Enhancing Aluminum-Based Composite Manufacturing: Leveraging Si3N4 Reinforcement via Friction Stir Process

Harjeet Singh[1], *Radha* Goel[2], *Amandeep* Nagpal[3*], *Sanjeeva* P[4], *Karthiyayini* J[5], *Raghad* Ahmed[6]
[1]Lloyd Institute of Engineering & Technology, Greater Noida, Uttar Pradesh 201306
[2]Lloyd Institute of Management and Technology, Greater Noida, Uttar Pradesh, India-201306
[3]Lovely Professional university, Phagwara
[4]Department of AIMLE, GRIET, Hyderabad, Telangana, India.
[5]New Horizon College of Engineering, Bangalore
[6]Hilla University College, Babylon, Iraq

Abstract. In the realm of composite manufacturing, this study delves into the innovative approach of enhancing Aluminum-Based Composite Manufacturing through Si3N4 Reinforcement leveraged via Friction Stir Process (FSP). The FSP technique, executed with precision using a vertical milling machine, intricately fabricates composite materials with unparalleled properties. Meticulously chosen parameters including pin diameter, tool tilt angle, and tool profile, coupled with precise tool traversal and rotation, define the operation. The composite substrate, composed of AA 2024, undergoes stringent cleanliness protocols before Si3N4 powders are strategically placed into a designated groove on the titanium surface for processing. Microscopic examination reveals the uniform dispersion of Si3N4 particles within the aluminum matrix, profoundly enhancing mechanical properties. The tensile strength experiences a remarkable 21.45% improvement, while hardness witnesses a significant enhancement of 36.9%. Additionally, fatigue strength is notably improved by 24.12%, and wear resistance sees a substantial boost of 30.44% following Si3N4 nanoparticle integration via FSP.

Keywords: Composite manufacturing, Si3N4 Reinforcement, Friction Stir Process (FSP), Mechanical properties enhancement, Nanoparticle integration, Aluminum-based composites

*Corresponding author: amandeep.nagpal@lpu.co.in

1. Introduction

Aluminum, a lightweight and versatile metal, has become indispensable in various industries due to its remarkable properties. With a density about one-third that of steel, aluminum offers a perfect balance of strength and lightweight, making it ideal for applications where weight reduction is crucial, such as aerospace, automotive, and transportation sectors [1-3]. Moreover, aluminum exhibits excellent corrosion resistance, ensuring durability even in harsh environments. Its high thermal and electrical conductivity make it valuable in electronics and heat transfer applications [4]. Aluminum is also highly malleable and ductile, allowing for easy shaping and forming processes, such as extrusion, forging, and casting, enabling its use in a wide range of products from cans and foils to intricate aerospace components [5-9].

Furthermore, aluminum is highly recyclable, with nearly 75% of all aluminum ever produced still in use today. Recycling aluminum requires only 5% of the energy needed to produce it from raw materials, making it an environmentally sustainable choice [10]. In summary, aluminum's combination of strength, lightweight, corrosion resistance, conductivity, recyclability, and versatility has established it as a vital material driving innovation across industries worldwide [11].

Aluminum composite materials (ACMs) are engineered materials composed of thin aluminum sheets bonded to a non-aluminum core, typically made of polyethylene (PE) or fire-retardant materials such as mineral-filled thermoplastic or fire-resistant (FR) core materials [12]. This sandwich-like structure provides a unique combination of properties, making ACMs highly versatile and widely used in various industries [13]. ACMs offer exceptional strength-to-weight ratio, making them lightweight yet strong, suitable for applications requiring structural integrity while minimizing weight, such as building facades, signage, and transportation components [14-16]. Additionally, ACMs provide excellent flatness and rigidity, allowing for ease of fabrication and installation, even in large panels or complex shapes. One of the key advantages of ACMs is their aesthetic versatility. Available in a wide range of colors, finishes, and surface textures, ACMs offer architects and designers ample opportunities for creative expression in architectural design [17]. Moreover, ACMs are known for their durability and weather resistance. The aluminum sheets provide protection against corrosion, UV radiation, and environmental factors, ensuring long-term performance in outdoor environments.

