Effect of Reinforcement Morphology and Composition on the Properties of Aluminum Matrix Composites

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Abstract:

The increasing demand for lightweight and high-performance materials in engineering applications has led to extensive research on aluminum metal matrix composites (AMMCs). These composites, when reinforced with suitable materials, exhibit enhanced mechanical and tribological properties, including improved hardness, tensile strength, and wear resistance. In this review, a comprehensive assessment has been carried out on the effects of various reinforcements such as Al_2O_3, SiC, B_4C, fly ash, coconut shell ash, graphite, and graphene added to aluminum alloys. Reinforcement additions have been shown to significantly influence the microstructural behavior and property outcomes of the composites, based on the type, size, and weight fraction of the reinforcement employed. Studies have also highlighted challenges such as agglomeration, poor matrix-reinforcement bonding, and uneven distribution, which adversely affect composite performance. Additionally, the methods of fabrication, especially stir casting, have been extensively employed due to their cost-effectiveness and scalability, though they also contribute to variability in properties due to process limitations. This paper summarizes the improvements achieved through reinforcement and provides insights into their applicability in critical sectors such as aerospace, automotive, and thermal systems. Emphasis has also been placed on hybrid composites and natural reinforcements as emerging sustainable alternatives.

Keywords: Aluminum, Al_2O_3, SiC, B_4C, fly ash, coconut shell ash, graphite.

1. Introduction:

In the last few decades, the demand for advanced materials with superior mechanical, thermal, and tribological properties has driven substantial growth in the development and application of metal matrix composites (MMCs). Among various matrix materials, aluminum and its alloys are extensively studied for their lightweight strength, outstanding corrosion resistance, efficient thermal conductivity, and fabrication versatility. These characteristics make aluminum-based composites highly attractive for automotive, aerospace, marine, defense, and structural applications where performance and weight reduction are critical parameters [1,2]. However, the intrinsic limitations of monolithic aluminum such as relatively low wear resistance, inadequate hardness, and limited strength at elevated temperatures have led to the reinforcement of the aluminum matrix with suitable secondary phases. These reinforcing agents are introduced to form Aluminum Metal Matrix Composites (AMMCs), which demonstrate enhanced mechanical behavior, improved dimensional stability, and increased service life under demanding working conditions [3]. Reinforcements can be broadly classified into ceramic particulates (e.g., SiC, Al_2O_3, B_4C), natural or industrial waste materials (e.g., fly ash, coconut shell ash), and carbon-based materials (e.g., graphite, graphene, CNTs). Each category contributes distinct advantages depending on its morphology, size, distribution, and volume fraction [4,5]. The method of fabrication also plays a vital role in achieving homogeneous dispersion of reinforcements, strong interfacial bonding, and minimized porosity within the matrix. Among the various fabrication methods, stir casting continues to be the most widely employed and economically viable process for producing aluminum matrix composites (AMMCs), although advanced techniques such as powder metallurgy, squeeze casting, and friction stir processing are also being explored for their potential to yield superior microstructural control and mechanical properties are also employed for specific applications requiring finer microstructures and near-net shape components [6,7]. Extensive research has demonstrated that SiC is highly effective in improving the hardness, wear resistance, and tensile strength of aluminum alloys, although challenges such as agglomeration and interfacial reactions need to be controlled [8]. Similarly, Al_2O_3 reinforcements enhance mechanical strength and thermal stability but may adversely affect ductility when added in high volume fractions [9]. On the other hand, B_4C exhibits exceptional hardness and neutron absorption capabilities, making it highly suitable for nuclear and ballistic applications [10]. The use of industrial by products such as fly ash and biomass-based materials like coconut shell ash (CSA) has been explored as sustainable reinforcement alternatives. These not only reduce material costs but also support environmental sustainability by promoting the reuse of waste materials. Studies have shown that fly ash-reinforced AMMCs exhibit good wear resistance and lightweight characteristics, making them suitable for brake rotors, pistons, and structural parts [11,12]. Recent developments have further expanded to include nanomaterials, such as graphene, carbon nanotubes (CNTs), and graphite, which impart superior wear resistance and self-lubricating properties while maintaining low density and high strength [13,14]. However, achieving uniform dispersion and stable bonding of these nano-reinforcements remains a key research challenge, often necessitating the use of surface treatments or hybrid reinforcement strategies. This review provides an in-depth examination of the various reinforcements employed in AMMCs, highlighting their impact on mechanical properties and tribological properties, processing complexities, and relevance to targeted engineering applications.

