Comminution kinetics of steel slag: Influence of microwave pretreatment

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Appliance of microwave treatment as a preceding step in the comminution processes has been recognized in many scientific and industrial communities. This work presents the effect of such technique on the comminution efficiency of steel slag, in term of process kinetics.

Steel slag samples, defined as diverse monosized fractions, have been used in this study. Microwave treatment was conducted in a domestic, multi-mode microwave unit at a constant power input. Dry grinding experiments were performed in a laboratory, planetary ball mill. Dynamic aspect of the process was observed at a constant process conditions: operational speed, pot volume, number of balls, etc. Process kinetics was expressed via selection function parameter.

Microwave treatment significantly influences steel slag comminution kinetics. Divergence in determined selection function parameters depends on the initial sample size. This investigation indicates possible implementation of microwave treatment in steel slag processing for further application.

1. Introduction

Comminution is recognized as highly energy-demanding process. The finer product size is, more input energy is required. Enhancement of energy efficiency could be achieved in different ways. According to Wang and Forsberg (2007) there are several development trends leading to more efficient comminution:

- development and application of new mills/classifiers
- adjustment of bead characterization in stirred bead mills
- hybrid comminution systems with roller-press and media mills
- assisted methods of comminution (grinding aids, microwave-assisted comminution, ultrasound-assisted comminution)
- simulation

The application of thermal energy in assisting material breakage dates from centuries BC when Egyptians used it for liberation of gold from other minerals. Novel methods are based on the same theory but using more efficient heating – microwave heating.

In his review work, Haque (1999) pointed some major advantages of microwave heating over conventional heating: non-contact heating, energy transfer (not heat transfer), rapid and selective heating, volumetric heating, greater control and higher level of safety.
Such advantages lead to minimization of input energy, reduction of equipment size and overall cost savings in comminution (Kingman and Rowson, 1998; Jones et al., 2002). Interest for research of microwave-assisted comminution mostly originates from mineral processing industry. Considerable effort was done in strength reduction of ores and liberation of valuable minerals using microwave energy as shown by Jones et al. (2002), Patnaik and Rao (2004), Kingman et al. (2004), Kingman et al. (2004a), Wang and Forssberg (2005), Jones et al. (2007), Scott et al. (2008). Interesting application of microwave energy is also found in environmental engineering. Jones et al. (2002) presented the role of microwave treatment in soil remediation and waste processing. Steel slag is a by-product of steel making, produced during the separation of the molten steel from impurities in steel-making furnaces. The chemical composition of steel slag may differ depending on raw materials, but usually contains oxides. Because of unique physical and chemical properties, steel slag is highly suitable substance, mostly in road construction, asphaltic concrete aggregate, portland cement manufacture and various concrete products. Prior to its use as a construction material or cement additive, steel slag must be crushed and screened to specified size required for the particular application. Yan et al. (2005) reported some changes in microstructure of Chinese slag submitted to microwaves. They also pointed out the benefits of internal and selective heating – shortening the process time and targeting the specified phase that heats effectively. This results indicate the potential application of microwave pretreatment of steel slag in enhancement of comminution efficiency. Within this work comminution kinetics of steel slag was investigated. Comminution efficiency of steel slag with and without microwave treatment was expressed in terms of selection functions (specific breakage rates). Estimation of those values was made according to well-known size-mass balance equation for batch grinding:

$$\frac{dw_i}{dt} = \sum_{j=1}^{i-1} S_j \cdot b_{ij} \cdot w_j(t) - S_i \cdot w_i(t)$$  \hspace{1cm} (1)

where \( w \) is mass fraction of material in size interval \( i \) or \( j \), \( S \) is selection function corresponding to specified size interval and \( b_{ij} \) is mass fraction of material broken from size interval \( j \) to size interval \( i \).

2. Experimental methods

2.1 Material
Slag was provided from CMC, Sisak, Croatia. The obtained slag was previously water cooled. Before further processing, slag was left to dry at room temperature for several days. Original slag was received in size smaller than 4 mm. Monosized fractions were obtained using ASTM sieves (-850+600 \( \mu \)m, -1180+850 \( \mu \)m, -1700+1180 \( \mu \)m). Chemical composition of steel slag is shown in Table 1.
Table 1 Chemical composition of steel slag

<table>
<thead>
<tr>
<th></th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>bal.</th>
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</thead>
<tbody>
<tr>
<td>mass %</td>
<td>33.22</td>
<td>10.86</td>
<td>1.66</td>
<td>13.09</td>
<td>6.18</td>
<td>29.64</td>
<td>5.35</td>
</tr>
</tbody>
</table>

2.2 Mill
Comminution kinetics was investigated using planetary ball mill, Fritsch Pulverisette 6. Experimental conditions are shown in Table 2.