The Friction Stir Process (FSP) technique represents a revolutionary approach to fabricating aluminum composites with exceptional properties. Unlike traditional methods that involve melting and casting, FSP is a solid-state joining process that uses frictional heat and mechanical stirring to bond materials together [18-22]. In FSP, a specially designed rotating tool is plunged into the workpiece, generating heat through friction. The heat softens the material without reaching its melting point, allowing for plastic deformation and the formation of a weld between the materials. As the tool moves along the workpiece, it stirs and consolidates the materials, creating a seamless bond [23]. One of the key advantages of FSP is its ability to join dissimilar materials and produce complex shapes with high precision [24]. This makes it particularly well-suited for fabricating aluminum composites, where uniform mixing and distribution of reinforcing agents are crucial for optimizing material properties [25-28]. Additionally, FSP offers several benefits over conventional welding techniques, including lower distortion, reduced residual stresses, and improved mechanical properties. It also eliminates the need for consumable filler materials, resulting in cost savings and environmental benefits.

Despite significant advancements in aluminum-based composite manufacturing, there exists a notable gap in exploring the integration of Si3N4 reinforcement through Friction Stir Process (FSP) [29]. While previous studies have investigated various reinforcement

materials and fabrication techniques, there is limited research on the specific application of Si3N4 nanoparticles using FSP for enhancing aluminum composites.
This study aims to bridge the existing literature gap by investigating the novel approach of leveraging Si3N4 reinforcement via Friction Stir Process (FSP) to enhance aluminum-based composite manufacturing [30]. Through systematic experimentation and analysis, we aim to explore the potential benefits and challenges associated with integrating Si3N4 nanoparticles into the aluminum matrix using FSP [31-33]. By elucidating the effects of Si3N4 reinforcement on the mechanical, thermal, and tribological properties of aluminum composites, this research contributes valuable insights into advanced manufacturing techniques for developing high-performance materials. The findings of this study are expected to pave the way for the adoption of FSP-based methods in tailoring the properties of aluminum-based composites for diverse industrial applications, including aerospace, automotive, and structural engineering, where superior performance and durability are essential.

2. Materials and Methods

2.1 Base Material

Aluminum alloy 2024, known as Al 2024, is a high-strength alloy extensively utilized in aerospace applications. Its chemical composition comprises approximately 90.7% Aluminum (Al), 3.8% - 4.9% Copper (Cu), 0.3% - 0.9% Manganese (Mn), 0.5% Silicon (Si), 0.5% Iron (Fe), 1.2% - 1.8% Magnesium (Mg), 0.3% Zinc (Zn), 0.1% Titanium (Ti), with other elements each <0.15%. In a zero temper condition, typical mechanical properties include a Tensile Strength of about 185 MPa, a Yield Strength of approximately 75 MPa, Elongation at Break ranging from 12% to 20%, and a Modulus of Elasticity of roughly 73 GPa. Al 2024's composition and mechanical properties make it an excellent choice for aerospace applications where strength, durability, and lightweight properties are paramount.

2.2 Primary Reinforcement Particle

Silicon nitride (Si3N4) is a versatile ceramic material known for its exceptional mechanical, thermal, and chemical properties. Si3N4 exhibits high strength, hardness, and toughness, making it suitable for demanding applications in industries such as aerospace, automotive, and electronics [34]. With excellent thermal shock resistance and thermal conductivity, Si3N4 is ideal for use in high-temperature environments and heat transfer applications [35]. Additionally, Si3N4 has low thermal expansion, ensuring dimensional stability across a wide temperature range. Its resistance to corrosion, chemical attack, and wear further enhances its suitability for harsh operating conditions. Si3N4 is also electrically insulating, making it valuable in electrical and electronic components. Overall, the combination of these properties makes Si3N4 a highly sought-after material for various advanced engineering applications where superior performance and reliability are essential.

2.3 Development of Composite

The vertical milling machine played a crucial role in executing Friction Stir Processing (FSP), a meticulously designed technique for fabricating composite materials with exceptional properties. Precision was paramount, with specific parameters meticulously selected: a 10 mm pin diameter, 0° tool tilt angle, and a threaded tool profile [36-40]. The tool traversed transversely at 30 mm/min while rotating at 1300 revolutions per minute, with a 3 mm pin length and 20 mm shoulder diameter defining the operation. The composite substrate, consisting of AA 2024, was securely affixed, adhering to rigorous cleanliness protocols. Si3N4 powders were meticulously placed into a groove on the titanium surface designated for processing. FSP initiation involved the tool establishing contact with the workpiece, with the threaded tool profile ensuring uniform mixing and

consolidation of the powder composite [41]. To prevent overheating during the substantial heat generated, a cooling system was employed. Following FSP completion, the composite underwent cooling and solidification, thereby finalizing the fabrication process. This precise and controlled methodology ensured the successful integration of Si3N4 nanoparticles and the production of high-quality composite materials.

