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A REVIEW ON MICROWAVE PROCESSING TECHNIQUES AND ITS POTENTIALS

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ABSTRACT

Microwaves are electromagnetic radiations, having magnetic and electrical components at right angles to each other. Microwaves fall into the frequency range of 300 MHz to 300 GHz.Microwave processing is gaining rapid attention, especially in the area of material processing, owing to various advantages like environmentally green processing, operator safety, reduced thermal gradients, time and energy consumption. Microwave processing technique leads to yield of better property of materials. Initially, microwave processing was limited to food processing, telecommunication and processing of direct microwave absorbing materials like ceramics. However, extensive research in this area led to processing of nearly all types of materials. Present paper discusses on applications of microwaves and its potentials.

Keywords*: Microwaves, Processing, Metals, Microwave Hybrid Heating.*

I. INTRODUCTION

Microwave processing of materials has emerged as one of the prominent and efficient methods. Microwaves find applications in food processing, telecommunication, radar system, material processing and so on [1,2]. Frequency of microwave processing varies depending on applications. Some of the frequencies set by Federal Communications Commission (FCC) for industrial processing are 915 MHz, 18 GHz and 2.45 GHz [3]. Most of the conventional processing techniques which are in existence have many drawbacks like excessive time consumption, non-uniform microstructure, energy and material losses [4]. Further advancement resulted in usage of non-conventional energy sources. However, energy and time required for processing are the similar problems associated. To hold back the disadvantages conventional processing and to provide better physical and mechanical properties to the materials, microwave processing is chosen.Mode of heat transfer in conventional and microwave processing differs. Heat is transferred from exteriorsurface to interior core of material in conventional heating, while microwaves interact with materials at molecular levelresulting in volumetric heating [5]. Advantages that are possible by microwave processing are selective heating, lower processing times, higher heating rate, precise heating control and reduced thermal gradients. A graph showing advancement in application of microwaves in various fields is shown in Fig. 1. Various advantages of microwave processing have resulted in wide applications in variety of domains. Some of them are telecommunication, food processing, drying wood, rubber processing, heat treatment of wastes, processing of ceramics, glasses and metallic materials.Present paper gives an overview of fundamentals of microwave processing techniques and its applications.

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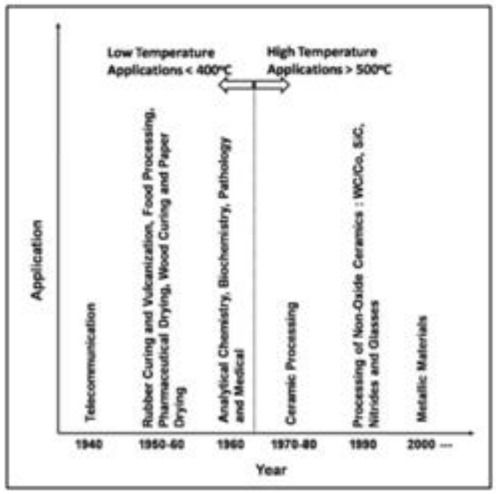
Figure 1



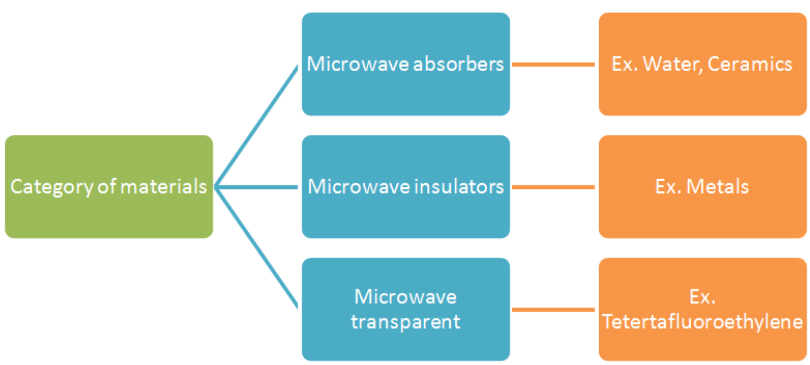
Developments of microwave processing applications [3]

