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Ceramics International 33 (2007) 1255–1261
CERAMICS INTERNATIONAL
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Gradient structures in ceramic nozzles for improved erosion wear resistance

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Received 22 December 2005; received in revised form 22 February 2006; accepted 24 March 2006
Available online 7 September 2006

Abstract

In sand blasting processes, the nozzle entry region suffers form severe abrasive impact, which may cause large tensile stress and lead to an increased erosion wear at the nozzle entry area. In this paper, a (W,Ti)C/SiC gradient ceramic nozzle was produced by hot pressing. The purpose is to reduce the tensile stress at the entry region of the nozzle during sand blasting processes. The erosion wear behavior of the gradient ceramic nozzle was investigated in comparison with the common ceramic nozzles. Results showed that the gradient ceramic nozzles exhibited an apparent increase in erosion wear resistance over the common ceramic nozzles. The mechanism responsible was explained as the formation of compressive residual stresses in nozzle entry region in fabricating process of the gradient ceramic nozzles, which may partially counteract the tensile stresses resulting from external loadings. It is indicated that gradient structures in ceramic nozzles is an effective way to improve the erosion wear resistance of common ceramic nozzles.

Keywords: Nozzles; Ceramic materials; Gradient materials; Erosion wear

1. Introduction

Sand blasting is the use of abrasive material for surface treatments [1,2], such as: surface strengthening, surface modification, surface smoothing or roughening, and surface clearing. This process is suitable for the treatment of hard and brittle metals, alloys, semiconductors, and non-metallic materials. The use of sand blasting in industries includes the shipbuilding industry, automotive industry, and other industries that involve surface preparation and painting. In the sand blasting process, a very high velocity jet of fine abrasive particles and carrier gas coming out from a nozzle impinges on the target surface and erodes it. The fine particles are accelerated by the gas stream, commonly compressed air at a few times atmospheric pressure. The particles are directed towards the surfaces to be treated. As the particles impact the surface, they cause a small fracture, and the gas stream carries both the abrasive particles and the fractured particles away.

The nozzle is the most critical part in the sand blasting equipment. There are many factors that influence the nozzle wear such as: the nozzle material and its geometry [3,4], the mass flow rate and impact angle [5,6], and the erodent abrasive properties [7,8]. Ceramics, being highly wear resistance, have great potential as the sand blasting nozzle materials. Several studies [9,10] have shown that the entry area of a ceramic nozzle exhibited a brittle fracture induced removal process, while the center area showed plowing type of material removal mode. As the erosive particles hit the nozzle at high angles (nearly 90°) at the nozzle entry section in sand blasting, the nozzle entry region suffers form severe abrasive impact, which may cause large tensile stresses as can be seen in Fig. 1 [9]. The stress along the axial direction of the nozzle decreases from entry to center, and increases from center to exit. The highest tensile stresses are located at the entry region of the nozzle. While the wear of the nozzle center area changes from impact to sliding erosion, the tensile stresses caused by the abrasive impact in this area are much smaller than those at the entry section. Thus, the erosion wear of the nozzle entry region is always serious in contrast with that of the center area.

The concept of functionally gradient material (FGM) was introduced in 1984; this was related to the development of heat-shielding structure materials for future space-plane use, with the compositional distribution of an FGM changing gradually from one surface to the other. Close attention has been paid to FGMs worldwide for their novel design ideas and outstanding properties. Various FGMs beyond thermal stress relaxing

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0272-8842/$32.00
doi:10.1016/j.ceramint.2006.03.034

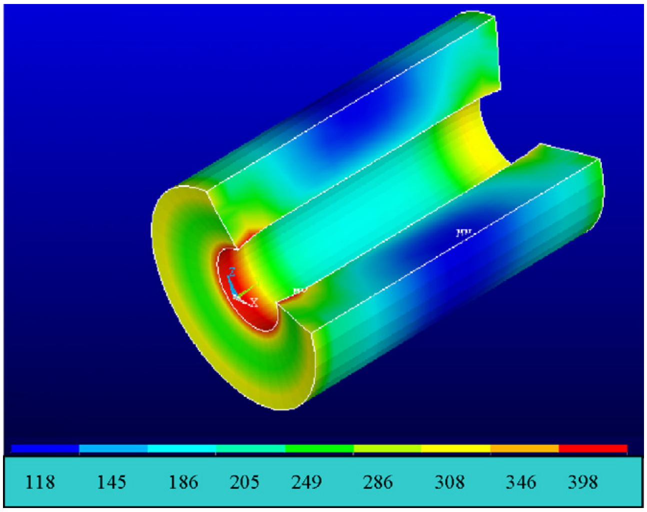


Fig. 1. The stresses in B4C ceramic nozzle calculated by finite element method [9].

materials have turned up continuously as a result of the introduction of the FGM concept into the fields of nuclear power, optics, and mechanical engineering [11,12].

