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Microwaves in extractive metallurgy: Part 2 – A review of applications

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ABSTRACT

In metal extraction processes, such as reduction or smelting, a source of energy is required for the endothermic reactions. This energy is often supplied by the combustion of carbonaceous materials or hydrocarbons or by inputting some electrical energy. Typically, large-scale reactors are used and the energy is transported to the reacting materials from the heat source via convective, conductive and radiative processes. Additionally, considerable heat is transferred to the containment vessel, the surroundings and the off-gases and this energy is difficult to recover. On the other hand, microwave heating systems can be designed such that only the material to be processed absorbs the microwaves, since microwave radiation is deposited directly in the material to be heated. Other potential advantages of microwave processing include; high energy densities, selective heating, improved control, environmental benefits and minimal off-gas generation. In the present research, the utilization of microwaves as an energy source in metal extraction and, in particular the pyrometallurgical processing of oxide ores, is reviewed.

1. Introduction

Microwave radiation is a relatively new energy source, which has considerable potential for various applications in mineral processing and extractive metallurgy, specifically hydrometallurgy and pyrometallurgy. The research activity in these areas has been growing significantly as evidenced by the exponential growth in publications, as shown in Fig. 1, for both minerals and metals. The major advantages of utilizing microwaves as an energy source in extractive metallurgy systems would be as follows:

(1) The energy is transported from the microwave source to the interior of the material in the form of microwaves, which are converted into thermal energy only in the interior of the material. There is very little heat deposited in or lost to the surroundings.
(2) In many cases, the temperature of the interior of the material to be heated is much higher than the surface. Thus, for materials such as oxides, where the poor thermal conductivity limits conventional heat transfer from the outside to the inside, significant improvements in heat transfer can be attained. Also, this inverted temperature gradient minimizes the temperature of the refractory container or crucible.
(3) The energy densities in microwave systems can be relatively high and this in combination with the low thermal conductivities of oxides and minimal heat absorption by the surroundings can lead to very high internal heating rates.
(4) The electrical energy source can be relatively clean and is easily controlled. Continuous processing is facilitated. Since there is no combustion of carbonaceous or hydrocarbon fuels, then the only gases generated are those produced as a result of the intended reactions. This minimizes the amount of off-gas and also the amount of entrained dust particles.
(5) The working conditions in microwave processes would be expected to be far superior to those in conventional processes.
(6) The thermal energy is generated on the atomic or molecular level and thus both endothermic and exothermic reactions can be promoted.
(7) In special cases, some degree of selective heating can be attained but this is restricted by heat conduction, which limits temperature gradients.

On the other hand, there are a number of issues to be addressed in microwave processing and these can be summarized as follows:

(1) The initial capital investment cost is higher than conventional processing.
(2) The maximum microwave power is limited to about 100 kW unless multiple microwave sources are used and this has already been done on other microwave applications.
(3) The operational costs are dependent on the lifetime of the magnetron (the usual heat source) but significant improvements are being made.
(4) Uneven heating can lead to thermal runaway and hot spots.

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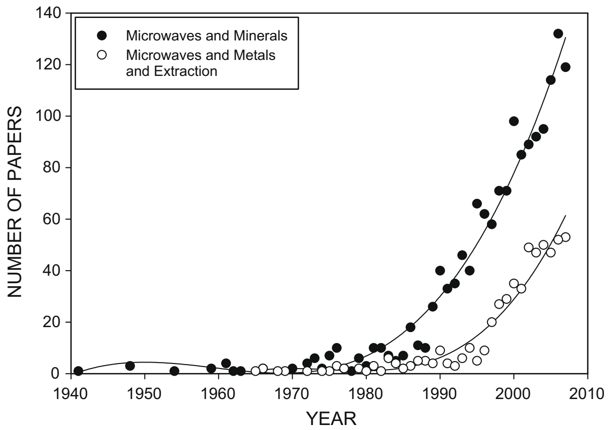

Fig. 1. Number of papers published on "microwaves and minerals" since 1940 and "microwaves and metals and extraction" since 1960 (from SciFinder Scholar™ 2006, American Chemical Society).

