RECENT ADVANCEMENT IN METAL MATRIX COMPOSITES: MATERIAL, METHODS AND APPLICATIONS

**Abstract**

The advancement of metal matrix composites (MMCs) has seen significant advancements in fundamental science and technology. These advancements include gaining a comprehending behaviour of composites, the significance of fibre-matrix interfaces, the importance of surface coatings, diverse manufacturing methods, and thermal-mechanical processing techniques used for MMCs. This knowledge has not only led to the improvement of MMC technology but also paved the way for the expansion of high-temperature intermetallic-matrix composites.

The quest for lighter materials with enhanced characteristics for diverse applications has led to the emergence of a novel category of materials called Metal Matrix Composites (MMCs). These composite materials offer excellent physical, mechanical, and developmental properties, making them extensive applications in various industries, including aircraft technology, automotive, defense, electronics, and space. The versatility of MMCs has led to extensive research and development in the field of production technologies, resulting in cost reductions and increased acceptance in the market.

The objective of this book chapter is to bring a inclusive summary of the present application situation of MMCs and the various production approaches presently employed in their invention. By reviewing the current state of MMC technology and fabrication techniques, the Chapter aims to shed light on the promising potential of MMCs as advanced materials in various industries.

**Key word: Metal matrix composite, Application, AMC**

**Authors**

**Kapil Banker1**

Research Scholar

Gujarat Technological University

Ahmedabad, Gujarat, India.

219999919024@gtu.edu.in

**\*Dr. Prof. Anand B. Dhruv1**

Professor and Head,

Government Engineering College,

Patan, At-Katpur, Gujarat, India.

dhruv\_30@rediffmail.com

# INTRODUCTION

Industrial revolution has been made since long back and during this revolution various manufacturing machines, methods have been invented to cater the nations requirements. The functionality of our engineering structure, daily requirements, transportation and communication all rely on the properties and applications of materials. Over the recent decades, composite materials have gained significant popularity due to their superior properties and versatile applications. Composites are advanced novel material in which numerous strengthening mediator is distributed within the matrix, either in a continuous or intermittent phase. In the 1950s, the concept of metal matrix composites emerged, incorporating two distinct phases: the matrix phase and the strengthening mediator phase. Challenges associated with the implementation of these composites comprise expensive production methods and explicit issues in certain applications, like external object impairment and erosion in engineering and automobile components[1]. In the past decade, the significance of MMC (Metal Matrix Composite) materials has grown significantly, driven by their notable benefits, including a extra ordinary strength-to-weight ratio, corrosion resistance and exceptional wear. These materials are now being utilized in diverse industries, such as motorized, space, and other sectors involved in spare parts manufacturing[2]. The mechanical properties and tribological characteristics of aluminium metal matrix composites, containing various forms of reinforcements, surpass those of traditional engineering materials used in the past. These composites exhibit lower weight, enhanced cost-effectiveness, improved strength, superior stiffness, and reduced wear rate[3].

Over the past two eras, particulate reinforced aluminium matrix composites (PRAMCs) have emerged as promising candidates to supplant traditional materials across various application domains, including transportation, military, marine, and advanced engineering industries. The addition of strengthening particles in the aluminium matrix alloy significantly enhances the mechanical and tribological properties of AMCs (Aluminium Matrix Composites). Various widely employed fabrication methods for these composites include compo casting, infiltration, powder metallurgy, vacuum casting, stir casting, squeeze casting and in-situ casting. Out of the available processes, stir casting stands out as the most capable method for producing particulate reinforced aluminium matrix composites. This method ensures a unvarying distribution of reinforcement particles within the matrix alloy[4] The stir casting method is favoured for metal matrix composite production due to its ability to minimize damage to the reinforcement material. The most cost-effective approach for fabricating metal matrix composites is the liquidity state method among all available methods. This technique allows for the effective production of larger casting components. Additionally, accelerating the weight percentage of reinforcements in the aluminium metal matrix enhances strength however reducing ductility[5]. Aluminium metal matrix composites refer to composites where aluminium is strengthened through the addition of other metals, carbon-based compounds, or ceramics. The reinforcement in aluminium matrix composites (AMCs) can take the form of particulates, continuous or intermittent whiskers and fibres, depending on the definite industrial application[6].

