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A REVIEW OF MICROWAVE-ASSISTED SINTERING TECHNIQUE

Summary

The present study examines the potential of microwave heating as an emerging and innovative energy-efficient alternative to conventional heating techniques used for different materials, with a focus on the processing of ceramic materials. Modern ceramics are studied extensively, and their use and different applications are wide due to many advantages of these materials. The most important factor in microwave sintering which differentiates it from conventional heating techniques is a unique heat transfer mechanism. Microwave energy is absorbed by the material, hence the transfer of energy takes place at the molecular level. This way, the heat is generated throughout the material, i.e. on the inside as well on the outside. This allows a very low temperature gradient throughout the material cross section. When conventional sintering is used, typically at high heating rates, high temperature gradients pose a problem. The accelerated microwave heating occurs through the whole volume, so the heating is uniform, which limits the grain growth and coarsening, and leads to a uniform and fine microstructure. The densification is accelerated as well during the unique heat transfer mechanism of microwave sintering, which enhances the mechanical properties of the sintered materials.

This paper discusses the use of microwave sintering in the manufacturing of different modern technical materials, namely ceramics, composites, metals and alloys, and glasses. The improvement of different properties is described using the available literature.

Key words: *microwave sintering, conventional sintering, ceramics, materials*

1. Introduction

Thermal processing plays a key role in the resulting microstructure and, consequently, in the final properties of the obtained ceramic material. Sintering is one of the most common processing techniques for the consolidation of ceramic powders. It is present in almost all areas of engineering, such as the production of different materials including stainless steels, superalloys, steel and bronze, intermetallics such as silicides and aluminides, tool steels, many electronic components, most carbides, oxides, borides, nitrides, and a wide variety of

composites. By using the sintering process, products can be tailored to a wide range of applications in engineering, – from high-temperature rocket nozzles to low-temperature copper-based solders for electronic circuits.

The main goal of sintering process is to achieve full densification of the material with near theoretical density values as possible. However, the sintering process can also be used to obtain porous materials with high surface areas. In that case, full consolidation is not reached.

Sintering of ceramics requires very high processing temperatures compared to metals and polymers. Sintering of materials is an energy-consuming process with high production costs. To optimize the sintering process, densification mechanisms can be modified to improve the microstructure and mechanical properties of the obtained sintered materials as well as to reduce the production time and costs [1].

Hence, new and improved technologies and sintering methods are constantly being investigated and developed. One of the non-conventional sintering methods is microwave-assisted sintering, which has been developed to reduce energy consumption, maintain or even improve the characteristics of the resulting ceramics, as well as to reduce the production costs and lessen their environmental impact [2,3].

2.   The process of sintering

"Sintering is a thermal treatment for bonding particles into a coherent, predominantly solid structure via mass transport events that often occur on the atomic scale. The bonding leads to improved strength and lower system energy" [4].

During the process of sintering, a ceramic powder compact ("green body") is exposed to high temperatures; during the exposure, the thermal activation of mass transfer mechanisms takes place. The main purpose of the process is to obtain a material with enhanced properties and a density as close to the theoretical one as possible [2].

When a material is heated, the atomic motion increases with an increasing temperature and induces bonding and neck formation, which leads to a lower system energy. With a decrease in particle size, the total surface energy increases, which leads to a shorter sintering time or a lower sintering temperature.

The rate of particle bonding during sintering depends on the material, sintering temperature, particle size, possible dopants or impurities, and processing factors. Thus, thermodynamics shows the importance of small, nanoscale powders, while kinetics emphasizes the importance of sintering temperature.

Sintering concepts are best developed in the case of loose, mono-sized spherical particles; however, non-spherical particles with broad particle size distribution and multiple phases are more common. Single phase, solid-state sintering is applicable to pure substances such as nickel, alumina (Al_2O_3), or copper.

Sintering process is carried out through a couple of stages shown in Figure 1. In the initial stage, the inter-particle neck starts growing, and a small linear shrinkage can be observed. Density is less than 70% of the theoretical one at this stage. The intermediate stage is the beginning of grain growth with a continuous inter-particle neck growth, the pores are open and tubular, and the density is from 70% to 92% of the theoretical one. In the final stage, the pores collapse into closed spheres and the remaining porosity is eliminated. The inter-particle neck can be observed in the image produced by scanning electron microscopy, see Figure 2. It shows spherical bronze particles after sintering at 800 °C. Neck growth provides strength; longer sintering time provides a larger neck, thus greater strength [4,5].

There are two main types of sintering based on the nature of the process: solid-state and liquid-phase.

During solid-state sintering, ceramic powder does not melt but the particles are joined, which results in porosity reduction, i.e. densification. The joining of particles occurs by atomic diffusion. The surface free energy of the consolidated particles is reduced, which leads to either densification or coarsening of the material. Densification processes remove the material from the grain boundary region, which leads to a decrease in the pore volume, while coarsening processes produce microstructural changes without causing a volume decrease. If the densification processes prevail, a dense body will be obtained. However, if the coarsening processes prevail, a highly porous body will be produced.

