and 3% MoS_2, aiming to understand the effects of different reinforcement ratios on the microstructure and mechanical properties of the magnesium matrix.

2.2 Analysis of Microstructural and Mechanical Properties

The microstructural and mechanical characteristics of magnesium hybrid nanocomposites reinforced with AlO_3 and MoS_2 nanoparticles were thoroughly examined in the study. Effective mixing during the stir casting process was shown by the equal distribution of the nanoparticles throughout the AZ61 magnesium alloy, as shown by scanning electron microscopy (SEM) analysis. The presence of nanoparticles resulted in a more complicated fracture morphology, exhibiting better connectivity between the matrix and reinforcements, according to fractographic investigations of the fracture surfaces. Dimpled structures, a sign of ductile failure, were found in the analysis; they were more noticeable in composites with the ideal reinforcement ratios.

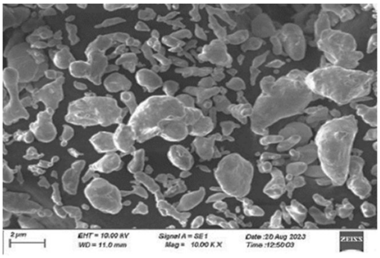

Fig. 1(a): Pure AZ61

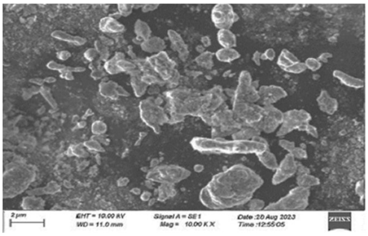

Fig. 1(b): AZ61 + 2% Al_2O_3

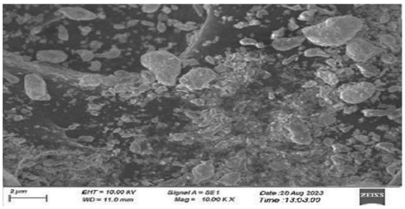

Fig. 1 (c): AZ61 + 2% MoS_2

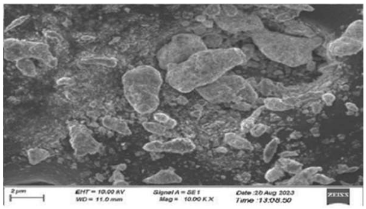

Fig. 1(d): AZ61+2% Al_2O_3+2% MoS_2

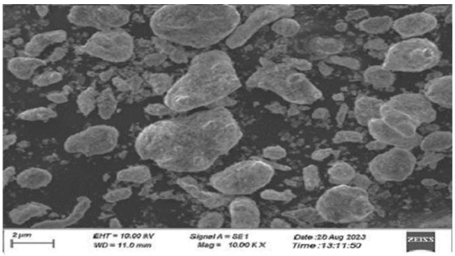

Fig. 1(e): AZ61 + 2% Al_2O_3 + 3% MoS_2
Figure. 1 SEM images

Vickers micro-hardness tests illustrated significant improvements in hardness values with the addition of Al_2O_3 and MoS_2. The pure AZ61 exhibited a hardness of 34 HV, while the composites displayed increases of up to 25% in hardness with 2% reinforcement. Specifically, the combination of 2% Al_2O_3 and 2% MoS_2 achieved the highest hardness of 47 HV, indicative of a synergistic effect from the dual reinforcement.

Furthermore, as table 1 illustrates, compression tests demonstrated improved strength properties in the nanocomposites. The pure AZ61 showed a load capacity of 20 kN and a compressive strength of 150 MPa. On the other hand, adding MoS_2 resulted in a compressive strength of 180 MPa with a load of 24 kN, whilst adding Al_2O_3 increased compressive strength to 185 MPa with a load of 25 kN. The composite with a maximum load capacity of 30 kN and the highest compressive strength of 210 MPa was the one that contained both 2% Al_2O_3 and 2% MoS_2The combined impact of combining these nanoparticles is responsible for this higher performance: MoS_2 improves lubrication and lowers friction, while Al_2O_3 increases hardness and wear resistance. When combined, they successfully overcome the drawbacks of employing individual nanoparticle kinds, leading to improved mechanical characteristics and functionality. But the strength of the composites with 3% reinforcement decreased to 195 MPa and 28 kN, indicating a possible threshold that could lead to agglomeration and poor bonding.

Table 1. Analysis of Microstructural and Mechanical Properties.

