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ORIGINAL PAPER

Application of pulsed plasma accelerators for surface modification

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Abstract A pulsed coaxial plasma accelerator was utilized in the experiments discussed in this paper. Plasma streams with ion energy up to 2 keV, plasma density 2–3×10^{14} cm^{-3}, and plasma energy density 5–40 J/cm^{-2}, were generated. Such a plasma was used for the surface modification of different constructional steels. Experimental results on improvement of physical properties of metal surfaces (first of all tribological characteristics), under their irradiation by pulsed plasma streams are presented. Optimization of the treatment process was carried out varying plasma energy flux, plasma density, and energy of ions. It was shown that microhardness of the steel samples, both non-quenched and previously quenched, was increased by several times after plasma irradiation. The main attention was paid to the analysis of wear resistance of the treated material by using different methods of wear tests. The possibility to achieve a sufficient decrease of the wear rate of the treated samples was demonstrated.

Key words modification • plasma stream • plasma treatment • surface • wear resistance

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Introduction

Special attention is paid to increasing working resources of details of the machine-building equipment and other devices. Alongside with the creation and use of a number of new constructional materials, and the perfection of conventional hardening methods used for gears and friction surfaces of units, the significant efforts are devoted to the development of new ecology-clean vacuum-plasma technologies. One of such methods is the surface modification by its irradiation with pulsed plasma (mainly nitrogen) streams [1, 2, 4].

Some experimental results that deal with improvement of physical and mechanical properties of different constructional steels (Russian trade marks 40H, 12HN3A, SHH15 and others) and surfaces, treated with a pulsed plasma, have been presented in our previous papers [1, 2, 4]. Various working gases were used for the plasma treatment [1]. The possibility to create a quasiamorphous Rayer upon a sample surface, with thickness >10 μm, was shown. The essential increase in wear resistance (by 10 times) at dry friction and in microhardness (~3–5 times) of modified layers upon non-quenched steels were found.

In this paper a comparative analysis of the influence of plasma processing on tribological characteristics of both non-quenched, and previously quenched steels, is presented. A correlation between microhardness and wear resistance change, after the surface treatment with plasma streams, was analyzed. The main attention was paid to the wear characteristics of treated surfaces when using different methods of wear tests, such as pin-on-disk, flat-on-flat, cavitation and others.

Installation and diagnostics

Experiments were carried out within the stand equipped with a pulsed plasma accelerator (PPA). The PPA consisted of a coaxial plasma accelerator (with the anode of 14 cm diameter, and the cathode of 5 cm diameter) and a vacuum chamber of 120 cm in length, and 100 cm in diameter. The power supply system was a condenser bank with stored energy up to 68 kJ. The discharge current was < 400 kA, a plasma stream duration was 3–6 μs. The PPA generates plasma streams with ion energy up to 2 keV, plasma density 2×10^{14} cm^{-3}, specific power 10 MW/cm^2, and energy density within the range of 5–40 J/cm^2. Spectroscopic equipment, a mass-energy analyzer, calorimeters, electric and magnetic probes, pyro-bolometers, and so on, were used for measurements of plasma parameters.

The variation of working regimes of the PPA was accomplished by choosing a gas quantity, supplied to the accelerating channel, and changing the delay of switching on the voltage between electrodes with respect to the start of the gas supply. It was important to get plasma streams with as large as possible radial cross-section providing irradiation of large surface areas of samples with homogeneous energy loading to the treated surface. Measurements of radial distributions of the plasma energy density were carried out for different regimes by using local movable calorimeters. The results, obtained at a distance of 35 cm from the PPA output for different working gases and capacitor bank voltages, are shown in Fig. 1.

One can see that the effective diameter of plasma stream is of the order of 8 cm for the operation either with hydrogen or with nitrogen. By increasing the distance from the PPI, the area of homogeneity increases, achieving 14–16 cm in diameter for z = 70 cm. The energy density decreases with the distance by 1.7–3 times, depending on the operational regime. Therefore, the effective variation of the energy density deposited on the sample surface can be provided by both changing the working voltage (and ion energy accordingly), and changing the distance from the accelerator (variation of density with constant ion energy).

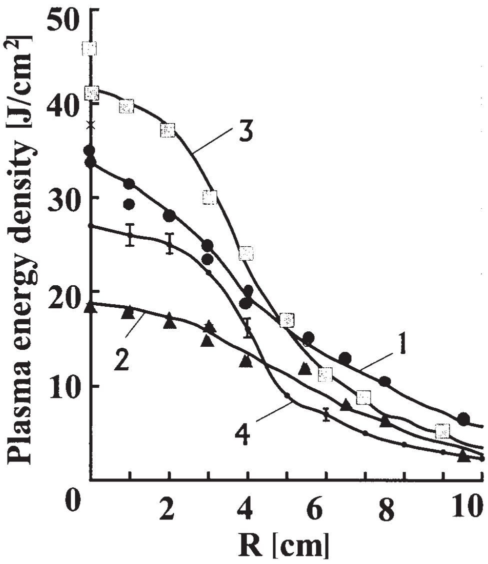

Fig. 1. Radial distributions of plasma energy density for the nitrogen plasma streams (1 and 2) and for the hydrogen ones (3 and 4): 1 – capacitor bank voltage U_c = 25 kV; 2 and 3 – U_c = 20 kV; 4 – U_c = 15 kV.

