A Review: Microwave Energy for Materials Processing

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Abstract— Microwave energy is a latest largest growing technique for material processing. This paper presents a review of microwave technologies used for material processing and its use for industrial applications. Advantages in using microwave energy for processing material include rapid heating, high heating efficiency, heating uniformity and clean energy. The microwave heating has various characteristics and due to which it has been become popular for heating low temperature applications to high temperature applications. In recent years this novel technique has been successfully utilized for the processing of metallic materials. Many researchers have reported microwave energy for sintering, joining and cladding of metallic materials. The aim of this paper is to show the use of microwave energy not only for non-metallic materials but also the metallic materials. The ability to process metals with microwave could assist in the manufacturing of high performance metal parts desired in many industries, for example in automotive and aeronautical industries.

Key words: Microwave, Cladding, Hybrid heating

I. Introduction

In almost every industry, heating is most often used for manufacturing. For the effective application of manufactured material it is required to provide optimal and effective heating to material. Many conventional methods have been used in industries for this purpose which have some advantages and some limitations over it. Microwave energy is a latest technique which can be used effectively to process the metallic materials. Initially microwave energy was mainly used for communication purpose. Afterwards, technician Percy Spencer has been realized that microwave energy can be used for heating applications and later, it has been used for food processing and processing of polymers, ceramics, minerals, inorganic materials etc. But the major limitation of microwave radiations is that, it cannot interact with metallic materials at room temperature and due to this fact it is very difficult to heat them. Hence, researchers have invented different methods to couple the electromagnetic waves with metals. After year 1999, this novel technique has been used to process metallic materials as well in different form and initially it was used for sintering of metallic materials. Afterwards the work has been expanded in the area of melting, joining, and alloying of metals through microwave processing. The properties achieved by microwave processing were remarkably excellent and the component has been processed in a shorter duration than the conventional methods. The application of microwaves in surface engineering has been recently explored and very few works has been reported. Microwave energy is mostly used for food processing for last 40 years; it is now being aggressively inspected and assessed for wide range of applications in material processing. Microwave material processing is comparatively new technology and alternative that provides new approaches for enhancement in materials properties with economic advantages through energy savings and accelerated product developments [1]. Till year 1999, this novel technique was only confined to process some ceramics, polymeric, inorganic, food processing, rubber industry etc. due easy interaction microwaves with materials. However, it is very difficult to heat bulk metallic materials at room temperature due to low skin (in terms of few microns) depth or poor absorption of microwave radiation by metallic materials. The researchers accepted the challenge and they have diversified the domain of heating and processing of metallic materials as per their need and the developed product exhibits better properties than a conventional one.

Microwave is a radio wave and radio wave is one of the electromagnetic wave. Since electromagnetic wave is spread by the interaction of electric field and magnetic field it can also be extent in vacuum. Electromagnetic wave is a wave that has two components, such as wavelength and frequency. Wave length is about the length of top to top of the wave, frequency is number of waves that appears in a second. Microwave has been applied to radar surveillance system, communication, radio telescope for astronomy, and also to GPS positioning system known as car navigation system. Another application of microwave is heating. Microwaves are electromagnetic waves with wavelengths 1 mm to 1 m and equivalent frequencies from 300 MHz to 300 GHz. For microwave heating 0.915 GHz to 2.45 GHz frequencies are commonly used.

A. The range of usable frequencies for microwave processing

Microwaves form a part of unceasing electromagnetic spectrum that encompasses from low frequency alternating current to cosmic rays. These microwaves transmits through empty space at the velocity of light and their frequency range from 300 MHz to 300 GHz. In this scale the radio frequency range is divided into bands as shown in Table 1.