In the present study, a (W,Ti)C/SiC gradient ceramic nozzle was produced by hot pressing. The purpose is to reduce the tensile stress at the entry region of the nozzle during sand blasting processes. The erosion wear behavior of the gradient ceramic nozzle was investigated in comparison with the common ceramic nozzles.

2. Materials and experimental procedures

2.1. Preparation of (W,Ti)C/SiC gradient ceramic nozzle materials

The starting materials were (W,Ti)C solid-solution powders with average grain size of approximately 0.8 μm, purity 99.9%, and SiC powders with average grain size of 1 μm, purity 99.8%. Six different volume fractions of SiC (25, 30, 35, 40, 45, 50 vol.%) were selected in designing the (W,Ti)C/SiC gradient nozzle material with a six-layer structure.

The compositional distribution of the gradient ceramic nozzle is shown in Fig. 2(a). It is indicated that the compositional distribution changes in nozzle axial direction. As the heat conductivity of SiC is higher than that of (W,Ti)C solid-solution, while its thermal expansion coefficient is lower than that of (W,Ti)C, the layer with the highest volume fraction of SiC was put in the nozzle entry with the compositional distribution changing from the entry layer to the exit layer with the lowest volume fraction of SiC. The common nozzle with no compositional change is shown in Fig. 2(b).

Six (W,Ti)C/SiC composite powders of different mixture ratios were prepared by wet ball milling in alcohol with cemented carbide balls for 80 h. Following drying, the mixtures composite powders with different mixture ratios were laminated into the mould. The sample was then hot-pressed in flowing nitrogen for 40 min at 1900 °C temperature and

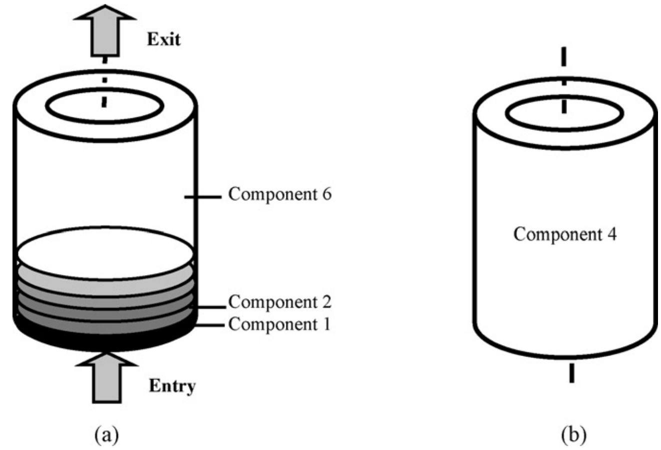


Fig. 2. Compositional distribution of (a) gradient ceramic nozzle, (b) common ceramic nozzle.

30 MPa pressure. This gradient ceramic nozzle is named GN-1, while the common ceramic nozzle is named CN-1.

2.2. Sand blasting tests

Fig. 3 shows the schematic diagram of the sand blasting machine tool (GS-6 type), which consists of an air compressor, a blasting gun, a control valve, a particle supply tube, a filter, a desiccator, an adjusting press valve, a dust catcher, an abrasive hopper, and a nozzle. The dust catcher was used to prevent fugitive dust emissions. The air and grit flow adjusting was controlled by the valves and regulators. The erodent abrasives used in this study were of silicon carbide (SiC) powders with 250–300 μm grain size. As these abrasives are more durable and create less dust than sand, and typically are reclaimed and reused.

The abrasive air jet is formed in the blasting gun using a suction-type process as schematically illustrated in Fig. 4. The gas flow rate is controlled by the compressed air.

