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Erosion wear of laminated ceramic nozzles

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Abstract

SiC/(W,Ti)C ceramic nozzles with laminated structures were produced by hot pressing in order to reduce the tensile stress at the entry and exit region of the nozzle. Finite element method was used to evaluate the residual stresses due to the different thermal expansion coefficients and shrinkage of the SiC and (W,Ti)C solid–solution during the sintering process of the composite. The erosion wear of the laminated ceramic nozzle was assessed by sand blasting; the results were compared with those obtained with an unstressed reference nozzle with the same composition. The experimental results have shown that the laminated ceramic nozzles have superior erosion wear resistance to that of the homologous stress-free nozzles.

Keywords: Nozzles; Ceramic materials; Laminated materials; SiC

1. Introduction

Sand blasting treatment is an abrasive machining process and is widely used for surface strengthening [1], surface modification [2], surface clearing and rust removal [3,4], etc. It is suitable for the treatment of hard and brittle materials, ductile metals, alloys, and nonmetallic materials. 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 mass flow rate and impact angle [5–7], the erodent abrasive properties [8–10], the nozzle material and its geometry [11–16], and the temperatures [17,18]. Ceramics, being highly wear resistance, have great potential as the sand blasting nozzle materials.

Several studies [11,15] 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 (see Fig. 1), the nozzle entry region suffers form severe abrasive impact, which may cause large tensile stresses. The highest tensile stresses are located at the entry region of the nozzle. Thus, the erosion wear of the nozzle entry region is always serious in contrast with that of the center area [11,15].

Laminated hybrid structures constituted by alternate layers of different materials can be properly designed to induce a surface compressive residual stress leading to an improved surface mechanical properties and wear resistance [19–22]. Residual stresses arise from a mismatch between the coefficients of thermal expansion (CTE), sintering rates and elastic constants of the constituent phases and neighbouring layers, and the residual stress field depends on the geometry of the layered structure and on the thickness ratio among layers [23–26]. Toschi [22]

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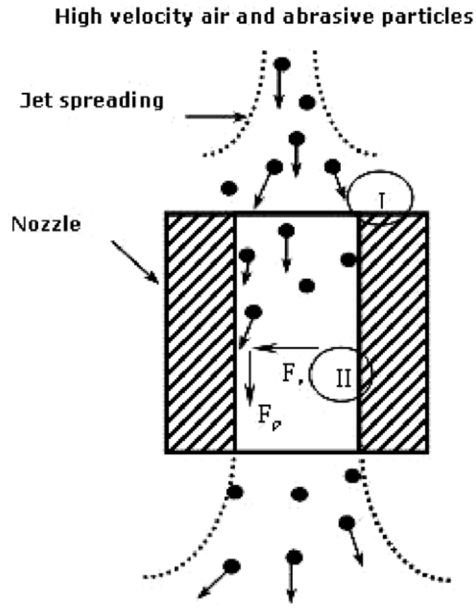

Fig. 1. Schematic diagram of the interaction between the erodent particle and the nozzle in sand blasting processes.

et al. reported that laminated hybrid structures can improve the sliding wear resistance of alumina. Portu [27] et al. showed that laminated structures with compressive residual stresses within the surface regions was a suitable way to obtain composite materials with superior tribological properties. Deng et al [28]. showed that gradient ceramic nozzle exhibited high wear resistance over common ceramic nozzles.

In the present study, SiC/(W,Ti)C ceramic nozzles with laminated structures were produced by hot pressing in order to reduce the tensile stress at the entry and exit region of the nozzle. The residual stress of the laminated nozzle during the sintering process was calculated by means of the finite element method. The erosion wear of the laminated ceramic nozzles was investigated in comparison with an unstressed reference nozzle with the same composition.

2. Materials and experimental procedures

2.1. Preparation of SiC/(W,Ti)C laminated 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 (W,Ti)C (55, 57, 59, 61, 63, 65 vol.%) were selected in designing the SiC/(W,Ti)C laminated nozzle material with a six-layer structure. The compositional distribution of the laminated ceramic nozzle materials is shown in Fig. 2. It is indicated that the compositional distribution of the laminated nozzle materials 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 both in the entry layer and in the exit layer (see Fig. 2(a)). The homologous stress-free nozzle with no compositional change is shown in Fig. 2 (b). The ceramic nozzle laminated both in entry and exit area is named GN-3, while the stress-free nozzle is named CN-2.

Six SiC/(W,Ti)C composite powders of different mixture ratios were prepared by wet ball milling in alcohol with cemented carbide balls for 80 h respectively. Following drying, the mixtures composite powders with different mixture ratios were laminated into the mould in turn. The sample was then hot-pressed in flowing nitrogen for 40 min at 1900 °C temperature with 30 MPa pressure.

