Investigation of Properties of Al-Graphite Composite from Powder Metallurgy Derived By Fly Ash

[1] WILLLIAM JAYAPRAKASH A, [2] Dr. D. KALAIMEGAM.,M.E.,PH.D.,
[2]Associate Professor, [1]Department of Mechanical Engineering,
Mahendra Engineering College, Namakkal- 637503

Abstract: Metal matrix composites (MMC) have been in high demand across numerous industries, particularly the aerospace and automotive sectors. The goal of this research is to advance MMC and enhance the mechanical properties of the material. A composite material, or MMC, is made up of two or more components. The other components would function as reinforcement, and one of them as a matrix. By combining the mutually exclusive property profiles of metallic and ceramic materials, MMC makes it possible to overcome the unique constraints of each material. This work examines the characteristics of fly ash-derived reinforcements used in powder metallurgy to create aluminum-graphite composites. The goal is to thoroughly evaluate the mechanical, tribological, and micro structural characteristics of these composites to comprehend how different graphite concentrations and reinforcement made of fly ash affect the materials' performance. Tests for impact, flexure, and tensile strength were used to assess mechanical behavior, and micro structural analysis revealed information on the distribution of particles inside the aluminum matrix. The mechanical behaviors of the composite samples were found to be heterogeneous, exhibiting differences in terms of strength, resilience, and deformation properties. The enhancement of mechanical characteristics by fly ash-derived reinforcements was validated by the micro structural investigation. These discoveries aid in the creation of cutting-edge, environmentally friendly materials as well as the optimization of composite production procedures. Further investigation into this field will improve the methods of manufacture, enabling wider uses across multiple industries.

Keywords: Aluminum-graphite composites, Powder metallurgy, Fly ash-derived reinforcements, Mechanical properties, Micro structural analysis, Sustainability

I.INTRODUCTION

Metal matrix composites, or MMCs, have attracted a lot of interest lately because of their adaptable qualities and possible uses in several sectors, such as industrial, automotive, and aerospace [1–5]. These composites, which offer a balance of strength, stiffness, and lightweight qualities, usually comprise a metal matrix supplemented with ceramic, metallic, or natural components. Aluminum-based composites are unique among the many MMC compositions investigated because of their exceptional mix of qualities, which include a high strength-to-weight ratio, resistance to corrosion, and thermal conductivity [6–9]. Adding graphite particles to aluminum matrix composites is a potentially effective way to reinforce them. One potential material to improve the mechanical and tribological performance of MMCs is graphite, a type of carbon with favorable characteristics such as high heat conductivity, low density, and self-lubricating action [10–12]. The potential applications of these composites in difficult conditions can be increased by adding graphite particles to an aluminum matrix, which can enhance wear resistance, thermal stability, and overall mechanical strength.

Because of its ability to precisely control composition, particle distribution, and microstructural characteristics, powder metallurgy (PM) has become the favored manufacturing method for making aluminum-based MMCs [13–16]. PM allows the creation of homogenous, finely dispersed composites with specific qualities by combining metal powders with reinforcing elements and then compaction and sintering the mixture. Furthermore, PM has benefits including cost-effectiveness, scalability, and the capacity to include different kinds and sizes of reinforcing particles. Fly ash, a byproduct of burning coal in thermal power plants has drawn interest as a possible material for MMC reinforcement because of its availability, affordability, and special physiochemical characteristics [17–19]. Fly ash is commonly composed of a complex mixture of ceramic particles, such as alumina, silica, and other oxides, which can function as useful reinforcements in metal matrices. Not only can environmental issues related to fly ash disposal be resolved by recycling fly ash into value-added products like MMCs, but new prospects for sustainable materials development can also be realized.

The purpose of this work is to examine the characteristics of aluminum-graphite composites made by PM with reinforcements made of fly ash. The mechanical, tribological, and microstructural properties of the composites will be assessed by methodical experimentation and characterization. The performance of aluminum matrix composites can be improved by knowing how different graphite contents and reinforcement made of fly ash affect the material's ability to perform. This knowledge can also be used to develop more sustainable and advanced materials with improved properties.

II. LITERATURE REVIEW

Several studies have been conducted to investigate the utilization of metal matrix composites (MMCs) in various industrial applications, particularly in the aerospace and automotive sectors. Ononiwu et al., 2022 [20] explored the impact of carbonized eggshells (CES) and fly ash on the microstructure and mechanical properties of Al-Si12. By employing stir casting, they kept the weight fraction of CES particles constant at 2.5 wt.%, while varying the fly ash content from 2.5 wt.% to 10.0 wt.%. Their findings revealed an increase in microhardness with the rise in fly ash content. Similarly, Senapati et al., 2015 [21] focused on the tribological properties of Al-Si alloy-based MMCs reinforced with thermally treated fly ash. They observed enhanced wear resistance in MMCs containing thermally treated fly ash compared to conventional Al-Si alloy and Al-Si-fly ash MMCs.

