1. Introduction

Microwave is a electromagnetic wave, whose frequency is between $3 \times 10^8$ Hz and $3 \times 10^{11}$ Hz, and it can be used as one of energy source. During microwave heating process, there are some special properties, such as volumetric heating, selective heating, rapid heating, environment-friendly and easy to control, which differ from the conventional heating. In the past years, microwave was applied in many fields, including food, material, chemistry and metallurgy process.

The utilization of microwave in metallurgy process in China or in the other countries is an interesting topic, and a lot of research works have been done. As earlier as 1991, a research about carbothermic reduction of iron ores with microwave irradiation was investigated. A weight loss was measured by using an electronic balance, from which the reduction rate of the sample is calculated. Figure 1 shows the difference of the microwave reducing behavior of lime and limestone is unconspicuous. It’s because the supply of heat by reaction of carbon and iron oxide has been more than adequate to the heat requirements of the calcinations of limestone. Figure 2 shows the reduction with char is faster than that with coke because of the higher absorptivity of microwave energy of char. The results in Fig. 3 establish convincing evidence of the superiority of microwave heating over conventional heating in the carbothermic reduction of iron ores. The carbothermic reduction using conventional heating have “cool centers” in hematite and magnetite pellets containing coal char. Nevertheless, microwave heating is volumetric and it distinct from conventional heating in which the heat is transferred from the surface to the interior. So microwave heating can provide pellets with “hot centers” and solve the impasse which appears in the conventional heating.

In 1995, Kelly and Rowson did a research about microwave reduction of oxidized ilmenite concentrates. Via a oxidation and reduction, the particle size of ilmenite is greatly decreased, which will benefit the next step of the treatment of minerals. One advantage of this work is to shorten processing time (from at least 4 h to 10 min). The results show that the extraction rate of iron is 3 times larger compared with that of conventional process.

Recently, Pickles investigated the research of microwave heating property of limonitic ores in order to get the feasibi-
ability of Ni extraction, which is the important step (or the first step) for the dehydration of limonitic laterite ores. During his study, the dielectric property of limonitic laterite ores—the most important factor for microwave heating, has been detected. It was found that loss tangent of ores has a sharp increase once it reaches certain temperature, and it also means that once the ores is heated to a fixed temperature, the ores can be self-heated rapidly under microwave irradiation.

The studies mentioned above arose the interest of Chinese researchers. In recent years, some laboratory studies had been done about application in metallurgy processing, because the microwave heating has the characteristics of energy-saving and environment-friendly.

2. The Main Development of Microwave Application in Metallurgy

In metallurgy field, microwave plays an important role in many aspects, such as in microwave roast, extraction of non-ferrous metal, treatment of iron ores and recycling utilization of dust and slag. The microwave application in the field of interest also attracted the attention of the researchers in China, and a lot of work have been done. Recently, some further work, especially in sintering of magnetite concentrates and reduction of iron ore concentrates have got a great improvement. So here, the development of the related research will be shown in detail.

2.1. Sintering of Magnetite Concentrate

Non-carbon sintering of magnetite concentrates with microwave is an interest subject in view of reducing CO₂ emission and environment protection. The research work on this subject is mainly done by Chongqing University. In 2003, a report about the effect of heating time, carbon content and calcium oxide addition in the sintering of magnetite concentrates under microwave irradiation was issued. The key point of this research is the heating effect of three different types of magnetite concentration, which is got from Chongqing Iron and Steel Company, in microwave sintering. The experimental procedure includes four parts: Firstly, the relationship between the temperature and heating time is obtained after measuring the samples temperature at the different time during microwave heating; Secondly, the effect of different addition of powder carbon on heating temperature is investigated; Thirdly, the relationship between different dual basicity (CaO/SiO₂) and heating temperature is investigated. The feasibility of sintering of the concentrates is considered. At last a preliminary research of microwave sintering with different compactness of the samples is conducted. Recently, the mass of the sample, magnetite addition and inert atmosphere (N₂) have been considered in the sintering of magnetite concentrates under microwave irradiation. And it was found that:

1. Under the same microwave heating condition (microwave out power (P)=1 000 W, microwave frequency (f)=2.45 GHz, heating time (t)=20 min), the temperature of sample (basicity=2.5) comes down as the mass of sample increases, which is opposite to the result of microwave sintering of ceramics.

2. Magnetite can be heated rapidly by microwave. Adding magnetite to concentrate is expected to improve the sinter condition of the sample (basicity=2.5), but it is shown that there is less liquid phase generated in the microwave sintering of magnetite concentrates samples compared with no magnetite addition condition. The more magnetite was added, the less liquid phase generated.