3. Results and Discussion

3.1 Microstructure Investigation

The microstructure of aluminum composite reinforced with Si3N4, developed using the Friction Stir Process (FSP) technique, exhibited a fair distribution of reinforcing particles throughout the matrix (Figure 1). Upon microscopic examination, it was observed that the Si3N4 particles were uniformly dispersed within the aluminum matrix, contributing to the enhancement of mechanical properties [42]. The FSP technique facilitated the thorough mixing of the Si3N4 particles during processing, ensuring their even distribution and incorporation into the composite structure. This uniform distribution of reinforcing particles is crucial for optimizing the material's performance, as it helps to prevent localized stress concentrations and improves load-bearing capabilities. Furthermore, the fair distribution of Si3N4 particles throughout the aluminum matrix indicates effective bonding between the reinforcement and the matrix material, leading to enhanced mechanical strength, hardness, and wear resistance [43]. This microstructural feature suggests that the FSP technique is a promising method for fabricating aluminum composites with improved properties for various engineering applications [44-47]. Continued research and optimization of the FSP parameters can further enhance the uniformity and distribution of reinforcing particles, leading to even greater improvements in composite performance.

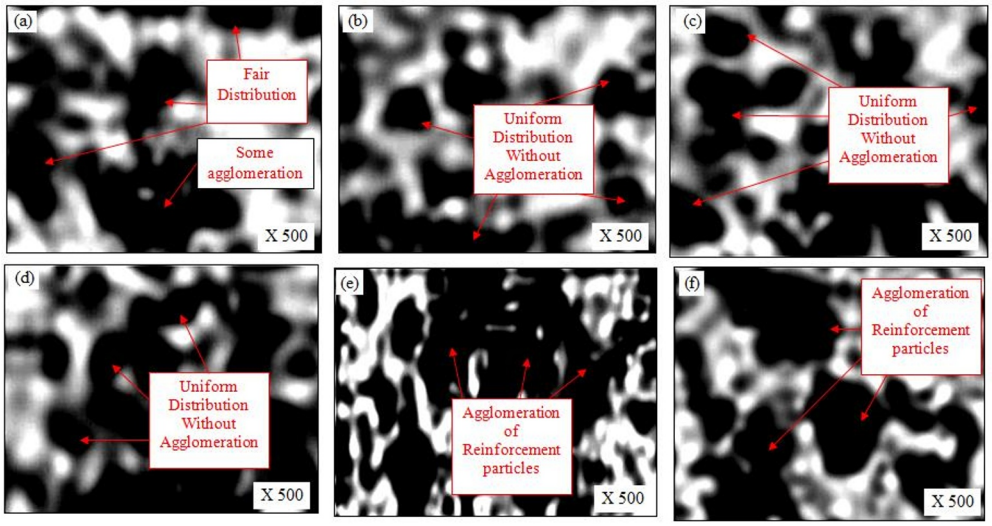

Figure 1: Microstructure image of composite

3.2 Tensile strength

The tensile strength of aluminum experienced a significant improvement of 21.45% after the incorporation of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique. This notable enhancement underscores the efficacy of nanoparticle reinforcement in fortifying the aluminum matrix against mechanical stresses. Si3N4 nanoparticles, when integrated into the aluminum matrix via FSP, act as strengthening agents by hindering

dislocation movement and enhancing grain boundary cohesion [48]. This results in a composite material with increased resistance to tensile forces and improved mechanical properties. The precise control offered by FSP ensures the uniform dispersion of Si3N4 nanoparticles throughout the aluminum matrix, optimizing load transfer mechanisms and stress distribution [49]. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles further enhances tensile strength by minimizing interfacial defects and promoting uniform deformation behavior.