Frequency Band	Designation	Frequency limits
4	VLF very low frequency	3 KHz to 30 KHz
5	LF low frequency	30 KHz to 300 KHz
6	MF medium frequency	300 KHz to 3 MHz
7	HF high frequency	3 MHz to 30 MHz
8	VHF very high frequency	30 MHz to 300 MHz
9	UHF ultrahigh frequency	300 MHz to 3 GHz
10	SHF super high frequency	3 GHz to 30 GHz
11	EHF extremely high frequency	30 GHz to 300 GHz

B. Characteristics of microwave heating

- **Internal Heating:** Microwaves reach the object as same as speed of light. It goes into object as wave and getting absorbed after that object generates heat.
- **Rapid Heating:** Rapid heating is possible in microwave heating because in this type of heating the heat is generated by the object by its own with penetration of microwaves by the object. On the other hand in case of conventional heating the object's temperature rises due to heating from surface to inside which is external heating.
- **High Heating Efficiency:** Microwave penetrates into the entity at the speed of light and the entity to be heated generates heat. There is no need to consider the heat losses of air inside the furnace due to which we get high heating efficiency.
- **Heating uniformity and clean energy:** Each part of the microwave heated entity generates heat internally so even for those objects which have complicated shapes can be heated uniformly. Microwave propagates only by the change of electric field and magnetic fields and it does not require medium. It can propagate in a vacuum and reaches the object and penetrates without heating the air. The heated object absorb the microwave energy and generates heat. Microwave energy heats the object without heating the air in furnace that's why it is also called clean energy.
- **Good working and healthy operating environment:** In case of conventional heating with rise in temperature of object there is also rise in temperature of furnace or working environment but in case of microwave heating there is only rise in temperature of object due to it's internal heating and there is no temperature rise in furnace or working environment.

C. Challenges of microwave with materials

Controlling accelerated heating, Effective transfer of microwave to material, Timing, Compatibility of microwave with other process line.

D. Interaction of microwaves with materials

Materials can absorb, reflect or transmit the materials. Reflection and absorption necessitate interaction of the microwaves with the material, transmission is the consequence of partial reflection and incomplete absorption. Energy in the form of heat is produced in the material mainly through absorption. Solid, liquid and gases can interact with microwaves and be heated. Figure 1 below showed the interaction of microwave with materials [2].

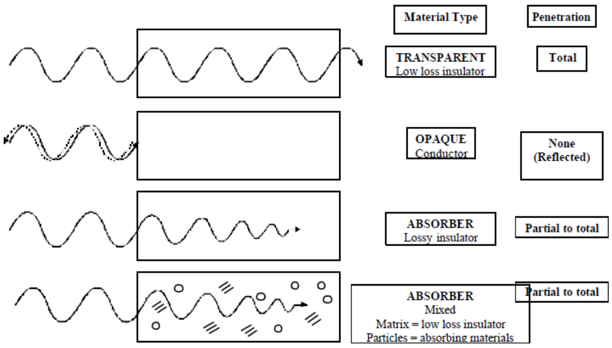

Fig. 1: Interaction of microwave with materials

Metals are excellent reflectors of microwaves and in general not heated considerably by microwave energy. Other materials absorb and reflect heat to several degrees depending on their structure, composition, temperature, and the frequency of the microwaves. Many ceramics and polymers do not absorb significantly at 2.45 GHz in room temperature. However, their absorption can be increased by increasing the temperature, accumulating absorbing constituents (e.g. carbon, SiC, binders), fluctuating their microstructure and defect structure, by changing their form (e.g. bulk vs powder), or by changing the frequency of the incident radiation. Interaction of microwaves with material is a very challenging job. Many researchers have used various techniques to couple the microwaves with materials. In interaction of electromagnetic waves with material there is a volumetric heating as compare to other conventional techniques. Heat is generated internally within the material instead of originating externally. Hence there is an inverse heating profile "inside-out" unlike a conventional heating "outside-in" as shown in Figure 2 below.