Aluminium matrix composites have a strong potential to serve as substitutes for copper alloys. The ease of melting aluminium metal or aluminium alloy and using it as a matrix material makes it a more favourable choice compared to copper alloys. When dealing with copper matrix composites, researchers utilized die compaction as a preferred method due to the high melting point of copper, which undoubtedly the range of 1000°C. Additionally, the toxicity of certain copper alloys limits their processing options to powder metallurgy[7]. Hybrid composites display greater mechanical properties when equated to metal composites with a single type of reinforcement. These hybrid MMCs encompass the amalgamation of more than one type of reinforcement, varying in size, shape, and weight percentages, to achieve enhanced mechanical characteristics. The amalgamation of rigid ceramic particles such as SiC, Boron Carbide, Al2O3, Tungsten Carbide, MgO and SiO2, into the aluminium matrix alloy is a common practice to enhance its mechanical properties. It has been observed that incorporating two different synthetic ceramic reinforcements into aluminium matrix materials can lead to enhanced mechanical behaviour, improved machining characteristics, and superior tribological properties in aluminium hybrid composites[8].

# SYNTHESIS OF COMPOSITES: (Various Methods of Manufacturing)

The manufacturing process chosen for fabricating any composite significantly influences the ultimate properties of the composite material. Numerous techniques are currently being utilized to produce high-quality MMC products. The fabrication methods for MMC products can be considered into three main categories

1. Solid-state processes or Powder metallurgy
2. Liquid-state processes or casting based processes
3. Deposition processes.

**1 Solid-state processes.**

Powder metallurgy is a method employed to produce metal matrix composites by mixing fine powders of the matrix material, such as aluminium and its alloys, with reinforcing particles. The blending is done at room temperature or somewhat above, and the resulting mixture is then compacted into the desired shape. Next, the compacted material undergoes solid-state sintering, which involves heating it in a meticulous atmosphere under its recrystallization temperature. This process helps diminish permeability and eliminate any extraneous matter presented during sintering. After solid-state sintering, the composite undergoes deformation, extrusion, or forging above room temperature to further enhance its mechanical properties by reducing porosity and strengthening the bond between the matrix and reinforcing particles. Powder metallurgy allows for the production of precisely shaped components with complex attributes and high accuracy. It is crucial to ensure that all particles are uniformly and consistently disseminated in the mixture when using this processing route. This even distribution of particles is essential to achieve a composite with a favourable microstructure and excellent mechanical properties. Proper mixing and distribution of the reinforcing particles inside the matrix contribute significantly to the overall performance and quality of the final composite material[9].

The powder metallurgy processing technique is highly attractive due to its ability to operate at lower temperatures, which theoretically allows for better control of interface kinetics. Additionally, this method enables the incorporation of matrix alloy compositions and microstructural refinements that can only be achieved through the utilization of rapidly solidified powders. Processing powder metallurgy amalgams comprises explicit and crucial steps, as illustrated in Figure 1 Powder Metallurgy Processing.[10].

