Mechanical Properties of ZrO₂ Honeycomb Sandwich Structures by 3D Printing

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Abstract: Honeycomb sandwich structures were widely used in lightweight design. However, the difficulties with the fabrication process actually highly limit their practical usage, especially for ceramic materials. In this paper, 3 mol% yttria-stabilized ZrO₂ (3Y-TZP) honeycomb sandwich structures with square and hexagonal cell were prepared successfully by using digital light processing (DLP) printing method. With a base material density of >6.02g/cm³, square/hexagonal honeycomb sandwich structures with structural density of 42.89%-66.24% were achieved by modifying unit cell wall thickness. It can be concluded that square honeycomb cell is preferred for getting higher bending strength at the same structural density.

1. Introduction

Typical sandwich structure is composed of two panels and a lightweight core[1]. Sandwich structure is more and more popular in lightweight design for high performance applications, especially in aerospace, sports and automotive fields[2]. Of all the possible structural applications of building materials, the core of sandwich panels may be of the most importance.

Because of its periodicity and anisotropy, honeycomb structures can achieve higher material efficiency if they can be designed for specific loading conditions[3]. Honeycomb structure has been widely used in railway vehicles, automobiles, subways, airplanes, ships, spacecraft re-entry capsules and other fields due to its lightweight, high rigidity and high strength [4-6]. Therefore, honeycomb structure is chosen as the core of sandwich structure in this paper.

At present, honeycomb sandwich structure can be made of aluminum alloy[7-9], composite material[10], non-metallic material (Nomex[11], ceramic[12] etc.). Sun et al. [13] Carried out bending and compression tests on aluminum honeycomb sandwich panels. Theoretical solutions of three-point bending tests were established and the peak load, energy absorption and collapse modes were predicted. Belingardi et al. [14] Studied the fatigue behavior of carbon fiber composites and aluminum honeycomb cores under four-point bending test. Wu et al. [11] Characterized the Nomex honeycomb sandwich structure by finite element method through bending and compression tests, and analyzed the fatigue failure mode and damage mechanism of Nomex honeycomb sandwich structure. Wang et al. [15, 16] studied the flexural properties of ceramic panel and aluminum honeycomb core sandwich structure. The mechanical properties of ceramic panel, honeycomb core thickness, honeycomb element...
length and honeycomb wall thickness were measured and analyzed by finite element method. Hussain et al. [17] Studied the static and fatigue properties of glass fiber panels and aluminum honeycomb sandwich structures under three-point bending.

In fact, ceramics have many properties which are not possessed by metals, such as heat resistance, abrasion resistance, corrosion resistance and so on. And due to the limitations of the preparation process and other conditions, the sandwich structure of ceramic materials is less studied. The bending properties, failure mechanism and deformation mode of ceramic sandwich are still to be studied.

In this study, 3D printing technology was used. 3D printing techniques can also be used to weigh additive manufacturing. Additive manufacturing is a layer-by-layer construction of the target manufacturing process. Additive manufacturing technology has a high degree of flexibility in shape and design[18]. Because of its high hardness and brittleness, the machining of ceramics is very difficult. By using 3D printing method, the honeycomb structure can be more applicable in ceramic manufacturing, can be directly parameterized from geometry, and can achieve enough manufacturing accuracy for each structure parameter. This is the traditional molding cannot be achieved. This technology makes it possible to make such structures.

In this paper, it was studied that three-point bending strength of ZrO₂ ceramic honeycomb sandwich structure prepared by 3D printing. The purpose of this paper is to realize the lightweight of ceramic materials and to explore the bending properties of its sandwich structure.

2. Experimental measurement

2.1. Structural design

In this study, the sandwich structure consists of two layers of panel and honeycomb core. The honeycomb core includes a hexagonal conventional honeycomb and a square honeycomb structure.

Figure 1. Design of unit cell of the square and hexagonal honeycomb structure.
As shown in Figure 1, the honeycomb core can be characterized as L, W and T, standing for the overall dimension sizes at L-direction, W-direction and T-direction. L is the length of the specimens; W is the width; T is the thickness of the sandwich structure. l is the length of inner cell walls of square and honeycomb structure; t is the thickness of the cell walls; \( \theta \) is the angle between the cell walls of 60°.

