Size Effects and Mechanisms in the Friction and Wear Processes of Ceramics Based on Zirconium Dioxide

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Abstract. This paper presents a study of the tribological properties of ceramics based on ZrO₂ stabilized with CaO in a ceramic-ceramic friction pair. The influence of the scale factor on the coefficient of friction in the micro- and nanoscale is established. A qualitative correlation of the theoretical and experimental curves is shown for friction coefficient dependence on the body-counterbody contact force. Friction and wear micromechanisms at a micro- and nanoscale are proposed for the investigated TZP ceramics.

1. Introduction

Today rather strict requirements are imposed on modern engineering materials, especially on the ones used in high-load applications. Advanced nanostructured ceramics is one of the novel materials that satisfy these requirements. One of them is the engineering ceramic based on stabilized zirconium dioxide [1] that form an important class of materials with a unique set of properties, where strength and tribological characteristics come to the fore. Although the result of friction and wear is usually seen at the macrolevel, initially the interaction of interacting surfaces takes place at submicroscale and nanoscale through multiple local short-term contacts. As a rule, these contacts arise between the promontories of the surface due to the roughness; typical size of the contact regions ranges from a few nm to a few um [2-9]. It is a promising approach to simulate physically the processes occurring during dry friction at the level of single micro- / nanocontacts. This approach may allow us to get more detailed understanding and description of this process. It lets us to characterize the deformation processes occurring in locally loaded submicrovolumes, under fully controlled conditions.

2. Methods

The technique, used in this study, makes it possible to study the behavior of the material at local lateral interaction during sliding into the technique of nanoindentation [10-14], consists in measuring of local deformation with nanometer resolution. The local deformation occurs under the action of normal and lateral forces applied to the test material surface according to the test protocol [8-15]. The technique allows us to control of all essential parameters during the experiment (normal and lateral components of the forces, contact area and geometry of interacting areas of interacting bodies, local deformation and the lost material volume, and fracture toughness). It leads to creating completely defined conditions in dynamic micro- / nanocontact, vary them as desired, and investigate the mechanical behavior of materials on a nanoscale. The tribomechanical studies were carried out on a TI 950 Hysitron Triboindenter (USA) and DNT Nanoindentometers developed in the Research Institute.
“Nanotechnology and Nanomaterials” branch of G.R. Derzhavin Tambov State University. Continuous recording of normal and lateral loading, as well as normal and lateral displacement, made it possible to evaluate the behavior of the material under the pressure of the tip touching the surface of the sample in fully controlled conditions at dependence on the displacement (Figure 1).

![Figure 1. Schematic representation of friction and wear tests used in the present investigation.](image)

The study shows tribological behavior of ZrO₂ stabilized with calcium oxide and ceramics with Nb₂O₅ additives were also used. A spherical tip made of ceramics based on ZrO₂ with a radius of \( R = 250 \) μm was used as a counterbody and the Berkovich indenter was used for small parts of tests.

3. Processes at micro- and nanoscale
Conducted research at the micro- and nanoscale has shown that the friction coefficient depends on the value of the normal force \( F_N \) under the tip (Figure 2). At the first stage, the friction coefficient was instantiated by quite a sharp decrease, and then a slight increase, and had a minimum at achieving a certain critical value of the normal force \( F_{Ncr} \). Such behavior was represented typically for each set of tests and interacting bodies. However the \( F_N \) value varied and depended on the materials of body and counterbody. The plot until critical load \( F_{Ncr} \) corresponds to elastic interaction, which was also confirmed by the dependences of the load on the counterbody penetration depth \( P = f(h) \) by reorganizing the obtained data during friction curves into \( P-h \) curves (Figure 3) where the load branch has the same slope like the unload curve. It is also confirmed by the absence of the tracks on the surface verified by atomic force microscopy.

![Figure 2. Dependence of the friction coefficient \( f \) on the normal load \( F_N \): for the ZrO₂ ceramics stabilised by 6.5 mol% CaO and additives with 1 – 0%, 2 – 1.5 %, 3 – 5% Nb₂O₅.](image)

![Figure 3. The typical load-displacement curve (P-h curve) for elastic zone ceramic reorganized from one of the friction curves.](image)

Such authors as F. Bowden, D. Tabor, B.V. Derjaguin et al. described the friction process as the interaction of the surface irregular spots of contacting bodies what always occurs discretely and separately and bases on mechanical and molecular contribution components [9, 15-21]. The expansion of the friction coefficient obtained in our experiments according to the equations from the theory of the authors mentioned above leads to the fact that the total value of the friction force \( F_f \) (numerically
equal to the measured lateral component of the acting forces during friction \( F_L \) is the sum of the molecular and deformation parts \( (F_{mol} \text{ and } F_{def}) \), depending differently on the normal load \( F_N \) [15,16], and the coefficient of friction is determined by the next equation \( \mu = \mu_{mol} + \mu_{def} \) [15,17,18].

