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Numerical simulation and experimental research on superplasticity of ceramic/ceramic laminated composite

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Abstract

In order to investigate the superplasticity of ceramic/ceramic laminated composite under tensile stress, the superplastic deep-drawing process was simulated by FEM. The results shown that, the strain and stress conditions of laminated composite, made by ceramic with different superplastic formability, are better than that of monolithic ceramic. Consequently, the material may exhibit high superplasticity. To testify this, some experiments were carried out. Tape casting and hot-press sintering are used to fabricate Al_2O_3/3Y-TZP laminated composite. As-received material is deep-drawing at high temperature to research its superplasticity. The results shown that, when suitable strain rate and forming temperature were used, the as-received material has excellent superplasticity.

Keywords: A. Tape casting; Hot-press sintering; Superplastic forming; Deep-drawing; Laminated composite

1. Introduction

Since 1990, ceramic/ceramic laminated composites have emerged as promising candidates to overcome the inherent brittleness of ceramics for use in structural applications [1–4]. Al_2O_3/TZP laminated composites have been receiving growing attention, mainly due to their oxidation stability at high temperature and drastic increases in strength and especially in fracture toughness at room temperature because of various crack-shielding phenomena related to the presence of the layers [5,6].

Because of the great advantage of laminated composites, the plastic forming technology becomes more and more important to manufacture actual product.

Flacher and Blandin [7] found superplastic compressive properties of Al_2O_3/ZrO_2 laminated composite at 1470 °C. Manuel and Clauss [8] examined the high temperature plastic deformation of Al_2O_3/Al_2O_3-YTZP laminated composite in uniaxial compression testing. The composite exhibit creep properties at low strain rate. The fine grain sizes and the good interfacial adhesion of the layers impart creep resistance and ductility simultaneously to the laminates [9]. However, these works are limited to compressive deformation. In this work, Fem simulation and superplastic deep-drawing of Al_2O_3/3Y-TZP laminated composites are carried out in consideration of the importance of plastic deformation under tensile stress for engineering applications.

2. Finite element simulation

In order to investigate the difference of ceramic matrix laminated composite and monolithic ceramic during superplastic forming, finite element simulation was carried out using the finite element software DEFORM2D.

The axisymmetric model of ceramic matrix laminated composite for superplastic deep-drawing is shown in Fig. 1. Both the punch and the female die are rigid. The shape of punch is hemisphere with a radius of 8 mm and that of female die is ring with an inner diameter of 20 mm. The deform body is a circle disc with diameter of 30 mm and

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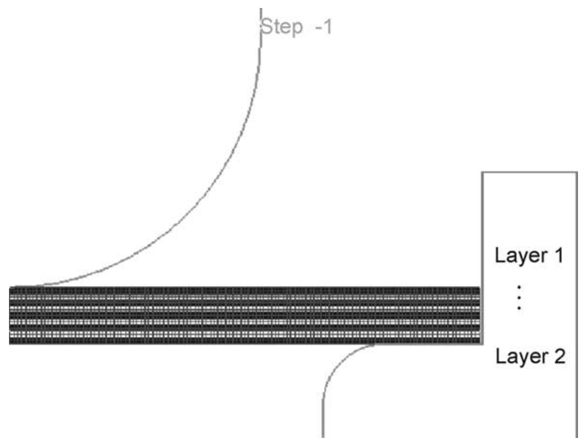

Fig. 1. Finite element model of superplastic deep-drawing for ceramic laminated composite.

thickness of 1.8 mm. There are nine layers in it, include five layers of Al_2O_3 and four layers of 3Y-TZP. They were stacked in an alternation sequence. There are 200 rigid-plastic elements in each layer. It was assumed that the strength of interface between two layers is so strong that no relative slide occurs during the deformation. Friction coefficient between the die and the disc is 0.2.

There are 100 steps in the simulation and the stroke of every step is 0.1 mm. The environment temperature is 1500 °C and the relationship between flow stress σ and strain rate $\dot{\varepsilon}$ under the temperature is

$$\sigma = K\dot{\varepsilon}^{\mathrm{m}}$$

Constant K of Al_2O_3 and 3Y-TZP are 4000 and 800, respectively. Strain rate sensitive coefficient of them is 0.5.