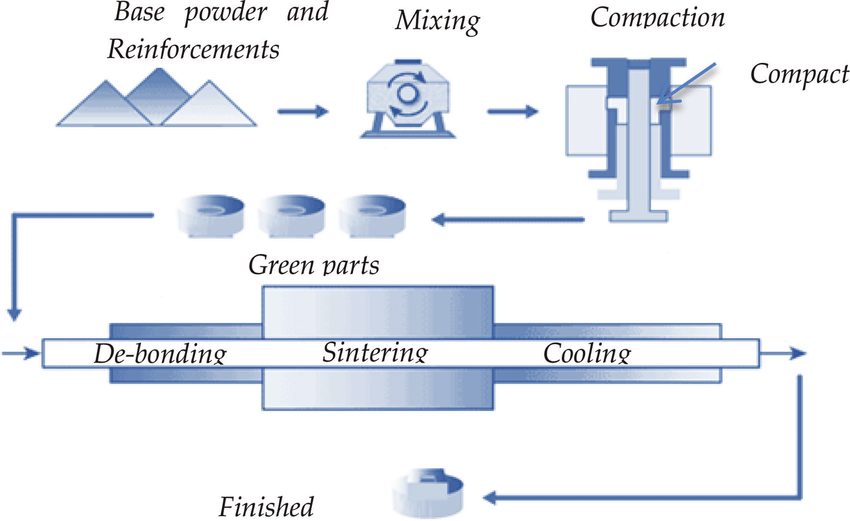


Figure 1 Powder Metallurgy Processing

1. **Liquid-state processes.**

Stir casting is a casting method that involves blending a reinforcing agent into the base matrix material using a mechanically operated stirrer. The stir casting process is broadly used in the expansion of MMCs because of its commercial feasibility, capability for mass production, ease of execution, and its capacity to improve the structural performance of the composite. The stir casting process involves three main components: a furnace, a mechanically operated stirrer, and a reinforcement distributor. The base material is liquefied in the furnace through heating. In this process, a bottom pouring furnace is more appropriate as it allows instantaneous feeding of the molten assortment into Molds, avoiding the material from stabilizing at the lowermost of the container. Proper mixing of the molten matrix material and strengthening material is crucial for accomplishing isotropic mechanical properties. Indeed, the mixing process is accomplished using a stirrer equipped with a stirrer rod and blades. The rotational motion of the stirrer produces eddies in the assortment, facilitating the thorough mixing of the molten materials. Mechanical stirrers can also be characterized based on their geometrical profile and the number of impeller blades they have. Among all types of stirrers, the utmost favourable one is the impeller with three flat blades. This design is selected because it promotes the growth of axial flow while also dropping power consumption throughout the stirring process. The speed of the stirrer can be controlled using a electronics speed regulator connected to the stirring mechanism, which delivers the essential rotational signal. To acquaint the strengthening material, a hopper is also placed. Once the slurry is ready, it can be dispensed into any type of Mold, such as sand Molds, permanent Molds, or investment Molds, based on the precise necessities of the casting process.

Figure 1 demonstrates the series of diverse activities involved in the stir casting process. The procedure begins by placing the matrix material in a furnace equipped with a lower hopper mechanism. Prior to feeding, the strengthening agent needs to be preheated to avoid wetness, impurities, and other undesirable factors. For this preheating step, a separate furnace is used in parallel with the main furnace for the matrix material. This ensures that both the matrix material and the reinforcing agent are appropriately prepared before they are combined in the stir casting process. Once the desired temperature is reached, which is determined based on the matrix material being used, the mechanically operated stirrer is activated to generate a swirl within the molten matrix material. Along the axis of this swirling motion, the strengthening agent is progressively introduced through the hopper at a stable proportion. The process continues until the anticipated quantity of strengthening material is thoroughly mixed with the liquefied matrix material. This confirms suitable distribution and uniform spreading of the strengthening agent throughout the mixture, resulting in a well-blended composite material[11].

Figure 2 Schematic diagram of Stir casting Method

1. **Deposition processes.**

The physical vapor deposition process is utilized for manufacturing MMCs, and it is typically a slow procedure. In this method, a fibre is endlessly passed through an area with a high partial pressure of the metal to be deposited. Throughout this process, the metal evaporates and then condenses onto the surface of the fibre, leading to the foundation of the metal matrix composite as seen in Figure 3. In the physical vapor deposition process, a relatively thick layer is obtained on the fibre by passing it through a region where condensation occurs. To produce vapours, a high-power electron beam is focused onto the end of a solid bar feedstock. Typically, the deposition rates are around 5-10 μm per minute.

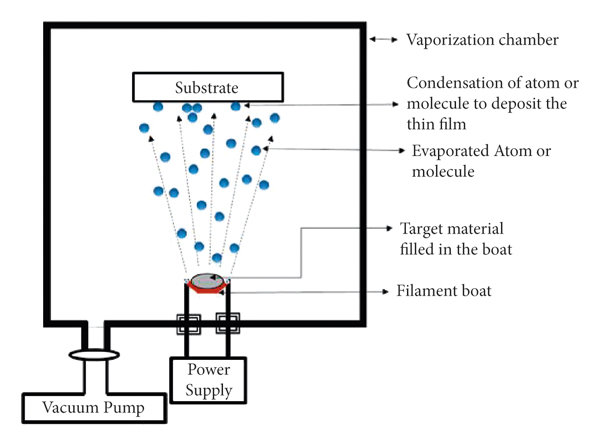


Figure 3 Schematic diagram of physical vapor deposition

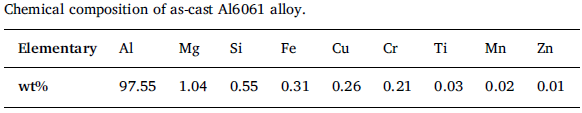
The layered fibres are then assembled into a bundle or array and combined using a hot press operation to produce the concluding composite material. This process confirms the proper bonding and integration of the layered fibres to form a robust and cohesive MMCs. PVD (Physical Vapor Deposition) can be separated into two main categories:[9].

1. Vaporization and characterization techniques (EBED - Electron Beam Evaporation Deposition)
2. Sputtering techniques.

# Materials:

Numerous materials have been utilized to fabricate MMCs. However, aluminium is one of the excellent material due to its outstanding strength to weight ratio, advanced thermal conductivity and corrosion resistance as well as easy to cast in to complex shape. The spectroscopy analysis of the Al-6061 alloy was conducted using atomic emission spectrometry, by means of the ASTM E1251 testing technique. Atomic emission spectrometry is a method used to assess the essential composition of a material by measuring the wavelengths of light released when the sample is excited by a high-energy source, such as an electric discharge or a flame. The ASTM E1251-2011 standard provides guidelines and procedures for performing this analysis in a standardized and reliable manner[12].

Table 1 Spectroscopy of Al6061[13]



Following information depict the utilization of various aluminium material as matrix material to fabricate metal matrix composite and reinforcement used to enriched mechanical properties.

