



REVIEW PAPER

Progress in Microwave Sintering for Magnetically Assisted Rheological Finishing of Biomedical Materials

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Abstract

Recently, microwave sintering has been considered an effective processing method for producing biomedical materials owing to its rapid volumetric heating, short processing time, and high energy efficiency, which can provide a refined microstructure with increased functionality and enhanced mechanical properties. The surface quality and dimensions of biomedical materials become important for their appropriate application. Chemomechanical magnetorheological finishing (CMMRF) has attracted considerable interest as a precision finishing process that can offer high surface integrity without compromising the functional properties of biomedical devices. The present paper provides a review of recent advancements in the microwave sintering of biomedical materials, with particular regard to the connection between this process and subsequent CMMRF. The effects of microwave sintering on the microstructure, density, hardness, residual porosity, and surface parameters are analyzed, along with their impact on the finishing process. The recent development of CMMRF for ceramics, metals, and composite biomaterials is reviewed to highlight advances in surface finishing, material removal characteristics, and process efficiency.

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1. Introduction

Materials used in biomedical applications are widely used in orthopedic implants, dental restorations, cardiovascular devices, and surgical tools, where mechanical strength, dimensional tolerance, and high surface quality are crucial for proper performance [1]. The performance of biomedical parts is governed not only by the bulk properties of the constituent material but also by its microstructure, density, and surface qualities, which are determined by the process used to fabricate such parts [2]. Sintering has therefore emerged as an interesting fabrication process owing to advantages such as near-net-shape forming, compositional control, efficient utilization of raw materials, and the ability to produce complex geometries [3]. In the realm of innovative sintering processes, microwave sintering (MWS) has gained significant popularity over traditional furnace sintering due to its volumetric heating, shorter processing times, lower energy consumption, and high

thermal efficiency [4]. Compared with conventional heating, in which heat is conducted from the surface to the core, microwave radiation heats the material itself through interactions with it, resulting in rapid and relatively uniform heating [5]. Such an approach to heating favors microstructure refinement, reduces the rate of grain growth, and enhances densification and mechanical properties, thereby making MWS very promising for the production of biomedical metal alloys, ceramics, and composites [6,7]. Roughness, the presence of pores, and other process-related imperfections may increase wear and friction and decrease corrosion resistance and biocompatibility of the materials. Therefore, modern high-precision surface treatment technologies play a crucial role in enhancing the functionality and durability of biomedical components [7,8]. Recently, there has been much interest in the CMMRF, an advanced hybrid finishing technique capable of achieving nanometre surface finishes while maintaining accurate dimensions. Recently, microwave sintering has

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proven useful for producing composite magnetic abrasives (CMAs), which provide magnetic stability, abrasive retention, and effective polishing during the CMMRF process. Thus, it becomes possible to establish a technological connection between microwave processing and surface finishing, providing new opportunities for the fabrication of biomedical components with excellent mechanical properties and surface finish [9-11]. This review highlights the recent advances in microwave sintering techniques applied to CMMRF of biomedical materials. Specific focus is made on the concept of microwave sintering, structural changes during the process, mechanisms of CMMRF, microwave-sintered magnetic abrasives, and their use in biomedical engineering applications. In conclusion, recent challenges and future research directions are highlighted to advance the development of advanced biomedical materials.

2. Literature Review

Cherepanov [12] emphasized the importance of defect chemistry, diffusion kinetics, and particle packing on sintering behavior. In contrast, Liu and German [13,14] revealed the significance of microstructural properties such as grain coordination, contiguity, and dihedral angle on densification and microstructure evolution. Hawley et al. [15] have demonstrated that microwave technology is efficient for composite materials due to its selective and homogeneous heating. The work by Liu et al. [16] demonstrated that reduced graphene oxide (rGO) was uniformly dispersed in the aluminum during the powder process, resulting in increased hardness and integrity of the material after sintering. Liu et al. [17] also highlighted the improved interfacial bonding of the TiO₂-rGO composite formed using a microwave-assisted synthesis method. Bhoi et al. [18] reported improved microstructure homogeneity and mechanical properties in Al-ZnO nanorod composites. The microwave hybrid sintering technique reported by Bhoi et al. [19] enables effective thermal processing, leading to strong particle bonding and composite formation. Chaudhari et al. [20] also used finite element analysis to optimize magnetorheological abrasive finishing parameters. According to this, a nanometre-scale surface finish on SS316L was obtained, along with increased hydroxyapatite formation on the surface after finishing, indicating improved bioactivity. Recent findings have revealed a direct connection between microwave sintering and CMMRF in the formation of composite magnetic abrasives. Overall, these studies demonstrate that microwave sintering is an efficient technique for manufacturing high-performance magnetic abrasives, thereby increasing the efficiency and repeatability of CMMRF. The combination of microwave processing and advanced magnetorheological finishing represents a valuable technology for biomedical manufacturing because both bulk characteristics and surface quality determine the performance of implant materials.