2. Literature Review

2.1. Aluminium alloy reinforced with Aluminium Oxide (Al_2O_3):

Aluminium alloys reinforced with aluminum oxide (Al_2O_3) have been extensively investigated for their ability to enhance mechanical and tribological properties. In multiple studies, stir casting has been the preferred fabrication technique, offering effective dispersion of reinforcements within the matrix. Abhishek Kumar et al. [15] observed that increasing Al_2O_3 content in A359 alloy led to a steady rise in hardness and ultimate tensile strength (UTS), attributed to finer grain formation and improved bonding. Similarly, Mohsen Hossein-Zadeh et al. [16] reported enhanced wear resistance and surface morphology when heat-treated Al_2O_3 was introduced into A356 alloy, noting reduced agglomeration and increased active surfaces. Bhaskar Chandra Kandpal et al. [17] further demonstrated grain refinement in Al6061 composites with Al_2O_3, though tensile strength gains were marginal due to potential stirring inefficiencies. Additionally, Chennakesava Reddy [18] showed that higher Al_2O_3 content reduced ductility, with fine particles leading to improved strength but excessive reinforcement causing agglomeration and the formation of intermetallic phases. Overall, the inclusion of Al_2O_3 in aluminium matrices significantly improves hardness and wear resistance, though careful control of particle size and distribution is essential to balance strength and ductility as shown in table 1.

Table 2.1. Summary of Studies on Al-Alloy Reinforced with Al_2O_3

Study	Base Alloy	Reinforcement	Method	Key Findings
Abhishek Kumar et al. [15]	A359	Al_2O_3 (2–8 wt%)	Electromagnetic Stir Casting	Increase in hardness and UTS, fine grain size, good bonding
Mohsen Hossein-Zadeh et al. [16]	A356	Heat-treated Al_2O_3	Stir Casting	Improved wear resistance, less agglomeration, better bonding
Bhaskar Chandra Kandpal et al. [17]	Al6061	Al_2O_3 (5–20 wt%)	Stir Casting	Hardness increased, marginal tensile

				gain, reduced ductility
Chennakesava Reddy [18]	Al6061, Al6063, Al7075	Al_2O_3 (12–20 wt%)	Stir Casting	Reduced ductility, fine particles improved strength, presence of intermetallics

2.2. Aluminum Matrix Composites Reinforced with Silicon Carbide (SiC):

Aluminum metal matrix composites (AMMCs) reinforced with silicon carbide (SiC) have garnered significant attention owing to their improved mechanical and tribological performance. Numerous studies have demonstrated that the incorporation of SiC particles into the aluminum matrix leads to notable enhancements in hardness, ultimate tensile strength (UTS), and wear resistance. These improvements are primarily attributed to the high hardness and thermal stability of SiC, which contribute to better load-bearing capacity and reduced material degradation under frictional conditions. Rahman et al. [19] fabricated AMMCs with varying SiC contents (5–20 wt%) and found that a 20% reinforcement resulted in the highest improvements in hardness and UTS; however, an increase in porosity and particle clustering was also noted. The dispersion of reinforcements plays a key role in determining the composite's effectiveness. Bhushan et al. [20] highlighted that proper addition of magnesium (Mg) aids in wetting, leading to better bonding between the matrix and SiC particles. Furthermore, scanning electron microscopy (SEM) revealed uniform particle distribution without significant chemical interaction at the interface, making such composites viable for applications below 1250 °C. Yang et al. [21] emphasized the impact of particle size, demonstrating that larger SiC particles are more prone to cracking, which adversely affects both ductility and flow strength of the matrix. Meanwhile, Valdez et al. [22] successfully synthesized Al-Mg/SiC composites using the vortex method, resulting in homogeneous distribution without forming undesirable oxide layers. Overall, the results support the use of SiC-reinforced aluminum alloys for structural and wear-critical applications, contingent upon the optimization of processing conditions to reduce porosity and achieve homogeneous particle distribution, as presented in Table 2.

