Applications of Microwave Technology for Industry

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Abstract

Microwave processing of materials is being looked as a promising option for enhancing material properties after heat treatment. Along with enhancement of properties, the technique also offers economic advantages through energy savings and accelerated product / process developments. Microwave processing is a new, powerful tool that is being exploited by material processors to achieve new goals that may not be attainable by employing conventional process routes. Apart from ceramic processing, the most recent application of microwave technology reported is in metallic materials specially for sintering, brazing/joining and melting etc. Developments of number of commercial powder-metal components using various alloys and different shapes have been reported by international researchers along with the advantages they could achieve. The study indicated a variety of possible microstructures that can be obtained by microwave sintering due to totally different heating mechanisms. This paper presents an overview of activities carried out in ceramics and powder metal processing internationally.

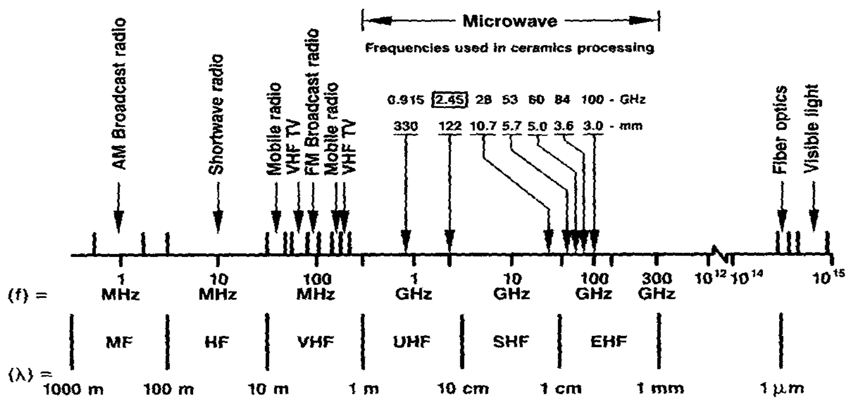
Introduction

In processing industries, Microwave technique is being tried out in wide spectrum of applications due to its unique and advantageous characteristics. Microwave processing is Selective, Effective, Rapid, Versatile and Energy Saving, so that we can state that it **SERVES.** This is the reason due to which it could attain added significance in different processing areas and sectors in Material Science. The present context of emphasis on energy saving through effective and efficient energy usage as well as stringent pollution control norms for industries, makes entry of Microwave Technology into various industries unavoidable. In this light, the importance of Microwave Assisted Processing (MAP) is being looked in seriously in ceramics, metallurgy, composites, polymers, and minerals based industries.

Conventional heating and sintering processes for different materials requires considerable power input. In many conventional processes, a major problem is that the time required for consolidation at high temperatures is quite long, and as a result, undesirable coarse microstructures with grain boundary impurity phases are invariably formed. To avoid this few critical components requires post sintering treatments (such as HIP) and machining, which add to the processing costs. Finer microstructures and near theoretical densities in metallic components are still elusive and challenging. For improving properties, new forming techniques are being introduced such as injection molding, HIPing, Spray forming etc. But still the ongoing debate has always centered on properties of the final products such as strength and size. As these properties are primarily based on the grain size and microstructure, the conventional sintering process is unable to deliver better product due to its inherent limitations. Microwave Heating Technique is found to be much more useful at this stage due to its several anticipated advantages, namely: a) the process produces fine microstructures and b) improved properties due to the enhanced diffusion processes with concomitantly reduced sintering times, c) reduced energy consumption, d) no environmental hazards.

Basics of Microwave

Microwaves are electromagnetic waves having frequencies in the range of 0.3 to 300 GHz corresponding wavelength ranging between 1m to 1 mm (Fig.1).



