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Layered structures in ceramic nozzles for improved erosion wear resistance in industrial coal-water-slurry boilers

Deng Jianxin[a,*], Yun Dongling[a], Zhou Houmin[b], Tan Yuanqiang[b]

[a] School of Mechanical Engineering, Shandong University, Jinan 250061, Shandong Province, PR China
[b] School of Mechanical Engineering, Xiangtan University, Xiangtan 411105, Hunan Province, PR China

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Abstract

The nozzle is the most critical part in the coal-water-slurry (CWS) boilers. Ceramics being highly wear resistant have great potential as CWS nozzle materials. In this paper, $Al_2O_3/(W,Ti)C + Al_2O_3/TiC$ layered ceramics (LN1, LN2, and LN3) with different thickness ratios among constituent layers were developed to be used as nozzles in CWS boilers. CWS burning tests in a boiler with these nozzles were carried out. The erosion wear behavior of the layered nozzles was investigated and compared with an unstressed reference nozzle (N5). Results showed that the layered ceramic nozzles exhibited an apparent increase in erosion wear resistance over the unstressed reference one. The mechanisms responsible were found to be that layered structure in the CWS nozzles can improve the hardness and fracture toughness of the external layer, and reduce the temperature gradients and the thermal stresses at the exit of the nozzle during CWS burning processes. It is suggested that layered structures in ceramic nozzles is an effective way to improve the erosion wear resistance over the stress-free ceramic nozzles in industrial CWS boilers.

Keywords: Nozzles; Ceramic materials; Residual stress; Layered materials; Slurry erosion

1. Introduction

The nozzle is the most critical part in a coal-water-slurry (CWS) burning system. During CWS burning processes, the nozzle is eroded continuously by the abrasive action of CWS, the working environmental temperature of nozzle can reach up to 1000 °C, and there is a very high temperature gradient inside nozzle [1,2]. Therefore, the nozzles in the CWS boiler must have high hardness, and good erosion and thermal shock resistance. In the author's previous studies [1,2], several ceramic composites were produced by hot-pressing for use in CWS nozzles. Detailed observations and analyses of the nozzle wear surface have revealed that the primary wear mechanisms of the CWS ceramic nozzle exhibited thermal shock damage with chipping at the nozzle exit. Greater temperature gradient and higher thermal stress were found to be the main reason that caused the failure of the nozzle exit.

Layered structures constituted by alternate layers with different compositions can be properly designed to induce a surface compressive residual stress [3–6]. 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 [7–9]. The design of layered ceramics has been proved to be a viable strategy to obtain significant increases of the fracture resistance, wear resistance, and tribological properties [10–12].

The idea of layered structures was first introduced to the design of sand-blasting ceramic nozzles so as to form compressive residual stresses at the nozzle entry (or exit) region in fabrication process, which may partially counteract the tensile stresses resulting from external loadings [13–15]. Results showed that layered structures in ceramic nozzle can induce an excess residual stress in the nozzle during fabrication,

* Corresponding author at: School of Mechanical Engineering, Shandong University, Jinan 250061, Shandong Province, PR China.
Tel.: +86 531 88392047.
E-mail address: jxdeng@sdu.edu.cn (J. Deng).

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and this residual stress is compressive whatever the sintering temperature. This kind of compressive residual stress can result in an improved erosion wear resistance of the layered ceramic nozzle compared with the homogeneous stress-free one in sand-blasting processes [13–15].

