J. Inst. Eng. India Ser. D
https://doi.org/10.1007/s40033-024-00651-6

REVIEW PAPER

Metal Matrix Composites Processed Through Powder Metallurgy: A Brief Overview

Ziyauddin Seikh[1] · Mukandar Sekh[1] · Gurudas Mandal[2] · Barnali Sengupta[2] · Arijit Sinha[2]

Received: 24 November 2023 / Accepted: 29 January 2024

Abstract Metal matrix composites (MMCs) synthesised through powder metallurgy (P/M) route have been extensively selected and utilized for the aerospace, automotive, petrochemical ordnance, and petroleum industries. P/M is an excellent process for creating parts with strong, hard, wear-resistant, and other desirable mechanical and tribological qualities. In comparison with other conventional processing techniques, P/M provides an ordered microstructure with better mechanical, tribological, and physical characteristics. Such desirable characteristics validate the adoption of the powder metallurgy as a favourable and economical process compared to other methods in a various industry, including automotive, aerospace, and even electronic components. It is well known and documented that engineered MMCs provide a superior strength-to-weight (σ/ρ) ratio. The present detailed review summarised an overview the processing of metal matrix composites using powder metallurgical route and opportunities for further research.

Keywords Casting · Powder metallurgy · Sintering · Composites · MMCs · Reinforcements · Performance

Introduction

In recent times, MMCs, have generated a lot of interest due to their unique combination of properties, including high specific strength, specific stiffness, and wear resistance. Powder metallurgy (P/M) has emerged as a promising technique for fabricating MMCs, providing enhanced control over the material's microstructure and properties. However, there are still several areas that warrant further research to fully exploit the potential of MMCs using P/M, such as optimising the dispersion of reinforcement particles within the matrix, improving wettability, and hence enhanced interfacial bonding between the matrix and reinforcement, and exploring novel reinforcement materials. Additionally, exploring the effects of processing parameters, such as sintering temperature and pressure on the final properties of MMCs, can open up new avenues for developing tailored composites with enhanced mechanical and thermal properties. The dispersion of reinforcement particles is a critical factor in determining the overall performance of MMCs, as it directly influences the transfer of load between the matrix and reinforcement. By optimising the dispersion, researchers can ensure a more uniform distribution of reinforcement particles, leading to improved mechanical properties and enhanced resistance to deformation. Moreover, improving the interfacial bonding between the matrix and reinforcement can further enhance the load transfer and prevent the occurrence of delamination or debonding at the interface. This can be achieved through various techniques, such as surface modification of reinforcement particles. One potentially practical, efficient as well as economically feasible way to manufacture both simple and complicated parts, is powder metallurgy (P/M). It has been demonstrated in recent times that the P/M technique, when used in place of traditional casting procedures, yields MMCs with ceramic particles serving as reinforcement [1–3]. MMCs based on powder metallurgy processing are now being selected and utilized for the progress of components in a range of industries

✉ Mukandar Sekh
mukandar@gmail.com

[1] Department of Mechanical Engineering, Aliah University, Kolkata 700160, India

[2] Department of Metallurgical Engineering, Kazi Nazrul University, Asansol 713340, India

Published online: 29 February 2024

like aerospace, automotive, and electronics [4]. Recently, additive manufacturing utilized P/M techniques [5]. In comparison with stir casting-based composites, powder metallurgy (P/M)-based composites exhibit a noticeable decrease in density and an increase in hardness together with a greater reduction in porosity. In contrast to traditional stir casting procedures, the P/M approach ensures that the reinforcements are evenly dispersed throughout the metal matrix [6]. In other words, the traditional casting method does not regulate a nearly uniform distribution of the reinforcing particles in the metal matrix, which frequently leads to inhomogeneous physical and mechanical properties of the selected composite material.