Table 2 Different Material for Fabrication of MMCs

| **Matrix material** | **Reinforcement** | **Processing Route** | **Reference** |
| --- | --- | --- | --- |
| ADC 12 | Boron carbide (B4C) | Stir Casting | [14] |
| Al6061 | Boron carbide (B4C), SiC | Bottom pouring stir casting | [15] |
| Al6061 | SiC-B4C | Stir Casting | [16] |
| Al6061 | SiC/WC | Stir Casting | [17] |
| Al6061 | Boron carbide (B4C) | Stir Casting | [18] |
| Al6061 | Boron carbide (B4C) | Stir Casting | [19] |
| LM24 | Boron carbide (B4C) | Stir Casting | [20] |
| Al6063 | Fly ash and Al2O3 | Stir Casting | [21] |
| Al−4.5%Cu | Bamboo leaf Ash (BLA) | Bottom pouring stir casting | [22] |
| AA6063 | SiC-TiC | Stir Casting | [23] |
| Al6061 | TiB2 | Stir Casting | [13] |
| AA7150 | WC | Stir Casting | [24] |
| Al6351 | Al2O3–C | Stir Casting | [25] |
| Al6061 | boron carbide and graphite | Bottom pouring stir casting | [26] |
| Al6061 | WC | Stir Casting | [27] |
| Al6061 | Al2O3 | Stir Casting | [28] |
| Al6063 | boron carbide | Stir Casting | [29] |
| Al7075 | WC and Fly Ash | Stir Casting | [30] |
| A356 | WC | Stir Casting | [31] |
| Al6061 | boron carbide and graphite | Bottom pouring stir casting | [32] |
| Al6061 | Boron carbide (B4C), SiC | Stir Casting | [33] |
| Al6061 | WC | Stir Casting | [34] |
| Al6061 | boron carbide | Stir Casting | [35] |
| AA7075 | Al2O3 | Stir Casting | [36] |
| AA6531 | Al2O3 and graphite | Stir Casting | [37] |
| Al7075 | WC | Stir Casting | [38] |
| Al7075 | WC and Cobalt | Stir Casting | [39] |
| Al5083 | Al2O3 and B4C | Stir Casting | [40] |
| Al6061 | B4C | Stir Casting | [41] |

Aluminium alloys are extensively preferred as the matrix material in MMCs, both in research and industrial applications, mainly because of their exceptional strength-to-weight ratio. Additionally, aluminium alloys are cost-effective equated to other lightweight materials like titanium and magnesium. These alloys exhibit outstanding mechanical properties, such as Hardness, strength, castability and ductility, and boast high corrosion resistance, making them versatile and adaptable to various requirements.

Among the various aluminium alloys, age-hardening grades (2xxx, 6xxx, 7xxx and 8xxx series) are commonly used as parent materials. Age-hardening alloys offer the advantage of further enhancing mechanical properties through different aging treatments, allowing for modifying their characteristics to meet definite requirements. This makes them a predominant choice for emerging high-performance MMCs with greater mechanical competences[13].

# Application of Composites:

* **Automobile Components:**

Light alloy composite materials hold significant potential for various applications in the automotive engineering industry. They are commonly utilized in components such as pistons road, pistons, piston pin, covers, car disc brake, cylinder heads, crankshafts, main bearings, engine blocks, cylinder blocks. These composite materials, which combine lightweight alloys with reinforcing elements, offer advantages such as reduced weight, improved strength-to-weight ratio, and enhanced performance, making them ideal for enhancing the efficiency and performance of automotive components.

An excellent example of the fruitful application of aluminium composite materials in this context is the somewhat short fibre-reinforced aluminium composite piston Figure 4. These pistons are engineered with a combination of aluminium and short reinforcing fibres, resulting in enhanced mechanical properties and performance compared to traditional pistons made solely from aluminium alloys. The incorporation of strengthening fibres in the aluminium matrix recovers the strength, durability, and resistance to wear and deformation, making them highly suitable for high-stress applications in internal combustion engines. This demonstrates the effectiveness of composite materials in optimizing automotive components and advancing the performance and efficiency of modern engines.[42]



1. (b)

Figure 4 short fibre reinforced composite Piston (a) , particulate reinforced composite Car brake disc (b)

Currently, the majority of metal matrix composites (MMCs) used in automotive applications are based on aluminium and its alloys. One of the primary reasons for using MMCs in automotive engines is to reduce the mass of reciprocating parts, resulting in lower noise and vibration levels. The use of aluminium and its alloys is widespread in the automotive industry due to their lightweight and cost-effective nature associated to other light metals like magnesium. In automotive engines, the piston crown is a common target for MMC implementation. The improved hot strength of MMCs allows for lighter pistons to be used, enhancing engine performance. Similarly, MMCs can be beneficial for piston pins and connecting rods.

