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Microwave sintering: An energy efficient process for sintering aluminium metal powder

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Microwave sintering process is quite significant and unique in recent times for sintering material for densification because of its intrinsic advantages such as rapid heating rates, reduced processing times, uniform temperatures with minimal thermal gradients. Microwave sintering process leads to substantial energy savings with higher efficiency, improved properties, finer microstructures, environmental friendly process and with less environmental hazards. The concept of sintering metals in microwave has been attempted by many researcher. Though metals are known to reflect microwave radiation, researchers have confirmed sintering of metas in powder form through microwave. In this study, sintering of aluminium metal powder through microwave route has been attempted. The study indicated that aluminium metal powder compacts sintered through microwave process showed better physical, tribological and thermal properties compared to the ones sintered through conventional sintering methods.

Keywords : *Microwave, sintering, aluminium powder, sintering ceramic, tribological properties*

1.0 INTRODUCTION

Processing of ceramic materials through microwave energy was known by the 1950s and has been investigated by Tinga *et al.* Levinson and Bennett *et al.* on a limited basis by the 1960s. Microwave sintering of materials is fundamentally different from conventional sintering in that the heat is generated internally within the material instead of originating from an external heating and subsequent radiant transfer. Microwave sintering is a very sensitive function of the material being processed and depends upon such factors such as size, geometry and mass of the sample. Microwave interacts with materials at molecular or atomic levels to generate heat. The degree of interaction between the microwaves and the material of choice strongly determine whether a material can be heated and how to design the microwave heating equipment and parameters used. Therefore, it is very important to understand how different materials absorb microwave energy. The microwave sintered materials are expected to yield better properties compared to the products that are obtained through conventionally sintering methods [1, 2, 3].

Microwaves induce rapid heating in the material depending upon its dielectric property. When the microwave propagates or penetrates through the material, the internal electric fields within the affected Volume induces translational motions of free and bound charges in the material such as electrons or ions and rotate the charge complexes such as the dipoles. These induced translational motions are resisted by elastic and frictional forces within the material thereby causing loss and attenuation of the field generating heat within. This causes rapid and uniform heating throughout [4].

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Microwave sintering is a process in which the materials to be sintered couple with microwaves, absorb the electromagnetic energy vol. umetrically, and transform into heat. This heating mechanism enhances diffusion process, reduces energy consumption, has rapid heating rates and reduces processing time. Microwave sintering improves physical and mechanical properties of the material [5, 1].

Materials that have a high dielectric loss couple well with microwaves while the poor lossy materials with no absorption at room temperature require initial heating using some kind of secondary susceptors. For most powder metals, no susceptor is needed, but it is mainly used to provide uniform temperature distribution throughout the sample to obtain uniform sintering.

Initially use of microwaves was to process microwave absorbing materials such as oxide or non-oxide ceramics only, but the concept has been extended to sinter metallic powders from commercial sources using a 2.45 GHz microwave field yielding dense products with improved mechanical properties compared to those sintered conventionally. These findings were surprising in view of the reflectivity of the bulk metals to the microwave frequencies.

The microwave research group at the materials research institute of the Pennsylvania State University, however, made the first step advance in the microwave sintering of many traditional and advanced ceramic materials such as alumina, mullite and hydroxyl apatite, by demonstrating rapid sintering in time intervals varying from 3-20 min. leading to transparency and almost full density. This same step function advance in ceramic processing has been extended to other commercial ceramics such as zirconia, zinc oxide, perovskites, and silicon nitride. Microwave sintering can lead to near theoretical densities in most materials in less than 30 min [6].

Over the past decade microwave sintering chambers capable of processing a variety of samples with different shapes and sizes, and maintaining any temperature ranges between RT to 1500° C has been developed, in exceptional cases up to 1800 to 2000° C. The microwave generators are operated at a frequency of 2.45 GHz with power output ranging from 1 to 6 kW in both single and multimode operations are possible [6]. A typical microwave oven has either an alumina or silicon carbide tube surrounded by ceramic high temperature insulation fibers. The primary function of the insulation is to preserve the heat in the oven. Insulation does not absorb microwave at the lower temperature range. But at higher temperatures there is some portion of power dissipation between the insulation and the sample. Temperatures are read by optical pyrometers or sheathed thermocouples placed very close to the surface of the sample. The relative temperature readings are accurate to ± 5° C. The absolute temperature monitoring is not established to anywhere near that precision. Different controlled atmospheres such as air to $H_{2,}$ to forming gas to oxygen can be used. Typically the total sintering time would be ~ 90 minutes. With the use of microwave susceptors, the heating cycle can be rapid.

It is reported that microwave sintered ceramic reinforced aluminium composites have good microstructure that helps to produce materials with better properties such as light weight, dense, hard, better engineering properties including effective Electro Magnetic Interference (EMI) shielding and vibration damping properties. The composites have also been reported to give rise to significant improvements in mechanical properties such as high strength, high stiffness, better thermal properties like low coefficient of thermal expansion and lower thermal conductivity, better acoustic property and damping characteristics.

In the conventional heat treatment, the heat penetrates the body from outside to inside creating a temperature gradient; therefore it is not possible to heat those samples at a very high heating rate. This results in long cycle time and makes the process energy intensive [7]. The consolidation of metal matrix composites has been reported to give rise to significant improvements in mechanical properties such as high strength, high stiffness, better thermal properties like low coefficient of thermal expansion and lower thermal conductivity, better acoustic property and damping characteristic and EMI shielding properties. The microwave sintered composites are expected to yield better properties compared to the composite products that are obtained through conventionally sintering methods.

