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Wear and Fracture Toughness of Partially Stabilized Zirconia Ceramics under Dry Friction Against Steel

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Abstract—The wear of two ceramic materials containing partially stabilized zirconia is studied under unlubricated friction against steel. The first material, with ZrO_2 and 3 mol% Y_3O_3, was obtained by cold isostatic molding and sintering. The second material, comprising ZrO_2 and 4 mol% Y_3O_3, was fabricated by additional hot isostatic molding. The samples of both materials were fabricated with high and low values of fracture toughness. The samples with high fracture toughness are found to wear more intensively. This fact can be explained by surface microcracking during braking as a result of phase transformations.

Key words: zirconia, wear, fracture toughness, phase transformations, isostatic molding.

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INTRODUCTION

It is common knowledge that the main cause of material wear during friction is degradation of the working surface [1, 2]. Shear stresses appearing in plastic materials during friction relax upon nucleation and multiplication of dislocations, which results in cracking and damage of the material surface layer, i.e., in material wear [3]. Shear stresses in materials where dislocation activity is either improbable or weakly expressed may initiate other relaxation processes prior to cracking, e.g., phase transformations. Almost no dislocation activity occurs in partially stabilized zirconia ceramics (PSZC), whereas phase transformations occur intensively under applied stresses. Evolution of the phase composition of the ceramics under study was investigated earlier in works devoted to the wear of these materials during unlubricated friction against steel [4, 5]. The present work discusses the results of study of the relationship between the fracture toughness and wear of PSZC.

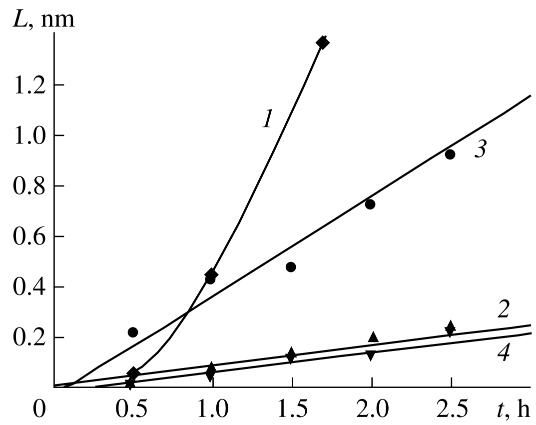
MATERIALS AND METHODS

The tested materials were PSZC, as well as materials containing 3 and 4 mol % of stabilized yttrium oxide. The ceramic samples of ZrO_2 with 3 mol % Y_2O_3 (samples 1 and 2) were produced from powder TZ-3Y produced by Tosoh company (Japan) using cold isostatic molding (CIM) followed by sintering. The molding pressure was up to 0.3 GPa. The samples were sintered following two regimes. Samples no. 1 were sintered under T = 1773 K for 2 h. Samples no. 2 were sintered for 6 h under T = 1623 K. As a result, the ceramic materials obtained differed in terms of grain size and, consequently, fracture toughness (see Table).

The ceramic samples of ZrO_2 and 4 mol % Y_2O_3 (samples nos. 3 and 4) were fabricated from a powder made by Vol'nogorskii Mining and Smelting Enterprise (Ukraine) using the processes of CIM, sintering, and further hot isostatic molding (HIM). The pressure during CIM was 0.3 GPA and the temperature during the 2-h sintering was T = 1773 K. Hot molding of the samples was carried out under T = 1623 K at 0.2 GPa pressure in

Physicomechanical properties of initial ceramic samples

Sample number	Imprint diagonal at indentation d, nm	Density, ρ, g/cm^3	Vickers hardness HV, GPa	Fracture toughness K_{IC}, MPa m$^{1/2}$
1	600–700	6.07	12.6 ± 0.1	13.2 ± 0.2
2	180–2000	5.99	12.2 ± 0.1	4.3 ± 0.1
3	1000	5.92	12.3 ± 0.1	10.1 ± 0.2
4	1000	5.65	12.4 ± 0.2	3.4 ± 0.1



Linear wear of ceramics vs. test duration: (*1–4*) sample numbers (see table).

argon atmosphere for 2 h. To vary the fracture toughness of the samples, a portion of the obtained samples (samples no. 4) were submerged in liquid nitrogen for 5 min. This resulted in a changed phase composition of the material and reduced inner stresses (crystallographic structure I_{002}/I_{200} changed from 1.80 to 1.68), leading in turn to decreased fracture toughness.

