MICROWAVE VERSUS CONVENTIONAL SINTERING PROCESSING IN IRON AND STEEL PLANTS : A REVIEW OF MICROWAVE SINTERING PROCESS IN IRON AND STEEL PLANTS

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ABSTRACT

Microwave sintering has emerged in recent years as a new method for sintering a variety of materials and has gained worldwide acceptance as a novel method for heating and sintering a variety of materials as it offers specific advantages in terms of speed, energy efficiency, process simplicity and lower environmental hazards. This review article first provides theoretical aspects of microwave and its application in iron and steel plants against conventional sintering for heating ferrous burden material and the benefits of this novel research over existing sintering process.

Keywords: *Conventional sintering, Microwave sintering, Agglomeration, Sinter roasting*

1. INTRODUCTION

The concept of using microwave energy for heat treatment of materials is well known [1]. In the past 20 years, the micro-wave oven has become an essential appliance in most kitchens. Faster cooking times and energy savings over conventional cooking methods are primary benefits .Although the use of microwaves for cooking food is widespread, the application of this technology to the processing of materials is a relatively new development [2]. The use of microwave energy for processing materials has the potential to offer similar advantages in reduced processing times and energy savings. In conventional thermal processing, energy is transferred to the material through convection, conduction, and radiation of heat from the surfaces of the material. In contrast, microwave energy is delivered directly to materials through molecular interaction with the electromagnetic field. In heat transfer, energy is transferred due to thermal gradients, but microwave heating is the transfer of electromagnetic energy to thermal energy and is energy conversion, rather than heat transfer. This difference in the way energy is delivered can result in many potential advantages to using microwaves for processing of materials. Because microwaves can penetrate materials and deposit energy, heat can be generated throughout the volume of the material. The transfer of energy does not rely on diffusion of heat from the surfaces, and it is possible to achieve rapid and uniform heating of ferrous burden materials [14].

In addition to volumetric heating, energy transfer at a molecular level can have some additional advantages. Microwaves can be utilized for selective heating of materials. The molecular structure affects the ability of the microwaves to interact with materials and transfer energy. When materials in contact have different dielectric properties, microwaves will selectively couple with the higher loss material [1]. This phenomenon of selective heating can be beneficial over existing sintering process i.e. Dwight Lloyd or down draft sinter machine, as it will eliminate the different zones formed during sintering in the sinter bed i.e. Wet zone, Drying zone, Preheating zone, Combustion zone, Oxidation zone, Equilibrium zone, Cooling zone and Sintered zone so the process is going to be simple [15].

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The rapid interaction of ferrous burden material with microwave result in rapid heating and will decrease the slag bonding and increase the number of microscope and increase the reducibility as compared to existing sintering process and there by decreasing the amount of flux needed to increase the reducibility in the existing sintering process. The rapid heating is going to improve the De-sulphurization process and also the sinter roasting process and reduce the amount of coke and flux needed for reduction and evolved SO_x[15] can be pumped out from the microwave furnace which there by can be used as a by-product.

The purpose of this article is to offer an overview of the advantages of using the Microwave sintering over existing sintering process for heating of ferrous burden material in Iron and Steel plants. It is hoped that this article will benefit for making changes in sintering process in Iron and Steel plants. The review of literature in this article is not intended to be inclusive and reader interested in the subject should refer to the bibliography, which gives the key sources of information.

2. THEORETICAL ASPECTS OF MICROWAVE SINTERING

Microwave energy is a form of electromagnetic energy with the frequency range of 300 MHz to 300 GHz and the corresponding wavelengths are between 1 mm and 1 m. The frequency and wavelength range of microwaves are shown in Fig. 1. Microwaves have longer wavelengths and lower available energy quanta than other forms of electromagnetic energy such as visible, ultraviolet or infrared light. The first microwaves application came to the extensive use in communication such as radar, television and satellite applications [1]. The second application is microwave heating of different materials. The most commonly used frequencies for heating purposes are 915 MHz and 2.45 GHz, which are derived from electrical energy with the transformation efficiency of about 85% and 50%, respectively [2].

