Enhancement of Thermal Stability and Energy Absorption Behaviour of Magnesium Alloy Hybrid Composites Embedded With Titanium Dioxide Nanoparticles

P Sakthi Sarukesh1, M Mounesh1, P Tamilarasu1 , U Vivek1, N Saravanan2, M Saravanan3,a), Jonnala Subba Reddy4,S KarthikAyan5, Mohanavel Vinayagam6

1 Department of Mechanical Engineering, K.S.Rangasamy College of Technology,

Tiruchengode, 637215, Tamil Nadu, India.

2Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thuduppathi, 638057, Tamil Nadu, India

3Department of Electrical and Electronics Engineering, Holymary Institute of Technology and Science, Bogaram, 501301, Telangana, India

4Department of Mechanical Engineering, Lakireddy Bali Reddy College of Engineering, Mylavaram, Andhra Pradesh, 521230, India

5Department of Mechanical Engineering , Mohan Babu University, Tirupati, India

6 Centre for Sustainable Materials Research, Department of Mechanical Engineering, Academy of Maritime Education and Training (AMET) Deemed to be University,Kanathur, Chennai 603112, Tamil Nadu, India.

**Corresponding author:** a)[saranvimal@gmail.com](mailto:saranvimal@gmail.com)

Abstract: This work studies the manufacture and performance of AZ91D magnesium alloy mixtures augmented with nano titanium dioxide by powder metallurgy. Different TiO₂ loadings (5, 10, and 15 wt%) were integrated to evaluate their influence on thermal stability, compressive strength and energy absorption capacity. The results revealed that TiO₂ additions considerably boosted thermal resistance and impact energy absorption, while retaining a balanced compressive response between strength and ductility and among the evaluated formulations and the higher TiO₂ content displayed improved functional performance indicating the efficiency of ceramic nanoparticle reinforcemen and these findings emphasize the applicability of AZ91D/TiO₂ nanocomposites for lightweight automobile housings and protective components where a combination of thermal reliability and impact resistance is crucial.

# Introduction

Magnesium alloys, particularly AZ91D, are widely recognized for their recyclability with high strengthtoweight ratio and corrosion resistancewhich make them attractive for lightweight structural and automotive applications [1-4]. Their relatively low thermal stability and limited energy absorption capacity restrict their deployment in demanding service environments. Reinforcement with ceramic nanoparticles has materialized as a promising approach to overwhelmed these limitations. In particular, titanium dioxide (TiO₂), with its high hardness, thermal stability, and grain refinement capability, has shown strong potential for enhancing the functional properties of magnesium alloys. Powder metallurgy (PM) has been extensively adopted for fabricating such composites, offering advantages in particle uniformity, porosity reduction, and controlled microstructural tailoring compared to conventional casting [5-9].

Extensive prior work supports this approach. The broad applications of Mg alloys in biomedical, automotive, and structural domains [10], while highlighted their role in aerospace for achieving fuel efficiency through weight reduction [11]. In the context of MMCs, emphasized the growing role of magnesium-based systems in high-performance engineering [12]. Reinforcement studies have confirmed the benefits of nanoparticles: reported significant gains in hardness and wear resistance with SiC nanoparticles in AZ31 alloys [13], while comprehensively reviewed nanoparticle-reinforced Mg composites, noting simultaneous improvements in tensile and tribological performance [14]. Hybridization strategies have also proven effective, with showing enhanced toughness and fatigue resistance in multi-reinforced Mg composites fabricated via PM, and demonstrating notable improvements in strength and tribo-corrosive wear behavior in nanoparticle-modified AZ91D [15-19].

Processing routes have been equally influential. It confirmed that powder metallurgy achieves uniform reinforcement dispersion and reduced porosity, while demonstrated that TiO₂ addition to Mg and Al matrices significantly improved hardness, compressive strength, and tensile performance [20]. Related advancements in aluminum MMCs further validate the benefits of ceramic reinforcements: reported improved tribo-mechanical performance and machinability in hybrid Al-based systems [21-22]. It specifically investigated extruded Mg–TiO₂ nanocomposites, revealing substantial improvements in high-temperature stability, thereby supporting TiO₂ as a promising reinforcement for thermal-critical components [23-26].

