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Wear of Ceramics Based on Magnesia- and Ceria-Stabilized Zirconia in Dry Friction Against Steel

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Abstract—Wear of two ceramic materials containing partially stabilized zirconia is studied in unlubricated friction against steel. The zirconia is stabilized by magnesia (Mg-PSZ ceramics) and ceria (Ce-TZP ceramics). The wear rate of the Mg-PSZ ceramics is found to be 1.5 times lower than that of the Ce-TZP ceramics. This difference is attributed to the fact that the wear of Ce-TZP ceramics occurs via tear of large grain blocks from the friction surface, whereas MG-PSZ ceramics are worn by way of grain attrition.

Key words: ceramics, partially stabilized zirconia, wear, fracture toughness, isostatic pressing.

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INTRODUCTION

The present authors have shown in a previous paper devoted to investigation of yttria-stabilized zirconia ceramics (Y-TZP, yttria tetragonal zirconia polycrystals) in unlubricated friction against steel that the wear of porous ceramics can be lower than the wear in dense ones [1]. Reduction in the grain size was found to decrease greatly the wear of the studied ceramic material [2]. It was also established that the wear of the ceramics was greater the higher its coefficient of fracture toughness [3]. Along with Y-TZP ceramics, magnesia-stabilized zirconia ceramic material Mg-PSZ (magnesia partially stabilized zirconia) and ceria-stabilized zirconia Ce-TZP (ceria tetragonal zirconia polycrystals) are often used in the manufacture of plain bearings and drawing dies for nonferrous metals due to their perfect physico-mechanical properties [4, 5].

The present paper summarizes the results of studies of the wear of Mg-PSZ and Ce-TZP ceramics in friction against steel without lubrication.

MATERIALS AND METHODS

The ceramic materials under study were of the following composition: ZrO_2—9 mol % MgO (Mg-PSZ); and ZrO_2—12.5 mol % CeO_2 (Ce-TZP). Powders obtained by coprecipitation were used for the production of the ceramic materials. The samples were obtained by cold isostatic pressing with postsintering. The pressure of powder compaction was 0.3 GPa. The pressed samples were sintered under the following conditions: MG-PSZ samples were sintered under $T = 1823$ K for 6 h and Ce-TZP samples were sintered under the same temperature for 4 h.

The properties of the sintered materials are presented in Table 1. The density of the ceramics ρ was measured by the method of hydrostatic weighing. The grain size, morphology, and chemical composition of the friction surface of the ceramics were determined by a scanning microscope JEOL JSM 6490LV. The hardness and fracture toughness were found by an indentation method. The indentation was performed by a four-sided pyramid under a load F = 98 N according to the

Table 1. Physico-mechanical properties of ceramics under study

Ceramics	Grain size D, µm	Density ρ, g/cm^3	Bending strength σ, MPa	Vickers hardness HV, GPa	Fracture toughness K_{IC}, MPa m$^{1/2}$
MG-PSZ	45	5.74	340	10.4 ± 0.1	4.0 ± 0.2
CE-TZP	2.5	6.10	1070	10.6 ± 0.1	6.5 ± 0.1

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Table 2. X-ray phase analysis results of ceramics studied after friction

Material	Phase composition, vol.%			
	M	*T*	*R*	*F*
Initial state				
Mg-PSZ	–	100	–	–
Ce-TZP	–	83	–	17
After rubbing				
Mg-PSZ	10	65	25	–
Ce-TZP	–	33	62	5

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method described elsewhere [6]. Further measurements of the imprint diagonal d and the radial crack length c served as the base for determining the Vickers hardness using relation (1) [6] and fracture toughness K_{IC} using Eq. (2) [7]:

$$HV = 1.854\frac{F}{d^2}; \quad (1)$$

$$K_{IC} = 0.018\left(\frac{E}{HV}\right)^{0.5}\frac{F}{c^{1.5}}, \quad (2)$$

where E is the modulus of elasticity of the ceramics.

Table 1 presents the mean values of HV and K_{IC} obtained in four replicate tests.

X-ray phase analysis using a DRON-3M diffractometer has shown that the Ce-TZP ceramics are composed of 100% tetragonal (T) phase (Table 2). The structure of Mg-PSz incorporates, along with the T-phase, monoclinic (M) and cubic (F) phases.