The dielectric interaction of materials with microwaves can be described by two important parameters: absorbed power (P) and depth of microwave penetration (D). They will determine the uniformity of heating throughout the material. The average absorbed power, P, which is volumetric absorption of microwave energy (W/m3) in material, is expressed as Eq. (1) [3] [4]:

$$P = \sigma |E|^2 = 2\pi f \varepsilon_0 \varepsilon''_{eff} |E|^2 = 2\pi f \varepsilon_0 \varepsilon'_r \tan\delta |E|^2 \tag{1}$$

tanδ is the loss tangent, which indicates the ability of the material to be polarized and heated. It can be expressed as Eq. (2):

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2}$$

$$\frac{\Delta T}{\Delta t} = \frac{2\pi f \varepsilon_0 \varepsilon''_{eff} |E|^2}{\rho C_p} \tag{3}$$

The loss factor measures the ability of the material to transfer microwave energy into heat and the dielectric constant measures the ability of the material to be polarized [4]. The absorbed microwave power in material is converted to heat and lead to increase in its temperature. Temperature increase is shown as Eq. (3) [3]:

The penetration depth D (m) is another important parameter that determines the depth of penetration at which the incident power is reduced by one half exhibiting the uniformity of heating throughout the material. The penetration depth can be expressed as in Eq. (4) [3][4][5]:

$$D = \frac{3\pi_0}{8.686\pi \tan\delta \left(\frac{\varepsilon_r'}{\varepsilon_0}\right)^{\frac{1}{2}}} = \frac{C}{2\pi f\sqrt{2\varepsilon'}\left(\sqrt{1+\tan^2\delta - 1}\right)^{½}} \tag{4}$$

As seen in Eq. (4), the higher the values of tanδ and ε_r' the smaller the depth of penetration for a specific wavelength.

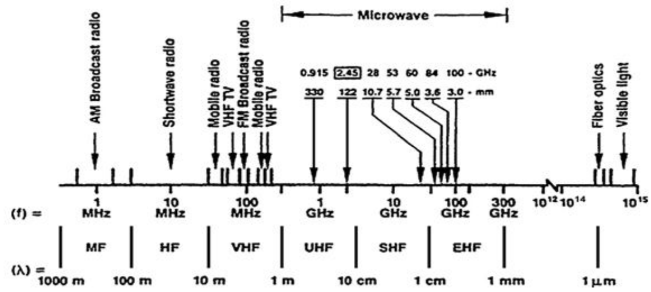

Fig.1. Electromagnetic spectrum and frequencies used in microwave processing (after Ref. 14)

High frequencies and large values of the dielectric properties will result in surface heating, while low frequencies and small values of dielectric properties will result in more volumetric heating [3].

The skin depth "d" (m) is defined as the depth into the conductor from the surface at which the current density is 1/e of its value at the surface [6] [7], given by Eq. (5):

$$d\sqrt{\frac{1}{\pi f \sigma \mu_a}} \tag{5}$$

A. Basic of microwave sintering

The particular requirements of sintering material powders make this process one of the most challenging applications for microwave processing. These requirements often include some or all of the following: high temperature, high heating rates, uniform temperature, and equivalent thermal history throughout the specimen. The process of sintering materials in the conventional methods is incorporated with mixing of material powder with additive, milling, and pressing into green parts followed by sintering with indirect heating of green pellets at about 0.6–0.8Tm in a refractory-type electrical resistance furnace, induction furnace or fossil fuel furnace. These furnaces use a large number of expensive heating elements, fuel and refractory materials to achieve and maintain the high temperature for a long time. Moreover, it consumes much electrical energy, much fuel, and longer time. These kinds of furnaces with indirect heating are called conventional sintering furnace and the heating mechanism is called conventional heating versus microwave heating which provide direct heating of the green part. The fundamental difference between microwave sintering and conventional sintering is in the heating mechanism. The temperature profile for both methods is shown in Fig. 2. For conventional sintering, heat is generated by heating elements and transferred to samples via radiation, conduction, and convection. In microwave sintering, however, the materials themselves absorb microwave energy, and then transform it into heat within their bodies [8] [9]. The microwave heating presents a potential economical sintering process with shortened processing time for the materials. This method is expected to overcome many of the shortcomings of the conventional sintering process [10]. Thus, there has been considerable interest in microwave heating for the synthesis and processing of materials. Microwave processing has gained worldwide acceptance as a novel method for heating and sintering a variety of materials, as it offers many advantages in terms of enhanced diffusion processes, reduced energy consumption and processing cost, very rapid heating rates and significantly reduced processing times, decreased sintering temperatures, improved physical and mechanical properties, simplicity, unique properties, new materials and products and lower environmental hazards, which are not observed in conventional processes [11] [13] [3] [6] [12].

