Effect of honeycomb structure parameters on the mechanical properties of ZTAp/HCCI composites

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Abstract
Zirconia toughened alumina particles (ZTAp)/high chromium cast iron (HCCI) matrix honeycomb composites were successfully prepared by a non-pressure infiltration casting process. This paper systematically investigates the effect of pore size (6 mm, 8 mm, 10 mm, 12 mm) on the compression resistance of honeycomb structure under the same wall thickness condition. Through the simulation software Ansys Workbench and compression performance test, it was found that the compression performance tends to increase gradually with the increase of the honeycomb pore size, and the optimal compression resistance is reached when the pore size is 12 mm. This optimum performance is attributed to the fact that the reinforcement mechanism of the composite depends not only on the load sharing of the reinforcing particles, but also on the strength of the matrix.

1. Introduction
Ceramic particle reinforced iron matrix composites are widely used in coal, aerospace and building materials because of their good wear resistance, high specific modulus, low cost and good mechanical properties [1–4]. Due to the poor wettability of ZTA particles with iron, most studies on ZTA/iron matrix composites focus on the formation mechanism of microscopic interfaces, physical phase characterization and testing of interfacial transition zones, which significantly improve the mechanical properties of the composites, but the development of materials has also fallen into a bottleneck.

In recent years, macrostructured composites have received a lot of attention because of their good fatigue resistance and fracture resistance, which is expected to further improve the mechanical properties of composites [5–8]. Zhipeng Liu et al [9] studied the properties of the macrostructured composites at what pore size/pore wall ratio of the preform, and the results showed that the composite exhibited good compressive and wear resistance at this ratio when the pore size/pore wall ratio was 1.25. Dehong Lu et al [10] studied the preparation of 3D interpenetrating hierarchical Al2O3/40Cr composites by extrusion casting, and the results showed that the cracks of fracture mainly appeared in the composite region, and the 40Cr steel in the matrix region could greatly inhibit the deformation and cracking in the composite region. Li Zulai [11] et al used vacuum sintering method to prepare WC preforms and immersion casting process to obtain WC/Fe composites, and the results showed that the wear resistance of WC/Fe composites for three-body abrasive wear increased and then decreased with the increase of preformed column spacing. Although a lot of work has been done by related researchers and good results have been achieved. However, there have been fewer studies on macroscopic simulations and mechanical properties of honeycomb configuration composites to predict experimentally.

Therefore, in this paper, the combination of finite element simulation and experiment is used to study the composite materials under different honeycomb structure parameters, and the effect of honeycomb pore size on the compressive properties of composite materials is obtained.
2. Experimental procedures

2.1. Sample preparation
The preparation of ZTA/HCCI honeycomb configuration composites consists of two main parts, the preparation of ceramic particle preforms and the casting and infiltration molding of high chromium cast iron. Mixing ZTA ceramic particles with micronized powder and binder in a certain ratio, allowing the ceramic particles to form a core–shell structure. The ceramic particles are mixed well and put into the pre-prepared mold and heated for 10 ~ 20 min. The structural parameters of the honeycomb preform include: pore wall, pore size. The macroscopic morphology of the honeycomb preform is shown in figure 1, a is the pore size and b is the pore wall.

The metal matrix in the composite is high chromium cast iron (table 1). The metal matrix was smelted at a medium frequency. Melting temperature is about 1550 °C, pouring speed is 3.5 kg s⁻¹, and pure aluminum is put in 2 min before the metal liquid is poured into the sand box to remove oxygen.

The fabricated ceramic particle preform is fixed in the sand cavity, the size of which is about 150 mm × 150 mm × 100 mm. The metal liquid is poured into the sand mold, and when the metal liquid cools to room temperature, the composite material with honeycomb structure is obtained.