Moreover, KE et al., 2015 [22] conducted experimental studies on Aluminum-Fly Ash composites fabricated via PM. They reported increased hardness and wear resistance in sintered Al-FA MMCs, suggesting their potential applications in industries such as covers, casings, brake rotors, or engine blocks. Additionally, electrochemical studies were carried out to evaluate the corrosion resistance of the composites. Jannet et al., 2021 [23] investigated Aluminum Metal Matrix Composites (AMMC) reinforced with eggshell powder to reduce composite costs. Their study demonstrated that varying percentages of eggshell powder affected mechanical properties such as tensile strength, hardness, and compression strength. Furthermore, Romero et al., 2017 [24] explored the mechanical characteristics of Aluminum Metal Matrix Composites (MMC) fabricated by stir casting and PM. Their study focused on enhancing the strength of MMCs at elevated temperatures, crucial for aerospace and automotive applications. Mechanical tests and wear studies were conducted to characterize the properties of MMCs.

Fatchurrohman et al., 2022 [25] investigated the fabrication of aluminum and graphite metal matrix composites using PM. They varied the volume percentages of graphite and observed improvements in tensile strength, Young's modulus, and hardness in MMCs with specific graphite ratios. Shankar et al., 2019 [26] provided a comprehensive review of fabrication techniques and tribological properties of fly ash-reinforced aluminum alloy composites. They highlighted the preference for PM and stir-casting methods in composite fabrication. Furthermore, Minh et al., 2023 [27] addressed the environmental concerns associated with coal-fired power plant fly ash and discussed methods for its recycling. They differentiated the physiochemical properties of fly ash from different coal combustion processes and explored applications for fly ash recycling. In summary, these studies contribute to the understanding of MMCs and the potential for utilizing waste materials such as fly ash and eggshell powder as reinforcements, thereby enhancing mechanical properties and addressing environmental concerns.

III. PROPOSED METHODOLOGY

In this study, graphite and aluminum were mixed by the sample volume ratio using PM. Aluminum was in the form of metal powder, as was graphite. Aluminum powder was combined with graphite powder at volume percentage ratios of 0%, 1.5%, 3%, 4.5%, and 6%. PM uses a hydraulic press brake machine to compaction to create the mixed material. The compressed sample was then sintered for four hours at 600°C in a laboratory furnace. The mechanical tests reveal that MMC aluminum with 1.5% volume graphite has the highest tensile strength and Young's modulus. Aluminum - 4% volume graphite was found to have the highest hardness, however. Parts are created by compacting metals and alloys in powder form within a die under high pressure in the precision manufacturing process known as PM. The important process of sintering, which occurs at temperatures lower than the melting point of the metal, joins the particles. The four main processes in the process are mixing, compacting, sintering, and powder preparation. Diverse part needs and engineering criteria have led to the evolution of variations such as conventional, injection molding, isostatic pressing, and metal additive manufacturing.

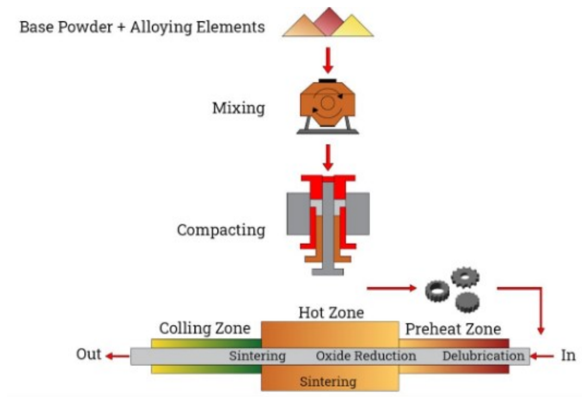

Figure 1: Basic Steps of PM

The PM process has evolved over 5,000 years, becoming more sophisticated, yet it has remained based on four basic phases (Figure 1):

- *Powder Production:* First, fine metal or alloy powders are produced via atomization, mechanical comminution, or chemical processes, among other techniques. This step makes sure the raw ingredients are ground into a suitable powder for use in other processes.
- *Mixing and Blending:* A uniform distribution of alloying materials or additions is achieved by carefully mixing and blending the powders after they are manufactured. For the composition and qualities of the finished product to be uniform and consistent, this stage is essential.
- *Compacting:* This stage involves compacting the blended powders into the desired shape by placing them into a die cavity and applying high pressure on them. Usually, the powder mixture is pressed under mechanical or hydraulic pressure throughout the compaction process to create a green compact with the required geometry.
- *Sintering:* The green compacts are heated in a furnace with a regulated environment throughout the sintering process. The compacted powders are heated to temperatures below their melting point during the sintering process, which causes particle bonding and diffusion. As a result, a strong, cohesive structure with better mechanical and physical qualities is formed, leading to densification.

