Surface Wear Structures and Mechanisms in Zirconia-Based Ceramics

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Abstract—Correlations between the scale of surface structures formed upon high-velocity friction and the wear intensity have been studied for Y-TZP ceramics with various values of the average grain size. An increase in the sliding velocity from 4 to 11 m/s in the ceramics–steel friction couple leads to a decrease in the wear rate (caused by a change in the mechanism of wear from high-temperature adhesive wear to that in the regime of friction with boundary quasi-liquid lubricant film formation) and is accompanied by a decrease in the scale of the crack network formed on the friction surface. © 2004 MAIK “Nauka/Interperiodica”.

High mechanical properties of partly stabilized zirconia-based ceramics, related to the stress-induced martensitic transformation from a metastable tetragonal (T) to the stable monoclinic (M) phase, make such ceramics promising materials for friction units operating at high loads [1, 2]. Of special interest in this respect are yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) ceramics [3].

As is known, realization of one or another mechanism of wear during friction is closely related to structural transformations in the surface layers of materials under particular tribodeformation conditions. For this reason, analysis of the surface structures formed during friction in the ceramics subject to structural transformations is of considerable importance.

This study was devoted to the analysis of correlations between the scale of surface structures formed upon high-velocity friction and the wear intensity for Y-TZP ceramics with various values of the average grain size.

The experiments were performed on samples of two-phase Y-TZP ceramics with the composition 

\[ \text{ZrO}_2 - 3 \text{ mol \% Y}_2\text{O}_3 \]

with an average grain size varying from 0.9 to 2.9 µm, comprising (in the initial as-fired state) a mixture of equiaxial grains of the tetragonal and cubic zirconia phases. The friction tests were performed using the rod-on-disk scheme without lubricant, with a stepwise increase in the relative sliding velocity from 4 to 11.2 m/s at a loading pressure of 5 MPa. The counterbody was a disk made of cast high-speed steel. The friction path in all experiments was 1000 m. The structural and chemical transformations on the friction surface of samples were studied by methods of optical metallography, scanning electron microscopy (SEM), and electron probe microanalysis (EPMA).

The results of tests showed that, as the relative sliding velocity \( v \) increases from 4 to 11 m/s, the wear intensity \( I \) and the friction coefficient \( f \) of the studied ceramics decrease (Fig. 1a). This behavior was observed for all ceramics irrespective of the average grain size. Figure 1b shows plots of the tribological characteristics versus grain size \( d \) for Y-TZP ceramics studied. As can be seen, the wear intensity \( I \) measured at a velocity of \( v = 4.3 \) m/s grows with increasing \( d \); at \( v = 11.1 \) m/s, the wear intensity slightly decreases with increasing grain size.

The results of SEM investigations showed that the surface of Y-TZP samples upon friction tests in the entire range of sliding velocities is covered with a network of cracks oriented along and across the sliding direction, forming a quasiperiodic pattern. As a result, the sample surface appeared to be cut by these cracks into rectangular fragments (blocks). After the tests at \( v = 7.7–11.1 \) m/s, the friction surfaces appeared relatively smooth and contained a smaller number of crashed and exfoliated regions as compared to the surfaces of samples tested at lower velocities. It should be noted that the observed crack networks appeared only during friction: the surface of the initial sample was free of cracks.

The dimensions of particles in the wear products depended on the sliding velocity. In the tests at \( v = 4–6 \) m/s, there appeared particles of two types: (i) relatively coarse fragments (with maximum size up to 70 µm) of irregular shapes and (ii) smaller particles of dimensions comparable with the ceramic grain size (1–3 µm). The tests at \( v = 7.7–11.1 \) m/s also led to the formation of two fractions of particles, but the size of...
fragments in the coarse fraction (8–15 μm) was significantly smaller than that observed for the lower sliding velocities (4–6 m/s).

The results of EPMA analyses of the friction surface of ceramic samples in all cases showed the presence of a surface layer containing the material transferred during friction from the steel counterbody. SEM images showed that, in samples tested at \( \nu = 7–11 \) m/s, this layer covers virtually the entire friction surface of ceramics. The content of steel components both on the friction surface and in the particles of wear products increased with the sliding velocity.

Upon measuring distances between transverse cracks in the direction of sliding and constructing their distribution, we obtained the normal (Gaussian) profile with a clear maximum. This is evidence of a certain periodicity in the mutual arrangement of transverse cracks in the sliding direction. Figure 2a shows the typical plot of the distance between cracks in the sliding direction versus sliding velocity, which were observed for ceramics with various values of the average grain size. All such curves exhibit the same peculiarity: the spacing of transverse cracks at \( \nu = 7–11 \) m/s is smaller than at \( \nu = 4–6 \) m/s; moreover, the average distance between cracks was virtually independent of the average grain size.

The process of wear at \( \nu = 4–6 \) m/s can be interpreted in terms of the high-temperature adhesive interaction between ceramics and steel. This regime is characterized by high wear intensities and large friction coefficients, which is confirmed by data in Fig. 1a. As was pointed out previously [4, 5], a decrease in the wear intensity with increasing relative sliding velocity (Fig. 1a) can be related to a decrease in the level of contact stresses as a result of formation of the transfer layer and its transformation from solid to quasi-liquid state. This transformation is favored by high temperatures developed in the friction contact zone (estimates obtained according to [6], this region can be heated up to 1500–2000°C, which is comparable with or even