3. Materials and Methods

Aluminum powder was pressed uniaxially at 580 MPa for 5 min. The green compact was subjected to microwave hybrid

sintering at 630 ± 5 °C, which was near the melting point of aluminum. The microwave hybrid sintering was carried out in a 2.45 GHz microwave furnace for 11 min with zero dwell time. Silicon carbide (SiC) was used as a susceptor for better microwave coupling and heating of the compact. The temperature of the specimen was measured during sintering using an infrared thermometer (for instance, Fluke 572). The schematic of the microwave hybrid sintering setup is shown in Fig. 1. The advanced three-dot laser sight with a resolution of 0.1 °C was used for temperature measurements.

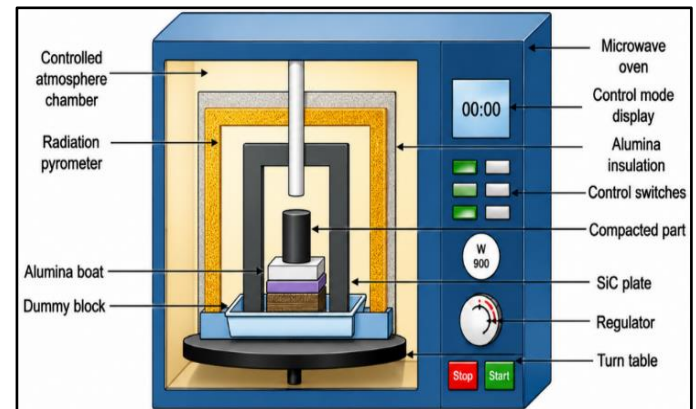


Figure 1: Schematic Diagram of microwave sintering setup [24].

The performance of the fabricated microwave-sintered composite magnetic abrasives was evaluated through surface-finishing experiments on the CMMRF machine, which was self-assembled in the laboratory. The experimental setup, as shown in Fig. 2, comprised a CNC milling machine combined with a slurry feeding mechanism, a magnetic field-generating device, a control mechanism, and a fixture for workpiece holding.

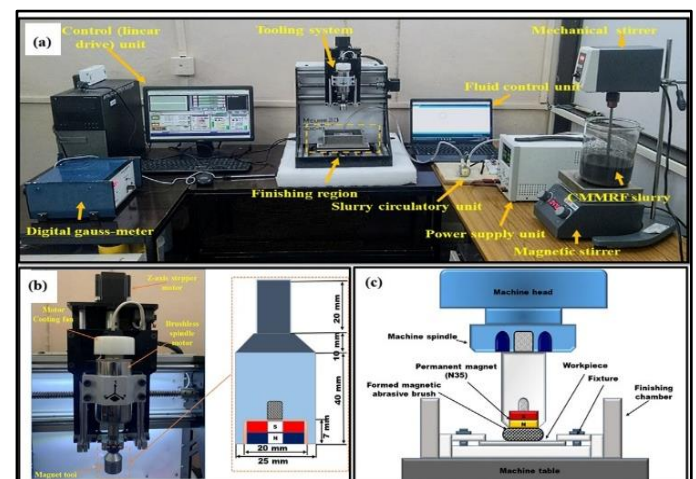


Figure 2: Schematic diagram of (a) in-house CMMRF process setup, (b) tooling system, and (c) CMMRF component involved [10].

4. Preparation of Microwave-Sintered Composite Magnetic Abrasive Particles

Composite magnetic abrasive particles were synthesized to improve the effectiveness of the polishing process of CMMRF

finishing slurry. The composition and the method for making composite magnetic abrasive particles are illustrated in Table 1 and Fig. 3, respectively. In the beginning, carbonyl iron powder (CIPs) and alumina (Al_2O_3) powders were mixed in a planetary ball mill using stainless steel balls having a 5 mm diameter. Mixing of the powders was performed at 400 rpm for 2 hours with a ball-to-powder ratio of 8:1, and 1 ml of ethanol was added as a process-controlling agent. The homogeneous mixture of powders was then pressed into cylindrical green

pellets with a diameter of 14 mm using a universal testing machine, applying a pressure of 10 tons for 15 minutes. The green pellets were sintered in a 900 W microwave furnace at 2.45 GHz and $950 \pm 5^\circ\text{C}$. Silicon carbide (SiC) powder was used as the susceptor for better heating. The microwave-sintered pellets were then cooled to room temperature and mechanically crushed, followed by sieving through a 25 μm sieve.