Even though the term liquid-phase may indicate that the sintering temperature is above the melting point of the material, it is used to describe the addition of compounds that form a small amount of liquid phase between the grains during sintering. They help with the consolidation of the main powder, which provides the main properties of the obtained material [2]. The liquid phase provides a significant increase in the mass transport rates with a further benefit from capillary forces pulling the particles together. This technique is one of the two solutions for controlling the problem of inadequate densification; the other solution is the application of external pressure to the body during heating in either the solid-state or the liquid-phase sintering. This method is referred to as pressure-assisted sintering or pressure sintering; hot pressing and hot isostatic pressing are well-known examples of this type of sintering. The densification process is improved by the applied pressure without a significant effect on the rate of coarsening; however, the increase in production costs is a big shortcoming of the pressure-assisted sintering. For that reason, over 70% of sintered products are formed using the liquid phase, which constitutes 90% of the commercial sintered product value.
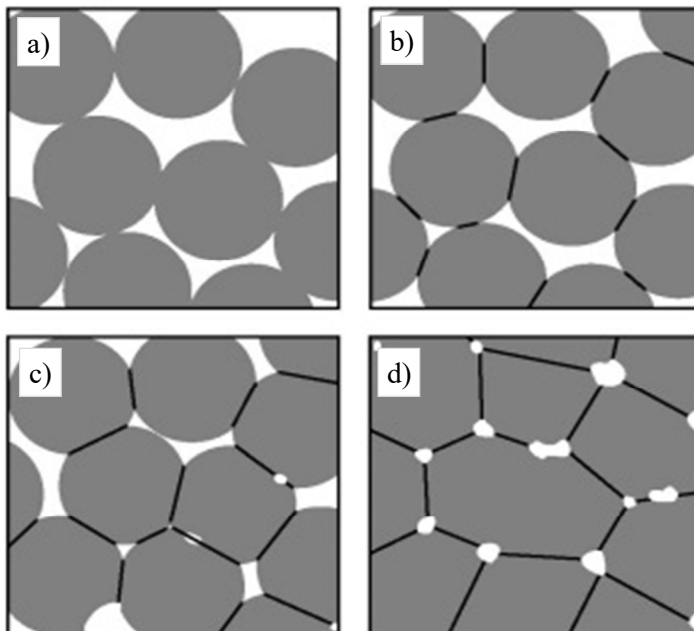
Fig. 1 The illustration of sintering stages with a focus on changes in the pore structure: a) loose powder, b) initial stage, c) intermediate stage, and d) final stage [3]
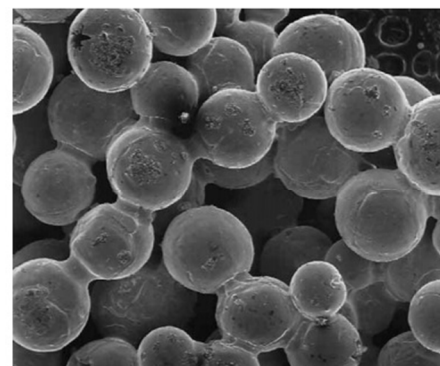
Fig. 2 SEM of sintering necks formed between 26 μm bronze particles after sintering at 800 °C [3]

Densification rate in the solid state, the liquid phase, and viscous sintering can be improved by pressure-assisted sintering (hot-pressing, hot-isostatic pressing, spark plasma sintering), i.e. by the application of external pressure.

The heating schedule in the sintering of industrial ceramics can have several temperature–time stages and steps. In isothermal sintering, the temperature is increased rapidly to a fixed (isothermal) sintering temperature, maintained at this value for a required time, and finally lowered to room temperature. Sintering models commonly assume idealized isothermal conditions which are not possible. Using a constant heating rate to a specified temperature may be simpler to analyse theoretically, given that the sintering mechanisms do not change over the temperature range [4,5].

3. Conventional sintering

Common requirements for the final sintered product are high density and small grain size because these microstructural characteristics enhance most mechanical properties. To achieve the above mentioned properties, it is necessary to produce green bodies with adequate homogeneity. One of the most common techniques for the consolidation of ceramic powder is slip casting, where an aqueous ceramic suspension is poured into a porous mould which withdraws water from the suspension, thus producing a green body ready for sintering [6]. If proper procedures of powder preparation and consolidation are adopted, successful fabrication remains dependent on the sintering process variables. In general, these variables involve the manipulation of the heating schedule, atmosphere, and the applied pressure. As it was mentioned before, sintering may be classified as solid-state sintering, liquid-phase sintering, pressure-assisted sintering, and vitrification through simple heating schedules (isothermal sintering and constant heating rate sintering). If no external pressure is applied during sintering, it is referred to as conventional sintering, free sintering, or pressureless sintering. Even though conventional sintering is a more economical method, pressure-assisted sintering provides higher density and improved microstructure due to the application of pressure. The most common way of heating the powder compact is by using an electrical resistance furnace with temperatures of up to ~2500 °C. The heating schedule can be simple isothermal sintering, or it may have a complex temperature-time relationship, as in some industrial processes. The sintering atmosphere is an important element of the sintering process. A precise control of the partial pressure of oxygen or nitrogen as a function of temperature may be valuable for the sintering process. The atmosphere has a strong effect on processes such as decomposition, evaporation of volatile constituents, and vapour transport. Insoluble gases can sometimes remain trapped in closed pores, which can later disrupt the process of densification or even lead to swelling. The best way to avoid these difficulties is to change the atmosphere or use a vacuum [5].

