Microplasma discharges exited by a plasma flow on constructional metals

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Abstract. Results are presented from experimental and theoretical studies of microplasma discharges excited by a plasma flow on constructional metals partially covered with a dielectric (oxide) film. Tribological tests of metal samples treated by microplasma discharges show a significant increase in their wear resistance due to the formation of a strong microrelief on the sample surface.

1. Introduction
The interaction of a pulsed plasma flow with a negatively biased (~100–450 V) metal surface partially covered with a ~1-μm-thick dielectric film results in the excitation of microplasma discharges at the film edge [1–3]. The mechanism of excitation is as follows. Under the action of the ion flow, the outer surface of the film acquires a positive electric potential with respect to the metal, due to which a strong electric field of about several MV/cm arises at the film edge. Being additionally amplified at the microroughness of the metal surface, this field initiates explosive emission from the metal and results in the development of microarcs (microplasma discharges) with a plasma density of ~10\textsuperscript{20} cm\textsuperscript{-3} and temperature of ~0.5–1 eV [4]. The high pressure (~10\textsuperscript{7} Pa) of the plasma and metal vapor heated to ~5000 K above the melted metal surface at the locations of microplasma discharges leads to the formation of microcraters on the metal surface. Since microplasma discharges evaporate the dielectric film, the area covered with the film gradually shrinks and, after several plasma pulses, the entire metal surface turns out to be remelted and cleaned of the film. As a result, a strong microrelief in the form of overlapped craters is produced on the metal surface.

2. Experiment
In our experiments, microplasma discharges on metal samples were excited by a pulsed plasma flow with a density of ~10\textsuperscript{12}–10\textsuperscript{13} cm\textsuperscript{-3} and an electron temperature of $T_e \approx 10$ eV. The plasma ion component consisted mainly of hydrogen ions (90–80%) and singly charged carbon ions (10–20%). The parallelepiped samples with a total surface area of 2–3 cm\textsuperscript{2} were made of constructional metals, such as VT1 titanium, V95 aluminum alloy, and Steel 45. Dielectric (oxide) films of thickness ≤2 μm were delosited on the sample surface by heating in open air [1, 2]. Thicker dielectric (SiO\textsubscript{2}) films on titanium samples were deposited by sputtering in high vacuum. Under the action of an ~20-μs-long plasma flow, microplasma discharges were excited at the border of the sample surface covered with
the dielectric film (figure 1). The microplasma discharges continued to burn for ~20 ms (while the negative voltage was being applied to the sample), i.e., long after the plasma pulse has terminated. After ~10 plasma pulses, the sample was completely cleaned of the film and its entire surface acquired a microrelief (figure 2). At MPD currents of 100–600 A, the microrelief height on all six faces of the sample was in the range of 2–18 μm. For a voltage applied to the sample of \( \phi_0 = -450 \) V, the probability of microplasma discharge excitation on a sample covered with a 1-μm-thick film was close to 100%. When using films with thicknesses of 4 μm and more (up to 12 μm), the probability of microplasma discharge excitation decreased with increasing film thickness (figure 3). When using films with thicknesses less than 1 μm, the probability of microplasma discharge excitation decreased from a value close to 100% for film thicknesses of 0.2–1 μm to lower than 0.3% for films thinner than 0.01 μm.

Figure 1. Plasma injector (on the right) and microplasma discharges burning at the boundary between the dielectric film and the open Ti surface (on the left).

Figure 2. Microrelief formed on the surface of a V95 Al sample under the action of microplasma discharges with a total current of 200 A and duration of 20 ms.

Figure 3. Probability of microplasma discharge excitation on Ti samples covered with dielectric films of different thickness \( d \) (\( \phi_0 = -450 \) V).