Electromagnetic spectrum and frequrncies used in microwave processing of ceramic materials

Figure 1: Electro magnetic spectrum and frequencies used in microwave processing of ceramic materials

The major application of microwaves is in communication. To avoid interference, only few selected bands are allocated by Federal Communications Commission for Industrial, Scientific and Medical applications known as **ISM** band. Frequency bands allocated are 896, 915, 2450, 5800, 28000, 60000 and 84000 Hz. Out of these, 2450 Hz is used worldwide while others used by few selected nations.

In contrast with visible light, except for lasers, microwaves are coherent and polarized. They obey the law of optics and can be transmitted, absorbed or reflected, depending on the material type *[W.H.Sutton, Am. Ceram. Soc. Bull., 68 (1989)376, D.E.Clark, W.H.Sutton, "Microwave Theory and Applications in Material Processing, IV, vol.80, Eds. David Clark, Jon Binner, David Lewis, Am. Ceram. Soc., 1997,61, John Brooske, Reid Cooper, Samual Freeman, Kirill Raybakov and Vladimir Semenov, "Microwave Theory and Applications in Material Processing, IV, vol.80, Eds. David Clark, Jon Binner, David Lewis, Am. Ceram.*

Soc., 1997,143]. Microwave interaction of materials could be broadly categorized in four different types.

i) Conductors i.e. metals having free electrons in bulk form are 'opaque' to microwaves and thus good reflectors.

ii) Insulators, where electrons do not flow freely are electrically non-conducting type materials such as ceramics (viz. Al_2O_3, MgO, SiO_2, glasses etc.) are 'transparent' to microwaves. But, electronic reorientation or distortions of induced or paramanent dipoles can give rise to heating.

iii) Dielectric materials possess the properties ranging from conductors to insulators. These materials are polarizable and have dipoles that reorient rapidly in response to changing electric field strength are amenable to microwave heating at low temperatures. Example of such ceramic materials are Co_2O_3, MnO_2, NiO, CuO, ZrO_2 etc. which are good 'absorbers' of microwaves at room temperature.

iv) In other materials such as composite materials the absorption of microwaves can be enhanced by adding conducting or magnetic materials. These additives absorb microwaves more rapidly than the matrix and hence material will be heated more rapidly and selectively.

Microwave heating

The microwave heating is a fundamentally different type of heating process compared to the traditional heating processes adopted in industry. In conventional heating process, the material is heated with external source of heating, such as oil, gas or electrical resistance heating etc. where energy is transferred to samples mainly by radiation, and then by conduction. Whereas in microwave processing, the heat is generated internally within the material. This is due to interaction of microwaves at an atomic level in the material. This results in uniform, internal, volumetric and selective heating of the material.

Microwaves are not forms of heat but rather forms of energy that are manifested as heat through their interaction with materials [*Robert Schiffmann, "Microwave Theory and Applications in Material Processing, IV, vol.80, Eds. David Clark, Jon Binner, David Lewis, Am. Ceram. Soc., 1997,41*]. As microwaves are electromagnetic waves the energy content and amplitude changes as it travels through a medium. They consist of electrical (E) and magnetic (H) components mutually perpendicular to each other in the direction of travel. When the E component at some point is zero; then it builds up to a maximum value, decays to zero, and again builds up to maximum value with the opposite polarity before again decaying to zero. This periodic flip-flopping of the wave polarity (in both electric 'E" and magnetic 'H' component) and decay through zero causes stress in the ions, atoms, and molecules and the energy is lost within the material in the form of heat. Greater the field strength, the greater will be the effect. At the macroscopic level, the dielectric properties control the microwave processibility of a wide range of nonmagnetic materials.

Many mechanisms are reported in the literature explaining the conversion of microwaves into heat. Two important mechanisms are taken into consideration viz. conduction and polarization while heating of material. Polarization involves the short-range displacement of charge through the formation and rotation of dielectric dipoles (or magnetic dipoles if present) and is dominant at higher frequencies. Conduction requires the long-range (compared to rotation) transport of charge and is dominant at low frequencies [*D.E.Clark, W.H.Sutton, "Microwave Theory and Applications in Material Processing, IV, vol.80, Eds. David Clark, Jon Binner, David Lewis, Am. Ceram. Soc., 1997,61*].