2.2. Characterization method
Metallographic polishing of different pore size composites using MP-1 polishing machine and ultrasonic cleaning for 2 ~ 3 min. The microstructure of the composite material was observed by an inverted optical microscope (Leica DMI 3000). The metallographic photographs of the composites were analyzed using Image Pro plus (IPP) software to obtain the percentage of ZTA ceramic particles in the cross-section of the samples. A hydraulic universal testing machine (MTS C64.106) was used to measure the mechanical properties of composite materials in compression. The compression specimens are prepared in accordance with GB/T232–2010 Chinese standard, size 12.5 mm × 12.5 mm × 25 mm, as shown in figure 2. The fracture morphology of the composite was observed by scanning electron microscopy (ZEISS EVO).

Scale modeling of compressed specimens using 3D modeling software Solidworks. In order to make the simulation more consistent with the experimental results, the compression model is equipped with a pressing head on the top and bottom, where one side of the indenter is set as a fixed pressing heads, and the other side is set as a dynamic indenter, and the constructed 3D model is converted to x.t format. The constructed model is

Table 1. Chemical composition of high chromium white cast iron matrix (wt%).

| Element | C  | Si | Cr | Mn | Cu | Mo | Ni | Fe      |
|---------|----|----|----|----|----|----|----|---------|
| Content | 3  | 0.4| 26 | 0.8| 0.1| 0.4| 0.3| Bal     |
|         | (wt%)| | | | | | | |

Figure 1. Macroscopic morphology of honeycomb prefabricated body.
imported into Ansys workbench software and the relevant parameters are set in the material module according to the physical properties of the selected ZTA ceramic particles and high chromium cast iron.

Figure 3 shows the meshing of the honeycomb composite. To simplify the model, the ZTA in the composite is considered as a single-phase material. The pressing heads were set as a rigid material, and the friction coefficient between the pressing heads and the composite material is set to 0.25 [12]. For meshing, tetrahedral meshes were selected for both HCCI and ZTA ceramics, and the meshes in the interface region were refined to ensure the quality of the meshes at more than 70% on average.

In order to cross-reference with the above 3D model composite, the geometric model of ZTA/HCCI matrix on the actual particles, is shown in figure 4. Projection of porous hexagonal prefabricated body into two-dimensional space by turning ceramic particles not into a whole but into individual particles. Due to the simplification of the model, the accumulation of ceramic particles in the 3D model is effectively avoided, and the quality of the mesh is further improved, which improves the efficiency of the calculation.
3. Results

3.1. Composite microstructure
Figure 5 shows the microstructure of the honeycomb composite. The corresponding honeycomb pore sizes are 6 mm, 8 mm, 10 mm and 12 mm, respectively. The results obtained by Image Pro plus (IPP) software were: 72.4%, 69.8%, 65.1%, and 60.9%, respectively. Thus, the degree of dispersion of ZTA ceramic particles in the composites was continuously increased. When the molten metal is immersed in the preform, the influence of the main impregnation resistance such as capillary force, solidification resistance and viscous resistance will be weakened. The flow rate of the molten metal will increase and the degree of impact of the molten metal on the ceramic particles is also enhanced accordingly to promote the uniform distribution of ceramic particles in the composite. When the aperture of the preform is 14 mm, the dispersion uniformity is better [12].

3.2. Simulation of compressive properties of configurational composites
The simulated stress distribution for different honeycomb composites is shown in figure 6. It can be seen from the figure that the maximum stress appears in the composite zone, while the stress distribution in the matrix
zone perpendicular to the loading direction is relatively uniform, so the composite zone bears most of the load and produces larger stresses at the sharp corners of the composite zone. Thus, the ceramic particles make the composite stronger and the stress concentration at the hexagonal sharp corners should be related to the stress transfer from the matrix region to the composite region [13].

Figure 7 shows the stress cloud based on the actual particle honeycomb composite. From the figure, it can be seen that the stress is mainly distributed in the composite zone, and the stress distribution is relatively uniform in the matrix. The increase in pore size in the composite zone correspondingly strengthens the load-bearing capacity of the high chromium cast iron matrix zone, and the ceramic particle composite zone is subjected to more stress than the high chromium cast iron matrix zone. Therefore, the cracks or fractures produced by the composite material during compression occur in the composite zone.

