1. Historical Tracing of MW Heating

Microwave (MW) was utilized for radar tele-communication during the World War II. In 1946, Percy Spencer found a candy bar in his pocket was melting during his experiments on the MW generation tube, thus he discovered MW heating. Since then, MW heating has been applied to various fields. At first, it was used in food production areas, such as drying of potato, roasting of coffee beans. It was in ’70s, when the MW oven has become popular in house kitchens for cooking. And it was also in ’70s when the oil shock or natural gas crisis occurred, which promoted the researches on MW heating in the western countries, because of their political necessity to be dependent on electric heating methods.

Application of MW heating to the energy and the environmental fields has also been attempted and realized. Their application extends to broad areas, such as incineration of medical wastes, devulcanization of rubber tire, treatment of sewage sludges, regeneration of spent activated carbon and chemical residues of petrol industries. In the nuclear engineering, MW de-nitration for producing MOX (Mixed OXide) nuclear fuels by re-disposal of the used plutonium. Vitrification of radioactive wastes by MW heating had been proposed in early ’90.

In the area of materials processing, MW application to polymer has started earlier. There are bunch of research reports, curing of thermosets is one of the examples. During MW drying of Al₂O₃ castable, it was recognized that they can be heated well by MW. MW heating of the ceramic powders above 1 400°C made it possible to perform the sintering of ceramics. Later, it was reported that MW sintering enhances the diffusion rate, and so-called non-thermal effect has been pointed out, though its origin has been a long debate. In this field, milli-wave techniques have been developed and applied to new processing of ceramics. On the other hand, studies on MW heating of metals are far behind comparing with them. Generally, it is known that a bulk metal reflects MW, however, the metal particles can be heated, and also known that ferro-magnetic metals can be heated more, indicating magnetism is related to the heating mechanism. Roy reported full sintering of metallic materials in 1999. MW heating of metals is a new technique and could be applied to synthesis of chemical regents and new functional materials, MW rapid heating of catalysis for the cold start of motor vehicles and so on. The MW heating research history is schematically shown in Fig. 1.

2. Classification of Microwave Heating Application and MW Characteristics

Among the broad applications of MW heating in various fields, it is possible to classify their application into two major classes. In the first class, MW heating applied to drying, cooking foods and to excitation of chemical reactions such as inorganic/organic synthesis. The MW acti-
activated reactions has been investigated in the field categorized as “MW Chemistry”. In these applications, the heating temperature is usually below 500°C. Mainly, the heating is caused by a dielectric relaxation loss due to rotation of molecules, which is as the result of the interaction of the MW electric field with the electric dipole of the molecules.

On the other hand, for the MW heating application to sintering of metal/ceramics, solid state reaction, solid state phase transition (such as vitrification or devitrification) and high temperature reduction reaction, elevated temperature is needed, which often exceeds above 500°C. In these cases, heating mechanism is not limited to dielectric loss but to the other mechanisms of ohmic loss due to eddy current, and the magnetic loss also becomes important. Most of the oxides become electric conductive above 1000°C. From these considerations, understanding the effect of MW magnetic field interaction with materials becomes important.17,18)

The relation between the MW heating and the dielectric loss was a main concept in the MW processing before ‘90s, however, it is expected to have more extended applications based on the different concepts of the MW heating mechanisms.

As the special characteristics of MW heating, three different heating aspects have been pointed out, namely they are the internal heating, the rapid heating and the selective heating.19) It is possible to consider the industrial application of MW heating from these aspects. Moreover, it has been claimed so-called “non-thermal effect” of MW heating20) exists and enhances the sintering and the reaction kinetics, as mentioned above. Although origins of their effects are not clarified completely yet, it still provides us with future prospect for further application of MW.

3. MW Application to Steel Industry and Environmental Techniques

There are large numbers of reports, concerning on the MW application to environmental techniques. Most of them are related with the MW chemistry, such as dechlorization from plastics,20) decontamination of the toxic materials9) and some application to heat treatment of materials and chemicals, as mentioned in Sec. 1. As the high temperature MW heating applications, there are examples of MW soil remediation and soil solidification of heavy metals by vitrification.21) The effectiveness of MW heating for grinding of minerals has been pointed out22,23) and the possibility of energy saving has been demonstrated.