The samples of different constructional steels of the Russian-Ukrainian trade marks (H12, steel 45, 12HN3A, 40H, SHH15, steel 10 and so on) as well as metalloceramic hard alloys WCo8 and WCo20 were placed within a vacuum chamber at a distance of 35–70 cm from the PPI. A number of diagnostics were utilized for the analysis of the treated surfaces, e.g. the Vickers method was used for microhardness measurements, and for measurements of surface roughness a profilometer was used. Analysis of the surfaces and cross-sections of the treated samples was carried out with optical and electron scanning microscopes. Investigation of the wear resistance of the treated samples was carried out by a method of tribological test [5], a cavitation method [3], and others.

Results of tribological tests and discussions

Analysis of the microhardness behavior in dependence on the treatment dose, as carried out earlier for some grades of steel, has shown that the microhardness was increased with the number of working pulses, achieving a maximum for 5–7 shots. These measurements were extended to a wider range of steel grades, including both non-quenched and previously thermally quenched steels. The values of microhardness, achieved after the materials processing by nitrogen plasma with the load 15–20 J/cm^2, are shown in Table 1. As a result, the treatment increased the microhardness, even for materials with very high initial hardness (WCo20).

The steel samples were examined by the pin on disk method under the following conditions: friction was realized in air at the sliding velocity of 0.8 m/s under normal load of 7 N and 10 N, at an air temperature of 293 K. The friction path varied within the range of 1–20 km. The test results, performed for different grades of steels for 1 km friction path (for the range of energy loads 15–20 J/cm^2), are shown in Fig. 2.

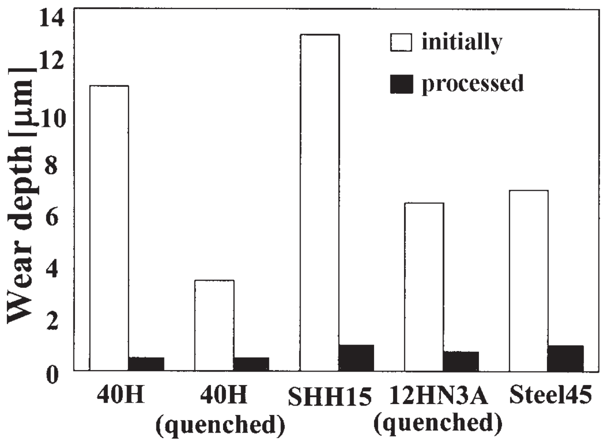

Fig. 2. The diagram of wear depth of initial and processed steel samples for friction path 1 km.

Table 1. Microhardness of materials processed by pulsed nitrogen plasma streams.

Material	H_v, kg/mm^2 Before processing	H_v, kg/mm^2 After processing
Steel 10	200	510
Steel 45	250	628
Steel 45	370	796
quenched*	400	870
40H	252	751
40H quenched	386	794
37CrS4	352	742
SAE 1040	264	527
65G	350	560
12HN3A	236	630
12HN3A quenched	387	715
H12	312	510
H12	439	554
quenched*	553	593
WCo20	1000	1400

* groups of samples quenched in different conditions and using different technologies.

The significant increase in the wear resistance, as a result of the plasma stream processing, was registered for all the investigated steels, including the previously quenched ones. For example, for the quenched steels of 12HN3A and 40H types, the wear resistance was increased approximately by 6–8 times, and by 3.5–6 times, accordingly. Plasma processing of the non-quenched steel of 40H type led to an increase in the wear resistance by 10–20 times.

The material behavior under conditions of various wear modes (especially for heavy loaded tools) can be different, even at the variation of velocity or load. For instance, it is well known that the optimal drill feed, and rpm for drills with TiN coatings, are differed from those observed for the ones with non covered surfaces. In the case of different wear modes realization, to achieve a maximum effect it may be necessary to change the regime of plasma processing, working gas, dose of treatment, etc. Therefore for investigations of wear characteristics of industrial steels, processed with plasma streams, and tested under different friction conditions, several additional methods (of wear tests) were used.

Flat-on-flat wear tests were carried out with a cylindrical indenter fot steel of ShH15 type (diameter – 25 mm, microhardness – 550–600 kg/mm^2), under the load of 70 N. A linear wear of the non-quenched steel 40H (sample of 30 mm in diameter), as measured after 10 km friction pass, was decreased from 70 μm (for the non-processed sample) to 30 μm for the sample irradiated with the plasma. For the previously quenched steel of 40H type these values were 12 and 8 μm, respectively.

