905. Tribological evaluation of nano-composite coatings in piezoelectric contact

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Abstract. Piezoelectric micro-engines (PEA) are used in precise positioning equipment in medical, measurement applications, space engineering etc. Tribological processes in the friction contacts of such actuators are very important because efficiency of PEA friction pairs is influenced by roughness and hardness of the surfaces. Studies indicate that friction pairs for the reliable constant operation of PEA could be developed when using surface materials of different roughness and hardness. These parameters could be controlled by application of metallic carbides and oxides as plasma coatings. The use of tribo-active materials can decrease volumetric wear of friction surfaces and increase the reliability of PEA.

Keywords: piezoelectric actuators, tribology, plasma sprayed coatings.

Introduction

Piezoelectric actuators (PEA) are considered as micro-engines of 21 century, which are used in precise positioning equipment where high accuracy is required. Such property is very important in such application areas as medical technologies, measurement techniques, space engineering etc. Modern high-tech technologies enable easy automation of manufacturing of small-sized precise details. Assembly of such components is conducted at the scale of microns.

Tribological processes in the friction contacts of such actuators are very important. Their investigation is complicated due to high-frequency vibrations (up to 500 kHz and higher) [1] and low-amplitude displacements (up to 10 μm) [2, 3]. The efficiency of PEA friction pairs is influenced by roughness and hardness of the surfaces. The wear of counter-body is very important because piezoelectric ceramic materials are very hard. When counter-body is too soft, its roughness reduces significantly and wear spot appears in the contact zone [4]. Such interaction of friction pair materials requires the research of the phenomena in the contact zone and the looking for the efficient solutions of this problem.

Tribo-active materials

Friction force in contact zone is very important factor for piezoelectric motor operation and influences the drive step of PEA. It depends of friction coefficient of materials and presence of lubricant. Different friction coefficients of contact materials (steel-steel, steel-alumina, alumina-sapphire) determine the smaller or bigger motion step of PEA [5]. This is presented in Fig. 1.

Piezo-element can have the friction pair and the mechanical properties of piezo-materials are important. Known piezo-materials are single-crystal materials, piezoceramics, piezopolymers, piezocomposites and piezofilms. Most common single-crystal piezo-materials are quartz (SiO_3), lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$). Widely used piezo-ceramic are polycrystalline materials. Barium titanate ($BaTiO_3$) is the most investigated piezo-ceramic material. Barium titanate ceramic was modified by the doping of lead (Pb) and calcium (Ca) ions to stabilize the tetragonal phase over a wider temperature range and such ceramic is used as commercial piezoelectric materials. Lead zirconate titanate Pb(Ti, Zr)O_3 solid solution piezo-ceramics is widely used because of their superior piezoelectric properties. Tetragonal distortion was reduced and the structure was transformed to rhombohedral by the doping of zircon (Zr). The borderline of those two structure phases is called the morphotropic phase boundary [6].

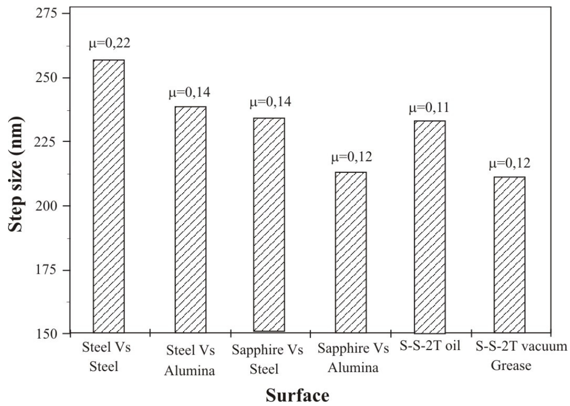

Fig. 1. Variation of average step size with different experimental conditions [5]

The crystal properties change dramatically after doping of donor ions. The use of niobium (Nb^{5+}) or thallium (Ta^{5+}) provides soft PZT and acceptor doping with iron (Fe^{3+}) leads to hard crystal. Such properties are determined by the facility of domain motion due to the resulting vacancies [6].