3.3. Analysis of compressive properties of configuration composites

Figure 8 shows the stress/strain curves of honeycomb composites with different pore sizes. For the repeatability and accuracy of the experiment, three samples were selected for the compression performance experiment under the same parameters, table 2 shows the compressive strength of different samples, and it can be seen from the graph that the composite material is deformed elastically, with no obvious yielding phase or necking. As the pore size of the honeycomb preform increases, the compressive strength of the composite increases. When the hole diameter is 6 mm, the compressive strength of the composite is 1207.40 ± 11.42 MPa. When the pore size is 12 mm, the compressive strength of the composite is 1286.14 ± 15.97 MPa, which is 6.14% more compared to the pore size of 6 mm. The variation of compressive strength is related to the degree of dispersion of ZTA ceramic particles inside the composite, when the higher the dispersion of ceramic particles inside the composite,
the greater the spacing between ceramics and ceramics will be, the greater the force that the particles can withstand, and thus the greater the compressive strength of the composite [14]. The trend of the compressive mechanical properties is consistent with the stress simulation results.

Figure 9 shows the macroscopic morphology of the honeycomb composite specimens after compression. Based on the stress simulation results, it can be seen that the reinforcing particles have a strong inhibitory effect on the crack propagation of the composite material under a small load [15, 16]. Due to the large difference in thermal expansion coefficient between ceramic particles and metal matrix, the two in the combination, especially the ceramic particles at the sharp corner of the stress concentration is easy to form a crack source. Under the applied load, cracks begin to sprout and expand along the metal and ceramic particles. Since the bond
between the ceramic particles and the metal matrix is a weaker region, the crack will extend along the interface around the particles. Due to the presence of ZTA ceramic particles in the composite material, a large number of holes are formed after the ceramic particles are broken off during the compression process [2, 14]. The composite materials are cracked along 45° direction, the presence of ceramic particles impede the movement of

Figure 9. Compressive macroscopic morphology of composites with different honeycomb configurations (a) 6 mm; (b) 8 mm; (c) 10 mm; (d) 12 mm.

Figure 10. Compression micromorphology of composites with different honeycomb configurations (a) 6 mm; (b) 8 mm; (c) 10 mm; (d) 12 mm.
dislocations in the matrix, making the shear force on both sides unevenly stressed, the loading direction shows 45° crack, through the crack to release the stress and thus lead to the failure of the composite materials [17, 18].

Figure 10 shows the compression fracture morphology of the honeycomb composite. From the compressive fracture morphology of honeycomb composites, it can be judged that the fracture form of the material is brittle fracture, and the fracture morphology exists river-like pattern, which is deconstruction fracture, and there are a lot of tearing ribs [10, 19]. Combined with the previous simulation results, it can be analyzed that when the composite is squeezed by the load, stress/strain concentration is generated around the ceramic particles, and when the load reaches a critical point, the pressure is released through cracks, which in turn makes the composite fracture [17].

4. Conclusions

In this study, the effect of the pore size of honeycomb preforms on the mechanical properties of HCCI honeycomb configuration composites was investigated. The following conclusions can be drawn:

(1) Under the condition of constant pore wall value, the percentage of ZTA ceramic particles in the cross-section of the sample decreased from 72.4% to 60.9% when the pore size of the honeycomb preform was increased from 6 mm to 12 mm, and the dispersion of ZTA ceramic particles in the composite was better and uniform.

(2) The crack source originated from the tip angle of ceramic particles and expanded along the 45° direction. The compressive stress is mainly concentrated in the composite zone and cracks appear at the interface between the composite zone and the metal matrix.

(3) The compressive strength increased with the increase of the honeycomb pore size. When the pore size is 12 mm, the compressive strength of the composite is 1286.14 ± 15.97 MPa, which is 6.14% higher compared to 6 mm.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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