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Investigations on container materials in high temperature microwave applications

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Abstract

Microwave heating is a promising technology for high temperature materials processing, in particular melting of oxidic materials. The special characteristics of microwave heating and melting require refractory materials with very specific properties. The foremost important properties are microwave transparency, high thermal shock resistance as well as chemical and mechanical stability. This paper compares the suitability of some widely available refractory materials for use in microwave melting applications with a focus on boron nitride.

Keywords: microwaves; high temperature; melting; refractory materials

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1. Introduction

The advantages of microwave heating are very well known and result from the manner of material heating by microwaves. The main advantages are rapid and uniform heating. Since energy is converted rather than transferred, heating rates as high as 400 K/min are possible. This results in reduced processing time and decreased energy losses within the process. Some studies also report improved mechanical properties and lowered reaction temperatures [1].

High heating rates may become problematic, when materials involved are not able to withstand thermal shocks. In sintering or ceramic burning, the heated bodies have to endure the thermal shock. For melting applications, the refractory materials used for the container have to tolerate thermal shock as well.

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Nomenclature

ε_r	relative permittivity
ε_r'	permittivity
ε_r''	loss factor
ε_0	vacuum permittivity
λ_0	wavelength in vacuum
D_p	penetration depth
E	electric field strength
f	frequency
V	volume

Generally, there are two ways to design a microwave heating process: Heating the material directly or heating a susceptor that heats the material to be processed. This paper focuses on the identification of affordable container materials with suitable properties for direct melting with microwaves.

Nowadays, several research groups are working on microwave heated melting furnaces for oxidic materials and even metals [1, 2]. Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz. For most heating applications, the ISM-frequencies (Industrial, Scientific and Medical) around 915 MHz, 2.45 GHz and 5.8 GHz are used. The 915 MHz and the 2.45 GHz ranges are preferred for applications with high power demand [1].

The dielectric properties of a material, especially the relative permittivity ε_r determine how well microwaves can heat the material. Relative permittivity is a complex number and is usually written as

$$\varepsilon_r = \varepsilon_r' - \varepsilon_r'', \tag{1}$$

where the real part describes the ability of a material to store an electromagnetic field and the imaginary part describes the ability to convert energy to heat. The imaginary part is often referred to as loss factor. Permittivity is a function of frequency and temperature. Minor impurities affect the permittivity of a material. Depending on the material and the impurities, this effect may reach an order of magnitudes. Materials with very low loss factors are called "microwave transparent" [3].

For engineering purposes, two aspects are of paramount importance: Transferred power to the goods P and the penetration depth D_p. P can be calculated using the dielectric heating equation [3]:

$$P = 2\pi f \varepsilon_r'' \varepsilon_0 |E|^2 V \tag{2}$$

where f *is* frequency, ε_0 is vacuum permittivity, E *is* electric field strength and V *is* the volume of the heated body. The penetration depth is defined as the point where the power flux in the material reaches $1/e$ of its surface value. It can be calculated by

$$D_p = \frac{\lambda_0}{2\pi \cdot \sqrt{2\varepsilon_r'}} \cdot \frac{1}{\sqrt{\left\{1 + \left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2\right\}^{0,5} - 1}} \tag{3}$$

where λ_0 is the wavelength in vacuum [3].

1.1. Melting oxidic materials with microwaves

Directly resulting from Eq. (2) and (3), microwave melting processes require a container material that is microwave transparent. Another property needed is high thermal shock resistance – in laboratory trials heating rates as high as 36 K/s have been observed. Due to the formation possibility of hot spots during melting, these temperature increases occur locally, thereby increasing the stress on the refractory.