The foundation of the PM process consists of these four processes, which allow for the creation of complicated parts with exact dimensions, complex geometries, and customized material properties. The PM process still relies heavily on the fundamentals of powder manufacturing, mixing, compacting, and sintering, even if advances in technology and materials have added complexity.

3.1 PM Processes

Processes for PM have been developed to meet a variety of industrial requirements, providing flexibility and effectiveness in the production of complex parts and components. These are a few important PM procedures in summary:

- *Conventional PM:* This procedure involves mixing, compacting, and sintering metal powders and alloys by the standard PM procedures. Conventional PM benefits from new technical breakthroughs even if it adheres to ancient methods, guaranteeing accuracy and dependability in part manufacture.
- *Injection Molding:* Injection molding is a unique process that uses specifically prepared powders coupled with binders like wax or thermoplastics to build complex structures in big quantities. Using traditional injection molding equipment, the resultant feedstock is injected into mold cavities. Green compacts that are prepared for sintering are produced when the binder is removed through solvent extraction or heat processing following compaction.

- *Isostatic Pressing:* Isostatic pressing ensures homogeneous density and microstructure throughout the part by applying equal pressure to the workpiece from all directions. The temperature at which this operation is carried out can vary based on the needs of the object. While hot isostatic pressing uses pressure and high temperatures to remove porosity and improve mechanical qualities, cold isostatic pressing is best suited for manufacturing large, complicated pieces.
- *Metal Additive Manufacturing:* Additive manufacturing for metal, also referred to as three-dimensional (3D) printing, creates items layer by layer from digital representations. This novel method is very efficient and produces very little waste, which makes it perfect for complicated component production and prototyping.

PM is used in a wide range of sectors, and its components and goods are essential to daily living. PM procedures are used in the manufacturing of several components, including household appliances and vehicle gears. For example, PM makes it easier to produce connecting rods, steering parts, transmission parts, and other engine parts in the automotive industry. Powders made of iron and stainless steel are widely used because they can be produced at a low cost, can take on complicated shapes, and produce little waste.

3.2 Material Properties

This section outlines the experimental methods for mechanical characterization as well as the specifics of manufacturing composites. The materials used in this investigation include fly ash, graphite, and aluminum.

- *Aluminum 7075:* Aluminum alloys are extensively utilized due to their lightweight nature, pliability, and prevalence across industries, notably aerospace and automotive. Aluminum 7075, a member of the 7xxx series alloys, is distinguished by its high strength and low density, primarily owing to its zinc alloying element. Experimental studies reveal an enhancement in hardness and strength with the incorporation of reinforcing fibers. For instance, optimal mechanical properties are attained with a volume fraction of 6% short basalt fiber in Aluminum 7075 alloy (Table 1). Widely employed in mold tool manufacturing, Aluminum 7075 finds applications in aircraft fittings, gears, missile parts, and various aerospace/defense components.

PROPERTY	VALUE
Density	2.25g/cm^3
Porosity (%)	0.7-53
Compressive Strength	20-200 MPa
Flexural Strength	6.9-100 MPa
Modulus of Elasticity	7-19 GPa
Thermal Conductivity	200 W/m-K
Melting Point	710 J/(kg·K)

Table 1: Mechanical Properties of Aluminum 7075

- *Graphite Powder:* Graphite, derived from the Greek word "graphein" meaning to write, exhibits properties of both metals and non-metals. It boasts high electrical and thermal conductivity, chemical inertness, and refractoriness. Graphite's unique properties stem from its crystalline structure, wherein carbon atoms arrange hexagonally in planar condensed ring systems. The two main classifications of graphite are natural and synthetic, each offering distinct properties and applications. Natural graphite encompasses high crystalline, amorphous, and flake varieties, while synthetic graphite is produced through carbonization processes.