Bulk materials can be processed from metal or composite powders, which are made of both and metallic and non-metallic constituents, by the process of powder metallurgy [7]. Currently, powder metallurgy finds extensive use in the domains of information, biology, new energy resources, electronics, aircraft, weapons, machinery, transportation, and the nuclear sector. The benefits of powder metallurgy include excellent stability, high precision, minimal energy and material consumption, and superior precision [8]. P/M is a type of near net forming technology that combines part forming with powder preparation to provide high-performance products with minimal or no cutting [9]. P/M has been extensively utilized in the domains of mechanical production, the car industry, etc., because of its benefits, which include small energy consumption, include little (or negligible) pollution, excellent product performance, great precision, and stability, as well as close net forming [10, 11]. The density of products is one of the key indicators used to assess P/M performance, so one of the primary areas of research in powder metallurgy is how to efficiently raise the density and produce high performing, reasonably priced parts. The following innovative powder metallurgy techniques and technologies are all available: high velocity compaction, spray deposition, injection moulding, warm compaction, dynamic magnetic compaction, mould wall lubrication technology, etc., that are available in recent years [12–18]. The issues with high performance, composite, and precision powder metallurgy materials have been partially resolved by the development of these technologies. It significantly broadens the application scope in the field. Using the powder metallurgy procedure, the matrix and reinforcement are combined to compact the material, which is then sintered to gain strength. The process of mechanical alloying forms reinforcement through component reactions. Stir casting is the most common and economical way to make MMC composites [19–27]. P/M technique is considered to be more economical with involvement of minimum temperature during fabrication. This P/M approach makes it simple to produce many common geometrical pieces, resulting in cheaper mass production [28–30]. The P/M technique enhances the mechanical characteristics of the manufactured material because the reinforcement particles are well-mixed inside the matrix. It has been determined that the qualities of the composites processed by P/M technique are correlated with the quantity, kind, size, and surface type of reinforcement in nanoparticle form. Although MMCs are generally difficult to fabricate at the nanoscale, their properties are good in when processed by P/M [31, 32]. One effective way to prevent issues such as the wetting of the reinforcements in the matrix and the improper dispersion of the reinforcement in the matrix alloy is to use the mechanical milling technique (MM) which produces very tiny particle sizes and a homogeneous distribution of reinforcing particles by preparing powder particles through ball impacts [33]. The P/M technique was used for producing the composite of pure aluminium (Al) reinforced with rice husk ash (RHA), and it was found that the effect of P/M process parameters (compaction pressure, sintering time, and also sintering time) had an significant impact on the developed composite's density, hardness, and volume loss [34]. In another investigation, cutting speed was used as a response parameter to study the cutting quality of Al-RHA Metal matrix Composite [35]. An efficient way to recycle materials based on aluminium is through powder metallurgy, which may also be used to make aluminium foam [36]. In P/M, as the material is subjected below the melting point there is limited loss due to oxidation and moreover the porosity level is easy to control. As product made through P/M route is of almost final form, there is minimal requirement for further secondary processing viz., machining [37, 38].

Considering all of this, the present report addresses the overview of MMCs fabrications using powder metallurgy processes, which is groundbreaking in both industrial and research fields.

Application of MMCs Made Through Powder Metallurgy

Benefits of P/M may be found in manufacturing of structural parts, tribological parts viz., heat and wear resistance parts, high contact pressure bearings, magnetic components. MMCs especially aluminium-based MMCs have lots of applications in automotive industry as well as variety of other industries [39]. MMCs based on magnesium are better suited for use in biomedical [40] industry. Through the process of powder metallurgy, composites based on metals, non-metals, and refractory metals can be processed. As products made from porous materials, such oil-impregnated bearing P/M may be manufactured by pressing powders into moulds, and these materials have good economic efficiency.

Structural Parts: P/M products help advance green technology, facilitate the switch to hybrid electric vehicles, and reduce production costs by enabling parts to be made lighter whilst retaining strength and accuracy. Vehicle components like pulleys, valves, drivetrains, valve control systems designed with such materials enable to improve fuel efficiency.

Tribological Parts: The parts that are strongly subjected to abrasion and lubrication may be processed by P/M technique which are resistant to wear and tear and can withstand oil and high temperatures with ease. Utilising these goods lowers the expense of car maintenance. Innovations in recent times have made it possible for turbo-chargers to handle high temperatures and pressures whilst also being smaller and lighter.

Vehicle-related parts: A tried-and-tested method for producing high-strength gears is powder metallurgy. These gears are less expensive, there is too little waste material, and less energy is used in their production. Not much machine finishing is needed for them. These are lighter and produce less noise when operating. These gears may self-lubricate by being impregnated with oil. But these parts have a negative effect too. The metal powder wears down quickly and is not as robust as steel. To be economical, these should be produced in big quantities.

Biomedical industries: MMCs made through powder metallurgy can be used to create bioimplants and other beneficial medical components. Through the right blending of reinforcing components, the various MMC manufacturing techniques also significantly improve its characteristics and made it ideal for a variety of applications.

