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Wear behavior of ceramic nozzles in coal water slurry burning

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Abstract

In this paper, Al_2O_3/(W,Ti)C ceramic composite and WC/Co cemented carbide were prepared for the use of nozzle materials in coal water slurry (CWS) burning. The wear behavior of nozzles made from these materials was compared by determining the cumulative volume loss and the erosion rates. Results showed that the hardness of the nozzles plays an important role with respect to its erosion wear in CWS burning processing. The Al_2O_3/(W,Ti)C nozzles possessing high hardness exhibited lower erosion rates, while the WC/Co cemented carbide nozzles with a low hardness showed higher erosion rates under the same test conditions. Examination of eroded bore surface of the nozzles showed that wear of the WC/Co cemented carbide nozzle occurred by a preferential removal of the metal binder followed by pluck out of the exposed WC grains, while the primary wear mechanisms of Al_2O_3/(W,Ti)C ceramic nozzle exhibited polishing action in the hole and thermal shock damage with chipping at the bore exit.

Keywords: Ceramic nozzles; Erosion wear; Coal water slurry; Wear behavior

1. Introduction

Coal water slurry (CWS) has been developed more than 20 years as a new coal fuel and a substitute for oil mainly in industry boilers. They are also a considerable potential for gasification applications. And now, CWS has been successfully applied around the world in various boilers for power generation, petroleum, chemical and metallurgical industries, etc. The attraction of the CWS is its complete independence of an oil supply. CWS can be stored without the danger of a coal dust explosion and burned in a similar way to heavy fuel oil in existing oil fired equipments with a few modifications, and can be transported in pipeline, leading to reduction in transportation costs and pollution compared to coal [1–5].

CWS is consisted of 60–70 wt.% coals (ranged from 40 to 120 μm), 30–40 wt.% water and about 1 wt.% additives, and contains high hardness minerals such as: iron pyrites, quartz, etc. The hardness of these materials can be up to Hv 2500 [1]. CWS can be regarded as an admixture of soft abrasives and hard abrasive [1]. In CWS burning process, the nozzle is eroded continuously by the abrasive action of CWS, and the working environmental temperature of nozzle can reach up to 1000 °C [1]. Also, there is a very high temperature gradient inside nozzle. So the nozzle is subjected to low angle of sliding impingement and thermal shock of CWS [1]. The nozzle materials in CWS burning must have good erosion, oxidation and thermal shock resistance. The nozzle is the most critical part in a CWS atomizing and burning system.

Ceramics have intrinsic characteristics, such as: high melting point, high hardness, good chemical inertness and high wear resistance, that make them promising candidates for high temperature structural materials and wear resistance materials, in situations where metallic components do not achieve satisfactory service lives, owing to inadequate heat and wear resistance. The industrial applications of advanced ceramics include nozzles, dies, cutting tools, drawing or extrusion, seal rings, valve seats, bearing parts, and a variety of engine parts, etc. In this study, Al_2O_3/(W,Ti)C ceramic composite were produced for the use of CWS nozzle materials.

There are many factors that influence the CWS nozzle wear such as: material properties, microstructure, nozzle geometry, the mass flow rate and temperature [6–10], etc. Various studies have already been published on the erosion behavior and mechanisms of ceramic materials such as in sandblasting surface treatment, water-jet cutting, abrasive

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air-jet machining [11–17] etc., in recent years. Little work has been published in the literature on the wear behavior of ceramic nozzle in coal water slurry burning. The aims of the present investigation were to characterize the effect of the properties and microstructure on the wear behaviors of ceramic nozzles in coal water slurry atomizing and burning system.

2. Materials and experimental procedures

2.1. Preparation of the nozzle materials

The materials used for the nozzles in the present investigation were hot-pressed Al_2O_3/45%(W,Ti)C ceramic composites fabricated by the authors (see Table 1) and WC/Co cemented carbide (YG8), a traditional wear resistant material.