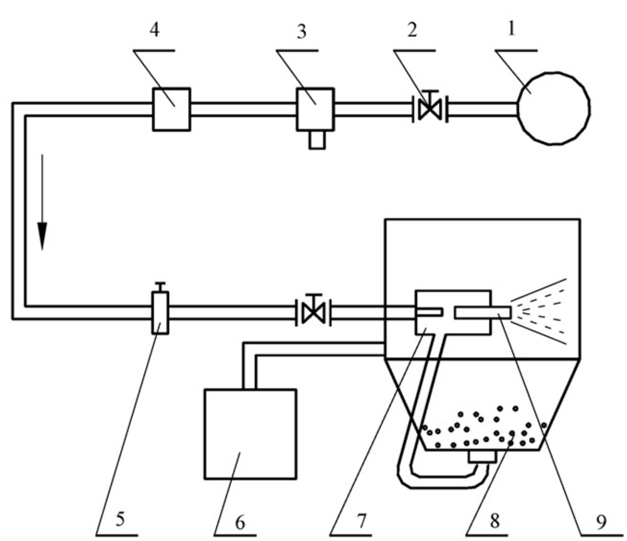


Fig. 3. Schematic diagram of the sand blasting machine tool (1: air compressor, 2: control valve, 3: filter, 4: desiccator, 5: press adjusting valve, 6: dust catcher, 7: blasting gun, 8: abrasive hopper, 9: ceramic nozzle).

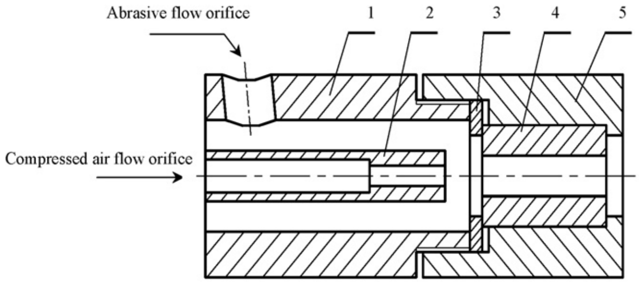


Fig. 4. Schematic diagram of blasting gun structure (1: gun support, 2: air flow nozzle, 3: adjusting gasket, 4: ceramic nozzle, 5: plastic jacket for the nozzle).

The compressed air pressure was set at 0.4 MPa, and the abrasive particle velocities through the nozzle is adjusted to 60 m/s. Nozzles with internal diameter 8 mm and length 30 mm made from common (W,Ti)C/SiC and gradient (W,Ti)C/SiC were manufactured by hot-pressing as can be seen in Fig. 5. The mass loss of the worn ceramic nozzle was measured with an accurate electronic balance (minimum 0.1 mg). All the test conditions are listed in Table 1.

The finite element method (FEM) was used as a means of numerically evaluating the residual thermal stress and its distribution of the gradient ceramic nozzle in the fabricating processes. The polished surfaces of the ceramic nozzle materials and the eroded bore surfaces of the nozzles were examined using scanning electron microscopy.

Table 1
Sand blasting conditions

Sand blasting equipment	GS-6 type sand blasting machine tool
Nozzle material	(W,Ti)C/SiC gradient nozzle and (W,Ti)C/SiC common nozzle
Dimension of nozzle	Ø 8 mm (internal diameter) × 30 mm (length)
Erodent abrasives	250–300 μm SiC powders
Compressed air pressure	0.4 MPa
Cumulative mass weigh	Accurate electronic balance (minimum 0.1 mg)

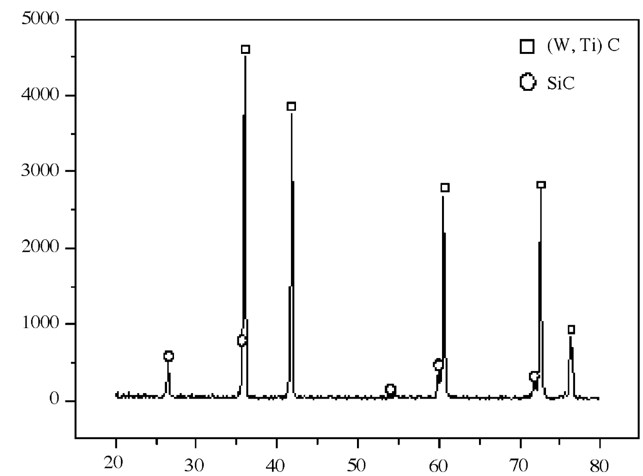


Fig. 6. X-ray diffraction analysis of the (W,Ti)C/SiC gradient ceramic nozzle material after sintering at 1900 °C for 40 min.

3. Results and discussion

3.1. Microstructural characterization and properties of (W,Ti)C/SiC gradient nozzle materials

Hardness measurements were performed by placing Vickers indentations on every layer of the cross-sectional surface of (W,Ti)C/SiC gradient nozzle material. The indentation load was 200 N and a minimum of three indentations were tested for each layer. The Vickers hardness (GPa) of each layer is given by:

$$\mathrm{Hv} = 1.8544\frac{P}{(2a)^2} \quad (1)$$

where P is the indentation load (N), a is the catercorner depth (μm) due to indentation. Hardness of each layer of (W,Ti)C/SiC gradient nozzle material is presented in Table 2.