The power dissipated in multimode systems is thus governed by the equation 1:

$$P = \omega\,(\varepsilon_0\,\varepsilon_{eff}''\,E^2 + \mu_0\,\mu''\,H^2) \qquad (1)$$

Where, P = power absorbed (W/m^3), ω = angular frequency = 2 πf where f is operating frequency, ε_0 = permittivity of free space (8.85×10^{-12} F/m), ε_{eff}'' = effective dielectric loss factor, E = internal electric field strength (V/m), μ_0 = permeability of free space, μ'' = magnetic loss factor, H = intensity of magnetic field.

International scenario in metal powder processing

The earliest work of microwave interaction with metallic powders is reported by Nishitani [T. Nishitani, "Method for sintering refractories and an apparatus therefor," US Patent # 4,147,911 Apr. 3, 1979] who reported that by adding few percent of electrically conducting powders such as aluminum, the heating rates of the refractory ceramics is considerably enhanced. Walkiewicz et al [J. W. Walkiewicz, Kazonich, G., and McGill, S. L., "Microwave heating characteristics of selected minerals and compounds," *Min. Metall. Processing*, 39-42, 1988] likewise simply exposed a range of materials, including six metals to a 2.4 GHz field, and reported modest heating and not sintering in the range from 120°C (Mg) to 768°C (Fe). Whittaker and Mingos [G. Whittaker, Mingos, D. M., "Microwave-assisted solid-state reactions involving metal powders*," J. Chem. Soc. Dalton Trans*. 2073-2079, 1995] used the high exothermic reaction rates of metal powders with sulfur for the microwave-induced synthesis of metal sulphides. But in all these studies no sintering of pure metal or alloy powders was reported. It was only in 1998 in this laboratory that the first attempt of microwave **sintering** of powder metals (15). This was a radical discovery and now has opened up entirely new avenues of research and processing of metallic materials including sintering, melting, brazing, joining, and coatings etc. The mechanism of microwave-matter interaction is unexplained so far. It is also not determined if microwave sintering will work on all metals, alloys, and intermetallics or if there will be selective heating, as in the case of many ceramics.

Microwave Processing and Engineering Center of The Pennsylvania State University , USA reported that virtually all metals, alloys and intermetallics couple and heat efficiently and effectively in microwave field, and their green parts produce highly sintered bodies with improved mechanical properties. They reported sintering of commercial steel compositions such as FN208 and FC208 in 90 min. when sintered between 1100 to 1300 deg. C and soaking time 5-30 min. The products were highly sintered bodies with increase in mechanical properties (in FN 208, the MOR higher by 60%) [R.Roy D. Agrawal, J. Cheng, and S. Gedevanishvili, "Full sintering of powdered metals parts in microwaves", Nature**,** 399, 664 (June 17, 1999), R. M. Ankalekar, D.K. Agrawal, and R. Roy, "Microwave Sintering and Mechanical Properties of P/M Steel", Powder Metal. Vol. 44[4], 355-362 (2001), D.Agrwal, Proc. Powd. Metallurgy World Congress, Kyoto, Japan, 797-800, 2000].

Microwave sintered commercial powder metal parts by Microwave Processing and Engineering Center of The Pennsylvania State University, USA.

Researchers of University of Edinburgh, UK, studied the ability of metal powders in synthesis of metal chalcogenides and metal cluster compound using microwave technique. They reported efficient coupling of microwaves without arcing and selective nature of heating that resulted into range of solid state reactions [A.Gavin Whittaker and Michael Mingos, J. Chem. Soc.Dalton Trans., 2073-2079 (1995)].