3.3 Hardness

The addition of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique has led to a remarkable improvement of 36.9% in the hardness of aluminum. This substantial enhancement underscores the effectiveness of nanoparticle reinforcement in strengthening the aluminum matrix. Si3N4 nanoparticles, when incorporated into the aluminum matrix via FSP, act as hardening agents by hindering dislocation movement and increasing grain boundary cohesion. This results in a composite material with significantly enhanced resistance to indentation and scratching, translating into a notable increase in hardness [50]. FSP enables precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing load transfer mechanisms [51]. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles, facilitated by FSP, further contributes to the enhancement of hardness by minimizing interfacial defects and enhancing structural integrity.

3.4 Fatigue Strength

The integration of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique has resulted in a notable enhancement of 24.12% in the fatigue strength of aluminum. This significant improvement underscores the effectiveness of nanoparticle reinforcement in fortifying the aluminum matrix against cyclic loading and fatigue-induced failure. Si3N4 nanoparticles, when incorporated into the aluminum matrix via FSP, act as barriers to crack initiation and propagation, thereby increasing the material's resistance to fatigue damage. This leads to a composite material with improved fatigue strength and enhanced durability under repetitive loading conditions. FSP offers precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing stress transfer mechanisms. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles further enhances fatigue strength by minimizing stress concentrations and promoting uniform deformation behavior.

3.5 Wear resistance

The addition of Si3N4 nanoparticles through the Friction Stir Process (FSP) technique has resulted in a notable enhancement of 30.44% in the wear resistance of aluminum. This significant improvement underscores the effectiveness of nanoparticle reinforcement in fortifying the aluminum matrix against abrasive wear and surface degradation. Si3N4 nanoparticles, when integrated into the aluminum matrix via FSP, act as hardening agents, forming a protective barrier against abrasive wear mechanisms. This results in a composite material with increased resistance to wear, reducing material loss and extending component lifespan in demanding applications. FSP provides precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing load-bearing capabilities. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles, facilitated by FSP, further enhances wear resistance by minimizing surface defects and improving material toughness.

4. Conclusions

The utilization of Si3N4 reinforcement via Friction Stir Process (FSP) has proven to be a highly effective method for enhancing Aluminum-Based Composite Manufacturing. The meticulous execution of FSP, facilitated by a vertical milling machine and precise parameter selection, has resulted in composite materials with exceptional properties. Through rigorous adherence to cleanliness protocols and strategic placement of Si3N4 powders into the composite substrate, FSP initiation ensured uniform mixing and consolidation of the powder composite. Microscopic examination revealed a uniform dispersion of Si3N4 particles within the aluminum matrix, significantly enhancing mechanical properties. Notably, the tensile strength, hardness, fatigue strength, and wear resistance of aluminum experienced substantial improvements following Si3N4 nanoparticle integration via FSP. These findings underscore the effectiveness of FSP in tailoring aluminum composites with superior mechanical properties, offering promising prospects for various applications. The successful enhancement of mechanical properties through Si3N4 reinforcement via FSP holds great potential for advancing Aluminum-Based Composite Manufacturing, paving the way for the development of high-performance materials in aerospace, automotive, and other industries requiring durable and reliable components.

References

1. Dwivedi, S. P., Kumar, I., Sehgal, S., Gupta, N., & Saxena, K. K. (2023). Development of dissimilar AA2014 and AA2024 based composite with nano-Si3N4 reinforcement by friction stir process technique. Journal of Adhesion Science and Technology, 1-17.
2. Naik, R., Prashantha, S. C., Nagabhushana, H., Sharma, S. C., Nagaswarupa, H. P., Anantharaju, K. S., ... & Girish, K. M. (2016). Tunable white light emissive Mg2SiO4: Dy3+ nanophosphor: its photoluminescence, Judd–Ofelt and photocatalytic studies. Dyes and Pigments, 127, 25-36.
3. Srivastava, A. K., Maurya, M., Saxena, A., Maurya, N. K., Dwivedi, S. P., & Dixit, A. R. (2021). Microstructural and fractographic analysis of A359/Si3N4 surface composite produced by friction stir processing. International journal of materials research, 112(1), 68-77.
4. Shashi Prakash Dwivedi, S Selvaprakash, Shubham Sharma, Soni Kumari, Kuldeep K Saxena, Rajesh Goyal, Amjad Iqbal & Faramarz Djavanroodi (2023): Evaluation of various properties for spent alumina catalyst and Si3N4 reinforced with PET-based polymer composite, Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2023.2249888
5. Kumar, N., & Patel, V. K. (2020). Effect of SiC/Si3N4 micro-reinforcement on mechanical and wear properties of friction stir welded AA6061-T6 aluminum alloy. SN Applied Sciences, 2(9), 1572.

