SVU-International Journal of Engineering Sciences and Applications (2024) 5(1): 13-18
Print ISSN 2785-9967| Online ISSN 2735-4571
DOI 10.21608/SVUSRC.2023.228672.1144

Overcoming Challenges in the Powder Metallurgy Process of Metal Matrix Composites

Amr Ali[1, □], and Wessam Arafa Hafez[2]

Abstract Metal matrix composites (MMCs) offer enhanced mechanical, thermal, and electrical properties compared to traditional materials, making them highly desirable for various applications. The powder metallurgy process is a widely used technique for manufacturing MMCs, but it is accompanied by several challenges that need to be overcome to achieve optimal composite properties. This review focuses on discussing the key challenges encountered in the powder metallurgy process of MMCs and the strategies employed to overcome them. The challenges include achieving uniform powder distribution, overcoming poor interfacial bonding, addressing particle agglomeration, controlling porosity, and ensuring proper reinforcement dispersion. Various techniques such as powder blending, surface modification, optimized sintering parameters, and advanced consolidation methods are explored as potential solutions to these challenges. Additionally, the influence of powder characteristics, reinforcement types, and processing parameters on the final composite properties are discussed. By understanding and effectively addressing these challenges, researchers and manufacturers can optimize the powder metallurgy process of MMCs, leading to the production of high-quality composites with tailored properties for specific applications.

Keywords:. **Metal Matrix Composites, Ball Milling, Magnetic Stirrer, powder metallurgy.**

1- Introduction

Metal matrix composites (MMCs) produced through powder metallurgy have gained significant attention in various industries due to their enhanced mechanical and physical properties compared to traditional monolithic metals. Powder metallurgy offers unique opportunities for the production of MMCs with tailored compositions and microstructures. However, this manufacturing process presents several challenges that need to be addressed to achieve optimal composite quality and performance [1-2].

Metal matrix composites (MMCs) have gained significant attention in recent years due to their exceptional mechanical, thermal, and electrical properties [3]. These composites consist of a metallic matrix reinforced with ceramic or metallic particles, fibers, or whiskers [4]. The powder metallurgy process is a commonly used technique for manufacturing MMCs, offering advantages such as high material utilization, near-net shaping capabilities, and the ability to tailor the composition and microstructure of the composites [5].

However, the powder metallurgy process of MMCs is not without its challenges. Several factors can hinder the successful production of high-quality composites, including poor powder distribution, inadequate interfacial bonding between the matrix and reinforcement, particle agglomeration, porosity formation, and inadequate dispersion of the reinforcement phase. These challenges can significantly impact the mechanical properties, thermal conductivity, and overall performance of the MMCs [6].

In this review, we will delve into the various challenges faced during the powder metallurgy process of MMCs and highlight the innovative techniques and approaches that have been developed to overcome these challenges. Additionally, the influence of powder characteristics, reinforcement types, and processing parameters on the final composite properties will be discussed. By gaining a comprehensive understanding of these challenges and their solutions, researchers and practitioners can enhance the efficiency and effectiveness of the powder metallurgy process for MMCs, paving the way for the widespread adoption of these advanced materials. Moreover, the

---

Received: 11 August 2023/ Accepted: 24 September 2023

□Corresponding Author Amr Ali, Email: Amr_Ali123@Techedu.Sohag.edu.eg.
[1]Department of Production, Faculty of Technology and Education, Sohag University, Sohag 82515, Egypt
[2]Department of Electrical, Faculty of Technology and Education, Sohag University, Sohag 82515, Egypt

challenges in post-processing techniques for powder metallurgy MMCs, such as heat treatment, machining, and surface finishing, will be discussed. The effects of these processes on the microstructure and mechanical properties of the composites will be examined.

2- Classification of composites:

These three main categories of composites provide a basis for classifying and understanding the different types of composite materials based on their reinforcement mechanisms and structural configurations. Each category has its unique advantages and applications, allowing for a wide range of possibilities in engineering materials with tailored properties [7].

A. Particle-reinforced composites: In this category, the composite material consists of a matrix material that is reinforced with particles. The particles can be of various shapes, such as spheres, flakes, or fibers, and they are typically embedded within the matrix material [8]. The particle reinforcement enhances the mechanical properties of the composite, such as strength, stiffness, and wear resistance. Examples of particle-reinforced composites include metal matrix composites (MMCs) and polymer matrix composites (PMCs) with particle reinforcements [9-10].

