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Application of Microwave Melting for the Recovery of Tin Powder

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A B S T R A C T

The present work explores the application of microwave heating for the melting of powdered tin. The morphology and particle size of powdered tin prepared by the centrifugal atomization method were characterized. The tin particles were uniform and spherical in shape, with 90% of the particles in the size range of 38–75 μm. The microwave absorption characteristic of the tin powder was assessed by an estimation of the dielectric properties. Microwave penetration was found to have good volumetric heating on powdered tin. Conduction losses were the main loss mechanisms for powdered tin by microwave heating at temperatures above 150 °C. A 20 kW commercial-scale microwave tin-melting unit was designed, developed, and utilized for production. This unit achieved a heating rate that was at least 10 times higher than those of conventional methods, as well as a far shorter melting duration. The results suggest that microwave heating accelerates the heating rate and shortens the melting time. Tin recovery rate was 97.79%, with a slag ratio of only 1.65% and other losses accounting for less than 0.56%. The unit energy consumption was only 0.17 (kW·h)·kg^{-1}—far lower than the energy required by conventional melting methods. Thus, the microwave melting process improved heating efficiency and reduced energy consumption.

1. Introduction

Microwaves are electromagnetic waves with wavelengths that range from as long as 1 m to as short as 1 mm, and with frequencies between 300 MHz and 300 GHz. The microwave frequencies used in industrial applications are mainly 915 MHz and 2450 MHz [1–4]. At present, microwaves are considered to be a new energy utilization technology that has wide application prospects [3–6], such as communication, medical applications, material applications, chemical reactions, metallurgical engineering, and so forth. Among these possibilities, microwave heating technology is one of the main forms of microwave energy application; this heating technology possesses the advantages of being clean, highly efficient, energy saving, and environmentally friendly. In the field of metallurgical engineering, it has been demonstrated that some metal oxides and sulfides can be quickly heated by microwaves [7–9]. Materials such as ilmenite, magnetite, and galena can be heated to over 1000 °C within minutes using microwave irradiation. Microwave heating technology has the characteristics of selectivity, chemical catalysis, easily realized clean production, and automation [10]. The application of microwave heating to a metallurgical process is expected to render that process more efficient, energy saving, and environmentally friendly. In particular, the application of microwave heating to metal smelting and alloy production is likely to improve the traditional process, thereby improving the production economics. Important studies by researchers such as Rong et al. [11,12], Yang et al. [13], and Fan et al. [14] have examined the microwave-activated hot-pressing sintering of alloys. These researchers took advantage of microwave technology

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to change traditional hot-pressing sintering, and achieved very good application.

The present work attempts to apply microwave heating to tin smelting and the tin recycling industry. Powdered tin is mainly used in the production of solder paste, powdered metallurgy products, and so on. In the electronics industry in particular, solder paste has become a new type of welding material with better technology and added value [15]. At present, the industrial production of spherical tin powder adopts methods such as gas atomization, centrifugal atomization, and ultrasonic atomization [16]. The centrifugal method is the most widely adopted of these methods for the production of tin powder [17]. However, this process demands large-scale (75%–80%) tin powder recovery and re-melting. Furthermore, the small particle size, high surface energy, and easy oxidation of the powdered particles make it difficult to re-melt powdered tin using traditional methods. Hence, the present work attempts to apply microwave melting to achieve efficient recovery and utilization of tin.

2. Experimental method

2.1. Materials

Tin alloy powder was provided by Yunnan Tin Group (Holding) Company Limited, China. Its main components are tin (Sn), silver (Ag), and copper (Cu) in a Sn-3.0Ag-0.5Cu alloy. The powdered tin was prepared using centrifugal atomization at an atomization rate of 24 000–30 000 $r\cdot min^{-1}$. To produce a specific size of solder balls in the production of industrial tin powder, a large amount of raw material is re-melted and recycled after screening.

2.2. Material characterization

The morphology and particle size of the powdered tin were analyzed using scanning electron microscopy (JSM-5610LV, JEOL Limited, Tokyo, Japan). The heating rate of the tin powder was measured by thermocouple (Type-K). A platform for dielectric performance testing was established using the resonant-cavity method and dielectric property testing. The testing temperature ranged from room temperature to 1200 °C.