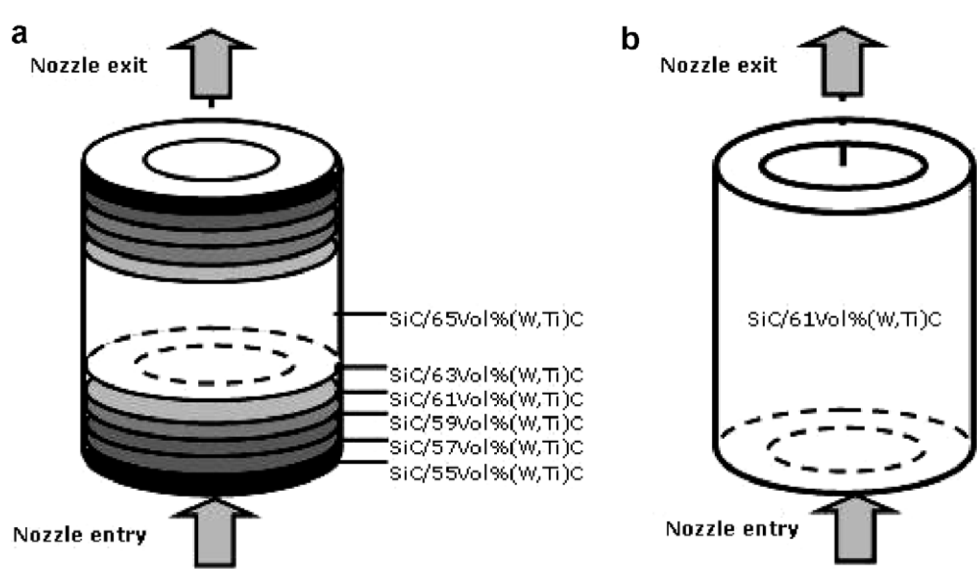

Fig. 2. Compositional distribution of (a) the SiC/(W,Ti)C ceramic nozzle laminated both in entry and exit area (GN-3), (b) the homologous stress-free nozzles (CN-2).

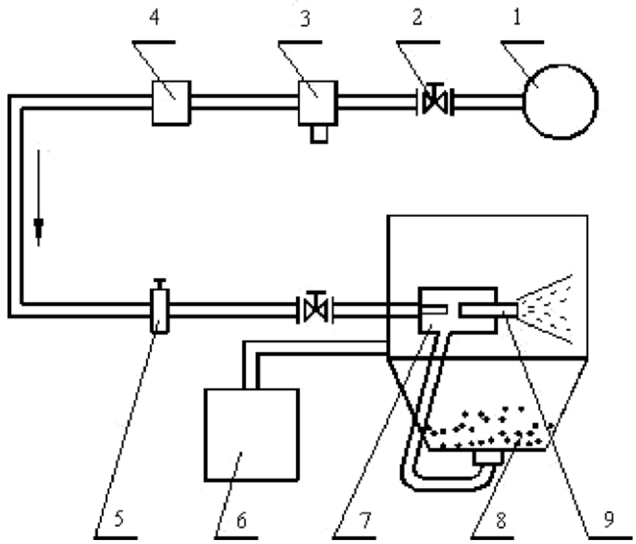

Fig. 3. Schematic diagram of the sand blasting machine tool ((1) air compressor, (2) control valve, (3) filter, (4) desiccator, (5) press adjusting valve, (6) dust catcher, (7) blasting gun, (8) abrasive hopper, (9) ceramic nozzle).

2.2. Sand blasting tests

Fig. 3 shows the schematic diagram of the abrasive air-jet 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 air and grit flow adjusting was controlled by the valves and regulators. The gas flow rate is controlled by the compressed air, and the abrasive particle velocity through the nozzle is adjusted to 60 m/s.

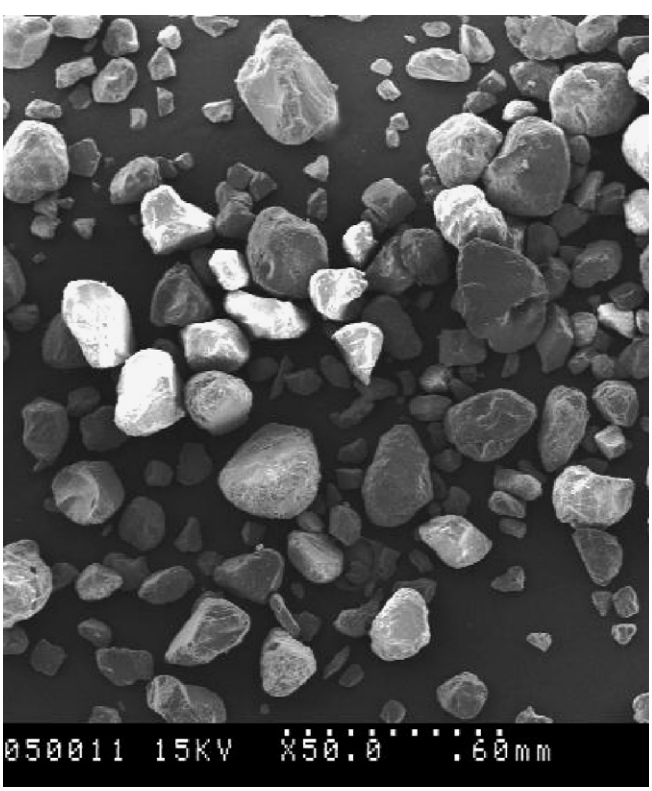

Fig. 4. SEM micrograph of the SiC abrasives used for sand blasting.