B. Fiber-reinforced composites: Fiber-reinforced composites are composed of a matrix material that is reinforced with fibers. The fibers are typically long and continuous, providing high strength and stiffness to the composite. The fibers can be made of various materials, such as glass, carbon, aramid, or natural fibers like bamboo or hemp [11]. The fiber reinforcement imparts excellent mechanical properties, such as high tensile strength, flexural strength, and impact resistance, to the composite. Fiber-reinforced composites find applications in industries like aerospace, automotive, and construction [12].

C. Laminate composites: Laminate composites are composed of multiple layers or plies of different materials that are bonded together. Each layer may have different properties, such as fiber orientation, thickness, or composition, to provide specific characteristics to the composite [13]. The layers are stacked and bonded together through processes like lamination or resin infusion. Laminate composites offer a combination of different properties, such as strength, stiffness, and durability, making them suitable for applications where a specific balance of properties is required. An example of a laminate composite is a carbon fiber-reinforced polymer (CFRP) composite used in high-performance sports equipment and aerospace applications [14].

3- Processing of metal matrix composites (MMCs)

In the powder metallurgy processing of metal matrix composites (MMCs), several steps are involved to achieve the desired composite structure and properties. These steps include powder preparation, powder blending, compaction, and sintering [15] as shown in Fig 2. The processing steps for MMCs in powder metallurgy are as follows:

A. Powder Preparation: The first step in the powder metallurgy process is the preparation of the matrix and reinforcement powders. The matrix material, usually a metal or alloy, is comminuted into fine particles through processes such as atomization or mechanical milling. Similarly, the reinforcement material, such as ceramic particles or fibers, is prepared in powder form using techniques like milling or grinding. The powders should have a suitable particle size distribution for effective mixing and compaction [16].

B. Powder Blending: In this step, the matrix and reinforcement powders are mixed together to achieve a uniform distribution of the reinforcement phase within the matrix material. The blending can be performed using techniques like dry mixing, wet mixing, or mechanical alloying. The goal is to ensure that the reinforcement particles are evenly dispersed throughout the matrix powder to enhance the mechanical properties of the resulting composite [17].

C. Compaction: After the powder blending step, the mixed powders are compacted into a desired shape using a suitable method, such as cold compaction or hot pressing. The compaction process involves applying pressure to the powder mixture in a die or mold to form a green compact. The pressure applied during compaction helps to consolidate the powders and create interparticle bonding. The compaction pressure and temperature are carefully controlled to achieve the desired density and porosity in the green compact [18].

D. Sintering: Sintering is a crucial step in the powder metallurgy process, where the green compact is heated to a temperature below the melting point of the matrix material. During sintering, the powders undergo a process of solid-state diffusion, where the particles bond together, resulting in densification and the formation of a solid composite. The sintering temperature, time, and atmosphere are carefully controlled to promote particle bonding and eliminate porosity as shown in Fig. 1. The sintered composite is then cooled and further processed as required [19].

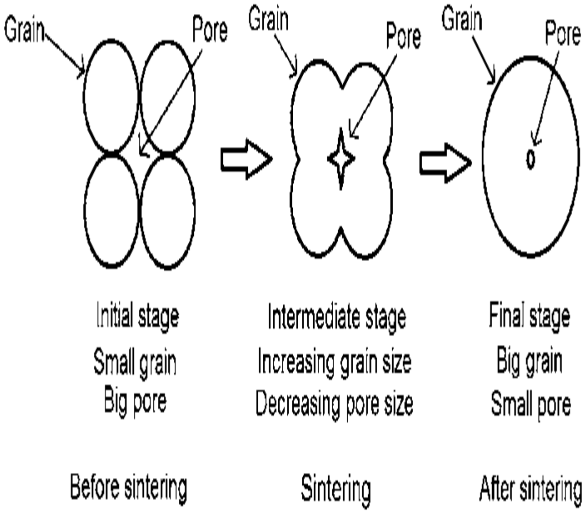

Fig 1: The sintering temperature, time.