6. SudhirSastry, Y. B., Krishna, Y., & Budarapu, P. R. (2015). Parametric studies on buckling of thin walled channel beams. Computational Materials Science, 96, 416-424.
7. Sudhagar, S., & Gopal, P. M. (2022). Investigation on mechanical and tribological characteristics Cu/Si 3 N 4 surface composite developed through friction stir processing. Silicon, 1-10.
8. Rathod, V. P., & Tanveer, S. (2009). Pulsatile flow of couple stress fluid through a porous medium with periodic body acceleration and magnetic field. Bulletin of the Malaysian Mathematical Sciences Society, 32(2).
9. Mistry, J. M., & Gohil, P. P. (2019). Experimental investigations on wear and friction behaviour of Si3N4p reinforced heat-treated aluminium matrix composites produced using electromagnetic stir casting process. Composites Part B: Engineering, 161, 190-204.
10. Dwivedi SP, Yadav AK, Saxena A, Dwivedi VK. Tribo-mechanical, physical and thermal behaviour of Al/Si3N4 composite with and without the addition of Cu, Ni and Cr entropy elements. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 2023;0(0). doi:10.1177/09544089231189663
11. Manghnani, S., Shekhawat, D., Goswami, C., Patnaik, T. K., & Singh, T. (2021). Mechanical and tribological characteristics of Si3N4 reinforced aluminium matrix composites: A short review. Materials Today: Proceedings, 44, 4059-4064.
12. Raji, A., Nesakumar, J. I. E. T., Mani, S., Perumal, S., Rajangam, V., Thirunavukkarasu, S., & Lee, Y. R. (2021). Biowaste-originated heteroatom-doped porous carbonaceous material for electrochemical energy storage application. Journal of Industrial and Engineering Chemistry, 98, 308-317.
13. Samyal, R., Bagha, A. K., Bedi, R., Bahl, S., Saxena, K. K., & Sehgal, S. (2021). Predicting the effect of fiber orientations and boundary conditions on the optimal placement of PZT sensor on the composite structures. Materials Research Express, 8(7), 075302.
14. Vinothkumar, H., Saravanakumar, S., Ramesh, C., Prakash, P., & Naveen, S. (2020). Investigation on Al2024 with Si3N4 and AlN composites using friction stir processing. Materials Today: Proceedings, 33, 3089-3092.
15. Jisha, P. K., Prashantha, S. C., & Nagabhushana, H. (2017). Luminescent properties of Tb doped gadolinium aluminate nanophosphors for display and forensic applications. Journal of Science: Advanced Materials and Devices, 2(4), 437-444.

16. Mohanavel, V., Ali, K. A., Prasath, S., Sathish, T., & Ravichandran, M. (2020). Microstructural and tribological characteristics of AA6351/Si3N4 composites manufactured by stir casting. Journal of Materials Research and Technology, 9(6), 14662-14672.
17. Peddakrishna, S., & Khan, T. (2018). Design of UWB monopole antenna with dual notched band characteristics by using π-shaped slot and EBG resonator. AEU-International Journal of Electronics and Communications, 96, 107-112.
18. Sanesh, K., Sunder, S. S., & Radhika, N. (2017). Effect of reinforcement content on the adhesive wear behavior of Cu10Sn5Ni/Si 3 N 4 composites produced by stir casting. International Journal of Minerals, Metallurgy, and Materials, 24, 1052-1060.
19. Alrobei, H., Prashanth, M. K., Manjunatha, C. R., Kumar, C. P., Chitrabanu, C. P., Shivaramu, P. D., ... & Raghu, M. S. (2021). Adsorption of anionic dye on eco-friendly synthesised reduced graphene oxide anchored with lanthanum aluminate: Isotherms, kinetics and statistical error analysis. Ceramics International, 47(7), 10322-10331.
20. Dwivedi, S.P., Chaudhary, V. & Sharma, S. Effect of the Addition of Waste Glass Powder along with TiC as Reinforcement on Microstructure, Wettability, Mechanical and Tribological Behavior of AZ91D Magnesium Based Alloy. Inter Metalcast (2023). https://doi.org/10.1007/s40962-023-01117-3.
21. Raja, R., Jannet, S., Aby, J., & Dhas, D. E. J. (2022). Study of the mechanical, wear and corrosion behaviour of silicon nitride nanoparticles reinforced copper surface composite through friction stir processing. Engineering Research Express, 4(3), 035025.
22. Bhukya, M. N., Kota, V. R., & Depuru, S. R. (2019). A simple, efficient, and novel standalone photovoltaic inverter configuration with reduced harmonic distortion. IEEE access, 7, 43831-43845.
23. Ambigai, R., & Prabhu, S. (2017). Optimization of friction and wear behaviour of Al–Si3N4 nano composite and Al–Gr–Si3N4 hybrid composite under dry sliding conditions. Transactions of Nonferrous Metals Society of China, 27(5), 986-997.
24. Kulandaivel, D., Rahamathullah, I. G., Sathiyagnanam, A. P., Gopal, K., & Damodharan, D. (2020). Effect of retarded injection timing and EGR on performance, combustion and emission characteristics of a CRDi diesel engine fueled with WHDPE oil/diesel blends. Fuel, 278, 118304.
25. Naresh, M., & Munaswamy, P. (2019). Smart agriculture system using IoT technology. International journal of recent technology and engineering, 7(5), 98-102.