Table 2.2: Summary of Studies on Aluminium Alloy Reinforced with SiC

Author(s)	Matrix Alloy	SiC wt.%	Method	Key Findings
Habibur R et al. [19]	AI (unspecified)	5, 10, 15 & 20	Stir Casting	Increased hardness and UTS with 20% SiC; porosity and particle clustering noted.
Bhushan et al. [20]	Al7075	10, 15, 20 & 25	Stir Casting	Improved wetting with Mg; uniform distribution; suitable for temperatures <1250°C.
J. Yang et al. [21]	Al (ductile alloy)	High vol. fraction	Powder Metallurgy	Particle cracking increased with size; reduced ductility; influenced matrix flow stress.
Valdez et al. [22]	Al-Mg Alloy	Not specified	Vortex Method	No oxide layer; uniform dispersion; no interfacial reactions observed.

2.3. Aluminum Matrix Composites Reinforced with Boron Carbide (B_4C):

The incorporation of boron carbide (B_4C) into aluminum matrices has gained attention for its ability to significantly enhance mechanical and tribological properties, attributed to B_4C's high hardness, low density, and excellent abrasion resistance. Several researchers have explored the incorporation of B_4C into Al6061 alloy using conventional stir casting methods, reporting significant improvements in mechanical and tribological characteristics. Boron carbide (B_4C) has been widely explored as a reinforcing agent in aluminum alloys to achieve significant improvements in mechanical and wear-related characteristics using the stir casting technique, various researchers have reinforced Al6061 with different weight percentages of B_4C particles, typically ranging from 2% to 15% by weight. The enhancement in mechanical properties such as tensile strength and hardness with rising B_4C content is largely attributed to the high hardness and low density of the reinforcement material [23, 25]. The grain refinement and enhanced interfacial bonding resulting from the uniform distribution of B_4C particles have been identified through microstructural studies as key contributors to increased wear resistance. [24]. Hybrid composites incorporating B_4C and graphite exhibit improved tensile strength and impact resistance, especially when the reinforcement phases are introduced in appropriate proportions. [24]. Additionally, wear tests have indicated a decrease in wear rate with the increase in B_4C content, which highlights the suitability of these composites for applications in aerospace, nuclear, and automotive fields [26]. The surface morphology after wear testing further confirms that increased B_4C leads to a more stable wear profile, indicating a clear correlation between reinforcement content and wear resistance as shown in table 3 [25].

Table 2.3 : Summary of Studies on Aluminium Alloy Reinforced with B_4C

Author(s)	Alloy	B_4C wt%	Method	Key Findings
Hynes et al. [23]	AA6061	5, 10, 15	Stir casting	Improved tensile strength, hardness, and wear resistance with increasing B_4C.
Mohan et al. [24]	AA6061	5–10 (B_4C + Gr)	Stir casting	5%B_4C+5%Gr improved tensile/hardness; 5%B_4C+2.5%Gr gave better impact strength.
Manjunatha et al. [25]	Al6061	2, 4, 6	Liquid metallurgy	Increased UTS, hardness, and wear resistance. RSM used for wear optimization.
Santhosh et al. [26]	Al6061	Not specified	Stir casting	Increased hardness and strength; decreased wear rate with B_4C addition.

2.4. Aluminum Matrix Composites Reinforced with Fly Ash

The incorporation of fly ash as a reinforcement in aluminum alloys has been recognized as a cost-effective and sustainable strategy for enhancing composite properties. Research indicates that fly ash particles, particularly within the 5-25 μm size range, when incorporated into Al6061 via stir casting, lead to notable improvements in ultimate tensile strength and hardness. These enhancements are primarily attributed to the uniform dispersion of the particles and the formation of strong interfacial bonding between the fly ash and the aluminum matrix [27]. However, an increase in particle size tends to reduce these mechanical benefits, indicating that finer particles are more effective for reinforcement. Edrard et al. further reported that incorporating graphite along with fly ash enhanced the tensile strength of the composite, although the accompanying rise in porosity contributed to deviations between theoretical and actual density values [28]. Vasekar et al. investigated hybrid composites incorporating SiC and MoS_2 with fly ash and reported superior mechanical performance in Al6061-fly ash/SiC systems, particularly in terms of hardness and tensile strength, thereby indicating their suitability for high-stress applications such as automotive brake components [29]. Complementary studies by Balakumar et al. concluded that fly ash, in conjunction with graphite and copper, reduced wear and frictional forces while enhancing composite hardness [30]. Overall, the results emphasize the effectiveness of fly ash as an economical and lightweight reinforcement for improving the mechanical and tribological performance of aluminum matrix composites, as demonstrated in Table 4.