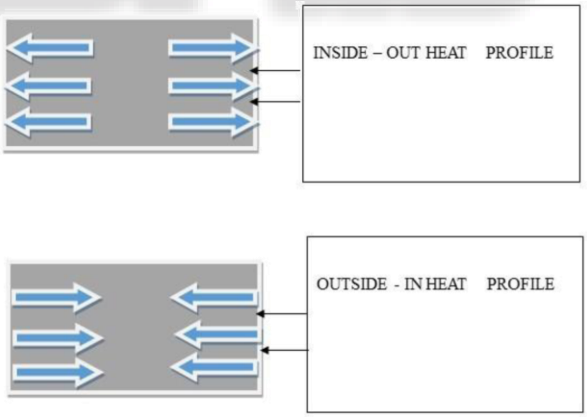

Fig. 2: Heat profile in microwave

II. PERSPECTIVE OF MICROWAVE

Das et al. [3] Showed the prospects of microwave processing on materials. Microwave processing has been emerging as an inventive sintering technique for many traditional ceramics, advanced ceramics, specialty ceramics and ceramic composites as well as polymer and polymer composites. Microwave heating has been used for the development joining, melting, fibre reinforcement, reaction synthesis of ceramics, synthesis of ceramic powder, phosphor material, whiskers, microtubes and nanotubes, glazing of coating surface. Microwave energy is being used for the sintering of metallic powders also.

D.Agarwal [4] showed latest global developments in microwave material processing. Microwave energy is a novel and very tremendous approach for material processing other than conventional techniques with many advantages such as reduced cycle process time which further saved substantial energy and cost, provide finer microstructure results in improved mechanical properties of material.

Clark and Sutton [5], reviewed the microwaves in material processing. In comparison to conventional furnaces, the material processed in microwave oven interacts with cold microwaves rather than radiant heat. By this technology the heating is more volumetric and can be selective or rapid because material generates heat itself. Also heating is instantaneous with power. These features result in better production uniformity, less floor space, faster production throughout and reduction in wasteful heating.

A. Microwave Cladding

In the year 2010, Gupta and Sharma have developed a novel process for deposition of metallic materials on metallic substrate by using a domestic microwave oven of frequency 2.45 GHz and the process was claimed for Indian Patent [6].

Gupta and Sharma [7] investigated sliding wear performance of WC10Co2Ni cladding developed through microwave irradiation on austenitic stainless steel (SS-316). To couple the microwave with metal, microwave hybrid heating concept was used in which charcoal was used as a susceptor. The clads were developed through microwave hybrid heating in multimode microwave in at 2.45 GHz frequency and at 900 W. The developed clads samples showed a microhardness of 1064±99 Hv and the distribution of microhardness at typical section of clad has been shown in Figure 3.

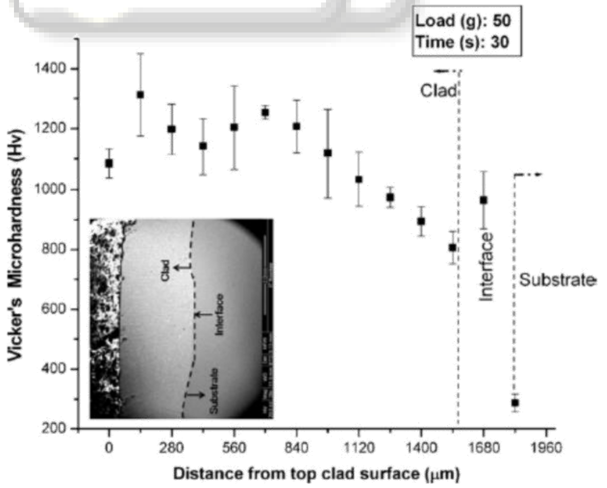

Fig. 3: Vicker's microhardness distribution of WC10Co2Ni clad

Gupta and Sharma [8] developed a microwave cladding of nickel based powder (EWAC) on austenitic stainless steel (SS316) substrate. Microwave cladding was developed to enrich the surface properties of austenitic steel (SS-316). Microwave irradiation used as a heating source for the development of cladding. The developed EWAC clads were metallurgical bonded with the substrate by partial mutual diffusion of elements. The microstructure of developed clads was cellular in nature and typical microstructure of clad is shown in Figure 4. The microhardness of clads was 304±48 Hv which was double of that austenitic stainless steel (SS-316).