The average particle size of Al_2O_3 starting powders was less than 0.8 μm, and additions of (W,Ti)C particles (average particle size 1.0 μm) were added to Al_2O_3 to form composite with the characteristics listed in Table 1. The combined powders were prepared by wet ball milling in alcohol with cemented carbide balls for 80 h. Following drying, final densification to produce a ceramic disks was accomplished by hot pressing using a sintering temperature in the range of 1650–1850 °C at a pressure of 36 MPa in argon atmosphere for 8–30 min.

Densities of the hot-pressed ceramics and cemented carbide were measured by the Archimedes's method. Test pieces of 3 mm × 4 mm × 36 mm were prepared from the disk by cutting and grinding using a diamond wheel and were measured to determine the flexural strength, Vickers hardness and fracture toughness. A three-point bending mode was used to measure the flexural strength over a 30 mm span at a crosshead speed of 0.5 mm/min. Fracture toughness measurement was performed using indentation method in a hardness tester (ZWICK3212) using the formula proposed by Cook and Lawn [18]. On the same apparatus the Vickers hardness was measured on polished surface with a load of 98 N.

2.2. Coal water slurry burning tests

Coal water slurry burning tests were conducted with a DNS2-1.0-SM boiler (made in China). The schematic diagram of this equipment is shown in Fig. 1. In this test apparatus, the CWS drawn by pump passed through pipeline, accelerated and mixed in the spray-gun (nozzle) by gas stream commonly compressed air (see Fig. 2a). The atomizing air pressure was set at 0.4 MPa, and CWS pressure was set at 0.2 MPa.

Nozzles (see Fig. 2b) with internal diameter 4.5 mm and length 15 mm made from Al_2O_3/(W,Ti)C and WC/Co were manufactured using hot-pressing techniques. The properties of the CWS used in this study are listed in Table 1. Since the

Table 1
Properties of the coal water slurry

Consistency (%)	Quantity of heat (MJ/kg)	Ash (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, FeS_2, K_2O, Na_2O) (%)	Sulfur (%)	Volatility (%)	Adhesiveness (MPa s)	Grit number (μm)
65 ± 2	18.81–20.48	<12	<0.8	>15	1000–2500	40–80

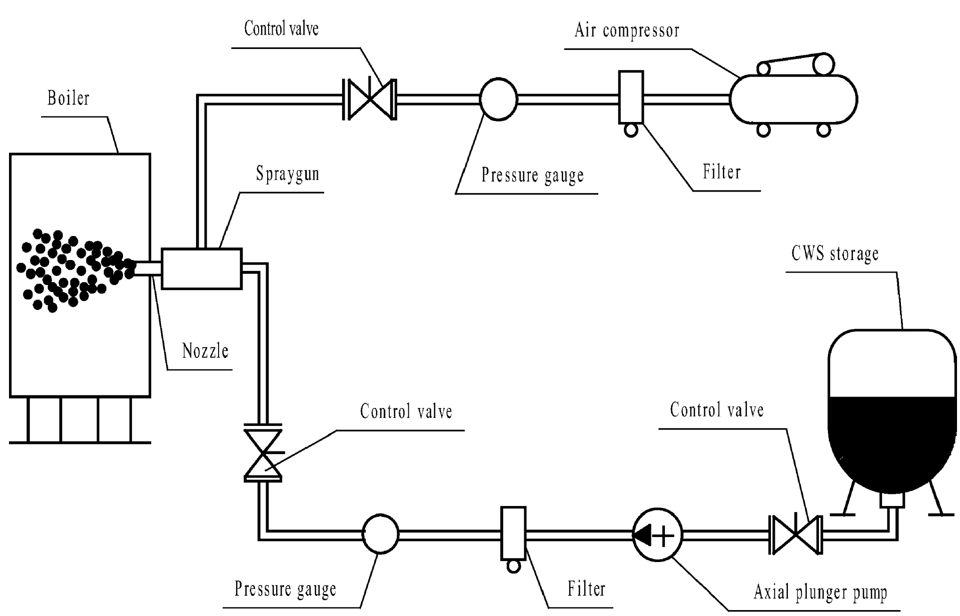


Fig. 1. Schematic diagram of the coal water slurry burning equipment.

