Aluminium Alloy Hybrid Nanocomposite With Nano-Sized Boron Carbide and Silica Nanoparticles Made By Squeeze Stir Casting: Performance Study

J Arun Prakash1, G.Sankaraiah 2, R Ashok kumar3, V Sathya4, S Kalaiarasan5, Jonnala Subba Reddy6, S Nanthakumar7, G Dhayanithi8,a), Mohanavel Vinayagam9

1Department of Aeronautical Engineering, Nehru Institute of Engineering and Technology, Coimbatore, 641105, Tamil Nadu, India.

2 Department of Mechanical Engineering, G.Pulla Reddy Engineering College, Kurnool, 518007, Andhrapradesh, India

3Department of Safety and fire Engineering, K.S.R College of Engineering, Tiruchengode637215, Tamil Nadu, India.

4 Department ofAgricultural Engineering, Rathinam Technical Campus, Coimbatore, Tamilnadu –641021,India.

5 Department of Chemistry, Sona College of Technology, Salem, 636005, Tamil Nadu, India.

6Department of Mechanical Engineering, Lakireddy Bali Reddy College of Engineering, Mylavaram, Andhra Pradesh, 521230, India

7Department of Mechanical Engineering, PSG Institute of Technology and Applied Research Neelambur, Coimbatore, 641062, Tamilnadu, India

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

9 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)**[gnanadhaya@gmail.com](mailto:gnanadhaya@gmail.com)

Abstract: The creation of aluminum-based composites that are both lightweight and thermally stable has drawn increasing interest for use in vehicle housing applications and the squeeze stir casting technique was used to reinforce the aluminum alloy AA2024 with nanoparticles of silica (SiO₂, 50 nm) and boron carbide of 30 nm. A thorough exploration was shown into the effects of single and hybrid reinforcements on energy absorption, compression strength and thermal stability. When hybrid reinforcement with silica improved both thermal stability and energy absorption, the addition of B₄C greatly increased compression strength. A potential material for lightweight vehicle housing applications, the hybrid composition including 3 weight % B₄C and 3 weight % SiO₂ had the most balanced performance among all specimens.

# Introduction

Because graphene-reinforced Al-MMCs are robust, have good heat transmission and function well in tribological conditions they have emerged as a promising kind of advanced material. Current developments in graphene Al composites were studied with a focus on their use in the structural and aeronautical fields [1-3]. One of the most studied processing techniques has always been simultaneous stir casting. While researchers [4-6] assessed the mechanical and tribological performance of stir cast aluminum composites in automotive, aerospace and military applications [7-9] provided a comprehensive assessment. The challenges of achieving defect-free microstructures during casting were the main emphasis of [10-11] detailed discussion of developments in Al-alloy processing.

Particle and hybrid reinforcements have been studied experimentally. Al6061 SiC B₄C composites made by stir casting were investigated by researcher [12] confirmed improvements in hardness and wear resistance. Authors [6] discovered that Al7075 composites enhanced with SiC and B₄C exhibited superior tribological properties, making them suitable for automobile applications. AA2024–B₄C composites, emphasizing improvements in mechanical strength and wear resistance [13-15]. The nano-B₄C content in Al-based hybrid nanocomposites resulting in improved corrosion and wear resistance [16]. Research on metal matrix composites especially aluminum based systems, has increasingly concentrated on enhancing reinforcement techniques to get better mechanical and tribological characteristics. Researcher [17-20] has highlighted the essential need to equilibrate hardness and toughness when integrating reinforcements such as silicon carbide and boron carbide since excessive hardness often undermines ductility and fracture resistance. In a related study, [21] showed that making the B₄C particles in A356 aluminum composites smaller greatly enhanced their mechanical performance. Building on this knowledge [22] looked into the effects of adding nano sized B₄C and they found that it made the material much stronger and less likely to rust, showing how useful nano reinforcements may be in many ways. [23-25] investigated AA2024 and AlO₃ with B₄C hybrid composites and discovered their ability to reinforce one another resulted in much greater tensile strength and wear resistance. Researchers [26] examined the tensile and fracture behavior of aluminum MMC reinforced with ceramic particles showing the need for a consistent reinforcement distribution for reliable performance while involving high stress or cyclic conditions. and aluminum nanocomposites and discovered a number of significant issues like poor interfacial bonding and processing induced porosity. They recommended the use of advanced processing methods like customized sintering and ultrasonic assisted dispersion to address these issues and in addition to highlighting the necessity of careful processing control to fully realize the mechanical and tribological capabilities of aluminum metal matrix composites these studies collectively highlight the revolutionary potential of nanoscale and hybrid reinforcements in tailoring these materials for high performance applications [27-28].

# Materials and Methods

## Materials

The aluminum alloy AA2024 was selected as the matrix material for this investigation because of its high strength relative to its weight and versatility in a variety of industries including automotive and aerospace. To strengthen the material silicon dioxide of around 50 nanometers and boron carbide particles were used. Before being applied they were heated to 200–250 degrees Celsius to remove any absorbed moisture and increase the nanopowders' wettability with the aluminum matrix [29-30].