Table 1: Sintering element purpose, composition, and particle size [10].

Material	Purpose	Composition (wt.%)	Average Particle Size (μm)	Density (g/cm^3)
Carbonyl iron powder (CIPs)	Ferromagnetic material	70	4	7.87
Alumina (Al_2O_3)	Abrasive	30	3	3.9
Ethanol	Controlling agent	1 mL	-	0.789

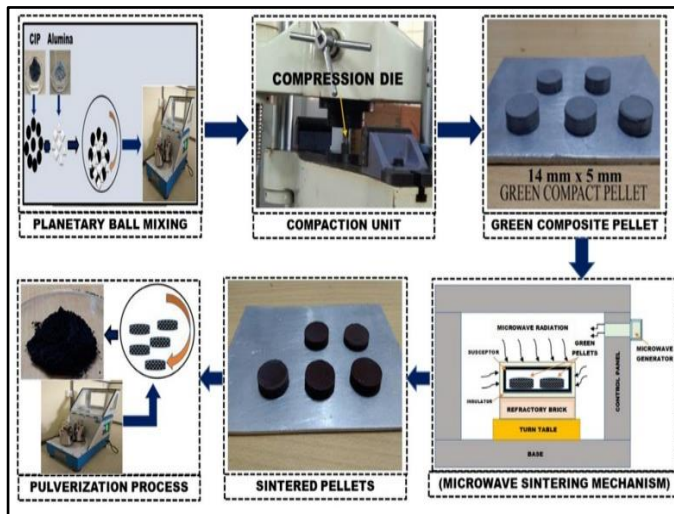


Figure 3: The procedural steps of composite magnetic abrasive manufacturing [24].

5. Comparison with Previous Studies

It has already been established through previous research that conventional sintering is commonly used to manufacture composite magnetic abrasives; however, long sintering times may lead to grain growth, poor densification, and poor magnetic and mechanical properties. In contrast, it has been stated that microwave sintering provides rapid volumetric heating and results in improved microstructure, densification, and interfacial bonding, leading to better abrasive strength and finishing. Previously, magnetorheological finishing (MRF) and magnetorheological abrasive flow finishing (MRAFF) relied on abrasive particles in loose form, which had low abrasive retention capacity, poor material removal capability, and accelerated tool wear. Recent advancements in the CMMRF process, however, have overcome these deficiencies, resulting in surface finishing at the nanometre scale and good surface integrity. Table 2 shows the comparative analysis.

Table 2. Comparative analysis of microwave-sintered composite magnetic abrasives and advanced CMMRF studies

Technique / Process Used	Material / Abrasive System	Major Findings	Research Gap / Limitation	Ref.
Microwave Sintering	Metallic and ceramic materials	Rapid volumetric heating, shorter sintering time, and improved densification compared with conventional sintering	Surface finishing applications have not been investigated	[4]
Microwave Sintering	Al-based metal matrix composites	Enhanced densification, refined microstructure, and improved mechanical properties	Finishing performance not evaluated	[5]
Microwave Hybrid Sintering	Al- Y_2O_3 metal matrix composites	Improved densification, hardness, and microstructural refinement	Surface finishing behavior has not been studied	[6]
CMMRF	Aluminium alloy	Achieved atomic-level surface finish with improved surface integrity	Conventional mixed abrasives exhibited lower abrasive retention	[9]
Microwave Sintering + CMMRF	Microwave-sintered CIP- Al_2O_3 composite magnetic abrasives	Higher MRR, improved rheological behavior, and superior surface finish than mixed abrasives	Validation limited to Al-6061	[10]
Microwave Sintering + Hybrid CMMRF	CIP- Al_2O_3 composite magnetic abrasives	Improved polishing efficiency, enhanced abrasive bonding, and lower tool wear.	Industrial-scale validation required	[11]
Magnetorheological Abrasive Finishing (MRAF)	SS316L	Process optimisation using FEM produced improved surface quality	Microwave-sintered abrasives were not investigated	[20]