Building on this foundation, the present work examines the role of TiO₂ nanoparticle concentration (5, 10, and 15 wt%) in AZ91D magnesium composites fabricated via powder metallurgy. The study focuses on the interrelationship between thermal stability, compressive strength, and energy absorption, with the objective of identifying optimized compositions for lightweight automotive housing applications where thermal reliability and impact resistance are essential.

# Materials and Methods

## Materials

AZ91E magnesium alloy ingots were designated as the basic matrix due to their superior strength to weight ratio and widespread use in automotive applications. Nano sized silicon carbide and boron nitride powders were applied as reinforcements owing to their high hardness, thermal stability and tribological benefits. To promote wettability and eliminate moisture induced flaws both reinforcements were warmed to 300 °C prior to integration.

For comparative evaluation, AZ91D magnesium alloy composites supplemented with titanium dioxide (TiO₂, 50 nm) were also manufactured utilizing the powder metallurgy process and AZ91D powder nanoparticles were combined in different weight fractions using a high energy ball mill to guarantee homogenous dispersion. The blended powders were compressed under a uniaxial pressure of 500 MPa to form cylindrical billets and the green compacts were sintered at 500 °C in a controlled argon environment to accomplish densification while preventing oxidation of the magnesium matrix [27-30].

## Composite Formulations

To explore the effect of nano TiO₂ reinforcement on the enactment of AZ91D magnesium alloy four distinct composite formulations were produced. The reinforcement levels were changed regularly while keeping the processing route constant. The detailed compositions are reported in Table 1.

**TABLE 1.** Composite Configurations Table

|  |  |
| --- | --- |
| **Sample ID** | **Composition** |
| Sample ID -1 | AZ91D- (Unreinforced) |
| Sample ID - 2 | AZ91D + 5 wt% TiO₂ |
| Sample ID -- 3 | AZ91D + 10 wt% TiO₂ |
| Sample ID -4 | AZ91D + 15 wt% TiO₂ |

The compressive power of the specimens was noted in according to the ASTM E9 standards ensures a reliable assessment of their load bearing capacity and the energy absorption capacity of each composite was calculated by means of the area under the stress strain curve, which demonstrates their ability to resist impact and dissipate mechanical energy before failure. The TGA examined the thermal stability of the manufactured AZ91D-TiO₂ composites under a controlled nitrogen atmosphere, providing insight into their degradation behavior at higher temperatures [31-35].

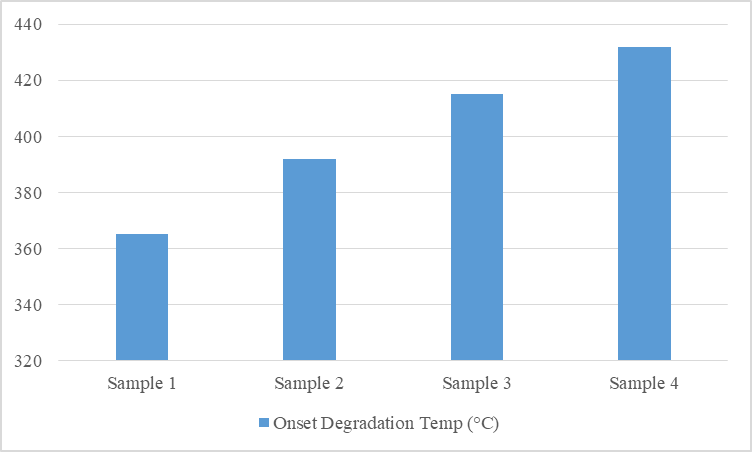
# Results and Discussion

## Thermal Stability

The thermogravimetric study results demonstrated that the accumulation of TiO₂ nanoparticles considerably increased the heat resistance of the AZ91D matrix and the onset degradation temperature climbed steadily from 365 °C for the unreinforced alloy to 432 °C for the composite with 15 wt% TiO₂ suggesting the effectiveness of ceramic reinforcement in delaying thermal breakdown. The residual mass after thermal exposure also rose with larger TiO₂ concentration ranging from 7.8% in the base alloy to 12.1% in Sample 4, demonstrating the stability conferred by the thermally resistant TiO₂ phase [36-42]. These results reveal that TiO₂ functions as a barrier to oxidation and boosts the high temperature durability of AZ91D composites making them acceptable for thermally demanding applications