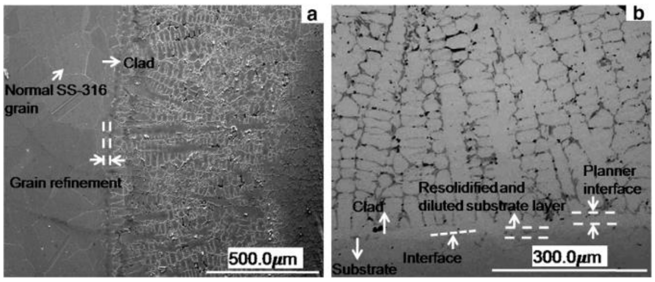

Fig. 4: (a) Typical microstructure of clad (b) back scattered image showed cellular structure in microwave clad

Gupta et al. [9] developed a composite cladding on austenitic stainless steel (SS-316) through microwave heating. EWAC (Ni based) + 20% $Cr_{23}C_6$ composite cladding was done on SS-316. Microwave cladding has been developed in domestic appliance microwave multimode in 2.45 GHz frequency for the duration of 360 s. Typical composite clad cross sections showed good metallurgical bonding with substrate by partial dilution. Results revealed that clads are free from solidification cracking and exhibits significant less porosity of the order 0.90%. Hardness of the developed clads was observed as 425±140 Hv. The microwave clads developed through this technology can be effectively used in wear resistant applications.

Gupta and Sharma [10] developed metal ceramic composite cladding through microwave heating. Flexural strength and microstructure of developed clads were investigated. A multimode microwave oven was used to develop carbide reinforced (tungsten carbide based) metal matrix composite cladding on austenitic steel. Cladding was developed through microwave heating at 2.45 GHz for 420 seconds**.** The schematic arrangement for experiments is shown in Figure 5.

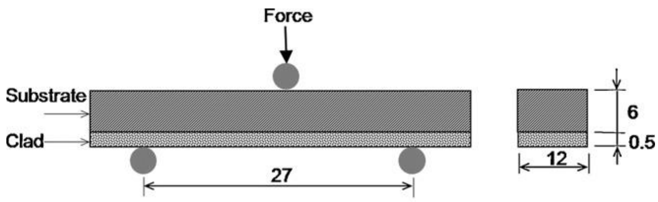

Fig. 5: Schematic arrangement for 3-point test

Prasad and Gupta [11] did a microwave processed cladding of nickel based lanthanum oxide composite powder particle having particle size of 40 μm on mild steel. The substrates were cut into average dimensions of 10mm × 10mm × 5mm. Then they were polished with emery paper to obtain the artificial texture. After that the composite powder was preplaced manually on mild steel substrate. The sample was put in microwave oven with 2.45 GHz frequency, 900 W power and exposed for 240 S. The approximately 500 μm clad thickness has been developed on mild steel. The average vicker's microhardness of developed clad was 319 Hv and clads can be effectively used for wear resistant applications.

B. Microwave Joining of Metal

Joining of metal can be done by many techniques to make the high strength joints but microwave energy played a vital role in this field to join the metals with improved mechanical properties. There are many techniques to join the metals like welding, brazing, laser welding etc. but these all techniques consumes lot of energy and time. Microwave assisted joints are clean and more efficient than conventional ones.

Siores et al. [12] discussed pioneering work and development in the area of microwave applications into materials welding and joining. Authors also explained the engagement of microwaves for fast curing adhesives for joining transparent to microwave radiation materials. The facility of microwaves in joining a variety of materials was examined. As primary processing parameters are optimized the bonding strength attained with each microwave joining technique for a range of materials.