M. Gupta *et al.* [1] have reported the enhanced overall mechanical performance of metallic materials processed using two directional microwave assisted rapid sintering. The feasibility of densifying α SiC powder compacts based on a liquid assisted sintering approach by the use of microwave furnaces was examined by A. Goldstein *et al.* [8]. They have also reported the properties of the material.

Ramesh D *et al.* [2] studied the microwave induced reaction sintering of $NiAl_2O_4$. The anisothermal reaction condition leading to enhanced reaction kinetics of $NiAl_2O_4$ formation have been achieved by the group when they carried out simultaneous synthesis and sintering of $NiAl_2O_4$ from NiO+ Al_2O_3 powder mixture in just 15 minutes in a 2.45 GHz microwave field. Mulletization and Densification of powder compacts of 3 Al_2O_3 and 2 SiO_2 by microwave sintering were achieved by Piluso *et al.*[3].

Ebadzadeh *et al.* [9] also reported the microwave assisted synthesis and sintering of ceramics like mullite. A comparative study of microwave and conventional processing of $MgAl_2O_4$ based spinel material has been reported by Idalia Gomez *et al.*[10].

Hermann Riedel *et al.* [11] have studied on the simulation of microwave sintering with advanced sintering models. Panneer Selvam *et al.* [12] have studied on the preparation of Si_3N_4SiC composite by microwave route. Gerdes *et al.* [13] have reported that on sintering of metal powder in an unprecedented approach, sintering of fine metallic powders, intermetallic compounds and alloys was achieved by microwave sintering process wherein the sintered products showed better properties. Rustum Roy *et al.* [14] have reported that the ability to sinter metals with microwaves would assist in the preparation of high-performance metal parts needed in many industries, for example, in the automotive industry and Mg–Cu nanocomposites have been developed using microwave assisted sintering method [15].

Unlike bulk metals that act as reflector, it is believed that in finely divided metallic powder, multiple scattering coupled with eddy current loss play a significant role in microwave absorption S Das *et al.* [16]. During drying of high alumina castables, Sutton [4] observed that in addition to removing of water, microwave also heated the ceramics. Some microwave ovens are available in the temperature range of 1400^0 C that are lined with non-microwave absorbing refractories. Hence microwave energy can be used for processing full scale ceramic products. Microwave processing is observed to be faster, highly cost effective and products with superior performance can be achieved.Ananda Kumar *et al.* [17] have studied the physical and morphological characteristics of aluminium cenospheres composite sintered at high temperature in microwave.

2.0 MICROWAVE

Microwaves can be defined as that part of the electromagnetic radiation spectrum having a wavelength ranging from about 1 mm to 1 metre in free space and the frequency ranging from 300 MHz to 300 GHz. However, only narrow frequency bands centered at 915 MHz and 2.45 GHz, 28-30 GHz and 80-81 GHz are actually permitted for research purposes (Figure 1). They are coherent and polarized waves obeying the laws of optics. Depending upon the type of material the microwave may get transmitted, absorbed or reflected by the materials [4].
The power absorbed per unit Volume, P (W/m^3) is expressed as [18, 4].

$$P = \sigma \, |E\,|^2 = 2\pi \, f \, \varepsilon_0 \, \varepsilon' r \tan \delta \, |\, E|^2 \qquad \text{....(1)}$$

where E (V/m) is the magnitude of the internal field, σ the total effective conductivity (S/m), f the frequency (GHz), ε_0 the permittivity of free space ($\boldsymbol{\varepsilon_0} = 8.86 \times 10^{-12}$ F/m), ε'_r the relative dielectric constant and tan δ the loss tangent. Equation (1) demonstrates that the power absorbed varies linearly with the frequency, the relative dielectric constant, loss tangent and the square of the electric field.

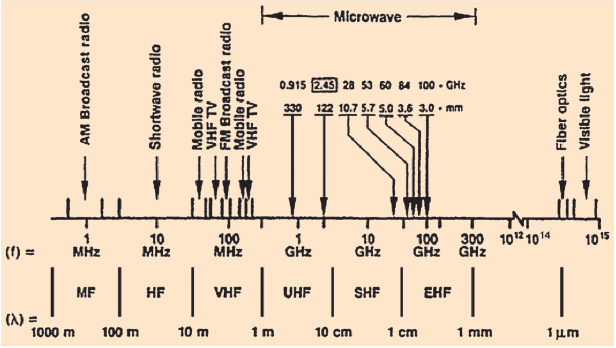

FIG. 1 THEELECTROMAGNETIC SPECTRUM AND MW FREQUENCIES FOR PROCESSING MATERIALS [18]

The penetration depth of microwaves (D) at which the incident power is reduced by one half is expressed as [4]

$$D = 3\lambda_0/8.686\ \pi\ \tan\delta\ (\varepsilon'\ r/\varepsilon_0)^{\frac{1}{2}} \qquad \ldots.(2)$$

where $\boldsymbol{\lambda_0}$ is the incident or free-space wavelength. The relative dielectric constant and the loss tangent are the parameters that describe the behaviour of a dielectric material under the influence of the microwave field. During heating, the relative dielectric constant and the loss tangent change with temperature [16]