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>Pot and ball material</th>
<th>agate</th>
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</thead>
<tbody>
<tr>
<td>Pot volume</td>
<td>10 mL</td>
</tr>
<tr>
<td>Revolution speed (operational)</td>
<td>400 rpm</td>
</tr>
<tr>
<td>Pot diameter</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Disc diameter</td>
<td>13.5 cm</td>
</tr>
<tr>
<td>Ball diameter</td>
<td>12 mm</td>
</tr>
<tr>
<td>Number of balls</td>
<td>2</td>
</tr>
<tr>
<td>Rotation/revolution ratio</td>
<td>0.82</td>
</tr>
</tbody>
</table>

2.3 Microwave oven
Microwave heating of slag samples was performed in a domestic multi-mode microwave oven operating at 2.45 GHz and 1000 W input power. Prepared size fractions were portioned in smaller quantities and 5 g of sample was placed in a small glass pot, put into the center of MW cavity and heated for 10 min at maximal input power. After cooling at room temperature, sample was heated again for 20 min at the same input power. Microwave pretreated samples were then comminuted using experimental set shown in Table 2.

3. Results and discussion
Selection function can be calculated according to eq. (1) using one-size interval method. For the top size fraction eq. (1) can be written as:

\[
\frac{dw_i}{dt} = -S_i \cdot w_i(t)
\]  
(2)

or

\[
\ln w_i(t) = -S_i \cdot t
\]  
(3)

Equation (3) applies to first-order grinding kinetics.
Fig. 1, 2 and 3 show the change of unbroken material content with comminution time for all tested size intervals with and without microwave treatment. Linear dependence would suggest linear kinetic model. Nevertheless, results showed non-linear change and
so-called abnormal breakage. Austin and Bhatia (1971/72) reported that abnormal breakage occurs when the particles are too large in relation to the ball and mill diameter. Such breakage behavior they described with the sum of two first-order breakages.

Fig. 1. Feed disappearance in comminution process, size interval -850+600 μm

Fig. 2. Feed disappearance in comminution process, size interval -1180+850 μm

Objective of this work was to investigate the influence of microwave treatment on particle breakage behavior. Therefore, selection function determination is only a first approximation in considering mentioned effect. Selection function was evaluated according to linear kinetic model for comminution time greater than 3 minutes. However, further analysis of comminution kinetics would require more detailed modeling and evaluation of selection function according to some non-linear kinetic models.

Results showed that the selection function parameter varies with initial particle size. Selection function of smaller untreated particles showed higher probability of breakage. The same trend was observed for microwave treated samples.
Fig. 3. Feed disappearance in comminution process, size interval -1700+1180 μm

Selection function deviations imply on the effect of microwave pretreatment on the steel slag grindability. Major impact is recorded for the smallest size interval (-850+600 μm) where breakage rate increases from 0.029 min⁻¹ to 0.039 min⁻¹. Explanation for microwave influence was found in selective heating of steel slag. Compounds, noted as good absorbers of microwave energy, Fe₂O₃ and MgO, constitute the majority of steel slag mass. They heat rapidly and very intensively. Consequently, distinctive microwave energy susceptibility in steel slag would lead to attenuation of constitutive binds. Similar results were reported in work of Patnaik and Rao (2004) and Haque (1999). Intensity of microwave treatment is less perceived as initial particle size increase. Although, it cannot be neglected that particle size is probably too large in relation to pore diameter in those cases.

Fig. 4. Breakage rates for different feed sizes of treated and untreated samples.
Fig. 4 summarizes obtained results. Microwave energy can reduce strength of steel slag of smaller initial sizes. Further research, which will include larger pot volumes, larger ball diameters and wider range of particle sizes, is necessary. However, according to presented results, it can be concluded that there is a potential use of microwave energy as a pretreatment method that improves steel slag comminution efficiency.

4. Conclusions

Comminution tests of steel slag samples were provided. Influence of microwave treatment on comminution kinetics was investigated. Comminution kinetics of steel slag was described as a sum of two first-order kinetics. Alterations in selection function values imply on the effect of microwave pretreatment on the steel slag grindability and necessity for further research in this area.

References

Austin L.G., Bhatia V.K., 1971/72, Experimental methods for grinding studies in laboratory mills, Powder Technol. 5, 261-266
Yan C., Yoshikawa N., Taniguchi S., 2005, Microwave heating behavior of blast furnace slag bearing high titanium, ISIJ Int. 45, vol 9, 1232-1237.