Evaluation of tribotechnical properties of modified surfaces after plasma electrolytic treatment

T L Mukhacheva, T M Kalinina and S A Kusmanov
Department of Physical, Mathematical and Natural Science, Kostroma State University, 17 Dzerzhinskogo Street, Kostroma 156005, Russia
E-mail: sakusmanov@yandex.ru

Abstract. The article considers the study of the effect of plasma electrolytic processing on the tribotechnical characteristics of medium-carbon steel. Friction tests were carried out in dry friction mode. Electron microscope and profilometer were used to study the friction tracks. For a comprehensive assessment of the quality of the modified surface layer, the Kragelsky-Kombalov complex parameter was calculated. It was found that plasma electrolytic treatment leads to a decrease in the coefficient of friction and weight wear in comparison with hardened and untreated steel. It has been determined that the mechanism of wear of samples after plasma electrolytic treatment is fatigue wear at boundary friction and plastic contact.

1. Introduction
Chemical heat treatment of steel products occupies an important place among the methods of increasing their wear resistance. Many publications have shown the possibility of effectively increasing the wear resistance of steel parts by means of their plasma electrolytic saturation with nitrogen, carbon or boron. Cathodic plasma electrolytic nitriding reduces the wear rate of G3500 cast iron by 2.5 times, and S0050A steel by 3 times under dry friction conditions [1]. However, the effect of electrical discharges during cathodic treatment led to an increase in the coefficient of friction. Similar results were obtained for plasma electrolytic nitriding high-speed steel R6M5 [2] or alloy steel 34CrNi1Mo [3], where the resistance to abrasive wear is reduced by 1.5 times. Positive results were obtained with cathodic plasma electrolyte boriding of steel H13 [4] Anodic processes are characterized by a decrease in surface roughness due to the anodic dissolution of the sample, which makes it possible to reduce the friction coefficient and the intensity of wear [5].

The disadvantage of the existing works is the lack of study of the wear mechanism and a comprehensive study of the effect of surface microgeometry on the tribotechnical characteristics of treated materials. This paper proposes to consider this issue.

2. Materials and methods
Cylindrical samples of medium-carbon steel (0.45 wt.% C) 10 mm in diameter and 10 mm in height were subjected to various types of plasma electrolytic processing.

Anodic plasma electrolytic nitrocarburising was carried out in an aqueous solution of ammonium chloride (10 wt.%) and carbamide (20 wt.%) at the sample temperature of 750 °C for 7 min, followed by quenching in the same electrolyte by turning the electrolyzer voltage off.
Anodic plasma electrolytic nitriding was carried out in an aqueous solution of ammonium nitrate (5 wt.%) and ammonium chloride (15 wt.%) at the sample temperature of 850 °C for 5 min, followed by plasma electrolytic polishing in the aqueous solution of ammonium sulfate (5 wt.%) under voltage of 300 V and the solution temperature of 80 °C for 1 min.

Cathodic plasma electrolytic boriding was carried out in an aqueous solution of boric acid (3 wt.%) and ammonium chloride (10 wt.%) at the sample temperature of 850 °C for 30 min, followed by plasma electrolytic polishing in the aqueous solution of ammonium sulfate (5 wt.%) under voltage of 325 V and the solution temperature of 70 °C.

The friction scheme "shaft-block" was used in friction tests (figure 1). The counter body was made of tool alloy steel (wt. %: 0.9–1.2 Cr, 1.2–1.6 W, 0.8–1.1 Mn, 0.9–1.05 C) in the form of a plate with a semicircular notch 10 mm in diameter, enclosing the surface of the sample. The sample was mounted on a shaft driven by an electric motor. The counter body was mounted on a platform sliding along cylindrical guides. The platform was moved using a pneumatic cylinder. The cylinder, guides and platform were able to rotate with the pendulum. The pendulum shaft was located coaxially with the sample. Such a scheme makes it possible to preserve the common rotation axis for the sample and the counter body as they wear out and to avoid the influence of misalignment on the results of measurements of the frictional moment.

Friction tests were carried out in dry friction mode under a load of 10 N. The sliding speed of the sample along the counter body was 1.555 m/s. The friction path was 1000 m.

The friction tracks images were obtained using a Quanta 3D 200i scanning electron microscope. The characteristics of the microgeometry of the friction track surface were investigated on a TR-200 profilometer.

