Study of erosion wear behavior of MgO stabilized ZrO₂ ceramics due to solid particles impact at elevated temperature

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Erosion wear behavior of MgO stabilized ZrO₂ (MgSZ) ceramics was studied at elevated temperature by a self-made solid particle impact erosion wear testing apparatus. Volume erosion wear rate of MgSZ ceramics was measured at up to 1400°C with an impact angle of 90°. The effects of erosion temperature on erosion wear behavior and mechanism for different temperature ranges have been discussed. The results indicate that volume erosion wear rate of MgSZ ceramics increased with temperature. Specifically, volume erosion wear rate increased at a rate of 1.87×10^{-4} from room temperature to 600°C, 5.99×10^{-4} from 800 to 1000°C, and tended to be constant from 1000 to 1400°C. Volume erosion wear rate reached its maximum value of 0.60 mm³/g at around 1000°C. The increase in erosion wear rate is related to the decrease in mechanical performance of MgSZ with increasing temperature. When MgSZ ceramics were impacted by corundum particles, the main material removal mechanism was found to be plastic deformation from room temperature to 600°C and crack crisscross leading to flaky exfoliation of material from 1000 to 1400°C. Between 600 and 800°C, a transition region from plastic deformation to flaky exfoliation was found.

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1. Introduction

Zirconia ceramics are widely used as structural materials due to their high melting point, high strength and fracture toughness, good wear and corrosion resistance as well as excellent high temperature performance.^{1)–3)} Numerous studies have been conducted on magnesia stabilized zirconia ceramics, including studies on phase stability, mechanical properties at room and elevated temperatures, as well as abrasive and erosion wear properties at room temperature.^{4)–7)}

Solid particles impact erosion wear is the main cause of material loss in high temperature combustion equipment such as circulating fluidized bed boiler, pulverized coal boiler, cement kiln cyclone preheater with pre-calciner, and garbage incineration.^{8)–10)} Under such conditions, target material is impacted by solid particles accelerated by a high speed air flow which eventually leads to the erosion and removal of target material. Generally, mechanical properties of advanced ceramic materials at elevated temperatures are better than those of metallic materials. Hence advanced ceramic materials outperform metallic materials under extreme conditions which involve solid particles impact erosion wear at high temperature, such as air pipes, temperature tubes in circulating fluidized bed boilers.^{11)–13)} However, understanding of solid particle impact erosion wear behavior of advanced ceramic materials at high temperatures remains incomplete, especially at temperatures above 1000°C, possibly due to the unavailability of testing equipment.¹⁴⁾

In this paper, a self-made high temperature solid particle impact erosion wear testing apparatus was used to investigate the erosion wear behavior of MgO stabilized ZrO₂ (MgSZ) ceramics. The effects of temperature (room temperature to 1400°C) on erosion wear performance and mechanisms of MgSZ have been discussed.

2. Experimental

2.1 Preparation of MgSZ ceramics

8 mol % MgO stabilized ZrO₂ powder (purity > 99.9%, specific surface area $S_{\text{BET}} = 4.24 \text{ m}^2/\text{g}$, $D_{50} = 0.43 \mu\text{m}$, Jiangxi Jiujiang Fanmeiya Materials Co., LTD., Jiangxi Province, China) was used as the raw material. The powder wet ball milled for 6 h with ethanol as the medium and dried at 80°C for 12 h. Then it was sieved through a $0.15 \mu\text{m}$ mesh and put into a steel die. MgSZ Green samples (sample size of $4 \text{ mm} \times 6 \text{ mm} \times 40 \text{ mm}$ and $\Phi 75 \text{ mm}$ in diameter) were made by pressing at 30 MPa followed by cold isostatic pressing at 200 MPa. These MgSZ green samples were sintered under atmospheric pressure at 1650°C for 3 h to get MgSZ ceramic.

2.2 Characterization

Bending strengths of MgSZ samples at room and elevated temperatures were measured by three point bend method. Fracture toughness of MgSZ samples at room and elevated temperatures was measured by single edge notched beam method (SENB). Vickers hardness was determined by TMC HXD - 1000 micro hardness tester with a test force of 500 gf and time duration of 15 s. Elastic moduli of the samples at room and elevated temperatures was measured by three point bending deflection method.

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The solid particle impact erosion wear test was performed using a self-designed high-temperature (up to 1400°C) erosion wear test apparatus. Its schematic diagram is reported in literature.⁹⁾ The surfaces of MgSZ samples were polished by various specific diamond pastes and then cleaned ultrasonically. Target surfaces were impacted by 300 g of angular corundum particles (with a particle size of 0.5 mm and the number of the corundum particles was about 826800) at a velocity of about 50–60 m/s. Impact angle of 90°, which has been defined as the angle made by the particles' velocity vector and the plane of the target surface, was used during the whole process. All the tests were performed under atmospheric conditions.