Singh et al. [13] joined the green composites through microwave processing. In this research green sisal fibre fiber reinforced polylactic acid composites were prepared by a compression molding technique. Two types of PLA/SF composites were developed with a fiber content of 10 and 20 percent by weight. Microwave energy was used to join PLA/SF composites in a microwave oven. Green composites were joined successfully by microwave heating in different time and intensities. A charcoal improver was used to accelerate the rate of joining. Results showed that the microwave energy is a feasible route to join green composites.

Srinath et al. [14] explained a novel method for joining of metallic bulk material through microwave irradiation. Copper in bulk has been joined using microwave energy in a multimode applicator at 2.45 GHz and 900 W. Schematic of microwave heating process for joining of copper is shown in Figure 6. A solid uniform microstructure with good metallurgical bonds between the sandwich layer and interface was formed. The hardness was observed to be 78±7 Hv and porosity was observed to be 1.92 %. Microwave processed copper joints possessed significant tensile strength with significantly high elongation.

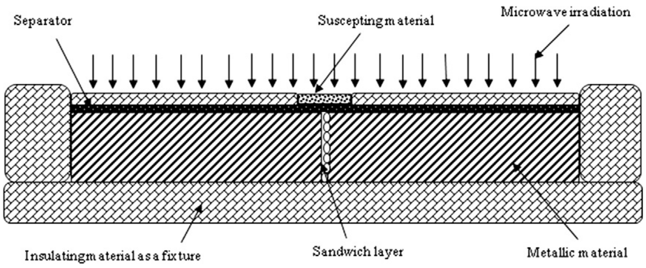

Fig. 6: Schematic of microwave heating process of joining of metallic powder

Srinath et al. [15] investigated microstructural and mechanical properties of microwave processed dissimilar joints. Microwave joining of SS-316 to mild steel in bulk has been carried out successfully in microwave multimode applicator at 2.45 GHz and 900 W. To initiate coupling of microwave with metals principle of microwave hybrid heating was used using a susceptor medium. Schematic view of experimental process for microwave joining has been shown in Figure 7. The volumetric heating nature of microwave causes complete fusing of the interface layer and which developed a metallurgical bonding with bulk interfaces. Bulk joint has a Vickers microhardness 133 Hv and porosity of bulk joint has been observed to be 0.58 %. The microwave processed dissimilar joints paraded tensile strength of 346.6 MPa with an elongation of 13.58 %.

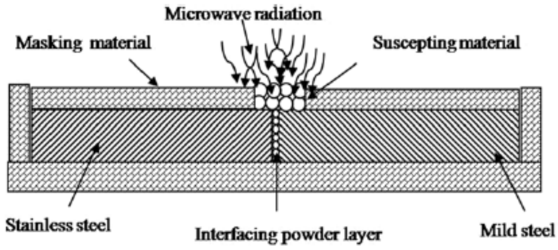

Fig. 7: Schematic view of the experimental process for microwave joining

C. Microwave Sintering

Sintering is the process of forming a solid mass of material by heat and pressure without melting it to the point of liquification. Sintering happens naturally in mineral deposits or as a manufacturing process used with metals, ceramics, plastics, and other materials. Sintering can be done by conventional methods but the microwave assisted sintered materials have possessed higher properties.

D. Agarwal [16] has developed a sintering of ceramics and W/Cu composites in microwave oven. The microwave process is progressively being exploited to create better and cheaper products mainly specialty ceramics. Sintering by microwave improved the sintering time, sintering temperature, total cycle time, density, average grain size, bending strength and hardness. The microwave coupling in the occurrence of a defect structure causes extremely rapid reaction and new reaction formed materials at much lower temperatures than mostly attained by conventional heating process.