The degree of absorption by dielectric material is related to the materials complex permittivity $\boldsymbol{\varepsilon^*}$ (F/m)) which is composed of two components i.e. $\boldsymbol{\varepsilon'}$ (dielectric constant) the real part and an imaginary part $\boldsymbol{\varepsilon''}$(dielectric loss factor) by:

$$\varepsilon^* = \varepsilon' - j\,\varepsilon'' = \varepsilon_0\,(\varepsilon^* r - j\,\varepsilon''_{eff}) \qquad \ldots.(3)$$

where $j = (-1)^{1/2}$, $\varepsilon_0$is the permittivity of free space ($\varepsilon_0 = 8.86 \times 10^{-12}$ F/m), ε'_r is the relative dielectric constant, and ε'' is the effective relative dielectric loss factor. The dielectric constant K or the relative permittivity ε_r, the dissipation factor (tan δ) and the dielectric loss ($\varepsilon_r \times \tan\delta$) of the material that is being processed and their dependence on temperature generally dictates to a large extent the microwave power absorption characteristics during microwave sintering of ceramic materials. For dielectric heating the generated power density per Vol.ume is calculated by

$$p = \omega\ .\ \varepsilon''_r\ .\ \varepsilon_0\ .\ E^2 \qquad \ldots.(4)$$

where ω is the angular frequency ε_r'' is the imaginary part of the complex relative permittivity, $\boldsymbol{\varepsilon_0}$ is the permittivity of free space and E the electric field strength. The imaginary part of the complex relative permittivity is a measure for the ability of dielectric material to convert radio frequency electromagnetic field energy into heat.

Theoretically, the degree of microwave interaction with a material can be inferred through its dielectric and magnetic properties. For a material that is not significantly magnetic, the microwave interaction with that material depends on the complex permittivity ε, which is defined as follows:

$$\varepsilon = \varepsilon' - i\varepsilon'' \qquad \ldots.(5)$$

where ε' is the real component of the complex permittivity and ε'' is the imaginary component of the complex permittivity.

The real permittivity is a measure of a material's ability to store electrical energy, while the imaginary permittivity represents the loss of electric field energy in a material. The power absorbed by a material per unit Vol.ume (P) is proportional to the frequency of the applied electric field, as well as to the loss factor and to the square of the local electric field intensity. It can be expressed as follows:

$$P = 2\pi\ f\ \varepsilon 0\ \varepsilon'' E2 \qquad \ldots.(6)$$

where f is the microwave frequency and E is the root mean square (rms) internal electric field intensity, which is related to the local geometry and ε'. When the microwave energy heats a material, the rate of temperature increase in the material can be derived as follows:

$$\frac{dT}{dt} = P/(C_p \rho) \qquad ....(7)$$

where C is the specific heat of the material and ρ is the density of the material. [Chun Li He *et al.* 2013].

3.0 MICROWAVEMATERIAL INTERACTION

Various types of materials interact with microwave in which the microwave may get transmitted (transparent), absorbed or reflected by the materials depending upon the material type. Metals reflect microwave since they are opaque to microwave whereas ceramic materials such as Silica, Alumina, Magnesium Oxide and other glasses are transparent to microwave at ambient temperatures. Above a critical temperature (T_{crit}) these materials absorb and couple effectively with microwave. [6, 4].

The microwave transparent materials are those which have low dielectric losses where in the microwaves pass through them and there is no loss of microwave energy. Whereas in an opaque material the microwave energy gets reflected from the material surface and does not penetrate into the bulk of the material (Figure 2). This property of the material that is opaqueness is used in the radar detection. The microwave absorber materials are high loss materials in which the microwave energy is absorbed into the material depending on its dielectric loss factor. There are a fourth type of material in which there is a mixed absorb of the microwave energy. This type of interaction is common in composite materials which are multiphase material having different materials where one is high loss material and the other is a low loss material. This mixed type absorber material take advantage of the significant characteristic of microwave processing that is selective heating [18].

Materials that have a high dielectric loss couple well with microwaves while the poor lossy materials with no absorption at room temperature require initial heating using some kind of secondary susceptors. For most powder metals, no susceptor is needed, but it is mainly used to provide uniform temperature distribution throughout the sample to obtain uniform sintering.

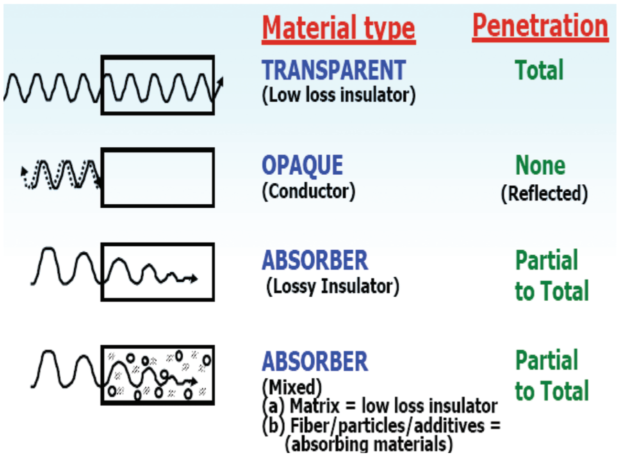

FIG. 2 MICROWAVE MATERIAL INTERACTION [4]

Initially use of microwaves was to process microwave absorbing materials such as oxide or non-oxide ceramics only, but the concept has been extended to sinter metallic powders from commercial sources using a 2.45 GHz microwave field yielding dense products with improved mechanical properties compared to those sintered conventionally. These findings were surprising in view of the reflectivity of the bulk metals to the microwave frequencies.

