The structure and properties of modified surface carbon steel by compression plasma flow

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Abstract. The influence of the compression plasma flow generated by the magnetoplasma compressor of the edge type on the carbon steel surface in different modes is investigated. The half-period of the oscillations was \( T/2 = 6 \mu s \). The voltage on a capacitor bank with a capacitance \( C = 18 \mu F \) was varied by \( U = 10–20 \) kV. The impulse treatment was carried out in a residual air atmosphere at a pressure \( p = 133 \) Pa at a fixed distance to the sample \( d = 44 \) mm. The behavior of the plasma stream was visualized by the shadow method of Tepler and the calculated velocity was \( \vartheta = 10^4 \) m/s. The hardness of the surface was measured by the Oliver-Farr method, and an increase in hardness was recorded, including an anomalous hardening \( \sigma = 16 \) GPa.

1. Introduction
Over the past twenty years in applied research of the interaction of high-intensity energy fluxes and particles with a condensed matter several common methods for structural modification of materials have been formed [1-3]. The classification of these methods is based on the selection according to the sort of particles carrying energy: electron beams [4], ion beams [5, 6], plasma flows [7] and laser radiation [8, 9]. All of the above methods are well researched; they have their advantages and disadvantages. In addition, along with listed methods above the broadband radiation [10, 11] treatment takes place, but it’s not well developed. The bulk of researches is devoted to the first wall materials of fusion reactor [12] and considered their erosion resistance, but radiation may improve some functional properties of the material surface. The influence of the broadband radiation to functional characteristics of the material surface is still poorly understood, that’s why this investigations are important.

One of devices, which can generate broadband radiation, is the erosive magnetoplasma compressor (MPC) [13] of the edge type electrodes. Unlike the gas-discharge MPC [14–16] with long accelerating channel MPC of erosion type [17] has a short accelerating channel, which determines an efficient energy conversion into radiation. That may significantly influence the surface processes in the material. When material exposed by erosive MPC compressive plasma flow, then we can mark several features: 1) the powerful broadband radiation; 2) the supersonic compressive plasma flow 3) a short time duration impulse \( >10 \mu s \).

Despite of many publications on the listed methods, there are no papers, which considered the effect of powerful broadband radiation on the material surface, have been published. In addition, investigations were carried out during the operation of the MPC in a quasi-stationary mode at pulse duration from 100 to 1000 \( \mu s \), and effects with a shorter duration were not studied.

2. Experimental setup
In the experiment the experimental setup (figure 1) was used, where the possibility of the compression plasma flow and radiation treatment on the carbon steel (C=0.2%) surface was take place. The magnetoplasma compressor (insulator material \( C_2F_4 \) fluoroplastic) of the edge type had the external and
inner electrodes. Diameter of the external electrode was 34 mm, and the inner electrode diameter - 6 mm, the material of the electrodes was stainless steel AISI 321.

MPC 1 was placed in a vacuum chamber 2 and connected to a vacuum station (Pfeiffer HiCube 80Eco) 3. The pressure in the chamber was measured with a vacuum gauge (Ceravac ctr 100) 4 and was \( p = 133 \) Pa. A sample 5 (a cube made of carbon steel with a side of 15 mm) was placed in the geometric center of the vacuum chamber, and it could be rotated about the axis with the motion manipulator aid. So it was able to use two surfaces at a same time (front and back sides). A capacitive energy storage device (\( C = 18 \mu F \), \( U_{\text{max}} = 28 \) kV) was connected to the MPC, which was charged from a high-voltage power supply 6. The thyatron 7 was connected to the ignition unit 8. The key delay was carried out with a pulse delay generator 9, which supplied a control signal to the thyatron ignition unit. The calibrated current monitor (Pearson 304/20) 10 measured the discharge current. The signal from the current monitor was measured by the oscilloscope 11. The spectrometer 12 for registering the radiation of the discharge was connected to a computer 13. The protection of the measuring equipment from electromagnetic interference was carried out with the help of Faraday cup 14. Also, a diagnostic module for the schlieren method was at the setup. It made possible to visualize the process on a nanosecond time scale.

