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Short communication

Asymmetric temperature distribution during steady stage of flash sintering dense zirconia

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ABSTRACT

Surface temperature of zirconia is measured during flash sintering using thermal imaging camera. The results reveal that in the steady stage the temperature along the longitude of electric field is uneven: the temperature at the end of gauge section close to the anode is much higher than that close to the cathode; and the highest temperature locates at the three-quarter of the length of gauge section from the cathode. We further demonstrate that the asymmetric temperature distribution is related to the flashing since temperature distribution in the specimen without flashing is symmetric. The possible mechanisms that resulted in the asymmetric distribution are discussed.

1. Introduction

Flash sintering has attracted extensive attentions due to the ultrafast densification and non-linear conductivity during the flash transition [1–3]. While the mechanisms behind these phenomena have not been uncovered yet, it is believed that joule heating is one of the reasons for the abnormal phenomena [4]. Hence, finding out the specimen temperature and temperature distribution during flash sintering is important subject of several previous studies.

The specimen temperature and temperature distribution during flash sintering were studied both theoretically [4–9] and experimentally [8,10–15]. These studies revealed that (1) the temperature of the specimen can be a couple of hundreds degree higher than the furnace temperature due to joule heating; and (2) there are significant temperature gradients from the surface to inside of the specimen and along the transverse of the electric field due to heat convection. However, the temperature distribution along the longitude of the electric field has not been studied and was assumed being uniform (except near the ends of the specimen). Such an assumption may not be valid since the difference in the grain size at the anode, center and cathode sections of the flash sintered specimen has been widely observed [16–18], which implied that the temperature distribution could be more complex.

In this paper, the surface temperature distribution of dense zirconia ceramics was measured during flash sintering using thermal imaging camera. We show that the temperature distribution is asymmetric referenced to the center of the specimen with the highest temperature located at three-quarters of the gauge section from the cathode. The asymmetric is likely related to the electric-field driven electrochemical reactions.

2. Experimental procedure

Commercially available 8 mol% yttria stabilized zirconia (8YSZ) powder (Beijing HWRK Chem Co., Beijing, China) was used as the starting material. Dog-bone shaped green bodies were made from the powder by uniaxial pressing at 120 MPa, followed by isostatic pressing at 290 MPa. The green bodies were pre-sintered at 1000 °C for 2 h to achieve certain strength. A hole with a diameter of 1.6 ± 0.1 mm was then drilled on each end of the specimens for electric connection. Finally, the specimens were sintered at 1550 °C for 2 h to achieve > 99% of theoretical density. The gauge section of the prepared specimens is 15.25 mm × 2.49 mm × 1.32 mm.

The specimen was connected to Pt wires via the holes and placed onto a heating plate (CHPS 250DN, ASSRE, Japan). Platinum paste was applied between the Pt wires and the holes to minimize contact resistance. The efforts have been made to keep the bottom surface of the specimens as close as possible to the heating plate; and specimens are parallel to the heating plate so that the specimens are uniformly heated

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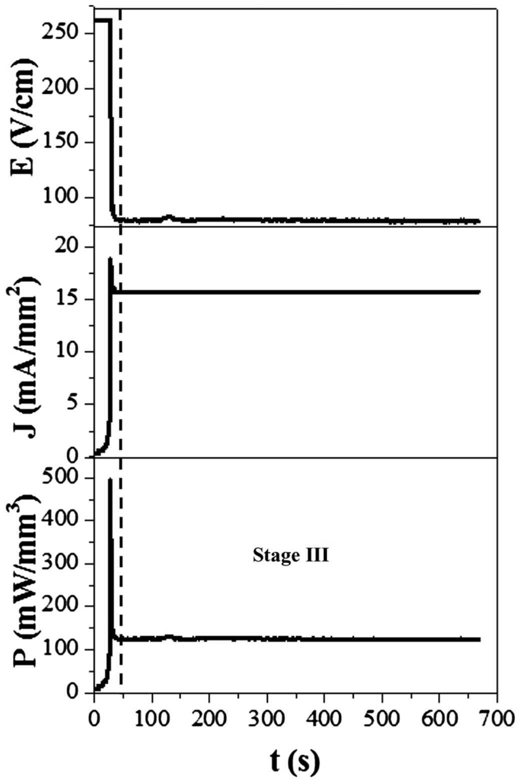

Fig. 1. Plots of the variations in the electric field strength, current density, and power density as a function of time.