Wear of the ceramics was studied according to a method described elsewhere [8]. The test samples were made in the form of cylinders 8 mm in diameter. The

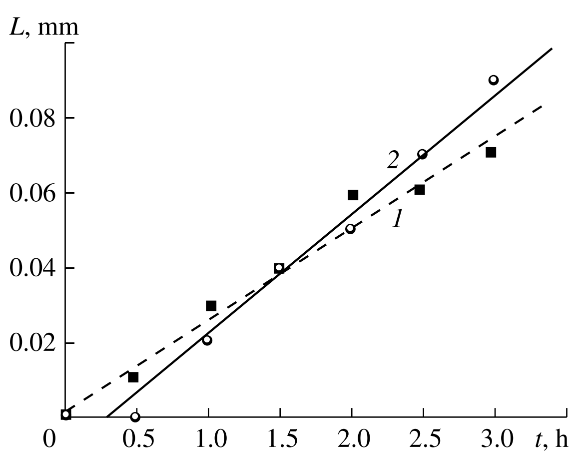

Fig. 1. Dependence of linear wear of ceramics on test duration: *1*—Mg-PSZ; *2*—Ce-TZP.

friction surfaces of the samples were polished before testing. The counterbody was a ground disc of steel 40kHN (*GOST* (State Standard) 4543-71) hardened to 55 *HRC*. After each 30 min of testing, the counterbody surface was ground again. The sample moved over a circumference of 100 mm in diameter at a sliding velocity of 2.5 m/s under 1.4 MPa pressure. The linear wear of the samples was determined by a micrometering method and measurement of the changes in the sample mass per unit of ceramic density. Wear measurements were made each 30 min of testing.

RESULTS AND DISCUSSION

The data on the linear wear of ceramics MG-PSZ and Ce-TZP are presented in Fig. 2. Figures 2 and 3 show the SEM images of the friction surface of these materials after three hours of wear testing. It is especially interesting that the friction surface of the Mg-PSZ ceramics is devoid of tear traces. In contrast, such phenomena occupy rather large areas on the Ce-TZP friction surface. Morphological analysis of the friction surface of these areas shows that separation of the material occurs almost fully over the grain boundaries. The regions between the cracks on the friction surface of Ce-TZP include a considerable number of grains, while on the surface of Mg-PSZ these areas practically coincide with the grain size of this material.

Proceeding from the above stated, it is justifiable to conclude that wear of the Ce-TZP ceramic occurs as follows. First, cracks appear on the friction surface under the effect of shear stresses that induce relaxation of these stresses. The cracks propagate to some depth and then under the same shear stresses they develop along the friction surface, leading to tear of some material fragments. The combination of these elementary events of material separation bring about material wear. Since tear occurs over the grain boundaries (see Fig. 3b), wear of the given ceramic material is evidently conditioned by its strength characteristics along the grain boundaries. Tear of the surface-layer fragments in Mg-PSZ ceramics is not observed, although some wear is recorded. Consequently, wear of the Mg-PSZ ceramics is induced not by tearing of separate grains but by their attrition.

The differences noted in the wear mechanism of the ceramic materials under study is conditioned by the differences in their grain size. Tearing off of Mg-PSZ ceramic grains means the removal of fragments from the surface averaging 45 μm in length, width, and depth. Analysis of the surface images of Ce-TZP ceramics (Fig. 3) leads to the conclusion that fragments about 30 μm wide and up to 70 μ long are separated from its surface. We were unable to make conclusions as to the depth of the torn-off fragments, nor to establish a correlation between the material strength (over the grain boundaries) and its wear. The Mg-PSZ ceramic shows a strength three times lower than that of Ce-TZP, but its wear rate is 1.5 times less; this runs con-