- *Fly Ash:* Fly ash, a by-product of coal combustion in power plants, exhibits properties such as high compressive strength, low water absorption, and chemical inertness. It is utilized in diverse applications including construction materials and soil stabilization. Fly ash composition varies depending on coal bed composition, typically comprising silicon dioxide, aluminum oxide, and calcium oxide, along with trace elements. Manufacturing of fly ash involves the capture of fine particles through particulate emission control devices, followed by mineral processing to concentrate the ash. Table 2 presents the Composition of Graphite and Fly Ash in a 4:4 Mass Ratio, while Table 3 outlines the Composition of Graphite and Fly Ash in a 3:5 Mass Ratio.

Metal	Percentage (%)	Volume (cm^3)	Mass (g)
Aluminum 7075	92	69	193.89
Graphite	4	3	13.56
Fly Ash	4	3	5.1

Table 2: Composition of Graphite and Fly Ash in 4:4 Mass Ratios

Metal	Percentage (%)	Volume (cm^3)	Mass (g)
Aluminum 7075	92	69	193.89
Graphite	3	2.25	10.17
Fly Ash	5	3.75	6.37

Table 3: Composition of Graphite and Fly Ash in 3:5 Mass Ratios

The total mass used for this project comprises Aluminum 7075, Graphite, and Fly Ash, each in specified ratios, amounting to 387.78 grams, 23.73 grams, and 11.47 grams, respectively.

3.3 Mechanical Properties Analysis

3.3.1 *Flexural Formula*

Understanding the material's resistance to bending loads is possible through flexural testing. The E-glass epoxy composite demonstrated exceptional modulus and flexural strength. The flexural stress (σ_f) and modulus are calculated using the following equations:

$$\sigma_f = \frac{3PL}{2bh^2} \quad (1)$$

$$Flexural\ modulus = \frac{L^3 m}{4bh^3} \quad (2)$$

Where, σ_f = Flexural stress (MPa), P = Applied load (N), L = Span length (mm), b = Width of the specimen (mm), and h = Thickness of the specimen (mm).

3.3.2 *Impact Toughness Formula*

The impact toughness (U_T) in the SI system is determined by calculating the area underneath the stress-strain ($\sigma - \epsilon$) curve, providing a measure of a material's ability to absorb energy before fracture.

3.3.3 *Tensile Formula*

To determine the composite specimens' strength and ductility, their tensile characteristics were assessed. The percentage elongation, particularly in coconut-glass fiber-reinforced composites, indicates a higher ductile nature. The formula for tensile stress (σ_t) is calculated as follows:

$$\sigma_t = \frac{P}{bh} \quad (3)$$

Where: σ_t= Tensile stress (MPa), P = Applied load (N), b = Width of the specimen (mm), and h = Thickness of the specimen (mm). Young's modulus (E), representing the material's stiffness, is determined by the ratio of tensile stress to tensile strain:

$$E = \frac{\sigma_t}{\epsilon} = \frac{\frac{N}{mm^2}}{\frac{N}{m^2}} = GPa \quad (4)$$

3.4 Material Testing Process

3.4.1 *Tensile Test*

The tensile test was conducted following ASTM D3039-76 standards on flat specimens. Uni-axial load was applied through the ends, with specimens having fibers parallel to the loading direction, 11.5 mm wide, and a length of 120 mm as per ASTM recommendations. Notably, the hybrid sample-12 exhibited a significant increase in tensile strength, reaching a peak load of 276.49 kg/cm² as the percentage of glass fiber increased to 12 gm. Each combination underwent testing with three specimens, and the average results were analyzed.

3.4.2 *Toughness Impact Test*

An analog impact tester was employed to assess the impact properties of the composite specimens reinforced with calotropis fiber. The equipment provided multiple scales and hammers to cover various working ranges, with an impact energy of 6.559 J observed for the composite containing 20% calotropis stem fiber and an increased glass fiber content.

3.4.3 *Flexural Testing*

Flexural testing, also known as transverse beam testing, was conducted to determine the bending properties of the material. Samples were placed between two supports, and the load was initiated using a third point or through 3-point Bend testing. Maximum stress and strain were calculated, with materials such as plastics, composites, metals, and woods typically tested. Load vs Displacement graphs were generated from the Universal Testing Machine (UTM) for tensile and flexural test samples.

These testing processes provide crucial insights into the mechanical properties and performance of the composite materials, aiding in material selection, quality control, and product development efforts.