Fig. 6 illustrates the X-ray diffraction analysis of the (W,Ti)C/SiC gradient ceramic nozzle material after sintering at 1900 °C for 40 min. It can be seen that both (W,Ti)C and SiC existed in the sintered specimens. Fig. 7 shows the six-layer structure of the hot-pressed (W,Ti)C/SiC gradient ceramic nozzle material. SEM micrographs of each polished layer of (W,Ti)C/SiC gradient ceramic nozzle material are shown in Fig. 8. The black areas were identified by EDX analysis as SiC, and the white phases with clear contrast were (W,Ti)C. It can be seen that the SiC particles are quite uniformly distributed throughout the microstructure, porosity is virtually absent.

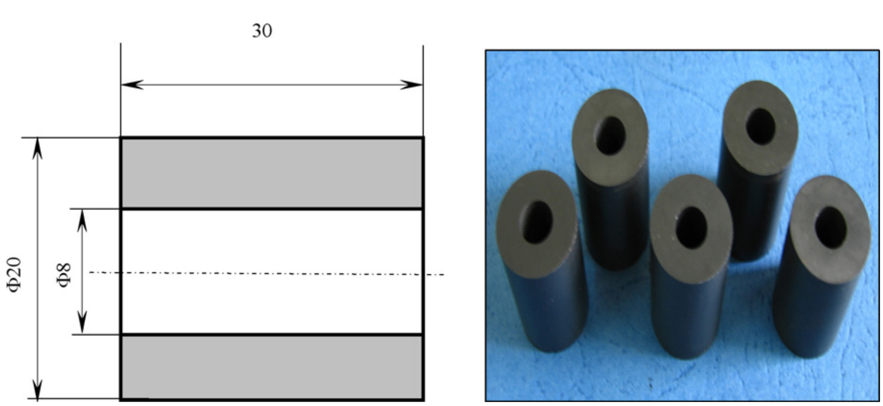


Fig. 5. Geometry, dimensions, photo of the ceramic nozzle.

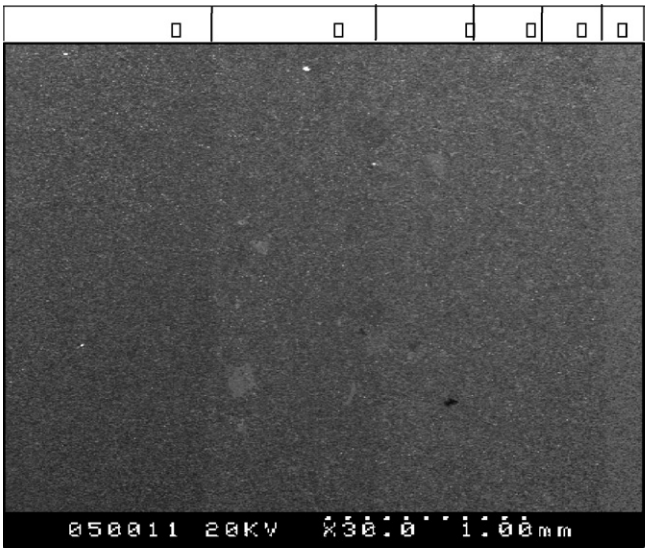


Fig. 7. Cross-section surface of the SiC/(W,Ti)C gradient ceramic nozzle material.

3.2. Residual thermal stress analysis of (W,Ti)C/SiC gradient nozzle material

The residual thermal stress of the gradient ceramic nozzle in the fabricating process was calculated by means of the finite element method by assuming that the compact is cooled from sintering temperature 1900 °C to room temperature 20 °C.

Table 2
Hardness of different layers of the gradient nozzle materials

V_{SiC} (vol.%)	Vickers hardness Hv (GPa)
25	23.08
30	23.65
35	22.25
40	21.28
45	20.75
50	20.29

Thermo-mechanical properties of (W,Ti)C and SiC are as follows:

$$(\mathrm{W,Ti})\mathrm{C}: E = 480\,\mathrm{GPa},\ \ \nu = 0.25,$$
$$\alpha = 8.5\times10^{-6}\,\mathrm{K}^{-1},\ \ k = 21.4\,\mathrm{W/(mK)}.$$

$$\mathrm{SiC}: E = 450\,\mathrm{GPa},\ \ \nu = 0.16,\ \ \alpha = 4.6\times10^{-6}\,\mathrm{K}^{-1},$$
$$k = 33.5\,\mathrm{W/(mK)}.$$