Fig. 5. Photo of the GN-3 laminated ceramic nozzles.

The erodent abrasives used in this study were of silicon carbide (SiC) powders with 50–150 μm grain size. The SEM micrograph of the SiC powders used for the dry sand blasting is shown in Fig. 4.

Nozzles with internal diameter 8 mm and length 30 mm made from SiC/(W,Ti)C laminated structure (GN-3) and stress-free structure (CN-2) were manufactured by hot-pressing as can be seen in Fig. 5.

The mass loss of the worn nozzles was measured with an accurate electronic balance (minimum 0.1 mg). All the test conditions are listed in Table 1. The erosion rates (W) of the nozzles are defined as the nozzle mass loss (m_1) divided by the nozzle density (d) times the mass of the erodent abrasive particles (m_2):

Table 1
Sand blasting test conditions

Sand blasting equipment	GS-6 type sand blasting machine tool
Nozzle material	GN-3 laminated nozzle CN-2 stress-free nozzle
Dimension of nozzle	Φ8 mm (internal diameter) × 30 mm (length)
Erodent abrasives	50–150 μm SiC powders
Compressed air pressure	0.4 MPa
Cumulative mass weigh	Accurate electronic balance (minimum 0.1 mg)

Table 2
Hardness of different layers of the laminated nozzle materials

Layer	(W,Ti)C content (vol.%)	Vickers hardness Hv (GPa)
1	55	26.89
2	57	26.52
3	59	25.93
4	61	25.70
5	63	24.67
6	65	24.15

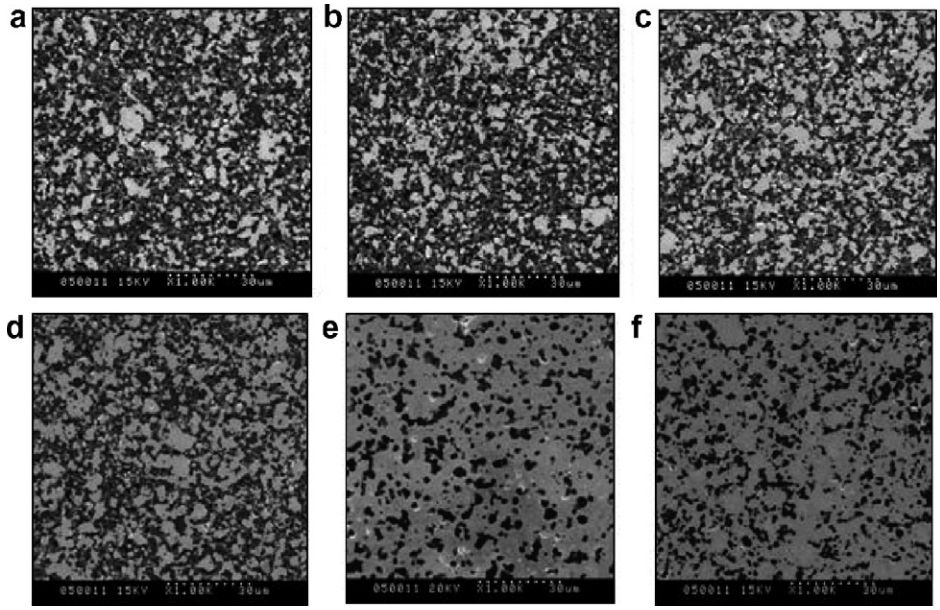

Fig. 6. SEM micrographs of each polished layer of the GN-3 laminated ceramic nozzle material (a) the first layer (entry zone), (b) the second layer, (c) the third layer, (d) the fourth layer, (e) the fifth second layer, and (f) the sixth layer.