## Fabrication Process

We made the hybrid nanocomposites using squeezing stir casting which spreads the particles out better and makes the material less porous than regular casting and the stages in the procedure were as follows:

* Melting: The AA2024 alloy was melted at around 750 °C in a controlled environment to keep it from oxidizing. Semi solid stage: The melt was cooled to the semi solid state to let the particles mix in better.
* Adding reinforcement: The preheated B₄C and the SiO₂ nanopowders were slowly added to vortex created by mechanical stirring at 600 rpm for 8 minutes.
* Ultrasonic treatment: An ultrasonic probe was used to break up clumps and make sure that the nanoparticles were spread out evenly.
* Squeeze casting: The slurry was poured into steel dies that had already been heated and a squeeze pressure of 100 MPa was applied during solidification to make the microstructure more uniform and the less porous.

## Composite Formulations

**TABLE 1.** Composite Configurations [31-33]

|  |  |
| --- | --- |
| **Model ID** | **Composition** |
| Model 1 | AA2024 (Unreinforced) |
| Model 2 | AA2024 + 3 wt% B₄C |
| Model 3 | AA2024 + 3 wt% B₄C + 1 wt% SiO₂ |
| Model 4 | AA2024 + 3 wt% B₄C + 3 wt% SiO₂ |

These formulations were created to test how B₄C reinforcement and hybrid B₄C SiO₂ additions worked together to change the mechanical, thermal and wear characteristics of AA2024 alloy.

## Testing Standards

The thermal stability of the manufactured composites was tested using thermogravimetric analysis in a nitrogen controlled environment to determine how reinforcements affected degradation behavior and resistance to high temperatures. Compression strength was tested using ASTM E9 standards to ensure that the ability of composites to support weight under static compressive stress was accurately evaluated, and the area under the stress-strain curves was used to determine the energy absorption capacity, which gave us a sense of how well the composites could withstand impact and disperse mechanical energy [34-36].

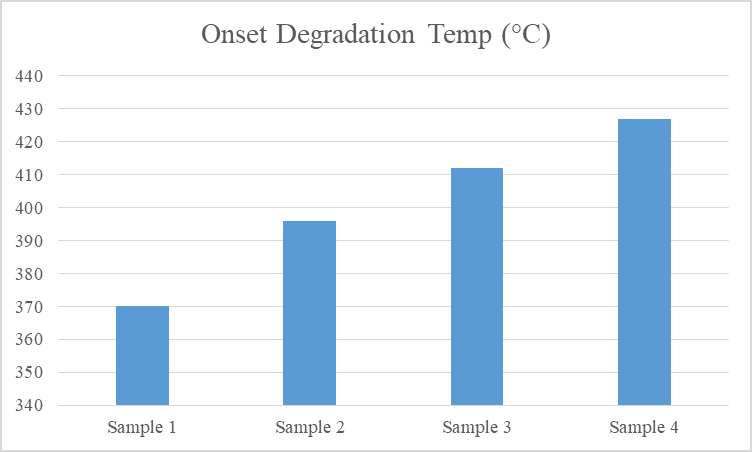
# Results and Discussion

## Thermal Stability

While the addition of SiO₂ as a hybrid reinforcement made a greater difference because it had a better heat barrier effect and could stop oxidative deterioration, the addition of B₄C nanoparticles made the AA2024 matrix slightly more thermally stable by acting as ceramic barriers that resist heat. Because of this the hybrid composites had a much higher beginning degradation temperature. For example Model 4 had an increase of over 57 °C equated to the unreinforced alloy. This means that the combination of B₄C and SiO₂ makes the composites better able to withstand maximum temperatures which marks them perfect for use in applications that need a lot of heat [37-39].

**TABLE 2** Thermal Stability

|  |  |  |
| --- | --- | --- |
| Specimen | Onset Degradation Temp (°C) | Residual Mass (%) |
| Model 1 | 370 | 6.8 |
| Model 2 | 396 | 8.9 |
| Model 3 | 412 | 9.8 |
| Model 4 | 427 | 11.2 |



**Figure 1.** Thermal Stability

## Compression Strength and Energy Absorption

The AA2024 based composites ability to handle compression steadily improved when B₄C and SiO₂ nanoparticles were added. The strong ceramic phases made it easier to refine the grains and move loads efficiently which made the material more resistant to compressive deformation. Model 4 had the greatest compressive strength of all the Models with an increase of almost 21% above the base alloy. Also the hybrid system had the highest energy absorption capacity, which was measured as the area beneath the stress-strain curve. This showed that B₄C and SiO₂ worked together to make the system stronger and these improvements show that the reinforcements serve two purposes, they make the matrix stronger and better able to handle impact and dynamic loading. This makes the composites good for structural customs that is essential both strength and toughness [40-43].