Roy et al. [17] accomplished the sintering of metallic powders with microwave energy. As recently the work has been done on heating/sintering of ceramics or non-metallic materials by microwave energy but due to the extensive use of metals in industrial applications it was the need to process metals with electromagnetic waves. They were able to sinter a wide range of standard powdered metals from commercial sources using 2.45-GHz microwave field with good mechanical properties than those from conventional heating. They have sintered many powders of pure metals with microwave energy. The schematic view of microwave processing is shown in Figure 8.

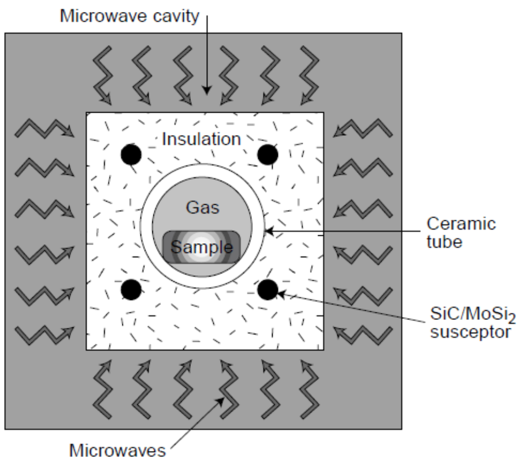

Fig. 8: Schematic view of microwave processing

Gupta and Wong [18] used two directional rapid sintering to improve the overall mechanical performance of the metallic materials. Aluminum, magnesium and lead free solder were chosen as candidate materials. Two directional sintering of aluminum, magnesium and lead free solder was done in microwave oven with 2.45GHz frequency and 900 W. Sic was used a susceptor to couple microwave with the materials. The setup is shown in Figure 9.

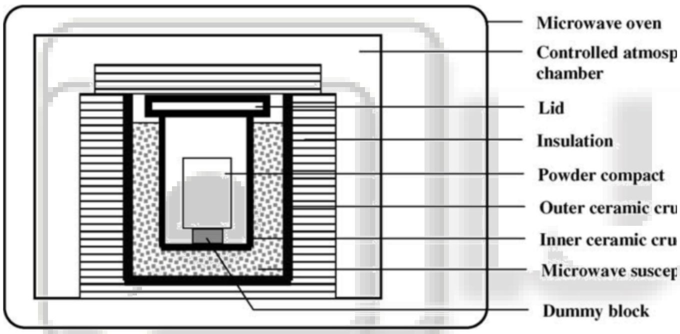

Fig. 9: Schematic of microwave oven

Saitou [19] established sintering of iron, cobalt, nickel, copper and stainless steel powders using microwave radiation. The results of microwave assisted sintering were compared with the conventional sintering. The sintering was done in microwave oven with 2.45 GHz frequency. Microwave energy promoted the sintering of metal powders but it did not affect the activation energy of sintering. Microwave sintered samples showed good mechanical properties as compared to conventional ones.

Agarwal [20] did a sintering, brazing and joining of metallic material using microwave energy. Many common steel compositions, pure metals and refractory metals have been sintered to nearly full density with enhanced mechanical properties in microwave. In this research author has taken iron and steel, aluminum, copper, nickel, Mo, Co, Ti, W, Sn, etc. and their alloys have been sintered in microwave oven. Further these elements have been brazed and joined with microwave energy. Various metallic materials have been microwave processed in microwave cavity with 2.45 GHz frequency. It has been found that microwave sintered powders produces superior product. Al, Cu, Mo, Ni, Ti, Co, WC W, Sn, etc. and their alloys have also been sintered in microwaves produced approximately fully dense bodies. Figure 10 showed the microstructure of sintered Mo sample in microwave for 1 minute at 1600°C.