The mass loss of the MgSZ samples was obtained by averaging values from three trials. Volume erosion rate was used to characterize the solid particle impact erosion resistance, as shown in Eq. (1).

$$\omega = \frac{M_1 - M_2}{d \cdot m} \quad \text{Eq. (1)}$$

Where ω is the volume erosion rate expressed in a unit of mm³/g; d is the density of the MgSZ samples expressed in a unit of g/mm³; M_1 and M_2 with units of g are the masses of the specimen before and after the erosion wear test, respectively; m is the mass of abrasive particles in a unit of g.

Field emission scanning electron microscopy (FESEM, Hitachi S4800) was used to microscopically characterize the sample surface before and after the erosion wear test.

3. Results

3.1 Solid particle impact erosion wear performance of MgSZ samples at elevated temperature

Figure 1 shows the volume erosion wear rates of MgSZ samples at different erosion temperatures under the test conditions (300 g of corundum particles; 90° impact angle). It can be seen that the volume erosion wear rate of MgSZ samples shows a trend of gradual increase with temperature. It grows linearly with a fitting coefficient of 1.87×10^{-4} from room temperature to 600°C. From 600 to 1000°C, volume erosion wear rate increases with a fitting coefficient of 5.99×10^{-4} and reaches its maximum value of 0.60 mm³/g at 1000°C. The volume erosion wear rate tends to be constant above 1000°C.

Fig. 1. Volume erosion wear rate of MgSZ samples at different temperatures (room temperature to 1400°C).

3.2 Erosion morphology of MgSZ samples after solid particle impact erosion tests at different temperatures

Figures 2(a) and 2(b) show the SEM morphologies of MgSZ powders and MgSZ sample surface before the erosion, respectively. Here, a dense structure of MgSZ samples can be seen and the grain size grows up obviously (with a size of about 30 μm) comparing with that of MgSZ powders. Figures 2(c)–2(i) present the morphology of MgSZ sample surfaces after being erosion tested by 300 g of corundum particles at an erosion angle of 90° at different temperatures (room temperature to 1400°C). As can be seen from Figs. 2(c)–2(i), there are scratches on the surfaces of all tested samples. The number of scratches is found to gradually reduce with temperature. As the temperature rises from 800 to 1400°C, materials loss at the surface can be seen to become significant in the MgSZ samples.

3.3 Mechanical properties of MgSZ ceramics

MgSZ samples at room temperature were tested and found to have a bending strength of 375 ± 42 MPa, fracture toughness of 7.33 ± 0.24 MPa m^{1/2}, Vickers hardness of 12.64 ± 0.81 GPa,

Fig. 2. SEM morphology of MgSZ powders (a), and microstructure of MgSZ samples surface (b) before test, and (c)–(i) after solid particles impact erosion wear at different temperatures: (c) room temperature, (d) 400°C, (e) 600°C, (f) 800°C, (g) 1000°C, (h) 1200°C, and (i) 1400°C.

Table 1. Mechanical properties of MgSZ at room temperature

	Bending strength /MPa	Fracture toughness /MPa·m ^{1/2}	Vickers hardness /GPa	Elastic modulus /GPa
MgSZ samples	375 ± 42	7.33 ± 0.24	12.64 ± 0.81	136.2 ± 8.1

Fig. 3. Bending strength and elastic modulus of MgSZ samples at different temperatures.

Fig. 4. Fracture toughness of MgSZ samples at different temperatures.

and elastic modulus of 136.2 ± 8.1 GPa, as shown in **Table 1**. (The value after plus/minus sign is the standard deviation.)

Bending strengths and elastic moduli of MgSZ samples at different temperatures are shown in **Fig. 3**. The bending strength of MgSZ ceramic samples gradually decreases with increasing temperature. While there were only small changes in its value from 150 to 130 MPa in the temperature range of 600 to 1400°C, it dropped drastically from 375 to 150 MPa when temperature rose from room temperature to 600°C.

Elastic modulus of MgSZ samples also decreased gradually with increasing temperatures. Its value dropped rapidly between room temperature and 600°C and changed only slightly between 600 to 1200°C, which was similar to the trend observed in the case of bending strength.

The fracture toughness of MgSZ samples at different temperature is shown in **Fig. 4**. Fracture toughness of MgSZ samples gradually decreases with increasing temperature. It decreases significantly from room temperature (7.33 ± 0.24 MPa·m^{1/2}) to 1000°C (3.98 ± 0.37 MPa·m^{1/2}) but changes only slightly from 1000 to 1400°C (3.93 ± 0.27 MPa·m^{1/2}).

Fig. 5. Microstructure and surface morphology of MgSZ sample after solid particles impact erosion wear test at low temperature (400°C).

4. Discussion

Based on the observation of the surface microstructures, it can be said that in the samples that were erosion wear tested at low temperatures, there were significant number of scratches on the MgSZ sample surfaces. The amount of such scratches reduced gradually from room temperature to 1400°C while the appearance of exfoliation increased at temperature above 800°C.