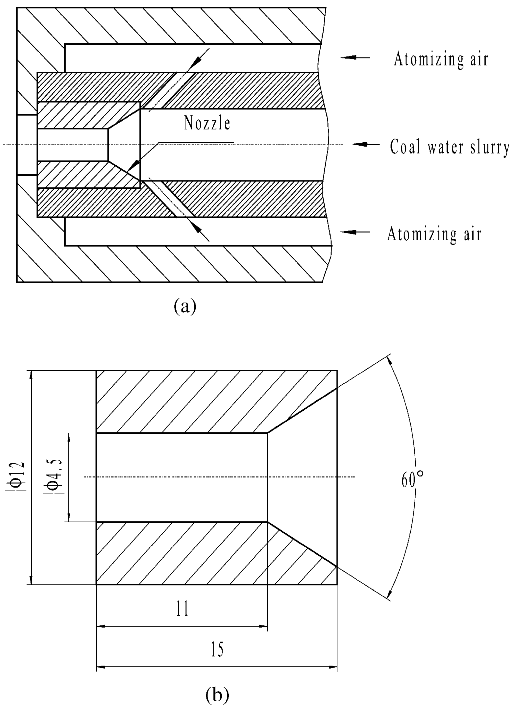


Fig. 2. (a) Schematic diagram of the spray-gun, (b) geometry and dimensions of the nozzle insert in the spray-gun.

test parameters were kept constant, wear of nozzles should only depend on the properties and microstructure of the nozzle materials.

The mass loss of the worn nozzles was measured with an accurate electric balance (minimum 0.01 mg). The erosion rates (W) of the nozzles are defined as the nozzle mass loss (m_1) divided by the nozzle density (d) times the burn mass of CWS (m_2).

$$W = \frac{m_1}{d \times m_2}$$

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

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.

3. Results and discussion

Data for density, hardness, flexural strength, fracture toughness, thermal expansion coefficient, and thermal conductivity of Al_2O_3/(W,Ti)C ceramic composite and WC/Co cemented carbide are listed in Table 2. Fig. 3a shows the SEM micrograph of the fracture surface of Al_2O_3/(W,Ti)C ceramic composite. It can be seen that Al_2O_3/(W,Ti)C composite showed mainly an intergranular fracture mode. The grain sizes were ranged from 0.5 to 1.5 μm. Typical SEM micrograph of the fracture surface of WC/Co cemented carbide is shown in Fig. 3b. From this SEM micrograph, the fracture mode was mixed transgranular and intergranular.

Fig. 4 shows the variation of cumulative volume loss with the operation time for Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles in CWS burning process. It can be seen that the cumulative volume loss continuously increased

Table 2
Composition and mechanical properties of the nozzle materials

Code name	Compositions (vol.%)	Flexural strength, σ_f (MPa)	Fracture toughness, K_{IC} (MPa m$^{1/2}$)	Hardness, Hv (GPa)	Density, d (g/cm^3)	Thermal expansion, α (10^{-6} K^{-1})	Thermal conductivity, λ (W/m K)	Elastic modulus E, (GPa)	Poisson ratio, ν	Thermal shock resistance parameter, R (K)
SG4	Al_2O_3/45%(W,Ti)C	850	4.9	21.5	6.64	7.25	29.5	448	0.23	201
YG8	WC/8%Co	1500	14.5	14.8	14.8	4.5	75.4	600	0.26	411

