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Design, fabrication and performance of $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ multilayered ceramic nozzles

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ABSTRACT

$Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ multilayered ceramic nozzles (N1, N2, N3 and N4) with different thickness ratios among constituent layers were produced by hot-pressing. The value of the residual stress inside the layered nozzle during fabricating process was calculated by means of the finite element method. The mechanical properties at the surface layer of these layered materials were measured, the microstructure was examined. The wear behaviors of the multilayered nozzles were investigated and compared with an unstressed reference nozzle (N5). Results showed that the multilayered nozzles had superior erosion wear resistance to that of the stress-free one. The erosion wear resistance of the layered nozzles was influenced by the thickness ratio among constituent layers. The N4 nozzle with thickness ratio of two between adjacent layers exhibited higher erosion wear resistance over the N1, N2 and N3 nozzles.

1. Introduction

Laminated hybrid structures constituted by alternate layers with different compositions can be properly designed to induce a surface compressive residual stress [1–4]. The basic idea is to couple material layers with different thermal expansion coefficients (CTE) so that residual stresses arise during cooling from the sintering temperature. Residual stresses arise from a mismatch between the 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 [5–8]. The design of ceramic laminates has been proved to be a viable strategy to obtain significant increases of the fracture resistance of ceramic materials. The effectiveness of laminated structures in improving the tribological properties has been also reported [9,10]. Toschi et al. [11] reported that laminated hybrid structures can improve the sliding wear resistance of alumina. de Portu et al. [12] showed that laminated structures with compressive residual stresses within the surface regions were a suitable way to obtain composite materials with superior tribological properties.

The nozzle entrance section suffers severe abrasive impact, and generates the largest tensile stress. The stresses along the axial direction of the nozzle decreases from entry to center, and increases from center to exit. The highest tensile stresses are located on the entry section of the nozzle [13,14]. In the author's previous studies [15–18], the idea of laminated structures was firstly introduced to the design of ceramic nozzles so as to form compressive residual stresses at the nozzle entry (or exit) region in fabricating process, which may partially counteract the tensile stresses resulting from external loadings. Results showed that laminated structures in SiC/(W, Ti)C nozzle can induce an excess residual stress in the nozzle during fabricating process, and this residual stress at the nozzle entry zone is compressive whatever the sintering temperature [16]. This kind of compressive residual stress can result in an improved erosion wear resistance of the laminated nozzle compared with the homologous stress-free one.

In the present study, $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ multilayered ceramic nozzles with different thickness ratios among constituent layers were produced by hot-pressing in order to induce a compressive residual stress both at the entry and at the exit regions. The residual stress inside the layered nozzles during the sintering process was calculated by means of the finite element method (FEM). The mechanical properties at the surface layers of the layered materials were measured, the microstructure was examined. The wear behaviors of the multilayered nozzles were investigated and compared with an unstressed reference nozzle. Particular attention was paid to the effect of thickness ratio among constituent layers on the wear behaviors of $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ multilayered nozzles.

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2. Materials and experimental procedures

2.1. Preparation of the $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ layered ceramic nozzles

The dimension and compositional distribution of the layered ceramic nozzles with different thickness ratios among constituent layers are shown in Fig. 1. These nozzles possess a three-layer symmetrical structure. The composition at the nozzle entry and exit is Al_2O_3/45 vol.% $(W_{0.7}Ti_{0.3})C$, while the composition at the nozzle center area is Al_2O_3/55 vol.% TiC. Four layered nozzles with different thickness ratio p ($p = A_1/A_2$) among constituent layers were produced. The layered nozzles with the thickness ratio of 0.2, 0.5, 1 and 2 are named N1, N2, N3 and N4, respectively (see Fig. 1).

The starting powders used to fabricate the layered nozzles are listed in Table 1 with their physical properties. 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 composite powders with different mixture ratios were layered into the graphite mould in turn. The sample was then hot-pressed in flowing nitrogen for 15 min at 1700 °C temperature with 30 MPa pressure. For the purpose of comparison, a homologous stress-free ceramic nozzle was also manufactured by hot-pressing. This stress-free nozzle made from Al_2O_3/45 vol.% $(W_{0.7}Ti_{0.3})C$ is named N5.

2.2. Abrasive air-jet machining

The erosion wear tests were conducted with a GS-6 type abrasive air-jet machining machine tool [14]. The compressed air pressure was set at 0.4 MPa. The erodent abrasives used were of Al_2O_3 powders with 150–250 μm grain size. The mass loss of the worn ceramic nozzle was measured with a balance (minimum 0.01 mg). Nozzles with internal diameter 8 mm and length 30 mm made from layered structure (N1, N2, N3 and N4) and stress-free structure (N5) were manufactured by hot-pressing. All the test conditions are listed in Table 2.