According to A. G. Evans' elastic-plastic indentation fracture theory,¹⁵⁾ the region of ceramic underneath the impacting rigid particles would show a certain extent of plastic deformation. Kinetic energy of the impacting particles is absorbed by plastic deformation of the target material. Cracks initiate and propagate when the local tensile stress at the deformation region builds up and exceeds critical fracture stress.

Moreover, the total kinetic energy of the impacting particles can be absorbed by the target material through plastic deformation only when the velocity of the particles is smaller than a critical value. Above that critical value, tensile stresses are generated in the region underneath the impacting particles. When these tensile stresses become larger than the critical fracture stress of the material, cracks are generated in the material. The maximum tensile stress generated by particles impacting with a velocity of about 50–60 m/s is less than the critical fracture stress of MgSZ at low temperatures. Therefore considerable amount of plastic deformation was generated by impacting corundum particles on the surface of MgSZ samples. The surface microstructural morphology of MgSZ sample was characterized after erosion testing at 400°C. A characteristic of erosion wear mechanism of typical plastic deformation was shown in **Fig. 5**. From another point of view, the Vicker's hardness of corundum particles of ~ 17.00 GPa is higher than that of MgSZ samples, roughly 12.60 GPa, at room temperature. Hence scratches can easily be generated on the MgSZ samples surface by impact of corundum particles at relatively low temperature.

The velocity of the impacting particles stays almost constant, which means the kinetic energy of the particles stays constant as erosion temperature gradually rises. However, the strength and fracture toughness of MgSZ decrease significantly with temperature. When the strength of MgSZ is lower than a critical value, the maximum tensile stress, cracks are produced along the impacting point in tensile stress area. As the particles impact the surface, each particle can be assumed to be capable of producing a certain length and number of cracks. Once the crack density is high enough, the cracks in irregular crisscross patterns result in

Fig. 6. Microstructure and surface morphology of MgSZ samples after solid particles impact erosion wear test at higher temperatures (a) 800°C, and (b) 1000°C.

flaky exfoliation of the material. As the mechanical properties of MgSZ decrease, the length of cracks is further extended.

Both transverse and longitudinal cracks which are perpendicular to each other theoretically are generated during the impacting process. Only transverse cracks can lead to the flaky exfoliation of material; the longitudinal cracks just lead to reduction in strength of the material. However, in reality, the transverse and longitudinal cracks are not always perfectly perpendicular to each other. It was observed that many cases of flaky exfoliation of material at the impacting surface were resulted by this crack crisscrossing. Moreover, plastic deformation and flaky exfoliation could happen at the same time. But the scratches on MgSZ sample surfaces caused by plastic deformation could be removed by flaky exfoliation of materials. Only the latter was left to be observed.

The surface morphology of MgSZ samples after the erosion testing with corundum particle at temperature of 800 to 1000°C is shown in Fig. 6. The characteristic flaky exfoliation due to crack crisscross can be observed at the surface.

Rarely visible cracks can be observed at the surface of MgSZ ceramic samples at low temperatures (from room temperature to 600°C). Moreover, at these temperatures the increase in volume erosion wear rate is small and the fitting slope of the curve of volume erosion wear rate versus temperature is only of 1.87×10^{-4} . It can be concluded that the fracture strength of MgSZ samples is still higher than the critical tensile stress at those temperatures. As a result, plastic deformation is the main erosion mechanism from room temperature to 600°C. Correspondingly, the fracture strength of MgSZ samples from 600 to 1000°C is lower than the critical tensile stress. The rate of change of volume erosion wear rate versus erosion temperature is found to be of 5.99×10^{-4} . Even though volume erosion wear rate itself is small, it is larger than that of the previous temperature stage. The primary erosion wear mechanism leads to the formation of cracks in irregular crisscross patterns leading to the flaky exfoliation of material. Fracture toughness of MgSZ samples drops significantly from 600 to 1000°C. The erosion wear mechanism here is a mix of plastic deformation and formation of crisscross cracks leading to flaky exfoliation. The latter one becomes the main mechanism as the erosion temperature increases, which causes the volume erosion wear rate to increase sharply. The morphol-

ogy of the impacted target surface and volume erosion wear rate were almost unchanged at temperature above 1000°C, as a result of small changes in wear mechanism of MgSZ samples above 1000°C.

5. Conclusions

Solid particle impact erosion wear behavior of MgSZ ceramics was studied from room temperature up to 1400°C using an impact angle of 90° with corundum particles as impact particles. Volume erosion wear rate of MgSZ increased with increasing temperature. Specifically, volume erosion rate increased at a fitting rate of 1.87×10^{-4} from room temperature to 600°C, 5.99×10^{-4} from 800 to 1000°C, and tended to be constant from 1000 to 1400°C. Volume erosion wear rate reached its maximum value at around 1000°C. At low temperatures (room temperature to 600°C), main erosion wear mechanism of MgSZ by the impact of corundum particles was plastic deformation. At high temperatures (1000 to 1400°C), the main erosion wear mechanism consisted of formation of mutually crisscrossing cracks leading flaky exfoliation of the material.

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