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A lightweight, high compression strength ultra high temperature ceramic corrugated panel with potential for thermal protection system applications

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ABSTRACT

ZrB_2–SiC–graphite ultra high temperature ceramic (UHTC) corrugated panel was firstly proposed and fabricated with potential application for sandwich structured thermal protection system. The compression properties of the as-prepared ultra high temperature ceramic corrugated panel were evaluated at 1600 °C in air. The compression modulus and strength of this ultra high temperature ceramic corrugate panel were 312 MPa and 17 MPa respectively. The design of corrugated panel exhibited an excellent combination of lightweight and excellent compression properties. This study would provide a novel concept of ultra high temperature ceramic corrugated panel for the design of ultra high temperature thermal protection system applications.

1. Introduction

Hypersonic vehicles that will fly at speeds above Mach 7 have been extensively studied over the last decade [1–4]. Sharp leading and trailing edges, nose cones and some other thermal protection systems designed for these high speeds are subjected to severe aerodynamic heating during the launch and re-entry flight. In order to ensure the flight safety and to protect the underlying structures within acceptable temperature limits, and to provide sufficient structural strength and stiffness to retain the aerodynamic shape, the thermal protection systems should meet two key needs: high temperature tolerance and lightweight [5].

On one hand, the thermal protection systems must be made from materials with high melting points and good oxidation resistance behavior, in order to endure the severe aerodynamic heating. In the past decades, super alloys [6], rigid quartz fiber woven ceramic tiles [7], C/C [8] and C/SiC [9] composite materials have been used in TPSs. However, with the increasing of the flight speed (Mach > 7), the inherent low melt points of super alloys limit the application of metallic thermal protection systems to the harsh environment of hypersonic in excess than 1000 °C [6]. Rigid quartz fiber woven ceramic tiles usually cannot work above 1200 °C [7]. Although C/C, C/SiC composites based thermal protection systems can withstand higher temperature than super alloy and rigid ceramic tile, unfortunately, severe oxidation ablation will still occur when temperature exceeded 1600 °C [8,9]. Therefore, finding a novel material for thermal protection systems which can work above 1600 °C is an enormous challenge and deemed necessary for the future development of hypersonic aircrafts. Recently, ZrB_2-based ultra high temperature ceramics (UHTCs) have attracted much attention owing to their unique combination of high melting temperature [10], thermal shock resistance [11], as well as excellent mechanical and chemical stability at elevated temperatures [12,13]. Based on their combination of properties, ZrB_2-based ultra high temperature ceramics are becoming promising candidates for applications in extremely severe environments, including sharp leading edges and nose cones and other thermal protection systems for reusable atmosphere re-entry hypersonic flights [14,15]. That is the basis of the design of ZrB_2-based ultra high temperature ceramics for thermal protection system applications in this paper.

On the other hand, while satisfying the high temperature tolerant requirement, thermal protection systems for hypersonic flight must also be lightweight in order to lower the launch costs and to improve the effective loading weight. Efforts are on to develop integral thermal protection systems, a kind of sandwich structure, which not only perform the function of thermal protection, but also withstand loads to a large extent [5]. Based on this concept, various kinds of sandwich structures, such as honeycombs, lattices and corrugated panel, have been widely investigated for

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lightweight thermal protection systems. However, there are limited works on high temperature tolerant thermal protection systems. In addition, although many studies on ultra high temperature ceramics have been reported, virtually nothing has been published in the open literature discussing sandwich structured ultra high temperature ceramics based thermal protection systems.

Therefore, in this study, ZrB_2–SiC–graphite corrugated panel, a typical sandwich structure, was proposed and fabricated for potential thermal protection system applications. And as one of the most important properties, the high temperature compression behavior of this ZrB2-based corrugated panel was studied and analyzed. Finally, a lightweight, high compression strength ultra high temperature ceramics corrugated panel with potential for thermal protection system applications. We believe this study can give some ideas for the design of thermal protection systems for future hypersonic flight.

2. Experimental procedure

2.1. Starting materials

Commercially available ZrB_2 (2 μm; >99.5%; Beijing Zhongxinyan Micro-powder Co., Ltd., China), SiC (1 μm; >99.5%; Weifang Kaihua Micro-powder Co., Ltd., China) and graphite flake (mean diameter and thickness are 15 μm and 1.5 μm, respectively; >99%; Qingdao Tiansheng graphite Co., Ltd., China) powders were used as staring materials.