Al_2O_3/(W,Ti)C and Al_2O_3/TiC ceramics are widely used in industrial applications such as cutting tools and dies [16–18], they both have high hardness and wear resistance. These two materials have different thermal expansion coefficients; and different shrinkage during sintering. The thermal expansion coefficient (CTE) of Al_2O_3/(W,Ti)C is $7.2 \times 10^{-6}\ K^{-1}$, and the CTE of Al_2O_3/TiC is $8.0 \times 10^{-6}\ K^{-1}$ [16–18]. These differences are sufficient to induce residual stresses in the laminated structures, and compressive residual stresses are induced in the layers with lower CTE. As for Al_2O_3/(W,Ti)C + Al_2O_3/TiC layered ceramic material, the CTE of the surface layer (Al_2O_3/(W,Ti)C) is lower than that of the center layer (Al_2O_3/TiC), so compressive residual stresses will be formed in the surface layer of the layered materials during fabrication. In the present study, Al_2O_3/(W,Ti)C + Al_2O_3/TiC layered ceramics with different thickness ratios among constituent layers were produced to be used as the CWS nozzles. The mechanical properties at the surface layers of the layered materials were measured, and the micro-structure was examined. The wear behaviors of the layered ceramic nozzles were investigated and compared to an unstressed reference nozzle. The purpose was to characterize the erosion wear of the layered ceramic nozzle in industrial CWS boilers.

2. Materials and experimental procedures

2.1. Preparation of the Al_2O_3/(W,Ti)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 or exit is Al_2O_3/45 vol.%(W,Ti)C, while the composition at the nozzle center area is Al_2O_3/55 vol.%TiC. Three 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, and 1 are named LN1, LN2, and LN3, 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. Following drying, the composite powders with different mixture ratios were layered into a graphite mould. 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 homogeneous stress-free ceramic nozzle was also manufactured by hot-pressing. This stress-free nozzle made from Al_2O_3/45 vol.%(W,Ti)C is named N5.

2.2. Hardness and fracture toughness measurements at surface layer of the layered nozzle materials

Fracture toughness measurement was performed using indentation method at the nozzle external layer (entry or exit) in a hardness tester (MH 6) using the formula proposed by Cook and Lawn [19]. Hardness measurements were performed by placing Vickers indentations on external layer of the layered nozzle material. The indentation load was 200 N and a minimum of five indentations were tested. The Vickers hardness (GPa) is given by:

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

where P is the indentation load (N), $2a$ is the catercorner length (μm) due to indentation.

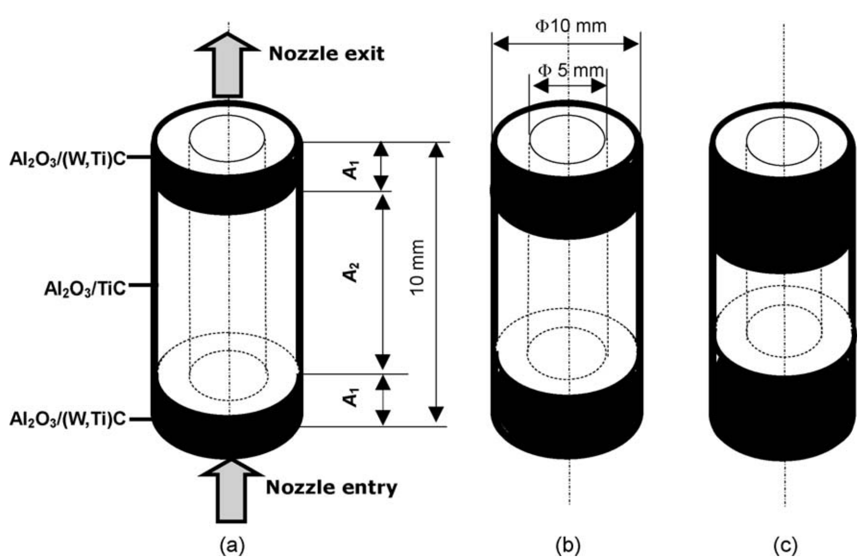

Fig. 1. Compositional distribution of the layered ceramic nozzles with different thickness ratio among constituent layers: (a) N1 nozzle ($p = A_1/A_2 = 0.2$), (b) N2 nozzle ($p = 0.5$), and (c) N3 nozzle ($p = 1$).