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Short communication

Moderate temperature compression incorporating plastic deformation and rearrangement in Al_2O_3–ZrO_2 ceramics

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Abstract

In this article, we described an unusual plastic deformation of Al_2O_3–ZrO_2 ceramics under uniaxial compression at 500 °C with constant engineering strain rate of $3.5 \times 10^{-3}\,s^{-1}$. The Al_2O_3–ZrO_2 ceramics displayed different deformations from either the traditional ceramics or the amorphous material. The Al_2O_3–ZrO_2 ceramics started to yield at about 1.5 GPa. A large elastic strain of about 27% had been achieved when the material began to yield. The elastic deformation transited to yield smoothly without any evident peak stress. The compressive stress continuously increased to about 2.2 GPa before unloading. This unusual deformation might be related to the porous structure of the sample and coexistence of the amorphous phases and crystalline phases.

Keywords: A. Hot pressing; C. Plasticity; D. Al_2O_3–ZrO_2; Compression

1. Introduction

Ceramics is a kind of indispensable materials for various engineering applications owing to their excellent physical and mechanical properties, such as high melting point, good chemical stability, high hardness and high strength at elevated temperature. However, their inherent brittle property impedes their further applications. Normally, ceramics show almost no plastic deformation at low temperature and ambient pressure. This is mostly due to the strong covalent and ionic bonds, which make the movement of dislocation through the crystalline structure almost impossible [1]. In recent years, a number of researchers have found that ceramics could display plastic deformation under some conditions. Relevant scientific reports have mostly focused on two different aspects to investigate the ceramics plasticity. The first is to investigate the ceramics superplasticity (ZrO_2, Al_2O_3, Si_3N_4, SiC, hydroxyapatite, and their composites) at high temperature. As the primary deformation mechanism of the ceramics superplasticity is the grain-boundary sliding, the achievement of superplasticity is restricted to low strain rate and high temperature in excess of 1300 °C [2–4]. The second aspect is to improve the plasticity at moderate temperature by developing amorphous ceramics. Gandhi and coworkers [5–9] found that the amorphous ZrO_2–Al_2O_3 displayed a large yield drop followed by a plastic flow up to strains of 15% at 600 °C and under uniaxial pressure of 250–400 MPa. Later, Arindam and Jayaram [10] found the analogous plastic deformation of up to 30% in amorphous Al_2O_3–Y_2O_3. These unusual plastic deformations were explained in term of the open structure of the amorphous phases as indicated by the low density.

In recent studies, we found that the Al_2O_3–ZrO_2 crystalline ceramics with low relative density could display large compressive deformation which is quite different from either the traditional ceramics or the amorphous ceramics. The present paper was to describe this unusual compressive deformation of Al_2O_3–ZrO_2 crystalline ceramics, and propose several possible reasons to explain this deformation behavior.

2. Experimental

Amorphous Al_2O_3–ZrO_2 powders were synthesized through the citrate route [11–14]. Aluminum nitrate [$Al(NO_3)_3 \cdot 9H_2O$] and zirconium nitrate [$Zr(NO_3)_4 \cdot 5H_2O$] were dissolved in

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ethanol with Al/Zr molar ratio of 3:2. Citric acid (CA) was added to the solution at a molar ratio of [(Al+Zr):CA] = 1:2. The resulting solution was continuously stirred for several hours and kept at temperature of 70 °C until it became yellow and viscous. Then the solution was rapidly heated to 100 °C to accelerate the polymerization and vaporize the remaining water. The viscosity of the solution increased and the solution reached a gelatinous state. The gel was heated at 120 °C overnight and a fluffy precursor was obtained. The precursor was calcined at 700 °C for 1 h to obtain amorphous powders. The amorphous Al_2O_3–ZrO_2 powders were uniaxially pressed at room temperature for 5 min to yield cylinders of 10 mm diameter and 3 mm height by using a universal pressing machine (NYL-500A, JiangSu, China). These cylinders were then hot pressed using a cubic hydraulic pressing machine (CS-1B, GuangXi, China). The amorphous cylinders were pressed at 1 GPa and then heated to the final temperature of 650 °C, at a heating rate of 50 °C/min. After reaching the required temperature, the pressure was kept constant for 10 min.

Compression test was carried out using an electro-mechanical universal material testing machine (Instron5500R, USA) at 500 °C with constant engineering strain rate of $3.5 \times 10^{-3}\ s^{-1}$. Porosities of the sample before and after compression were determined by the water-immersion technique using the Archimedes method according to the China National Standard (GB/T 1966–1996). The phase identifications of hot-pressing cylinders before and after compression were recorded by X-ray diffraction analysis (XRD, D/Max-2500 Rigaku, Japan) with Cu Kα radiation. Scanning electron microscopy (SEM, XL-30Philips) was performed on the sample before and after compression.