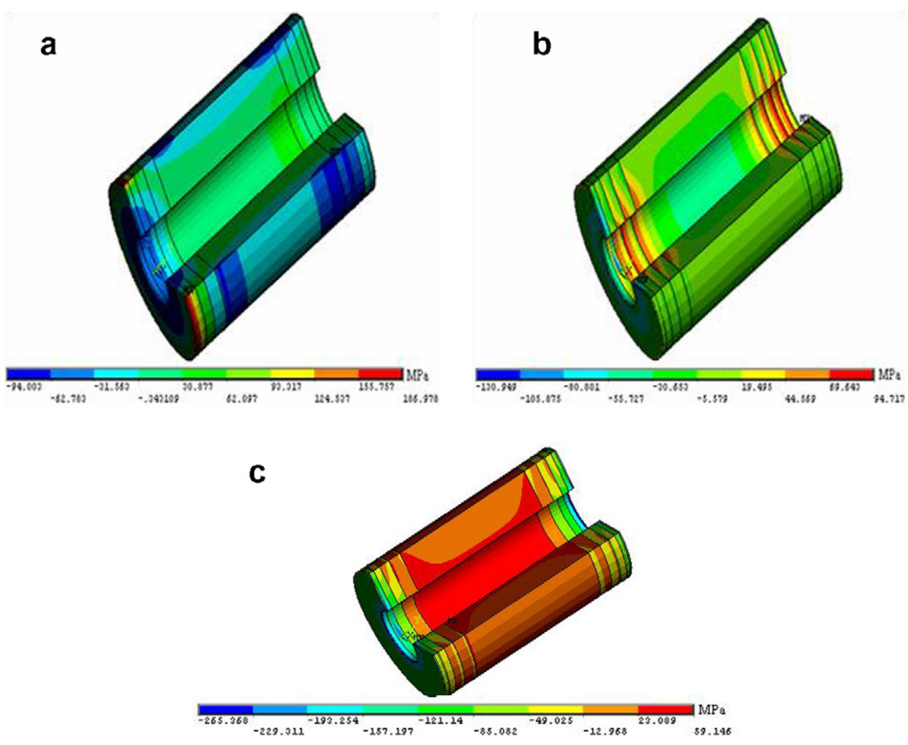

Fig. 7. Distribution of (a) the axial (σ_z), (b) the radial (σ_r), and (c) the circumferential (σ_θ) residual stresses in the GN-3 laminated nozzle in fabricating process.

$$W = m_1/(d.m_2) \quad (1)$$

where the W has the units of volume loss per unit mass (mm^3/g).

The finite element method (FEM) was used as a means of numerically evaluating the residual stress and its distribution of the laminated ceramic nozzle in the fabricating processes.

For observation of the micro-damage and determination of erosion mechanisms, the worn nozzles were sectioned axially. The eroded bore surfaces of the nozzles were examined by scanning electron microscopy.