Composite Composition	Hardness (HV)	Compressive Strength (MPa)	
Pure AZ61	34 HV	150 MPa	20 kN
AZ61 + 2% Al_2O_3	43 HV	185 MPa	25 kN
AZ61 + 2% MoS_2	42 HV	180 MPa	24 kN
AZ61+2%Al_2O_3+2% MoS_2	47 HV	210 MPa	30 kN
AZ61+3%Al_2O_3+3% MoS_2	45 HV	195 MPa	28 kN

Because the composites with 2% reinforcement had better particle distribution and therefore higher mechanical properties, the analysis highlighted the importance of choosing the right reinforcement ratios. Additionally, the billets' surface qualities were improved by the sol-gel coating, which increased corrosion resistance and wear resistance. This made the composites very useful for applications in hostile environments.

This study shows that dual reinforcement of Al_2O_3 and MoS_2 nanoparticles significantly improves microstructural and mechanical properties. Better matrix-reinforcement bonding was highlighted by SEM examination, which showed enhanced particle distribution and dimples suggesting ductile failure. In contrast, earlier research revealed a less robust fracture behavior by identifying voids and microcracks as the main reasons of failure. In addition to demonstrating a compressive strength of 210 MPa, this study's peak hardness of 47 HV for 2% reinforcement matched the greatest values ever reported. The lack of coatings in this work explains the discrepancy, demonstrating the baseline strength of uncoated composites, even though this is less than the 432 MPa reported in other investigations. This study also demonstrates that accumulation causes decreased performance at 3% reinforcement, highlighting the necessity of ideal particle dispersion. By emphasizing better bonding and fracture behavior, this study lays the groundwork for next improvements that will further optimize composite performance, like adding coatings and sophisticated dispersion techniques.

3. Conclusion

In summary, this study effectively illustrates notable improvements in the mechanical and microstructural characteristics of magnesium hybrid nanocomposites reinforced by MoS_2 and AlO_3 nanoparticles. Improved hardness and compressive strength were the outcome of the successful incorporation of these nanofillers using the stir casting technique and sol-gel coating, demonstrating the potential of these composites in high-performance applications. The results demonstrate that the optimal reinforcement ratio of 2% for both Al_2O_3 and MoS_2 improves the mechanical properties, providing better wear resistance and structural integrity when compared to unreinforced magnesium. The work opens the door for more research into the uses of magnesium-based hybrid nanocomposites in lightweight, high-strength materials by demonstrating its adaptability in wide range of industries such as the automotive, aerospace and biomedical sectors. The sol-gel coating that was given to the billets greatly improved the composites' resistance to corrosion and wear, making them suitable for demanding settings and contributing to an overall improvement in performance.

The magnesium matrix's mechanical characteristics are greatly enhanced by the complementing effects of adding both MoS_2 and Al_2O_3 nanoparticles. By encouraging a finer microstructure that increases tensile strength and hardness, Al_2O_3 aids in grain refinement. The material is more resistant to deformation because the nanoparticle acts as a barrier to dislocation motion. On the other hand, MoS_2 reduces friction between the matrix and external surfaces during mechanical loading by acting largely as a solid lubricant. In applications where wear resistance is paramount, this lubricating action is essential. The composite's ability to transfer load is enhanced by the combination of these nanoparticles. In particular, MoS_2 reduces wear during operation, while Al_2O_3 increases the load-bearing capacity. This interaction preserves the material's structural integrity under stress in addition to preventing catastrophic failure.

When compared to composites reinforced with a single kind of nanoparticle, the hybrid nanocomposites' superior mechanical properties are made possible by these combined methods. The results of this study are supported by additional research into these synergistic interactions, which also aids in directing future studies into optimizing hybrid nanocomposite formulations for specific applications in the automotive and aerospace industries.

Overall, this study offers useful perspectives to develop innovative substances that address the difficulties of improving performance without compromising the abilities required for contemporary engineering applications.