A variety of furnaces are available, ranging in size from small, research type to large furnaces for industrial production. The furnaces most widely used for the conventional sintering are electrical resistance furnaces, in which heat is produced by the internal resistance to the flow of the electric current. The generated heat then passes through the refractory material by radiation and convection. When selecting a sintering furnace, there are a few considerations that have to be kept in mind: maximum temperature capability (which is conditioned by the material which the furnace elements are made of), atmosphere in which the furnace can operate and, of course, the size and cost. For lower temperatures (up to ~1200 °C) several metal alloys can be used, while higher temperatures (up to ~2000 °C) require the

furnace elements to be made of various refractory metals, such as molybdenum (Mo), tungsten (W), and tantalum (Ta). For obtaining the desired temperature cycle, a temperature controller is used. For laboratory-scale experiments, a tube furnace (Figure 3) can often provide the desired temperature and atmosphere control.
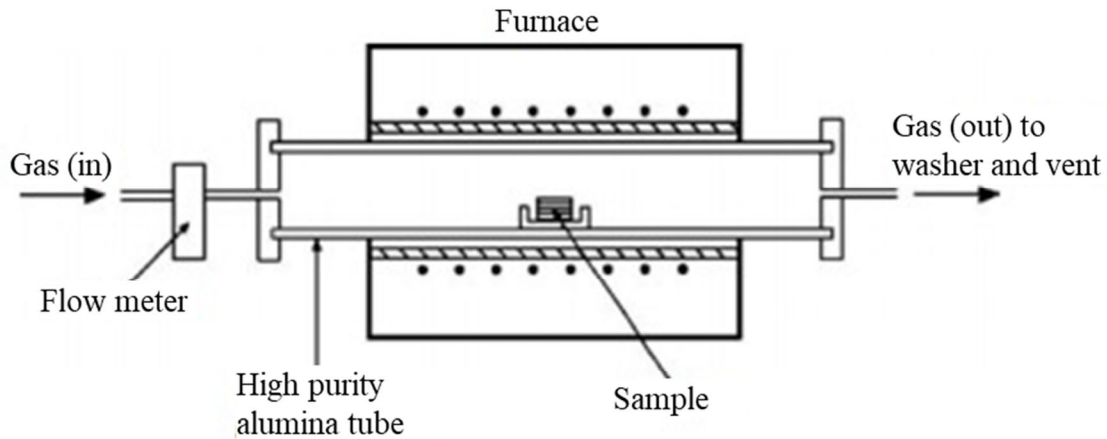
Fig. 3 A schematic diagram of a tube furnace used for controlled atmosphere sintering [5]

In order to achieve the desired microstructure, it is necessary to monitor the process of sintering to provide data for understanding and optimizing the process and its variables. Measurement of the shrinkage or density as functions of time or temperature, combined with an examination of the final microstructure using microscopy are performed routinely. It is also useful to examine the microstructure at several intervals during the heating cycle to characterize the grain growth and microstructural evolution [5].

4. Microwave sintering

The history of microwave processing of ceramics started with the development of the radar during WWII. However, serious efforts to process ceramics using microwave energy were made only in the late 60s and early 70s of the 20th century. While some work on the microwave heating of ceramics was reported in the 70s, a much greater effort was concentrated on unconventional sintering all the way into the late 80s and 90s. In 1988, the first international symposium on the microwave processing of materials was held at the Materials Research Society's Spring Meeting, in Reno, NV, USA. Since that time, the participation and the number of contributions from foreign nations and the number of papers related to ceramic materials and their processing has increased significantly. One of the variables affecting the efficient coupling between microwaves and materials is the frequency (and the wavelength) of microwaves, which ranges from 300 MHz to 300 GHz. The most commonly used frequency for the processing of ceramics is 2.45 GHz with a corresponding wavelength of 122 mm [7].