E. Post-Processing: After sintering, additional post-processing steps may be performed to further enhance the properties of the MMC. These steps can include heat treatment, machining, surface finishing, or coating. Heat treatment processes like aging or solution treatment can be used to optimize the microstructure and mechanical properties of the composite. Machining and surface finishing processes are employed to achieve the desired shape, dimensions, and surface quality of the final component.

By following these processing steps, powder metallurgy can be effectively utilized for the production of metal matrix composites with tailored compositions, microstructures, and properties. The powder metallurgy approach offers advantages such as good control over the distribution of reinforcement, high material utilization, and the ability to produce complex-shaped components [20].

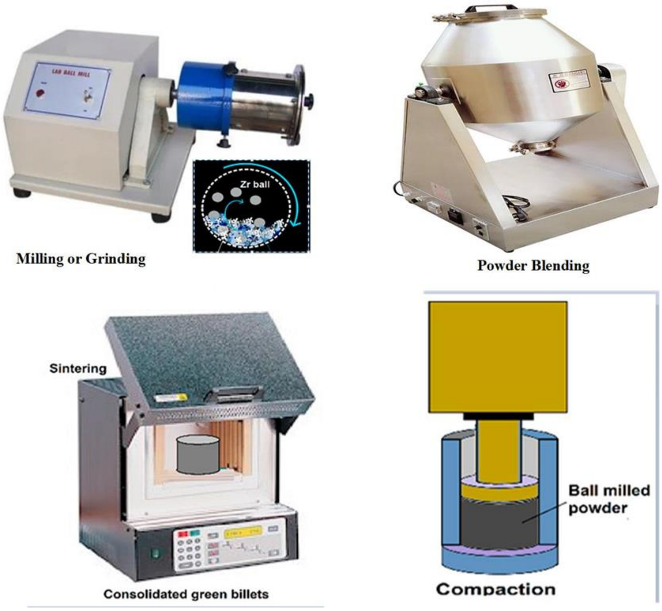

Fig.2: Steps of preparation powder metallurgy.

4- Challenges which faces of the powder metallurgy process

The powder metallurgy process of metal matrix composites (MMCs) faces several challenges that need to be addressed to achieve high-quality composites with desired properties. Some of the key challenges include:

A. Powder Mixing and Dispersion: Achieving a uniform distribution of the reinforcement particles within the matrix material is crucial for the performance of MMCs as shown in **Fig 3.** However, achieving proper mixing and dispersion of the powders can be challenging, especially when using different particle sizes or materials. Inadequate mixing can result in uneven distribution of the reinforcement, leading to variations in mechanical properties and potential defects in the final composite. **Tao Peng et al.** [21] studied the wet shake-mixing technique utilized in this study offers several advantages over traditional methods of composite powder fabrication. Firstly, it provides a homogeneous distribution of multi-walled carbon nanotube (MWNTs) within the Al matrix, ensuring uniform reinforcement throughout the composite material. This is crucial for achieving enhanced mechanical and electrical properties in the final product.

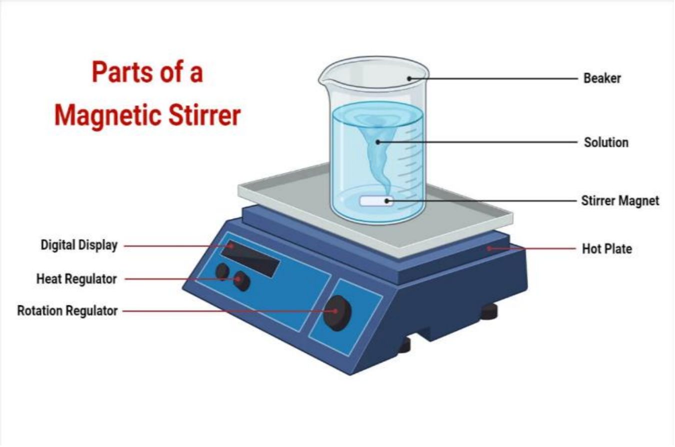

Fig.3: Magnetic Stirrer.