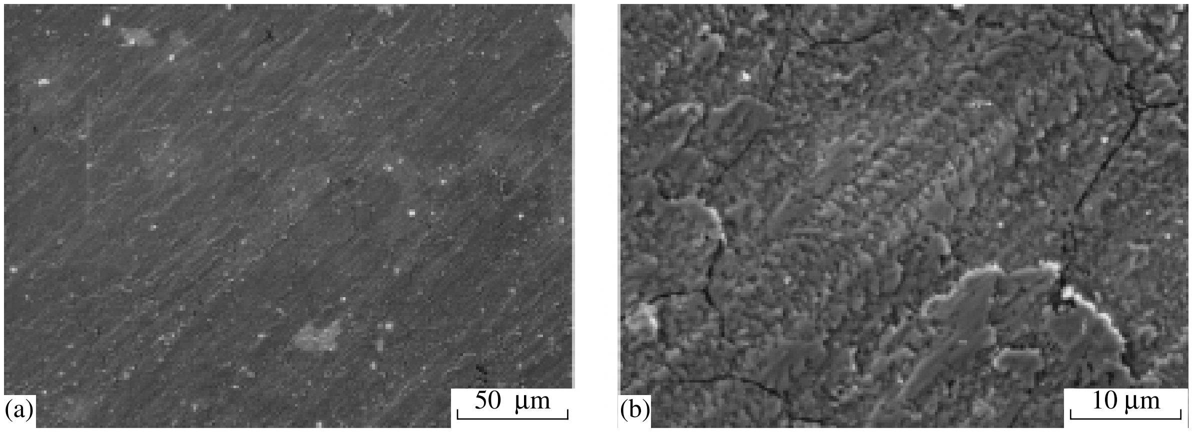

Fig. 2. SEM images of friction surface of Mg-PSZ ceramics: a—small magnification; b—large magnification.

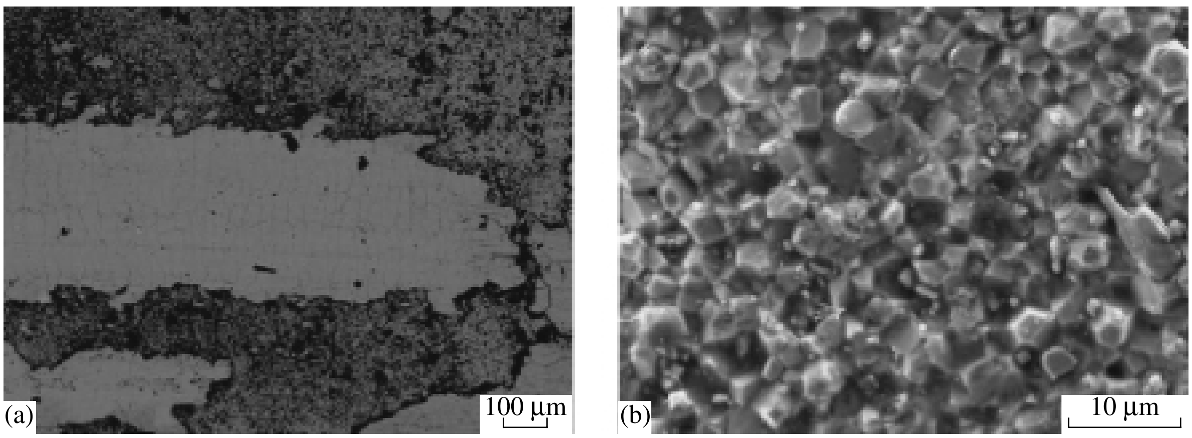

Fig. 3. SEM images of friction surface of Ce-TZP ceramics: a—small magnification; b—large magnification.

trary to the general assumption that higher material strength should correspond to lower wear rate.

Friction brings about changes in the phase composition of the surface material (Table 2). The appearance of orthorhombic and monoclinic phases due to the reduced amount of tetragonal and cubic phases may be one of the reasons for the low friction of the given ceramic materials as compared to the Y-TZP material. This is because transformation of the tetragonal into the monoclinic phase is accompanied by increased material volume by up to 9%, while the appearance of the orthorhombic phase, which is also accompanied by changes in volume, leads to generation of compressive strains that promote wear reduction.

CONCLUSIONS

The wear process of two zirconia-based ceramic materials has been studied, namely materials with magnesia-stabilized zirconia (Mg-PSZ) and ceria-stabilized zirconia (Ce-TZP). Both materials were sintered to a density close to the theoretical one. Their physical characteristics (density, phase composition, mean grain size) and mechanical (tensile strength) and tribological properties (wear resistance under dry friction against steel) were determined. The Ce-TZP ceramic was found to have 20 times smaller grain size but 3 times higher strength and 1.5 times higher wear rate than the Mg-PSZ ceramic. Analysis of the surface morphology of the ceramic materials has proved that the difference in wear resistance is because of different wear mechanisms. The Mg-PSZ ceramic wears via attrition of its grains, while the Ce-TZP ceramic wears by tearing of its grains or even of conglomerations of grains. This difference in the wear mechanisms of the two ceramic types may be due to the differences in their grain size.

DESIGNATIONS

D—ceramic grain size; T—sintering temperature; F—load at indentation; d—imprint diagonal; c—radial crack length; ρ—density; σ—bending strength; K_{IC}—fracture toughness; HV—hardness; L—linear wear; t—time.

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