Figure 4 shows some microwave frequencies reported in the literature that have also been used to process ceramics. However, frequencies of 915 MHz and 2.45 GHz, which have been assigned by the Federal Communication Commissions, USA., for medical, industrial, and scientific applications, are the two most widely used frequencies. At the highest frequencies, microwaves can be focused by lenses or mirrors to provide additional flexibility to the processing of ceramics [7].
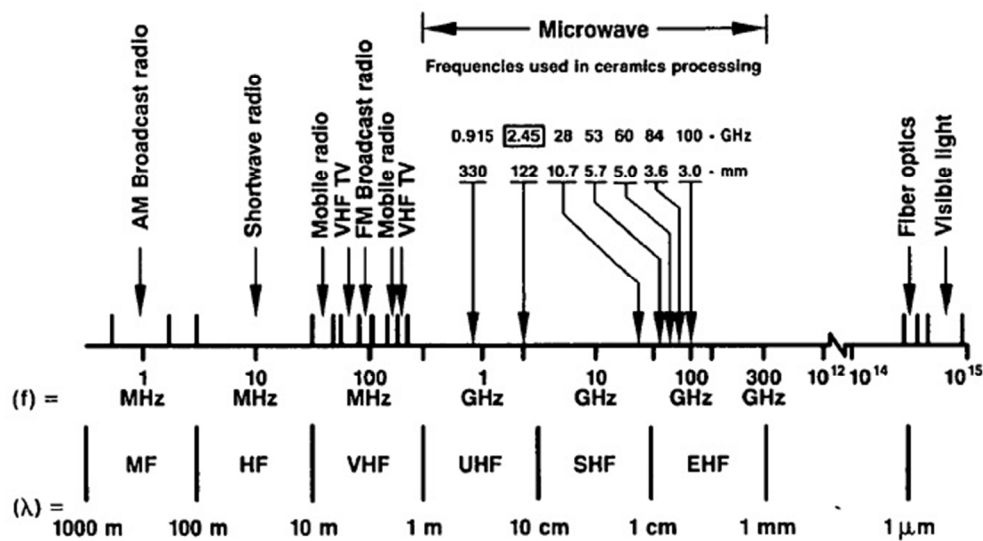
Fig. 4 The electromagnetic spectrum and frequencies used in the microwave processing of ceramics [8]

As opposed to conventional sintering, where heat is transferred through the material via conduction from the outside to the inside of the material, in the microwave heating process, the energy is absorbed by the material, and the heat generated internally is transferred to the outside (Figure 5). Microwave heating is a function of the material being processed. In microwave heating there is almost a 100% conversion of electromagnetic energy into heat, largely within the sintered material itself, while in conventional heating, there are significant thermal energy losses. Microwave heating has many advantages, such as time and energy savings, very high heating rates (>400 °C/min), considerably reduced processing time and temperature, fine microstructures and, consequently,, improved mechanical properties [9].
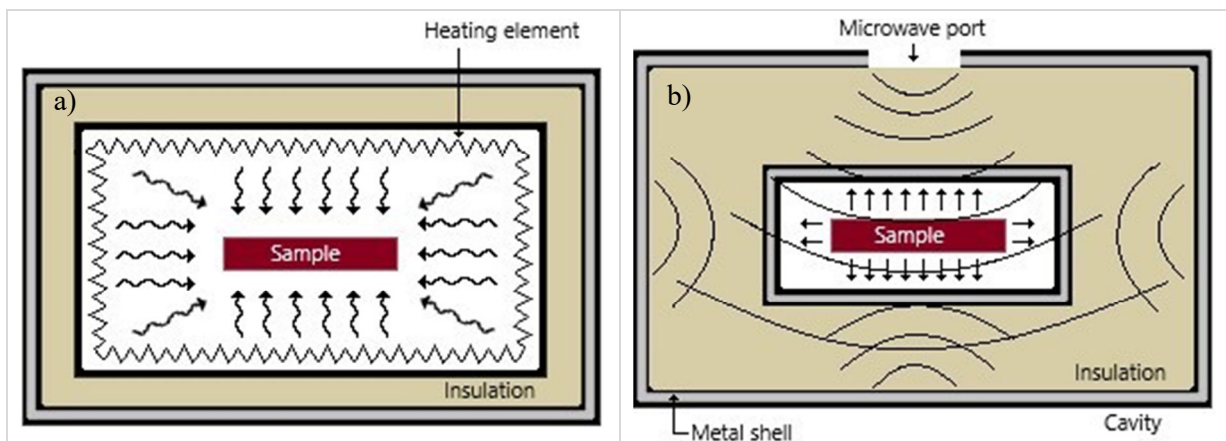

Fig. 5 Heating patterns in: a) a conventional furnace and b) a microwave furnace [9]

The interaction of microwaves with different materials depends on electrical and magnetic properties of the material as well as on the grain size and porosity. Regarding these properties, materials can be classified as transparent (no energy transfer – low dielectric loss materials), opaque (no penetration into the material – bulk material, conductors) and absorbent (absorption and exchange of energy, high dielectric loss materials), as shown in Figure 6.
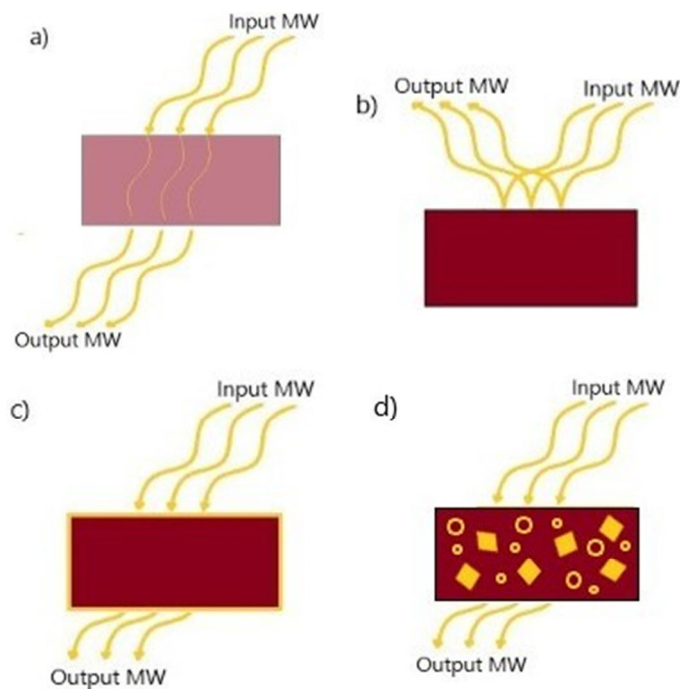
Fig. 6 A schematic diagram illustrating the interactions of microwaves with: a) a transparent material (low loss insulator) – total penetration, b) an opaque material (conductor) – no penetration, c) an absorber (lossy insulator) – partial to total penetration, and d) an absorber (mixed) – the matrix is transparent but fibres/particles/additives in it are absorbing materials – partial to total penetration [2]

