Analysis of the Microwave Heating Effect in the Comminution Efficiency of Iron Ore Particles

L. M. Silva\textsuperscript{1}, M. Nascimento\textsuperscript{2}, I. O. Mota\textsuperscript{1}, E. M. Oliveira\textsuperscript{1}, J. A. Castro\textsuperscript{1}

\textsuperscript{1} Metallurgical Graduate Program in Engineering, Fluminense Federal University – UFF Av. dos Trabalhadores, 420, Vila Santa Cecilia, Volta Redonda, RJ, CEP 27255-125, Brazil

\textsuperscript{2} Mineral Technology Center - CETEM - Av. Pedro Calmon, 900, Cidade Universitária, RJ, Brazil

leonardouffsilva@gmail.com

Keywords: reduction of phosphorus; iron ore; leaching; microwave.

Abstract: Heating iron ore fine particles using microwave energy has been effective due to the different interactions between minerals and gangue in the magnetic field generated by the microwave. In this way, this paper proposes to use microwave energy to heat the particles of iron ore to promote micro cracks and fissures, which would facilitate the comminution and pulverization process to produce pellet feed. It was analyzed different conditions of heating and cooling in the comminution step. By using techniques of scanning electron microscopy (SEM) and image analysis it was possible to assess and quantify the micro cracks and subsequent analysis of the energy and size fragmentation in the comminution step of ultrafine particles.

Introduction

The element phosphorus when found in the steel at levels above 0.04 % (mass %) becomes detrimental to the quality of steel. In Brazil and in several places in the world are found large quantities of iron ore deposits with grades above 0.1 % occurring so the devaluation of the ore by the high cost of the phosphorus so is necessary the processing of reduction of phosphorus during the production process steel. However depending on the way the element phosphorus is contained in the iron ore it will depend on the addition of extra energy for his release [1]. Although, this addition of energy can be applied using the microwave energy this energy can cause fractures in the iron ore particles thus enabling a lower power expense in the comminution process [2].

The research of Roy and Agrawal (2001) [3] showed that the interaction of the magnetic field with some materials contributes in heating rate compared to the materials exposed to the electric field. According Haque (1999) [4] to microwave energy provides a possible mechanism for inducing the breakage between the amount of minerals in the ore and the gangue or host rock, due to differential absorption of energy from the microwave and thermal differences given by coefficients of expansion between the various mineral phases in the particles of iron ore [6]. In this context, the present study aims to investigate the effect of the cracks caused by the heating of iron ore particles in contact with the microwave energy to promote the rupture of the particles thereby improving the efficiency of the comminution process of the ore particles of iron.

Materials and methods

Samples of iron ore used for this study were obtained from the mining process located in the Iron Quadrangle region of Minas Gerais, Brazil. All samples were comminuted using rod mill and chemical analysis was performed using the optical emission spectrometry method with inductively coupled plasma located in the Center for Mineral Technology, Brazil. The X-ray diffraction pattern of the sample is shown in Fig. 1, indicating that the ore sample was mainly composed of kaolinite 4.64 %, gibbsite 3.18 %, goethite 7.25 %, hematite 72.89 % and 12.05 % quartz as shown in Tab. 1.
Table 1. Chemical composition of the sample of iron ore (% by mass fractions).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mass fractions %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)* hematite [Fe₂O₃]</td>
<td>72.89</td>
</tr>
<tr>
<td>(2) kaolinite [Al₂Si₂O₅(OH)₄]</td>
<td>4.64</td>
</tr>
<tr>
<td>(3) quartz [SiO₂]</td>
<td>12.05</td>
</tr>
<tr>
<td>(4) gibbsite [Al(OH)₃]</td>
<td>3.18</td>
</tr>
<tr>
<td>(5) goethite [FeO(OH)]</td>
<td>7.25</td>
</tr>
</tbody>
</table>

(* Numbers indicated in previous Fig. 1.

Experimental procedure

Fractions were obtained from size below and above to 2380 mm to 595 mm range and fractions less than 595 mm and greater than 500 mm and less than 500 mm. The fractions were separated and a portion where divided followed for the pre-treatment and grinding tests on a laboratory scale. The rest of the sample continued to conventional comminution step being called non-plotted samples.

