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Discussion on magnetic-induced polarization Ampere's force by in situ observing the special particle growth of alumina during microwave sintering

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ABSTRACT

Internal microstructure evolution during alumina microwave sintering was in situ investigated with synchrotron radiation computed tomography (SR-CT). Two special microstructure evolution phenomena were continuously observed from the experimental images of the sample at different sintering times throughout the entire process of the sintering, which we called "suppressed particle growth" and "particle homogenization". These two special phenomena were further confirmed by the two curves of "average particle radius" and "particle radius standard deviation" versus sintering time which were directly extracted from the full-field SR-CT results. A polarization Ampere's force model was proposed to provide a possible explanation for these special phenomena, which introduced the effect of magnetic field on insulating ceramic materials, a topic rarely discussed in previous studies. The polarization Ampere's force model may explain these two special sintering phenomena observed in the in situ experiment. On one hand, ceramic particles may sustain "Ampere's force" that pointed toward the particle center according to this model, thereby possibly leading to the special suppressed-particle-growth phenomenon; on the other hand, large particles may sustain a strong force in our model, which may explain the other special phenomenon of particle homogenization. In return, these two special phenomena can also serve as probable experimental evidence of our polarization Ampere's force model. This study may offer some help for revealing the complex mechanisms during microwave sintering and for preparing materials with expected microstructure and excellent properties.

1. Introduction

Microwave sintering is a novel method of processing different kinds of ceramic materials [1], such as Al_2O_3 [2,3], TiB_2 [4], ZrB_2 [5], and SiC [6]. Many studies have implied that compared with conventional sintering, microwave sintering can improve material properties by optimizing the microstructure. For example, Cheng et al. [2] indicated that during alumina microwave sintering, the polycrystalline structure can be converted to a single crystal structure, thereby enabling the alumina specimen to obtain high transparency. Zhu et al. [5] indicated that the microwave-sintered ZrB_2–B_4C achieves lower porosity than the conventionally sintered specimen, thereby leading to an increase in the hardness of specimen (from 16.6 GPa to 17.5 GPa). The mechanisms of microstructure evolution during microwave sintering must be revealed to make preparing materials purposefully effective. However, the mechanisms of microstructure evolution are very complex, because microstructure evolution is a continuous dynamic process that is influenced by many factors, including electromagnetic field, temperature, dielectric properties of a material, and the microstructure itself [6–13]. These factors may interact with one another and may change during sintering process. Thus, a deep understanding of the microstructure evolution mechanisms cannot be obtained easily if studies simply focus on sintered materials, as what has been done in previous works.

The most effective way to make the mechanisms clear is to perform online observation of the internal microstructure evolution during microwave sintering. However, an in situ investigation of the internal microstructure evolution under the extreme complex sintering conditions with the traditional experimental techniques (e.g., SEM and TEM) cannot be performed easily. The synchrotron radiation computed tomography (SR-CT) technique is a latest advanced detection technology that can achieve a non-destructive, real-time, and three-dimensional (3-D) investigation

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of a microstructure. The internal microstructure evolution during microwave sintering can be observed directly and continuously with application of the SR-CT technique, thereby providing complete experimental data for theoretical analysis and mechanism research [14–16].

In this study, an in situ investigation of the internal microstructure evolution during alumina microwave sintering was conducted by applying SR-CT technique. Two special microstructure evolution phenomena of "suppressed particle growth" and "particle homogenization" were continuously observed from the SR-CT experiment results of the sample at different sintering times throughout the whole process of alumina microwave sintering. These two special phenomena were further proved by two curves of "average particle radius" and "particle radius standard deviation", respectively, with sintering time. These curves were extracted from the full-field SR-CT results. A polarization Ampere's force model was proposed to reveal the mechanisms of the special sintering phenomena. The model focused on the peculiar effect of the magnetic field on the insulating ceramic material, which was seldom discussed in previous studies. According to this model, ceramic particles may sustain "Ampere's force" caused by the interaction between the magnetic-induced molecule polarization current and the microwave magnetic field itself. The force may point toward the particle center, thereby possibly leading to the special suppressed particle growth phenomenon observed in the SR-CT experiment. The strength of the force may have a positive correlation with the particle radius, i.e., large particles may sustain strong force, so that it may be the reason for another special phenomenon of particle homogenization. In conclusion, the polarization Ampere's force model can explain the two special microwave sintering phenomena observed in the in situ SR-CT experiment and in return these special phenomena can also serve as the experimental proof for the model.