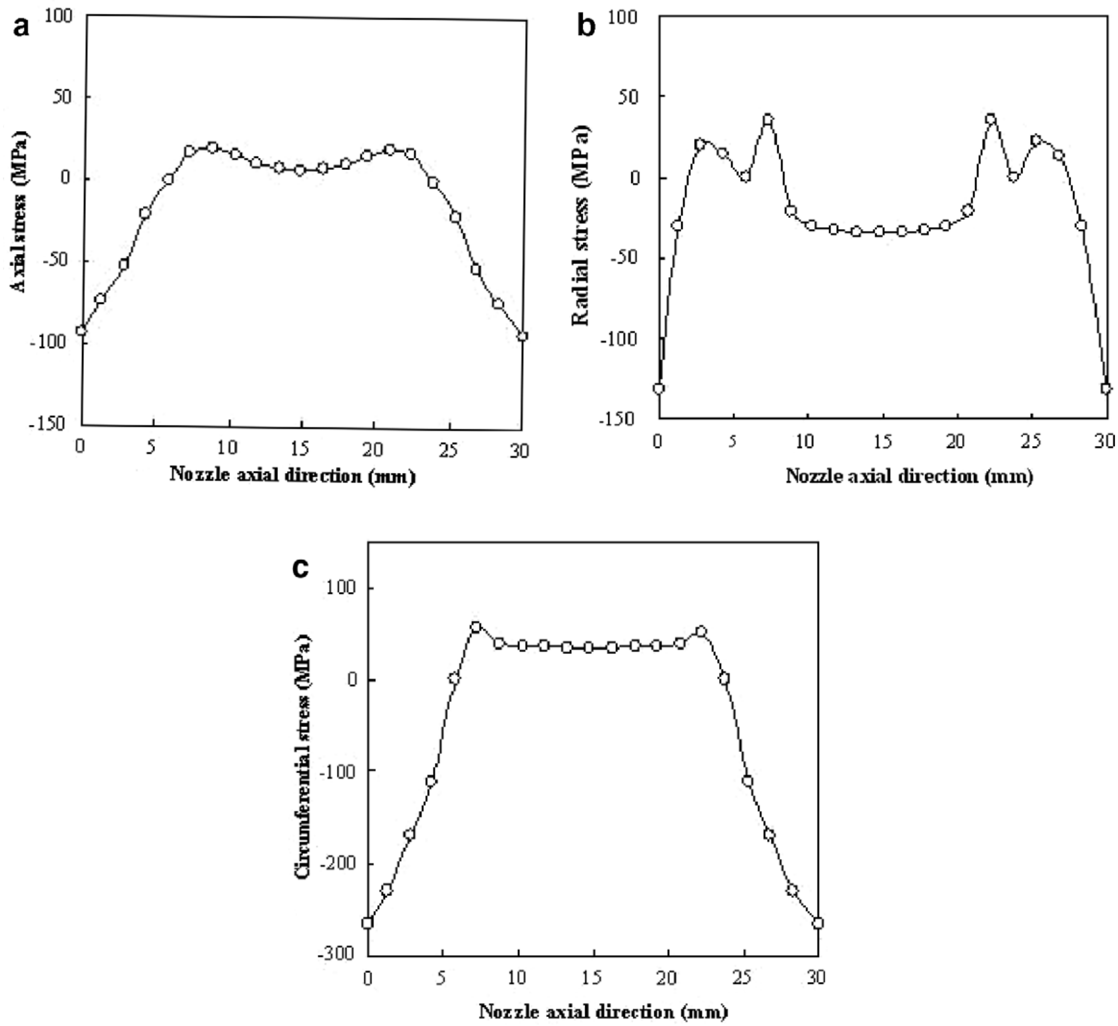

Fig. 8. (a) The axial (σ_z), (b) the radial (σ_r), and (c) the circumferential (σ_θ) residual stresses in the GN-3 laminated nozzle in fabricating process at different position along the axial direction of the nozzle.

3. Results and discussion

3.1. Microstructural characterization and properties of the laminated nozzle materials

Hardness measurements were performed by placing Vickers indentations on every layer of the cross-sectional surface of GN-3 laminated 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

$$Hv = 1.8544\frac{P}{(2a)^2} \tag{2}$$

where P is the indentation load (N), $2a$ is the catercorner length (μm) due to indentation. Hardness of each layer of the GN-3 laminated nozzle material is presented in Table 2.

SEM micrographs of each polished layer of GN-3 laminated ceramic nozzle material are shown in Fig. 6. 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.

3.2. Residual stress at the laminated nozzles

The residual stress of the laminated 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. Thermo-mechanical properties of (W,Ti)C and SiC are as follows:

$$\text{(W, Ti)C}: \; E = 480 \text{ GPa}, \; \nu = 0.25, \; \alpha = 8.5 \times 10^{-6}\ \text{K}^{-1}, \; k = 21.4\ \text{W/(m K)}.$$

$$\text{SiC}: \; E = 450 \text{ GPa}, \; \nu = 0.16, \; \alpha = 4.6 \times 10^{-6}\ \text{K}^{-1}, \; k = 33.5\ \text{W/(m K)}.$$

Owing to the symmetry, an axisymmetric calculation was preferred. Presume that it was steady state boundary conditions. The results of the distribution of the axial

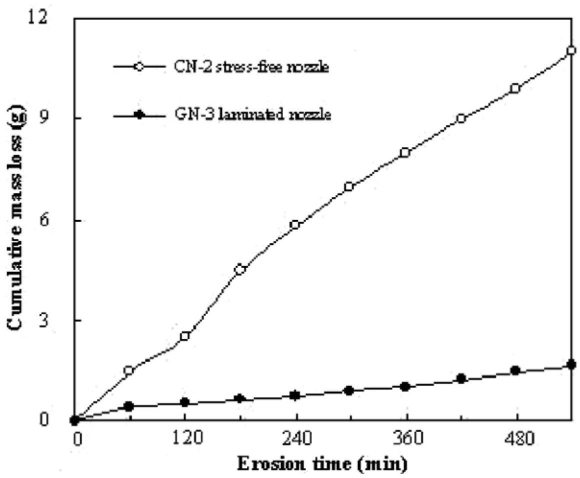

Fig. 9. Cumulative mass loss of the GN-3 laminated nozzle and the CN-2 stress-free nozzle in sand blasting processes.

(σ_z), the radial (σ_r), and the circumferential (σ_θ) residual stresses calculated by FEM in the GN-3 laminated nozzle in cooling process from sintering temperature to room temperature are showed in Fig. 7. It is obvious that an excess compressive residual stress is formed both at the entry and the exit region of the GN-3 laminated nozzle. Fig. 8 shows the axial (σ_z), the radial (σ_r), and the circumferential (σ_θ) residual stresses in GN-3 laminated nozzle at different position along its axes. It in indicated that σ_z, σ_r, and σ_θ residual stress both at the entry zone and at the exit zone is compressive, and the maximum value is −94.003 MPa, −130.949 MPa, and −265.368 MPa respectively. Therefore, laminated structures in ceramic nozzles can form an excess compressive residual stresses at the entry and exit region of the nozzle during fabricating process.