Major automotive companies such as Toyota and Honda have commercially adopted Al-based MMCs in their engines. Toyota has incorporated MMC pistons in its diesel engines, while Honda has utilized steel wire reinforced aluminium connecting rods and Al-Si matrix MMCs for cylinder blocks in their vehicles. This indicates the increasing importance of MMCs in the automotive industry for achieving lightweight, efficient, and high-performance engine components[43].

* **Aircraft Components:**

Magnesium-matrix composites with B4C or SiC reinforcement have demonstrated favourable properties at both room and higher temperatures, making them suitable materials for fan blade applications in high-temperature environments. Although magnesium and titanium have a higher density compared to aluminium, it still exhibits outstanding strength-to-weight and stiffness-to-weight ratios when compared to steels.

Continuous SiC fibre-reinforced Ti-MMCs are under development for aviation applications in numerous nations, including the UK, USA, Caneda, China and France. These advanced materials show promising potential for enhancing engine performance and efficiency, contributing to the ongoing efforts to improve aircraft propulsion technology and achieve greater overall performance.

* **Defense Components:**

Metal matrix composites (MMCs) have found significant applications in various critical parts of missiles and other defense systems due to their unique properties and advantages. One notable application is in missiles, which were traditionally mass-produced by means of beryllium. However, MMCs offer a viable alternative with a higher weight percentage of reinforced aluminium, which is both cost-effective and avoids the toxicity.

Fins of guided weapons are another significant application of MMCs due to their high stiffness. MMCs reduce the bending of fins, thus increasing the precision of the weapon. In armoured fighting vehicles like tanks, MMCs are used in components such as tracks and engine parts to enhance battlefield manoeuvrability. The use of MMCs leads to a reduction in overall weight, significantly improving the vehicle's manoeuvrability and survival rates.

In space applications, magnesium alloys are reinforced with graphite to generate newer material, particularly for scramjet engines where properties like light weight, high specific stiffness, lesser coefficient of thermal expansion are essential.

Figure 5 showcases examples of MMC applications, including missile fins, armors, and tank tracks, further highlighting the versatility and significance of MMCs in modern defense systems[43].

Figure 5 (a) Fin of guided missile, (b) Vehicle armour, (c) Tank Track

* **Sports Components:**

Sports equipment often requires materials that combine various types, such as metals, ceramics, polymers, and composite concepts. Creative design concepts are employed to fabricate these materials into the desired sports equipment. The use of MMCs has been broadly studied in various sports equipment, including horse feet base, golf clubs, tennis racquets, and bicycle frames and bodies.

For sports bicycles, frames are commonly made from a mixture of aluminium, magnesium, titanium, and carbon fibre-based composites. Carbon-fibre-reinforced composites are the preferred choice for many sports equipment due to their high strength-to-weight ratio and toughness. These materials are particularly advantageous for achieving lightweight and high-performance sports gear.

****However, in some cases, aluminium and magnesium-based MMCs are also employed in sports equipment like tennis rackets, vaulting poles, and prosthetic limbs. These materials offer a cost-effective alternative while still providing the required performance and durability for specific sports applications. Overall, the use of MMCs allows for the creation of innovative and high-performing sports equipment to meet the diverse needs of athletes and sports enthusiasts.

Figure 6 (a) Prosthetic limbs, (b) bicycle frame, (c) Golf club

* **Space Components:**

To withstand the crucial demanding conditions, materials with high specific stiffness and low coefficient of thermal expansion (CTE) are essential. Specific stiffness relates to the material's stiffness-to-density ratio, making it crucial to have lightweight structures with high stiffness. A low CTE is essential to maintain dimensional stability and prevent distortion due to temperature variations in the harsh space environment.

Developing materials with these characteristics is critical to ensuring the reliability and longevity of space missions and spacecraft components. Advanced composite materials, like carbon-fibre-reinforced composites, and other innovative materials are often used to meet these demanding requirements in space applications. These materials play a dynamic role in the creation of lightweight, dimensionally unchanging, and high-performance assemblies for space exploration and satellite missions.

# Conclusion

Materials research in the field of light MMCs has been highly active over the past two eras. The findings indicate that the foremost marketplace for MMCs is currently the automotive industry, followed by microchip technology and thermal management systems. Continuous expansion in material and processing practices has resulted in the formation of MMCs that are lighter in weight, more cost-effective, and offer higher performance for various applications.

The advancements in MMC technology have broadened the scope for their utilization across industries, including aerospace, automotive, electronics, and thermal management systems. The ongoing research and development efforts in this area continue to improve the properties and performance of MMCs, making them increasingly desirable materials for meeting the demands of various modern applications.