B. Particle Reinforcement-Matrix Interface: The interface between the reinforcement particles and the matrix material plays a significant role in determining the mechanical properties of the composite. Achieving a strong and durable interface bonding is crucial for efficient load transfer between the reinforcement and matrix. However, achieving a good interface can be challenging due to issues such as poor wetting, chemical reactions between the reinforcement and matrix, or the formation of undesirable intermetallic phases **Lakshmi Yadav et al** studied impact add Calcium on Mg-Sn alloy improve in Thermal diffusivity, electrical conductivity, hardness and wear resistance [22].

Anna J. Dolataet et al. [23] mentioned that The research findings highlight the critical importance of selecting the appropriate chemical composition for the aluminum matrix alloy in metal matrix composites (MMCs). The chemical composition of the matrix alloy plays a significant role in determining the structure and stability of the interface between the ceramic reinforcement and the aluminum matrix. This is particularly crucial when using the casting method for composite fabrication

C. Densification and Porosity Control: During the sintering process, achieving high densification and controlling porosity are critical for the mechanical properties of the MMCs. However, achieving full densification while minimizing porosity can be challenging, especially in complex-shaped components or when using a high-volume fraction of reinforcement. Inadequate densification and excessive porosity can lead to reduced mechanical strength, increased brittleness, and compromised fatigue properties [24].

D. Thermal Mismatch: MMCs often exhibit a significant difference in the coefficient of thermal expansion (CTE) between the reinforcement and matrix materials. This can result in thermal stresses and residual stresses during cooling and subsequent thermal cycling, leading to microcracks, delamination, and reduced mechanical properties. Managing the thermal mismatch between the reinforcement and matrix is crucial to minimize these issues and ensure the long-term reliability of MMCs.

E. Particle Degradation [25]: During the powder processing steps, such as blending, compaction, and sintering, the reinforcement particles can undergo degradation or damage. This can result in changes in particle size, morphology, or chemical composition, leading to variations in the microstructure and mechanical properties of the composite. Controlling particle degradation and preserving the integrity of the reinforcement is essential for achieving consistent and reliable MMCs.

F. Cost and Scalability: Powder metallurgy processes, including the production of MMCs, can be cost-intensive, especially when using high-performance reinforcement materials or complex shaping techniques. Achieving cost-effective manufacturing processes while maintaining high-quality standards can be a challenge. Additionally, scaling up the production of MMCs from lab-scale to industrial-scale can present challenges in maintaining consistent quality, process control, and cost efficiency.

5- Developments of powder metallurgy process

There have been several research developments in the field of powder metallurgy process, aiming to improve the manufacturing of various materials, including metals, alloys, and composites. Some of the notable research developments in powder metallurgy process are as follows:

A. Advanced Powder Characterization: Researchers are focusing on developing advanced techniques for powder characterization to understand the particle size distribution, morphology, chemical composition, and surface characteristics of powders. Techniques such as laser diffraction, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) are being used to analyze and optimize the powder properties, ensuring better process control and product quality.

B. **Powder Synthesis and Modification:** Researchers are exploring innovative methods for synthesizing and modifying powders to improve their properties and performance. Techniques such as gas atomization, mechanical alloying, and chemical precipitation are being used to produce powders with controlled particle size, shape, and composition. Surface modification techniques, such as coating or functionalization, are also being investigated to enhance the compatibility between the powders and matrix materials [26].

C. **Additive Manufacturing:** Additive manufacturing, also known as 3D printing, is an emerging field within powder metallurgy. Researchers are developing new techniques and materials for additive manufacturing, enabling the production of complex-shaped components with improved mechanical properties. Additive manufacturing offers advantages such as design flexibility, reduced material waste, and the ability to create graded structures, making it a promising area of research in powder metallurgy.

D. **Process Optimization:** Researchers are continuously working on optimizing the powder metallurgy process parameters to improve the densification, microstructure, and mechanical properties of the final products. Techniques such as hot isostatic pressing (HIP), spark plasma sintering (SPS), and microwave sintering are being investigated to achieve higher densification and shorter processing times. Process modeling and simulation techniques are also being used to predict and optimize the process parameters for better control and efficiency [27].

E. **Composite Materials:** Research in powder metallurgy is focusing on the development of advanced composite materials with improved properties. This includes the synthesis and dispersion of reinforcement materials such as nanoparticles, fibers, and whiskers within the matrix material to enhance mechanical, thermal, and electrical properties. Researchers are also exploring different reinforcement architectures and hybrid composites to achieve specific property combinations for various applications [28].