Hybrid CMMRF	Composite magnetic abrasives for Ti-6Al-4V	Improved polishing efficiency and nano-scale surface finish	Slurry chemistry requires further optimization	[21]
Eco-friendly CMMRF	Fe ₃ O ₄ @SiO ₂ composite magnetic abrasives	Sustainable polishing with excellent surface integrity and corrosion resistance	Limited validation on biomedical materials	[22]
Rotational Magnetorheological Abrasive Flow Finishing (R-MRAFF)	Knee joint implant	Successfully finished freeform knee joint implants with improved surface quality.	Microwave sintering and composite magnetic abrasives were not considered	[23]
Microwave Sintering + CMMRF	CIP/EIP-Al ₂ O ₃ composite magnetic abrasives	Microwave-sintered abrasives exhibited 28.15% higher MRR than conventionally sintered abrasives, with improved grain structure and polishing efficiency.	Validation limited to aluminum alloys; biomedical applications not explored.	[24]
Magnetorheological Dynamic Pressure Polishing	Sapphire wafer	Achieved Ra $\approx$ 0.091 nm and MRR $\approx$ 17.56 nm/min using gap-varying polishing	Microwave sintering and composite abrasives are not employed	[25]
Magnetic Abrasive Finishing using Core-Shell Composite Magnetic Particles	CaF ₂ optical material	Improved polishing efficiency and surface quality using core-shell magnetic particles	Microwave processing is not considered	[26]
Chemical Mechanical Polishing (CMP)	Al ₂ O ₃ -CeO ₂ mixed abrasive slurry for sapphire	Achieved atomically smooth surface (Ra $\approx$ 0.079 nm) with high material removal rate through chemical-mechanical synergy	No magnetic field or microwave sintering employed	[27]
Microwave Sintering + Composite Magnetic Abrasive + CMMRP	Microwave-sintered CIP-Al ₂ O ₃ slurry for convex Al surface	Achieved Ra = 13.72 nm, 97.66% improvement in surface finish, and higher MRR than simply mixed abrasives	Validation restricted to convex aluminum surfaces; biomedical components remain unexplored	[28]

6. Applications of Microwave-Sintered Composite Magnetic Abrasives in Biomedical Manufacturing

Microwave-sintered composite magnetic abrasives have immense potential in CMMRF for the fabrication of superior biomedical components. This process can be effectively employed to precisely machine metallic, ceramic, and composite biomaterials, producing nanometre-scale surface finishes with high dimensional accuracy and surface integrity. High surface quality improves the component's corrosion, wear, and fatigue resistance, as well as its biocompatibility, which are vital to ensuring the proper performance of the implant over time.

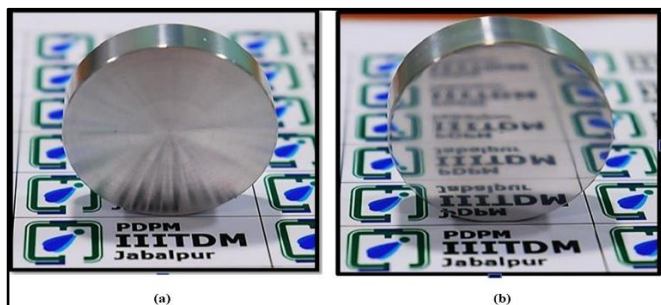


Figure 4: Photograph of specimen (a) before finishing, (b) after finishing [10].

It is highly versatile and can be used to machine different orthopaedic implants such as hip implants, knee implants, shoulder implants, elbow implants and ankle joint implants, besides dental implants, spinal implants, craniofacial implants, bone fixing devices, prosthetic components, surgical

instruments and the related achieved surface, required for these implants, as shown in Fig. 4. Besides, microwave sintering of composite magnetic abrasives proves to be extremely efficient when applied to additively manufactured biomedical components that cannot be machined through traditional finishing techniques.

7. Conclusions

Microwave sintering is an effective process route for manufacturing composite magnetic abrasives due to rapid volumetric heating, reduced processing time, and improved densification compared with conventional sintering. The results obtained from this study can be summarized as follows:

- The microwave-sintered composite abrasives have better interfacial bonding, a finer microstructure, and improved mechanical properties, which provide a high material removal rate, low abrasive wear, and better finishing performance compared to those made using traditional technology.
- Some recent studies have shown significant success in improving surface quality, achieving nanometre-scale surface roughness, on various aluminum and titanium alloys and optical materials using optimal abrasive composition and finishing parameters.
- Environment-friendly slurry solutions, hybrid abrasives, and advanced composite magnetic particles have improved finishing efficiency and minimized environmental impact and abrasive wear.
- Although there have been many advancements, most of these studies are limited to engineering materials, while biomedical components with complex surfaces have

attracted little attention.

- Future work should focus on microwave-sintered multifunctional composite magnetic abrasives and sustainable finishing chemistry for efficient, environmentally friendly finishing of advanced biomedical materials.

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