The distribution of axial (σ_z), radial (σ_r), and circumferential (σ_θ) residual thermal stresses calculated by FEM in the (W,Ti)C/SiC gradient nozzle in cooling process from sintering temperature to room temperature are showed in Fig. 9. As can be seen, an excess residual thermal stress is formed in the nozzle entry region for the (W,Ti)C/SiC gradient nozzle. Fig. 10 shows the residual thermal stresses in axial (σ_z), radial (σ_r), and circumferential (σ_θ) directions of (W,Ti)C/SiC gradient nozzle at different position along its axes. It in indicated that axial (σ_z),

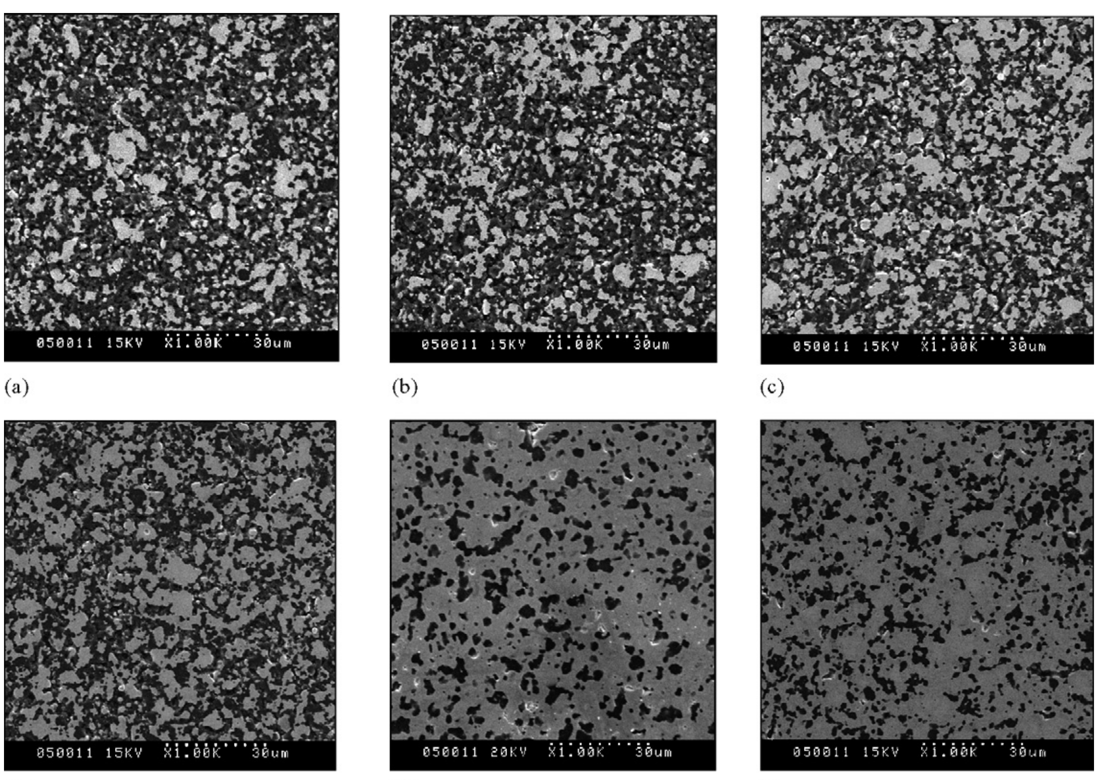


Fig. 8. SEM micrographs of each polished layer of SiC/(W,Ti)C gradient ceramic nozzle material. (a) The first layer (entry zone) (50 vol.%SiC); (b) the second layer (45 vol.%SiC); (c) the third layer (40 vol.%SiC); (d) the fourth layer (35 vol.%SiC); (e) the fifth second layer (30 vol.%SiC); (f) the sixth layer (exit zone) (25 vol.%SiC).