Table 1 Geometrical of testing specimens for the three-point bending tests.

|                   | Length (mm) | Width (mm) | Panel thickness Tp(mm) | Core thickness Tc(mm) | Length of unit cell | Cell wall thickness (mm) | Hole Diameter Dh(mm) |
|-------------------|-------------|------------|------------------------|-----------------------|----------------------|--------------------------|----------------------|
| Hexagonal honeycomb | 35          | 4          | 0.2                    | 2.6                   | 1                    | 0.1-0.25                 | 0.6                  |
| square honeycomb   | 35          | 4          | 0.2                    | 2.6                   | 1                    | 0.1-0.25                 | 0.6                  |

The geometrical parameters of the prepared ZrO\(_2\) ceramic honeycomb sandwich structure in Table 1. In this paper, the sizes of the specimens are L=35mm W=4mm and T=3mm, Tp is thickness of the panel of 0.2mm; Tc is the thickness of the core of 2.6mm; the length of the unit cell is 1mm, the cell wall thickness is 0.1-0.25 mm; Dh is diameter of the hole in the panel.

Considering the principle of 3D printing technology, and the pore sizes of the upper and lower cover plates are 0.6 mm, all the sample was designed to be perforated on both surfaces in order to allow the slurry to flow out. All edges were rounded to avoid crack formation in the ceramic components.

Figure 2. The ZrO\(_2\) ceramic honeycomb sandwich structure specimen of the three-point sandwich (a) Schematic of square honeycomb core (b) Photo diagram of square honeycomb core (c) Photo diagram of hexagonal honeycomb core.

2.2. Sample preparation
The samples were prepared using 3Y-TZP material (CeramPlus DLP-50, Jiaxing CeramPlus Co., Ltd. (China)) by 3D printer (DLP) technique. Then, green bodies of ZrO\(_2\) ceramic honeycomb sandwich
structure were obtained. After that the surfaces of the sandwich skins and honeycomb core were cleaned to avoid the effect of remaining glue on the bending test. According to the sintering curve, pressureless sintering was used to heat to 1550°C for 2 hours. Finally, the sintered body of ZrO₂ ceramic honeycomb sandwich structure was obtained.

2.3. Mechanical testing
After that, measure sample length and density. The bulk density of sintered samples was measured by water immersion method based on Archimedes principle. The relative density was calculated according to the ratio of bulk density to theoretical density. The microstructure of ZrO₂ ceramic honeycomb sandwich structure was observed by SEM.

Geometry of specimen and experimental set-up are illustrated in Figure 3, according to GB/T 6569-2006 /ISO 14704:2000 standard for the three-point bending test to study the bending strength. The specimen was tested by SUN-500 universal material tester at a room temperature and the crosshead speed was set to be 0.05mm/min and effective span was 30mm.

![Experimental setup and three-point loading arrangement](image)

**Figure 3.** (a) Experimental setup ad three-point loading arrangement. (b) Schematic of the bending test arrangement.

The final test and damage modes are recorded. Before the experiment, the crosshead of the machine is needed vertical correction and two supports are adjusted to keep horizontal.

The load is cleared before the test to facilitate the later calculation. In addition, it is interesting to note that there is no widely accepted test criterion for the three-point bending strength of sandwich panels of ceramic materials.

3. Result and discussion

3.1. Microstructure
ZrO₂ ceramics sandwich structure with two kinds of honeycomb topological cores were prepared. There are square honeycomb and hexagonal traditional honeycomb structures.
According to Archimedes drainage method, the density is about 6.02g/cm$^3$, and the density is 99%. The fracture surface microstructure of the prepared ZrO$_2$ ceramic honeycomb sandwich structure is shown in Figure 4. There are no obvious stomatal pores, which also shows that the prepared samples are dense.

![Figure 4. SEM image of the fracture surface in ZrO$_2$ ceramic honeycomb sandwich structure.](image)

3.2. Comparison of Theoretical Relative Density and Actual Relative Density

Figure 5 shows the theoretical relative density, the actual relative density, and the error between the two. As can be seen from Figure 5, the relative density of the ZrO$_2$ ceramic honeycomb sandwich structure increases as the wall thickness increases. The actual density is slightly higher than the relative density, indicating that there is a deviation in the sample preparation. The actual relative
density of the square honeycomb structure can reach 42.89-62.5% and hexagonal honeycomb structure can reach 46.65-66.24%.

