RECENT DEVELOPMENT IN ALUMINIUM MMCs: MATERIALS, METHODS AND APPLICATIONS

Abstract

The development of Aluminium MMCs has seen significant improvements 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 inter metallic-MMCs

The challenges for lighter materials with improved characteristics for miscellaneous 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 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.

Keywords: Metal matrix composite, Application, AMC.

Authors

Kapil Banker
Research Scholar
Gujarat Technological University
Ahmedabad, Gujarat, India.

Assistant Professor
Mechanical Engineering Department
Government Engineering College
Palanpur, Gujarat, India.
219999919024@gtu.edu.in

Dr. Prof. Anand B Dhruv
Professor and Head
Government Engineering College
Patan, Gujarat, India.
dhruv_30@rediffmail.com

I. 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 and mixture of strengthening agent. 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 aextra ordinary strength, corrosion resistance and excellent thermal conductivity. These materials are now being utilized in diverse industries, such as motorized, space, and other sectors involved in spare parts manufacturing[2]. The frequent characteristics of aluminium MMCs, 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, aluminium composites have emerged as promising candidates to supplant traditional constituents across various application domains, including transportation, military, marine, and advanced engineering industries. Widely employed fabrication methods for these composites include compo casting, stir casting, and in-situ casting[4].The stir casting method is favoured for aluminium MMCs production owing 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[5].Aluminium metal matrix composites refer to composites where aluminium is strengthened through the addition of other metals, carbon-based compounds, or ceramics[6].

Aluminium MMC has been found excellent alternative than copper alloy composites. 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, Al_2O_3, Tungsten Carbide, MgO and SiO_2, 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].

II. 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

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

1. **Solid-State Processes:** In powder metallurgy process 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 re-crystallization temperature. It is crucial to ensure that all particles are uniformly and consistently disseminated in the mixture when using this processing route[9].

   Processing powder metallurgy amalgams comprises explicit and crucial steps, as illustrated in Figure 1 Powder Metallurgy Processing.[10]

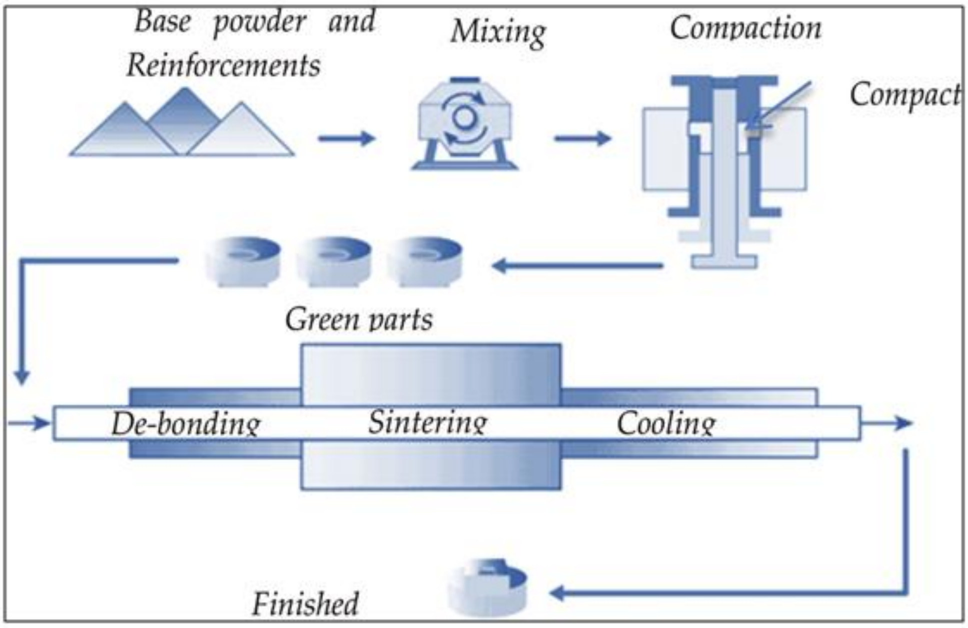


Figure 1: Powder Metallurgy Processing

2. **Liquid-state processes:** Stir casting is one of the efficient and economical way to produce composites. Different processes have their own advantages and limitations, However this process having excellent result in the production of aluminium MMCs with little bit challenges. Some challenges associated with the stir casting are wettability issues and agglomeration of reinforcement materials at one location. Wettability issues could be eliminated by adding 0.5 to 1 weight percentage of Magnesium powder during the stirring process.[10]

Figure 2 claimed the well-known liquid stir casting method towards the development of aluminium composites for lighter and strengthen structural application. In stir casting process aluminium or copper material have been melted in the high temperature furnace, once metal has melted reinforcement materials are added and stir the mixture with specified rpm and time to develop improved composite.[11]