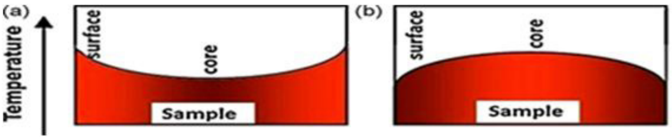

Fig.2. Temperature profile within the sample in: (a) conventional heating ,(b) microwave heating(after Ref.[14])

3. MICROWAVE / MATERIALS INTERACTION

Energy is transferred to materials by interaction of the electromagnetic fields at the molecular level, and the dielectric properties ultimately determine the effect of the electromagnetic field on the material. Thus, the physics of the microwave/materials interaction is of primary importance in microwave processing. The interaction of microwaves with molecular dipoles results in rotation of the dipoles, and energy is dissipated as heat from internal resistance to the rotation. In the following section, the principles behind microwave/materials interactions, power absorption, and measurement of dielectric properties are presented. Whenever possible, simplified models and analogies for microwave/materials interactions are presented to assist in understanding the physics behind the material response. Readers who are interested in more detailed models should consult the references.

A. Dielectric properties

For heat to be generated within the material, the microwaves must be able to enter the material and transmit energy. The dielectric constant (ε') and the dielectric loss factor (ε'') quantify the capacitive and conductive components of the dielectric response. These components are often expressed in terms of the complex dielectric constant $(\varepsilon *)$

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{6}$$

Another commonly used term for expressing the dielectric response is the loss tangent.

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{7}$$

At microwave frequencies, dipole polarization is thought to be the most important mechanism for energy transfer at the molecular level [16] [17]. In addition, in composite materials, Maxwell– Wagner polarization, which results from the accumulation of charge at the material interface, is also an important heating mechanism [16].

B. Dielectric relaxation

Relaxation phenomena are often encountered in a variety of chemical, mechanical or electrical systems. Relaxation times are generally defined by differential equations of the following form where 'h' and 'k' are variables:

$$\tau \frac{\partial k}{\partial t} + k = h. \tag{8}$$

Debye equations based on the microscopic interaction of the dipoles with applied electromagnetic fields [18] [19]. When the electromagnetic field is applied, the dipoles tend to orient in the direction of the electric field. A force balance on the dipole yields the following equation:

$$I \frac{\partial^2 \theta}{\partial t^2} + C \frac{\partial \theta}{\partial t} - pE \sin\theta = 0 \tag{9}$$

Where E is the magnitude of the electric field, θ is the angle between the dipole and the microwave field, I is the dipole moment of inertia, C is the internal viscous damping within the material, and p is the dipole moment.

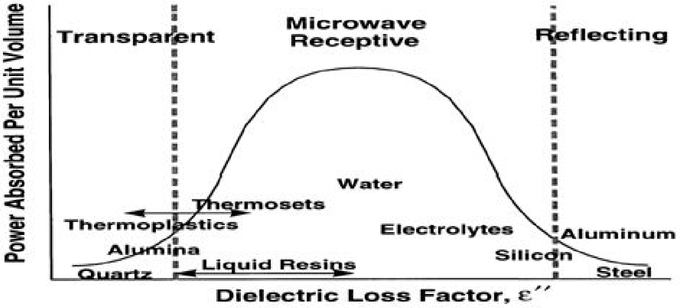

Fig.3. Relationship between the dielectric loss factor and ability to absorb microwave power for some common materials.(After Ref.[1])

From the foregoing equation of motion, a statistical analysis of the dipole orientations could be considered, and the following relation for the complex dielectric constant can be obtained [19].

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1+(\omega\tau)^2} - \frac{i(\varepsilon_0 - \varepsilon_\infty)\omega\tau}{1+(\omega\tau)^2} \tag{10}$$

Where ε_0 is the dielectric constant where the frequency is zero and ε_∞ is the dielectric constant, where the frequency is infinite.

The Debye solution for an ideal liquid is quite simplified and is often not applicable to many materials. The Debye model results in only one relaxation time and often materials exhibit more than one relaxation time. As a result, more complicated models have been developed to describe the dielectric behavior of different types of materials [17]. The Debye model for dielectric properties is analogous to the Voigt and Maxwell models consisting of springs and dashpots that are used in polymer visco-elasticity (Fig. 7).The phenomenon of relaxation in dielectric materials is analogous to visco-elasticity because the governing equations are of the same form [20].