At the same time, the error between the actual relative density and the theoretical relative density is calculated, and it is found that the error value is inversely proportional to the wall thickness. The results show that when the wall thickness of honeycomb core increases to certain thickness, the sample size error can be controlled in a good range.

This is due to the 3D printer light scattering resulting in the actual size of the sample will be larger than the set. Secondly, the setting of shrinkage coefficient will change the sample size after sintering. The larger actual relative density may also be due to the larger shrinkage coefficient in the setting, which results in the larger sample size than the theoretical value.

3.3. Bending performance of ZrO2 ceramic honeycomb sandwich structure

Because ceramics are brittle materials, there are many defects (such as cracks, pores or inclusions) in the interior and surface of the samples, which will affect the strength of the ceramics. The use of 3D printing technology and good suspension can effectively avoid this defect. And the plasticity of ceramics is very low, the strength of ceramics is mainly fracture strength. In this paper, three-point bending tests were carried out on different specimens and their fracture strength was analyzed.

Figure 6 shows a photograph of the specimen after the test fracture, where the fracture crack is wound with a red line. The results showing that the fracture occurs in the middle of the ZrO2 ceramic honeycomb sandwich structure and that the deformation of the honeycomb sandwich structure after unloading is irreversible. For square honeycomb and hexagonal honeycomb sandwich structures, the stress concentrates in the area near the loading point, and there are defects at the local failure point. Sandwich panels are typically loaded in a bending manner, which results in the panels being compressed and stretched, while the core is loaded in a shear manner. The shear strength or shear strength of core material plays an important role in the bending process of sandwich structure [19]. This complex stress state cannot be well described.

**Figure 6.** Image of fracture of specimens after three-point bending test (a, left) Square honeycomb sandwich structure. (b, right) Hexagonal honeycomb sandwich structure.

**Figure 7.** Interior diagram of three-point bending test sample (a, left) Square honeycomb sandwich structure. (b, right) Hexagonal honeycomb sandwich structure.
Figure 7 shows an interior view of the three-point bending test samples, with the red-coiled area showing the interior square honeycomb core structure and the hexagonal honeycomb core structure.

3.3.1. Effect of the core thickness. At normal room temperature, when the load is not large, the deformation of ceramics is simple elastic deformation. It can be seen that the load and displacement have a linear relationship, which conforms to Hooke's law. Beyond this load value, the crack propagates throughout the sample, causing the entire ceramic to fracture, and the load decreases. In the three-point bending test, a load-displacement curve for different cell wall thicknesses is depicted in Figure 8.

![Load-displacement curves](image)

**Figure 8.** Load-displacement curves of ZrO$_2$ ceramic honeycomb sandwich structure with different wall thickness in the three-point bending test (a) Square honeycomb core (b) Hexagonal honeycomb core.

Figure 8 shows that the strength of the ZrO$_2$ ceramic honeycomb sandwich structure become higher and higher as the wall thickness increases. The rigidity of square honeycomb core structure has little change and the displacement changes greatly. The hexagonal honeycomb core structure is the opposite. This is because hexagons are more stable than square structures. When the load is applied, both of them resist the external load by bending the inner cell walls, which is a typical bending-dominated deformation mechanism [20].

3.3.2. Effect of core topology. The relative strength of the sandwich structure of ZrO$_2$ ceramic honeycomb core also has a significant effect on the strength. This is as expected because ceramic honeycomb sandwich structures with relatively high core density will become harder, stronger, but more brittle. The influence of different honeycomb topology on bending performance was studied by experiments.

Figure 9 is a comparison of flexural strength between a square honeycomb core and a hexagonal conventional honeycomb core over a range of actual relative densities. As shown in Figure 9, the strength of the ZrO$_2$ ceramic honeycomb sandwich structure is approximately proportional to the actual relative density. The flexural strength of ZrO$_2$ ceramic honeycomb sandwich structure increases with the increase of actual relative density. The sandwich structure of ZrO$_2$ ceramic honeycomb core with different topologies has influence on the strength. At the same actual relative density, the bending strength of square honeycomb is higher than that of hexagonal honeycomb. The maximum three-point bending strength of square honeycomb was measured to be 222.6 MPa, the hexagonal honeycomb was 210.29 MPa.