According to the equation and the classical approach to tribology, the friction coefficient contains both the molecular and deformation components. The ratio of the contribution to the friction coefficient depends on many factors, such as surface topology, the nature of the contacting bodies, etc. [22-24].

The adhesive part of the friction coefficient \( \mu_{mol} \) at nanoscale (Figure 4) is dominant and contribute the main part into the obtained friction coefficient that was true for all friction pairs that were studied. The deformation part of friction coefficient \( \mu_{def} \) plays an insignificant role when the normal loads are not high, and opposite, \( \mu_{def} \) gives the main contribute at relatively high loads \( F_N > F_{Ncr} \).

The contribution of the deformation part is arising from 0 to 80% at \( F_N = 1000 \text{ mN} \), but at the same time, the contribution of the adhesive component is falling from ≈100% to 20% (at \( F_N = 0.2 \text{ mN} \) and \( F_N = 1000 \text{ mN} \) respectively) for the ZrO₂ ceramic with 6.5 mol%. CaO.

![Figure 4. Interdependence of the friction coefficient \( f \) on the normal load \( F_N \): for the ZrO₂ ceramics with 6.5% CaO additives
1 – friction coefficient obtained in the tests; 2 – \( f_{mol} \) adhesive part of the friction coefficient; 3 – \( f_{def} \) deformation part of the friction coefficient.](image)

4. Processes at macroscale
The carrying out of friction and wear at a macroscale were simulated by lateral sliding of a sharp tip (Berkovich indenter) under the impact of relatively high normal loads \( F_N \) (up to 1 N). This approach made it possible to form a sufficiently large deformation zone, where the processes of crack formation and destruction begin to be observed in addition to the typically observed track because of the counterbody sliding.

The results of experiments showed that separated cracks are detected under loads up to 0.2 N, further increasing of the load \( (F_N \geq 0.5 \text{ N}) \) leads to the appearance of multiple cracking and spalling of ceramics separate grains. Figure 5. shows a typical example of the onset of cracking at dry friction of zirconium ceramics with 6.5 mol%. CaO.

A more detailed study of the identified cracks shows that they have a noticeable tendency towards a predominant direction of propagation, and it is to be about 60 degrees with the direction of the Berkovich's triangular indenter motion and corresponding to the highest tangential mechanical stresses existing along the ribs of the sliding tip.

The load increasing up to \( F_N = 500 \text{ mN} \) leads to the fact that except the typical cracks, areas of greater destruction of the material were revealed inside the track left by the counterbody, in which spalling of individual grains was observed. Such spalling is characterized by a change in spatial orientation and practical exfoliation of individual grains.
Figure 5. SEM of the track left by the Berkovich indenter on the surface of ZrO$_2$-based ceramics stabilized by 6.5 mol%. CaO: $F_N = 0.2$ N (a); $F_N = 1$ N (b).

The further increasing of the load when $F_N \geq 1$ N leads to the increasing in crack formation, and microerosion of the surface is observed with chipping of fine particles like individual grains or their intergrowths and the formation of the debris. The formation of cracks and further spalling of the material can be caused by the generation, displacement and further coalescence of point defects (for example, vacancies), destruction of grain boundaries, as well as phase transitions in the contact zone of the counterbody, which were revealed by micro-Raman spectroscopy.

5. Conclusions

It can be concluded that, purely elastic deformation mechanisms are initially implemented under the experiment conditions of dry friction, which are replaced by elastoplastic mechanisms with an increase of the normal load. When the load $F_N$ keeps growing, crack formation and spalling of individual grains are added to elastic and elastoplastic mechanisms of deformation.

Based on this, we can say that the wear of the studied ceramics is based by a decrease in roughness at low loads (by cutting off singular protrusions of nano size), then mechanisms of plastic deformation begin to turn on with increasing in the load, and at the end, cracking and micro-erosion of the material are added at high loads, due to cutting off of the singular grains and restructuring of intergrowths borders.