II. FUNDAMENTALS OF MICROWAVE PROCESSING

Microwaves are electromagnetic radiations, having magnetic and electrical components at right angles to each other. Microwaves fall into the frequency range of 300 MHz to 300 GHz. Microwaves have effective wavelength from 1 mm to 1 m. Interaction of microwaves with materials depends on the material properties. Based on the type of interaction with microwaves, materials can be classified into three groups (Fig. 2);

i. Microwave absorbing materials: Field strength of electric magnetic components attenuates along the thickness of the material in absorbing materials. However, the rate of decreasing in field strength depends on the dielectric loss factor of the materials.
   Ex. Water, ceramics, polymers, etc.
ii. Microwave insulating materials: Field strength of microwaves fall only upto certain negligible thickness in the materials falling into this category. This is because of lower skin depth of these materials.
   Ex. Metallic materials.
iii. Microwave transparent materials: Microwave transparent materials are also called low loss insulators. There is no decrease in the electrical and magnetic field strength along the thickness of the materials.
   Ex. Tetrafluoroethylene.

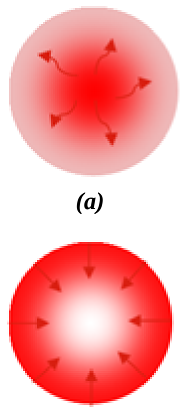
Figure 2



Classification of materials based on microwave interaction

Characteristic nature of microwave processing that makes it as one of the most attractive processing techniques is the inside-out heating due to interaction with materials at molecular level. Microwaves penetrate into materials and generate heat at molecular level, while the conventional heating takes place from outside to inside nature of the material. This nature of conventional heating results in temperature difference between layers of the material, causing energy and material losses. Heat transfer in microwave and conventional processing methods is schematically shown in Fig. 3.

Figure 3



(a)

(b)

Heat transfer in (a) microwave processing (b) conventional processing

Possibility for achieving uniform heating of material by microwave processing is due to the depth of penetration of microwaves into the materials. Depth of penetration is also called 'skin depth' in metallic materials. Skin depth can be defined as a distance from the surface of the material at which the value of current density falls to 0.3679 of its value to the surface. Depth of penetration or skin depth (δ) is given by the relation (1) [6];

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (1)$$

Where, δ – Skin depth

f- Frequency of microwaves, GHz
μ - Magnetic permeability, H/m
σ – Electrical conductivity,S/m

From the equation (1), it is worth noting that the skin depth decreases with the increase in conductivity of the materials. Hence, good conductors (metallic materials) possess lower skin depth at room temperature. However, skin depth increases with increase in temperature [6]. Due to lower skin depth, microwaves are reflected by the metals, which cause difficulty in processing them in microwave environment. A solution to overcome this problem exists by the name Microwave Hybrid Heating (MHH) technique. MHH utilizes microwave absorbing materials called susceptors, which converts microwave energy to heat energy. Heat generated by the susceptor is transferred to the metal [7]. After reaching certain higher temperature, metals begin to absorb microwaves, there by resulting in volumetric heating. The temperature at which metals begin to absorb microwaves is called 'critical temperature', which may be denoted by T_C. Fig. 4 shows the behaviour of metallic materials to incident microwaves at different temperatures.

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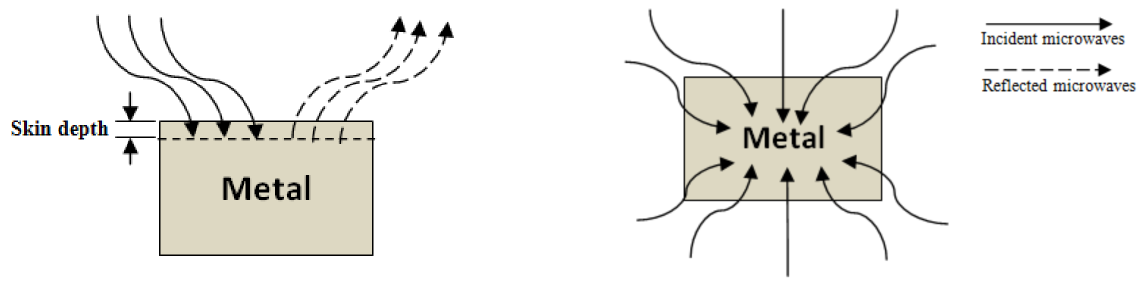
Figure 4



(a) (b)

Interaction of microwaves - metals at (a) room temperature (b) elevated temperature

III. APPLICATIONS OF MICROWAVES IN METAL PROCESSING

Some of the metal processing operations through microwave energy has been described in the following section.