3.3. Erosion wear of the laminated nozzle

The erosion wear of the GN-3 laminated ceramic nozzle was assessed in comparison with the CN-2 stress-free ceramic nozzle by sand blasting. Fig. 9 shows the cumulative mass loss of the GN-3 and CN-2 nozzles in sand blasting processes. It can be seen that the cumulative mass loss continuously increased with the operation time. Compared with GN-3 laminated nozzle, the CN-2 stress-free nozzle showed higher cumulative mass loss under the same test conditions.

The worn ceramic nozzles were cut after operation in longitudinal directions for failure analysis. Fig. 10 shows the photos of the inner bore profile of the GN-3 and CN-2 nozzles after 540 min operation. It is showed that inner bore diameter of the worn CN-2 nozzle along the nozzle longitudinal directions is larger than that of the worn GN-3 laminated nozzles, especially at the nozzle entry region.

The results of the nozzle entry bore diameter variation with the erosion time of for GN-3 and CN-2 nozzles are shown in Fig. 11. It is indicated that the entry bore diameter enlarges greatly with the operation time for CN-2 stress-free nozzle. While the entry bore diameter increases slowly with the operation time for GN-3 laminated nozzle. Fig. 12 shows the comparison of the erosion rates for GN-3 and CN-2 nozzles in sand blasting processes. It is obvious that the erosion rate of the stress-free nozzles is higher than that of the laminated nozzles. Therefore, it is apparently that the GN-3 laminated nozzles exhibited higher erosion wear resistance over the CN-2 stress-free nozzle under the same test conditions.

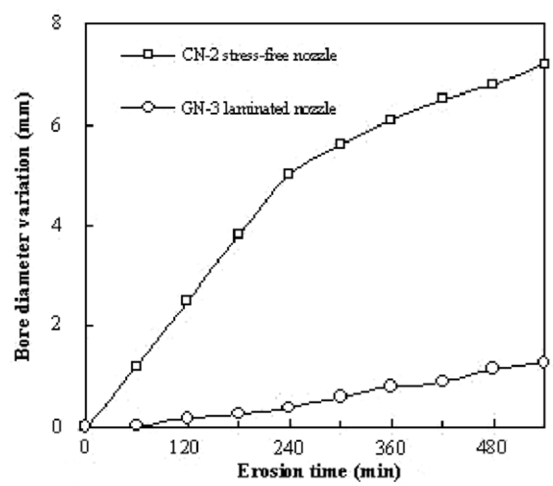

Fig. 11. Nozzle entry bore diameter variation with the erosion time for the GN-3 laminated nozzle and the CN-2 stress-free nozzle in sand blasting processes.

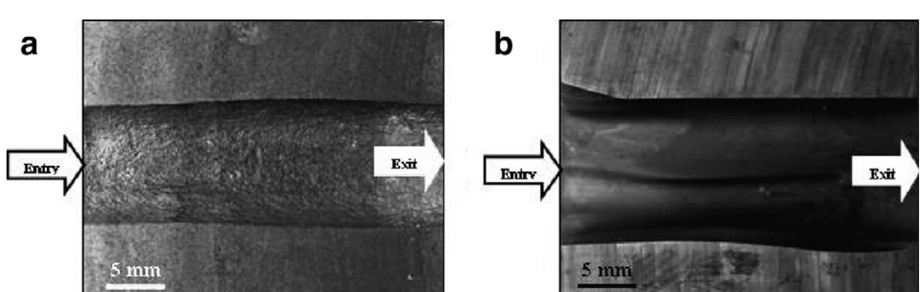

Fig. 10. Photos of the worn inner bore profile of (a) the GN-3 laminated nozzle, (b) the CN-2 stress-free nozzle after 540 min operation.

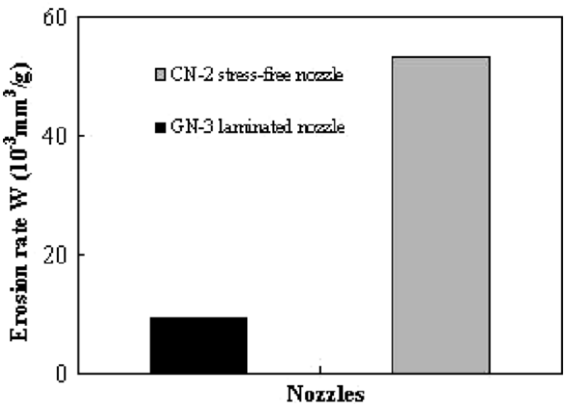

Fig. 12. Comparison of the erosion rate of the GN-3 laminated nozzle and the CN-2 stress-free nozzle in sand blasting processes.