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References

[1] Zhigachev A O, Umrikhin A V, Korenkov V V, Tyurin A I, Rodaev V V and Dyachek T A 2018 Ceramic materials based on zirconium dioxide (in Russian) ed Yu.I. Golovin, (Moscow: TECHNOSPHERE)
[2] Hu J and Ogletree D F 1995 Salmeron M. Atomic scale friction and wear of mica Surface science, 3 327 358-70
[3] Carpick R W, Agrait N, Ogletree D F and Salmeron M 1996 Measurement of interfacial shear (friction) with an ultrahigh vacuum atomic force microscope Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena 14 2 1289-95
[4] Zhang W et al 2019 Influence of surface roughness parameters and surface morphology on friction performance of ceramics Journal of the Ceramic Society of Japan 127 11 837-42
[5] Yang M et al 2019 Effect of friction coefficient on chip thickness models in ductile-regime
grinding of zirconia ceramics The International Journal of Advanced Manufacturing Technology 102 5-8 2617-32

[6] Basu B and Kalin M 2011 Tribology of Ceramics and Composites (New Jersey: Wiley & Sons, Inc., Hoboken)

[7] Bhushan B 2013 Introduction to tribology (New York: John Wiley & Sons)

[8] Bhushan B 1995 Handbook of Micro/Nano Tribology (New York: CRC Press LLC)

[9] Braunovic M, Myshkin N K and Konchits V V 2006 Electrical contacts: fundamentals, applications and technology. (London: Taylor & Francis Group, LLC)

[10] Oliver W C and Pharr G M 2004 Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology Journal of materials research 19 1 3-20

[11] Golovin Yu I, Tyurin A I, Aslanyan E G, Pirozhkova T S and Vorobev M O 2016 Local physicomechanical properties of materials for use in calibration of nanoindentation instruments Measurement Techniques 59 9 911-15

[12] Golovin Yu I, Tyurin A I, Aslanyan E G, Pirozhkova T S and Vasyukov V M 2017 The physical and mechanical properties and local deformation micromechanisms in materials with different dependence of hardness on the depth of print Physics of the Solid State 59 9 1803-11

[13] Golovin Yu, I Ivolgin V I, Korenkov V V and Tyurin A I 1997 Determination of the time-dependent plastic properties of solids by dynamic nanoindentation Technical Physics Letters 23 8 621-23

[14] Golovin Yu I, Tyurin A I and Iunin Yu L Strain-rate sensitivity of the hardness of crystalline materials under dynamic nanoindentation 2003 Doklady Physics 48 9 505-08

[15] Burlakova V E, Belikova M A, Tyurin A I, Pirozhkova T S, Drogan E G, Novikova A A and Sadyrin E V 2019 Mechanical properties and size effects of self-organized film Journal of Tribology 141 5 051601

[16] Myshkin N and Petrokovets M 2018 Friction lubrication, wear. Physical foundations and technical applications of tribology (in Russian) (Moskow: Litres)

[17] Tyurin A I, Pirozhkova T S and Shuvavin I A 2016 Research of processes of deformation when forming a print and friction in micro- and nanoscale (in Russian) Izvestia of higher educational institutions. Physics 59 7-2 243-47

[18] Tyurin A I and Pirozhkova T S 2016 Research of the processes of friction and wear of solids in the micro- and nanoscale (in Russian) Vestnik of Tambov University. Series: Natural and technical sciences 21 3 1375-80

[19] Bowden F P and Tabor D 1964 Friction and lubrication of solids (Oxford: Clarendon Press)

[20] Deryagin B V 1955 Problems of adhesion Research (London) 8 70-74.

[21] Moscow, 1949 Kragelskii I V 1982 Friction and wear (Elmsford: Pergamon Press)

[22] Nakayama K, Bou-Said B and Ikeda H 1997 Triboelectromagnetic Phenomena of Hydrogenated Carbon Films -Tribo-electrons, -Ions, -Photons and -Charging, J. Tribol. 119 764-68

[23] Hu J Ogletree D F 1995 Salmeron M Atomic scale friction and wear of mica Surface science 3 327 358-70

[24] Carpick R W, Agrait N, Ogletree D F and Salmeron M 1996 Measurement of interfacial shear (friction) with an ultrahigh vacuum atomic force microscope Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena 14 2 1289-95