**TABLE 2** Thermal Stability

|  |  |  |
| --- | --- | --- |
| Specimen | Onset Degradation Temp (°C) | Residual Mass (%) |
| Sample ID -1 | 365 | 7.8 |
| Sample ID - 2 | 392 | 9.5 |
| Sample ID - 3 | 415 | 10.7 |
| Sample ID - 4 | 432 | 12.1 |



**Figure 1.**Thermal Stability

## Compression Strength and Energy Absorption

Adding TiO₂ nanoparticles made AZ91D's compressive behavior better in a consistent way. The compression strength went up from 182 MPa in the base alloy to 224 MPa in Sample 4. This shows that grain refinement and good load transmission to the ceramic reinforcement made the material stronger. At the same time, energy absorption went increased from 0.85 MJ/m³ to 1.30 MJ/m³, showing that the material can better handle impact and plastic deformation before it breaks [43-45]. These findings show that adding TiO₂ not only makes the composites stronger when they are under static stress, but it also makes them tougher when they are under dynamic load. This means that the composites may be used in situations when both strength and energy dissipation are needed [49-54].

**TABLE 3.** Compression Strength and Energy Absorption

|  |  |  |
| --- | --- | --- |
| **Specimen** | **Compression Strength (MPa)** | **Energy Absorption (MJ/m³)** |
| Sample 1 | 182 | 0.85 |
| Sample 2 | 201 | 1.05 |
| Sample 3 | 216 | 1.21 |
| Sample 4 | 224 | 1.30 |

# 

**Figure 2.**Compression Strength

# Applications in Lightweight Automotive Housing

The AZ91D/TiO₂ nanocomposites have a unique combination of better heat resistance, better compressive strength and better energy absorption capacity, which makes them perfect for lightweight vehicle housing applications. Gearbox casings clutch covers and engine enclosures are some of the most important parts that need materials that can handle high temperatures and withstand stresses and dynamic mechanical loads caused by vibration. By adding TiO₂ nanoparticles, the composite may provide dimensional stability, resistance to wear and better impact tolerance. This means that parts is last longer and need less maintenance [46-48].

# Conclusion

Tallying nano TiO₂ particles to AZ91D magnesium alloy by powder metallurgy ended the composite much better at captivating heat, stress and energy. Sample 4 (15 wt% TiO₂) had the best and most balanced attributes of all the formulations tested. It had about 23% higher compressive strength about 53% higher energy absorption and far better thermal stability than the unreinforced alloy and these results show that AZ91D/TiO₂ composites are very attractive options for next-generation automobile housings where lightweight design, thermal durability and multifunctional performance are all very important for efficiency and dependability