Microwave cladding

Surface modifications plays an important role when there is a need for resistance from external damage to the material. Surface modification may be increasing the hardness of a material, increasing the resistance of the material to corrosion or erosion or a combination of both.Surface modifications can be achieved by thermal spraying, laser cladding, TIG surface based welding and so on. However, these conventional techniques suffer from many drawbacks like excessive deformation and energy consumption. To overcome the drawbacks of conventional surface modification techniques, microwave cladding process has appeared as a new technology with major advantages.Some of the claddings developed and their results have been overviewed.

Gupta et al. investigated on wear performance of WC10Co2Ni cladding developed on austenitic stainless steel (SS-316) using microwave energy developed by a 900 W microwave oven. Developed clads were characterized by various techniques. It is reported that the clads developed were formed by partial dilution of base material and were free from cracks. It is to be noted that the clads were formed with negligible porosity (~0.89 %). Wear test concluded that the resistance shown by clads to wear were better at lower sliding speeds [8]. Composite (EWAC (Ni based) + 20 % $Cr_{23}C_6$ powder) cladding was developed on the same metallic substrate (SS-316) using a domestic microwave oven at 2.45 GHz frequency. Close observation of the clad surface showed uniformly distributed chromium carbide particles in Ni matrix. Average Vicker's microhardness of the developed composite clad was 425 ± 140 Hv. It is also concluded that the developed clad can be used in wear applications effectively [9].

Zafar and Sharma have reported few works on developing nanometric clads and their characterization. Major work to be noted is the dry sliding wear performance of WC-12Co nanostructured clad developed through microwave energy. It is informed that WC-12Co powder at nanometric and micrometric scale was used to develop clads on austenitic stainless steel. Clads were developed by microwave exposure for duration of 540 s and 600 s respectively. Nanocarbides distributed as clusters was observed in nanometric clads, while skeleton like structures of carbides distributed in the metal matrix was observed in micrometric clads. Wear test showed that the nanometric clads exhibited 54 % higher resistance to wear than the micrometric clads, which is due to the higher volume fraction and uniform distribution of nanocarbides in the clad [10].

Hebbale and Srinath demonstrated the method of developing nickel based clad on austenitic stainless steel (SS-304) by microwave irradiation. Nickel was used as clad material as it is highly resistant to erosion. Clads were developed using a domestic microwave applicator having 900 W power and operating at frequency of 2.45 GHz. Clads developed was metallographically and mechanically characterized. Microstructural study revealed uniform distribution of metallic carbides and crack-free clad surface [11].It is also reported that the hardness of the developed clad has increased due to distribution of intermetallics and metal carbides. Similarly, Cobalt cladding was developed on martensitic stainless steel (AISI-420). Developed clad was subjected to erosion and microstructural study. Taguchi Orthogonal Array was used to study the parameters that affect the erosion rate. Finally, it is reported that slurry speed influenced the mass loss significantly [12].

Microwave joining

Joining two or more materials permanently plays a key role in most of the manufacturing and assembling industries. Conventional joining techniques such as welding, brazing and soldering have their limitations like materials involved, time for processing, etc. Solution to these limitations can be obtained by an alternative technique where microwaves are used as a source of energy for joining of materials. Major advantages related to microwave joining are that dissimilar materials can also be joined.