3. Results and discussion

Fig. 1 shows the morphology and particle size of the powdered tin. This figure shows that the tin alloy powdered particles are all regularly spherical, with particle sizes ranging from 38 μm to 75 μm accounting for more than 90%. Different heating mechanisms occur during the microwave heating of metal powder [18], such as eddy currents, discharge, Joule heating, and so forth. Mishra et al. [19] reported that microwave interaction with metals is restricted to the surface only. The skin depth can be mathematically expressed as follows:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = 0.029\sqrt{\rho \lambda_0} \tag{1}$$

where f is the microwave frequency; μ is the magnetic permeability; σ is the electrical conductivity; ρ is the electrical resistivity; and λ_0 is the incident wavelength. The skin depth of the microwave couples with the dimensions of particulate metals, as shown in Fig. 2.

In general, skin depth is relatively small in metals (varying between 0.1 μm and 10 μm); however, most metallic powders have equivalent dimensions. For powdered tin with a particle size range of 38–75 μm, the electrical resistivity ρ is about 11.3×10^{-8} Ω·m at room temperature and the skin depth is 3.377 μm. Thus, the "effective skin" (the portion of metal powder that couples with microwaves) can reach 24.66%–44.40% of the volume. The surface area and hence the "effective skin" are large enough to contribute to the heating of the surface area. Therefore, tin powders undergo volumetric heating through microwave penetration.

In addition, when microwaves act on metal particles, electrons gather on the surface. Under the action of the microwave electromagnetic field, an induced eddy current will be produced on the surface of the tin particle (Fig. 3). This induced electrical field generates a surface current, which causes resistive Joule heating in metal powders and promotes the migration of matter on the surface of metal particles. Thus, absorption and transformation of the microwave energy can be realized.

Furthermore, the mechanism of microwave heating of ceramic and dielectrically lossy materials has been widely investigated. Microwaves penetrate the dielectric material and generate an internal electric field within a specific volume, thus inducing polarization and the movement of charges. The internal, electric, and frictional forces attenuate the electric field to resist these induced motions. These losses result in volumetric heating [20]. Therefore, the dielectric parameter is an important index that reflects the ability of matter to absorb microwaves. In particular, the dielectric loss tangent is a measure of the ability of the material to convert electromagnetic waves into heat at a specific frequency and temperature [21].

There are two main loss mechanisms for non-magnetic materials:

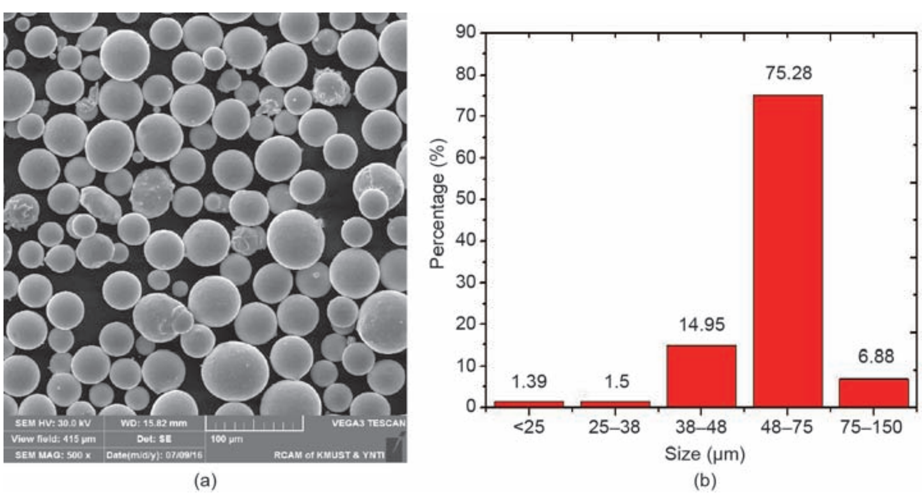

Fig. 1. The (a) morphology and (b) particle size of the powdered tin.

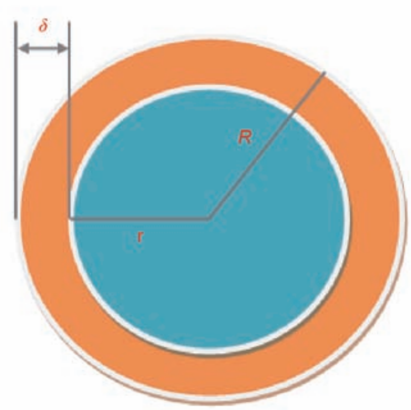

Fig. 2. Schematic of microwave penetration of particulate metals.