Effective strain distributions of ceramic laminated composite during superplastic deep-drawing are shown in Fig. 2. It can be seen that, at the beginning of the deformation, the strains near the center of the punch are greater than other place. Moreover, the strains of different layers are different too. 3Y-TZP layers and layer 9 have greater strain than other Al_2O_3 layers.

In the midst of the deformation, the strain extends to the sidewall of the part and the difference between different layers still exists. At the end of the deformation, every place has great deformation except the zone adhere to the punch.

During superplastic forming of ceramic, maximum tensile stress has great influence on fracture. Cracks often occur and extend firstly in the region where the greatest tensile stress locates. Consequently, maximum tensile stress is an important parameter that reflects the formability of ceramic.

The maximum tensile stress, the greatest value of maximum principle stress of all the nodes, was calculated to investigate the superplastic formability of ceramic matrix laminated composite. In order to compare with laminated composite, the stresses of monolithic Al_2O_3 and monolithic 3Y-TZP are also calculated. The finite element models are

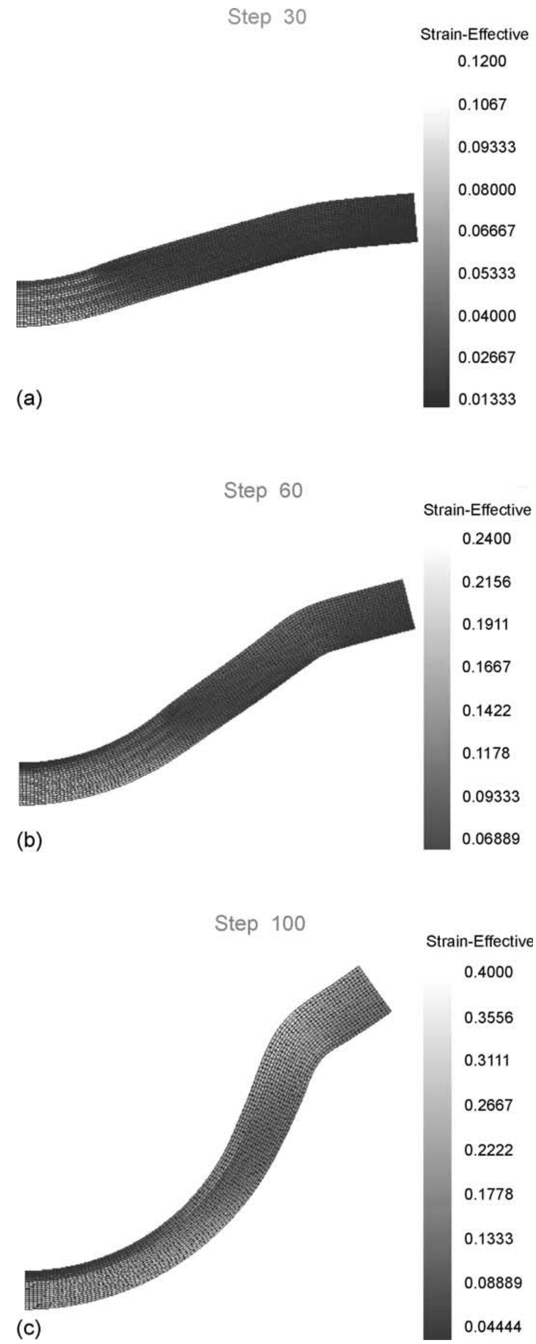

Fig. 2. Effective strain distribution of ceramic laminated composite during superplastic deep-drawing at different positions: (a) 3 mm; (b) 6 mm; (c) 10 mm.

same. However, the disc has only one layer with 1800 elements. The results are shown in Fig. 3.