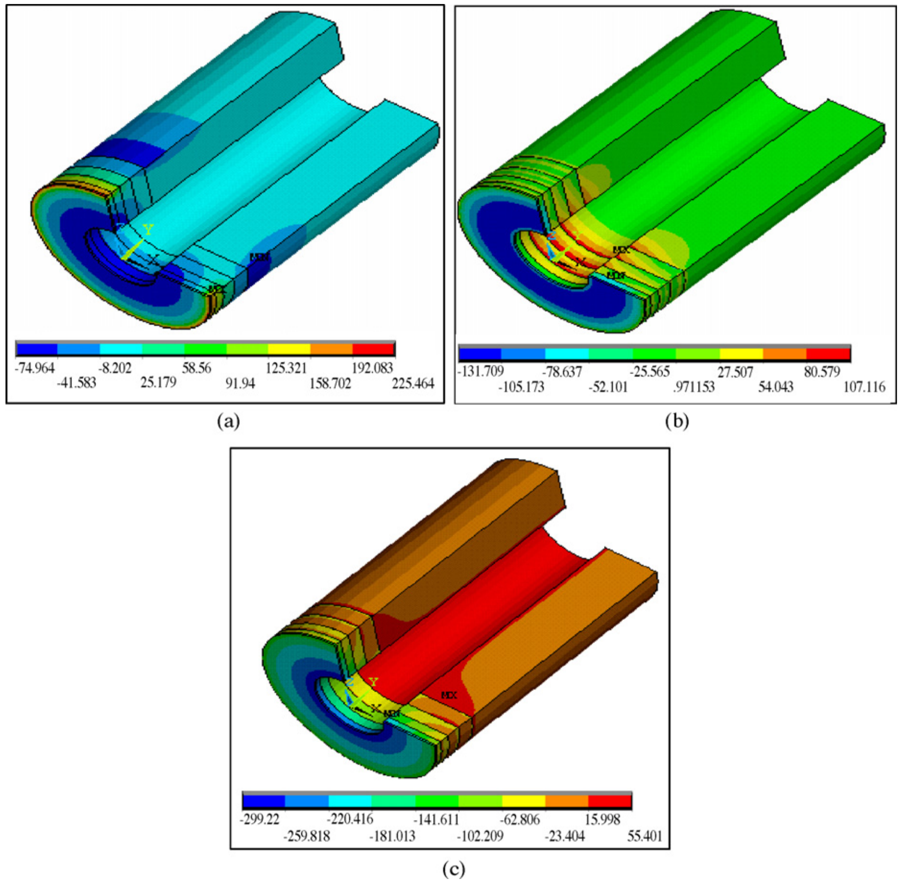


Fig. 9. Distribution of (a) axial (σ_z), (b) radial (σ_r), and (c) circumferential (σ_θ) residual thermal stresses of (W,Ti)C/SiC gradient nozzle.

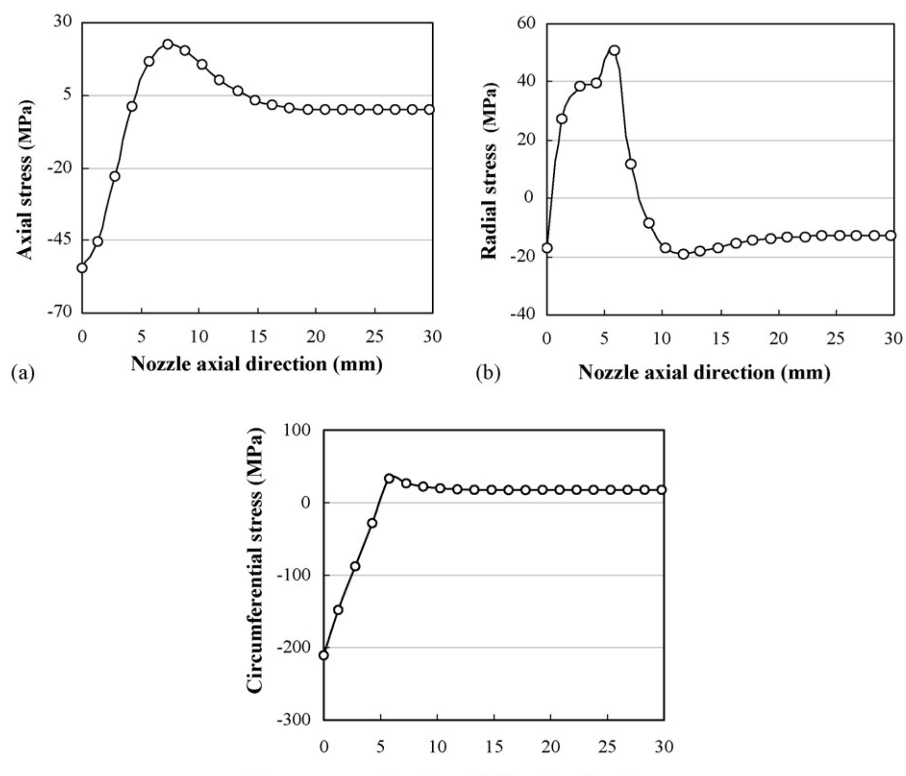


Fig. 10. Residual thermal stresses in (a) axial (σ_z), (b) radial (σ_r), and (c) circumferential (σ_θ) directions of (W,Ti)C/SiC gradient nozzle at different position along the axial direction of the nozzle.