Relaxor ferroelectric materials (with phase transition from the paraelectric to ferroelectric state) can be prepared either in polycrystalline form or as single crystals. Relaxor-type electrostrictive materials, such as lead titanate, ($Pb(Mg_{1/3}Nb_{2/3})O_3$ - $PbTiO_3$), solid solution are highly suitable for PEA applications. Besides it the polymeric materials could be used for PEA applications, such as Polyvinylidene difluoride (PVDF or PVF2). It is piezoelectric when stretched during fabrication. Thin sheets of the cast polymer are then drawn and stretched in the plane of the sheet, in at least one direction, and frequently also in the perpendicular direction, to transform the material to its microscopically polar phase. Piezo-composites comprised of a piezoelectric ceramic and a polymer phase are promising materials because of their excellent and readily tailored properties [6].

High efficiency of current design PEA requires components, forming the translation motion contact between the acting piezo-ceramics and the moving parts, to have a constant coefficient of friction of about 0.5. This places high demands on the wear resistance of coatings protecting the respective components in order to use the maximum of the force. Friction surfaces are covered by such coats of titanium chromium oxides ($Ti_2Cr_2O_7$; Ti_4O_7/Ti_5O_9), titanium molybdenum (TM23), Magneli-type coatings ($Ti_{n-2}Cr_2O_{2n-1}$ and Ti_nO_{2n-1}) and other materials. Plasma spraying technology is used for such coatings [7, 8, 9].

Research of different materials shows how the volumetric wear changes when different materials on contact surfaces are used. The tests were performed when the sonotrode was always the moving part, while the disc was stationary. Investigation results demonstrated that higher wear appears when only one friction surface was coated comparing to the tests of both non-coated steel surfaces. When the tests were performed with the both coated surfaces (sonotrode coated with $Ti_2Cr_2O_7$ and disc coated with TM23) the volumetric wear was significantly lower than in previous tests. Long-duration tests of the various Magneli-type coatings were performed too (Table 1). The tests were running at about 40 kHz for around 30 days non-stop to reach about 1×10^{11} cycles. All Magneli-type coatings tested here seem to lead to superior low volumetric wear volumes. Exchanging the sonotrode coating (moving part) with the disc coating (stationary) or vice versa does not seem to have a significant effect on the values of the wear volume what was the case with $Ti_2Cr_2O_7$ and Ti_4O_7/Ti_5O_9 coats. In the case of the self-mated tests of the $Ti_2Cr_2O_7$ coating, the load was increased by a factor of three and the temperature in the contact has been increased up to 210 °C. Comparing the respective results with those of a test carried out at standard load and temperature with the same coatings indicates that such levated load and temperature do not seem to have an effect on the volumetric wear values [7].

Table 1. Volumetric wear values of long duration tests with strokes of about 5 μm and frequencies around 40 kHz under dry conditions [7]

Sonotrode/ coating material	Disc/ coating material	Load (N)	Cycles (10^8)	Distance ($\times 10^6$ m)	K_v sonotrode (10^{-6} mm^3/(Nm))	K_v disc (10^{-6} mm^3/(Nm))	K_v total (10^{-6} mm^3/(Nm))
AlMgZnCu1.5/ $Ti_2Cr_2O_7$	AlFeXY/ TM23	2.8	1.08×10^3	1.14	1.28×10^{-4}	6.19×10^{-4}	7.47×10^{-4}
AlMgZnCu1.5/ $Ti_2Cr_2O_7$	AlFeXY/ $Ti_2Cr_2O_7$	3.0	5.96×10^2	0.64	8.69×10^{-5}	0.69×10^{-4}	1.56×10^{-4}
AlMgZnCu1.5/ $Ti_2Cr_2O_7$ (210ºC)	AlFeXY/ $Ti_2Cr_2O_7$	9.4	7.55×10^2	0.80	7.53×10^{-5}	0.95×10^{-4}	1.70×10^{-4}
AlMgZnCu1.5/ $Ti_2Cr_2O_7$	AlFeXY/ $Ti_4O_7Ti_5O_9$	3.1	1.11×10^3	1.10	2.20×10^{-4}	1.38×10^{-4}	3.78×10^{-4}
AlMgZnCu1.5/ $Ti_4O_7Ti_5O_9$	AlFeXY/ $Ti_2Cr_2O_7$	3.4	1.04×10^3	1.02	9.11×10^{-5}	1.05×10^{-4}	1.96×10^{-4}
AlMgZnCu1.5/ TM23	AlFeXY/ $Ti_4O_7Ti_5O_9$	3.0	0.90×10^3	0.96	1.74×10^{-4}	0.50×10^{-4}	2.24×10^{-4}

The investigations show that the friction pairs for the reliable constant operation of PEA could be developed when using the surface materials of different roughness and hardness values.