The applicability of microwave sintering to metals has been simply ignored due to the fact that metals are known to reflect microwaves. The sintering community had explicitly ignored the possibility of sintering their metals using microwaves. Very few papers have reported microwave sintering of powders and alloys, although a couple of papers do report modest heating of metal powders using microwaves [6].

Morteza Oghbaeet al.[18] have reported that metal powders are used for diversified products and applications in the engineering industries. Before the microwave sintering of metal powders, there was a misconception among the researchers that metals reflect microwave or cause plasma formation. The metal powders cannot be heated since microwave has a limited surface penetration on metals. It is reported that this argument is valid only for sintered or bulk metals at room temperatures and not for the metal powders. Presently it if found that the microwave sintering can be efficiently carried out on metal powders as is been done with ceramics. It is also reported that the penetration of microwave in the bulk of the metals is very less which is in the order of a few microns where as the penetration is good and that rapid heating can occur when microwave interacts with metal powders. It is predicted that if the metal powders particle size is less than 100 microns, they effectively absorb microwave at 2.45 GHz and this absorption depends on the electrical conductivity, temperature and frequency.

Further literature survey reports that the following theories put forth by various researchers with regard to the microwave material reactions and their sintering kinetics are as follows:

Ponder motive force interaction in which microwave-excited ionic currents become locally rectified (near the interface), giving rise to an additional driving force for mass transport [19].

Materials with substantial amount of porosity, an enhancement in the electric field at convex surfaces of the pores, providing an non-ohmic and a localized plasma contribution to the driving force for pore removal and thereby accelerated material diffusion [20].

Anisothermal heating caused in two different phases of widely varying microwave absorption characteristics, would provide a strong driving force to cause enhancement in the reaction kinetics followed by sintering [14].

Effect of Electric and Magnetic fields at the grain boundaries [14].

High integrity advanced engineering materials demand for finer microstructure coupled with near theoretical densities in special powder metallurgy products, which are difficult to attain and is a costly process. Microwave sintering offers this need of obtaining finer microstructures in an economical and energy saving process.

4.0 MICROWAVE VERSUS CONVENTIONAL HEATING

Conventional heating usually in Vol.ves the use of a furnace or oil which heats the walls of the reactors by convection or conduction. The core of the sample takes much longer to achieve the target temperature. On the other hand microwave penetrates inside the material and heat is generated through direct microwave-material interaction (Figure 3). Moreover volumetric heating, reaction rate acceleration, higher chemical yield, lower energy usage and different reaction selectivity the advantages microwave heating has over conventional methods.

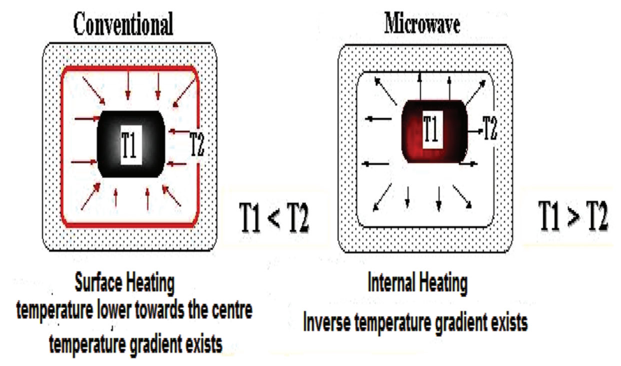

FIG. 3 ILLUSTRATION OF MICROWAVE AND CONVENTIONAL SINTERING OF MATERIAL[21]

Morteza Oghbaei *et al.* [18] and Sutton [4] have concluded that sintering materials with microwave consumes much lower energy than conventional sintering. Due to the enhanced mechanism while sintering in microwave, the diffusion process is intensified leading to better microstructure. Higher heating rates can be attained rapidly which reduces the sintering time by using microwave. The material will attain higher density and better grain distribution through microwave sintering leading to better physical and mechanical properties.

Chandrasekaran *et al.* [22] have reported that the time and energy required for melting of metals was half when using microwave as compared to conventional heating. The melting of metals could be achieved in a microwave sintering furnace of 1300 W capacity where as to melt the metals of the same quantity, it required 2500 W conventional furnace. A temperature of 1673-2073 K can be reached in a low power microwave oven operating at 2-6 kW as compared to conventional induction heating which required 10-150 kW power. They have also reported that a microwave oven of 1300 W took 9 minutes to melt aluminium at a temperature raise rate of 82° C/min where as conventional 2500 W capacity conventional furnace took 29 minutes to melt the same quantity of aluminium at a heating rate of 29° C/min. Conventional heating is much slower compared to microwave sintering which is rapid (Figure 4).