Manufacturing or Fabrication Technique for MMCs Productions

Production of MMC can be done using a variety of fabrication processes. Fabrication methods for MMCs are liquid-state fabrication, solid-state and in-situ fabrication approaches. A number of fabrication techniques, such as spray co-deposition, infiltration, squeeze casting, and stir casting are available. During the solid-state processing, the reinforcement material is injected and fully mixed into the matrix. Solid-state powder metallurgy, spark plasma sintering, and friction stir processing (FSP) are some related fabrication techniques. Conventional casting and powder metallurgy approaches were widely adopted by most of the industries as well as for various research outcomes. Table 1 lists the various MMC production processes along with their benefits and drawbacks.

Factors Influencing Composite Fabrication Through Casting Process

Casting is considered as the fundamental and popular technique for processing of composites. It entails pouring a liquid substance typically molten plastic or metal into a mould, letting it solidify and take on the shape of the Mould. This method is renowned for its adaptability and capacity to produce intricate structures and forms. It is frequently utilized to manufacture different products and components in industries like construction, automotive, and aerospace. To obtain the desired casting, the reinforcement and molten metal are combined, then poured into a mould cavity and allowed to solidify. Numerous vehicle parts, including the engine block, brake rotors, piston, connecting rods, etc., are subject to this procedure. It was observed that several parameters, including temperature, stirring and holding times, along with the types, sizes and shapes of the reinforcements were vital to the creation and characteristics of MMCs [58]. Figure 1 displays the factors that impact casting quality.

Since the liquid-state method is simpler and less expensive, several businesses use it to manufacture MMCs. Typically, the casting procedure involves mixing molten metal directly with reinforced particles. However, casting techniques for composite fabrications have some drawbacks. These restrictions may have an impact on the viability and quality of composite parts manufactured by casting technique. Some drawbacks of casting process for MMCs fabrications are stated in Fig. 2.

Merits of Powder Metallurgy Route Over Casting for Fabrications of MMCs

Fabricating parts and components, including composites, can be done using two distinct manufacturing processes: casting and powder metallurgy. Every process has pros and cons, and the decision between them is based on the particular needs of the application. For composite fabrications, powder metallurgy has the following benefits over casting:

1. Accurate composition control: By combining powders with various compositions in the right ratios, powder metallurgy enables accurate composition control over the material. This is especially helpful when creating composite materials using specialised material combinations to get the desired results.
2. Homogeneous reinforcement distribution: In powder metallurgy, it is simpler to accomplish a homogeneous reinforcement material distribution in the matrix, such as fibres or particles. More consistent and predictable material qualities are the outcome of this.

Table 1 Various MMC production processes along with their merits and demerits

Fabrication process	Benefits	Adverse benefits	Uses	References
Stirs casting	Easy to use and appropriate for large quantities	Better properties must be induced by a secondary process and appropriate stir parameter control	Pump housing and cylinder heads	[41, 42]
Compo casting	enhanced wettability and even dispersion	Porosity and parameter management are essential	Production of gears	[43]
Rheo casting	Porosity-free, complex part casting, well-finished surface, and strong wear resistance	Pricier	Use of tribology in practise	[44]
Squeeze casting	Homogeneity is improved by less porosity and casting imperfections	Higher production costs as a result of more setup, restrictions on complicated shapes,	Fuel pipe, pump casing, engine block, connecting rod, and piston	[45]
Centrifugal casting	Better mechanical strength, less porosity, as well as a denser grain structure over stir casting	Internal components could have certain flaws	Nozzles, braking rotors, and piston	[46]
Processing by friction stir	outstanding strength, super plasticity, reduced porosity, and superior wear resistance in a fine-grain microstructure	The mechanics of the procedure are still unknown	transportation systems and aerospace	[47, 48]
Spark plasma sintering	Compaction stage is also paired with uniform sintering Suitable for basic symmetrical shapes	Costly procedure	Transmission, arsenal and nozzle	[49, 50]
Vacuum sintering	High productivity and uniform microstructure	Costly procedure since it requires suction chamber	Tiny drills and cutter tools	[51]
Microwave sintering	Low sintering temperature, quick heating rate, and low energy consumption	Only advantageous for materials possessing dielectric qualities	Biomedical	[52–54]
Ultrasonic-assisted casting (UAC)	Due to its low wettability and strong propensity for nanoparticle clustering, the UAC method is effective at breaking up agglomeration formation	Flexible and economical for mass production	Nano composite	[55–57]