3. Results and discussion

3.1. Moderate temperature deformation

The stress–strain curve of the Al_2O_3–ZrO_2 sample compressed at 500 °C and at a constant engineering strain rate of $3.5 \times 10^{-3}\ s^{-1}$ is shown in Fig. 1. The stress–strain curve reveals that the sample started to yield at about 1.5 GPa followed by a limited increase in stress, and displayed substantially large strain of about 27%. The test was continued beyond the yield stress and the stress steadily rose to about 2.2 GPa. A large plastic stain of more than 40% was exhibited before unloading.

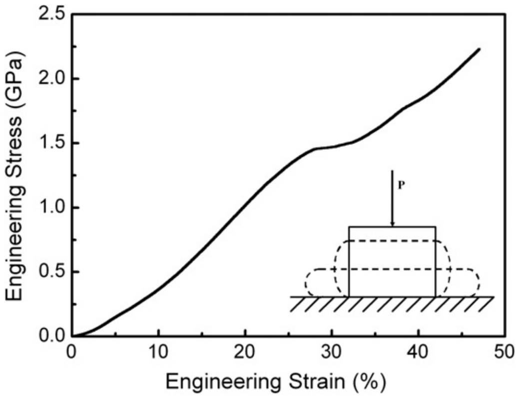

Fig. 1. Stress–strain curve of Al_2O_3–ZrO_2 ceramics during uniaxial compression at 500 °C and at a strain rate of $3.5 \times 10^{-3}\ s^{-1}$.

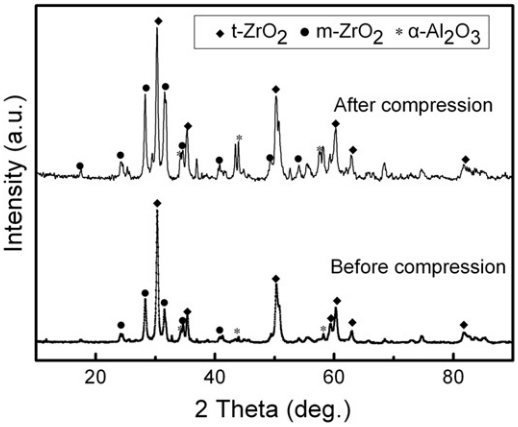

Fig. 2. XRD patterns of sample before and after compression.

3.2. Phase composition

Fig. 2 shows the X-ray diffraction (XRD) patterns of the sample before and after compression. The XRD patterns of the sample before and after compression show that the main phases were t-ZrO_2 and m-ZrO_2, while the peaks of α-Al_2O_3 were weak in both the XRD patterns. However, the molar ratio of Al/Zr in the whole sample was 3:2. This phenomenon indicated that most of the Al_2O_3 were amorphous before compression. Therefore, the sample was composed by the crystalline and amorphous phases before and after the compression test.

3.3. The change of porosity

The change of the porosity during the compression test was also investigated. It is found that the porosity of the sample decreased from 20.97% to 3.85% after the compression test. This variation could be attributed to the particle rearrangement at moderate temperature and the compression of pores during the test. The rearrangement of Al_2O_3 and ZrO_2 particles occurred inevitably during the compression test at 500 °C. However, it does not mean that the rearrangement of particles was the only reason for the variation of the porosity. In this work, the whole compression test was less than 3 min. In such a short time, the rearrangement of particles could not lead to such a large deformation. On the other hand, during the compression test the pores were compressed and the particles were compacted against one another with the increasing pressure. Fig. 3 shows the SEM observation of the top surface of the sample(a) before and(b) after compression. It clearly