Fig. 13 shows the SEM micrographs of the entry bore surface of the worn CN-2 stress-free nozzle. From these SEM micrographs, different morphologies and fracture modes of the nozzles can be seen clearly. The CN-2 stress-free nozzle at the entry area failed in a highly brittle manner, and exhibited a brittle fracture induced removal process. There are a lot of obvious pits located on the nozzle bore surface indicating that brittle fracture took place. Characteristic SEM pictures taken on the eroded entry bore surface of the GN-3 laminated ceramic nozzle are shown in Fig. 14. It is shown that the appearance of the eroded areas of the laminated nozzle showed a relative smooth surface by contrast with that of the stress-free nozzle.

Ceramic nozzle failure by erosion wear is generally caused by fracture owing large the tensile stress at the nozzle entry zone [11–15]. Because the nozzle entrance region suffers form severe abrasive impact, 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 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-3 laminated nozzle compared with that of the CN-2 stress-free nozzle can be analysed in terms of the formation of compressive residual stresses both on the entry area and on the exit region. As calculated above, compressive residual

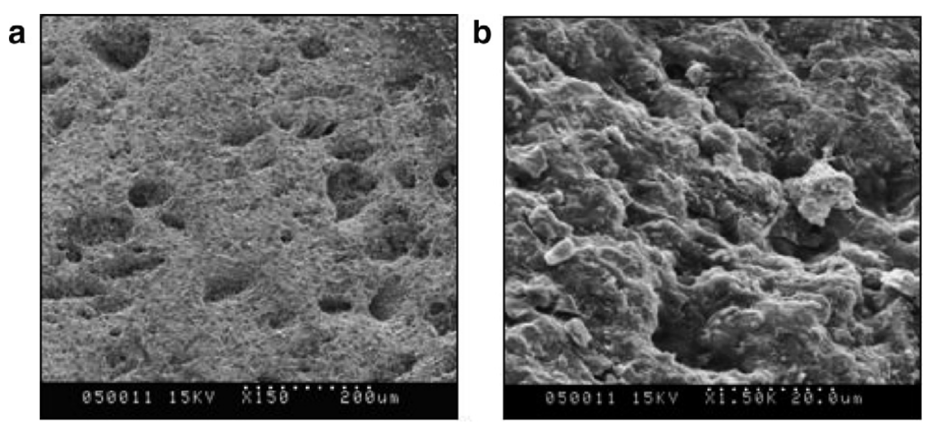

Fig. 13. SEM micrographs of the entry bore surface of the worn CN-2 stress-free ceramic nozzle.

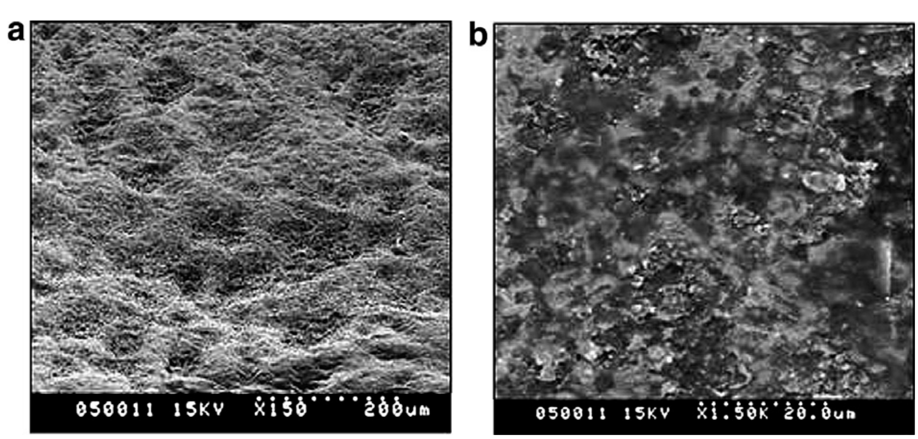

Fig. 14. SEM micrographs of the entry bore surface of the worn GN-3 laminated ceramic nozzle.

stresses were formed at the entry and exit region of the GN-3 laminated nozzle in fabricating process from sintering temperature to room temperature, which may partially counteract the tensile stresses in the nozzle entry and exit 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 laminated nozzle.

4. Conclusions

SiC/(W,Ti)C laminated ceramic nozzles were produced by hot pressing. The purpose is to reduce the tensile stress at the entry and exit area of the nozzle during sand blasting processes. Particular attention was paid to the erosion wear of this kind laminated ceramic nozzle. Results showed that the laminated ceramic nozzles have superior erosion wear resistance to that of homologous stress-free ceramic nozzle. The mechanism responsible was explained as the formation of compressive residual stresses both at the entry area and at the exit region of the laminated ceramic nozzle in fabricating process, which may partially counteract the tensile stresses resulting from external loadings. Laminated structure in ceramic nozzles is an effective way to improve the erosion wear resistance of the stress-free ceramic nozzles.