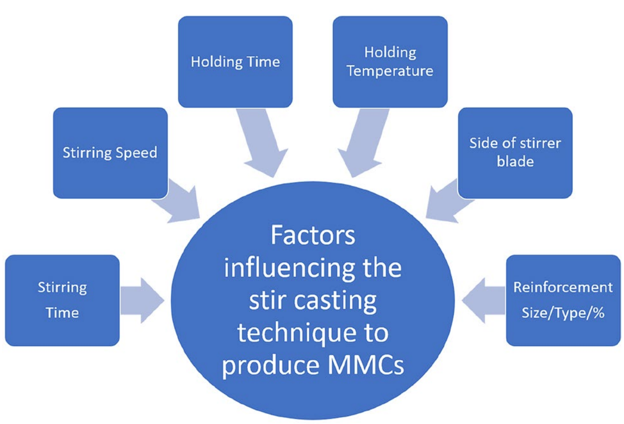

Fig. 1 Factors influencing the stir casting method's ability to create MMCs [59]

3. Better mechanical properties: Hot isostatic pressing (HIP) and sintering are two powder metallurgy techniques that can give rise to better mechanical properties of composite materials, providing them with more strength, hardness, and resistance to wear.
4. Near-net shape manufacturing: Powder metallurgy makes it possible to produce complicated composite products with tight tolerances at a lower cost by reducing the amount of machining and material waste.
5. Customization and design flexibility: Powder metallurgy is a viable option for specialised composite components that are suitable for certain applications since it allows for the design and manufacturing of intricate shapes and structures.
6. Increased corrosion resistance: Powder metallurgy-produced composite materials can be designed to have

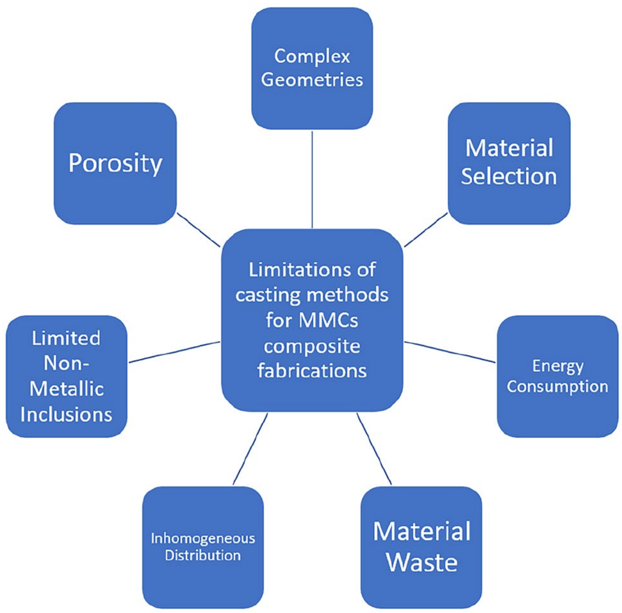

Fig. 2 Restrictions of casting process for fabrication of MMCs [60]

increased corrosion resistance, which qualifies them for use in severe environments.

7. Decreased porosity: When compared to some casting techniques, powder metallurgy processes can produce composites with reduced porosity, which improves their mechanical and physical qualities.
8. Improved thermal and electrical properties Powder metallurgy is appropriate for applications where these features are crucial because it enables the introduction of materials with improved thermal or electrical conductivity into the composites.
9. Production of small batches and prototypes: Powder metallurgy is a great method for producing small batches and prototypes, which makes it perfect for applications requiring a small number of composite components or for research and development.
10. Environmental benefits: Because powder metallurgy uses recycled or scrap materials and generally produces less waste than some casting procedures, it can be more environmentally friendly. Usually, the temperature used is also not very high with limited emission of harmful gases.

Although powder metallurgy presents a number of benefits for composite fabrications, it is imperative to take into account the particular demands of the application as well as the trade-offs inherent in each process. For some composite fabrications, casting might still be the better option depending on the part geometry, cost, and availability of materials.