4. RESULTS AND DISCUSSION

4.1 Impact Test Results

Sl. No	Theoretical Impact Velocity (m/s)	Angle of Release (^{o})	Total Mass (kg)	Work Capacity (J)	b (mm)	h (mm)	W (J)	AK (Kj/m^2)	Type of Failure	Angle of Rise (^{o})	AK-series
1	3.458	153	0.4613	3.70	12.7	7.167	2.45443	25.32	P	42.95	20.86C(P)
2	3.458	154	0.4612	3.70	12.7	7.167	2.64124	27.92	H	26.36	
3	3.458	153	0.4613	3.70	12.7	7.167	1.32161	12.32	C	94.45	

Table 4: Results of the Impact Test

Table 4 presents the main parameters and test findings from an analysis of an AL-GRAPHITE composite made with fly ash PM. Concerning the material's strength and resilience, this information illuminates how the material behaves under impact situations. A section on the Charpy Impact test on the composite is also included. It includes information on the test standard (ISO 179-1), the testing apparatus (HIT 5.5p), and the hammer's energy (2.7J). The previously mentioned Charpy Impact test validates the assessment of the material's impact strength by standard protocols (ISO 179-1). The impact test findings offer a thorough insight into how the material behaves in different situations. A constant theoretical impact velocity of 3.458 m/s was observed in all tested samples.

Nonetheless, some fluctuations in the release angle were noted, suggesting a possible sensitivity to launch angles. The material performed consistently in terms of mass characteristics and energy absorption capacity despite these fluctuations, as evidenced by the overall mass and work capacity of the material remaining reasonably stable. Sample 2 showed somewhat greater specific impact strength and absorbed energy than Sample 1, which showed moderate specific impact strength and absorbed energy. Sample 3 on the other hand showed a much lower specific impact strength and absorbed energy, suggesting a lower level of resilience and a propensity for failure brought on by impacts. In addition, different failure types were seen in each sample; these included the classifications "P," "H," and "C." These categories include discrete failure modes, like fracture, combination failure, or plastic deformation, and they offer important information about the failure mechanisms of the material when subjected to impact loads.

4.2 Flexure Test Results

Sl. No.	E_f (MPa)	σ_{fc} (MPa)	σ_{fM} (MPa)	S_{fM} (%)	σ_{fB} (MPa)	S_{fB} (%)	Lv (mm)	h (mm)	b (mm)
1	589	-	29.5	3.8	29.5	3.8	64	10.6	11.5

Table 5: Results of the Flexure Test

Table 5 provides important information about the material's mechanical properties under different loading scenarios. The DIN EN ISO 178 standard was adhered to when conducting the flexure test. The samples were not pre-treated before testing; the specimen removal was done by hand. A Z2.5 kN testing apparatus fitted with a flexure kit was used, and the pre-load and flexure modulus speed settings were set at 0.1 MPa and 2 mm/min, respectively. A steady test speed of 10 mm/min was kept throughout the test. The stiffness of the material is indicated by the modulus of elasticity (E_f) at 589 MPa; larger values imply more resistance to deformation. Its capacity to bear compression pressures before failing is shown by its compressive strength (σ_{fc}) at 29.5 MPa, and its resistance to pulling or stretching forces is indicated by its tensile strength (σ_{fM}) at the same value. The equivalent strain at 3.8% tensile failure (S_{fM}) measures the tensile strain capacity of the material. Its resistance to bending forces is indicated by its bending strength (σ_{fB}) at 29.5 MPa, and its deformation behavior under such loads is indicated by its strain at bending failure (S_{fB}) at 3.8%. Comprehending these criteria is imperative in evaluating the material's appropriateness for structural purposes, steering engineering determinations, and guaranteeing safety and efficacy.

4.3 Tensile Test Results

Sl. No	Curve	E_t	Yield Stress (MPa)	Yield strain (%)	σ_m (N)	Max Load (MPa)	S_m (%)	Stress at Bread (MPa)	Strain at Break (%)	S_{tb} (mm)	b	h
1	Type 3	14.8	8.89	12	999	8.89	12	1.58	-	30	12.6	10.05
2	Type 1	21.5	-	-	1040	7.86	5.9	7.76	5.9	-	12.7	10.50
3	Type 1	15.4	-	-	857	6.88	8.1	5.98	8.1	-	13.52	10.60
4	Type 1	11.2	-	-	1160	7.80	8.7	6.80	8.7	-	13.95	12.24
5	Type 1	19.4	-	-	679	6.39	6.5	5.39	6.5	-	11.44	11.02

Table 6: Results of the Tensile Test

Table 6 on the tensile test provides valuable insights into the mechanical properties of the tested materials. The DIN EN ISO 527-1 standard was followed when conducting the tensile test. Without any prior treatment, specimens were physically removed and processed into dumbbell shapes. The Z2.5kN Zwicki testing apparatus was used, and it has an Xforce HP load cell installed. Interestingly, no extensometer was used for the test. Before testing, a pre-load of 0.1 MPa was applied at a speed of 1 mm/min to calculate the tensile modulus. A steady pace of 50 mm/min was maintained throughout the test. Method B was used to compute the nominal strain after measuring the grip-to-grip separation at the start position, which came out to be 89.00 mm. Several parameters were examined to evaluate the tensile behavior of the materials under analysis. Sample 1 had a yield stress of 14.8 MPa and a yield strain of 8.89%; it was described by Curve Type 3. The material showed a maximum load of 999 N, a strain at a break of 30%, and a stress at a yield of 1.58 MPa.