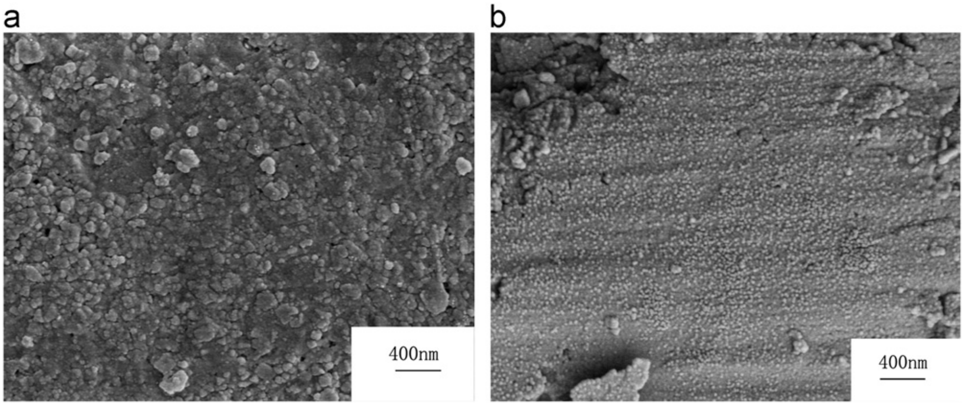

Fig. 3. (a) SEM micrograph of the compressive surface before compression and (b) SEM micrograph of the compressive surface after compression.

reveals that the particles become more compacted after compression.

3.4. *Reasons of the unusual deformation*

The moderate temperature deformation of Al_2O_3–ZrO_2 was an unusual and surprising behavior. It was known that the Al_2O_3–ZrO_2 sample had special phase composition and high porosity. Based on these special characteristics of the sample, we proposed two possible reasons to explain the unusual deformation behavior of Al_2O_3–ZrO_2 at 500 °C.

The first reason was the high porosity of the pellet. The pores could be compressed during the compression test, and therefore the volume of the pellet decreased and the engineering stain increased with the increasing pressure. Deformation process of the pellet with high porosity could be described as follow: the initial elasticity was partly controlled by the structure changes of the ceramics, such as elastic compressing and bending of the relative weak particle edges, stretching of particle faces and compression of pores among particles. With the increasing stress, the particles collapsed via plastic deformation, compression of pores and rupture of grain edges. Finally, the pores were compressed and the particles were compacted against each other. This compression behavior was analogous to the compression of porous materials [15–19]. However, the compressive strength of the pellet was much higher than that of the porous materials.

Another reason was related to the coexistence of the crystalline phases and amorphous phases. Because of the existence of crystalline phases, the material retained the inherent high compressive strength. Besides, the amorphous phases could produce shear bands during the compression process. Fig. 4 reveals that the parallel shear bands appeared at the side surface of the sample after compression. These shear bands could accommodate energy and absorb deformation to prevent the propagation of cracks [20, 21]. In summary, because of the high porous structure and the phase composition, this material displayed different plastic deformations from either the traditional ceramics or the amorphous materials.

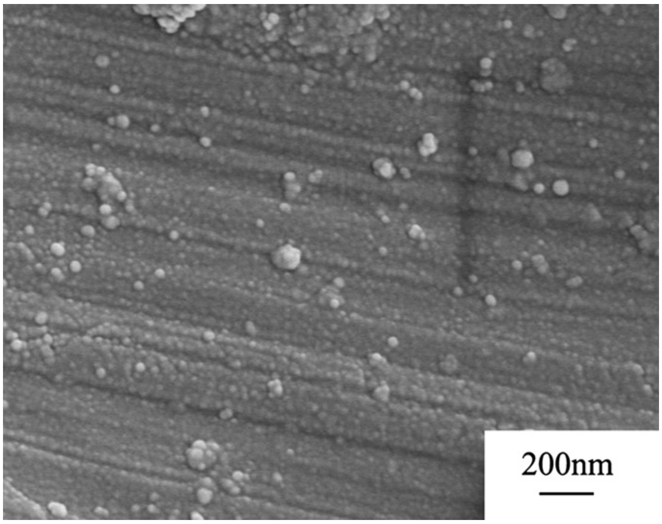

Fig. 4. SEM micrograph of the side surface after compression shows shear bands.

4. Conclusion

In this paper, we described an unusual compressive deformation of Al_2O_3–ZrO_2 ceramics. At the moderate temperature of 500 °C, the Al_2O_3–ZrO_2 sample started to yield at about 1.5 GPa with large strain of 27%. The stress continuously increased to about 2.2 GPa before unloading. This unusual deformation might be due to two possible reasons, including porous structure of the cylinder and coexistence of the amorphous phases and crystalline phases. High porosity contributed to the analogous plastic deformation of the sample with that of the porous materials. However, compared with the low compressive strength of porous materials, the sample remained high compressive strength due to its crystalline phases. The amorphous phase could produce shear bands which could prevent the propagation of the cracks. The Al_2O_3–ZrO_2 ceramics displayed a large plastic deformation as well as a high compressive strength before unloading at a moderate temperature. Further studies are still underway to investigate other properties of the ceramics with large plasticity and to explore other ceramic systems for the similar deformation behavior.

Acknowledgments

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