C. Energy conversion

The dielectric properties of materials in combination with the applied electromagnetic fields result in the conversion of electromagnetic energy to heat. The power that is transmitted to an object can be determined by the use of the Pointing Vector Theorem [21], which can be derived from the Maxwell equations. The power that is transmitted across the surface, S, of a volume, V, is given by the real portion of the following equation:

$$\frac{1}{2}\oint_s E \times H^* \cdot dS \tag{11}$$

Where E × H* is the Pointing vector and the *, in this case, denotes complex conjugate. Using the divergence theorem, the Maxwell equations, and by assuming materials properties for the volume the following equation can be obtained for the real portion of the Pointing power theorem:

$$\frac{1}{2}\oint_v \omega\mu H \cdot H^* + \omega\varepsilon'' E \cdot E^* + \sigma E \cdot E^* \ dV \tag{12}$$

Where, μ'' represents the imaginary component of the magnetic permeability and σ is the conductance. In dielectric materials, the magnetic permeability is usually small and the first term can be neglected. In addition, $\omega\varepsilon''$ can be considered as an equivalent conductance [21]. If the electric field is assumed to be uniform throughout the volume, the following simplified equation for power, P, absorbed per unit volume can be obtained from Eq. (13):

$$P = 2\pi f \varepsilon'' E^2 \tag{13}$$

As energy is absorbed within the material, the electric field decreases as a function of the distance from the surface of the material. Therefore, Eq. (13) is valid for only very thin materials. The penetration depth is defined as the distance from the sample surface where the absorbed power is 1/e of the absorbed power at the surface. Beyond this depth, volumetric heating due to microwave energy is negligible.

$$d = \frac{c\varepsilon_0}{2\pi f \varepsilon''} \tag{14}$$

The penetration depth and knowledge of how the electric field decreases from the surface are particularly important in processing thick materials. If the penetration depth of the microwave is much less than the thickness of the material only the surface is heated. The rest of the sample is heated through conduction. Eq. (14) shows the dependence of the penetration depth on the frequency of operation. As mentioned earlier, greater uniformity achieved in multimode applicators by operating at higher frequencies is at the expense of penetration depth.

Eqn. (13) and (14) give an insight as to which dielectric materials are suitable for microwave processing. Materials with a high conductance and low capacitance (such as metals) have high dielectric loss factors. As the dielectric loss factor gets very large, the penetration depth approaches zero. Materials with this dielectric behavior are considered reflectors. Materials with low dielectric loss factors have a very large penetration depth. As a result, very little of the energy is absorbed in the material, and the material is transparent to microwave energy. Because of this behavior, microwaves transfer energy most effectively to materials that have dielectric loss factors in the middle of the conductivity range. In contrast, conventional heating transfers heat most efficiently to materials with high conductivity.

4. EXISTING SINTERING MECHANISM

At this time sintering machine used in the Iron and steel plant is almost Dwight Lloyd type, down draft sinter machine. Therefore, explanation of sintering process will be following the Dwight-Lloyd type. Raw material discharge from proportioning bin is feed to the mixer, and then water is added while mixing to make granules and then fed to pallet in the sinter machine. Pallet is transferred from feed to discharge end through sinter machine rail. The coke in the surface of sinter mix is ignited at the ignition furnace, and then starts the sintering reaction. After ignition, sinter mix has chemical/physical treatment by the combustion heat of the coke and suction air through the sinter mix. After sintering is finished up to the bottom of the sinter mix, sinter is discharge to primary crusher then passes to cooling and screening process. +5 mm sinter is transferred to Blast Furnace as sinter product and the –5 mm is returned to sinter plant as return fines. Some size of sinter product is return to hearth layer hopper as hearth layer.

5. MICROWAVE SINTERING MECHANISM

Instead of using conventional sintering ,we will use the microwave sintering .Therefore, explanation of sintering process will be, Raw material will be discharge from proportioning bin and is feed to the mixer, then water is added while mixing to make granules and then fed to pallet in the microwave sintering machine. Pallet will be transferred from feed to discharge end through sinter machine rail. The microwave interaction with ferrous burden material will start the sintering reaction. After interaction, sinter mix has chemical/physical treatment by the heat generated inside the material by molecules of the ferrous burden material with the interaction of microwaves and suction air through the sinter mix. After the sintering process will be finished up, sinter is discharge to primary crusher then passed to cooling and screening process. +5 mm sinter will be transferred to Blast Furnace as sinter product and the –5 mm will be returned to sinter plant as return fines.

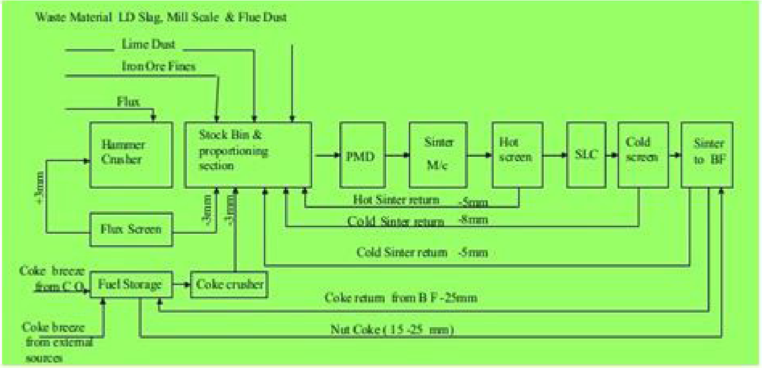

Fig.4. Material flow diagram in existing sintering plant (After Ref. [15])