Researches on application of MW to the iron & steel production and the related environmental problems have been performed recently. Pickles treated nickel-ferrous limonite ores by MW.24) Chinese researchers performed the MW heating application to the field of iron and steel making. Bai et al.25) has performed researches on MW processing of slags and attempted application to sintering of the iron ores.

In Japan, Morita et al. presented the first academic report26) on MW heating of steel making slags. The effect
of carbon addition on the heating of synthesized slag is shown in Fig. 2, indicating the improvement of MW heating by carbon addition. Currently, various researches have been performed by different groups in the MW processing research group in ISIJ (High temperature division, Novel processing forum). The research field and the related MW heating phenomena are illustrated in Fig. 3. Morita extended his application studies to carbo-thermal reduction of magnesia refractory27) and blast furnace slag processing.28) Fujisaki and Taira29) reported MW drying of inner lining refractory. It is expected that MW drying has such merits of thick penetration depth (internal heating) for drying large volume, and inverse temperature profile, which results in the equi-direction of heat and mass (water vapor) transfer vectors. Heating treatment of contaminated soils by Taira 30) for the remediation is the recent attempts for environmental technologies. Nagata and Sato 31) have been conducting researches on the MW iron making process, using a large-scaled MW reactor. Nishioka et al. has attempted utilization of RDF (Refuse Derived Fuel) for reduction element of iron making.32) This is a positive trial for utilization of the municipal wastes related reduction elements. Their work initiated with a study of reduction kinetics of ZnO or the fundamental study of Zn, Pb-containing dusts.33) The example of the results is shown in Fig. 4.

The authors have performed collaborative studies with Bai in Chongqing Univ., for MW processing of Ti containing Chinese slags.34) And we conducted some basic studies on MW reduction of pickling sludges of stainless steel. The authors' works on these areas are briefly introduced in the next section.

All of these researches are attempted with consideration on saving energy by reducing reaction time and temperature, utilization of electricity for heating without using fossil fuel and to develop effective disposal methods of wastes.

4. Recent Study on MW Processing in Authors’ Lab.

4.1. Heating of Ti-containing BF Slags

The BF slag is generally composed of Al₂O₃, CaO and SiO₂, which are not heated well by MW, because their permittivity are not large. On the other hand, the BF slag in southeastern part of China contains Ti, and they can be heated by MW very well. It was demonstrated that the heating of the slag is accomplished by existence of a perovskite (CaTiO₃) phase.34) Separation of this phase and their utilization have been taken into consideration.35) The details of the experimental procedures and the results are shown in the other reports.36)

As MW irradiation causes preferential growth of CaTiO₃ phase from the glassy state, (shown in Figs. 5(a), 5(b)), they can be further cyclic-heated to induce cracks between the phases. Figure 5(c) shows the induced cracks, by which degradation of the slag strength was obtained.35) Using this phenomenon, it is intended to separate the CaTiO₃ phase for their utilization.

4.2. MW Carbo-thermal Reduction of Sludges

In a rolling process of stainless steel, a scale is formed because of high temperature oxidation, which is removed by acid-washing. The sediments or sludges are generated from the waste water, containing precious metals such as Ni, Cr and Fe. Carbo-thermal reduction reaction heated by MW has been attempted for their recycling. As the fundamental study, it was attempted to measure the reduction reaction kinetics of NiO with carbon. Graphite powder is a good MW absorber, and can be heated easily, as shown in Fig. 6, their mixture as well. Ni particles are obtained as shown in Fig. 7. The reduction temperature at 600°C was possible,37) which is lower than the conventional heating cases in the report.38) Moreover, difference in reduction kinetics in electric field and magnetic field of MW in a single mode applicator was observed, a possible mechanism has
been proposed. Along with these fundamental studies, the applicability of MW reduction to the actual sludge is being investigated, though further detailed studies are still required.

5. Conclusion

MW heating history for these 60 years has been briefly reviewed, and it was shown that they are extended to broad area. Among them, the application of the MW heating can be divided into two classes with respect to their heating temperature. Heating by contribution of MW magnetic field has been pointed out and the new applications are expected to be explored more in future.

Application to steel industry and the relevant environmental field has been also reviewed, especially emphasizing the research activities of ISIJ members. Although applications in this area are relatively new, active research reports are published. The authors’ recent results on the Chinese slag treatment and the carbo-thermal reduction kinetics are also presented.

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