F. **Sustainable and Green Manufacturing:** There is growing emphasis on sustainable and environmentally friendly manufacturing practices in powder metallurgy. Researchers are exploring alternative raw materials, such as recycled powders, to reduce the dependence on primary resources. Additionally, efforts are being made to develop energy-efficient processing methods, minimize waste generation, and optimize the use of resources in the powder metallurgy process.

6- Conclusion

The powder metallurgy process of metal matrix composites (MMCs) presents several challenges that need to be overcome to achieve optimal composite properties. Through this review, we have identified key challenges such as achieving uniform powder distribution, overcoming poor interfacial bonding, addressing particle agglomeration, controlling porosity, and ensuring proper reinforcement dispersion.

Various strategies and techniques have been explored to overcome these challenges. Powder blending techniques, such as mechanical mixing and advanced mixing methods, have shown promising results in achieving a uniform powder distribution. Surface modification techniques, such as coating or functionalizing the reinforcement particles, have been effective in improving interfacial bonding between the matrix and reinforcement.

Optimization of sintering parameters, such as temperature, time, and atmosphere, has been crucial in controlling porosity and achieving densification in the final composite. Advanced consolidation methods, such as hot pressing, spark plasma sintering, and additive manufacturing techniques, have also shown potential in overcoming challenges related to particle agglomeration and reinforcement dispersion.

References

[1] V. Kumar, A. Mishra, S. Mohan, K. K. Singh, and A. Mohan, "The effect of titanium carbide particles on microstructure and mechanical properties of copper/graphite composites prepared by flake powder metallurgy route," *Mater. Today Proc.*, vol. 26, pp. 1140–1144, 2020.

[2] G. Ahmadpour *et al.*, "Microstructure, composition and magnetic properties of Nd-(Fe1-xCox)-B oxide magnetic particles synthesized by Pechini-type chemical method," *Adv. Powder Technol.*, vol. 32, no. 11, pp. 3964–3979, 2021.

[3] Y. Z. Tian *et al.*, "Attaining exceptional electrical conductivity in Cu-Fe composite by powder rolling strategy," *Scr. Mater.*, vol. 227, p. 115302, 2023.

[4] S. Zan, Z. Liao, J. A. Robles-Linares, G. G. Luna, and D. Axinte, "Machining of long ceramic fibre reinforced metal

matrix composites–How could temperature influence the cutting mechanisms?," *Int. J. Mach. Tools Manuf.*, vol. 185, p. 103994, 2023.

[5] B. J. Hall and G. B. Schaffer, "Statistical experimental design of Al–Cu–Mg–Si P/M alloys," *J. Light Met.*, vol. 2, no. 4, pp. 229–238, 2002.

[6] N. Kumar, A. Bharti, and 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.*, vol. 26, pp. 1953–1959, 2020.

[7] O. Okolie, J. Latto, N. Faisal, H. Jamieson, A. Mukherji, and J. Njuguna, "Advances in structural analysis and process monitoring of thermoplastic composite pipes," *Heliyon*, 2023.

[8] V. Mandal, P. Tripathi, A. Kumar, S. S. Singh, and J. Ramkumar, "A study on selective laser melting (SLM) of TiC and B4C reinforced IN718 metal matrix composites (MMCs)," *J. Alloys Compd.*, vol. 901, p. 163527, 2022.

[9] Y. Wang and T. Monetta, "Systematic Study of Preparation Technology, Microstructure Characteristics and Mechanical Behaviors for SiC Particle-Reinforced Metal Matrix Composites," *J. Mater. Res. Technol.*, 2023.

[10] S. Venugopal, S. Baskar, and P. N. F. Samuel, "Study on the mechanical behaviour of metal matrix composites (MMC)," *Mater. Today Proc.*, 2023.

[11] L. Mészáros, A. Horváth, L. M. Vas, and R. Petrény, "Investigation of the correlations between the microstructure and the tensile properties multi-scale composites with a polylactic acid matrix, reinforced with carbon nanotubes and carbon fibers, with the use of the fiber bundle cell theory," *Compos. Sci. Technol.*, p. 110154, 2023.