Coating of friction surfaces with tribo-active materials

The molecules are spitted to the atoms when the plasmas spraying at 2000 °C temperature is used. Increasing the temperature up to 3000 °C the electrons are separated and the ionization is taking place. The ions of metals can make bonds and the strong compounds are formed [8].

The type of plasma gas is very important because the speed of plasma is depending on it. Fig. 4 presents the structures of formed coats when two different gases were used. When the speed of plasma particles is higher its scattering increases and that determines the thinner layer and the shorter cooling time (Fig. 2a) [9].

The cooling with dry ice flow was introduced to improve the properties of metallic alloys and ceramic coatings [10, 11]. This method can be considered as environmentally sustainable technology. Comparison of this method with regular air cooling show that more dense coats of steel and CoNiCrAlY alloys with less oxides could be obtained with dry ice flow. Moreover, the adhesion with bulk material of Al_2O_3 coat was by 30 % higher (over 60 MPa) when the dry ice flow cooling was used (Fig. 3) [12].

The roughness, hardness and consequently friction coefficient of friction pair could be controlled using the coating with tribo-active materials. The corrosion resistance of surface could be also considered. The coating with such materials is made also by plasma spraying. The powder of required material is supplied to plasma injector sprayed on the surface [13, 14]. The fine-grained powder of Cr_2O_3, Cr_3C_2-NiCr, Al_2O_3, TiO_2 etc. could be used for the spraying

[15, 16]. The data for such experimental coatings indicates that deposition thickness is close to standard samples when the chromium oxide coating was used. The difference of deposition thickness reaches 4 times when Cr_3C_2-NiCr powder was used. Obtained roughness was lower and hardness was the same as in standard samples [10].

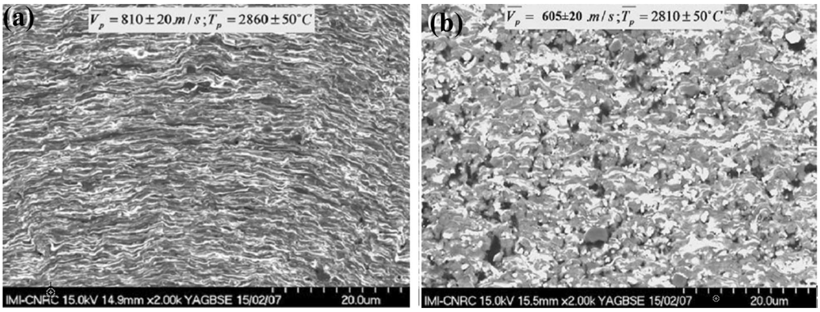

Fig. 2. Coating obtained in plasma spray process when using (a) hydrogen gas with high particle velocities and (b) helium auxiliary gas with lower particle velocities [9]

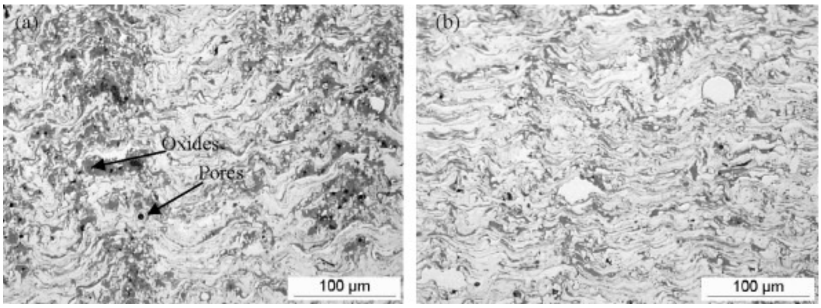

Fig. 3. Coatings deposited by plasma spray (a) with air cooling and (b) dry-ice blasting [11]

Piezoelectric actuators with anisotropic surfaces

PEA are operating in ultra-precise mode in micro-positioning and micro-manipulation devices. Very important parameter for PEA is stroke or displacement range, which is very small for such actuators and that limits their application possibilities. The advantage of anisotropic surfaces is their ability to increase stroke range and to change the friction coefficient depending on the motion direction. Friction of isotropic surfaces is equal or similar in all directions and anisotropic surface has a different friction resistance in different directions because of asymmetric triangular structure (Fig. 4) [17, 18].