The error values of the strength of each group of three-point bending specimens are calculated and the error bars are marked in the figure. The error range is 6.65-28.6%. The reason is that the precision of the printer will affect the performance of ZrO$_2$ ceramics in the process of 3D printing. In the process
of printing, the porosity, spall defects, or hidden cracks may occur in the cleaning and final sintering process, which will affect the test results[21].

![Figure 9. Bending behavior of square and hexagonal honeycomb core ZrO2 ceramic sandwich structures.](image)

4. Conclusions
The honeycomb sandwich structure of ZrO₂ ceramics was fabricated by 3D printing technique. Square honeycomb cores and traditional hexagonal honeycomb cores are designed as sandwich core topologies. The bending strength of ZrO₂ ceramic sandwich with square honeycomb core and hexagonal honeycomb core at different wall thicknesses and relative densities was analysed by three-point bending test.

1. The relative density of ZrO₂ ceramics with honeycomb sandwich structure increases with the increase of wall thickness, and the actual density is slightly higher than the relative density. When the wall thickness of honeycomb core increases to a certain thickness, the printing error of the sample can be controlled in a good range. Lightweight could be realized successfully through the square and hexagonal honeycomb ceramic sandwich structure.

2. With the increase of honeycomb core wall thickness, its flexural strength also increases. Square honeycomb core with the increase of wall thickness, the displacement increases and the stiffness changes little. Hexagonal honeycomb core with the increase of wall thickness, structural stiffness increases, displacement changes little.

3. Under the same structure density, the square honeycomb structure has higher flexural strength.

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References
[1] Petras A SMPF 1999 Compos. Struct. 44 237
[2] Schaedler T A, Carter W B 2016 Annu. Rev. Mater. Res. 46 187
[3] Khan TB, Mirza S 2012 Mater. Sci. Eng. A.539 135
[4] Wadley H N 2006 *Philos Trans A Math Phys Eng Sci.* **364** 31
[5] Wang Z 2019 *Composites Part B.* **166** 731
[6] Zhang Q, Yang X, Li P, Huang G, Feng S, Shen C, Han B, Zhang X, Jin F, Xu F, Lu T 2015 *Prog. Mater. Sci.* **74** 332
[7] Wang Z, Liu J 2019 *Composites Part B.* **165** 626
[8] Tiwari G, Thomas T, Khandelwal R P 2018 *Thin-Wall. Struct.* **126** 238
[9] Piekło J, Małysza M, Dańko R. 2018 *Arch. Civ. Mech. Eng.* **18** 1300
[10] He W, Yao L, Meng X, Sun G, Xie D, Liu J 2019 *Thin-Wall. Struct.* **137** 411
[11] Wu X, Yu H, Guo L, Zhang L, Sun X, Chai Z 2019 *Compos. Struct.* **213** 165
[12] Mei H, Zhao X, Zhou S, Han D, Xiao S, Cheng L 2019 *Chem. Eng. J.* **372** 940
[13] Sun G, Huo X, Chen D, Li Q 2017 *Mater. Des.* **133** 154
[14] Belingardi G, Martella P, Peroni L 2007 *Composites Part A.* **38** 1183
[15] Wang Z, Li Z, Xiong W 2019 *Composites Part B.* **164** 763
[16] Wang Z, Li Z, Xiong W 2019 *Composites Part B* **164** 280
[17] Hussain M, Khan R, Abbas N 2019 *Journal of King Saud University - Science.* **31** 222
[18] Chen Z, Li Z, Li J, Liu C, Lao C, Fu Y, Liu C, Li Y, Wang P He Y 2019 *J. Eur. Ceram. Soc.* **39** 661
[19] Li T, Wang L 2017 *Compos. Struct.* **175** 46
[20] Deshpande V S AMF, Fleck N A 2001 *Acta Mater.* **49** 1035
[21] Scheithauer U, Schwarzer E, Moritz T, Michaelis A 2017 *J. Mater. Eng. Perform.* **27** 14