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

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

# 

**Figure 2.** Compression Strength

# Applications in Lightweight Automotive Housing

The AA2024/B₄C–SiO₂ nanocomposites that were made show great promise for use in lightweight automobile housing applications such engine covers, gearbox casings and structural housings and these parts frequently have both mechanical and thermal strains at the same time, which might cause material failure that could affect safety and performance [44-47]. The low density of AA2024, together with the fact that SiO₂ makes it more resistant to heat and B₄C makes it stronger means that it can be made much lighter without losing strength or durability. Also, the composites are better at absorbing energy which makes them more resistant to impacts. This makes them perfect for current car systems that need to be efficient, durable and reliable even when circumstances change [48-50].

# Conclusion

Adding a nano B₄C and SiO₂ reinforcements to AA2024 alloy by squeeze stir casting improved its thermal stability, compressive strength and ability to absorb energy. Model 4 (AA2024 + 3 wt% B₄C + 3 wt% SiO₂) had the best inclusiveenactment of all the formulations and it was stronger mechanically and better at resisting thermal deterioration and these findings show how well hybrid nanoparticle reinforcement works to change the multifunctional characteristics of aluminum based composites and the AA2024/B₄C SiO₂ nanocomposites that were made have a lot of potential for use in lightweight vehicle housing where both structural durability and thermal management are important for long term dependability.

# References

1. Md Ali, Afifah, Mohd Zaidi Omar, HanizamHashim, MohdShukorSalleh, and IntanFadhlina Mohamed. "Recent development in graphene-reinforced aluminium matrix composite: A review." Reviews on Advanced Materials Science 60, no. 1 (2021): 801-817.
2. Sankhla, Arvind, and Kaushik M. Patel. "Metal matrix composites fabricated by stir casting process–a review." Advances in Materials and Processing Technologies 8, no. 2 (2022): 1270-1291.
3. F. M. Anjalin et al. (2023). Inorganic Adsorption on Thermal Response and Wear Properties of Nanosilicon Nitride-Developed AA6061 Alloy Nanocomposite. Adsorption Science and Technology, 2023. https://doi.org/10.1155/2023/8468644
4. Biswas, Prasenjit, JagadishNayak, Arjun Kundu, Deepak Patel, ArchanaMallik, and Sanjeev Das. "A review on the development of processing techniques for the production and casting of Al-alloy and metal matrix composite material." Iranian Journal of Science and Technology, Transactions of Mechanical Engineering 49, no. 1 (2025): 35-66.
5. Ranjitha, P., D. SaravanaBavan, B. S. Ajaykumar, T. HemanthRaju, and S. Udayashankar. "Investigation of mechanical properties of Al6061–SiC–B4C composites produced by using stir casting method." Journal of The Institution of Engineers (India): Series D 106, no. 1 (2025): 339-351.
6. Bharathi, P., and T. Sampath Kumar. "Effect of silicon carbide and boron carbide on mechanical and tribological properties of aluminium 7075 composites for automobile applications." Silicon 15, no. 14 (2023): 6147-6171.
7. Verma, Akarsh, V. K. Singh, and Sakshi Chauhan. "Advances in the AA2024-B₄C Metal Matrix Composites: Development, Characterization and Performance Analysis." Engineering Research Express (2025).
8. Çanakçı, Aykut, Abdullah HasanKarabacak, MüslimÇelebi, SerdarÖzkaya, and Kürşat Alp Arpacı. "A study on the optimization of nano-B4C content for the best wear and corrosion properties of the Al-based hybrid nanocomposites." Arabian Journal for Science and Engineering 49, no. 11 (2024): 14625-14641.
9. 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>
10. 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>
11. 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)
12. 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.
13. 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)
14. 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
15. 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
16. 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>
17. 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>
18. 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>
19. 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>
20. 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>
21. 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>
22. 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>
23. 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>
24. 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>
25. 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
26. 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)
27. 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>
28. 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>
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. 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
31. 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.
32. 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>
33. 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>
34. 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>
35. 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>
36. 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>
37. 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>
38. 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
39. 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
40. Padhyet 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
41. 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>
42. 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
43. 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>
44. 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)
45. 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>
46. 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
47. 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)
48. 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>
49. Arunraja, K. M., Muthugounder, P., Karthikeyan, S., Ganesan, S., Gowrishankar, A., & Muruganandhan, B. P. (2025). Influences of jute fiber and alumina nanoparticles on behaviour of polyester composite synthesized via hand layup route. In AIP Conference Proceedings (Vol. 3267, No. 1, p. 020290). AIP Publishing LLC.
50. Karthikeyan, S., Manivannan, S., Venkatesh, R., Karthikeyan, S., Anand, R., & Sasikaran, S. V. (2024). Optimization and characteristics of multimodal binder on polymer nanocomposite for lightweight applications. Journal of Environmental Nanotechnology, 13(3), 207–216.