3. Simulations
A decisive factor governing plasma–solid interaction is the strength of the electric field arising in the Debye sheath with a thickness on the order of \( r_D = \left( T_e / 4 \pi e^2 n_e \right)^{1/2} \), where \( T_e \) is the plasma electron temperature, \( n_e \) is the electron density, and \( e \) is the electron charge. Under our experimental conditions
(\(n_e = 10^{12} - 10^{13} \text{ cm}^{-3}, T_e \approx 10 \text{ eV}\)), the Debye radius is \(r_D \approx 10 \mu\text{m}\) and the characteristic electric field in the sheath (for \(\phi_0 = 0\)) is as low as \(E^* \approx 10 \text{ kV/cm}\). Application of a high (compared to \(T/e\)) negative (with respect to the plasma) electric potential \(\phi_0\) to the metal does not alter the situation qualitatively, because the thickness of the Debye sheath increases with increasing applied voltage as \(\mid \phi_0 \mid^{3/4}\) and, accordingly, the electric field strength on the metal grows very slowly, \(E \sim \mid \phi_0 \mid^{1/4}\). For \(T_e = 10 \text{ eV}\) and \(\phi_0 = -400 \text{ V}\), the electric field on the metal surface increases compared to \(E^*\) by only a factor of 4, i.e., to \(\sim 40 \text{ kV/cm}\). The situation, however, changes radically if the metal surface is covered with a thin \((d \ll r_D)\) dielectric film. In this case, the flux of positive ions from the plasma charges the outer surface of the film and its potential tends toward the floating potential \(\phi_f \approx -3T/e \approx -30 \text{ V}\) with respect to the plasma. In our experiments, \(\mid \phi_f \mid \ll \mid \phi_0 \mid\); hence, almost the entire voltage between the plasma and metal turns out to be applied to the thin dielectric film and the electric field inside the film is \(E \sim \mid \phi_0 \mid / d\), i.e., for \(\phi_0 = -400 \text{ V}\) and \(d \sim 1 \mu\text{m}\), it can reach several MV/cm. At the film edge (as well as in the film breaks), this field turns out to be applied to the open metal surface. In this case, even a moderate (at a level of \(10-20\)) additional field amplification on the metal microroughnesses is sufficient to cause explosive emission from the metal surface and the formation of a microarc, i.e., excitation of a microplasma discharge at the film edge.

Generation of a strong electric field at the film edge was simulated using a modified particle-in-cell method, which takes into account that the time of flight of ions through the Debye sheath is several orders of magnitude shorter than both the duration of the plasma pulse and the characteristic time of the film charging. In this case, in the course of film charging, ions move in a quasi-stationary electric field, i.e., at each time step, ion motion can be considered established and the ion flow can be represented as an ensemble of positively charged “jets” propagating in a stationary electrostatic field. Such an approach can be called the “jet-in-cell” method [2].

To model electron emission from the metal surface near the film edge, we used the Fowler–Nordheim formula for the density of field emission [5, 6], assuming that the electron work function is \(\varphi = 3 \text{ eV}\) and the characteristic field amplification on the microroughnesses of the metal surface is \(\beta = 15\). According to [6], the threshold density of the electron emission current required for the development of explosive emission was assumed to be \(\sim 10^8 \text{ A/cm}^2\).

The simulations have shown that, without electron emission from the metal, the maximum value of the electric field at the open metal surface near the film edge is \(E_{\text{max}} = \mid \phi_0 \mid / 2d\) [1–3] in a wide range of experimental parameters (such as the plasma density, bias voltage \(\phi_0\), film thickness, film permittivity, and inclination angle of the film edge). For example, for a film thickness of \(\sim 0.5 \mu\text{m}\) and \(\phi_0 = -400 \text{ V}\), we have \(E_{\text{max}} \sim 4 \text{ MV/cm}\). Taking into account the 15-fold additional field amplification on metal microroughnesses, such a field strength is quite sufficient for the development of explosive electron emission [6], followed by the formation of a microplasma discharge at the film edge.

The simulations also have shown that, depending on the inclination angle of the film edge, there are two regimes of microplasma generation. At inclination angles of \(\alpha \leq 80^\circ\), the emitted electrons do not fall on the film and practically have no effect on the value of the generated electric field (figure 4).
Figure 4. Distribution of the electric potential near the film edge, trajectories of emitted electrons, and profiles of the electric field strength on the metal $|E_y|$ and the field-emission current density $j_e$ at $\phi_0 = -400$ V, $n_e = 4 \times 10^{12}$ cm$^{-3}$, $T_e = 10$ eV (hydrogen plasma), $d = 0.5$ µm, $\alpha = 80^\circ$, $\varphi = 3$ eV, $\beta = 15$. The potential difference between neighboring equipotential lines is $\Delta \phi = 0.5 T_e/e$.