For the process of pre-treating iron ore particles used was a conventional microwave reactor with power 1200 W radiation emitting frequency 2450 MHz with a conventional reactor, microwaves are generated by the equipment called magnetron, located in the upper right corner of the oven, however, it was observed the lower left location of the furnace as the location is higher incidence of microwave radiation thus where ore was added to sample iron. In each experiment it was used 13 g ore particles for 3 minutes contact with the microwave radiation. The sample was treated with the highest power level in an air atmosphere. Upon reaching the prescribed residence time, the treatment was stopped immediately once the sample was added to a reactor containing 500 mL of water at room temperature. The mass of 13 g the fractions obtained after pre-treatment (pre-treated samples) were subjected to a ball mill milling in bench scale during the time interval of 20 s as well as the mass of 13 g of iron ore untreated sample.

After the milling step both treated and untreated samples were sieved sequentially with openings 0.297 mm; 0.210 mm and 0.105 mm. For each size classification was repeated grinding test and pretreatment thereby generating samples having values mass of 50 g. The mass of passers particles were weighed and recorded and the percentage of passers of treated and untreated particles were carried out.

![Fig. 1. X-ray diffraction pattern of the iron ore sample.](image-url)
Results

According to the authors Haque et al. (1999) [4] it was observed that the heating process by microwaves can accumulate in internal energy on materials. In this study it was confirmed that the samples accumulate sufficient energy to promote cracking during heating. According to Haque (1998) [5] the behavior of the mineral constituents present in iron ore by heating through contact with microwave energy was investigated under consideration overactive magnetite, hematite and the active silica considered inactive in the microwave field. In Fig. 2 is shown the pattern of cracks iron ore particles with particle size less than 0.595 mm.

![Fig. 2. Micrographs of iron ore in 0.595 mm before (a) and after (b) the heating in microwave oven.](image)

According to Hake (1998) [5] minerals present in the iron ore particles occur in different heating rates under microwave irradiation, thus, different temperatures may thus cause thermal stresses and fractures on the particles of iron ore. Walkiewicz et al. 1988, [6] have shown that the rapid warming of iron ore particles can be caused by high energy absorption of microwaves in minerals with high iron content. On the other hand, the matrix having with a higher amount of gangue can cause difficult on absorption of microwave energy causing generating large thermal gradients which allow the tension between minerals in particles of iron ore. This thermal stress causes micro fracture along the grain boundaries of mineral as a result the iron ore sample becomes more favorable for grinding. Kingman et al, 2004) [7] showed that the fracture iron ore samples caused by the treatment with microwaves is a function of electric field intensity. Numerical simulations have shown that pyrite ores containing quick heating occurs with the contact in a microwave transparent matrix showing that the sample was fractured due to temperature gradients in addition to the grain boundaries. It is also suggested that the fracture was caused by mineral phases that respond very quickly to warming in a transparent matrix microwaves.

Observing the sample fractures generated in the iron ore particles caused by the interaction of microwave energy with Fig. 3 is the observed mass of the pass measurement of the iron ore particles with granulometric size 0.500 mm untreated and treated the microwave energy. The size classification were used 0.105; 0.210 and 0.297 mm. Treated iron ore particles were subjected to the 300 s contact time with microwave energy reaching 7000 W absorption value.
The Fig. 3 shows the quantification of the mass of the bolt particle size of 0.5 mm grain size treated with microwave energy. It also shows the quantification of the mass of the through-sized particles with particle size of 0.5 mm were not treated with microwave energy. To evaluate the weight percentage of passing a fixed value was used grinding time for both samples. It was observed in the treated sample the occurrence of increased passing percentage in mesh 0.297 mm and 0.210 mm followed by the passing of mass reduction in the qualifying mesh 0.105 mm. This fact indicates that at higher particle size there is an increase in the percentage of the mass of passing ore. However with increasing difference between the original particle size and the size of the mesh classification is the reduction of the effect of pre-treatment of the microwave iron ore particles demonstrated by the decrease of the mass of particles in the graded bushings mesh 0.105 mm.

The effect of the microwave radiation in the iron ore grinding process was examined by Walkiewicz et al, 1988, [6] he reported that in their study, the iron ore was subjected to 3 kW levels of radiation at 2.45 GHz raising temperature between 840 and 940 °C. Milling tests showed that the treatment process of the particles using a microwave was able to reduce the labor content of the iron ore between 10 % and 24 %. In this sense Kingman et al, 2004 [7] studied the influence of microwaves on Norwegian ilmenite ores radiation and concluded that treatment with microwave energy leading to a reduction in the grinding work index up to 90 %, with the increased recovery of ilmenite. Chen et al (2009) [8] investigated the influence of the pre-treatment microwave in the process of grinding the particles of ilmenite ore, and concluded that the Microwave irradiation process has the potential to provide a new and efficient method of treatment of ilmenite obtaining low power consumption. These results were confirmed in this study as the results shown in Figure 3, where there was an increase in the percentage mass passing in smaller particle sizes. The Fig. 4 shows the quantification of changes in each through-treated iron ore fraction and untreated using microwave energy, especially in the larger size fractions.
In Fig. 4 was presented quantification of changes in the passing of the particles of 0.595 mm of ore treated and untreated. In the iron ore sample with an average particle size of 0.595 mm treated with microwave power, we observed an increase of 6% in the percentage of passing the 0.297 mm mesh followed by a 1% reduction in mass of the through-classifying the particles into the mesh of 0.210 mm and a 3% reduction in the through mass fraction of 0.105 mm thereby showing a reduction in the influence of the pretreatment of the particles as a function of the distance between the original particle size and particle size classification mesh.