For a comprehensive evaluation of the quality of the modified surface layer, the Kragelsky-Kombalov complex parameter was used, since, in addition to the height parameter, it includes the parameters of the distribution of irregularities along the height and the average radius of curvature of microprotrusions.

\[
\Delta = \frac{R_{\text{max}}}{rb} \tag{1}
\]
where \( R_{\text{max}} \) is the maximum height of irregularities; \( r \) is the radius of microroughness, determined by modelling the protrusions with bodies of double curvature:

\[
r = \frac{9R_{\text{a}}^2S_m^2}{128(5.5R_{\text{a}} - R_p)^3}
\]

(2)

The constants \( \nu \) and \( b \) are determined experimentally from the measurement results of the profilograms of a rough body [6]:

\[
\nu = 2l_m \left( \frac{R_p}{R_{\text{a}}} \right) - 1
\]

(3)

\[
b = l_m \left( \frac{R_{\text{max}}}{R_p} \right)^{\nu},
\]

(4)

where \( R_{\text{a}} \) is the arithmetic mean deviation of the profile; \( R_p \) is smoothing height or distance from the line of protrusions to the centre line within the base length [5], \( l_m \) is relative reference length of the profile at the level of the centre line.

3. Results and discussion

Parameter (1) determines the load-carrying capacity of the roughness profile. The results of its calculation are presented in table 1.

Table 1. Kragelsky-Kombalov criterion (\( \Delta \)), wear resistance and frictional properties.

| Processing type                          | \( \Delta \)     | Average friction coefficient | Maximum wear (mg) |
|------------------------------------------|------------------|------------------------------|-------------------|
| Anodic plasma electrolytic nitrocarburising | 0.253±0.004 | 0.445±0.007                  | 3.02±0.03         |
| Anodic plasma electrolytic nitriding with plasma electrolytic polishing | 0.158±0.002 | 0.526±0.008                  | 1.19±0.02         |
| Catodic plasma electrolytic borizing with plasma electrolytic polishing | 0.161±0.002 | 0.388±0.006                  | 5.31±0.11         |
| Furnace quenching                        | 0.398±0.006 | 0.622±0.009                  | 8.02±0.15         |
| No processing                            | 0.892±0.013 | 0.798±0.014                  | 21.90±1.11        |

Plasma electrolytic processing with subsequent plasma electrolytic polishing allows obtaining the maximum bearing capacity of roughness at the friction contact, which is evident from the minimum values of the \( \Delta \) criterion. The bearing capacity of the profile is the smallest for untreated and quenched samples.

The relief observed in the photographs of the friction tracks (figure 2, 3 and 4) corresponds to the calculated values of the \( \Delta \) criterion in table 1. The distribution of the material along the height of the rough layer and the distribution of the tops of microprotrusions and their height along the base length are more even and smooth on the friction track of the sample after plasma electrolytic processing (figure 2). In the bright areas, plastically deformed microvolumes of the metal are formed, which, with repeated exposure, lead to the displacement of the material with permanent deformation after the passage of the microprotrusion.
The properties of the frictional contact, specified, in particular, by the Kragelsky-Kombalov criterion, largely determine the processes of friction and wear. Samples after all types of plasma electrolytic processing are characterized by a lower coefficient of friction and weight wear compared to quenching and untreated steel (table 1).

The type of wear of the samples modified with plasma electrolytic processing is fatigue wear at boundary friction and plastic contact. With classical quenching or no processing, the plastic contact is replaced by microcutting.

4. Conclusions
It has been established that plasma electrolytic treatment with subsequent plasma electrolytic polishing allows obtaining the maximum bearing capacity of the roughness at the friction contact, as evidenced by the minimum values of the Kragelsky-Kombalov criterion. The bearing capacity of the profile is the smallest for untreated and quenched samples.

A decrease in the coefficient of friction and mass wear after all types of plasma electrolytic treatment in comparison with hardened and untreated steel has been established.

It is shown that the type of wear of samples modified by plasma electrolytic treatment is fatigue wear at boundary friction and plastic contact. With or without conventional hardening, the plastic contact is replaced by microcutting.

Acknowledgments
This work was financially supported by the Russian Science Foundation (Contract No. 18-79-10094) from Kostroma State University.

References
[1] Nie X, Wang L, Yao Z C, Zhang L and Cheng F 2005 Surf. Coat. Technol. 200 1745
[2] Skakov M, Rakhadilov B, Scheffner M, Karipbaeva G and Rakhadilov M 2013 Appl. Mech. Mater. 379 161
[3] Skakov M, Verigina L and Scheffner M 2015 Appl. Mech. Mater. 379 161
[4] Taheri P, Dehghanian Ch, Aliofkhazraei M and Sabour Rouhaghdam A 2007 Plasma Process. Polym. 4 S711
[5] Mukhacheva T L, Belkin P N, Dyakov I G and Kusmanov S A 2020 Wear 462-463 203516
[6] National standard of the Russian Federation. Geometrical Product Specifications (GPS). Moscow, Standartinform, 2015 http://docs.cntd.ru/document/1200116337