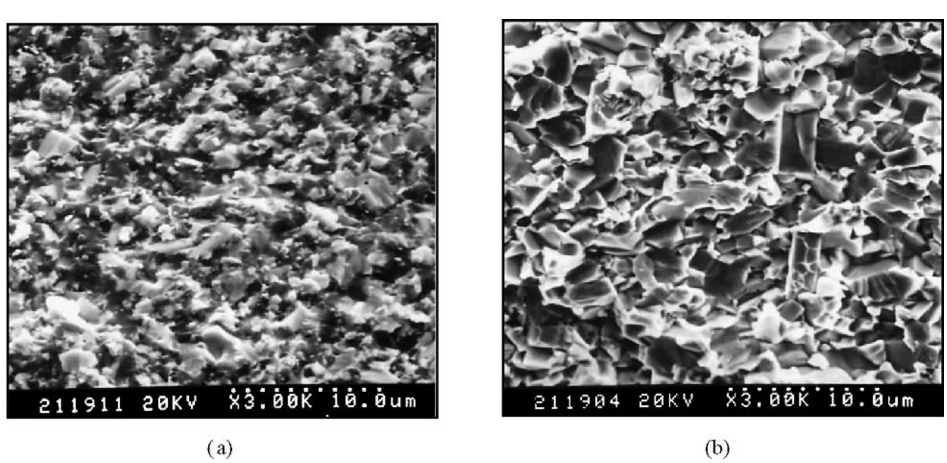


Fig. 3. SEM micrographs of the fracture surface of (a) Al_2O_3/(W,Ti)C ceramic nozzle, and (b) WC/Co cemented carbide nozzle.

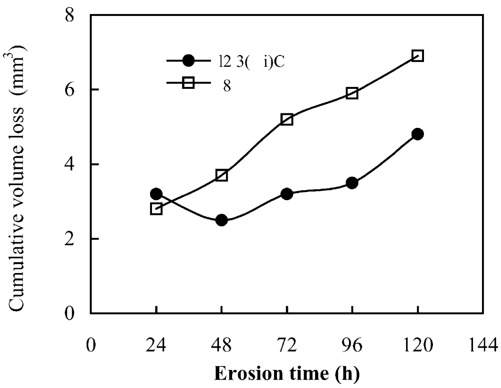


Fig. 4. Cumulative volume loss of CWS nozzle with the operation time.

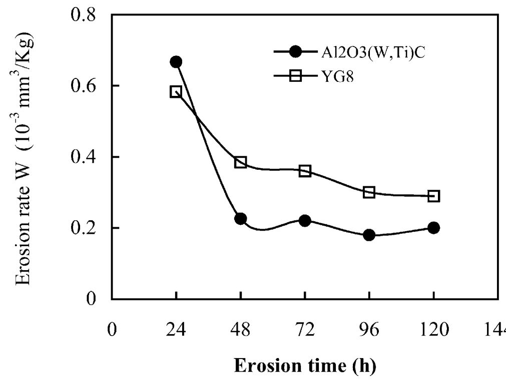


Fig. 5. Variation of CWS nozzle erosion rates with the operation time (a) Al_2O_3/(W,Ti)C nozzle, (b) WC/Co nozzle.

within the operation time for both the nozzle materials. The cumulative volume loss of the WC/Co cemented carbide nozzle is higher than that of the Al_2O_3/(W,Ti)C ceramic nozzle under the same test conditions. The Al_2O_3/(W,Ti)C ceramic nozzle showed a little increase in cumulative volume loss at 24 h operation, while the cumulative volume loss for WC/Co cemented carbide nozzle increased steadily with the operation time.

Fig. 5 shows the variation of erosion rates with the operation time for Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles in CWS burning process. The erosion rates showed a significant decrease up to 48 h operation, and within further 80 h operation it almost remains constant both for Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles. The Al_2O_3/(W,Ti)C ceramic nozzles possessing with high hardness and low fracture toughness had smaller erosion rates, while the WC/Co cemented carbide nozzles with high fracture toughness and low hardness showed higher erosion rates. Under the same test conditions, Al_2O_3/(W,Ti)C ceramic nozzle performed better than the WC/Co cemented carbide nozzle by a factor of 1.4. This can be explained by the high hardness of the Al_2O_3/(W,Ti)C nozzles and the low angle impact in this CWS burning process.