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References

[1] Li Guoying. Surface engineering. Beijing: Mechanical Industry Publishing House; 1998.
[2] Deng Jianxin, Lee Taichiu. Techniques for improved surface integrity and reliability of machined ceramic composites. Surface Engineering 2000;16(5):411–4.
[3] Raykowski A, Hader M. Blasting cleaning of gas turbine components: deposit removal and substrate deformation. Wear 2001;249: 127–32.
[4] Djurovic B, Jean E. Coating removal from fiber composites and aluminum using starch media blasting. Wear 1999;224:22–37.
[5] Oka YI, Ohnogi H. The impact angle dependence of erosion damage caused by solid particle impact. Wear 1997;203–204:573–9.
[6] Finnie I, Stevick GR, Ridgely JR. The influence of impingement angle on the erosion of ductile metals by angular abrasive particles. Wear 1992;152:91–7.
[7] Wellman RG, Allen C. The effect of angle of impact and material properties on the erosion rates of ceramics. Wear 1995;186–187:117–23.
[8] Srinivasan S, Scatterrgood RO. Effect of erodent hardness on erosion of brittle materials. Wear 1988;128:139–52.
[9] Shipway PH, Hutchings IM. The influence of particle properties on the erosive wear of sintered boron carbide. Wear 1991;149:85–98.
[10] Bahadur S, Badruddin R. Erosion particle characterization and the effect of particle size and shape on erosion, Proceedings of the international conference on wear of materials, ASME, New York, (1989): 143–53.
[11] Deng Jianxin. Erosion wear of boron carbide nozzles by abrasive air-jets. Materials Science Engineering A 2005;408(1–2):227–33.
[12] Deng Jianxin, Feng Yihua, Ding Zeliang. Wear behaviors of the ceramic nozzles in sand blasting treatments. Journal of the European Ceramic Society. 2003;23:323–9.
[13] Deng Jianxin, Zhang Xihua, Niu Pingzhang, et al. Wear of ceramic nozzles by dry sand blasting. Tribology International 2006;39(3): 274–80.
[14] Deng Jianxin. Sand erosion performance of B_4C/(W,Ti)C ceramic blasting nozzles. Advances in Applied Ceramics 2005;104:59–64.
[15] Deng Jianxin, Zheng Zhongcai, Ding Zeliang, et al. Erosion wear of ceramic and cemented carbide nozzles in dry sand blasting process. British Ceramic Transactions 2003;102:61–5.
[16] Wood RJK, Wheeler DW, Lejeau DC. Sand erosion performance of CVD boron carbide coated tungsten carbide. Wear 1999;233–235:134–50.
[17] Deng Jianxin, Ding Zeliang, Yuan Dongling. Erosion wear mechanisms of coal-water-slurry (CWS) ceramic nozzles. Materials Science Engineering A 2006;417(1–2):1–7.
[18] Ding Zeliang, Deng Jianxin, Li Jianfeng, et al. Wear behavior of ceramic nozzles in coal water slurry burning. Ceramics International 2004;34(4):591–6.
[19] Lakshminarayanan R, Shetty DK, Cutler RA. Toughening of layered ceramic composites with residual surface compression. Journal of American Ceramic Society 1996;79(1):79–87.
[20] Cai PZ, Green DJ, Messing GL. Mechanical characterization of Al_2O_3/ZrO_2 hybrid laminates. Journal of the European Ceramic Society 1998;5:2025–34.
[21] Tarlazzi A, Roncari E, Pinasco P, Guicciardi S, et al. Tribological behaviour of Al_2O_3/ZrO_2- ZrO_2 laminated composites. Wear 2000;244:29–40.
[22] Toschi F, Melandri C, Pinasco P, et al. Influence of residual stress on the wear behaviour of alumina/alumina–zirconia laminated composites. Journal of American Ceramic Society 2003;86(9):1547–53.
[23] Hillman C, Suo Z, Lange FF. Cracking of laminates subjected to biaxial tensile stress. Journal of American Ceramic Society 1996;79:2127.
[24] Marshall DB, Ratto JJ, Lange FF. Enhanced fracture toughness in layered microcomposites of Ce–ZrO_2 and Al_2O_3. Journal of American Ceramic Society 1991;74:2979.
[25] Sergo V, Lipkin DM, Portu GD, et al. Edge stresses in alumina/zirconia laminates. Journal of American Ceramic Society 1997;80(7):1633–8.
[26] Portu GD, Micele L, Sekiguchi Y, et al. Measurements of residual stress distributions in Al_2O_3/3Y-TZP multilayered composites by fluorescence and Raman microprobe piezo-spectroscopy. Acta Materialia 2005;53:1511–20.
[27] Portu GD, Micele L, Prandstraller D, et al. Abrasive wear in ceramic laminated composites. Wear 2006;260(9–10):1104–11.
[28] Deng Jianxin, Liu Lili, Li Jianfeng et al. Development of functionally gradient ceramic nozzle materials for sand blasting surface treatments. International Journal of Refractory Metals and Hard Materials, in press, corrected proof.