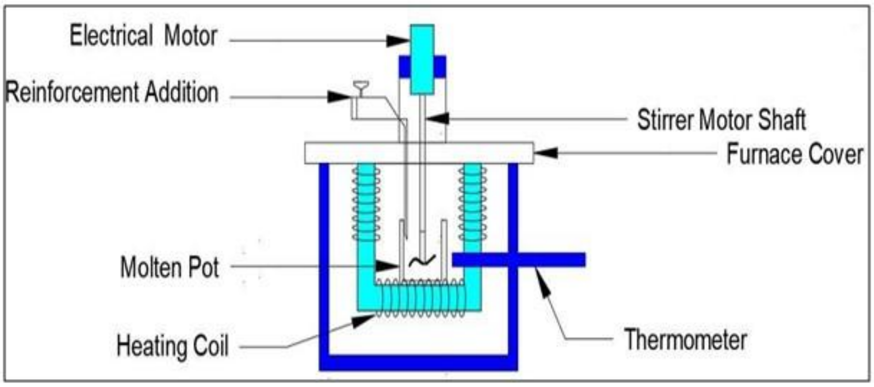


Figure 1: Schematic Diagram of Stir Casting Method

2. **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.

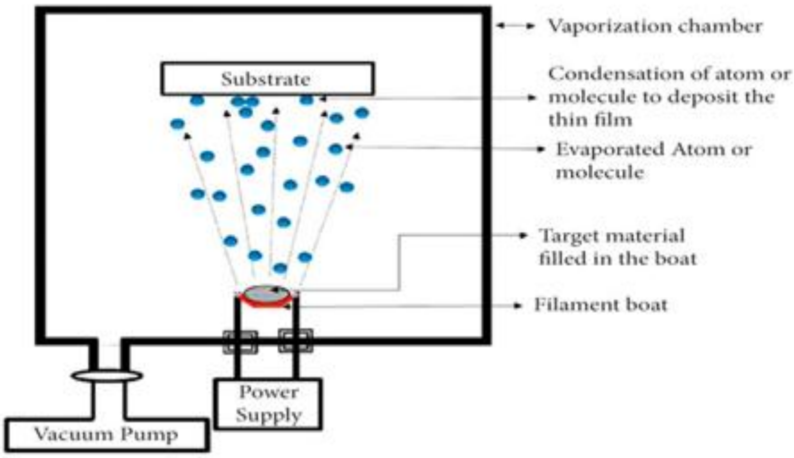


Figure 2: Schematic Diagram of Physical Vapor Deposition

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 some categories listed as EBED and sputtering[9].

- Electron Beam Evaporation Deposition)
- Sputtering techniques.

III. MATERIALS

Numerous materials have been utilized to fabricate MMCs. However, aluminium is one of the excellent material sowing to its superiors strength, advanced thermal conductivity and corrosion resistance as well as easy to cast in to complex shape. 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]

Chemical composition of as-cast Al6061 alloy.

Elementary	Al	Mg	Si	Fe	Cu	Cr	Ti	Mn	Zn
wt%	97.55	1.04	0.55	0.31	0.26	0.21	0.03	0.02	0.01

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 (B_4C)	Stir Casting	[14]
Al6061	Boron carbide (B_4C), SiC	Bottom pouring stir casting	[15]
Al6061	SiC-B_4C	Stir Casting	[16]
Al6061	SiC/WC	Stir Casting	[17]
Al6061	Boron carbide (B_4C)	Stir Casting	[18]
Al6061	Boron carbide (B_4C)	Stir Casting	[19]
LM24	Boron carbide (B_4C)	Stir Casting	[20]
Al6063	Flyash 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	Al_2O_3–C	Stir Casting	[25]
Al6061	boron carbide and graphite	Bottom pouring stir casting	[26]
Al6061	WC	Stir Casting	[27]
Al6061	Al_2O_3	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 (B_4C), SiC	Stir Casting	[33]
Al6061	WC	Stir Casting	[34]
Al6061	boron carbide	Stir Casting	[35]
AA7075	Al_2O_3	Stir Casting	[36]
AA6531	$Al_2O_3$and graphite	Stir Casting	[37]
Al7075	WC	Stir Casting	[38]
Al7075	WC and Cobalt	Stir Casting	[39]
Al5083	$Al_2O_3$and B_4C	Stir Casting	[40]
Al6061	B_4C	Stir Casting	[41]