It can be seen that, in the process of superplastic deep-drawing, the maximum tensile stresses of monolithic Al_2O_3 and monolithic 3Y-TZP have no great change. They are about 170 and 35 MPa, respectively. However, for the ceramic matrix laminated composite, the maximum tensile stresses of most layers are only about two third of that of monolithic ceramic except layer 1 and layer 9, the stresses of

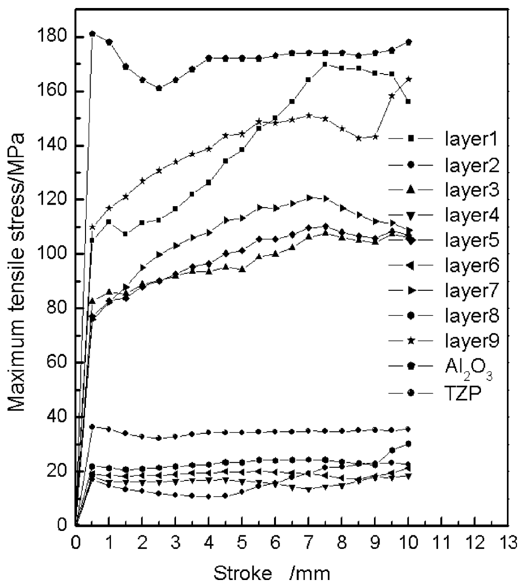

Fig. 3. Maximum tensile stress curves during superplastic deep-drawing.

which are close to that of monolithic ceramic at the end of the deformation.

The maximum principle stresses of step 100 are shown in Fig. 4. It can be seen that the maximum stress appears on the outside of sidewall for both monolithic ceramic and laminated composite. However, the area of laminated composite is much less than that of monolithic ceramic.

The results shown that the strain and stress condition of ceramic matrix laminated composite in the process of superplastic forming are better than that of monolithic ceramic. Consequently, it can be predicted that the ceramic laminated composite can have better formability than monolithic ceramic if the crack-shielding phenomena related to the presence of the layers is taken into consideration at the same time.

To testify this, following experiments were carried out.

3. Superplastic deep-drawing

A α-Al_2O_3 powder and a 3Y-TZP powder, with particle sizes of 50–200 nm and 15–40 nm, respectively, were used.

The tapes of Al_2O_3 and 3Y-TZP were prepared by tape casting, the details of which can be seen in the paper of Xuemin et al. [10]. The dried tape was punched into ϕ 30 mm discs. The Al_2O_3 and 3Y-TZP circle discs were stacked in an alternation sequence to a total of 21 layers, with both of the surface layers being Al_2O_3 layer.

The discs were placed in a low-temperature furnace at 800 °C for 2 h for binder burnout. Cooling was controlled at 3 °C/min.

The laminates were sintered in a cylindrical die with inner diameter of 30 mm. The heating rate was 20 °C/min and the pressure was 25 MPa. The laminates were heated to 1550 °C and hold for 90 min. The thickness of all discs were 2 mm. Prior to the forming tests the samples were polished on one side (diamond paste 0.3 μm). The discs were placed on a cylindrical graphite ring with an inner diameter of 20 mm. A hemispherical punch with radius of 8 mm was pushed on the non-polished side of the laminate using a velocity of 0.2 mm/min while the force was monitored. The tests were performed in vacuum at 1400, 1500 and 1600 °C.