Ceramics with the best insulating properties such as alumina (Al_2O_3), magnesia (MgO), silica (SiO_2), and glasses are transparent to microwaves at room temperature, but when heated above a critical temperature, T_c, they begin to absorb them and react more effectively with the microwave radiation. Improved microwave heating can also be achieved by adding a material with a high loss (susceptor) which absorbs microwaves. When designing susceptors and their shape, size, and arrangement, some factors must be taken into consideration. Some susceptor materials have a high loss factor, thus, low penetration depths. With high temperatures, the dielectric loss rises, which further decreases the penetration depth. Because of this phenomenon, it can be difficult to determine which fraction was sintered via microwaves and which fraction was sintered conventionally via the susceptor material radiation, as shown in Figure 7.

Other ceramics, such as silicon carbide (SiC) are able to absorb microwave energy more efficiently at room temperature. Therefore, the addition of a microwave-absorbing second phase to ceramics that behave as transparent material at room temperature, can greatly enhance the system interaction with microwaves, allowing hybrid heating of the material [2]. This hybrid heating of the material distributes the temperature field more evenly, thus achieving uniform heating throughout the cross-section of the material (Figure 8) and, consequently, avoiding the density gradient. Due to this uniform heating, a material with a more homogeneous microstructure, and therefore improved final properties, can be obtained.
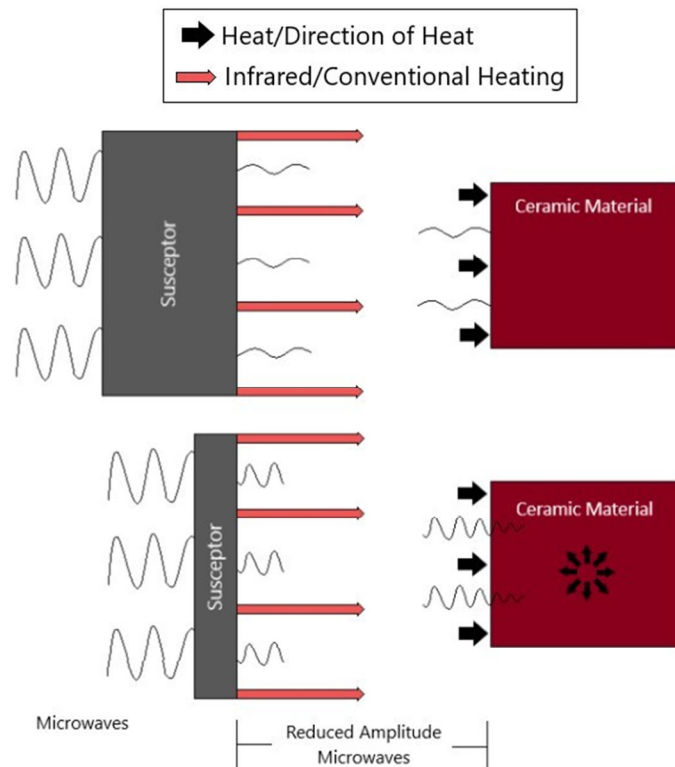
Fig. 7 The microwave hybrid heating arrangement/effect of the susceptor material volume
on the final heating pattern [10]
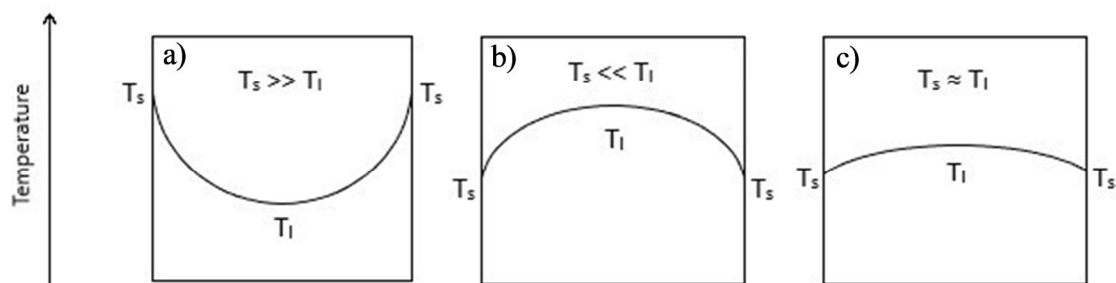
Fig. 8 Temperature distribution in a ceramic material heated by a) conventional, b) microwave, and c) hybrid
heating (T_s – surface temperature; T_I – internal temperature) [10]

Microwave radiation includes several physical mechanisms that explain the interaction with absorbing materials:

- bipolar rotation - when exposed to a microwave field, polar molecules rotate in the direction of increasing amplitude. Because of this rotation, friction is created among molecules and this generates heat;

- resistive heating - occurs in conductors or semiconductors which possess free electrons;

- electromagnetic heating - in materials with magnetic properties which make the material to rotate when irradiated;

- dielectric heating - a combination of bipolar rotations and resistive heating, the prevailing mechanism in the microwave sintering of ceramics [2].