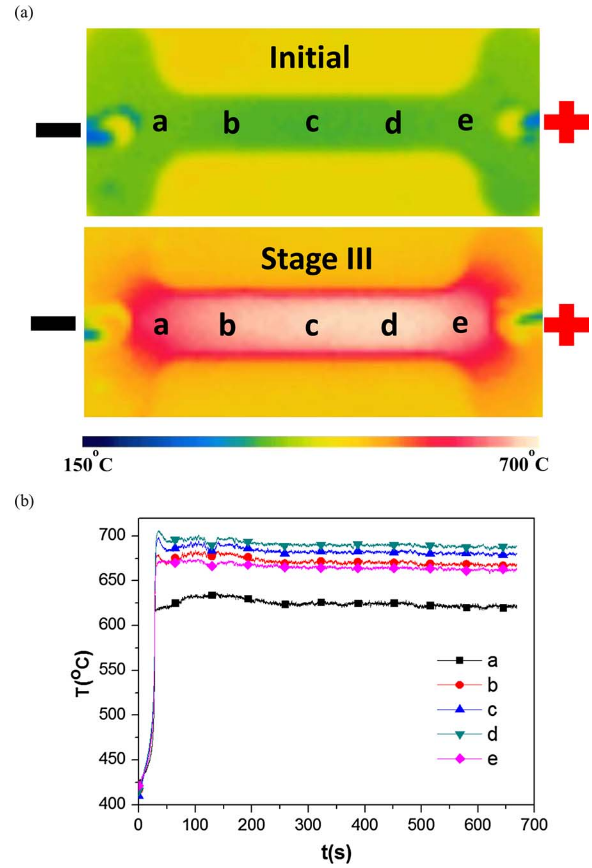

Fig. 2. (a) The thermal images showing the surface temperatures of a zirconia specimen before the application of electric field (initial stage) and during steady stage of flash sintering, as labeled. (b) Plots of the temperature as a function of time at five points selected in gauge section as marked in (a). (The color figure is available in the online journal).

by the plate. The temperature of the heating plate was set to 540 °C, which gives the temperature of the specimen to be ~ 420 °C. After stabilizing at the temperature for 20 min, the electric field of 260 V/cm was applied on the specimen by a DC power source (APS DCP1200V-1A, Adaptive Power System, CA).

The voltage and electric current, thereby the power dissipation (product of the voltage and current), were monitored using the power source. The temperature of the specimen surface was measured using a thermal imaging camera with spectral range 7.5–13.0 µm (A600, FLIR system Inc., Sweden). To calibrate the camera, the surface temperature of the heated 8YSZ sample without electric field applied had been measured by the camera and a thermocouple that was attached the sample surface. The result gives the reflection coefficient of the specimen to be 0.98 and the accuracy of the temperature measurement to be ±2 °C.

3. Results and discussion

Fig. 1 shows the variations in electric field strength, current density and power density as a function of time. The curves exhibit a typical isothermal flashing behavior. At beginning, where the power source was set at voltage-control, the voltage remained constant and the current was increasing with time. After a short incubation period, the current surged to the preset limit of ~15 mA/mm^2. Once the current reached the limit, the power source automatically switched from voltage-control mode to current-control, where the current remained as the preset value (Fig. 1b), but the voltage decreased quickly to the stable value of ~79 V/cm (Fig. 1a). At the steady stage, the power dissipation was stabilized at ~125 mW/mm^3 (Fig. 1c), which corresponds to 6.26 W in the gauge section.

Fig. 2a are thermal images taken from the surface of the specimen before the application of the electric field (initial stage) and at the steady stage of the flashing, as labeled. The images show that before the application of the electric field the temperature of the gauge section is ~420 °C. The temperature distribution is uniform through the gauge section, except that the electrodes and holes show lower temperatures. On the other hand, the temperature of the specimen is much higher than the initial value at the steady stage, manifesting significant joule heating during flash, as reported previously [7,12,19]. More interestingly, the temperature distribution in the specimen is no longer uniform, with the highest temperature locating away from the midpoint of the gauge section.

To further illustrate the temperature distribution, the temperatures at five selected points (marked in Fig. 2a) were monitored during flash sintering (Fig. 2b). It is seen that all five points showed rapid temperature rise, which concurs with the power surge. After the power dissipation reached steady stage, the temperatures were also stabilized. However, at steady stage temperature distribution is asymmetric along the longitude of the gauge section. The points a and e (the ends of the gauge section) showed lower temperatures, with the point a (close to the cathode) exhibiting the lowest temperature. The highest temperature appeared at the point d, which locates at three quarters of the gauge section from the cathode, instead of the center of the gauge section (the point c). The biggest temperature difference between the points a and d reaches 70 °C. Such an asymmetric temperature distribution has not been reported previously.

Fig. 3a plots the detailed temperature distribution along the gauge section taken in the steady stage. It clearly confirms that the temperature distribution is asymmetric along the longitude of the section. This asymmetric can be reflected by followings. First, the temperature at the end of the gauge section close to the cathode is about 30–40°C lower than that at the end close to the anode. Second, the highest temperature is not located at the midpoint of the section, but at the three-quarter of