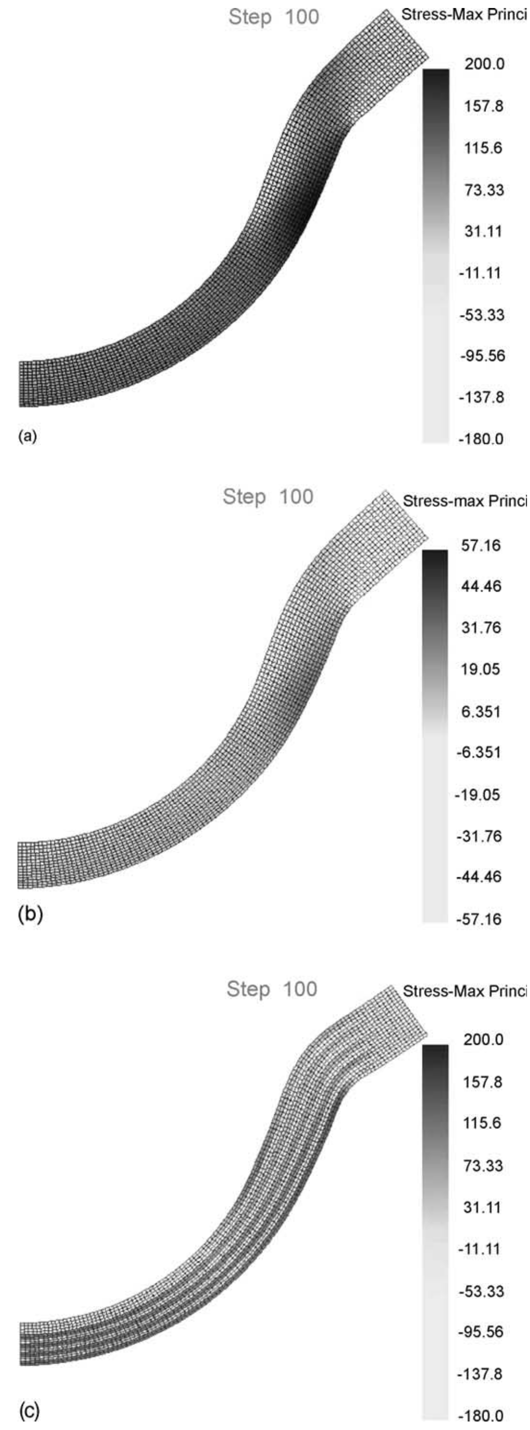

Fig. 4. Maximum principle stress distribution of superplastic deep-drawing (step 100): (a) Al_2O_3; (b) 3Y-TZP; (c) Al_2O_3/3Y-TZP laminated composite.

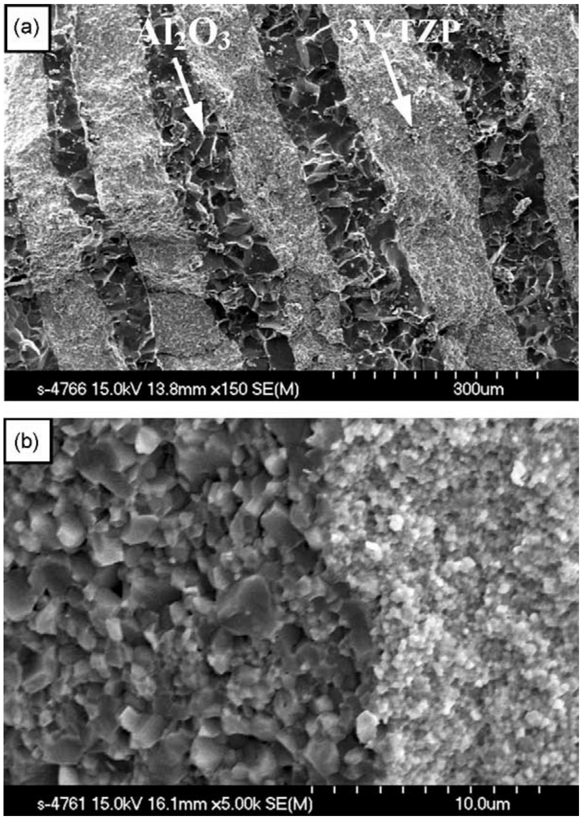

Fig. 5. Morphologies of the cross section of laminated composite after sintering: (a) macroscopic; (b) interface.

The axial displacement was measured externally during all tests. Microstructure examination of samples after hot-pressing sintering and superplastic forming was carried out using scanning electron microscope (SEM, Philips XL 20) equipped with an image analyzer.

Fig. 5 shows the cross-section of the as-received laminated composite. The dark zones correspond to Al_2O_3 layer. The two types of layers are well defined with interfaces and no significant residual porosity was detected

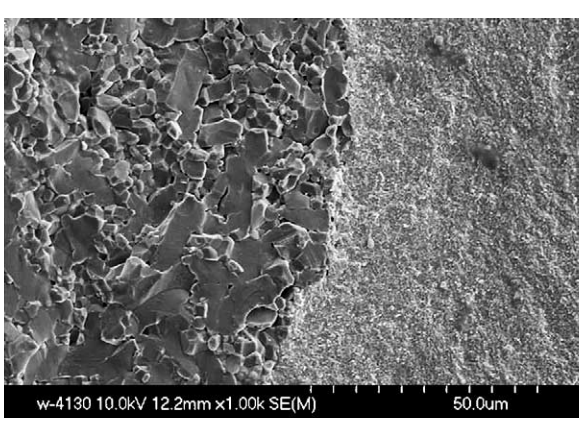

Fig. 6. SEM morphologies of cross section of laminated composites after superplastic forming at 1500 °C.