Fig. 6a and b shows the SEM micrographs of the nozzle exit bore profiles for worn Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles. It can be seen that the exit bore profile of the worn Al_2O_3/(W,Ti)C ceramic nozzle appeared to be entirely brittle in nature with the evidence of large scale-chipping (Fig. 6a), and exhibited a brittle fracture induced removal process, suggesting that brittle fracture was the main method of material removal. As there is a high temperature gradient inside nozzle during the CWS burning processes, and which may cause severe thermal stresses. High temperature gradient inside ceramics often yields an instantaneous thermal stress, which is, in some case, sufficient to cause considerable cracking damage or even catastrophic failure [19,20].

High temperature gradient can weaken the fracture strength of the material significantly, and the presence of the thermal stress is the primary reason for decrease in the strength. The tensile stress on the surface by the thermal shock is given by:

$$\sigma_t = \frac{\alpha E(1-\nu)}{\Delta T} \quad (1)$$

where σ_t is the tensile stress on the surface by the shock, α is the thermal expansion coefficient, E is the elastic modulus, ν is the Poisson ratio, ΔT is the temperature difference. In general, the strength of ceramics remains constant until the temperature difference reaches a critical value (ΔT_c).

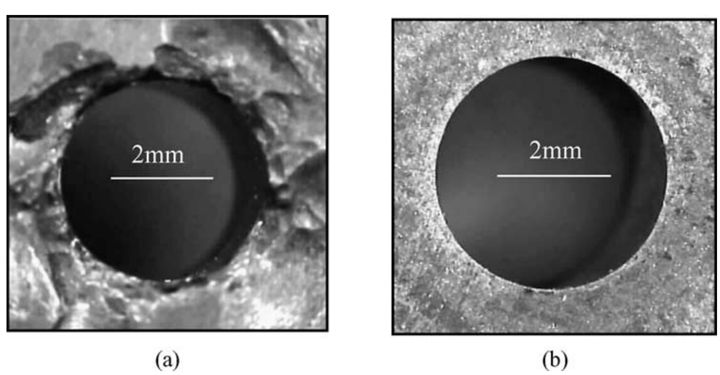
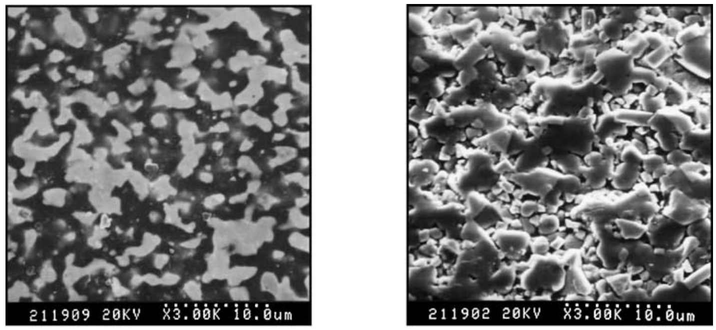


Fig. 6. Photographs of the exit bore surfaces of the worn nozzles. (a) Al_2O_3/(W,Ti)C nozzle, (b) WC/Co nozzle.



(a) (b)

Fig. 7. SEM micrographs of the worn bore surfaces of CWS nozzles. (a) Al_2O_3/(W,Ti)C nozzle, (b) WC/Co nozzle.

Therefore, ΔT_c is often used to characterize the thermal shock behavior of ceramics and is represented by [21–23]:

$$R = \frac{\sigma(1-\nu)}{\alpha E} \tag{2}$$

where R is the thermal shock resistance parameter, σ is the tensile strength. Higher R represents greater resistance to the initiation of fracture under rapid temperature difference. The damage of ceramics subjected to temperature gradient environments is a major limiting factor in relation to service requirements and lifetime performance. Repetitive thermal shock also results in thermal fatigue, which has a significant effect on the life of ceramic nozzles.