Figure 1. Experiment scheme: 1 — MPC, 2 — vacuum chamber, 3 — vacuum pump, 4 — vacuum gauge, 5 — sample, 6 — power supply, 7 — thyatron, 8 — ignition unit, 9 — time delay generator, 10 — current monitor, 11 — oscilloscope, 12 — spectrometer, 13 — computer, 14 — Faraday cup.

3. Experimental resultes and decisions
Two factors influencing the modification of the surface layer were considered in the experiment: the value of energy impulse (10, 15, 20 kV) and the number of processing pulses (1, 5 pulses). The effect was on a carbon steel sample with an initial microhardness of 157 HV0,5. The distance to the machined surface was 44 mm. Impulse treatment of the target material was carried out in an air atmosphere at a residual pressure of 133 Pa.

Figure 2. The propagation of shock wave front.
For the experimental series, the following modes were selected: 1) \( U = 15 \text{ kV}, n = 1 \); 2) \( U = 15 \text{ kV}, n = 5 \); 3) \( U = 10 \text{ kV}, n = 1 \); 4) \( U = 20 \text{ kV}, n = 1 \). Where \( U \) is the voltage across the capacitor, \( n \) is the number of processing pulses. The experimental setup operated in a single pulse mode.

Figure 2 shows the visualization of the pulse treatment process of a sample with microsecond time resolution using the shadow method of Tepler (schlieren method). The plasma flow velocity may be calculated from a propagation of the shock wave front (figure 2). The value was estimated as \( 10^4 \text{ m/s} \) for 15 kV capacitor voltage.

The hardness of the treated surface was measured on microsections using Oliver-Far method [18], according to which the nanohardness is determined as the ratio of the maximum load to the contact area of the trihedral pyramid of Berkovich. The measurements were carried out at a load of 5, 10, 25, 50 mN according to ISO 14577 (GOST R 8.748-2011). The location of the measurement was chosen in the middle of modified layer (figure 3a).

It was studied plasma flow influence zones of normal and tangent fall to the surface. In case of the tangent plasma flow interaction with the surface, the effect was not fixed. When normal plasma flow was, the thin surface layer was recorded.

Morphological analysis of the section shows that in addition to the standard pearlitic and ferritic inclusions can be noticed a fused surface layer with an uneven wavy structure, which indicates structural-phase transformations. The thickness of the surface layer varied from 2 to 8 \( \mu \text{m} \), although in some places the modified layer quite was not. The mean value of measured data of the listed regimes was evaluated for 90% probability. In Mode 1, the highest hardness of the surface layer reached an anomalous value of 16.4 GPa, although the average value was 5.05±0.7 GPa. In regime 2, the mean hardness of the layer was 2.97±0.4 GPa, the thickness became smaller and amounted to 2 to 6 \( \mu \text{m} \). In regime 3, the mean hardness reached its maximum value of 15.1±2.6 GPa (values lying in the range from 9 to 25 GPa), the thickness of the layer varied from 2 to 8 \( \mu \text{m} \). In regime 4, the surface layer had a vanishingly small character and did not exceed 2 \( \mu \text{m} \). In directly after the layer so the measured data indicates the hardness of another unknown structure and it was 3.5±0.27 GPa. So it seems mode 3 has to be the most optimal.

![Figure 3. Microsections: a) \( U = 15 \text{ kV}, n = 1 \); b) \( U = 15 \text{ kV}, n = 5 \); c) \( U = 10 \text{ kV}, n = 1 \); d) \( U = 20 \text{ kV}, n = 1 \).](image)

4. Conclusion
Thus, the pulse treatment carbon steel by the compression plasma stream generated by the edge type magnetoplasma compressor with a half-period of 6 \( \mu \text{s} \) duration, provides the hardening of the surface layer with a thickness of up to 8 \( \mu \text{m} \). An anomalous increase of the steel surface hardness up to a value of 16.4 GPa was recorded. This can be explained not only due to the quenching mechanisms of carbon steels, but the introduction of nitrogen atoms into the surface and the formation of new chemical structures may influence. It may also be noted that the increasing in discharge energy does not influence on a permanent hardening and has some optimal value in range of 10 kV. Among the all, mode 3 had to be the optimum.
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