Among the parameters, Sample 1 performed consistently and showed moderate strength and ductility. This is noteworthy. However, the tensile characteristics of Samples 2, 3, 4, and 5, which are all part of Curve Type 1, varied. For Samples 2, 3, 4, and 5, particular yield stresses and strains were not given; nonetheless, their maximum loads varied, ranging from 679 N to 1160 N, indicating different strengths. The maximum load observed in Sample 2 was 1040 N. The strain at break and stress at yield were 5.9% and 7.76 MPa, respectively. Maximum loads of 857 N and 1160 N, respectively, were shown in samples 3 and 4, with different stress at yield and strain at break values. The highest load in Sample 5 was 679 N, and the strain at break and stress at yield was measured at 5.39 MPa and 6.5%, respectively. Samples 2, 3, 4, and 5 showed different levels of strength and deformation properties, whereas Sample 1 showed moderate strength and ductility.

4.4 Overall Discussion

Understanding the mechanical characteristics of the AL-GRAPHITE composite made from fly ash by PM is made simpler by reviewing the comprehensive discussion of the findings. Different levels of strength, resilience, and deformation properties were shown by the material in impact, flexure, and tensile testing. Slight differences in launch angles were seen in the impact test, suggesting that the system may be sensitive to loading circumstances.

Both Sample 1 and Sample 2 showed moderate to high absorbed energy and specific impact strength, but Sample 3 showed lower values, suggesting diminished resilience. The samples' mass characteristics and energy absorption capabilities were consistent. The material's stiffness, compressive strength, tensile strength, and bending strength were all highlighted by the flexure test, which is crucial for determining whether or not the material is suitable for structural applications. Sample 1 consistently showed moderate strength and ductility in the tensile test, however, Samples 2, 3, 4, and 5 showed different strength and deformation characteristics. All things considered, these results highlight the intricate mechanical behavior of the composite, which is impacted by variables including composition and testing settings. Knowing these characteristics is essential for informing engineering choices, guaranteeing the material's performance in practical applications, and pointing up possible directions for additional study and improvement.

5. CONCLUSION

In conclusion, the investigation into the AL-GRAPHITE composite derived from fly ash via PM has provided valuable insights into its mechanical properties. Variations in the samples' strength, resilience, and deformation characteristics were noted by impact, flexure, and tensile tests. The study emphasizes how fly ash may be used to strengthen lightweight metals, improving their mechanical qualities and lowering their density. Before there were widespread industrial uses, however, further study is necessary, especially in the areas of microstructure analysis and structure-property correlation. A promising technique for detailed characterization that provides information on the evolution of microstructure is correlative microscopy. In summary, this study highlights the intricate nature of composite materials and highlights the necessity of thorough comprehension and refinement to fully realize their potential across diverse industrial domains. The development of innovative composite materials with better mechanical performance and wider applicability will be made possible by ongoing work in material characterization and optimization.

REFERENCES

[1] Singh, B., Kumar, I., Saxena, K.K., Mohammed, K.A., Khan, M.I., Moussa, S.B. and Abdullaev, S.S., 2023. A future prospects and current scenario of aluminium metal matrix composites characteristics. *Alexandria Engineering Journal*, *76*, pp.1-17.

[2] Garg, P., Jamwal, A., Kumar, D., Sadasivuni, K.K., Hussain, C.M. and Gupta, P., 2019. Advance research progresses in aluminium matrix composites: manufacturing & applications. *Journal of materials research and technology*, *8*(5), pp.4924-4939.

[3] Kishawy, H.A., Hosseini, A., Kishawy, H.A. and Hosseini, A., 2019. Metal Matrix Composites. *Machining Difficult-to-Cut Materials: Basic Principles and Challenges*, pp.139-177.

[4] Ranjan, R. and Bajpai, V., 2021. Graphene-based metal matrix nanocomposites: Recent development and challenges. *Journal of Composite Materials*, *55*(17), pp.2369-2413.