Table 2.5: Summary of Studies on Al-Fly Ash Metal Matrix Composites

Author(s)	Matrix Material	Fly Ash wt.%	Key Findings	Fabrication Method
H.C. Anil Kumar et al. [27]	Al6061	10–20%	Small particles (5–25 µm) improved UTS and hardness; large particles showed property degradation.	Stir Casting
Charles Edrard et al. [28]	Al6061	0–8% (with Gr)	Combined fly ash and graphite improved tensile strength but increased porosity reduced density.	Liquid Metallurgy Route
Milind K. Wasekar et al. [29]	Al6061	5–15% (with SiC, MoS_2)	Hybrid composites had superior hardness and tensile strength over single-reinforcement AMCs.	Stir Casting
S. Balakumar et al. [30]	Al6061	5–15% (with Cu, Gr)	Taguchi optimization showed fly ash addition reduced wear rate and friction significantly.	Stir Casting + Taguchi DOE

2.5. Aluminum Matrix Composites Reinforced with Coconut Shell Ash (CSA):

In recent years, significant attention has been directed toward the development of eco-friendly and cost-effective reinforcement materials for aluminum matrix composites. Among them, coconut shell ash (CSA), a by-product of agricultural waste, has emerged as a promising alternative due to its low density, availability, and good wear resistance. Several researchers have investigated the incorporation of CSA into aluminum alloys, particularly Al6061, using the stir casting technique, which ensures effective distribution of particulates and ease of fabrication. Aluminum alloys reinforced with coconut shell ash (CSA) have been increasingly explored as sustainable alternatives to conventional ceramic reinforcements, owing to their low cost, lightweight nature, and promising mechanical properties. In recent studies, Al6061 was used as the matrix material with CSA added in varying weight percentages using the stir casting method, resulting in notable enhancements in composite properties. Improvements in mechanical properties, including increased hardness and tensile strength, alongside reduced density and porosity, point to efficient CSA particle dispersion and strong matrix–reinforcement bonding [31]. Microstructural examinations further confirmed uniform dispersion of CSA and minimal clustering, contributing to the improved mechanical behavior of the composite [33]. Moreover, increasing the CSA content up to an optimal level led to reduced wear rates, which was attributed to the presence of oxide-rich and ceramic phases in the ash acting as dislocation barriers and enhancing load-bearing capacity [32]. However, the friction coefficient and frictional force were found to increase with higher reinforcement levels, possibly due to the formation of debris during wear processes [32]. These findings underscore the effectiveness of coconut shell ash (CSA) in enhancing the mechanical and tribological properties of aluminum matrix composites, while simultaneously promoting the sustainable utilization of agricultural waste in engineering applications. Overall, the incorporation of CSA has shown significant potential in improving mechanical strength, hardness, and wear resistance, making CSA-reinforced aluminum alloys suitable for lightweight, wear-resistant applications in automotive and structural components, as illustrated in Table 5.

Table 2.5: Summary of Literature on Al6061-CSA Composites

Researcher(s)	Reinforcement (%)	Key Findings	Fabrication Method
K. Varalakshmi et al. [31]	1, 3, 5	Increase in hardness and tensile strength; decrease in density and porosity	Stir casting
P. Lakshmikanthan et al. [32]	3, 6, 9, 12, 15	Improved properties at low CSA%; higher CSA% increased friction due to debris	Stir casting (pellet)
Kolusu Varalakshmi et al. [33]	0–6	Hardness and strength increased; wear rate decreased; uniform particle dispersion	Stir casting