At $\alpha \approx 90^\circ$, the electron beam emitted from the metal surface falls on the end face of the film, which results in the accumulation of a negative charge at the film edge and a substantial reduction in the field strength in this region. Taking into account secondary electron emission from the film surface partially compensates for this reduction; however, the electric field strength turns out to be insufficient for the development of explosive electron emission from the metal surface. Nevertheless, under the action of the pulsed ($\tau \sim 0.1$ µs) beam of accelerated field-emission electrons with an energy of $\sim 100$ eV and a current density of $\sim 10^5$ MA/cm$^2$, the end face of the film is heated to a temperature of $\sim 1000^\circ$C (figure 5), which may result in efficient gas desorption from the dielectric surface. The development of a microplasma discharge in this case can be related to the formation of a dense plasma bunch near the film edge due to the electric breakdown of the desorbed gas and/or its ionization by the field-emission electron beam.

The shape of the experimental dependence of the probability of microplasma discharge excitation $P$ on the film thickness (figure 3) can be explained as follows. The decrease in $P$ at $d > 2$ µm can be attributed to the decrease in the maximum value of the electric field strength at the film edge, which is inversely proportion to film thickness. At film thicknesses less than 0.1 µm, leakage of the electric charge from the outer film surface due to the finite conductivity of the TiO$_2$ film ($\rho \sim 0.5 \times 10^7$ Ω cm, see, e.g., [7]) comes into play, which also leads to a decrease in the probability of microplasma discharge excitation [3].

4. Applications
The treated and untreated samples were subjected to standard tribological tests [8, 9]. It was found that the wear resistance depends on the current of microplasma discharges $i$, which determines the
parameters of the microrelief formed on the sample (the characteristic scale of microroughnesses and the thickness and structure of the remelted surface layer) in the course of microplasma treatment.

The results of tribological tests of steel 45 samples show that the allowable pressure $p_a$ (the maximum pressure applied to the samples at which no scuffing occurs on their friction surfaces) increases from 3 MPa (for polished samples without microplasma treatment) to ~25 MPa (for samples treated by microplasma discharges) (see figure 6). The maximum allowable pressure for steel 45 samples was achieved at $i \approx 400$ A (figure 7).

Figures 8 and 9 present results obtained from similar tests performed for samples made of D16T aluminum. Here, the allowable pressure applied to the samples increased from ~0.2 MPa for untreated samples to about 7 Ma for samples treated by microplasma discharges at a current of 100 A.

Finally, figure 10 presents results obtained for Ti samples treated by microplasma discharges at a current of ~300 A. The allowable pressure $p_a$ was found increase from ~0.2 MPa for untreated samples to about 10 MPa after microplasma treatment. In this case, the wear rate $I_h$ of treated samples in the pressure range of $p = 2–10$ MA turned out to decrease drastically (by many times) compared to that for untreated samples at $p \sim 0.2$ MPa.
Figure 10. Wear rate $I_h$ of titanium treated by microplasma discharges at a current of ~300 A vs. pressure $p$ applied to the samples.

It could seem paradoxical that the wear resistance of treated samples with the well-developed microrelief turns out to be much higher than that of smooth untreated samples. The matter is that, in standard tribological tests, the friction surfaces of the samples are lubricated with oil. At high pressures applied to untreated samples, oil is forced out of the friction gap, which leads to catastrophic wear and destruction of the sample surface. The microrelief on the sample surface in the form of craters retaining the lubricant prevents extrusion of oil from the friction gap, thereby significantly reducing the friction force and wear rate in a wide range of pressures applied to the samples treated by microplasma discharges.

Biological experiments on the fissiparity of stem cells of bone tissue [10] have shown their good affinity to the microrelief produced by microplasma discharges on titanium surface, which may be useful for medical applications.

Thus, the results of tribological and biological tests demonstrate that the phenomenon of a microplasma discharge excited on a metal surface by a plasma flow opens wide prospects for creating wear resistant materials that can find application in industry, orthopaedics, and stomatology.

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