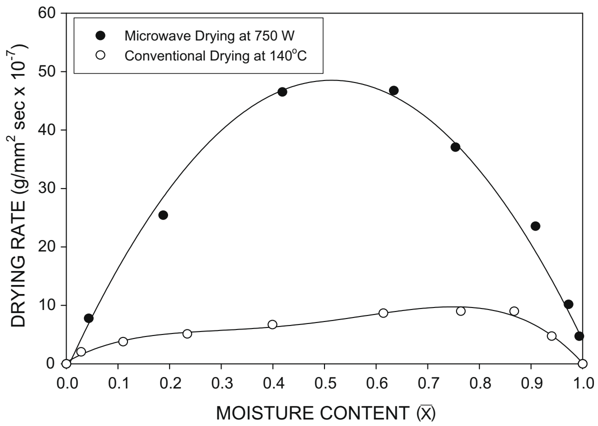

Fig. 2. Microwave drying rates at 750 W and the conventional drying rates at 140 °C of the limonitic nickeliferous laterite ore as a function of the moisture fraction (Pickles, 2005b).

(5) The efficiency of conversion of the electricity to microwaves is between 65% and 90% (depending on the system design and frequency selection), so energy is lost as heat in the microwave source.
(6) The technology is relatively complex in comparison to other heating techniques.
(7) Electrical energy can be an expensive in contrast to hydrocarbons or carbonaceous materials.

In the present paper, the research, which has been conducted at Queen's University over about the last decade, on the application of microwaves to mainly pyrometallurgical processing of oxide ores, is reviewed. These processes are as follows: drying, calcination and sintering, reduction and smelting, heating and reduction of slag, the segregation process, and the processing of electric arc furnace dust and gold-bearing materials.

2. Applications

2.1. Drying

The removal of water is a major cost factor in the processing of ores and concentrates. Microwaves have been utilized to dry iron oxide pellets (Pickles and Xia, 1997) and also nickeliferous limonitic laterite ores (Pickles, 2005a, b) and significant enhancement of the drying kinetics has been observed. Fig. 2 compares the drying rates of both the conventional and the microwave drying processes for the nickeliferous limonitic laterite ore and it can be seen that the microwave drying rates are typically two to five times higher than conventional (Pickles, 2005b). These improvements can be understood by considering the conventional drying of a non-hygroscopic solid. The drying process consists of three stages: (i) set-up, (ii) constant rate and (iii) falling or decelerating rate. The critical moisture content is the moisture content when stage two ends and stage three begins. In the first stage, the sample is being heated to the predetermined drying temperature. In the second stage, the water is removed from the surface of the sample and is replenished by water that moves to the surface via capillary action. The larger capillaries are drained first and then the smaller. When capillary action is no longer possible then the drying rate decreases and the removal of this internal or trapped moisture is more difficult. In order, to remove this remaining water it may be necessary to increase the temperature, which could involve overheating the surface.

In microwave drying, the heat is absorbed primarily by the water. Thus, after the moisture near the surface is evaporated by microwave heating, the microwaves penetrate deeper and heat the interior water directly, bypassing the heat transfer or moisture migration processes. In later stages, the temperature gradient can be inverted and the temperature in the interior may be higher than on the surface. This situation can result in transport phenomena, which are completely different than those in conventional drying. This results in significantly higher drying rates during both the constant rate drying period and the decelerating rate period and also the critical moisture contents are increased. These improvements are attributed to three possible mechanisms: (i) reflux condensation, (ii) enhanced capillarity and (iii) microwave pumping. Reflux condensation refers to the simultaneous evaporation and condensation of the water in the sample due to temperature and moisture gradients, which leads to higher mass transfer rates. Higher internal temperatures result in enhanced capillarity since the surface tension of water decreases with increasing temperature. Microwave pumping is due to the formation of gas bubbles, which push liquid to the surface. These bubbles could either be water vapour or air, which comes out of solution.

2.2. Calcination and sintering

The traditional manganese oxide-containing ores are being depleted and therefore manganese carbonate ores are becoming an increasingly important potential source of manganese oxide. In this regard, the application of microwave energy for the calcination and agglomeration of these ores was investigated (Amankwah and Pickles, 2005). The calcine was an excellent microwave absorber and the addition of a small percentage of calcine to the feed resulted in improved microwave coupling. The decomposition rate of the ore in both a conventional resistance furnace at a constant temperature of 1200 °C and also in a microwave system, are presented in Fig. 3. Since the resistance furnace was already preheated to 1200 °C, the decomposition rate for the initial 10 min was much higher than that for microwave heating. However, subsequently, the microwave calcination rate increased dramatically above that of conventional heating. At the end of 27 min, the microwaved sample had been calcined and sintered with a mass loss of 33.6%. In comparison, complete calcination of the sample heated in the conventional furnace, was achieved after 38 min but agglomeration did not occur. The loss in mass was 31.4%. Therefore, microwave calcination and sintering was much faster than the conventional process.

The differences in the morphological features of the calcines produced in the conventional resistance furnace and the micro-