# References

1. Tan, Jovan, and Seeram Ramakrishna. "Applications of magnesium and its alloys: a review." Applied Sciences 11, no. 15 (2021): 6861.
2. Bai, Jingying, Yan Yang, Chen Wen, Jing Chen, Gang Zhou, Bin Jiang, Xiaodong Peng, and Fusheng Pan. "Applications of magnesium alloys for aerospace: A review." Journal of Magnesium and Alloys 11, no. 10 (2023): 3609-3619.
3. Madhu, K. S., B. N. Sharath, S. Karthik, D. G. Pradeep, Madhu Puttegowda, Yashas Gowda TG, B. G. Premkumar, and R. Raghavendra Rao. "An introduction to metal matrix composites and their applications." In Applications of Composite Materials in Engineering, pp. 45-73. Elsevier Science Ltd, 2025.
4. Subramani, Murugan, Song-Jeng Huang, and Konstantin Borodianskiy. "Effect of SiC nanoparticles on AZ31 magnesium alloy." Materials 15, no. 3 (2022): 1004.
5. Monish, P., Krishna KL Hari, and K. Rajkumar. "Manufacturing and characterisation of magnesium composites reinforced by nanoparticles: a review." Materials Science and Technology 39, no. 15 (2023): 1858-1876.
6. Arora, Gurmeet Singh, and Kuldeep Kumar Saxena. "A review study on the influence of hybridization on mechanical behaviour of hybrid Mg matrix composites through powder metallurgy." Materials Today: Proceedings (2023).
7. Gnanavelbabu, A., E. Vinothkumar, Nimel Sworna Ross, Munish Kumar Gupta, and Muhammad Jamil. "Tribo-corrosive wear and mechanical properties of nanoparticles reinforced Mg-AZ91D composites." Tribology International 178 (2023): 108054.
8. Monish, P., Krishna KL Hari, and K. Rajkumar. "Manufacturing and characterisation of magnesium composites reinforced by nanoparticles: a review." Materials Science and Technology 39, no. 15 (2023): 1858-1876.
9. Liu, Zhiyuan, Li Jin, Jian Zeng, Fulin Wang, Fenghua Wang, Shuai Dong, and Jie Dong. "A review on particle reinforced mg matrix composites fabricated by powder metallurgy." Acta Metallurgica Sinica (English Letters) 37, no. 3 (2024): 391-400.
10. Alekhya, Ch, A. Prajoshna, Mirza Ayaz Baig, Ch Chandrika, A. Devaraju, and Saikumar Gadakary. "Preparation and characterization of Al-TiO2-Mg composites through powder metallurgy." Materials Today: Proceedings 66 (2022): 489-495.
11. S. Marimuthu et al. (2022). Incorporating tool identification system in normal machining centre using radio frequency identification. In Materials Today: Proceedings (Vol. 69, pp. 716–719). Elsevier Ltd. https://doi.org/10.1016/j.matpr.2022.07.137
12. Ali, H. M., Mothilal, T., & Reddy, V. (2024). Evaluation of Lightweight Cotton Textiles for Durable and Comfortable Automotive Interior Applications (No. 2024-01-5015). SAE Technical Paper. DOI: https://doi.org/10.4271/2024-01-5015
13. Kelagadi et al., (2024). An Analysis on the Integration of Machine Learning and Advanced Imaging Technologies for Predicting the Liver Cancer. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1082-1086). IEEE. <https://doi.org/10.1109/ICPCSN62568.2024.00180>
14. N. Nagarajan et al. Hybrid Stir Cast Featured with Wettability Agent and Ultrasonic Action of Magnesium Alloy Composite Composed with Nanofiller: Study Characteristics. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01603-w>
15. V. Mohanavel et al. Tribological characteristics and optimization of ZrB2 configured magnesium alloy composite via squeeze casting technique. J Mech Sci Technol. 39(5), 2025. <https://doi.org/10.1007/s12206-025-0425-9>
16. Manzoore Elahi M. Soudagar, Ravindra Pratap Singh, Nagabhooshanam Nagarajan. et al. Featuring of in-situ carbon capturing and functional performance study of hydrogen from aquaculture wastewater algae biomass via supercritical steam gasification route, Chemical Engineering Science 313 (2025) 121704. <https://doi.org/10.1016/j.ces.2025.121704>
17. Manzoore Elahi M. Soudagar et al. Higher performance solar air dryer functioned with palmitic acid phase change material and hybrid nanofluid: Thermal performance evaluation, Applied Thermal Engineering (2025). Volume 272, 2025,126413, <https://doi.org/10.1016/j.applthermaleng.2025.126413>
18. P. P. Singh et al. Hybrid Thin Film Coating Performance and Functional Characteristics of Silicon Nitride (SiNx) Layer for Solar Cell Application. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11888-6>
19. Manzoore Elahi M. Soudagar, et al. Enrichment of Solar Heat Exchanger Thermal Performance by the Integration of Beeswax and Hybrid Nanofluid (ZnO/MgO). ASME. J. Thermal Sci. Eng. Appl. (2025) <https://doi.org/10.1115/1.4067929>