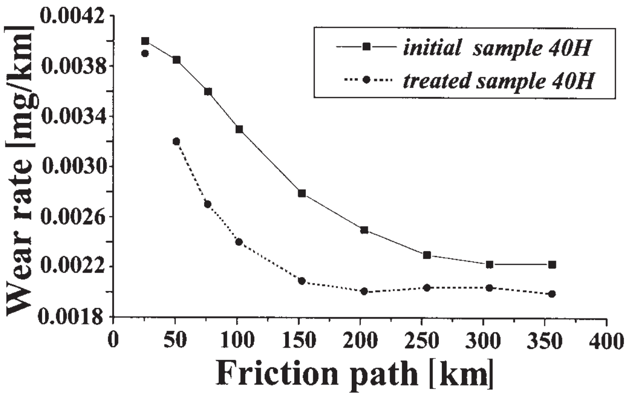

Fig. 3. Abrasive wear rate in dependence on friction pass.

Table 2. Cavitation wear rate of 40H samples.

	Initial 40H samples		Treated 40H samples	
Wear rate	non-quenched	quenched	non-quenched	quenched
V x 10^{-4}, g/h	1.6	0.4	0.2-0.6	0.2

Abrasive wear tests were fulfilled with a vulcanite wheal of 30 mm in diameter, rotating with a speed varying within the range of 200–3000 rpm, under the load of 128 G. The abrasive wear rate for the 40H steel, in dependence on the friction pass, is shown in Fig. 3. One can see that the wear rate for the treated sample is lower than that for the non-treated one at the beginning of the tests. It reaches a plateau sooner, and it remains smaller with a further increase in the pass.

Under a micro-impact effect, the material surface is exposed to specific loads characterized by dynamic stresses. These stresses are concentrated in the regions which are comparable with the size of the material structure. The micro-impact effect is realized when cavitation or high-velocity streams of solid particles, or liquid droplets, interact with the material surface. The aim of cavitation wear tests was to investigate the influence of the pulsed plasma processing on the resistance of steel against cavitation damages, and to inspect structure changes after the cavitation effect. The samples processed with plasma streams were examined for the cavitation resistance with the use of a magnetostriction vibrator. The vibrator frequency was 20 kHz, and an amplitude of oscillations was 30 μm. Such a scheme of tests is often used for an analysis of turbine blades of different devices, permanently operating in water. For the determination of a cavitation wear, the mass losses of the samples were measured in dependence on the duration of the cavitation exposure. The wear rates, as measured at the stage of the steady-state cavitation wear (after a long term cavitation influence), are shown in Table 2. From this Table one can see that even for the previously-quenched steel the cavitation wear rate was decreased at least two times, for the samples irradiated with the pulsed plasma streams, in comparison with the non-processed ones.

From the results described above and in Ref. [1] it follows that both microhardness and wear resistance (pin-on-disk tests) of all the treated steels were simultaneously increased several times. To verify this correlation, a special experiment was performed. Samples of the H12 steel, to be irradiated by plasma, were previously quenched to a high microhardness value (for this kind of steel H_v ~ 560 kg/mm^2). As a result of the plasma processing of these samples, only a weak increase (or not at all) in the initial microhardness value, was registered. As to the wear tests, their results are shown in Table 3.

From this Table it follows that wear resistance of the treated samples was increased up to 4 times in comparison with

Table 3. Results of wear tests for quenched steel H12.

Sample	Length of friction path (m)	Friction coefficient	Linear wear (µm)
H12 non treated	10000	0.01-1.2	1.5-1.7
	15000	0.01-1.7	2.0
H12 processed with 3 pulses	10000	0.01-1.2	Initial roughness smoothing
	15000	0.01-1.3	0.5-1.0
H12 processed with 6 pulses	15000	0.01-1.3	Initial roughness smoothing (<0.5)

its initial value. Only initial roughness smoothing, without visible wear track, was registered. Therefore, in general, the microhardness behavior and wear resistance are not correlated. As a whole, modified layers of the treated industrial steels are characterized by the considerable wear resistance under conditions of the dry friction and cavitation.

Conclusions

New experiments on metal sample treatments with pulsed plasma streams were carried out. It was shown that the uniform character of the surface processing with the plasma was achieved for the samples with diameters up to 80 mm at a small distance, and 140 mm at a distance of 70 cm from the accelerator. As a result of the samples processing with plasma streams, an increase in the microhardness of surfaces up to 4 times was achieved. The microhardness increase by 1.5–2 times was achieved, even for the majority of previously quenched steels. This result was possible due to the modification of surfaces. The thickness of a layer with an increased microhardness was as high as 10–30 µm, in dependence on the steel grade and treatment regime.

Different wear tests (pin-on-disk, flat-on-flat, abrasive, cavitation) were carried out for the samples irradiated with pulsed nitrogen plasma. The essential decrease of wear of the processed surfaces for all grades of steels including the previously thermally quenched ones was achieved. These results are of importance for the determination of optimal regimes of the pulsed plasma processing, i.e. for the identification of wear modes and optimal friction conditions for steels processed with plasma streams.

The correlation between the change of the surface layer microhardness, and the increase in its wear resistance, was investigated. It was shown that using the plasma treatment it is possible to increase the wear resistance considerably, even in cases when the surface microhardness is varied incidentally.

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