Utilization of microwave sintering technique for pressureless fast sintering of metal based composites was reported by University of Dortmund,Germany. They reported sintering of tungsten carbide-cobalt based hard metal based composites150 deg. C lower than conventional sintering process. The composites indicated much higher mechanical properties due to reduction in closed and open porosity (<1%) at the sintering temperature of 1150 deg. C compared to conventionally sintered samples at 1300 deg. C (>5 closed and 25% open porosity respectively). They interpreted that microwave processing influences the mechanism of liquid phase sintering. The mechanism reported is local formation of eutectic liquid due to thermal non-equilibrium during microwave sintering, or an accelerated distribution of carbon, Co by evaporation and condensation throughout the sintered body due to ohmic and local plasma heating, followed by dissolution of carbon and W within parent crystals [T.Gerdes, M.Willert Porada, K. Rodiger, Mat. Res. Soc. Proc., vol.430, 45-50, 1996].

Edward B. Ripley and Jason Oberhaus of BWXT Y-12 National Security Complex, Oakridge, USA reported melting and heat treating of metals using microwave heating. Metals that have been melted and cast include steels, titanium, zirconium, uranium, copper, brass, bronze, aluminum, and many alloy systems. Melt size range up to 350 kg. They also reported three distinct methods to heat treat metals using microwave furnace: molten salt-bath processing, granular suscepting media and fluidized bed process. Based on their results, it was concluded that microwaves can successfully heat treat metal components without any negative effects on the metal. Hardness values and microstructures were similar to those obtained using conventional heat treatment process.

Application of microwaves in ceramics & refractories

The use of microwave process in ceramic and refractory can be divided into two areas depending on temperature of application. Low temperature (i.e. < 500^0C) applications are in drying, binder-burnout, de-waxing etc. while, high temperature (i.e. >500^0C) in calcining, firing, sintering and melting.

Low temperature applications

Water readily interact with microwaves at room temperature, thus it is very efficient way to eliminate residual moisture in a product. It may be noted that removal of water above 5-10% is more economical by adopting conventional processes and not microwave technique. Conventional processes are very inefficient at low moisture contents, where microwave is very efficient. One of the first commercial application of microwave was in drying and curing of foundry mould was reported by Schroeder et al. [*R.E. Schroeder and W.S. Hackett, Br. Foundryman, Aug, 1971,293*], where time was reduced to half to one tenth of that required by conventional heating. Microwave technology was adopted in drying of space–shuttle tiles [*G.fisher, Ceram. Ind., 121 (1), 1983, 40*] and large fibrous silica insulating blocks [*R.E.Stengel, Process design news, Sept, 1974, 24*]. Microwaves have been used to precisely control the moisture content in clays, dry pigments and other powders to avoid agglomeration/clustering during transportation.

High temperature applications

Using microwave energy, calcinations, firing, sintering and melting of different materials have been investigated. Schurbring [*N.W.Schurbring, Tech. Repot. GMR4471, GM Res. Lab., 1983, 1*] sintered 186 alumina spark plug insulators at 1600^0C in 2.6 h having quality comparable to the conventionally gas fired product. Microwave firing required only 50% energy as compared to the conventional firing. Sutton [*W.H.Sutton, Microwave processing of materials, vol.124, Eds. W.H.Sutton, M.H.Brooks and I.J.Chabinsky, Mat. Res. Soc., Pittsburgh 1988, 287*] employed microwave technology in drying and firing of high alumina castables weighing 68 kg and lengths up to 1 m. In the first stage drying was done at low power while during second stage power was increased until firing temperature of around 1400^0C was achieved. They reported 50% faster, 20-30% lower energy cost during microwave processing compared to gas-fired production process for the same product.