Demerits of Powder Metallurgy Route Over Casting for Fabrications MMCs

Every approach has benefits and drawbacks. Powder metallurgy has the following drawbacks over casting in composite fabrications:

1. Processing of bulk components: When it comes to crafting elaborate and complex designs, casting is more adaptable. Sintering and pressing are the usual processes used in powder metallurgy, which may limit the ability to process and manufacture bulk components.
2. Selection of materials: A greater variety of materials such as metals and alloys can be cast. There are fewer material possibilities available because powder metallurgy is mostly employed for metal and ceramic composites.
3. Size restrictions: Large or oversized components are typically less well suited for powder metallurgy since the pressing and sintering process can be difficult and can result in problems like uneven density or cracking.
4. Porousness: Because there are spaces between the powder particles, porosity is a common problem in powder metallurgy. This may have a detrimental effect on the composite's mechanical qualities.
5. Price: Compared to casting, powder metallurgy is less economical for small production runs or simple items because of the high cost of the equipment and tools needed.
6. High gloss finish: Compared to powder metallurgy components, which could need extra finishing procedures like machining or grinding, cast parts frequently have a better surface finish.
7. Variability in density: It can be difficult to achieve equal density across a powder metallurgy composite, which can lead to differences in its mechanical properties.
8. Accuracy in dimensions and tolerance: In some applications, precise tolerances and dimensional accuracy can be crucial, but powder metallurgy might not be able to maintain them.
9. Restricted non-metallic additions: Powder metallurgy usually concentrates on metal and ceramic composites, which restricts the incorporation of non-metallic reinforcements. In contrast, casting permits the inclusion of non-metallic elements such as reinforcing fibres.

To sum up, casting is not as limited as powder metallurgy when it comes to composite fabrications. When deciding between these two approaches, one must take into account the project's particular requirements, the materials needed, the part's complexity, and the intended properties of the end products.

Opportunities for Further Research

Nowadays, material scientists are focussed on creating inexpensive, high-performing engineering components. Powder metallurgy can be used to minimise all the shortcomings of MMC fabrications that result from the casting process. Powder metallurgy reduces pores, improper wetting in composites which ultimately lead to better mechanical properties of the components. Compared to composites made using traditional methods, it is readily available and reasonably priced. Composites with enhanced and much improved mechanical properties were fabricated using powder metallurgical route. By adoption of powder metallurgical route, the fabrication of so-called MMCs can yield more uniform distribution of reinforcements with much improved quality of the same as compared to the traditional methods. Therefore, the creation of metal matrix composites using powder metallurgy processes is groundbreaking for both industry and research fields.

Summary

In the present detailed review study, casting and powder metallurgy as effective manufacturing processes are compared, each with advantages and disadvantages. Various considerations such as material selection, part complexity, size, precision requirements, manufacturing volume, and budget limits influence the distinction between them. Choosing the best manufacturing technique for a given project generally requires careful consideration of these variables and a comprehensive cost–benefit analysis. To get the best outcomes, it is frequently possible to combine the two methods. Since each has pros and cons of its own, it is impossible to say which is clearly superior when comparing casting and powder metallurgy. The particular needs of a project and the desired qualities of the finished product determine which of these two production processes better suited for MMCs fabrications. In comparison with composites made using traditional methods, better strength and hardness can be achieved using powder metallurgy due to improved distribution of reinforcements in the matrix and easy control over process parameters. Thus, powder metallurgy techniques for the manufacture of metal matrix composites are innovative in both industrial and research domains.

Funding There is no funding associated with this present study.

Declarations

Conflict of interest There is no conflict of interest.