This difference can be explained by the fact of hematite being an active material against the power microwave heating of the particles of iron ore. However, the gangue minerals are considered inactive against the microwave energy. When exposed to microwave radiation, mineral hematite most expands in volume in relation to the gangue minerals, thus resulting in the formation of intergranular fracture. According to Omnran, et al., (2015) [9], microwave heat minerals with higher speed compared to conventional heating methods, which would generate intergranular thermal gradients inducing the formation of cracks. The speed with which the materials are heated is an important factor in both conventional methods and by microwave heating. In the case of microwave heating, the transfer of heat generated by absorption in the ore particle occurs quickly and directly delivered to the materials by molecular interaction with the electromagnetic field. However, in the conventional thermal processing, energy is transferred to the material through the phenomenon of convection heat conduction thus leading initially to the surface of the particle, then driving into the interior of the material, being a slower transfer process thus creating temperature gradients lower and lower thermal stresses. The results of this study are therefore in accordance with the currently accepted theories to explain the area of mechanisms to increase the leaching of minerals, important stage of the integrated route proposed in this thesis.

When thermal stress reaches a critical level, cracks and fissures are formed on the edge of the material, against this claim with Jones et al., (2005) [10] observed that after the microwave radiation, intergranular fractures occur around the grain boundaries between mineral absorbent and transparent. Amankwah et al., (2005) [11] found that differential heating of the different mineral phases result in thermal stress fractures causing and allowing the ore to be amenable to size reduction, resulting in reduced labor content. The Fig. 5 shows the quantification of the percentage of passing iron ore into a particle size of 2.38 mm, commonly found in commercial sinter feed. Therefore, this study can be extended to the application from the finest materials from the mine, intermediate and larger in the case of granulates.

The Fig. 5 shows the quantification of the mass of the through-size particles of grain size 2.38 mm treated with microwave energy and for particles not treated with microwave energy. To evaluate the passing mass was used qualifying mesh 0.297 mm and 0.210 mm and 0.105 mm. It was observed that due to the large difference between the value of the original particle size and particle size classification of the mesh occurred for the particles treated with the reduction of the mass through-all classification of iron ore.

![Fig. 5. Quantifying of passing of 2.380 mm particle of iron ore treated and untreated in each size of fraction.](image)
According Omran, et al (2015) [9] there are many benefits with time and convenience in the treatment of iron ore to microwave energy may be included to reduce the ore comminution energy. However one of the most important benefits in the treatment of iron ore to microwave energy consists in the release of particles into larger granulometric size thus decreasing the wear of the grinding equipment in the plant [12]. Compared with conventional methods, pre-treatment using microwave energy consumes lower amounts of energy, improves the performance of grinding and phosphorus removal and reduces the processing time [13].

Conclusion

Based on results of this study, it is considered that the viability of the pre-treatment process for iron ore grinding particles occurs only when granulometric sizes decrease to values close to initial particles, which comprises the first step on the grinding sieve. Each of these steps has been studied and its impact on mass of comminuted particles was analyzed. Thus it is possible to highlight the following points:

- Fractures generated in the iron ore particles promote increased yield of comminution process due to the reduction in grain size for values close to the original ones. It was observed that around 6% was increased in mass for the next mesh aperture opening size.
- For further comminution efficiency repeated microwave treatment would be necessary but the amount of energy needs increases for the cascade.

Acknowledgment

The authors thanks to CAPES and CNPq for partial support and CETEM - RJ- Centre for Mineral Technology of Rio de Janeiro for the technological support.

References

[7] S.W Kingman, K. Jackson, N. A. Bradshaw, R. Rowsome, Greenwood School of Chemical Environmental and Mining Engineering, University of Nottingham, Nottingham, NG7 2RD, United Kingdom 2004.