4.1 Dielectric heating

The most relevant property of a ceramic material during microwave sintering is its permittivity, ε. Commonly, relative permittivity, ε_r (dielectric constant), which is equal to $\varepsilon/\varepsilon_0$, is used. A higher value of permittivity enables the material to polarize in the electric field applied, and thus provides a large amount of energy in the material. When a material is exposed to microwave heating, the electromagnetic field causes electrons, ions and dipole molecules to move. This movement causes deviation from the natural equilibrium of the system and thus dissipates energy, which reduces the electric field and initiates the heating of the material. The amount of dissipated power (W, watt) is given by [5]:

$$W = \pi E_0^2 f \varepsilon_0 \varepsilon_r^{''} = \pi E_0^2 f \varepsilon_0 \varepsilon_r^{'} \tan\delta \tag{1}$$

where E_0 is the amplitude of the electric field, f is the frequency, and $\tan\delta$ is the loss tangent equal to [5]:

$$\tan\delta = \frac{\varepsilon_r^{''}}{\varepsilon_r^{'}} \tag{2}$$

where $\varepsilon_r^{''}$ is the loss factor, i.e. the ability of the material to convert microwave energy into heat, and $\varepsilon_r^{'}$ is the dielectric constant. In microwave material processing, maximum values of $\varepsilon_r^{''}$ in combination with medium values of $\varepsilon_r^{'}$ are desired.

High frequencies and permittivity values result in superficial heating, while low frequencies and permittivity values result in volumetric heating.

In order to achieve uniform heating of the material, the depth of microwave penetration into the material must be taken into account. It is given by [5]:

$$D_p \approx \frac{c}{10f\left(\varepsilon_r^{'}\right)^{1/2}\tan\delta} \tag{3}$$

with c being the speed of light in vacuum. Given the above-mentioned equations, it is easy to conclude that microwave heating mostly depends on the loss tangent and the dielectric constant of the material. To better control and adjust the process of microwave sintering, the knowledge of the changes in these properties with respect to temperature is required [2,5].

There is a growing need for the production of dense ceramic materials with nanostructured grains which contribute to the improved physical and mechanical properties of nanomaterials. During the conventional processing of ceramic powders at high temperatures, large grain sizes occur due to Ostwald ripening (the re-deposition of small particles on larger ones). This phenomenon complicates the fabrication of dense materials with nanostructured grains. However, microwave sintering offers an alternative route for the sintering of dense ceramic materials with suppressed grain growth [10].

5. Application of microwave sintering in the fabrication of different engineering materials

5.1 Ceramics

Liu et al. successfully prepared a transparent ceramics, magnesium aluminate spinel (MgAl₂O₄), by both microwave and conventional sintering. The microwave-sintered samples reached a high relative density (95.4%) at a shorter time and a lower temperature compared to the conventionally sintered ones. The phase of $MgAl_2O_4$ ceramics is not changed by microwave sintering [11].

Chanda et al. studied microwave-sintered hydroxyapatite (HA) and tri-calcium phosphate (TCP) ceramics using a commercial 2.45 GHz, 3 kW fully automated microwave

system. The obtained samples showed good densification, uniform shrinkage without cracking, uniform microstructure and no major change in the phase. Sintering time was reduced to 60 minutes compared to 8 hours of conventional heating [12].

The study carried out by Orlik et al., demonstrated that barium calcium zirconate titanate, $(Ba,Ca)(Zr,Ti)O_3$, BCZT, a piezoelectric lead-free ceramics can be prepared by microwave sintering with the treatment duration reduced from 12.5 hours to 1.5 hours. The obtained samples had a finer microstructure and better mechanical properties compared to the ones obtained by conventional sintering methods [13].

In the study conducted by Ramesh et al., microwave sintering was proved to be beneficial for reducing the densification temperature in the sintering of yttria-tetragonal zirconia (Y-TZP) ceramics. When compared to conventionally sintered samples, the samples obtained by microwave sintering exhibited enhanced densification and mechanical properties when sintered at a low temperature (1200 °C) [14].

Using microwave sintering, Mangkonsu et al. successfully fabricated a dense calcium phosphate (CP) ceramics with improved mechanical properties. The results indicated improved hardness, density, and microstructure compared to conventionally sintered samples [15].

Microwave sintering of dental ceramics (e.g. zirconia) was examined by Vanderhobli and Saha. The results suggested that complex dental ceramics can be produced by microwave sintering, which achieves better microstructural properties of the material and energy savings [16].