References

1. M. Kok, Production and mechanical properties of Al_2O_3 particle-reinforced 2024 aluminium alloy composites. J. Mater. Process. Technol. **161**, 381–387 (2005)
2. U.A. Usca, M. Uzun, M. Kunto glu, S. Sap, K. Giasin, D.Y. Pimenov, Tribological aspects, optimization and analysis of Cu–B–CrC composites fabricated by powder metallurgy. Materials **14**, 4217 (2021)
3. S. Chintada, S.P. Dora, D. Kare, S.R. Pujari, Powder metallurgy versus casting: damping behavior of pure aluminum. J. Mater. Eng. Perform. **31**(11), 9122–9128 (2022). https://doi.org/10.1007/s11665-022-06886-2
4. D.R. Kumar, C. Loganathan, R. Narayanasamy, Effect of glass in aluminium matrix on workability and strain hardening behavior of powder metallurgy composite. Mater. Des. **32**, 2413–2422 (2011)
5. M. Gräbner, H. Wiche, K. Treutler, V. Wesling, Micromagnetic properties of powder metallurgically produced Al composites as a fundamental study for additive manufacturing. Appl. Sci. **12**, 6695 (2022)
6. H. Abdizadeh, R. Ebrahimifard, M.A. Baghchesara, Investigation of microstructure and mechanical properties of nano MgO reinforced Al composites manufactured by stir casting and powder metallurgy methods: a comparative study. Compos. Part B **56**, 217–221 (2014)
7. R.M. German, *Powder Metallurgy Science*, 2nd edn. (Metal Powder Industries Federation, New Jersey, Princeton, 1994)
8. H.H. Hausner, *Modern Developments in Powder Metallurgy* (Springer, Boston, 1966)
9. B. Ma, J. Liu, X. Hu, Study on the influencing factors of temperature rise in high velocity compaction of metal powder based on Johnson–Cook model. Therm. Process. Technol. **1**, 91–95 (2016)
10. P. Huang, *Principles of Powder Metallurgy* (Metallurgical Industry Press, Beijing, 1982), pp. 182–184
11. G.W. Donald, P/M in North America. Int. J. Powder Metall. **32**(3), 221–228 (1996)
12. E. Caroline, Hoganaos promotes potential of high velocity compaction. Met. Powder Rep. **56**(9), 6–8 (2001)
13. P.S. Grnat, Spray forming. Prog. Mater. Sci. **39**(4), 497–503 (1995)
14. G. Hu, L. Zhang, Y. Fan, Y. Li, Fabrication of high porous NiTi shape memory alloy by metal injection molding. J. Mater. Process. Technol. **206**(1), 395–399 (2008)
15. G.F. Bocchini, Warm compaction of metal powders: why it works, why it requires a sophisticated engineering approach. Powder. Metall. **42**(2), 171–180 (1999)
16. J. Barber, B. Chelluri, Magnetic compaction process nears market. Met. Powder Rep. **55**(2), 22–25 (2000)
17. W.G. Ball, A New die wall lubrication system. Met. Powder Rep. **52**(7–8), 38 (1997). https://doi.org/10.1016/s0026-0657(97)80175-0
18. B.A. James, Die wall lubrication for powder compaction: a feasible solution. Powder Metall. **30**(4), 273–280 (1987)
19. M.A. Taha, Industrialization of cast aluminum matrix composites (AMCCs). Mater. Manuf. Process. **16**(5), 619–641 (2001). https://doi.org/10.1081/AMP-100108625
20. C.S. Kim, K. Cho, M.H. Manjili, M. Nezafati, Mechanical performance of particulatereinforced Al metal-matrix composites (MMCs) and Al metal-matrix nanocomposites (MMNCs). J. Mater. Sci. **52**, 13319–13349 (2017). https://doi.org/10.1007/s10853-017-1378-x
21. M. Anthony, B.F. Schultz, P.K. Rohatgi, N. Gupta, in *Metal Matrix Composites for Automotive Applications*, ed. by A. Elmarakbi (Wiley, 2014). https://doi.org/10.1002/9781118535288