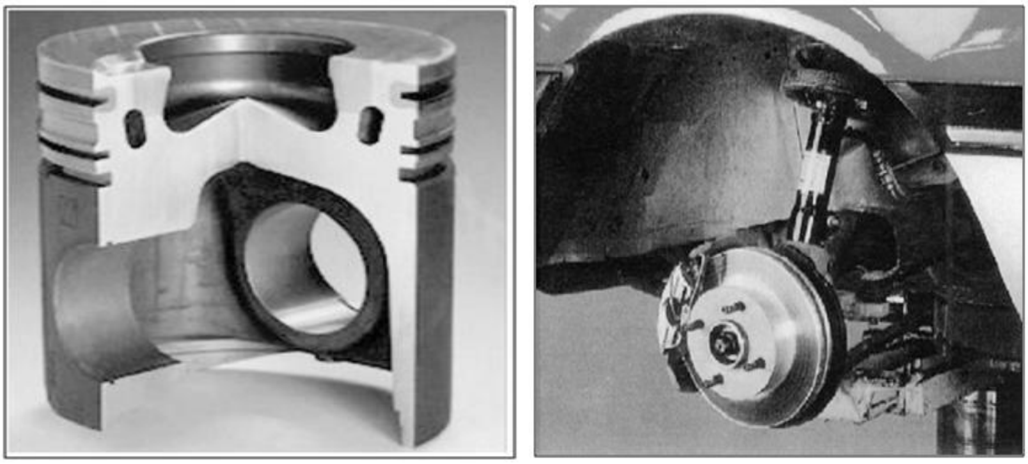
Aluminium alloys are extensively preferred as the matrix material in MMCs, both in research and industrial applications, mainly because of their exceptional strength-to-weight ratio. Additionally, aluminium alloys are cost-effective equated to other lightweight materials like titanium and magnesium. 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].

IV. APPLICATION OF COMPOSITES

1. **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. 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]



(a) (b)

Figure 3: Short Fibre Reinforced Composite Piston (a), Particulate Reinforced Composite Car Brake Disc (b)

Major automotive companies such as Toyota and Honda have commercially adopted Al-based MMCs in their engines[43].

2. **Aircraft Components:** Magnesium-matrix composites with B_4C 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.

3. **Defense Components:** Aluminium MMCs have found significant applications in various critical parts of missiles and other defines 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. 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].

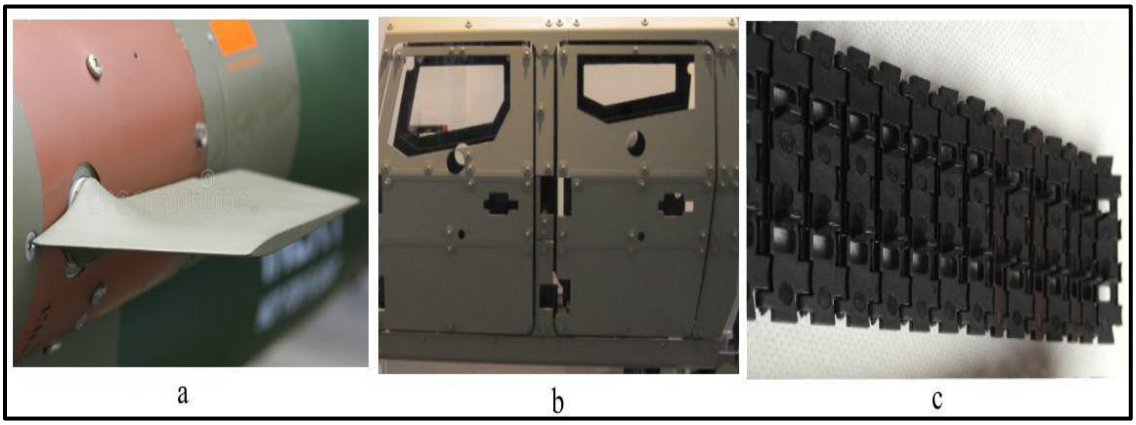


Figure 4: (a) Fin of Guided Missile, (b) Vehicle Armour, (c) Tank Track

4. **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. Some researcher studied about sports equipment such as artificial limb for disabled people. sports bicycle frames and also in golf sticks.

   For sports bicycles, frames are commonly made from a mixture of aluminium, magnesium, titanium, and carbon composites. Carbon composites are the preferred choice for many sports equipment due to their strength 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 5: (a) Artificial Limbs, (b) Bicycle Structure, (c) Golf Sticks

5. **Space Components:** Developing materials with excellent 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 have a great emphasise in the construction of lightweight, dimensionally unchanging, and structurally efficient assemblies for space exploration and satellite missions.

V. CONCLUSION

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 EditoraLtda, 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 Renforced 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. YeasinArafath, 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.