The results of the calculated thermal shock resistance parameter (R) for Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles are given in Table 2. It can be seen that the thermal shock resistance parameter (R) for WC/Co cemented carbide is much higher than that of the Al_2O_3/(W,Ti)C ceramic. Therefore, the exit bore fracture of Al_2O_3/(W,Ti)C ceramic nozzle may be attributed to its low thermal shock resistance and fracture toughness. At the beginning (24 h), the cumulative volume loss and erosion rate of Al_2O_3/(W,Ti)C ceramic nozzles is higher than that of WC/Co cemented carbide nozzle (Figs. 4 and 6), the presence of the thermal stress owing to the high temperature gradient inside the nozzles during the CWS burning processes may be the primary reason. After 24 h operation, the wear mode changes from severe brittle fracture to sliding erosion.

Fig. 7 shows the SEM micrographs of the worn bore surfaces of the Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles respectively. From these SEM micrographs, different morphologies and fracture modes of the Al_2O_3/(W,Ti)C ceramic and WC/Co cemented carbide nozzles can be seen clearly. The wear surface of Al_2O_3/(W,Ti)C nozzle is very smooth, the micro-structure can be seen clearly. In this structure, the "white" phase with clear contrast is (W,Ti)C, and the gray phase is Al_2O_3. It can be seen that the (W,Ti)C second phase was uniformly distributed with the Al_2O_3 matrix, and there were few second phase agglomerates or matrix-rich regions. Since the erodent particles in CWS were much softer than the Al_2O_3/(W,Ti)C ceramic, sliding abrasive particles in the CWS acted as a polishing process on the bore surface. It is suggested that the primary wear mechanisms of Al_2O_3/(W,Ti)C ceramic nozzles under these conditions is polishing by the abrasive particles.

Characteristic SEM picture taken on the center bore surface of the WC/Co cemented carbide nozzle was showed in Fig. 7b. It can be seen that the appearance of the eroded areas of the WC/Co cemented carbide nozzle showed a relative rough surface in contrast to that of Al_2O_3/(W,Ti)C ceramic nozzles, with obvious cavities of varying diameter and morphology and molten-looking bumps features characteristic for these nozzles can be seen. The sliding abrasives of CWS impact the bore surface of the WC/Co cemented carbide nozzle that results in slight displacement of the metal grains in WC/Co cemented carbide in each collision and consequent gradual extrusion of the binder material. At the same time, the binder Co with low melting point became softer and softer, and was eroded by the hard grains of CWS under the high temperature environment. Small metal grains spall off and result in lots of cavities located on the nozzle entry bore surface. The erosion mechanism appeared to be a preferential removal of the metal binder followed by pluck out of the undermined WC grains, probably in a grain-by-grain mode. No signs of ploughing were found.

4. Conclusions

Al_2O_3/(W,Ti)C ceramic composite and WC/Co cemented carbide nozzles were produced using hot pressing techniques. The wear behavior of these nozzles in coal water slurry burning processes was investigated. Results showed that:

1. The hardness of the nozzles plays an important role with respect to its erosion wear in coal water slurry burning processes. The Al_2O_3/(W,Ti)C ceramic nozzles being with high hardness exhibited lower erosion rates, while the WC/Co cemented carbide nozzles with relative low hardness showed higher erosion rates under the same test conditions.

2. Examination of eroded bore surface of the nozzles showed that wear of the WC/Co cemented carbide nozzle occurred by a preferential removal of the metal binder followed by pluck out of the exposed WC grains, while the primary wear mechanisms of Al_2O_3/(W,Ti)C ceramic nozzle exhibited polishing action in the hole and thermal shock damage with chipping at the bore exit.

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