22. N.K. Bhoi, H. Singh, S. Pratap, Developments in the aluminum metal matrix composites reinforced by micro/nano particles: a review. J. Compos. Mater. **54**(6), 813–833 (2020). https://doi.org/10.1177/0021998319865307
23. A. Macke, B.F. Schultz, Metal matrix composites offer the automotive industry and opportunity to reduce vehicle weight, improve performance. Adv. Mater. Process. **170**, 19–23 (2012)
24. T. Dursun, C. Soutis, Recent developments in advanced aircraft aluminium alloys. Mater. Des. **56**, 862–871 (2014). https://doi.org/10.1016/j.matdes.2013.12.002
25. P. Rohatgi, Cast aluminum-matrix composites for automotive applications. JOM **43**(4), 10–15 (1991). https://doi.org/10.1007/BF03220538
26. P. Rambabu, N.E. Prasad, V.V. Kutumbarao, R.J.H. Wanhill, Aluminium alloys for aerospace applications. Adv. Mater. Technol. (2017). https://doi.org/10.1007/978-981-10-2143-5
27. J. Hashim, L. Looney, M.S.J. Hashmi, Metal matrix composites: production by the stir casting method. J. Mater. Process. Technol. **92–93**, 1–7 (2019). https://doi.org/10.1016/S0924-0136(99)00118-1
28. L. Singh, B. Singh, K.K. Saxena, Manufacturing techniques for metal matrix composites (MMC): an overview. Adv. Mater. Process. Technol. (2020). https://doi.org/10.1080/2374068X.2020.1729603
29. S.K. Sharma, K.K. Saxena, K.H. Salem, K.A. Mohammed, R. Singh, C. Prakash, Effects of various fabrication techniques on the mechanical characteristics of metal matrix composites: a review. Adv. Mater. Process. Technol. (2022). https://doi.org/10.1080/2374068x.2022.2144276
30. B.C. Kandpal, J. Kumar, H. Singh, Manufacturing and technological challenges in stir casting of metal matrix composites: a review. Mater. Today Proc. **5**(1), 5–10 (2018). https://doi.org/10.1016/j.matpr.2017.11.046
31. H.K. Issa, A. Taherizadeh, A. Maleki et al., Development of an aluminum/amorphous nano SiO_2 composite using powder metallurgy and hot extrusion processes. Ceram. Int. **43**, 14582–14592 (2017)
32. E. Savary, F. Gascoin, S. Marinel et al., Spark plasma sintering of fine Mg_2Si particles. Powder Technol. **228**, 295–300 (2012)
33. S. Ozkaya, A. Canakci, Effect of the B4C content and the milling time on the synthesis, consolidation and mechanical properties of AlCuMg–B4C nano composites synthesized by mechanical milling. Powder Technol. **297**, 8–16 (2016)
34. Z. Seikh, M. Sekh, G. Kibria, R. Haque, S. Haidar, Density, hardness, and wear responses of rice husk ash reinforced aluminium composites. MSF **1074**, 67–78 (2022). https://doi.org/10.4028/p-78710r
35. Z. Seikh, S. Kunar, R. Haque, S. Haidar, M. Sekh, WEDM machining performance of Al based metal matrix composites reinforced with rice husk ash. MSF **1048**, 261–269 (2022). https://doi.org/10.4028/www.scientific.net/msf.1048.261
36. N. Kumar, A. Bharti, Review on powder metallurgy: a novel technique for recycling and foaming of aluminium-based materials. Powder Metall. Met. Ceram. **60**, 52–59 (2021). https://doi.org/10.1007/s11106-021-00214-4
37. M. Dixit, R.K. Srivastava, Effect of compaction pressure on microstructure, density and hardness of copper prepared by powder metallurgy route. IOP Conf. Ser. Mater. Sci. Eng. **377**, 012209 (2018)
38. N. Kumar, A. Bharti, K.K. Saxena, A re-analysis of effect of various process parameters on the mechanical properties of Mg based MMCs fabricated by powder metallurgy technique. Mater. Today Proc. **26**(2), 1953–1959 (2020)
39. Z. Seikh, M. Sekh, S. Kunar, G. Kibria, R. Haque, S. Haidar, A study on various applications of aluminium metal matrix composites. AIP Conf. Proc. (2023). https://doi.org/10.1063/5.0144283
40. A. Abbas, V. Rajagopal, S.J. Huang, *Magnesium Metal Matrix Composites and Their Applications, Magnesium Alloys Structure and Properties* (Intech Open, 2022). https://doi.org/10.5772/intechopen.96241
41. S. Soltani, R.A. Khosroshahi, R.T. Mousavian, Z. Jiang, A. Boostani, D. Brabazon, Stir casting process for manufacture of Al–SiC composites. Rare Met. Mater. Eng. **36**(7), 581–590 (2017). https://doi.org/10.1007/s12598-015-0565-7
42. M. Raei, M. Panjepour, M. Meratian, Effect of stirring speed and time on microstructure and mechanical properties of cast Al–Ti–Zr–B4C composite produced by stir casting. Russ. J. Non-Ferrous Met. **57**(4), 347–60 (2016). https://doi.org/10.3103/S1067821216040088
43. A. Mazahery, M.O. Shabani, The effect of primary and secondary processing on the abrasive wear properties of compocast aluminum 6061 alloy matrix composites. Prot. Met. Phys. Chem. Surf. **50**(6), 817–24 (2014). https://doi.org/10.1134/S2070205114060021
44. F.A. Girot, L. Albingre, J.M. Quenisset, R. Naslain, Rheocasting AI matrix composites. J. Met. **7**, 18–21 (1987)
45. E. Hajjari, M. Divandari, H. Arabi, Effect of applied pressure and nickel coating on microstructural development in continuous carbon fiber-reinforced aluminum composites fabricated by squeeze casting. Mater. Manuf. Process. **26**(4), 599–603 (2011). https://doi.org/10.1080/10426910903447311
46. T.K. Adelakin, O.M. Suarez, Study of boride-reinforced aluminum matrix composites produced via centrifugal casting. Mater. Manuf. Process. **26**(2), 338–45 (2011). https://doi.org/10.1080/10426910903124829
47. P.A. Bajakke, V.R. Malik, A.S. Deshpande, Particulate metal matrix composites and their fabrication via friction stir processing: a review. Mater. Manuf. Process. **34**(8), 833–81 (2019). https://doi.org/10.1080/10426914.2019.1605181
48. N. Gangil, A.N. Siddiquee, S. Maheshwari, Aluminium based in-situ composite fabrication through friction stir processing: a review. J. Alloys Compd. **715**, 91–104 (2017). https://doi.org/10.1016/j.jallcom.2017.04.309
49. M.O. Durowoju, E.R. Sadiku, S. Diouf, M.B. Shongwe, I.M. Makena, M.M. Ramakokovhu, Wear and corrosion studies of graphite-aluminum composite reinforced with micro/nano-TiB2 via spark plasma sintering. Mater. Sci. Eng. Technol. **50**(2), 126–139 (2019). https://doi.org/10.1002/mawe.201700062
50. C.O. Ujah, A.P.I. Popoola, O.M. Popoola, V.S. Aigbodion, Enhanced tribology, thermal and electrical properties of Al-CNT composite processed via spark plasma sintering for transmission conductor. J. Mater. Sci. **54**, 14064–14073 (2019). https://doi.org/10.1007/s10853-019-03894-x
51. Y. Gao, B. Luo, K. He, H. Jing, Z. Bai, W. Chen et al., Mechanical properties and microstructure of WC–Fe–Ni–Co cemented carbides prepared by vacuum sintering. Vaccum **143**, 271–282 (2017). https://doi.org/10.1016/j.vacuum.2017.06.028
52. M.P. Reddy, A. Shakoor, A. Mohamed, M. Gupta, Microwave rapid sintering of Al-metal matrix composites: a review on the effect of reinforcements, microstructure and mechanical properties. Metals (2016). https://doi.org/10.3390/met6070143
53. Z. Asadipanah, M. Rajabi, Production of Al–ZrB_2 nano-composites by microwave sintering process. J. Mater. Sci. Mater. Electron. **26**(8), 6148–6156 (2015). https://doi.org/10.1007/s10854-015-3195-9
54. N. Kumar Bhoi, H. Singh, S. Pratap, Synthesis and characterization of zinc oxide reinforced aluminum metal matrix composite produced by microwave sintering. J. Compos. Mater. **54**(24), 3625–3636 (2020). https://doi.org/10.1177/0021998320918646