2.6. Aluminium alloy reinforced with graphite/grapheme:

In the study conducted by Manivannan et al. [25], the incorporation of graphite into the Al6061 matrix resulted in significant improvements in wear resistance and reduced friction coefficient. These enhancements were primarily attributed to the solid lubricating effect of graphite, which formed a protective tribolayer at the contact surface during sliding. Additionally, the study reported modest increases in hardness and tensile strength, indicating that graphite not only enhanced tribological performance but also contributed to maintaining structural integrity under mechanical loads, the reinforcement of Al6061 alloy with SiC and graphite through stir casting led to significant improvements in mechanical strength and wear resistance, attributed to the combined effects of SiC's hardness and graphite's lubricating behavior. The composite containing 1.2% SiC and 0.5% graphite demonstrated superior tribological performance with a low friction coefficient of 0.23 and minimal surface roughness, attributed to the hardness and lubricating nature of the reinforcements. Similarly, Rita Mourya et al. [26] observed that incorporating carbonaceous materials such as graphite, carbon nanotubes, and graphene into Al6061 via friction stir processing significantly improved damage tolerance and wear resistance. Furthermore, Wu et al. [27] reported that even small amounts (0.1–0.5 wt%) of bio-based reactive graphene oxide in epoxy-based composites led to notable enhancements in thermal stability, mechanical strength, and tribological performance. These results confirm the role of graphene in reducing wear and friction due to its high surface area and layered structure. Kesavulu et al. [28] also demonstrated that the addition of graphene nanoplatelets in an epoxy hybrid matrix increased hardness and improved surface finish. Therefore, the use of graphite or graphene as reinforcement in aluminium alloys holds promise for applications requiring light weight, high strength, and enhanced wear resistance. Collectively, these studies emphasize the critical role of dispersion quality, interfacial bonding, and optimal reinforcement ratios in determining the performance of Al-graphite/graphene composites. Though promising, the field requires further exploration in terms of scaling, cost-effective synthesis, and hybrid combinations to unlock their full industrial potential.

Table 2.6: Summary of Studies on Aluminium Alloy Reinforced with Graphite/Graphene

Author(s)	**Matrix & Reinforcement**	**Fabrication Method**	**Key Findings**
Manivannan et al., [34-38]	Al6061 + SiC + Graphite	Stir Casting	Enhanced wear resistance, reduced friction; best at 1.2SiC/0.5Gr composition
Mourya et al., [35-43]	Al6061 + Graphite/Graphene/CNT	Friction Stir Processing	Improved wear and mechanical properties; graphene showed superior performance
Haowu et al., [36].	Epoxy + Reactive Graphene Oxide	Solution Mixing	Increased thermal stability, low friction coefficient, improved mechanical strength
Kesavulu et al., [37]	Epoxy + Graphene/Alumina	Liquid Phase Exfoliation	Increased hardness, better surface quality, optimal reinforcement at 0.2 wt% graphene

3. Conclusion:

Based on the literature reviewed, it has been established that aluminum and its alloys exhibit enhanced mechanical, tribological, and thermal properties when reinforced with suitable materials. A wide range of reinforcements, including ceramic particles like Al_2O_3 and SiC, boron carbide, industrial waste like fly ash, and bio-based reinforcements such as coconut shell ash, Aluminum metal matrix composites (AMMCs) incorporating these reinforcements have commonly been produced using the stir casting process due to its simplicity and cost-effectiveness. These reinforcements were found to improve properties such as tensile strength, hardness, wear resistance, and thermal stability. However, challenges such as agglomeration, non-uniform distribution, and interfacial bonding issues were frequently reported and are critical to the composite's overall performance. It has also been shown that hybrid composites incorporating multiple reinforcements can yield better performance through synergistic effects. The influence of particle size, distribution, and percentage reinforcement has been consistently emphasized as determining factors for tailoring composite behavior. With these enhancements, aluminum-based MMCs are increasingly seen as promising materials for automotive, aerospace, and structural applications, especially where lightweight and high-strength materials are essential. Therefore, the continued development and optimization of reinforcement strategies remain imperative for realizing the full potential of aluminum MMCs in engineering applications.

4. References:

[1]. Brian Ralph, H.C. Yuen, W.B. Lee, The Processing of Metal Matrix Composites — An Overview, J. Mater. Process. Technol., 63 (1997), pp. 339–353.

[2]. McDanels, D. L., Analysis of Stress-Strain, Fracture and Ductility Behavior of Aluminum Matrix Composites Containing Discontinuous SiC Reinforcement, Metall. Trans. A, 16 (1985), pp. 1105–1115.

[3]. Narayana Murty, S.V.S., et al., Hot Working Characteristics of 6061Al–SiC and 6061–Al_2O_3 Particulate Reinforced MMCs, Compos. Sci. Technol., 63 (2003), pp. 119–135.

[4]. Abhishek Kumar et al., Fabrication and Characterization of A359/Al_2O_3 MMC Using Electromagnetic Stir Casting Method, J. Mater. Res. Technol., 2(3) (2013), pp. 250–254.