Sharma et al. demonstrated that microwaves can also be used to join metallic materials by overcoming the difficulty of microwave reflection. It has been shown that microwave metal joining was a green process, which could be carried out even using a domestic microwave oven. Joints of considerably good strength were obtained [13].
Srinath et al. reported work on development of joints between bulk copper plates and coins by microwave irradiation. Joints were obtained by exposing the substrate and interface material to microwaves for an exposure time of 300 – 900 s, using a 900 W microwave oven [5]. It is to be noted that the particles were fused better. Joint developed has hardness around 84 % of the base material, with negligible porosity of ~1.92 %. Similar work has been carried out by the same authors where bulk stainless steel (SS-316) has been joined by microwave irradiation [14]. The joining was effected by better fusion of particle leading to metallurgical bonding of the interface layer. Characterization of the joints showed that the hardness at interface layer was higher, which could be due to precipitation of metallic carbides. Measurement of porosity in the joint region showed negligible porosity of ~0.78 %. Extensive research in the area led to joining of dissimilar metals. Joint was developed between stainless steel (SS-316) and mild steel using a multimode microwave applicator, at 2.45 GHz [15]. Microwave Hybrid Heating (MHH) technique was used to develop the joint. Cementite and metal carbide formation was evident at the joint region, with negligible porosity of ~ 0.58 %.

Further, joints were developed between Inconel-625 and reported by Badiger et al. Commercially available Inconel-625 plates were joined by microwave irradiation from a 900 W multimode microwave applicator. Nickel based powder was used as an interface material.Microstructural study of the joint revealed the formation of carbides of nickel, chromium and molybdenum. Average hardness of 350 ± 10 Hv was recorded at the joint. Fractography of the joints revealed that the failure was due to mixed mode of deformation [7].

Microwave melting

It was believed that microwave melting of metals was impossible, owing to lower skin depth of metallic materials at room temperature, which restricts microwaves from penetrating into the metal. However, by carrying deep research in this area, it was able to achieve melting of metallic material using microwave energy.

Clark et al. showed that microwaves can be absorbed by metallic material at higher temperature. Later, a variety of metals and alloys were melted by exposure of microwaves. Microwave melting was developed at Oak Ridge Y-12 National Security Complex (NSC) [16]. However, no reports regarding characterization was available. Later, Chandrasekaran et al. reported experimental and theoretical investigation on melting of tin, lead, aluminium and copper at various power levels of the microwave applicator. A multimode microwave applicator was used for achieving the objective. Metals in the form of granules were used for melting purpose. A lumped parameter model was also developed to validate the experimental results [17].

Melting of non-ferrous metal like tin (60Sn40 Pb) in bulk form was first reported by Gowtham et al. [18]. A 900 W domestic microwave oven was used to achieve the melting of tin alloy. A comparative study of melting tin alloy using a conventional muffle furnace was also carried out by the authors. It was reported that microwave melting of bulk tin was achieved in less than half of the time consumed by conventional process.

Further, in-situ casting of bulk aluminium by MHH technique was reported by Mishra and Sharma [19]. 1400 W microwave applicator operating at 2.45 GHz was used to melt AA 7039 alloy. Principles involved in heating and melting of the candidate material by microwave irradiation is also reported. Characterization of the cast aluminium showed dense cast with negligible porosity of less than 2 %.
Microwave drilling of metal sheets of 0.5 mm and 1mm thickness was also reported by some of the authors [20]. However, further characterizations have been lacked. The nature of interaction of microwaves with materials and

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their consequent results have proved that microwave processing of metallic materials is better than the conventional processing techniques.

Potentials for research in the area of microwave processing

Further, potential for research and development in the area of microwave processing is vast. Some of the areas are listed below.

- Casting of higher melting temperature metals and alloys
- Development of composites
- Actual interaction of microwaves and metallic materials
- Critical temperature measurement
- Optimization of process parameters
- Development of joints between metallic and non-metallic materials
- Development of cladding on cutting tools

IV. CONCLUSIONS

After reviewing the applications of microwaves in processing metallic materials, following conclusions have been drawn;

i. Microwaves interact with materials at molecular level, resulting in uniform volumetric heating.
ii. Depth of knowledge on the physics of microwave interaction with metallic materials is still immature.
iii. Microwave processing of metallic materials are advantageous over conventional techniques.
iv. Microwave material processing results in clean processing, reduced processing time and improving mechanical properties.

Most of the microwave processing techniques have to be optimized and the technology has to be transferred to industries.