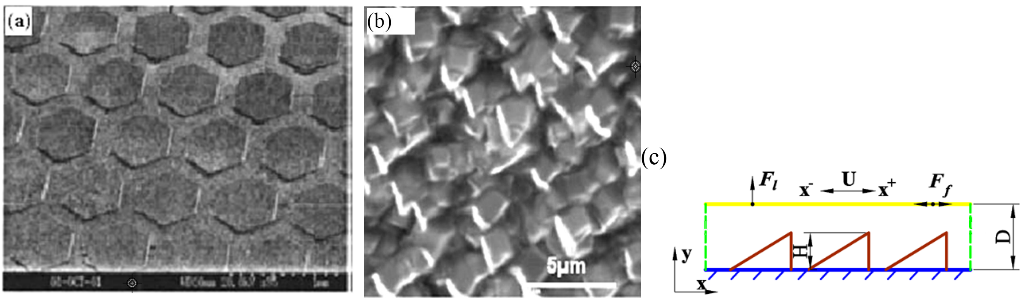

Fig. 4. Isotropic (a) and anisotropic (b) surfaces [17, 18]
and (c) general geometry scheme of anisotropic asperity surface [19]

Research on the anisotropic structures revealed that the declination change of asymmetric triangles caps can change the friction force depending on motion direction. Such structure of anisotropic asperity surface (Fig. 4c) [19] could be achieved by the control of material spraying parameters.

Ion beam etching in the micron level was conducted on the diamond coating following the chemical vapor deposition (CVD) process to receive the anisotropic structure of the surface. The graphs in Fig. 5a reveal significant difference of friction coefficient depending on motion direction (A and B) [20].

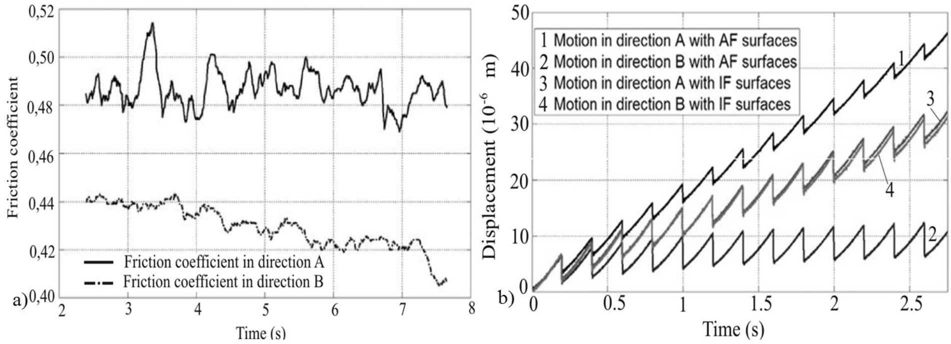

Fig. 5. (a) Friction coefficients of ball-on-disc tests of anisotropic surface and (b) experimental result of performance of anisotropic (AF) and isotropic (IF) friction surfaces [20]

Displacement speed measurements of anisotropic and isotropic friction surfaces in PEA with stick-slip motion indicate that displacement of anisotropic surface differs significantly in contrary A and B directions (Fig. 5b). For isotropic surfaces the PEA displacement in both directions is very similar [20].

Investigations of anisotropic friction surfaces show its high application potential for the stick-slip PEA increasing its displacement range. However there is the problem in increasing the tribological efficiency in the opposite direction.

Conclusions

Piezo-ceramic contact with widely used materials (steel, alumina, copper, bronze) induces surface wear in the softer counter-body. Such interaction requires the investigation of tribological processes in contact zone and identification of possible solutions to this problem by means of coatings which can stabilize friction surfaces.

Surface roughness and hardness parameters could be controlled by the using of metallic carbides and oxides. The use of tribo-active materials can decrease volumetric wear of friction surfaces and increase the reliability of PEA.

Main technology of coating with tribo-active material is plasma spraying when the ionized coating materials show best adhesion efficiency with the bulk material.

The use of anisotropic friction surfaces in PEA with stick-slip motion can improve the efficiency of friction surfaces up to 50 % comparing to isotropic surfaces. The tribological efficiency in contrary direction could be improved by the investigation of operation parameters of PEA and the use of additional tribo-technical materials.

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