Y. Chen et al. successfully prepared high density yttria and lanthana co-doped zirconia dioxide (ZrO_2) via hybrid microwave sintering. The obtained samples exhibited superior mechanical properties, a homogeneous microstructure, and a smaller grain size. The toughness of the material was enhanced by the weakening of grain boundaries that cause intergranular fractures [17].

The sintering of magnesium oxide, MgO, doped alumina powders by conventional and direct microwave heating was conducted by Croquesel et al. Samples sintered by direct microwave heating exhibited a much lower density than conventionally sintered ones due to the presence of MgO which reduced the densification rate [18]. The same research team also carried out the direct microwave sintering of pure alumina in a single mode cavity. The obtained results showed that pure alumina powders can be fully densified to a homogeneous microstructure by direct microwave sintering in a shorter time and at a higher heating rate than by conventional sintering [19].

Figiel et al. conducted a study to obtain alumina ceramics via conventional and unconventional sintering methods. By microwave sintering, they obtained ceramic materials with improved mechanical and physical properties, increased density at lower temperatures and a shorter sintering time [20].

Double perovskite La_2MMnO_6 (M = Ni, Co) was successfully prepared by Matli et al. using the microwave sintering technique. The obtained material exhibited improved magnetic and dielectric properties with a reduced sintering time in comparison to conventionally obtained products [21].

Borrell et al. investigated the sintering of 3 mol% Y_2O_3-stabilized tetragonal zirconia using microwave and conventional sintering. The microwave sintering method provided a material with a homogeneous microstructure and a higher density compared to the conventionally sintered one. They also found slightly smaller grain size and superior hardness values in microwave-sintered samples than in conventionally-sintered ones [22].

A comparative study on conventional and microwave sintering of Al_2O_3-yttria-stabilized ZrO_2 was conducted by Shukla et al. Enhanced densification and hardness values were observed in the microwave-sintered samples, at lower temperatures of processing,

compared to the conventionally sintered ones. Microwave sintering provides a shorter sintering time, thus lower energy consumption [23].

J. Cheng et al. concluded that sintering in the microwave field can produce transparent Al_2O_3 ceramic samples with enhanced densification [24].

Wei Cai et al. used the microwave sintering method to fabricate bismuth ferrite (BFO, a shorter form of $BiFeO_3$) ceramics with a denser structure and smaller and more uniform grains. The obtained BFO ceramics exhibits a typical antiferromagnetic behaviour [25].

Using microwave sintering, Yang et al. successfully prepared lithium titanate, Li_2TiO_3, ceramic pebbles with a fine, uniform microstructure and high density. The phase transition from α to β-Li_2TiO_3 was enhanced by microwave sintering [26].

Zhan et al. synthesized β-SiC via microwave sintering and achieved uniform heating and a short production cycle, which makes the process more energy efficient. The obtained material had a uniform particle size distribution [27].

Complex-shape alumina parts were produced using microwave sintering by Curto et al. The shaped parts had high relative density (98%) and improved elastic modulus and Vickers hardness [28].

Microwave sintering was applied by Presenda et al. to consolidate yttria-stabilized zirconia polycrystalline ceramics. The results showed a finer microstructure and improved mechanical properties such as hardness and fracture toughness in comparison to conventional sintering as well as a reduction in time and energy [29].

Khalid et al. used hybrid microwave sintering to prepare Al_2O_3-ZrO_2 ceramics. The sintering time was significantly reduced while the obtained samples exhibited very high relative densities and increased fracture toughness [30].

Porous silicon nitride ceramics were prepared via microwave sintering by Chun-Fang et al. The samples showed an interwoven microstructure, a high closed-cell ratio and a uniform grain size [31].

Xu et al. produced silicon nitride, Si_3N_4, ceramics by microwave sintering. The process enhanced the grain growth and the formation of a bimodal microstructure. Mechanical properties such as relative density, hardness, and fracture toughness were improved [32].

5.2 Composites

Mohankumar Madhan and Gopalakrishnan Prabhakaran produced Al_2O_3-SiC ceramic composites by both conventional and microwave sintering. The results show that the addition of SiC particles, in combination with the microwave sintering method, enhance the properties of Al_2O_3-SiC ceramic composites such as higher density and hardness, uniform grain formation, enhanced fracture toughness and reduced sintering time [33].

Wei et al. fabricated W-30Cu composites by microwave sintering [34].

In order to improve the properties, Yao et al. prepared HA/TiO_2 (titanium dioxide) composite by microwave sintering. The obtained composites exhibited high densification and fine grains as well as improvements in micro-hardness and elastic modulus [35].

The grain growth kinetics of $10Nb_2O_5$-$7.5La_2O_3$-$82.5Al_2O_3$ composite ceramics was investigated by Lü et al. They found that microwave sintering is superior to the conventional sintering technology regarding the growth of Al_2O_3 columnar crystal in the composite ceramics [36].

Prakash et al. fabricated Ti-Nb-HA composites with a highly porous structure, low elastic modulus, high compressive strength and enhanced bioactivity [37].