[12] M. Sundeep, K. Limbadri, N. Manikandan, A. P. Savio, and J. Joseph, "Study of mechanical properties of pineapple leaf fiber and E-glass fiber reinforced hybrid epoxy matrix composite materials," *Mater. Today Proc.*, 2023.

[13] Y. Wang, X. Peng, W. Zhao, H. Xu, B. Liu, and H. Mao, "Preparation of CoCrFeMnNi-based high-entropy/aluminide laminated composites: Multielement interdiffusion reactions," *J. Alloys Compd.*, p. 171606, 2023.

[14] D. Jing *et al.*, "Microstructure and mechanical properties of highly biomimetic brick-and-mortar structure Ti6Al4V/Al3Ti metal-intermetallic laminate composite," *Mater. Des.*, p. 112195, 2023.

[15] V. S. Akash and J. E. R. Dhas, "Processing and characterization of aluminium reinforced metal matrix composite," *Mater. Today Proc.*, 2023.

[16] H.-Y. Wang, Y. Li, S.-Q. Jiao, and G.-H. Zhang, "Preparation of glass-ceramic by low-pressure hot-pressing sintering of CaO-MgO-Al2O3-SiO2 (-CaCl2) glass powder," *J. Eur. Ceram. Soc.*, 2023.

[17] S. Das, M. Aguayo, G. Sant, B. Mobasher, and N. Neithalath, "Fracture process zone and tensile behavior of blended binders containing limestone powder," *Cem. Concr. Res.*, vol. 73, pp. 51–62, 2015.

[18] O. Al-Shantir *et al.*, "Mechanical properties of electroporcelain as a function of temperature and compacting pressure," *Ceram. Int.*, vol. 49, no. 11, pp. 18203–18209, 2023.

[19] Y. Otsuka, I. Yamamoto, M. Iijima, and J. Tatami, "Analysis of sintering behavior of alumina green bodies molded under a strong magnetic field based on master sintering curve theory," *Ceram. Int.*, vol. 48, no. 20, pp. 29669–29675, 2022.

[20] Q. Yang, G. Wang, A. Sadeghi, G. B. Giannakis, and J. Sun, "Two-timescale voltage control in distribution grids using deep reinforcement learning," *IEEE Trans. Smart Grid*, vol. 11, no. 3, pp. 2313–2323, 2019.

[21] T. Peng and I. Chang, "Uniformly dispersion of carbon nanotube in aluminum powders by wet shake-mixing approach," *Powder Technol.*, vol. 284, pp. 32–39, 2015.

[22] L. Yadav and S. Dondapati, "Effect of calcium on mechanical and tribological properties of Mg-Sn alloy system fabricated by powder metallurgy (PM) process," *Mater. Today Proc.*, vol. 5, no. 2, pp. 3735–3744, 2018.

[23] A. J. Dolata, M. Dyzia, and S. Boczkal, "Structure of interface between matrix alloy and reinforcement particles in Al/SiCp+ Cgp hybrid composites," *Mater. Today Proc.*, vol. 3, no. 2, pp. 235–239, 2016.

[24] J. Mottye, B. Ratzker, S. Kalabukhov, B. Favelukis, S. Hayun, and N. Frage, "Effect of Mn doping on the densification and properties of transparent alumina by high-pressure spark plasma sintering," *Ceram. Int.*, 2023.

[25] T. Zhang, G. Bai, N. Cai, Y. Lei, P. Guo, and J. Xu, "The carbon-doped Fe3O4 montmorillonite particle electrode for the degradation of antiviral drugs in electro-Fenton system," *Appl. Clay Sci.*, vol. 243, p. 107056, 2023.

[26] S. V Prasad and R. Asthana, "Aluminum metal-matrix composites for automotive applications: tribological considerations," *Tribol. Lett.*, vol. 17, no. 3, pp. 445–453, 2004.

[27] F. Li, J. X. Zhou, X. Yang, T. Tressel, and B. Lee, "Current therapeutic antibody production and process optimization," *Bioprocess. J.*, vol. 5, no. 4, p. 16, 2007.

[28] A. J. Dolata, "Interaction of Al-Si alloys with SiC/C ceramic particles and their influence on microstructure of composites," *Solid State Phenom.*, vol. 176, pp. 55–62, 2011.