2. Experiment and results

In the experiment, alumina powders with an average diameter of approximately 100 μm were used. Before sintering, the specimen was manufactured by pouring the loose powders into a quartz capillary (1.6 mm internal diameter, 10 mm height), and it was placed vertically on a sintering crucible.

The experiment was performed on the BL13W1 beam line at Shanghai Synchrotron Radiation Facility (SSRF; China). The schematic of the SR-CT experimental setup at SSRF is shown in Fig. 1. The photon energy of the X-ray beam was chosen to be 28 keV. The X-ray passed through the specimen and was recorded with an X-ray charge-coupled device detector utilizing a 4928×3247 pixels chip with a unit pixel of $7 \times 7\ \mu m^2$ and 16-bit dynamic range. During the test, the specimen (together with the sintering crucible) was placed on the rotation device and rotated with an interval of 0.5° ranging from 0° to 180°. Therefore, 360 projections of the specimen were acquired. The cross-sectional slices of the specimen were reconstructed with filtered back-projection algorithm. The slices were further stacked so that the 3-D images of microstructures were obtained for analysis.

The microwave sintering was performed in a particularly designed multimode microwave sintering furnace (microwave frequency: 2450 ± 50 MHz; output power: 0–3 kW). As shown in Fig. 1, the furnace was fixed with SR-CT facility. The specimen was placed in the microwave cavity at the same height of the X-ray beam. A SiC susceptor was used to preserve heat and to accelerate the increase in the temperature of the sample because of the small sample and large space of a multimode cavity chamber.

In the experiment, the heating rate was controlled by adjusting the output power of the microwave. As shown in Fig. 2, from the beginning to the 6th, 12th, and 18th minute, the power increased gradually from 0.05, 0.2, and 2 kW; from the 24th minute, the power was maintained at 3 kW. For the influence of microwave, the temperature was measured with an infrared thermal tracer (type: TH5104; temperature measurement range: −10 °C to 1500 °C; accuracy: ±1.0%). The temperature profile is also shown in Fig. 2. The temperature reached 1500 °C at the 30th minute and remained at this temperature.

As shown in Fig. 3(a)–(e), the whole process of the 3-D microstructure evolution during microwave sintering was observed. Meanwhile, Fig. 4(a)–(e) shows the microstructure of the same cross section at different sintering times, in which the white parts represented the alumina particles, whereas the black parts represented the pores. In Figs. 3 and 4, some typical sintering phenomena that were similar to conventional sintering of alumina could be observed (results of conventional sintering experiment could be found in our previous work [14]), such as the contact among particles, formation and growth of sintering necks, and shrinkage of pores.

3. Discussion

Except for the common sintering phenomena mentioned in

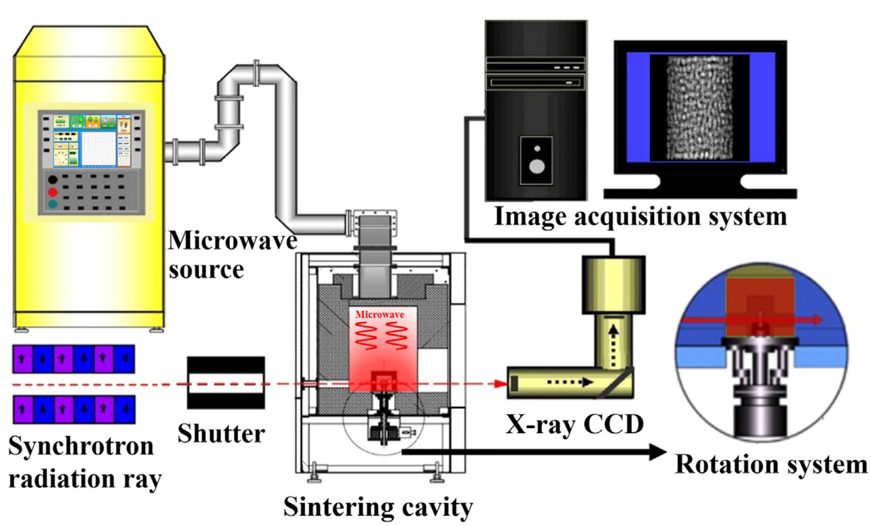

Fig. 1. The SR-CT experiment system of microwave sintering.