Sung-Tag Oh et al. fabricated porous ceramic Al_2O_3/ZrO_2 composites with mechanical properties improved by microwave sintering. The microstructure of the obtained composite

showed enhanced neck growth due to the selective heating effect. During the heating of the composite, there is a large increase in the dielectric loss factor of ZrO_2, which leads to localized heating. This heating effect causes the preferential neck growth between particles [38].

Hou et al. used pressureless microwave sintering to fabricate a high performance metal-diamond composite material with excellent mechanical properties [39].

Peng et al. synthesized boronised Ti6Al4V/HA composite by microwave sintering. The composite exhibited satisfactory mechanical performance and bioactivity for usage as a dental implant material with a superior quality [40].

WC-Co samples were microwave-sintered at varying sintering temperatures by Rumman et al. They achieved rapid and uniform heating and a reduced temperature with grain growth inhibition while the obtained material exhibited improved microstructural and mechanical properties [41].

Wong et al. reported that the use of hybrid microwave sintering showed great potential improvements: a reduction in the sintering time (by 85%) and an increased energy efficiency of 96% with respect to the conventional sintering of magnesium-based composite containing nano-size Al_2O_3 particulates. Characterization revealed a continuous network of nano-size Al_2O_3 and an improvement in hardness [42].

The sintering behaviour of zirconia nanocomposite powders doped with ceria and toughened with alumina (10Ce-TZP/Al_2O_3) was investigated through conventional and microwave sintering by Gil-Flores et al. Microwave sintering produced a composite with a fine microstructure and improved mechanical properties and resulted in time and energy savings [43].

Nie et al. found that doping hydroxyapatite (HA) with nano-TiO_2 by using microwave heating is an effective technique for producing HA/βTCP composite load-bearing implants in clinical applications due to the improvement in relative density and inhibited grain growth [44].

5.3 Metals and alloys

A novel method for preparing FeMn78C8.0 bulk alloy via microwave sintering was presented by Chen et al. The obtained bulk alloy possessed an enhanced volume density with a much lower phosphorus content in comparison with traditionally produced ones [45].

Hou et al. developed a high performance metal-diamond composite material with excellent mechanical properties by microwave sintering [39].

Porous Ti-3Cu alloys with high antibacterial rates and improved mechanical properties were successfully prepared via microwave sintering by Tao et al. [46].

Wang et al. fabricated FeCuCo metallic matrix diamond tool bits by microwave sintering. The obtained tool bits exhibited better adhesive strength, a relative density of 95.14% and improved hardness. Moreover, the sintering time was dramatically shortened [47].

Nagaraju et al. successfully fabricated stainless steel 316L (X2CrNiMo17-12-2) powder samples using the microwave sintering route. The sintered material had a relative density of 90%, with a reduced pore concentration and an enhanced pore size [48].

Anklekar et al. successfully sintered the rupture bar samples of copper steel by using the microwave technique. They obtained a material with mechanical properties superior to those of conventionally sintered materials, such as higher density and better hardness and flexural strength [49].

Microwave-assisted sintering of Al-Cu-Mg-Si-Sn alloy was conducted by Padmavathi et al. A pre-alloyed powder compact was successfully fabricated with a 55% decrease in processing time while still achieving a high sintered density of 98% [50].

Pre-mixed and pre-alloyed Cu-Sn bronze was sintered in a microwave furnace by Sethi et al. Compared to the conventional sintering, the microwave sintering produced bronze compacts with improved hardness and a uniform microstructure which offers an opportunity for extending their use [51].

Zhou et al. successfully sintered 90W–7Ni–3Fe heavy alloys by the microwave technique at different heating rates. The obtained samples exhibited a relative density of over 99%, improved yield and tensile strengths and elongations of around 20%. Moreover, the mechanical properties are further improved under optimized conditions [52].

5.4 Other

Gunnewiek et al. successfully applied rapid microwave sintering to obtain a ZnO (zinc oxide)-based varistor with low additive levels. Samples were sintered at 950 °C for only 10 minutes and subsequently showed a homogeneous microstructure, 94% of theoretical density and improved electrical properties [53].

Microwave heating was reported as a potential method for preparing glass with a substantial reduction in energy consumption and processing time. Mandal et al. successfully prepared barium borosilicate glass [54] and alumino-phosphate glass [55] in a microwave furnace.

Boccaccini et al. fabricated porous glass matrix composites by microwave-assisted densification of powder compacts. Spherical pores are obtained while the time and energy required for the process are reduced [56].

6. Conclusion

As opposed to conventional sintering where heat is transferred via conduction from the outside to the inside of the material, in the microwave heating process, the energy is absorbed by the material, and the heat is generated internally and transferred to the outside. This ensures a uniform nanometric microstructure of the final product and therefore improved mechanical properties. Besides, microwave heating has other advantages, such as a reduced processing time, thus a lower energy consumption, reduced processing costs, very high heating rates (> 400 °C/min), ability to achieve a high degree of densification, and enhanced mechanical properties of the final product. In addition to the improvement in mechanical properties, microwave heating, as a promising technology, has potential for improving the material physical properties and the production quality, while enabling the production of innovative and advanced materials.

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