3. There is no big difference in the microwave heating (P=1 000 W, f=2.45 GHz, t=20 min, basicity=2.5) of magnetite concentrates with or without inert atmosphere. The exposing area of sample is the main reason, and the possibility of reaction between magnetite concentrate and N₂ maybe is the second reason which still needs a further research. The details of the research are described in the paper.

Recently, analyzing past study and experiment, factor of affection on magnetite concentrates temperature maybe as follows: magnetite concentrates mass (≤100 g), area of radiating heat, thickness of heat insulator and size of magnetite concentrates, etc. In order to reducing area of sample radiating heat and loss of heating, shape of reactor is the cylinder and thickness of heat insulator is increased comparing previous one.

Firstly, under the same addition (microwave power
(P)=1000 W, microwave frequency (f)=2.45 GHz, heating time (t)=20 min), three different mass (≤100 g) of less 80 mesh of size sinter by microwave, relation of temperature of different mass sample and heating time is followed in Fig. 4. The figure indicate that temperature of three samples is above 1400°C, in addition, as well as all known, the melting point of magnetite concentrates is about 1300°C. Obviously, there is less liquid phase generated in the three samples.

Secondly, maintaining the same power and heating time, three different size samples of 75 g sinter in the microwave oven, relation between temperature of different size samples and heating time is obtained after measuring the samples temperature (Fig. 5), from the graph, it indicate clearly that the highest temperature of three samples exceed 1300°C, certainly, liquid phase generate in the three samples.

2.2. Drying of Agglomerates

Agglomerates are another main raw material for blast furnace. In the production process of the modern agglomeration, the dry speed is slow and the green ball is easy to burst, and so on. In the roasting stage, nonuniformity in the temperature distribution causes the states of ores to also become nonuniform. The superheated area appears and causes the liquid phase excessive between the ball group caking. These phenomena lower the production rate of the agglomeration end product, cause the difference in strength of the agglomerates, and deteriorate the reproducibility. In 1994, a report appeared in Journal of University of science and technology Beijing presented a study about microwave drying and roasting pellets.11) This research made mainly use of selective heating and volumetric heating properties of microwave. With a microwave oven of 1400/850 W, pellets were dried and roasted. Heating rate (Fig. 6 and Fig. 7) and drying rate (Fig. 8) were studied.

The results show that the temperature of pellets increases rapidly and the temperature distribution inside the pellets is very uniform compared with the conventional heating process. The drying rate is also very large without crack and burst in pellet. The strength of a roasted pellet ranged from 170 to 230 kg, and there is no superheat during roasting.

In 2001, the effects of the stacked state and the amount of pellets on microwave roasting were studied. Under the microwave irradiation(700 W, 2.45 GHz), the pellets in centre are better than ones in the outside, and the strength is higher too.

A laboratory research have been done that titanium concentrate is dried applying microwave technology. By comparing microwave drying effect with traditional drying cabinet, the results shows the drying time ratio value between microwave and traditional drying cabinet is 1/72. Based on orthogonal experimental design, the best condition of experiment that titanium concentrate is dried applying microwave technology is as follows: the microwave power is 700 W, drying time is 90 s and material weight is 10 g. The range analysis results show that the primary factor is microwave power, the second is drying time and the least is...
material weight.\textsuperscript{12)}

And now, the researches mentioned above are in lab-scale. Researchers are finding ways to apply this technology to industry, which maybe need a long time.

### 2.3. Reduction of Iron Ore Concentrates

Compared with sintering and agglomeration, maybe the reduction of iron ore concentrates is a more effective way in ironmaking process. In China, this research is mainly done by J. Chen et al. Firstly, in 2001, the basic principle and application of the microwave heating of pellets containing coal were discussed in their papers.\textsuperscript{13)} The result shows that binder containing water can increase the microwave absorption effectiveness and heating rate of the pellets containing coal. Then, they presented some problems on the microwave heating of pellets containing coal.

In 2003, the calculation on energy consumption in microwave reduction of iron ore concentrates were done,\textsuperscript{14)} and the energy consumed in total was calculated as 20.98 GJ. This research made use of that self-fluxing iron ore concentrate containing coal, namely a good characteristic of absorbing microwave. Combining its essential nature with the voluminal heating property of microwave, the feed fines can be reduced uniformly and swiftly. The phenomena of nonuniform heat transfer can be avoided. So the preparation of self-fluxing pellets containing coal will be abolished. The results of the research show that radiation heating of microwave can compensate calorific power which is necessary for reducing Fe\textsubscript{3}O\textsubscript{4} with coal, which carries on the self-reduction. Carbon monoxide which is produced by self-reduction can preheat and prereduce the fines ore and improve the capacity usage ratio. It has the following advantages. Firstly, self-reduction reaction time is short (about \(\leq 12\) min). Secondly, it may reduce the self-reduction reaction temperature (about 200°C). Thirdly, it may use the fine ore directly. Thus, the process realizes the clean production.