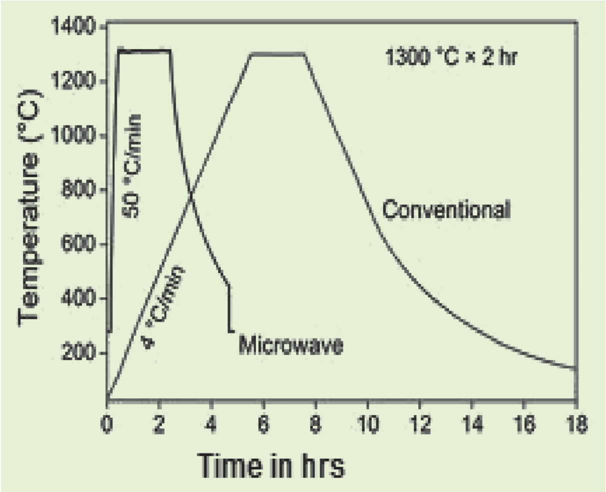

FIG. 4 ILLUSTRATION OF RAPID MICROWAVE SINTERING WITH THAT OF CONVENTIONAL SINTERING OF MATERIAL [21]

While comparing the conventional heating to that of microwave heating, the energetic aspects need to be considered to understand the heating sequence in each of the processes. In case of conventional sintering, the sample has equalized its temperature with the furnace surroundings before the actual heat energy goes into the sample for actual synthesis. This is time consuming since the source of heat is supplied from outside the material during sintering.

In case of microwave sintering, the absorption of heat energy is not limited by the furnace surroundings, and in fact the sample itself becomes the source of heat energy rather than the supply of heat energy from external source. The maximum temperature achieved by microwave sintering depends on the thermal balance between the heat losses and the heat required for synthesis against the microwave input[10].

5.0 EXPERIMENTAL

A study was conducted to assess the sintering behaviour of metal powders in microwave. Aluminium powder (Figure 2) of purity of about 99.5% from M/s. NICE Chemicals [23], which had a particle size range of ASTM 200 mesh (75 µm)was used for the study.

FIG. 5 ALUMINIUM POWDER

The aluminium powder was pressed through cold compaction into cylindrical shaped samples of size 40 mm x 8 mm diameter at a pressure of 25 MPa in a laboratory Enkay make hydraulic press through single ended uniaxial compaction.

The cylindrical shaped samples were prepared for evaluating the compression strength, thermal shock resistance and hardness of the composites. Another set of samples of size having length 50 mm x 15 mm width x 12 mm depth rectangular bar shaped specimens were prepared for the evaluation of flexural strength. The compacted pellets were then taken up for sintering. One set of pellets were sintered in a BHEL make multimode microwave sintering facility model-Sinterware^{TM} (Figure 5) which operates at 1.1 kW and microwave frequency 2.45 GHz. The equipment is programmable with thyristor based controller for sintering cycles, soaking time and temperature.

FIG. 6 MICROWAVE SINTERING FACILITY

The microwave sintering equipment was operated at power level of 100 % with a 90 minutes sintering cycle with soaking time of 42 minutes at maximum set temperature. The sintering time comprised of total 90 minutes from Room Temperature (RT) to maximum set temperature with inclusion of soaking/ dwell time. The sinter cycle comprised of rate of heating at 12° C per minute for sintering and the mix was sintered. The X-Ray Diffraction (XRD) pattern at Figure 7 indicate the presence of pure aluminium metallic phase without oxidation after sintering in microwave at 665° C.

Another set of aluminium pellets were sintering conventionally in a laboratory make muffle type resistance furnace heated with kanthal element, both at a temperature of 665° C which is nearer to the aluminium metal melting temperature.

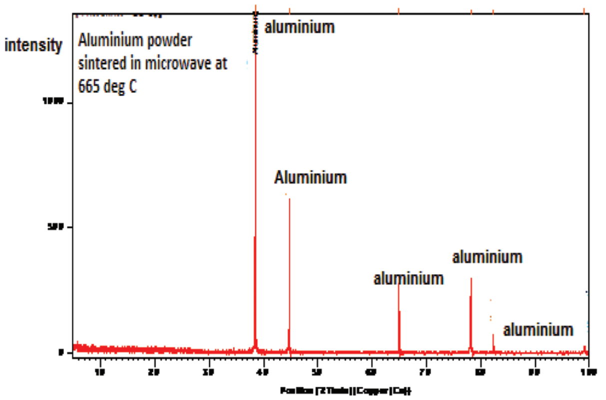

FIG. 7 XRD PATTERN OF ALUMINIUM POWDER SINTERED IN MICROWAVE AT 665° C

Both the type of sintered samples was later taken up for characterization of tribological properties such as wear and erosion loss, mechanical properties such as compression, flexural strength and brinell hardness test and thermal property such as thermal shock resistance test. The findings of the studies have been presented in the results and discussions below.

6.0 RESULTS

6.1 Jet Erosion Resistance Test

The conventionally and microwave sintered samples were subjected to Jet Erosion Test to assess the erosion properties of the composites as per the guidelines of ASTM G76-04 standard [24] which specifies the standard test method for 'Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets'. The test was conducted in the Jet Erosion test rig using silica sand particles for impingement on the sample surface using gas jets supplied through an air compressor. The erosion test was carried out at angles of 30°, 45°, 60° and 90°.

It can be seen from the Figure 8, that the conventionally sintered sample showed more erosion loss compared to the microwave sintered sample. The erosion loss is slightly lower at angle of 90° for both the samples. The erosion loss varied from high as 0.01 g to low as 0.009 g for the conventionally sintered sample and high as 0.0085 g to low as 0.0074 g for the microwave sintered samples.