[5]. Md. Habibur Rahman et al., Characterization of Silicon Carbide Reinforced Aluminum Matrix Composites, Procedia Engineering, 90 (2014), pp. 103–109

[6]. Valdez, S., et al., Synthesis and Microstructural Characterization of Al–Mg Alloy–SiC Particle Composite, Mater. Lett., 62 (2008), pp. 2623–2625.

[7]. Wu, H., et al., Enhancing Mechanical and Tribological Properties of Epoxy Composites via Bio-Based Reactive Graphene Oxide, RSC Adv., 10 (2020), pp. 40148.

[8]. Kandpal, B. C., et al., Fabrication and Characterisation of Al2O3/Al6061 MMCs Fabricated by Stir Casting, Mater. Today: Proc., 4 (2017), pp. 2783–2792.

[9]. Chennakesava Reddy, Evaluation of Mechanical Behavior of Al alloy/Al_2O_3 MMCs Using Taguchi Technique, IJETAE, 4(2) (2011).

[10]. Rajesh Jesudoss Hynes, N., et al., Mechanical and Tribological Characteristics of Boron Carbide Reinforced AA6061 Matrix Composite, J. Braz. Soc. Mech. Sci. Eng., 42:155 (2020).

[11]. Anil Kumar, H. C., et al., Effect of Fly Ash Reinforcement on Mechanical Properties of Al6061 MMCs, Int. J. Mech. Mater. Eng., 6(1) (2011).

[12]. Wasekar, M. K., et al., Analysis of Reinforcements on Al-Fly Ash Composites, Integrità Strutturale, 56 (2021), pp. 217–228.

[13]. Manivannan, I., et al., Mechanical Properties and Tribological Behavior of Al6061–SiC–Gr Self-Lubricating Hybrid Nanocomposites, Trans Indian Inst Met., 71 (2018), pp. 1897–1911.

[14]. Mourya, R., et al., Effect of Carbonaceous Reinforcements on Tribological Properties of Al6061 Alloy, Mater. Des., 98 (2016), pp. 155–166.

[15]. Abhishek Kumar, Shyam Lal, Sudhir Kumar, Fabrication and characterization of A359/Al_2O_3 metal matrix composite using electromagnetic stir casting method, Journal of Materials Research and Technology, 2013.

[16]. Mohsen Hossein-Zadeh et al., Structural and mechanical characterization of Al-based composite reinforced with heat treated Al_2O_3 particles, Materials & Design, 2014.

[17]. Bhaskar Chandra Kandpal et al., Fabrication and characterisation of Al_2O_3/aluminium alloy 6061 composites, Materials Today: Proceedings, 2017.

[18]. Chennakesava Reddy, Evaluation Of Mechanical Behavior Of Alalloy/Al_2O_3 Metal Matrix Composites, IJETAE, 2011.

[19]. Md. Habibur Rahman et al., Characterization of silicon carbide reinforced aluminum matrix composites, Procedia Engineering, 90 (2014) 103–109.

[20]. Rajesh Kumar Bhushan et al., Fabrication and characterization of 7075 Al alloy reinforced with SiC particulates, Int J Adv Manuf Technol, 2015.

[21]. J. Yang et al., Effects of damage on the flow strength and ductility of a ductile Al alloy reinforced with SiC particulates, Acta Metallurgica et Materialia, Vol. 38, No. 12, 1990.

[22]. S. Valdez et al., Synthesis and microstructural characterization of Al–Mg alloy–SiC particle composite, Materials Letters, 62 (2008) 2623–2625.

[23]. Hynes, N. R. J., Raja, S., Tharmaraj, R., Pruncu, C. I., & Dispinar, D. (2020). Mechanical and tribological characteristics of boron carbide reinforcement of AA6061 matrix composite. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42:155.

[24]. Mohan, M., Balamurugan, A., Jagadeeshwar, V., & Ramkumar, M. (2017). Analysis Of Mechanical Properties for Al6061 Alloy Metal Matrix With Boron Carbide & Graphite. IJNRD, 2(5).

[25]. Manjunatha, B., Niranjan, H.B., & Satyanarayana, K.G. (2018). Effect of amount of boron carbide on wear loss of Al-6061 matrix composite by Taguchi technique and Response surface analysis. IOP Conf. Series: Materials Science and Engineering, 376(1), 012071.

