Wear behavior of zirconia-based ceramics under high-speed dry sliding on steel

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Cirkónium-dioxid alapú kerámiák kopási viselkedése acélon történő nagy sebességű száraz csúszás esetében

Tanulmányoztuk a cirkónium-dioxid alapú kerámia kompozit anyagok viselkedését, acélon történő, nagy sebességű száraz csúszás esetében. A vizsgálatot tű-a-tárcsán módszerrel végeztük, maximálisan 47 m/s sebességgel. Kimutattuk, hogy a vizsgálat során egy nagyon komplex összetételű közbülső réteg alakul ki, és ez szabályozza a kerámia-acél páros nem monoton kopását és súrlódási viselkedését. Az első fázisban a kopás normális mértékű, ami azonban katasztrófálisan megnövekszik. A második fázisban a kopás mértéke csaknem az eredeti értékig csökken (amilyen a kis, 0,1 m/s sebességnél tapasztalható). Az ilyen sebességtartományban az anyag gyakorlatilag nem mutat kopást.

1. Introduction

The development of industry requires the design of new wear resistant materials that are able to work in the widest possible range of speeds and loads [1]. Transformation-toughened ceramics are shown much promise for being applied in heavily loaded friction units [2]. Of special note among them are ceramics on the basis of yttria-stabilized tetragonal zirconia polycrystals (Y-TZP [2]). The major toughening mechanism for Y-TZP ceramics is the phase transformation from the tetragonal ZrO_2 phase to monoclinic, which occurs under applied stresses [2]. Besides this, composites Y-TZP- Al_2O_3 are widely applied due to their high thermal stability [2] in which Al_2O_3 particles play a role of reinforcement phase. Our preliminary researches [3] of wear process in zirconia based ceramics with different content of Al_2O_3 carried out in speeds 0,2–9,4 m/s and pressures 1–10 MPa have shown that wear rate has a maximum at pressures 5–10 MPa and speeds about 5 m/s.

It should be noted that there are currently no sufficient data on the behavior of such materials at high sliding speeds, above 10 m/s. The main emphasis is now put on studying the material behavior at low speeds (up to 1 m/s) under abrasive wear [4–5], at cutting and polishing [4–5].

At the same time, in order to choose an optimal structure of composites and their possible application areas, it is necessary to gain data on friction and wear and to study structural changes in composites in speed intervals characterized by high temperatures in the tribocontact zone.

Particularly, at sliding speed increase above 10 m/s temperature in the tribocontact grows, which can significantly change the structural phase state of the composite material and its tribotechnical properties. As shown in [6], under high-speed friction of $SiC-Al_2O_3-Al$ composite on steel the coefficient of friction and wear decreases due to the formation of a layer containing various oxide mixtures on the friction surface. At elevated contact temperatures this layer has low shear stability, playing the role of lubricant [6]. Similar cases of preserving high tribological characteristics and protective function of transfer layers formed in high-speed friction on steel have

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been discussed in [7,8], which consider zirconia- and alumina-based ceramic materials. According to [8], at high sliding speeds up to 37 m/s Y-TZP ceramic specimens demonstrate high wear resistance despite high temperatures in the tribocontact zone and related high-temperature phase transitions.

The present paper is aimed at studying tribological characteristics and the friction surface of Y-TZP and Y-TZP- Al_2O_3 after dry sliding on steel in a wide speed interval.

2. Materials and experimental procedure

Sliding tests were carried out on a friction machine UMT-1 using a pin-on-disk technique with a stepwise speed increase under dry friction. The disk was made of cast high-speed steel (HRC60) and rotated in the vertical plane. The test pressure made up 2–5 MPa, and the sliding speed varied up to 47 m/s. The test time was chosen so that the sliding distance at all speeds amounted to 2 000 meters. Prior to each test the specimens were grinded at speed 0,2 m/s and pressure 2 MPa to get friction surfaces of specified geometry. In every experiment the friction force moment was recorded by the computer at 1 sec intervals and later it was recalculated into the friction coefficient. The measure of wear intensity was the ratio between the volume of the material removed from a specimen during test and sliding distance. The structure and phase composition of friction surfaces were examined with X-ray structural analysis, optical and scanning electron microscopy.

The ceramic specimens has composition of $ZrO_2 + 3 \text{ mole } \% Y_2O_3$ and 80 wt. % $ZrO_2(3 \text{ mole } \% Y_2O_3) + 20 \text{ wt. } \% Al_2O_3$.

This ceramics are characterized by high flexure strength, namely, ≈ 800 MPa for Y-TZP and ≈ 900 MPa for Y-TZP- Al_2O_3 , as well as high fracture toughness (K_{Ic}) $\approx 13 \text{ MPa} \times \text{m}^{1/2}$ for Y-TZP and $\approx 10 \text{ MPa} \times \text{m}^{1/2}$ for Y-TZP- Al_2O_3 , and grain size $\approx 2 \mu\text{m}$ for Y-TZP and $\approx 1.5 \mu\text{m}$ for Y-TZP- Al_2O_3 . Both ceramics had 5% porosity and similar phase composition - 90% tetragonal and 10% of cubic phases.

3. Results and discussion

The performed tests have shown that at sliding speed growth the wear intensity of ceramics firstly increase and then decrease with speed growth, Fig. 1a, Fig. 2a. The friction coefficient for both ceramics reduced from 0,5–0,8 at low sliding speeds to $\approx 0,15$ –0,2 for 25–47 m/s, Fig. 1b, 2b. By the electron scanning and optical microscopy data, friction in the speed interval up to 1 m/s results in the formation of grooved surface typical of abrasive wear. Above sliding speeds 3 m/s the worn surfaces have large areas with traces of pitting, and at speeds above 6 m/s they appear smoother, Fig. 3, a, b. Of special note is that there is a network of cracks on friction surfaces of Y-TZP and Y-TZP- Al_2O_3 which divides the surface into separate fragments. We have measured crack spacings along the sliding direction and found that their size distributions are nearly normal with a clear peak.