[5] Kotteda, T.K., Kumar, M., Kumar, P. and Chekuri, R.B.R., 2022. Metal matrix nanocomposites: future scope in the fabrication and machining techniques. *The International Journal of Advanced Manufacturing Technology*, pp.1-19.

[6] Lakshmikanthan, A., Angadi, S., Malik, V., Saxena, K.K., Prakash, C., Dixit, S. and Mohammed, K.A., 2022. Mechanical and tribological properties of aluminum-based metal-matrix composites. *Materials*, *15*(17), p.6111.

[7] Fanani, E.W.A., Surojo, E., Prabowo, A.R. and Akbar, H.I., 2021. Recent progress in hybrid aluminum composite: Manufacturing and application. *Metals*, *11*(12), p.1919.

[8] Ashebir, D.A., Mengesha, G.A. and Sinha, D.K., 2022. An insight into mechanical and metallurgical behavior of hybrid reinforced aluminum metal matrix composite. *Advances in Materials Science and Engineering*, *2022*.

[9] KALISHWARAN, C., MOHAMED ASHITHAN, K., REXON, J., SELVA KUMAR, R. and ABBASKIYASUDEEN, P., 2023. GRAPHENE REINFORCED ALUMINUM MATRIX COMPOSITES FOR STRUCTURAL APPLICATIONS.

[10] Moghadam, A.D., Omrani, E., Menezes, P.L. and Rohatgi, P.K., 2015. Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene–a review. *Composites Part B: Engineering*, *77*, pp.402-420.

[11] Ye, W., Shi, Y., Zhou, Q., Xie, M., Wang, H., Bou-Saïd, B. and Liu, W., 2024. Recent advances in self-lubricating metal matrix nanocomposites reinforced by carbonous materials: A review. *Nano Materials Science*.

[12] Dorri Moghadam, A., Schultz, B.F., Ferguson, J.B., Omrani, E., Rohatgi, P.K. and Gupta, N., 2014. Functional metal matrix composites: self-lubricating, self-healing, and nanocomposites-an outlook. *Jom*, *66*, pp.872-881.

[13] Sadeghi, B., Cavaliere, P., Pruncu, C.I., Balog, M., Marques de Castro, M. and Chahal, R., 2024. Architectural design of advanced aluminum matrix composites: A review of recent developments. *Critical Reviews in Solid State and Materials Sciences*, *49*(1), pp.1-71.

[14] C.Nagarajan and M.Madheswaran - ‘Experimental verification and stability state space analysis of CLL-T Series Parallel Resonant Converter’ - Journal of ELECTRICAL ENGINEERING, Vol.63 (6), pp.365-372, Dec.2012.

[15] C.Nagarajan and M.Madheswaran - ‘Performance Analysis of LCL-T Resonant Converter with Fuzzy/PID Using State Space Analysis’- Springer, Electrical Engineering, Vol.93 (3), pp.167-178, September 2011.

[16] C.Nagarajan and M.Madheswaran - ‘Stability Analysis of Series Parallel Resonant Converter with Fuzzy Logic Controller Using State Space Techniques’- Taylor & Francis, Electric Power Components and Systems, Vol.39 (8), pp.780-793, May 2011.

[17] C.Nagarajan and M.Madheswaran - ‘Experimental Study and steady state stability analysis of CLL-T Series Parallel Resonant Converter with Fuzzy controller using State Space Analysis’- Iranian Journal of Electrical & Electronic Engineering, Vol.8 (3), pp.259-267, September 2012.
[18] Nagarajan C., Neelakrishnan G., Akila P., Fathima U., Sneha S. “Performance Analysis and Implementation of 89C51 Controller Based Solar Tracking System with Boost Converter” Journal of VLSI Design Tools & Technology. 2022; 12(2): 34–41p.
[19] C. Nagarajan, G.Neelakrishnan, R. Janani, S.Maithili, G. Ramya “Investigation on Fault Analysis for Power Transformers Using Adaptive Differential Relay” Asian Journal of Electrical Science, Vol.11 No.1, pp: 1-8, 2022.
[20] G.Neelakrishnan, K.Anandhakumar, A.Prathap, S.Prakash “Performance Estimation of cascaded h-bridge MLI for HEV using SVPWM” Suraj Punj Journal for Multidisciplinary Research, 2021, Volume 11, Issue 4, pp:750-756
[21] G.Neelakrishnan, S.N.Pruthika, P.T.Shalini, S.Soniya, “Perfromance Investigation of T-Source Inverter fed with Solar Cell” Suraj Punj Journal for Multidisciplinary Research, 2021, Volume 11, Issue 4, pp:744-749
[22] C.Nagarajan and M.Madheswaran, “Analysis and Simulation of LCL Series Resonant Full Bridge Converter Using PWM Technique with Load Independent Operation” has been presented in ICTES’08, a IEEE / IET International Conference organized by M.G.R.University, Chennai.Vol.no.1, pp.190-195, Dec.2007
[23] M Suganthi, N Ramesh, “Treatment of water using natural zeolite as membrane filter”, Journal of Environmental Protection and Ecology, Volume 23, Issue 2, pp: 520-530,2022
[24] M Suganthi, N Ramesh, CT Sivakumar, K Vidhya, “Physiochemical Analysis of Ground Water used for Domestic needs in the Area of Perundurai in Erode District”, International Research Journal of Multidisciplinary Technovation, pp: 630-635, 2019