Noteworthy progresses in the expansion of production routes for MMCs have played a crucial role in bringing down their production costs to acceptable levels. Researchers are continually working on refining the production methods of MMCs to enhance their performance, optimize their properties, and broaden their range of applications

As a result of these technological advancements, MMCs have found increasing applications in various industries. According to a global MMC market survey, a substantial growth of more than 20% in the usage of MMCs is forecast for the next two years. This indicates a growing demand for MMCs and reflects the increasing recognition of their benefits and advantages in various engineering and industrial applications. The continuous research and development efforts in the field are likely to further enhance MMC technology and expand their utilization in diverse sectors in the coming years.

References.

[1] B. Vinod, S. Ramanathan, V. Ananthi, and N. Selvakumar, “Fabrication and Characterization of Organic and In-Organic Reinforced A356 Aluminium Matrix Hybrid Composite by Improved Double-Stir Casting,” *Silicon*, vol. 11, no. 2, pp. 817–829, Apr. 2019, doi: 10.1007/s12633-018-9881-5.

[2] T. MYTHILI and R. THANIGAIVELAN, “Optimization of wire EDM process parameters on Al6061/Al2O3 composite and its surface integrity studies,” *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 68, no. 6, pp. 1403–1412, Dec. 2020, doi: 10.24425/bpasts.2020.135382.

[3] A. Bhowmik, D. Dey, and A. Biswas, “Characteristics Study of Physical, Mechanical and Tribological Behaviour of SiC/TiB2 Dispersed Aluminium Matrix Composite,” *Silicon*, vol. 14, no. 3, pp. 1133–1146, Feb. 2022, doi: 10.1007/s12633-020-00923-2.

[4] V. Mohanavel, K. Rajan, S. Suresh Kumar, G. Vijayan, and M. S. Vijayanand, “Study on mechanical properties of graphite particulates reinforced aluminium matrix composite fabricated by stir casting technique,” in *Materials Today: Proceedings*, Elsevier Ltd, 2018, pp. 2945–2950. doi: 10.1016/j.matpr.2018.01.090.

[5] D. Sethi, V. Kolli, and B. Saha Roy, “ScienceDirect Experimental investigation of Aluminium Matrix Composite production and joining,” 2019. [Online]. Available: www.sciencedirect.com

[6] A. Jamwal, U. K. Vates, P. Gupta, A. Aggarwal, and B. P. Sharma, “Fabrication and characterization of Al2O3–TiC-reinforced aluminum matrix composites,” in *Lecture Notes in Mechanical Engineering*, Pleiades journals, 2019, pp. 349–356. doi: 10.1007/978-981-13-6412-9\_33.

[7] R. Venkatesh, V. S. Rao, and S. Ashwin Kannan, “Machinability analysis and edm process optimization on the hybrid nano particle reinforced aluminum matrix composites,” *Int J Eng Adv Technol*, vol. 9, no. 1, pp. 1162–1174, Oct. 2019, doi: 10.35940/ijeat.A9512.109119.

[8] C. Fenghong, C. Chang, W. Zhenyu, T. Muthuramalingam, and G. Anbuchezhiyan, “Effects of Silicon Carbide and Tungsten Carbide in Aluminium Metal Matrix Composites,” *Silicon*, vol. 11, no. 6, pp. 2625–2632, Dec. 2019, doi: 10.1007/s12633-018-0051-6.

[9] P. Garg, A. Jamwal, D. Kumar, K. K. Sadasivuni, C. M. Hussain, and P. Gupta, “Advance research progresses in aluminium matrix composites: manufacturing & applications,” *Journal of Materials Research and Technology*, vol. 8, no. 5. Elsevier Editora Ltda, pp. 4924–4939, Sep. 01, 2019. doi: 10.1016/j.jmrt.2019.06.028.

[10] G. F. Aynalem, “Processing Methods and Mechanical Properties of Aluminium Matrix Composites,” *Advances in Materials Science and Engineering*, vol. 2020. Hindawi Limited, 2020. doi: 10.1155/2020/3765791.

[11] G. Upadhyay and K. K. Saxena, “Role of Stir Casting in development of Aluminium Metal Matrix Composite (AMC): An Overview,” *IOP Conf Ser Mater Sci Eng*, vol. 1116, no. 1, p. 012022, Apr. 2021, doi: 10.1088/1757-899x/1116/1/012022.

[12] R. Sharma, V. Aggarwal, and H. S. Payal, “Optimization of micro hardness of Al-SiC 6061 MMC machined by wire EDM with taguchi method,” *Int J Eng Adv Technol*, vol. 8, no. 6, pp. 5375–5382, Aug. 2019, doi: 10.35940/ijeat.F8472.088619.