REFERENCES

1. *M. Gupta, W. W. Leong and W. L. Wong,"Microwaves And Metals", John Wiley and Sons, Singapore, 2007.*
2. *A. C. Metaxas,R. J. Meredith,"Industrial microwave heating",PeterPeregrinus Ltd., London, 1983.*
3. *S. Singh, D. Gupta, V. Jain and A. K. Sharma, "Microwave processing of materials and applications in manufacturing industries: a review", Materials and Manufacturing Processes, 30(1), 2015, pp. 1-29.*
4. *A. F. Moore, D. E. Schechter and M. S. Morrow,"Method and apparatus for meltingmetals", U.S Patent 20030089481, (2003)*
5. *M. S. Srinath, A. K. Sharma and P. Kumar, "A new approach to joining of bulk copper using microwave energy", Materials and Design, 32(5), 2011, pp. 2685-2694.*
6. *R. R. Mishra, A. K. Sharma,"Microwave–material interaction phenomena: heating mechanisms, challenges and opportunities in material processing", Composites Part A: Applied Science and Manufacturing, 81, 2016, pp.78-97.*
7. *R.I. Badigera, S. Narendranath and M.S. Srinath, "Joining of Inconel-625 alloy through microwave hybrid heating and its characterization", Journal of Manufacturing Processes, 18, 2015, pp. 117-123.*
8. *D.Gupta and A. K. Sharma, "Investigation on sliding wear performance through of WC10Co2 Nicladding developed microwave irradiation", Wear, 271(9), 2011, pp. 1642-1650.*
9. *D. Gupta, P. M. Bhovi, A. K. Sharma and S. Dutta, "Development and characterization of microwave composite cladding", Journal of Manufacturing Processes, 14, 2012, pp/ 243-249.*
10. *S. Zafar and A. K. Sharma, "Dry sliding wear performance of nanostructured WC-12Co deposited through microwave cladding", Tribology International, 91, 2015, pp. 14-22.*
11. *A. M. Hebbale and M. S. Srinath. "Microstructural investigation of Ni based cladding developed on austenitic SS-304 through microwave irradiation", Journal of Materials Research and Technology, 5(4), 2016,pp. 293-301.*
12. *A. M. Hebbale and M. S. Srinath, "Taguchi analysis on erosive wear behavior of cobalt based microwave cladding on stainless steel AISI-420", Measurement, 99, 2017, pp.98-107.*
13. *A. K. Sharma, M. S. Srinath and P. Kumar, "Microwave joining of metallic materials", Indian patent, Application no. 1994/Del/2009, 2009.*

14. *M. S. Srinath, A. K. Sharma, and P. Kumar, "A novel routefor joining of austenitic stainless steel (SS-316) usingmicrowave energy", Proceedings of IMechE Part B: Journal of Engineering Manufacture,225, 2011, pp. 1083-1091.*
15. *M. S. Srinath, A. K. Sharma, and P. Kumar, "Investigationon microstructural and mechanical properties of microwaveprocessed dissimilar joints", Journal of Manufacturing Processes, 13, 2011,pp. 141- 146.*
16. *E. B. Ripley and J. A. Oberhaus, "Melting and heat treatingmetals using microwave heating", Industrial Heating, 72, 2005, pp. 61-69.*
17. *S. Chandrasekaran, T. Basak and S. Ramanathan. "Experimental and theoretical investigation on microwave melting of metals", Journal of Materials Processing Technology, 211(3), 2011, pp. 482-487.*
18. *T. R. Gouthama, G. Harisha, Y. R. Manjunatha, S. M. Mohana Kumara, M. S. Srinath and M. Shashank Lingappa, "Melting of tin using muffle furnace and microwave energy and its characterization", IOP Conference Series: Materials Science and Engineering, 149(1), 2016, doi:10.1088/1757-899X/149/1/012100.*
19. *R. R. Mishra, A. K. Sharma, "On mechanism of in-situ microwave casting of aluminium alloy 7039 andcast microstructure", Materials and Design, 112, 2016, pp. 97-106.*
20. *S. Das and A. K. Sharma, "Microwave drilling of materials",BARC Newsletter, 329, 2012,pp. 15- 21.*