20. Saadh M J et al., (2024). Recent progress and the emerging role of lncRNAs in cancer drug resistance; focusing on signaling pathways. Pathology-Research and Practice, 253, 154999. <https://doi.org/10.1016/j.prp.2023.154999>
21. Lakshmaiya, N. (2024). High ionic permeability of Piper ION membrane boosts efficiency in CO2 electrolysis cells. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 172-180). SPIE. <https://doi.org/10.1117/12.3030841>
22. Anitha, Cuddapah, Naveena Kumar RR, Swapnil Uttamrao Deokar, Harshal Shah, and Praful V. Nandankar. Optimal Scheduling of Microgrid with Electric Vehicle Integration in Smart Grid using Progressive Graph Convolutional Network. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 375-380. IEEE, 2025.
23. Socrates, S., Bharathi, G. B., & Aluvala, S. (2024). A Framework for Automated Diagnosis and Management of Autoimmune Disorders with Neural Networks. In 2024 International Conference on Advancements in Smart, Secure and Intelligent Computing (ASSIC) (pp. 1-6). IEEE. https://doi.org/[10.1109/ASSIC60049.2024.10507903](https://doi.org/10.1109/ASSIC60049.2024.10507903)
24. Anitha, Cuddapah, Naveena Kumar RR, Swapnil Uttamrao Deokar, Harshal Shah, and Praful V. Nandankar. Optimal Scheduling of Microgrid with Electric Vehicle Integration in Smart Grid using Progressive Graph Convolutional Network. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 375-380. IEEE, 2025.
25. Socrates, S., Bharathi, G. B., & Aluvala, S. (2024). A Framework for Automated Diagnosis and Management of Autoimmune Disorders with Neural Networks. In 2024 International Conference on Advancements in Smart, Secure and Intelligent Computing (ASSIC) (pp. 1-6). IEEE. https://doi.org/[10.1109/ASSIC60049.2024.10507903](https://doi.org/10.1109/ASSIC60049.2024.10507903)
26. Selvan et al., (2024). Investigation of the Use of Renewable Energy in Microgrid Applications. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE . https://doi.org/10.1109/ICONSTEM60960.2024.10568631
27. Vinodh, D et al., (2024). Experimental investigation on tensile strength of novel metal matrix composite of aluminium alloy 5083 with SiC and eggshell powder reinforcement. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 297-306). SPIE.  https://doi.org/10.1117/12.3030843
28. Deepthi et al., (2024). Deep Learning-Enabled Human Resource Analytics in Predicting Employee Performance. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). EEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568716
29. Singh et al., (2024). Enhancing Mobile Robot Speed Control: PID Controller Optimization with Bio-Inspired Algorithms. In 2024 International Conference on Expert Clouds and Applications (ICOECA) (pp. 365-370). IEEE. https://doi.org/10.1109/ICOECA62351.2024.00071
30. Rafi et al., (2024). Improving Prostate Cancer Diagnosis with Weakly Supervised Learning and Radiology-Confirmed Negative MRI Data. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1183-1188). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544551
31. Lakshmaiya, N. (2024). Detection and impact of stochastic anomalies in investigations of urban pollution. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 269-277). SPIE. <https://doi.org/10.1117/12.3030839>
32. Kalam, S. A., Sheela, S., Paramasivam, P., & Shanmugam, K. (2024). Bio-synthesis of nano-zero-valent iron using barberry leaf extract: classification and utilization in the processing of methylene blue-polluted water. Discover Applied Sciences, 6(12), 1-15. https://doi.org/10.1007/s42452-024-06327-w
33. Padhy et al., (2024). Enhancing IoT-Enabled Healthcare with Genetic-based Encryption and Authentication for Secure and Efficient wireless Data Transmission. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1873-1878). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544722
34. Chakrapani et al., (2024). Optimizing sample length for fault diagnosis of clutch systems using deep learning and vibration analysis. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089241272791. https://doi.org/10.1177/095440892412727
35. N. Nagabhooshanam et al. Influences of Potassium Fluoride and Ultrasonic Vibration on Functional Performance of AZ91 Alloy Hybrid Nanocomposite with Nano-SiC/TiO2. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01552-4>
36. Soudagar, M. Manzoore Elahi et al. Effect of electron transport layer thickness and characteristics behaviour of hybrid copper indium gallium selenide thin film solar cells, Journal of Power Sources (2025). Volume 639, 2025,236657, <https://doi.org/10.1016/j.jpowsour.2025.236657>