[26]. Santhosh, T. U., Kumar, H. T. R., Kumar, S. N. G., & Sridhar, H. S. (2018). Evaluation of Tribological Properties of Al 6061 Reinforced with B4C Particulate composites. IJIRSET, 7(Special Issue 7).

[27]. Anilkumar, H. C., Hebbar, H. S., & Ravishankar, K. S. (2011), Mechanical properties of fly ash reinforced aluminium alloy (Al6061) composites. International Journal of Mechanical and Materials Engineering, 6(1), 41–45.

[28]. Edrard, C. N., et al. (2013), Preparation and evaluation of mechanical properties of Al6061 reinforced with graphite and fly ash. International Journal of Scientific & Engineering Research, 4(December 2013), 1–8.

[29]. Vasekar, M. K., & Khond, M. P. (2021), Microstructure and mechanical characterization of Al–fly ash composites. Materials Today: Proceedings, 56, 217–228.

[30]. Balakumar, S., et al. (2018), Wear and friction characteristics of aluminum matrix composites reinforced with fly ash/Cu/graphite. International Journal of Advanced Research in Engineering and Technology, 9(6), 94–105.

[31]. K. Varalakshmi et al. (2019), Characterization of Al 6061–Coconut Shell Ash metal matrix composites using Stir Casting, Int. J. of Latest Engineering Science, vol. 2, no. 3.

[32]. P. Lakshmikanthan and B. Prabu, (2016), Mechanical and Tribological Behaviour of Aluminium Al6061–Coconut Shell Ash Composite Using Stir Casting Pellet Method, J. of the Balkan Tribological Association, vol. 22, no. 4-I.

[33]. K. Varalakshmi et al., (2019), Analysis of Dry Sliding Wear Behaviour of Al 6061–Coconut Shell Ash Metal Matrix Composites Using Stir Casting, Applied Engineering Letters, vol. 4, no. 2.

[34]. Manivannan, I., Ranganathan, S., Gopalakannan, S., Suresh, S. (2018), Mechanical Properties and Tribological Behavior of Al6061–SiC–Gr Self-Lubricating Hybrid Nanocomposites, Transactions of the Indian Institute of Metals, 71, pp. 1897–1911.

[35]. Mourya, R., Kumar, B., Ariharan, S., Ramkumar, J., Balani, K. (2016), Effect of Carbonaceous Reinforcements on Mechanical and Tribological Properties of Friction Stir Processed Al6061 Alloy, Materials & Design, 98, pp. 155–166.

[36]. Wu, H., Liu, C., Cheng, L., Yu, Y., Zhao, H., Wang, L. (2020), Enhancing the Mechanical and Tribological Properties of Epoxy Composites via Incorporation of Reactive Bio-Based Epoxy Functionalized Graphene Oxide, RSC Advances, 10, pp. 40148–40158.

[37]. Kesavulu, A., Mohanty, A., Sahoo, D., Mishra, S. C. (2020), Tribological Characterization of Graphene Nanoplatelets/Alumina Particles Filled Epoxy Hybrid Nanocomposites, Journal of Applied Polymer Science, 137(22), pp. 48615.

[38]. Devaraj, E., & Kumar, N. (2024). Matrix and reinforcement for biopolymer composites—A review. Journal of Engineering and Technology Management, 72, 1135–1167.

[39]. Kumar, N., & Irfan, G. (2021). Green synthesis of zinc oxide nanoparticles: Mechanical and microstructural characterization of aluminum nano composites. Materials Today: Proceedings, 38, 3116–3124.

[40]. Kumar, N., & Irfan, G. (2021). Mechanical, microstructural properties and wear characteristics of hybrid aluminium matrix nano composites (HAMNCs)—Review. Materials Today: Proceedings, 45, 619–625.

[41]. Kumar, N., & Irfan, G. (2021). A review on tribological behaviour and mechanical properties of Al/ZrO_2 metal matrix nano composites. Materials Today: Proceedings, 38, 2649–2657.

[42]. Kumar, N. (2017). Production of biodiesel and property evaluation from waste coconut oil and performance, emission and combustion characterization using diesel engine. International Journal of Mechanical Engineering and Technology (IJMET), 8(4), 184–193.

[43]. Naveen Kumar (2025), Investigation on the Cooling Rate and Microstructural Characteristics of Cast Low Melting Alloys, Journal of Engineering and Technology Management 77, 278-289.