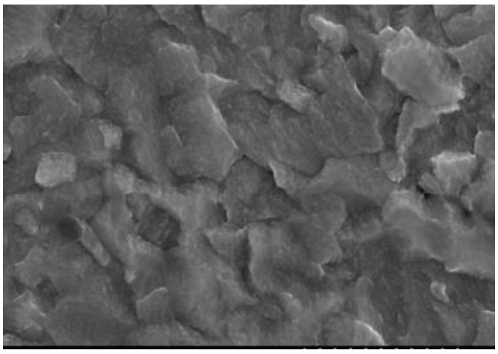

Fig. 10: Microstructure of microwave sintered Mo powder

Wong and Gupta [21] developed Mg/Cu nanocomposites using microwave assisted rapid sintering. In this research magnesium composites containing different amounts of nano-size Cu particulates were successfully synthesize during powder metallurgy (PM) technique including microwave assisted two-directional sintering. Cu particulates lead to an increase in hardness, 0.2%yield strength, elastic modulus, ultimate tensile strength and work fracture of matrix. Tensile properties were increased using microwave energy.

Upadhyaya et al. [22] sintered W – Ni – Fe alloy using microwave heating. In this research the effect of heating mode on the mechanical and microstructure properties of 92.5W-6.4Ni – 1.1Fe were compared. The compacts were sintered at 1500°C in (conventional) radiatively furnace and in 2.45 GHz microwave furnace. Both samples prepared from conventional method and microwave processed were compared. It has been found from results that hardness and tensile properties of microwave sintered samples was better than conventional ones. The mechanical and microstructural properties of microwave sintered alloys were higher than that of conventional sintered alloys.

Padmavathi et al. [23] studied and compared the corrosion behavior of microwave sintered austenitic stainless steel composites with conventionally sintered austenitic stainless steel. Pure316L and 316L – YAG composite were sintered in microwave furnace with 2.45 GHz frequency and also in conventional furnace. The results were compare from which it has been found that microwave sintered samples have fine microstructure and better mechanical properties as compared to conventional ones. Also the corrosion resistance of microwave sintered samples was enhanced more than conventional sintered samples.

Rajkumar and Aravindan [24] have successfully sintered a metal matrix composite (copper and graphite) using microwave. Copper - graphite composite was prepared through powder metallurgy route. Both copper and graphite mixed together in which electrolytic copper powder having average grain size of 12 µm and graphite having an average grain size of 50 µm. An industrial microwave furnace was used to process the materials with 2.45 GHz frequency as shown in Figure 11.

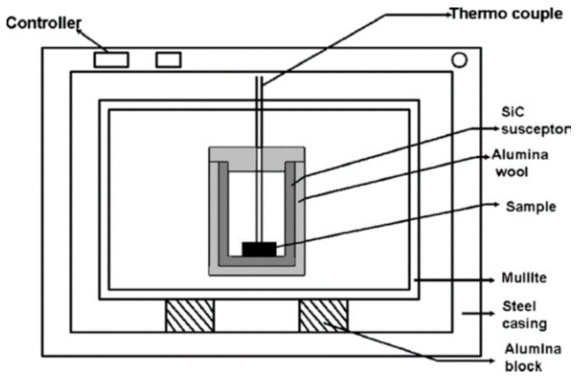

Fig. 11: Schematic view of microwave oven

There was a significant improvement in the microhardness of microwave processed (sintered) copper – graphite composite in different volume fractions and the developed samples were free from cracks. The finer microstructure with moderately smaller and round pores caused due to microwave heating increases the performance of the composite.

III. Conclusion

Microwave material processing is getting more importance due to environmental concerns and energy inadequacy. This technique is energy efficient in which microwaves are used for various applications which offer volumetric heating, selective heating depends upon microwave – material interaction rather than conventional heating which use conductive and radiative heat transfer methods. This novel technique has been used for melting, sintering, joining of metals and cladding so far. Some points which refers to the future scope of this process:

(1) The possibility for other metallic materials for improvement of surface characteristics can be possible by microwave cladding.
(2) Other designed suitable metallic powders of desired properties can be used for microwave cladding.
(3) Wear and corrosion characteristics can be improved very significantly by this method.
(4) The possibility of composite cladding can be explored.
(5) Microwave processing can also be used for other machining operations like drilling, casting etc.

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