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Sand erosion performance of SiC/(W,Ti)C gradient ceramic nozzles by abrasive air-jets

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Abstract

A SiC/(W,Ti)C ceramic nozzle with gradient structures was produced by hot pressing. The purpose is to reduce the tensile stress at the entry region of the nozzle in abrasive air-jet. The sand erosion performance of this kind gradient ceramic nozzle caused by abrasive particle impact was investigated by abrasive air-jets in comparison with the common one. 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; Erosion wear; Gradient materials

1. Introduction

Abrasive air-jet (or sand blasting) is the use of abrasive material for the surface treatments [1,2], such as: surface strengthening, surface modification, surface smoothing or roughening, surface clearing or rust removal, surface texturizing, etc. In abrasive air-jet processes, fine particles are accelerated in a gas stream commonly air at a few times atmospheric pressure. The particles are directed towards surfaces need to be machined. 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 abrasive air-jet equipment. There are many factors [3–6] that influence the nozzle wear such as: the nozzle material and its geometry, the mass flow rate and impact angle, and the erodent abrasive properties. Several studies [7,8] 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 abrasive air-jet, the nozzle entry region suffers form severe abrasive impact, and generates large tensile stress [7,8]. 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, which may cause subsurface lateral cracks and facilitates removal of material chips. 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.

Silicon carbide (SiC) is one of the most useful ceramics in modern engineering applications because of its high hardness, high wear resistance, high melting point, good chemical inertness, high Young's modulus and thermal conductivity

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as well as high thermal shock resistance; that make it promising candidates for wear resistance components. Compared with the ceramics such as Si_3N_4, ZrO_2, etc., the strength and fracture toughness of monolithic SiC ceramic material is rather lower. Moreover, the poor sinterability of SiC limits its application because both high temperature and high pressure are required for a complete densification. In earlier studies [9–11], some of the SiC-based-composites have been developed and used in various applications, mechanical properties and microstructure studies on them are also extensively carried out. It has been shown that the additions of secondary phases to SiC matrix can improve its mechanical properties, i.e. fracture toughness and flexural strength.

Functionally graded materials (FGMs) are materials that comprise a spatial gradation in structure and/or composition, tailored for a specific performance or function. Close attention has been paid to FGMs worldwide for their novel design ideas and outstanding properties since 1980s. Various FGMs have turned up continuously as a result of the introduction of the FGM concept into the fields of nuclear power, optics, and mechanical engineering. For example, a compositionally graded approach has been applied to Co–WC, TiC–Ni–Mo, and diamond–SiC materials systems, and these have been shown to exhibit superior wear resistance compared to monocomposition materials [12]. Cutting tools typically require the exterior to be hard and the interior to be tough and strong. The concept of FGMs has been introduced in the design of graded cutting tools, and it has been shown that resistance to wear may be achieved by appropriately grading the composition of the tools [13]. The compositional gradient for wear resistance materials should be designed with two objectives in mind [12–14]. First, the material with highest hardness should be at the surface to maximize hardness there. Second, if it is processed at an elevated temperature, the material with the lowest thermal expansion should be at the surface so that upon cooling, compressive stresses develop, thereby increasing the effective hardness.

From this point of view, formation of compressive residual stresses in the entry region of the ceramic nozzle should taken as the aim to relax stresses resulting from external loadings in abrasive air-jet. In the present study, a SiC/(W,Ti)C ceramic nozzle with gradient structures was produced by hot pressing. The purpose is to reduce the tensile stress at the entry region of the nozzle in abrasive air-jet. The sand erosion performance of this gradient ceramic nozzle was investigated in comparison with the common ceramic nozzles.

2. Materials and experimental procedures

2.1. Preparation of SiC/(W,Ti)C 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%. Different volume fractions of (W,Ti)C (50, 55, 60, 65, 70, and 75 vol%) were selected in designing the SiC/(W,Ti)C gradient nozzle material with a six-layer structure.

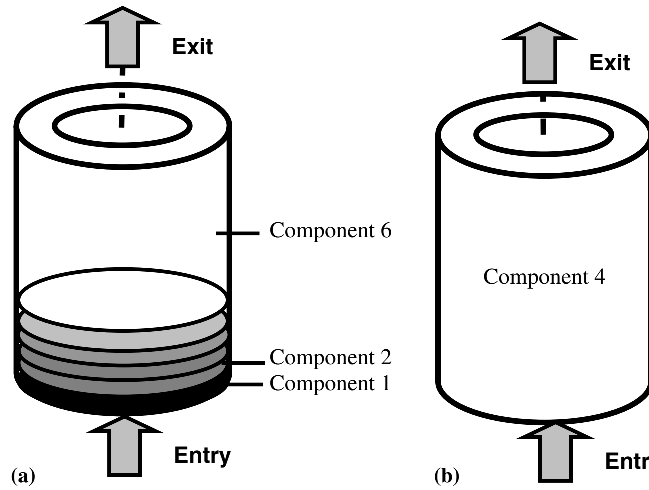

Fig. 1. Compositional distribution of: (a) SiC/(W,Ti)C gradient ceramic nozzle, and (b) common SiC/(W,Ti)C ceramic nozzle.

The compositional distribution of the gradient ceramic nozzle is shown in Fig. 1(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 (50 vol%) 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 (25 Vol. %). While the common nozzle (SiC/65 vol%(W,Ti)C) with no compositional change is shown in Fig. 1(b).

Six SiC/(W,Ti)C composite powders with 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 30 MPa pressure. This ceramic nozzle with gradient structures is named GN-1, while the common ceramic nozzle with no compositional change is named CN-1.

2.2. Abrasive air-jets

Erosion wear tests were conducted with a GS-6 abrasive air-jet machine tool. The schematic diagram of this equipment is shown in Fig. 2. The compressed air pressure was set at 0.4 MPa. The erodent abrasives were of silicon carbide (SiC) powders with 50–80 μm grain size. Nozzles with internal diameter 8 mm and length 30 mm made from SiC/(W,Ti)C common and SiC/(W,Ti)C gradient were manufactured by hot pressing as can be seen in Fig. 3. Since the test parameters were kept constant, wear of ceramic nozzles should only depend on the nature of the nozzle materials. The entry and exit bore diameter variation of the nozzle were measured with an optical microscopy. All the test conditions are listed in Table 1.

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

3. Results and discussion

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

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