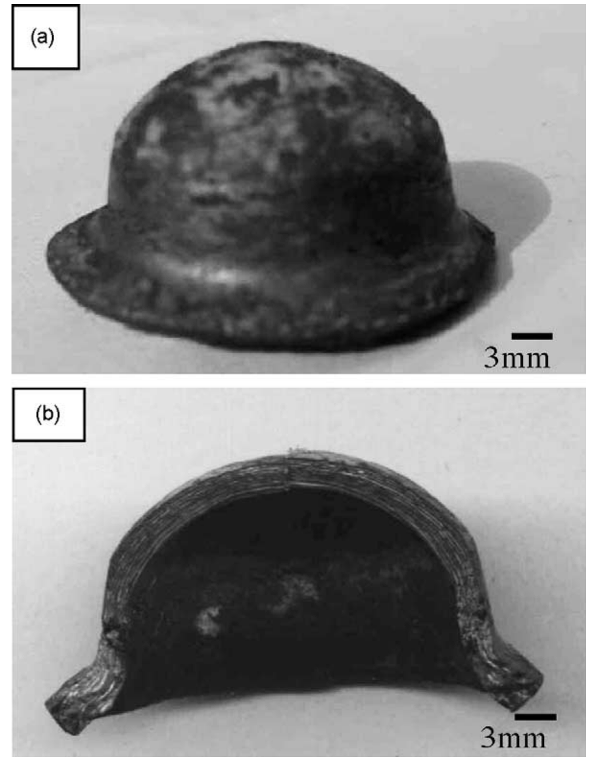

Fig. 7. Al_2O_3/3Y-TZP laminated composite part formed by superplastic deep-drawing: (a) the part; (b) the cross section.

from SEM observations at the interfaces between the two types of layers. The thickness of one layer is about 90 μm. However, it must be mentioned that the interfaces are not so straight because the material was pressed during the sintering. The composite sintered at 1550 °C has a fine grain size. Mean grain sizes are 200 nm and 0.8 μm, respectively, for the 3Y-TZP and Al_2O_3 layers. The relative density has great improvement. There is little cavity existing in the Al_2O_3 layer.

Superplastic deep-drawing was carried out at 1400, 1500 and 1600 °C using the laminated composite sintered at 1550 °C. At 1500 °C the laminated composite can be stretched to a height of 11.1 mm without fracture and was interrupted. If a higher or lower forming temperature is used, the chance of fracturing during deep-drawing increases.

Grain sizes are fine and little cavities appear after deep-drawing at 1500 °C, as shown in Fig. 6. So, the best superplastic deep-drawing temperature of Al_2O_3/3Y-TZP laminated composite is 1500 °C.

Al_2O_3/3Y-TZP laminated composite part formed by superplastic deep-drawing at 1500 °C and the cross section of the part are shown in Fig. 7. The diameter of the flange reduces from 30 to 25 mm and the mean thickness reduces from 2 to 1.7 mm. This shows that the shape of hemisphere is achieved by the shrinkage of diameter and the reduction of thickness.

The results shown that, when suitable strain rate and forming temperature were used, the as-received material has excellent superplasticity and the formability of Al_2O_3 layers is improved greatly by 3Y-TZP layers.

4. Conclusions

(1) The superplastic deep-drawing process of ceramic/ceramic laminated composite was simulated by FEM. The results shown that, the strain and stress conditions of laminated composite, made by ceramic with different superplastic formability, are better than that of monolithic ceramic. Consequently, the material may exhibit high superplasticity.
(2) As-received laminated composite has good superplasticity. At 1500 °C it can be deformed to hemisphere without fracture. However, the superplastic forming ability will decreases rapidly at higher or lower temperature.

Acknowledgements

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