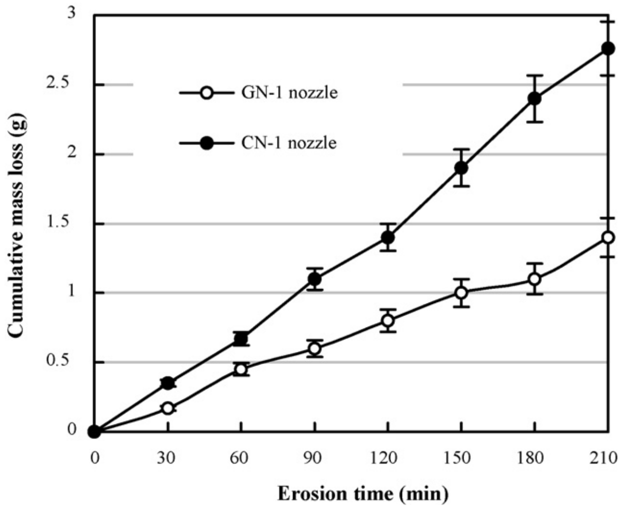


Fig. 11. Cumulative mass loss of ceramic nozzles in sand blasting processes.

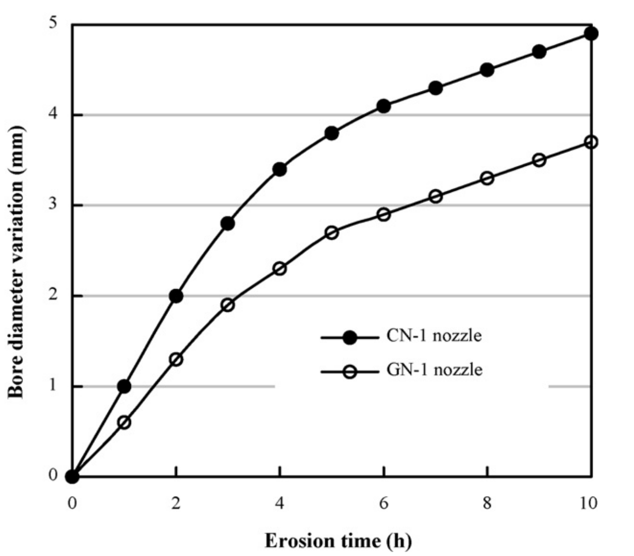


Fig. 12. Nozzle entry bore diameter variation with the erosion time in sand blasting processes.

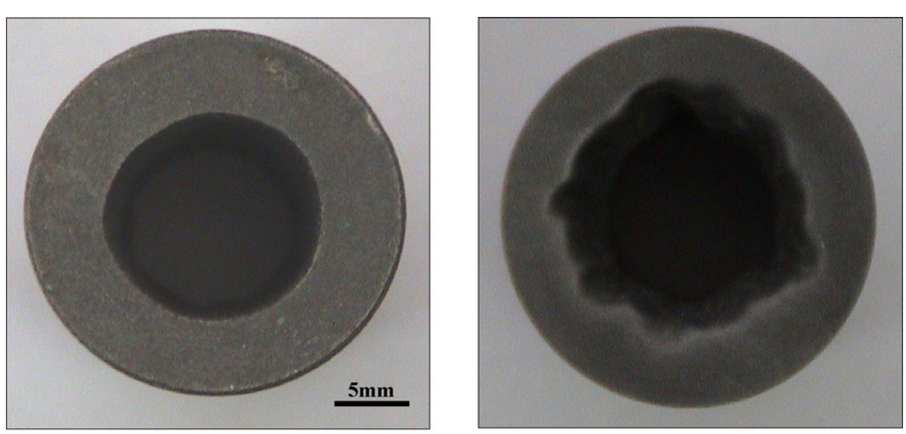
radial (σ_r), and circumferential (σ_θ) residual thermal stresses at the nozzle entry zone are compressive, and the maximum value is −54.7.0, −19.5, and −210.6 MPa, respectively. Therefore, gradient structures in ceramic nozzles can form compressive residual stresses in the nozzle entry region during fabricating process.