Many ceramic materials such as alumina, glass-ceramic materials exhibit low loss tangent values below critical temperature T_{crit}. However, their heating rate can be greatly increased by adding second conducting phase such as SiC. The microwave absorption of lithium alumino-silicate glass ceramic could be dramatically increased by adding SiC fibers. Conventionally bonded non-oxides such as carbides and nitrides are not effectively densified by conventional pressureless sintering without adding sintering aids which eventually forms an unwanted second phase. Kartz et al.[*J.D.Katz, R.D.Blake, J.J.Petrovic and H.Scheinberg, Microwave processing of materials, vol.124, Eds. W.h.Sutton, M.H.Brooks and I.J.Chabinsky, Mat. Res. Soc., Pittsburgh 1988, 219*] sintered B_4C without adding sintering aid at 2000^0C and reported 95% theoretical density which could be achieved by conventional heating at 2100^0C after addition of sintering aids such $C/TiB_2/AlF_3$. Over a decade, the Penn State's Microwave Research Center headed by Dr. Dinesh Agrawal and his group reported processing of wide verity of materials at high temperature. The work includs oxides and non-oxides, electro-ceramics and composites [*D.Agrawal, J.Cheng, Y.Fang and R.Roy, Microwave solutions for ceramic engineers, Eds. David Clark, Diane Folz, Carlos Folgar, and Morsi Mahmoud, The Am.Ceram.Soc.2005,205*]. They reported sintering of refractory oxides such as alumina, and zirconia to near full density at much lower temperatures and dramatically shorter sintering times than required in a conventional methods. Sintering of Indian alumina grit with particle size 0.8 -1.0 mm was sintered in microwave at 1500^0C for 15 min. to achieve density of 3.96 g/cm^3. At this center, alumina tube with diameter 1 cm to 10 cm and length up to 2 m were prepared using continuous microwave system. These products indicated uniform sintering with density around 95% theoretical. They have reported fabrication of transparent ceramics using alumina, spinal, mullite, ALN and AlON in a single step processing at ambient pressure.

Concluding remarks

From the above the benefits of microwave technology reported can be summarized as:

1) Cost savings due to dramatic reduction in processing time and energy.
2) Precise, controlled, instantaneous and selective heating.
3) Volumetric and uniform heating.
4) Improved quality and properties.
5) Environment friendly process as it is clean, and quiet process that reduces hazardous emissions,
6) Synthesis of new materials is possible
7) Processing of materials not possible with conventional means can be processed.

Although considerable work and investment has been made over many years for developing microwave processing systems for a range of products, most of them are by small industrial the microwave companies working closely with the user company where the user gets a proprietary process and microwave company gets exclusive manufacturing rights. Due to which the technology that has developed is not freely available. Other significant reasons responsible for slower growth are :The complexity and cost of the equipment, Limited applicability, The inherent inefficiency of conversion of electric power, Need to perform expensive feasibility studies.

To popularize this technology, the technocrats need to do generate and collect complete and consistent information about dielectric properties of wide range of materials at high temperatures and at various frequencies, develop empirical simplified models and "microwave heating diagrams" to predict the internal fields, heating patterns and rates, so the optimum process parameters can be developed to meet product requirements. Establish standards for measurements of temperature to ensure reproducibility and reliability and establish a multidisciplinary interactions with experts. The real key to success is to understand the basics with respect to microwave heating.

Blind application of microwave may lead to disappointment. However, Wise application may have greater advantages than had been anticipated

Please Note:

A research facility "INDUSTRIAL MICROWAVE RESEARCH CENTER" has been established by M/s Pradeep Metals Ltd. at Navi-Mumbai, to carry out applied research for real life requirements for Indian industry and to convert potential applications to reality. The center has established a laboratory set up where around 300 g sample can be treated up to 1100 deg. C using microwave technique for preliminary exploratory trials. A pilot-scale Microwave system with 3 KW power is also installed for conducting scale up trials (~2 kg) up to 1600 deg. C under normal/controlled atmosphere. We welcome you to visit us and discuss in details about your ideas. We also undertake designing and supply of microwave system as per client's requirements. Shortly a continuous high temperature microwave system will be installed where the industry can see how samples can be heated continuously in a commercial microwave system.