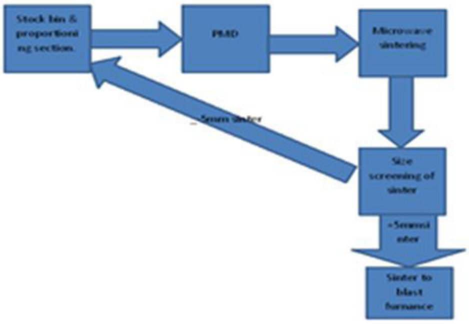

Fig.5. Material flow diagram in existing sintering plant

6. CONCLUSION

Microwave sintering has many benefits and can be accepted over existing sintering process. A summary of these are: Sintering material with microwave consumes much lower energy than existing sintering method. Higher heating rates can be attained and thus the sintering time reduces by using microwave sintering. Higher sinter quality and higher flexibility in raw material and there by improves the performance of Blast furnace by using microwave sintering. Maximum system and plant availability by using microwave sintering. Reducing the coke consumption lowers the production cost, maintenance costs and reduce the emission of SO_x ,CO_x, and NOx.

REFERENCES

1. *E.T.Thostenson,T.W. Chou, 1999, Composites science and technology:PartA30 , pp. 1055–1071.*
2. *K.E.Haque, 1999, InternationalJournalofMineralProcessing, Vol 5, Issue 1 , pp. 1–24.*
3. *D.E.Clark,D.C.Folz,J.K.2000, West,MaterialsScienceandEngineering, A287, pp. 153–158.*
4. *W.H.Sutton,1989, American Ceramic Society Bulletin, Vol 68, Issue 2,, pp. 376–386.*
5. *Y.Zhao,Y.Chen,2008, Progress in Nuclear Energy, Vol 50, pp. 1–6.*
6. *C.Leonelli, P.Veronesi,L.Denti,A.Gatto,L.Iuliano,2008, Journal of Materials Processing Technology, Vol 205, pp. 489–496.*
7. *R.J.Meredith,1998, Engineers' Handbook of Industrial Microwave Heating, IEEPowerSeries25,ISBN0852969163,TheInstitutionofElectricalEngineers,London,UK, pp.1–55.*
8. *A.Goldstein, Travitzky,A.Singurindi,M.Kravchik, 1999, Journal of the European Ceramic Society, Vol 19, Issue 12, pp. 2067–2072.*
9. *V.Tsakaloudi,E.Papazoglou,V.T.Zaspalis, 2004, Materials Science and Engineering B, 106, pp. 289–294.*
10. *J.H.Yang,K.W.Song,Y.W.Lee,J.H.Kim,K.W.Kang,S.K.Kim,Y.H.Jung, 2004, Journal of Nuclear Materials, 325, pp. 210–216.*
11. *P.Yadoji, R.Peelamedu,D.Agrawal,R.Roy,2003, Materials Science and Engineering B, 98, pp. 269-278.*
12. *R.R.Menezes,P.M. Souto,R.H.G.A. Kiminami, 2007, Journal of Materials Processing Technology, 190, pp. 223–229.*
13. *D.Agrawal, 1999, Journal of Materials Education, 19, pp. 49–58.*
14. *M.Oghbaei,O.Mirazee,2010, Journal of Alloys and Compounds, 494 ,pp. 175-189.*
15. *M Gan,XFan,ZJi,XChen,TJiang,Z Yu, 2014, J. Cent. South Univ., 21, pp. 4109–4114.*

16. *J. Mijovic, J. Wijaya., 1990, Review of cure of polymers and composites by microwave energy, Polymer Composites, Vol 11, Issue 3 , pp. 184–190.*
17. *M. Chen,E.J. Siochi,TC. Ward,JE. McGrath.,1993, Basic ideas of microwave processingof polymers, Polymer Engineering and Science, Vol 33, Issue 7 , pp. 1092–1109.*
18. *V V Daniel,1967, Dielectric relaxation. New York: Academic Press.*
19. *G.Roussy, J A., 1995, Pierce, Foundations and industrial applications of microwave and radiofrequency fields, NewYork:Wiley.*
20. *I D Ferry,1980, Visco elastic properties of polymers, NewYork:Wiley.*
21. *RE. Collin, 1966, Foundations of microwave engineering, New York: McGraw-Hill.*