Fig. 1. The sliding speed dependence of the wear rate (a), the friction coefficient (b) of Y-TZP ceramic. The contact pressure is 5 MPa.

1. ábra Az Y-TZP kerámia kopásának mértéke (a) és súrlódási együtthatója (b) a csúszási sebesség függvényében. Érintkezési nyomás: 5 MPa.

Fig. 2. The sliding speed dependence of the wear rate (a), the friction coefficient (b) of Y-TZP- Al_2O_3 ceramic. The contact pressure is 5 MPa.

2. ábra Az Y-TZP- Al_2O_3 kerámia kopásának mértéke (a) és súrlódási együtthatója (b) a csúszási sebesség függvényében. Érintkezési nyomás: 5 MPa.

The monoclinic phase in initial state of both ceramics is absent and is appeared only after testing with speeds up to 2 m/s for Y-TZP and 11 m/s for Y-TZP- Al_2O_3 and its volume fraction is about 7–15%.

The amount of cubic phase which was 10% for initial state of ceramics remain invariable for Y-TZP and Y-TZP- Al_2O_3 until reaching the speed of 20 m/s. The further increase in the sliding speed resulted in its $\approx 17\%$ increase for Y-TZP and $\approx 15\%$ for Y-TZP- Al_2O_3 ceramics. The appearance of the cubic phase on the specimen surface after maximum sliding speeds is evidently due to that part of the tetragonal phase transforms to cubic by the diffusion mechanism. This transition is favored by high temperatures in the tribocontact zone, e.g., in [9] temperature in the tribocontact zone at speed 10 m/s is estimated to be $\sim 2000^\circ\text{C}$.

Fig. 3. The SEM micrographs of the wear surface of Y-TZP (a) Y-TZP- Al_2O_3 (b) after tests at 47 m/s. Arrow shows the sliding direction.

3. ábra Az Y-TZP (a) és Y-TZP- Al_2O_3 (b) kerámiák koptatási felületének pásztázó elektronmikroszkópos (SEM) felvétele a 47 m/s sebességű vizsgálat után. A nyíl a csúszás irányát mutatja.

Optical and scanning electron microscopy revealed that above high speeds (higher than 6 m/s) friction surfaces were uniformly covered with a transfer layer. After low- and medium- speed sliding friction the transfer layer distribution on the surfaces was extremely inhomogeneous, which appeared as large friction surface areas with absolutely no transfer layer.

We have also examined near-surface regions of the Y-TZP ceramics and found that this surface layer (evidently having submicrocrystalline structure, Fig. 4a) is rather thin, about 1–2 μm . In the speed interval from 0,2 to 6 m/s where the wear rate rapidly increases, there is a material region beneath the layer in which the grain shape is significantly changed in the sliding direction, Fig. 4a. The thickness of this region is maximum 10 μm at medium sliding speeds (~ 4 m/s), i.e. at the

Fig. 4. The SEM micrographs of the subsurface regions of the Y-TZP ceramics after wear at (a) 4.3 and (b) 11.1 m/s. Arrow shows the sliding direction
4. ábra Az Y-TZP kerámiák felület alatti rétegének SEM felvétele a 4,3 (a) és a 11,1 (b) m/s sebességű koptatás után. A nyíl a csúszás irányát mutatja.

Fig. 5. The SEM micrographs of the subsurface regions of the Y-TZP-Al₂O₃ ceramics after wear at (a) 4.3 and (b) 40 m/s. Arrow shows the sliding direction.
5. ábra Az Y-TZP-Al₂O₃ kerámiák felület alatti rétegének SEM felvétele a 4,3 (a) és 40 (b) m/s sebességű koptatás után. A nyíl a csúszás irányát mutatja.

speeds when the wear rate is maximum, Fig. 1a. On increasing the sliding speed above 6 m/s, there is no changes of grain shapes they are approximately equiaxed alike in initial material Fig. 4b. In case of Y-TZP-Al₂O₃ ceramics these areas have never been found for all testing speeds even in average speeds of sliding where severe wear has been observed (Fig. 5a, b).

The wear processes occurring at speeds 2–6 m/s correspond to high-temperature adhesive interaction between ceramics and steel. This wear regime is characterized by high wear intensity, which is illustrated in Fig. 1a, Fig. 2a. Subsequent decrease in wear intensity at sliding speeds higher than 6 m/s is a result of contact stress reduction owing to the formation of the transfer layer and its transition from the ductile to quasi-liquid state, which is also favored by high tribocontact temperature. The formed quasi-liquid film uniformly covers the ceramic friction surface and acts as “soft” coating. The latter facilitates contact stress decrease on the surface by reducing the true contact area between the specimen and disk. In case when the quasi-liquid “soft” film covers the ceramic surface, the friction coefficient is minimum and approaches values typical of boundary lubrication friction.

It should be noted that inspite of general similarity in tribology behaviour of samples of both Y-TZP and Y-TZP-Al₂O₃, the latter system shows a higher wear resistance under the conditions of high-speed sliding. It is possible that the microstructure of such a material serves to higher bearing ability of the worn surface.

4. Conclusions

The performed experiments have revealed that at high sliding speeds up to 47 m/s Y-TZP and Y-TZP-Al₂O₃ ceramic specimens have high wear resistance, despite high temperatures in the tribocontact zone and related high-temperature transitions. In this case, there is a wide interval of speeds where the process is nearly “wearless”.

We gratefully acknowledge the partial financial support from the RFBR (the project 06-03-96929-p_ofi).

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