[13] Y. Pazhouhanfar and B. Eghbali, “Microstructural characterization and mechanical properties of TiB2 reinforced Al6061 matrix composites produced using stir casting process,” *Materials Science and Engineering A*, vol. 710, pp. 172–180, Jan. 2018, doi: 10.1016/j.msea.2017.10.087.

[14] A. Z. Syahrial and M. A. Pratama, “The influence various boron carbide reinforcement on the microstructure and mechanical properties of ADC12/B4C composite by stir casting,” in *AIP Conference Proceedings*, American Institute of Physics Inc., Apr. 2020. doi: 10.1063/5.0001985.

[15] K. P S, “An Investigation on the Mechanical Properties of Aluminium 6061 Alloy Reinforced with Boron Carbide and Silicon Carbide,” *Int J Res Appl Sci Eng Technol*, vol. 9, no. 12, pp. 726–735, Dec. 2021, doi: 10.22214/ijraset.2021.39363.

[16] H. Alrobei, “Effect of different parameters and aging time on wear resistance and hardness of SiC-B4C reinforced AA6061 alloy,” *Journal of Mechanical Science and Technology*, vol. 34, no. 5, pp. 2027–2034, May 2020, doi: 10.1007/s12206-020-0424-9.

[17] P. Vijay, K. V Brahma Raju, K. Ramji, and S. Kamaluddin, “EFFECT OF TUNGSTEN CARBIDE ON Al6061/SiC HYBRID METAL MATRIX COMPOSITES,” vol. 21, no. 4, pp. 169–180, 2021.

[18] D. Lee, J. Kim, S. K. Lee, Y. Kim, S. B. Lee, and S. Cho, “Experimental and thermodynamic study on interfacial reaction of B4C–Al6061 composites fabricated by stir casting process,” *J Alloys Compd*, vol. 859, Apr. 2021, doi: 10.1016/j.jallcom.2020.157813.

[19] C. Ravi, B. Naik, and U. U. Prakash, “Fabrication and Mechanical Characterization of Boron Carbide Reinforced Aluminium Matrix Composites,” 2016. [Online]. Available: https://www.researchgate.net/publication/323614518

[20] K. Singh, R. S. Rana, and A. Pandey, “Fabrication and Mechanical properties characterization of aluminium alloy LM24/B4C composites,” in *Materials Today: Proceedings*, Elsevier Ltd, 2017, pp. 701–708. doi: 10.1016/j.matpr.2017.01.075.

[21] D. Chandra, N. R. Chauhan, and S. Rajesha, “Hardness and toughness evaluation of developed Al metal matrix composite using stir casting method,” in *Materials Today: Proceedings*, Elsevier Ltd, 2019, pp. 872–876. doi: 10.1016/j.matpr.2019.12.026.

[22] B. P. KUMAR and A. K. BIRRU, “Microstructure and mechanical properties of aluminium metal matrix composites with addition of bamboo leaf ash by stir casting method,” *Transactions of Nonferrous Metals Society of China (English Edition)*, vol. 27, no. 12, pp. 2555–2572, Dec. 2017, doi: 10.1016/S1003-6326(17)60284-X.

[23] A. Kumar, M. Yeasin Arafath, P. Gupta, D. Kumar, C. Mustansar Hussain, and A. Jamwal, “Microstructural and mechano-tribological behavior of Al reinforced SiC-TiC hybrid metal matrix composite,” in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 1417–1420. doi: 10.1016/j.matpr.2019.08.186.

[24] V. Mohanavel, S. Prasath, K. Yoganandam, B. G. Tesemma, and S. Suresh Kumar, “Optimization of wear parameters of aluminium composites (AA7150/10 wt%WC) employing Taguchi approach,” in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 4742–4745. doi: 10.1016/j.matpr.2020.08.356.

[25] N. Ahamad, A. Mohammad, K. K. Sadasivuni, and P. Gupta, “Phase, microstructure and tensile strength of Al–Al2O3–C hybrid metal matrix composites,” *Proc Inst Mech Eng C J Mech Eng Sci*, vol. 234, no. 13, pp. 2681–2693, Jul. 2020, doi: 10.1177/0954406220909846.

[26] SM. Sutharsan, P. Senthilkumar, B. Koodalingam, U. Nattarselvi, K. Murali Kumar, and B. Gnanakumar, “WITHDRAWN: Analysis of mechanical behavior of Al 6061 metal matrix with boron carbide and graphite,” *Mater Today Proc*, Apr. 2021, doi: 10.1016/j.matpr.2021.03.354.

[27] P. Anand, D. Rajesh, N. Lenin, V. Balaji, V. K. Bupesh Raja, and K. Palanikumar, “Enhancement of mechanical characterization of aluminum alloy with tungsten carbide metal matrix composite by particulate reinforcements,” in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3690–3692. doi: 10.1016/j.matpr.2021.01.848.