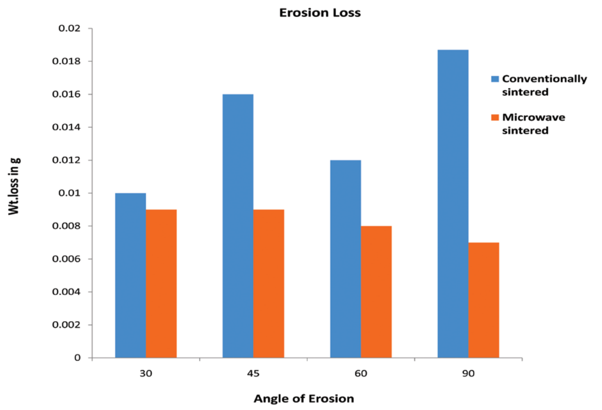

FIG. 8 JET EROSION TEST RESULTS

6.2 Sliding Wear behaviour

The experimental work involved studying the sliding wear behavior of the aluminium-cenospheres metal matrix composites system as a function of sliding distance for a constant sliding velocity and applied load. The wear properties of the composite samples were carried out on a computer interfaced Pin on disc apparatus.It can be seen from the Figure 9 that the weight loss of both the samples are low at 1 kg load and which progressively increases when the load is also increased to 2 kg and maximum wear loss occurs at 3 kg loading. The conventionally sintered samples showed higher wear loss than the microwave sintered samples.

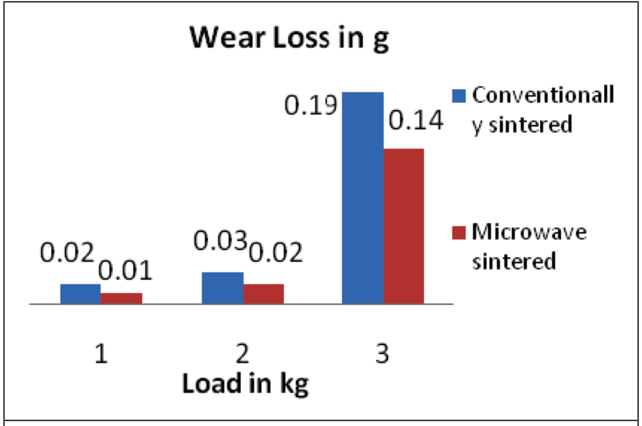

FIG. 9 WEAR LOSS BEHAVIOUR

The wear loss for the conventionally sintered sample was 0.02 g at 1 kg load, 0.03 g at 2 kg load and 0.19 g at 3 kg loading whereas the microwave sintered sample exhibited wear loss of 0.01 g at 1 kg load, 0.02 g at 2 kg load and 0.14 g at 3 kg load which is comparatively less than the conventionally sintered sample which is about 50% less at 1 kg, 33.3% less at 2 kg and 26.3% less at 3 kg load respectively.

6.3 Thermal Shock Resistance Test

The conventionally and microwave sintered samples were subjected to compressive yield strength (σ_y). The test was performed in the Universal Testing Machine (UTM) of Enkay make of capacity 100T. The compressive yield strength was evaluated for the sintered samples prior to, and after the thermal shock resistance test. The thermal shock resistance test comprised of heating the composite samples in a laboratory make resistance type muffle furnace which is heated with kanthal element. The samples were heated to a temperature of 500° C and held at this temperature for 15 minutes soaking time. Immediately the heated samples are quenched in water bath held at ambient temperature. This constitutes 1 thermal shock cycle. The composites samples are then evaluated for their compression strength after the thermal shock cycles. The conventionally and microwave sintered samples were subjected to thermal shock resistance tests comprising of 5, 10 and 25 thermal shock cycles and the compression strength values before and after thermal shock cycles were measured.

It can be seen from Figure 10 that for the conventionally sintered samples, the compressive yield strength of the sample 125.0 MPa prior to thermal shock test. The strength decreased to 123.8 MPa which is 1.0 % after 5 cycles, 121.7 MPa which is 4.9 % decrease in the strength after 10 cycles and 120.1 MPa which is 5.4% reduction in the compression strength after 25 cycles.

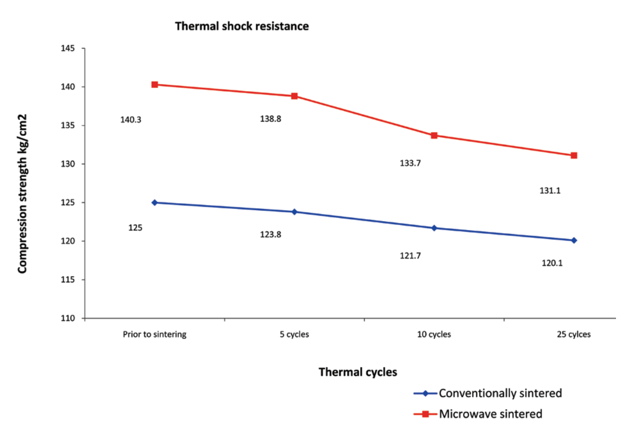

FIG. 10 THERMAL SHOCK RESISTANCE BEHAVIOUR

It can be seen that for the microwave sintered samples, the compressive yield strength of the sample 140.3 MPa prior to thermal shock test. The strength decreased to 138.8 MPa which is 0.9 % after 5 cycles, 133.7 MPa which is 4.7 % reduction in strength after 10 cycles and 131.1 MPa which is 5.1% reduction in compression strength after 25 thermal shock cycles. The microwave sintered showed 8.4 to 10.9 %less reduction in compression strength after thermal shock cycles compared to conventionally sintered ones.