55. N.V. Murthy, A.P. Reddy, N. Selvaraj, C.S.P. Rao, Preparation of SiC based aluminium metal matrix nano composites by high intensity ultrasonic cavitation process and evaluation of mechanical and tribological properties. IOP Conf. Ser. Mater. Sci. Eng. **149**, 012106 (2016). https://doi.org/10.1088/1757-899x/149/1/012106
56. R. Harichandran, N. Selvakumar, G. Venkatachalam, High temperature wear behaviour of nano/micro B4C reinforced aluminium matrix composites fabricated by an ultrasonic cavitation-assisted solidification process. Trans. Indian Inst. Met. **70**(1), 17–29 (2016). https://doi.org/10.1007/s12666-016-0856-1
57. D. Zhou, F. Qiu, H. Wang, Q. Jiang, Manufacture of nano-sized particle-reinforced metal matrix composites: a review. Acta Metall. Sin. (Engl. Lett.) **27**(5), 798–805 (2014). https://doi.org/10.1007/s40195-014-0154-z
58. P. Samal, P.R. Vundavilli, A. Meher, M.M. Mahapatra, Recent progress in aluminum metal matrix composites: a review on processing, mechanical and wear properties. J. Manuf. Process. **59**, 131–152 (2020). https://doi.org/10.1016/j.jmapro.2020.09.010
59. R. Ramamoorthi, J.J.M. Hillary, R. Sundaramoorthy, J.D.J. Joseph, K. Kalida, K. Manickaraj, Influence of stir casting route process parameters in fabrication of aluminium matrix composites: a review. Mater. Today Proc. **47**(7), 6660–6664 (2021). https://doi.org/10.1016/j.matpr.2020.12.068
60. Z. Seikh, M. Sekh, S. Kunar, G. Kibria, R. Haque, S. Haidar, Rice husk ash reinforced aluminium metal matrix composites: a review. Mater. Sci. Forum **1070**, 55–70 (2022). https://doi.org/10.4028/p-u8s016

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