2.2. Fabrication

The powder mixtures of ZrB_2–20 vol.% SiC–15 vol.% graphite flake were ball-milled for 8 h in a polyethylene bottle using ZrO_2 balls and ethanol as the grinding media. After mixed, the slurry was dried in a rotary evaporator (MCA-10B, Nanjing University Instrument Plant, China) at 240 *rpm*. After the ball-milling, ethanol was removed by a rotating evaporator (R-202, Shanghai Shensheng Biotech Co., Ltd., China) at 80 °C to minimize segregation. The as-received powder mixtures were sieved through a 200 mesh and then uniaxially hot-pressed in a BN coated graphite die at 1900 °C for 60 min under vacuum and 30 MPa applied pressure. Detailed procedure has been reported in our previous work [16]. The hot-pressed ceramic was designated as ZSG.

ZSG corrugated panel was cut from the hot-pressed billet through electrospark wire-electrode cutting, as shown in Fig. 1. The geometrical parameters of the corrugated panel were given in Table 1.

2.3. Characterization

The bulk density of the ZSG ceramic billet was measured by Archimedes' method in deionized water; the theoretical density was calculated by applying the law of mixture, and the relative density was calculated based on the ratio of bulk density to theoretical density.

The high temperature compression testing of the ZSG corrugated panel was conducted at 1600 °C in air using an ultra high temperature mechanical property testing system assembled in our laboratory. The as-prepared ZSG corrugated panel was fixed in the testing system, as shown in Fig. 2. Firstly, the testing furnace was heating to 1600 °C under an exposing air atmosphere, and the specimen was soaked at 1600 °C for 10 min for achieving thermal equilibrium. Compression test was subsequently carried out with a crosshead speed of 0.5 mm/min.

The microstructures of ZSG corrugated panel body before and after high temperature compression testing were observed by a scanning electron microscopy (SEM, S-4800, Hitachi, Japan). Finite element analysis (FEA) was used to simulate the stress distribution in the compression specimen during testing through commercial Abaqus software.

Table 1
Geometrical parameters of the ZSG corrugated panel.

t_f	3 mm
t_s	1.73 mm
l_s	13 mm
d_c	2 mm
W	40 mm
L	30 mm
H	17.26 mm
θ	60°

3. Results and discussion

The as-prepared ZSG ceramic billet had a measured bulk density of 4.90 g/cm^3. Using a rule of mixture calculation, and assuming the true densities for ZrB_2, SiC and graphite flake was 6.09, 3.21 and 2.16 g/cm^3, respectively, the theoretical density of the ZSG ceramic billet was calculated to be 4.92 g/cm^3. Based this true density, the as-prepared ZSG ceramic billet had a nearly full relative density (99.6%). The microstructure of the polished surface of the as-prepared ZSG ceramic was presented in Fig. 3. Dark SiC and the long and narrow dark graphite flake were homogeneously dispersed in the grey ZrB_2 matrix, and no obvious agglomeration was detected. However, the nominal density of the obtained ZSG corrugated panel was measured to be as low as 2.0 g/cm^3. It was found that the as-prepared ZSG corrugated panel was lightweight, and its density was only 40.6% of the ZSG bulk material. Therefore, the design of corrugated panel structure greatly reduced the weight by 59.4% and finally realized lightweight structure successfully.

Fig. 4 gives the compression stress–strain curve of the ZSG corrugated panel tested at 1600 °C in air. As a rule, the slope coefficient of the compression stress–strain stress curve represented

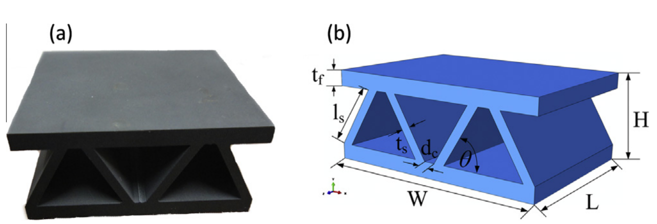

Fig. 1. The (a) photo and (b) geometrical parameters of the ZSG corrugated panel.

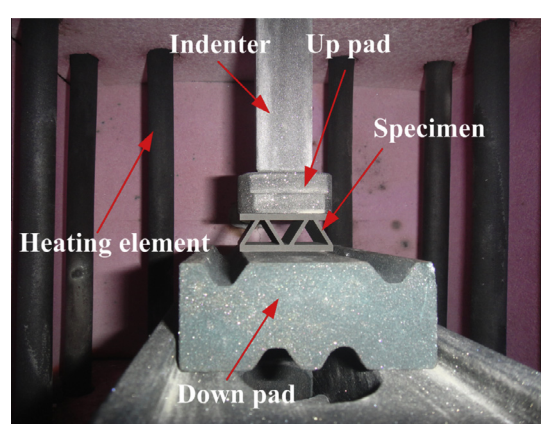

Fig. 2. Photograph of the compression testing system.