And now, the experiment about this process is done in lab-scale. With the microwave irradiation \((P=15\, \text{kW}, f=2.45\, \text{GHz})\), some factors, such as the kinds of raw materials (Fig. 9), sample mass (Fig. 10), coal mesh size (Fig. 11), are considered for the operation parameters.\textsuperscript{15)}

The results show that lime and the limestone powder are bad to the microwave absorbance; The elevation of temperature speed of the microwave heating containing powdered coal is higher than that of containing particle coal; Adding the few fluxing agent powder in the ore containing coal has no great influence to elevate the material temperature, but is beneficial to the reduction rate. Under the certain temperature, the material reduction rate increases along with the coal blending ratio increasing; The powdered coal granularity to the reduction rate of the iron powdered ore containing coal has the obvious function; The particle coal to the reduction of the iron powdered ore containing coal similarly has the better effect.

What’s more, the metallographic phase of the product is analyzed,\textsuperscript{16)} and the mechanism of microwave reduction is studied. The paper described that microstructures of coal containing iron ore concentrates reduced by microwave heating are classified as the microstructures of metal iron, the wustite and the slag phase. The self-reduction process of iron ore concentrates containing coal heated by microwave was that magnetite grains were initially reduced around coal grains to form metal iron granular structure, then jointed together to form metal iron semi-annular structure, annular structure and cincture structure. Being accompanied by the development of reduction reaction, the reduced metal iron increased between coal grains and magnetite grains, which obstructed the interface of direct reduction reaction. The core of FeO was sequentially reduced by CO and C diffusion in the metal iron, eventually the vermiciform iron jointed crystal texture was formed. Wustite pos-
sessed the absorbency of microwave to a certain degree and might be broken up itself in microwave field, which was helpful to carbothermic reduction. Slag also possessed the absorbency of microwave because its component is very complicated, and propitious to the reduction of its complex iron oxide.

The main stages to reduce iron ores with carbon are shown as follows:

1) Interaction between iron ore and coal
   This is the reaction about at 900°C, which is also the primary reaction at the reduction. In this period, the coal and slate are main composites.

2) Interaction between slate and Fe
   \[ C(s) = [C]_{metal} \] (1)
   \[ FeO(s) + [C]_{metal} = Fe(s) + CO(g) \] (2)
   Via diffusion, some part of carbon will enter the metal, so the goethite will be reduced in the interaction between [Fe] and FeO.

3) Interaction between CO and carburized Fe
   \[ CO_2(g) + C(s) = 2CO(g) \] (3)
   \[ CO + [O] = CO_2(g) \] (4)
   The reduction process is exposed to air, so some part of carbon will be oxidized by CO₂, then CO will reduce the carburized Fe, and more Fe will be produced (see Eqs. (3) and (4)).

2.4. Extraction of Au

As earlier as 1980s, China had completed the carbon slurry process for preparation of gold industry experiment. But because traditional preparation processing caused pollution, the energy consumption is big, the labor intensity is high, the time is long, the activated charcoal rate and the automation is low, the cost is higher and so on, all these factors seriously limited preparation and technology development of gold-extracting carbon in China. In the recently several years emerged the microwave radiation raised the gold activated charcoal and the technology of desorption, become more and more favorable, because the energy consumption is low, the activate rate of charcoal is high, the automation is high, the production cost is low, and so on. The technological flow sheet for preparation of gold-extracting activated carbon using microwave radiation is as follows in Fig. 12. The research is still in lab-scale, but the more factors, such as microwave power, heating time and atmosphere, which will have an effect on extraction of Au, are examined. It was shown that:

- 1) with the same extraction condition (NaCN content, PH, heating time, starting temperature), the stronger power of microwave oven, the more extraction rate of Au.
- 2) a shorter time for extraction of Au is possible: Once the heating time reach a point, the extraction rate gets a maximum.

3. Conclusion

Radiation heating of microwave used in pyrometallurgy has solved “cold center” problem which is crucial in the conventional heating. And carbon thermal reduction rate of metal oxide has greatly improved and has decreased energy consumption. In hydrometallurgy microwave heating compared with other processes has its own properties. It can reinforce extraction course, shorten extraction time and reduce energy consumption effectively. Research and application of microwave are important for hydrometallurgical development. In the ore pre-processing, selective heating of microwave, effectiveness is better than that conventional heating. Although the research findings of microwave in the metallurgy haven’t catered to commercialization, microwave will play an important role for the clean and effective use of energy in the metallurgy in future.

The research for microwave application in China is still underway, and some achievements have been attained. The field of interest is larger than before, and the factors involved in the research are more than ever. But now most of the works about microwave application are still in lab-scale, so how to apply these processing technologies or methods to industry is a further work to be solved in near future.

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