3.3. Erosion behavior of the (W,Ti)C/SiC gradient nozzle

The erosion behavior of (W,Ti)C/SiC gradient ceramic nozzle (GN-1) in sand blasting processes was investigated in comparison with the (W,Ti)C/35 vol.%SiC common ceramic nozzle (CN-1). Fig. 11 shows the cumulative mass loss of GN-1 and CN-1 nozzles in sand blasting process. It can be seen that the cumulative mass loss continuously increased with the operation time. The common CN-1 nozzle showed higher cumulative mass loss. The results of the nozzle entry bore diameter variation with the erosion time are shown in Fig. 12 for GN-1 and CN-1 nozzles. It is indicated that the entry bore diameter enlarges relatively fast up to 4 h operation, and within further 6 h operation it increases monotonically. At the beginning, wear in the nozzle entry area becomes a maximum, which may be attributed to severe impact erosion under large impact angles. After 4 h operation, a natural shape entry bore develops, and the wear mode changes from impact to sliding erosion. Results also revealed that the GN-1 gradient nozzle had higher erosion wear resistance over CN-1 common nozzle under the same test conditions.

The entry bore profiles of worn GN-1 and CN-1 nozzles after sand blasting for 10 h are shown in Fig. 13. It is showed that the entry bore of CN-1 common nozzle was severely worn. While the entry bore of GN-1 gradient nozzle had worn slightly compared with that of the common one.

Nozzle failure by erosion wear is generally caused by fracture owing large the tensile stress at the nozzle entry zone as can be seen in Fig. 1 [9]. Because the nozzle entrance region suffers form severe abrasive impact (see Fig. 14), and generates large tensile stress, which may cause the subsurface lateral cracks and facilitates removal of the material chips. Thus, the erosion wear of the nozzle depends on the stress distribution in



(a) (b)

Fig. 13. Entry profile of worn (a) GN-1 gradient nozzle, (b) CN-1 common nozzle after 10 h sand blasting.

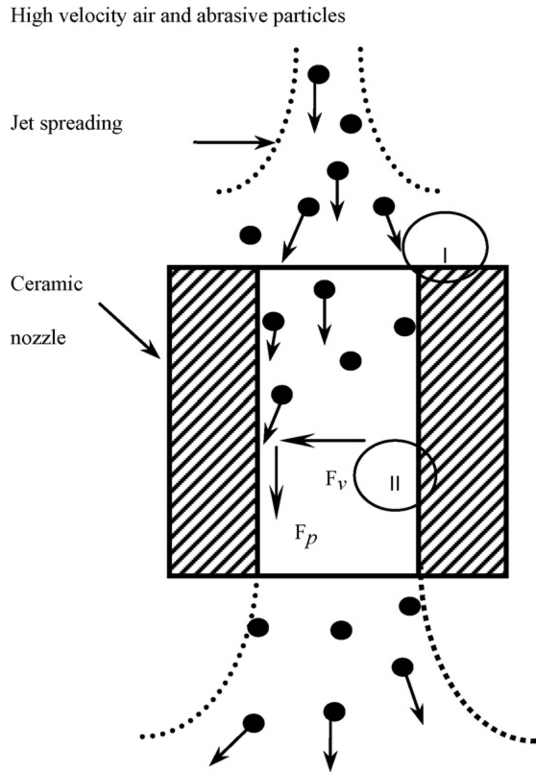


Fig. 14. Interaction of particles with nozzle in sand blasting processes.

the entry region. Once the maximum tensile stress exceeds the ultimate strength of the nozzle material, fracture will occur. The higher erosion wear resistance of the GN-1 gradient nozzle compared with the common one can be analysed in terms of the formation of compressive residual stresses on the entry region. As calculated above, compressive residual stresses were formed in the entry region of the (W,Ti)C/SiC gradient nozzle in cooling process from sintering temperature to room temperature, which may partially counteract the tensile stresses in the nozzle entry section resulting from external loadings. This effect may lead to the increase in resistance to fracture, and thus increase the erosion wear resistance of the gradient nozzle.

4. Conclusions

A (W,Ti)C/SiC ceramic nozzle with gradient structures was produced by hot pressing. Particular attention was paid to the erosion behaviors of this kind gradient ceramic nozzle in sand blasting processes. Results showed that:

1. Gradient ceramic nozzles exhibited an apparent increase in erosion wear resistance over the common ceramic nozzles. The mechanism responsible was explained as the formation of compressive residual stresses in nozzle entry region in fabricating process of the gradient ceramic nozzles, which may partially counteract the tensile stresses resulting from external loadings.
2. Gradient structure in ceramic nozzles is an effective way to improve the erosion wear resistance of common ceramic nozzles.

Acknowledgements

This work was supported by the ''National Natural Science Foundation of China (50475133)'', ''Specialized Research Fund for Doctoral Program of Higher Education (20030422105)'', ''Natural Science Foundation of Shandong Province (Y2004F08)'', and ''the Program for New Century Excellent Talents in University (NCET-04-0622)''.

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