[28] B. C. Kandpal, J. Kumar, and H. Singh, “Fabrication and characterisation of Al2O3/aluminium alloy 6061 composites fabricated by Stir casting,” in *Materials Today: Proceedings*, Elsevier Ltd, 2017, pp. 2783–2792. doi: 10.1016/j.matpr.2017.02.157.

[29] V. Singh, S. Kesarwani, and M. S. Niranjan, “IMPACT OF VARIATION IN SIZES OF BORON CARBIDE ON PROPERTIES OF NOVEL COMPOSITE OF ALUMINIUM ALLOY 6063-T6 AND BORON CARBIDE,” 2021. [Online]. Available: http://www.ijeast.com

[30] A. Dhilipa, “Investigation of Mechanical Properties of Aluminum Composite (Al-7075/WC& Fly-Ash) Fabricated by Stir Casting Process,” European Alliance for Innovation n.o., Jan. 2022. doi: 10.4108/eai.7-12-2021.2314709.

[31] A. R. Krishna, A. Arun, D. Unnikrishnan, and K. V Shankar, “An Investigation On The Mechanical And Tribological Properties Of Alloy A356 On The Addition Of WC,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings2214-7853

[32] S. Vijay, S. M. Sutharsan, and M. M. Prasad, “Investigation on Mechanical Properties of Aluminium 6061 Metal matrix with Boron Carbide and Graphite.” [Online]. Available: https://www.researchgate.net/publication/340874829

[33] P. S. Reddy, R. Kesavan, and B. Vijaya Ramnath, “Investigation of Mechanical Properties of Aluminium 6061-Silicon Carbide, Boron Carbide Metal Matrix Composite,” *Silicon*, vol. 10, no. 2, pp. 495–502, Mar. 2018, doi: 10.1007/s12633-016-9479-8.

[34] D. Rajesh, P. Anand, N. Lenin, V. K. Bupesh Raja, K. Palanikumar, and V. Balaji, “Investigations on the mechanical properties of tungsten carbide reinforced aluminium metal matrix composites by stir casting,” in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3618–3620. doi: 10.1016/j.matpr.2021.01.634.

[35] N. R. J. Hynes, S. Raja, R. Tharmaraj, C. I. Pruncu, and D. Dispinar, “Mechanical and tribological characteristics of boron carbide reinforcement of AA6061 matrix composite,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, no. 4, Apr. 2020, doi: 10.1007/s40430-020-2237-2.

[36] H. A. Al-Salihi, A. A. Mahmood, and H. J. Alalkawi, “Mechanical and wear behavior of AA7075 aluminum matrix composites reinforced by Al2O3 nanoparticles,” *Nanocomposites*, vol. 5, no. 3, pp. 67–73, Jul. 2019, doi: 10.1080/20550324.2019.1637576.

[37] V. Mohanavel, K. Rajan, P. V. Senthil, and S. Arul, “Mechanical behaviour of hybrid composite (AA6351+Al2O3+Gr) fabricated by stir casting method,” in *Materials Today: Proceedings*, Elsevier Ltd, 2017, pp. 3093–3101. doi: 10.1016/j.matpr.2017.02.192.

[38] N. A. Babu, B. Balu Naik, and B. Ravi, “ScienceDirect Microstructure and Mechanical properties of As-cast Al7075-Tungsten carbide metal matrix composites,” 2019. [Online]. Available: www.sciencedirect.com

[39] U. B. G. Krishna, B. Vasudeva, V. Auradi, and M. Nagaral, “Effect of Percentage Variation on Wear Behaviour of Tungsten Carbide and Cobalt Reinforced Al7075 Matrix Composites Synthesized by Melt Stirring Method,” *J Bio Tribocorros*, vol. 7, no. 3, Sep. 2021, doi: 10.1007/s40735-021-00528-1.

[40] T. Hariprasad, K. Varatharajan, and S. Ravi, “Wear characteristics of B4C and Al2O3 reinforced with Al 5083 metal matrix based hybrid composite,” in *Procedia Engineering*, Elsevier Ltd, 2014, pp. 925–929. doi: 10.1016/j.proeng.2014.12.368.

[41] A. Kumar, V. Hiremath, and V. Auradi, “Tensile and Compression Behaviour of Boron Carbide Reinforced 6061Al MMC’s processed through Conventional Melt Stirring,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings

[42] “AMC APPLICATION for industrial use 2017”.

[43] Akhil. R, “A Study on Recent Trends in the Applications of Metal Matrix Composites,” *Int J Res Appl Sci Eng Technol*, vol. 6, no. 5, pp. 172–180, May 2018, doi: 10.22214/ijraset.2018.5027.

\*\*\*\*\*\*\*\*\*\*