37. R, Rajarajan et al. (2025). Improving Tribological Performance and Structural Analysis of Aluminium Hybrid Nanocomposites with Nano ZrO2/SiC Reinforcement via Stir Casting Assisted with Ultrasonic Vibration. International Journal of Cast Metals Research, February, 1–14. <https://doi.org/10.1080/13640461.2025.2467611>
38. A. Sharma et al. Hybrid Reinforcement Actions on Microstructural, Physical and Mechanical Properties of Magnesium Alloy Composite by Two-Step Stir Casting Process. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-024-01537-9>
39. P. K. Singh et al. Enhancement of silicon nitride layer performance by Gallium–Copper–Zinc tri-layer thin films structure via plasma featured chemical vapour deposition route. J Mater Sci: Mater Electron 36, 243 (2025). <https://doi.org/10.1007/s10854-025-14326-9>
40. Ahmad et al., (2024). IoT-Enabled Smart E-Healthcare System with Predictive Prescription Algorithm for Automatic Patient Monitoring and Treatment. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1076-1081). IEEE. https://doi.org/[10.1109/ICPCSN62568.2024.00179](https://doi.org/10.1109/ICPCSN62568.2024.00179)
41. Kaushal et al., (2024). Evaluation of Deep Learning Approaches for Air Quality Analysis using an Image Dataset. In 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI) (pp. 1378-1383). IEEE. https://doi.org/[10.1109/ICoICI62503.2024.10696429](https://doi.org/10.1109/ICoICI62503.2024.10696429)
42. Agrawal et al., (2024). Deep Learning Methods for Detecting ImageBased Defects in Manufacturing Processes. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568644
43. Lakshmaiya, N. (2024). Influence of small non-capillary washing activity on flow boiling essential heat transfer. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 224-231). SPIE.  https://doi.org/10.1117/12.3030838
44. Babu et al., (2024). Enhancing Security with Machine Learning-based Finger-Vein Biometric Authentication System. In 2024 5th International Conference on Mobile Computing and Sustainable Informatics (ICMCSI)(pp. 797-802). IEEE. https://doi.org/[10.1109/ICMCSI61536.2024.00123](https://doi.org/10.1109/ICMCSI61536.2024.00123)
45. V.V. Upadhyay et al. Trapezoidal fin featured heat exchanger performance enriched by using alumina/GNP hybrid nanofluid: thermal characteristics study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-13997-0>
46. N. Nagarajan. et al. Thermal performance assessment of dish collector-integrated cooking application using TiO2/SiO2 hybrid nano-enhanced coated receiver. J Braz. Soc. Mech. Sci. Eng. 47, 148 (2025). <https://doi.org/10.1007/s40430-025-05454-8>
47. I. Hossain et al. (2025). Enriching performance of Al-Mg composites by incorporating nano-alumina and SiC via semi-solid stir processing. International Journal of Cast Metals Research, 1–11. <https://doi.org/10.1080/13640461.2025.2476826>
48. M. Aruna et al. Vacuum Die Casting Process and Microstructure/Mechanical Characteristics Study of Magnesium Alloy Composite Hybridize with Zirconium Dioxide and Silicon Nitride. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01550-6>
49. M. Aruna et al. Integration of Magnesium Fluoride and Nano Alumina–Silicon Carbide Actions on Properties of AZ91 Alloy Hybrid Nanocomposites. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01617-4>
50. Jothi Arunachalam et al. Integration of nanographene and action of fiber sequences on functional behaviour of composite laminates" International Polymer Processing, 2025. <https://doi.org/10.1515/ipp-2024-0149>
51. P. Sharma et al. Effect of paraffin with salt hydrates PCM and hybrid Al2O3/Tio2 nanofluid on thermal and energy storage characteristics of solar thermal heat exchanger. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14224-6>
52. P. K. Singh et al. Integration of phase change material for enriching the solar collector featured with dryer configuration enhanced via alumina/titanium dioxide nanoparticle: performance study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14302-9>
53. A. Sharma et al. Structural Modification and Enhancement of Optoelectronic Behaviour of ZnO Nanofilms Featuring Cu and Ti Particles. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11951-2>
54. Muthugounder, P., Kumar, R. D., Ganesan, S., Gowrishankar, A., Karthikeyan, S., & Jebasingh, B. E. (2025). Featuring of boron nitride on high density polyethylene/sisal fiber composite: Characteristics evaluation. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020246). AIP Publishing LLC.