The erosion rates (W) of the nozzles are defined as the nozzle mass loss (m_1) divided by the nozzle density (d_1) times the mass of the erodent abrasive particles (m_2):

$$W = m_1/(d_1 \cdot m_2) = V_1/m_2 \quad (1)$$

where V_1 is the nozzle volume loss, 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 within the layered 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 surface of the nozzles was examined by scanning electron microscopy (SEM).

3. Results and discussion

3.1. Residual stress in the $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ layered nozzle

The residual stress of the layered ceramic nozzles during fabricating process was calculated by means of the finite element method by assuming that the compact is cooled from sintering temperature 1700 °C to room temperature 20 °C. The physical properties of Al_2O_3, $(W_{0.7}Ti_{0.3})C$ and TiC are listed in Table 1.

Owing to the symmetry, an axisymmetric calculation was preferred. Presume that it was steady state boundary condition. The results of the distribution of axial (σ_z) and radial (σ_r) residual stresses in the N2 layered nozzle in fabricating process from sintering temperature 1700 °C to room temperature 20 °C is shown in Fig. 2. It is indicated that an excess residual stress is formed both at the entry and the exit of the layered nozzle.

Layered structures constituted by alternate layers with different compositions can be properly designed to induce a surface compressive residual stress. These residual stresses mainly arise from a mismatch between the coefficient of thermal expansion (CTE) of the constituent layers, and are influenced by the thickness ratio among layers [5–8]. Compressive residual stresses are induced in layers with lower CTE, while tensile stresses arise in those with higher CTE. As for $Al_2O_3/(W_{0.7}Ti_{0.3})C + Al_2O_3/TiC$ layered material, the CTE of $Al_2O_3/(W_{0.7}Ti_{0.3})C$ is $7.2 \times 10^{-6}\,K^{-1}$ and the CTE of Al_2O_3/TiC is $8.0 \times 10^{-6}\,K^{-1}$. That is to say, the thermal expansion coefficient of the entry section (surface layer) of the layered nozzle is lower than that of the center layer, so that compressive residual stresses will be formed in the nozzle entry region during fabricating process.

Fig. 3 shows the residual stresses (σ_z and σ_r) inside the N1, N2, N3 and N4 layered nozzles at the inner-hole surface along the nozzle axial direction in fabricating process. It is indicated that σ_z and

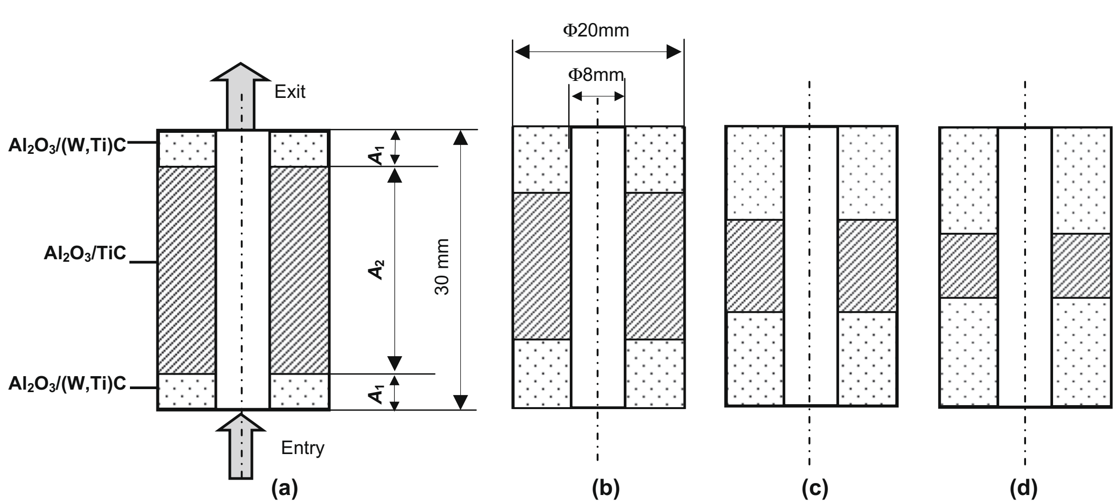

Fig. 1. Dimension and compositional distribution of the layered ceramic nozzles with different thickness ratios among constituent layers, (a) N1 nozzle ($p = 0.2$), (b) N2 nozzle ($p = 0.5$), (c) N3 nozzle ($p = 1$) and (d) N4 nozzle ($p = 2$).