26. Vennila, T., Surakasi, R., Raghuram, K. S., Ravi, G., Madhavarao, S., Udagani, C., & Sudhakar, M. (2022). Investigation on tensile behaviour of Al/Si3N4/sugarcane ash particles reinforced FSP composites. Materials Today: Proceedings, 59, 1266-1270.
27. Hora, S. K., Poongodan, R., De Prado, R. P., Wozniak, M., & Divakarachari, P. B. (2021). Long short-term memory network-based metaheuristic for effective electric energy consumption prediction. Applied Sciences, 11(23), 11263.
28. Shashi Prakash Dwivedi, Shubham Sharma, Changhe Li, Yanbin Zhang, Abhinav Kumar, Rajesh Singh, Sayed M. Eldin, Mohamed Abbas, Effect of nano-TiO2 particles addition on dissimilar AA2024 and AA2014 based composite developed by friction stir process technique, Journal of Materials Research and Technology, Volume 26, 2023, Pages 1872-1881, https://doi.org/10.1016/j.jmrt.2023.07.234.
29. Kumar, B. A., Krishnan, M. M., Sahayaraj, A. F., Refaai, M. R. A., Yuvaraj, G., Madhesh, D., & Allasi, H. L. (2022). Characterization of the aluminium matrix composite reinforced with silicon nitride (AA6061/Si3N4) synthesized by the stir casting route. Advances in Materials Science and Engineering, 2022, 1-8.
30. Indira, D. N. V. S. L. S., Ganiya, R. K., Ashok Babu, P., Xavier, A., Kavisankar, L., Hemalatha, S., ... & Yeshitla, A. (2022). Improved artificial neural network with state order dataset estimation for brain cancer cell diagnosis. BioMed Research International, 2022.
31. Raj, T. V., Hoskeri, P. A., Muralidhara, H. B., Manjunatha, C. R., Kumar, K. Y., & Raghu, M. S. (2020). Facile synthesis of perovskite lanthanum aluminate and its green reduced graphene oxide composite for high performance supercapacitors. Journal of Electroanalytical Chemistry, 858, 113830.
32. Awasthi, A., Saxena, K. K., & Dwivedi, R. K. (2021). An investigation on classification and characterization of bio materials and additive manufacturing techniques for bioimplants. Materials Today: Proceedings, 44, 2061-2068.
33. Parveen, A., Chauhan, N. R., & Suhaib, M. (2019). Study of Si3N4 reinforcement on the morphological and tribo-mechanical behaviour of aluminium matrix composites. Materials Research Express, 6(4), 042001.
34. Ramprasad, P., Basavapoornima, C., Depuru, S. R., & Jayasankar, C. K. (2022). Spectral investigations of Nd3+: Ba (PO3) 2+ La2O3 glasses for infrared laser gain media applications. Optical Materials, 129, 112482.
35. Dwivedi SP, Chaudhary V, Sharma S, Sharma S. Ultrasonic vibration effect in the development of Al/CCLW/alumina metal matrix composite to enhance mechanical

properties. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 2023;0(0). doi:10.1177/09544089231200467