6.4 Compression strength (σ_c)

The compression strength measurements were carried out in Enkay make hydraulically operated universal testing machine of capacity 100T. The compression strength was calculated by dividing the maximum load in kN by the original cross section area (cm^2) of the sample and the values are converted and given in MPa.

It is seen from Figure 11 that the compression strength of the conventionally sintered samples of aluminium powder is 125.0 kg/cm^2 whereas the compression strength of the microwave sintered samples of aluminium powder showed 140.3 kg/cm^2 which is higher compared to the conventionally sintered ones by about 11.0 %.

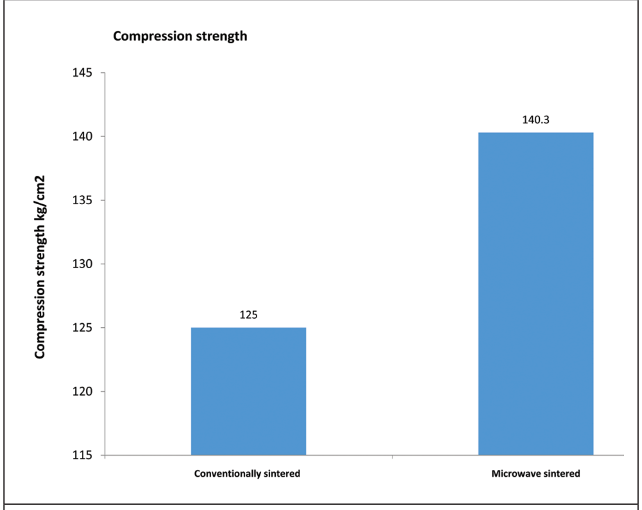

FIG. 11 COMPRESSION STRENGTH

6.5 Flexural strength (σ_f)

Flexural Strength also known as Modulus of Rupture (MOR), represents the highest stress experienced within the material at its moment of rupture. The flexural test was carried out as per the guidelines of ASTM D 790-15 standard [25]. Flexural Strength (σ_f) is measured in terms of stress, here given the symbol $\sigma_f$was calculated as follows:

$$\text{Flexural Strength } \sigma_f = \frac{3PL}{2BD^2} \qquad \text{....(8)}$$

Where P= the actual load at the fracture point, L is the length of the supports holding the test specimen, B is the width of the test specimen and D is the depth or thickness of the test specimen and the units of flexural strength is kg/cm^2 or MPa. Flexural Strength measurements of the composites were carried out in a laboratory make 3 point bending machine of capacity ranging from 1 to 20 kg.

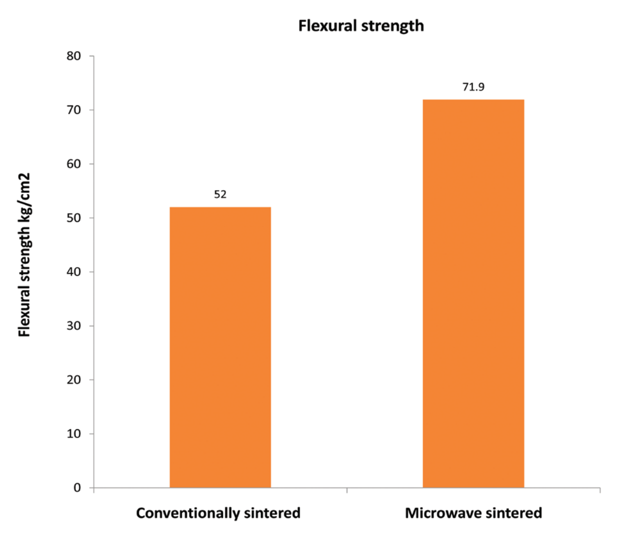

FIG. 12 FLEXURAL STRENGTH

It is seen from Figure 12 that the flexural strength of the conventionally sintered samples of aluminium powder is 52.0 kg/cm^2 whereas the flexural strength of the microwave sintered sample of aluminium powder showed 71.9 kg/cm^2 which is higher compared to the conventionally sintered ones by about 38.2 %.

6.6 Brinell Hardness Number (BHN)

Hardness of the composite materials was determined using Zwick Werkstoff-Prufmaschinen T 3212 B Digital Hardness tester. This hardness testing machine is designed according to DIN 51225 and ISO/R 146 for hardness testing machines with optical indentation measuring devices. A precision measuring microscope with bright field illumination was used to measure the Brinell impressions. Brinell Hardness Number was calculated as :

$$BHN = \frac{2P}{\pi D\left[D - \sqrt{D^2 - d^2}\right]} \qquad ....(9)$$

where P = load on the indenting tool (kg) on the sample, D= diameter of steel ball (mm), d = measure diameter at the rim of the impression (mm).