The density ρ of the obtained samples was measured by the method of hydrostatic weighing. The grain size d was determined by scanning electron microscopy. The hardness and fracture toughness of the ceramic samples were measured using indentation. The indentation was exercised by a diamond pyramid under a loading $F = 98$ N following the method described elsewhere [6]. Hardness HV was determined using relation (1) based on further measurements of the imprint diagonal d and the radial crack length c. Fracture toughness K_{IC} [7] was found from relation (2)

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

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

where E is the elasticity modulus of the ceramics.

In the table below one can see the mean HV and K_{IC} values obtained on the base of six replicate measurements.

The wear of the ceramic samples was studied according to the method presented in work [8]. The test samples were fabricated in the form of cylinders 8 mm in diameter. Their friction surface was polished before the experiments. The counterbody was a polished disc of steel 40 KhN *GOST* (State Standard) 4543-71 tempered up to 55 HRC hardness. The counterbody surface was subjected to polishing after each thirty-minute interval of testing. The sample moved over a circle 100 mm in diameter at a sliding velocity 2.5 m/s under 1.4 MPa pressure. The linear wear of the samples was found from micrometric measurements and weight changes as converted per material density. Wear measurements were carried out after each thirty-minute testing interval.

RESULTS AND DISCUSSION

The investigation results presented in the Figure demonstrate that the ceramic material with a higher K_{IC} value shows greater linear wear L. To explain this unexpected result the authors analyzed the mechanism of high fracture toughness of PSZC. It is admitted that high K_{IC} values of PSZC-based ceramics are attained due to mechanically activated transformations of the martensitic phase of the tetragonal (T) phase into a monoclinic one (M) that occurs with a 9% increase in material volume [9]. The described phenomenon hampers further crack growth. This mechanism is supported by the fact that K_{IC} shows extremely low values for the fully stabilized zirconium oxide in which only the cubic phase C is present, which does not undergo transformations under the applied stresses. At the same time, there are cases when PSZC ceramics demonstrate high strength but rather low fracture toughness and vice versa [10, 11]. It is also known that increase in the viscosity of ceramics (fracture toughness) can be attained by activating the mechanism of crack branching, when a crack quickly propagating on the boundaries between grains and different defects diverts from its main direction, thus forming a region of stress concentration and branching of its own. The resultant enlargement of the fracture region leads to energy dissipation, which raises the fracture toughness of the material.

Proceeding from the above-cited facts we may explain this phenomenon as follows. The above-indicated high K_{IC} value of the ceramics under study is attributed to the high efficiency of the mechanically activated martensitic phase transformations in the T-phase into the M-phase. Under this process, instead of overcoming an obstacle, an arrested crack tends to outflank it by branching. As a result, there occurs cracking, which loosens the material and leads to strength reduction and wear growth. This conclusion agrees well with the results presented in work [13], where the authors showed that for PSZC materials stabilized with 3 and 2% Y_2O_3, the wear value increased with decreasing Y_2O_3 content, i.e., when the efficiency of the T-phase transformation into the M phase was greater.

CONCLUSIONS

It has been established that the wear of materials made of partially stabilized zirconia during rubbing against steel without lubrication is greater with increased fracture toughness of the material, as measured by the method of microindentation. This phenomenon can be explained as follows. In the case of high fracture toughness resulting from mechanically activated transformation of the tetragonal phase into the monoclinal one, an arrested crack branches and induces cracking of the material's friction surface. To elucidate this phenomenon it is necessary to conduct further investigations concerning the relationship between the fracture toughness and wear of PSZC ceramics.

DESIGNATIONS

d—grain size of ceramics; *T*—sintering temperature; ρ—density; *HV*—hardness; K_{IC}—fracture toughness; *L*—linear wear; *t*—time; I_{002}/I_{200}—texture.

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