[25] Ashebir, D.A., Mengesha, G.A. and Sinha, D.K., 2022. An insight into mechanical and metallurgical behavior of hybrid reinforced aluminum metal matrix composite. *Advances in Materials Science and Engineering*, *2022*.
[26] Salur, E., Aslan, A., Kuntoğlu, M. and Acarer, M., 2021. Effect of ball milling time on the structural characteristics and mechanical properties of nano-sized Y2O3 particle reinforced aluminum matrix composites produced by powder metallurgy route. *Advanced Powder Technology*, *32*(10), pp.3826-3844.
[27] RUDIANTO, H., 2012. *Sintering Behavior of Powder Metallurgy Aluminum Metal Matrix Composites* (Doctoral dissertation, 부경대학교).
[28] Bahrami, A., Soltani, N., Pech-Canul, M.I. and Gutiérrez, C.A., 2016. Development of metal-matrix composites from industrial/agricultural waste materials and their derivatives. *Critical Reviews in Environmental Science and Technology*, *46*(2), pp.143-208.
[29] Mohammed Razzaq, A., Majid, D.L., Ishak, M.R. and Basheer, U.M., 2017. Effect of fly ash addition on the physical and mechanical properties of AA6063 alloy reinforcement. *Metals*, *7*(11), p.477.
[30] Khan, M.Z., Anas, M., Husain, A., Haque, M.I. and Rasheed, K., 2015. Effect on mechanical properties of aluminium alloy composites on adding ash as reinforcement material. *Journal of metals, materials and minerals*, *25*(2).
[31] Ononiwu, N., Ozoegwu, C., Madushele, N., Akinribide, O.J. and Akinlabi, E.T., 2022. Mechanical properties, tribology and electrochemical studies of Al/fly ash/eggshell aluminium matrix composite. Biointerface Res. Appl. Chem, 12, pp.4900-4919.
[32] Senapati, A.K., Mishra, P.C., Routray, B.C. and Rao, M.M., 2015. Experimental investigation on tribological properties of Al-Si alloy based MMC developed from an industrial waste material. Int J Concept Mech Civil Eng, 3, pp.13-16.
[33] KE, A.A. and Keerthiprasad, K.S., 2015. Characterization of AL–Graphite Composite Developed by Powder Metallurgy Technique. International Journal of Research in Engineering and Technology, 4(10), pp.2321-7308.
[34] Jannet, S., Raja, R., Ruban, S.R., Khosla, S., Sasikumar, U., Sai, N.B. and Teja, P.M., 2021. Effect of egg shell powder on the mechanical and microstructure properties of AA 2024 metal matrix composite. Materials Today: Proceedings, 44, pp.135-140.
[35] Del Real Romero, J.C., Jiménez Octavio, J.R., Manoharan, R., Muthuselvam, R.S., Joseph, R. and Sakthi Sudhan, H.H., 2017. Characterisation of mechanical properties of aluminium composites fabricated by stir-casting and powder metallurgy.
[36] Fatchurrohman, N., Mamat, A.N.B., Yetrina, M. and Muhida, R., 2022. Investigation of Metal Matrix Composites Aluminium Reinforced Graphite Particles Produced Using Powder Metallurgy. Jurnal Teknologi, 12(2), pp.76-81.
[37] Shankar, S. and Harichandran, S., 2019. Aluminium alloy reinforced with fly ash: Techniques and particle size. Jurnal Tribologi, 23(4), pp.13-37.
[38] Ngoc Minh, V.T., Pham, V.H., Tung, V.H., Tung, C.T. and Phuong, N.T.H., 2023. Firing-associated recycling of coal-fired power plant fly ash. Journal of Analytical Methods in Chemistry, 2023.