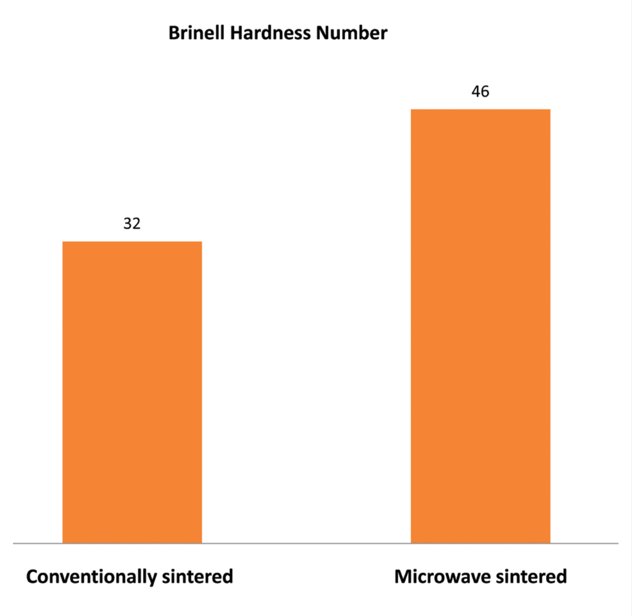

FIG. 13 BRINELL HARDNESS NUMBER

As can be seen from Figure 13, the BHN value for the conventionally sintered aluminium was 32 and for the microwave sintered sample was 46. Microwave sintered samples showed higher BHN value by about 30.4% compared to conventionally sintered one.

7.0 DISCUSSIONS

Morteza Oghbaei *et al.* [18] has reported that microwave sintering effectively assist the forward diffusion of ions which accelerates the sintering. This results in matrix densification by grain growth process. Sintering process aids re-crystallization, grain growth and densification at high temperatures in the body that is being sintered. This densification mechanism is strongly dependent on diffusion of ions between the same sample particles. The mechanism of grain growth rate is assisted by the grain boundary diffusion process. It has been found that intense microwave field concentration is active around the particles of the sample while sintering. The power of this microwave field between the particles of the sample in the bulk of the material is about 30 times higher than the external field and this is sufficient to ionize the sample particles at its surface. This accelerates ionic diffusion which promotes rapid densification of the material is promoted under microwave sintering.

Apart from the microwave radiation, the surrounding electromagnetic field also effectively enhances the ionic diffusion kinetics near the grain boundaries. The kinetic energy of the ions at the grain boundary increases which thereby decrease the activation energy required for the forward ion jump and in the process increases the barrier height for the reverse jump. This mechanism promotes forward diffusion of the inter grain ions which accelerates the grain growth during sintering.

By microwave sintering all the properties of a given material are enhanced by its microstructural development in which the densification of the material and coarsening occurs rapidly and effectively throughout the bulk of the material. The micro structural development depends on the parameters such as optimized temperature, sintering time, heating rate and the pressure. The rapid heating rate achieved by microwave heating is the key to produce products with a high sintered density for a given microstructure and grain size compared to slow heating for the same sintered density by conventional heating. Since microwave sintering is a non-contact sintering technique, the heat gets transferred to the product through electromagnetic radiation. By microwave sintering large amount of heat can be transferred to the material's interior which reduces differential sintering to a large extent. Hence the microwave sintered products have finer micro-structural development, with uniform grain growth and grain size distribution coupled with higher densification of the product thereby leading to enhanced engineering properties.

The above are the reasons attributed to the microwave sintered products which yield better tribolobical, mechanical and thermal properties in the powder pressed samples. The powder pressed metal samples produces finer grain size with shape of the porosity which is different compared to conventionally sintered products. Microwave sintered powder metallurgy products have round edged porosities which is responsible for high ductility and toughness [18].

8.0 CONCLUSIONS

1. The aluminium powder does not get converted into alumina (oxide of aluminium) when sintered in microwave at temperature of 665° C. The microwave sintering takes place uniformly throughout the bulk of the material. The sintering process is rapid, has high heating rates, reduced processing times, uniform temperature throughout with minimal thermal gradients.
2. Microwave sintered samples showed better tribological properties such as less wear and erosion losses compared to the conventionally sintered samples. The jet erosion loss varied from high as 0.01 g to low as 0.009 g for the conventionally sintered sample and high as 0.0085 g to low as 0.0074 g for the microwave sintered samples. The sliding wear loss of the microwave sintered samples were comparatively lower than the conventionally sintered sample which is about 50 % less at 1 kg, 33.3% less at 2 kg and 26.3% less at 3 kg load respectively.
3. The microwave sintered showed better thermal shock resistance compared to the conventionally sintered samples. Microwave sintered sample had higher compression strength by about 8.4 to 10.9 % after thermal shock cycles compared to conventionally sintered ones.
4. The compression strength of the conventionally sintered was 125.0 kg/cm^2 whereas the compression strength of the microwave sintered samples of aluminium powder showed 140.3 kg/cm^2 which was higher by about 11.0 %.
5. The Flexural strength of the conventionally sintered samples of aluminium powder was 52.0 kg/cm^2 whereas the flexural strength of the microwave sintered sample of aluminium powder showed 71.9 kg/cm^2 which was higher compared to the conventionally sintered ones by about 38.2 %.
6. Microwave sintered samples showed higher BHN value by about 30.4% compared to conventionally sintered one.

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