References

1. Bhargavi Rebba, N. Ramanaiah,: Evaluation of Mechanical Properties of Aluminium Alloy (Al-2024) Reinforced with Molybdenum Disulphide (MOS2) Metal Matrix Composites, Procedia Materials Science, Volume 6, Pages 1161-1169, ISSN 2211-8128. https://doi.org/10.1016/j.mspro.2014.07.189. (2014)
2. R.K. Bumataria, N.K. Chavda, H. Panchal.:Current research aspects in mono and hybrid nanofluid based heat pipe technologies, Heliyon, vol. 5, iss. 5, doi: 10.1016/J.HELIYON.E01627 (2019)
3. S. Gugulothu, V.K. Pasam.: Performance Evaluation of CNT/MoS2 Hybrid Nanofluid in Machining for Surface Roughness, International Journal of Automotive and Mechanical Engineering, vol. 16, no. 4, pp. 7413–7429, doi: 10.15282/IJAME.16.4.2019.15.0549 (2019)
4. T. Anand, L. Ranganathan, G. Prabaharan, A. Srithar, Mechanical behaviour of Al6061 hybrid nanocomposites reinforced with nano alumina and molybdenum disulfide, Materials Today: Proceedings, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.06.279 (2023).
5. Vida Khalili, Akbar Heidarzadeh, Sajjad Moslemi, Leila Fathyunes.: Production of Al6061 matrix composites with ZrO2 ceramic reinforcement using a low-cost stir casting technique: Microstructure, mechanical properties, and electrochemical behavior, Journal of Materials Research and Technology, Volume 9, Issue 6, Pages 15072-15086, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2020.10.095 (2020).
6. C. Suryanarayana,: Mechanical alloying and milling, Progress in Materials Science, Volume 46, Issues 1–2, Pages 1-184, ISSN 0079-6425, https://doi.org/10.1016/S0079-6425(99)00010-9 (2001).
7. M.E Smagorinski, P.G Tsantrizos, S Grenier, A Cavasin, T Brzezinski, G Kim.: The properties and microstructure of Al-based composites reinforced with ceramic particles, Materials Science and Engineering: A, Volume 244, Issue 1, Pages 86-90, ISSN 0921-5093, https://doi.org/10.1016/S0921-5093(97)00830-7, (1998)
8. G.B. Veeresh Kumar, C.S.P. Rao, N. Selvaraj.:Studies on mechanical and dry sliding wear of Al6061–SiC composites, Composites Part B: Engineering, Volume 43, Issue 3, Pages 1185-1191, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2011.08.046 (2012)
9. Wu D. M., Zhou X. D., Fu X., Shi H. Q., Wang D. B., and Hu Z. S.: Synthesis and characterization of molybdenum disulfide micro-sized solid spheres, Journal of Materials Science. 41, no. 17, 5682–5686, https://doi.org/10.1007/s10853-006-0245-y, 2-s2.0-33748547289 (2006).
10. Wu Z., Wang D., and Sun A., Surfactant-assisted fabrication of MoS2 nanospheres, Journal of Materials Science. 45, no. 1, 182–187, https://doi.org/10.1007/s10853-009-3914-9 (2010).
11. Park S.-K., Yu S.-H., Woo S., Ha J., Shin J., Sung Y.-E., and Piao Y.: A facile and green strategy for the synthesis of MoS2 nanospheres with excellent Li-ion storage properties, CrystEngComm. 14, no. 24, 8323–8325, https://doi.org/10.1039/c2ce26447a, 2-s2.0-84870497692 (2012).

12. Li J., Wu P., Ye Y., Wang H., Zhou Y., Tang Y., and Lu T., Electronic structure of MoSe2, MoS2, and WSe2. I. Band-structure calculations and photoelectron spectroscopy, CrystEngComm. (2014) 16, no. 4, 517–521, https://doi.org/10.1039/c3ce41571f, 2-s2.0-84890810513.
13. Zhang C., Wu H. B., Guo Z., and Lou X. W.: Facile synthesis of carbon-coated MoS2 nanorods with enhanced lithium storage properties, Electrochemistry Communications. 20, 7–10, https://doi.org/10.1016/j.elecom.2012.03.039 (2012).
14. Khatkar, Sandeep Kumar.: Hybrid magnesium matrix composites; A review of reinforcement philosophies, mechanical and tribological characteristics" REVIEWS ON ADVANCED MATERIALS SCIENCE, vol. 62, no. 1, pp. 20220294. https://doi.org/10.1515/rams-2022-0294 (2023)
15. G.B. Veeresh Kumar, C.S.P. Rao, N. Selvaraj, Studies on mechanical and dry sliding wear of Al6061–SiC composites, Composites Part B: Engineering, Volume 43, Issue 3, Pages 1185-1191, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2011.08.046.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (http://creativecommons.org/licenses/by-nc/4.0/), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.