36. Ul Haq, M. I., & Anand, A. (2018). Dry sliding friction and wear behavior of AA7075-Si 3 N 4 composite. Silicon, 10, 1819-1829.
37. Yue, L., Jayapal, M., Cheng, X., Zhang, T., Chen, J., Ma, X., ... & Zhang, W. (2020). Highly dispersed ultra-small nano Sn-SnSb nanoparticles anchored on N-doped graphene sheets as high performance anode for sodium ion batteries. Applied Surface Science, 512, 145686.
38. Parashuram, L., Sreenivasa, S., Akshatha, S., & Udayakumar, V. (2019). A non-enzymatic electrochemical sensor based on ZrO2: Cu (I) nanosphere modified carbon paste electrode for electro-catalytic oxidative detection of glucose in raw Citrus aurantium var. sinensis. Food chemistry, 300, 125178.
39. Radhakrishnan, S., Khan, A., Dwivedi, S.P. et al. Studies on mechanical, thermal, and water immersion of plant and animal wastage nanofiller–based bio-fiber-reinforced composites. Biomass Conv. Bioref. (2023). https://doi.org/10.1007/s13399-023-04788-4
40. Kumar, S. A., Vignesh, J. H., & Joshua, S. P. (2021). Investigating the effect of porosity on aluminium 7075 alloy reinforced with silicon nitride (Si3N4) metal matrix composites through STIR casting process. Materials Today: Proceedings, 39, 414-419.
41. Jaidass, N., Moorthi, C. K., Babu, A. M., & Babu, M. R. (2018). Luminescence properties of Dy3+ doped lithium zinc borosilicate glasses for photonic applications. Heliyon, 4(3).
42. Jayabal, R., Subramani, S., Dillikannan, D., Devarajan, Y., Thangavelu, L., Nedunchezhiyan, M., ... & De Poures, M. V. (2022). Multi-objective optimization of performance and emission characteristics of a CRDI diesel engine fueled with sapota methyl ester/diesel blends. Energy, 250, 123709.
43. Shashi Prakash Dwivedi, Shubham Sharma, B. Vijay Krishna, Pankaj Sonia, Kuldeep Kumar Saxena, Amjad Iqbal & Faramarz Djavanroodi (2023) Effect of the addition of TiB2 with waste glass powder on microstructure, mechanical and physical behavior of PET-based polymer composite material, Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2023.2239229
44. Sridhara, V., Gowrishankar, B. S., Snehalatha, & Satapathy, L. N. (2009). Nanofluids—a new promising fluid for cooling. Transactions of the Indian Ceramic Society, 68(1), 1-17.

45. Dwivedi, S.P. (2023), "Development and characterization of grinding sludge-reinforced aluminum-based composite by friction stir process technique", World Journal of Engineering, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/WJE-12-2022-0484.
46. Kumar, A., Rana, R. S., & Purohit, R. (2022). Investigation of wear and friction characteristic of Al/(Si3N4) np nano composites under as-cast and heat-treated conditions. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089221112070.
47. Siddhardh, K., Chandra, M. S., & Surya, S. (2020). An investigation on friction welding of tube to tube plate by using friction stir processing with CNT and Si3N4 composites. Materials Today: Proceedings, 22, 2452-2459.
48. Shashi Prakash Dwivedi, Indradeep Kumar, Shankar Sehgal, Nakul Gupta & Kuldeep K. Saxena (2023) Development of dissimilar AA2014 and AA2024 based composite with nano-Si3N4 reinforcement by friction stir process technique, Journal of Adhesion Science and Technology, DOI: 10.1080/01694243.2023.2242111
49. Bhushan, R. K., & Sharma, D. (2020). Optimization of parameters for maximum tensile strength of friction stir welded AA6082/Si 3 N 4 and AA6082/SiC composite joints. Silicon, 12, 1195-1209.
50. Jegan, G., Kavipriya, P., Sathish, T., Singaravelu, D., Samraj Lawrence, T., & Vino, T. (2021). Synthesis, mechanical, and tribological performance analysis of stir-casted AA7079: ZrO2+ Si3N4 hybrid composites by taguchi route. Advances in Materials Science and Engineering, 2021, 1-15.
51. Stalin, B., Kumar, P. R., Ravichandran, M., & Saravanan, S. (2018). Optimization of wear parameters and their relative effects on stir cast AA6063-Si3N4 Composite. Materials Research Express, 5(10), 106502.