Study of parameters of a facility generating compressive plasma flows

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Abstract. The prosperity of plasma technologies stimulates making of a facility generating compressive plasma flows at the South Ural State University. The facility is a compact-geometry magnetoplasma compressor with the following parameters: stored energy up to 15 kJ, voltage of a bank from 3 to 5 kV; nitrogen, air, and other gases can serve as its operating gas. The investigation of parameters of the facility showed the following parameters of compressive plasma flows: impulse duration of up to 120 µs, discharge current of 50-120 kA, speed of plasma flow of 15-30 km/s. By contrast to the available facilities, the parameters of the developed facility can be adjusted in a wide range of voltage from 2 kV to 10 kV, its design permits generating CPF in horizontal and vertical positions.

1. Introduction
Recently much attention has been given to the development of methods of treatment of structural materials by high-intensity beams of charged particles and plasma with the density of power flow of \((\sim 10^5-10^8 \text{ W/cm}^2)\), since the treatment allows enhancing performance properties of treated items. Radiation technologies are featured by a series of advantages as against methods conventionally used in machinery: the possibility to treat high-precision parts of complicated shapes, short treatment time, easy automation of the process, etc. Hence, investigations of processes of radiation effects on a substance aimed at the development of novel materials are a crucial task of the modern materials science.

The accumulated data on explored interaction of high-intensity charged particles and plasma with a solid body prove the prosperity of newly-developed radiation technologies for processing of different structural materials [1].

Lately issues of the treatment of materials by plasma have received primary consideration, since plasma treatment has a number of unanswerable advantages against laser technologies. Firstly, the plasma treatment of structural materials is much cheaper than laser technologies and traditional chemical methods. Moreover, plasma facilities have high capacity, i.e., high rate of modification of a unit area of the material surface per a unit of time. If a fine powder is introduced in plasma, a range of possible coatings is enlarged, if compared with evaporation of the material with other methods for further deposition. The electron-plasma treatment is an advanced subject [2]. In this case the adhesion of a plasma-applied coating is strengthened, when further exposed to an electron beam.

There are a variety of methods used to generate plasma for technological purposes. The most widely used are methods based on plasma of vacuum-arc charges [3,4] or of a discharge glowing in gas [5]; plasma generated when a material is evaporated under powerful energy flows (laser emission, electron or ion beams) and plasma is formed in a facility generating Compressive Plasma Flows (CPF)
The CPF [7] is featured by high density (up to $10^{18}$ cm$^{-3}$), velocity of plasma flow ($10^3$-$10^5$ m/s), temperature (from 2 to 5 eV), duration of exposure from 80 to 200 µs, allowing to settle a wide range of scientific and practical tasks of the exposure of various materials to high-intensity energy flows [8,9].

However, despite of a great promise in the CPF application the problem analysis demonstrates that theoretical and experimental investigations of the CPF interaction with a solid body are insufficiently explored. As a rule, the available publications mainly address particular technological tasks [9,10] and do not deeply analyse physical nature of the obtained results. Thus, with a bulk of experimental data on the CPF interaction with a solid body, there appears an urgent need in systematic experimental and theoretical study of the problem.

Although an idea on the CPF generation was formulated in 60-s of the last century [11], the number of facilities for such technological tasks is extremely low. Due to the need in the systematic study of the CPF interaction with a substance a facility generating Compressive Plasma Flows was developed at South Ural State University. By contrast to the available facilities, parameters of the developed facility can be adjusted in a wide range of voltage from 2 kV to 10 kV, its design permits generating CPF in horizontal and vertical positions.

2. Experimental facility

The CPF generating facility is a magnetoplasma compressor (MPC) [7]. It consists of three key components: a power source, a vacuum chamber and an MPC.

The power source has two main blocks - a charging device and an energy storage. The charging device is designed to charge an impulse sectional bank of capacitors (the energy storage). The charging device is a bridge inverter with a retardation coil. The bank of capacitors has the current of 0.7 A and voltage of 5 kV.

The bank with the total margin up to 15 kJ consists of 12 impulse capacitors K41-I7 (capacity 100 µF, nominal voltage 5 kV). The capacitors are connected into one sectional bank of capacitors with a copper bus 4x40 mm. 12 impulse capacitors are structurally packed in two sections, 6 capacitors each to enlarge voltage up to 10 kV. The battery is discharged into the MPC through an ignitron IRT-6. The ignitron can be controlled.

The vacuum chamber is made of a sheet of organic glass 16 mm thick. The chamber internal size is 250x250x500 mm. Flanges from stainless steel 12X18H10T are placed in end faces of the chamber. The flanges are screwed up with each other by studs M8 from stainless steel 12X18H10T. The front flange has 8 holes, M8 in diameter, symmetrically spaced in a circle 50 mm in diameter, which are designed to house electrodes of an anode, and a central orifice 22 mm in diameter to place a cathode pack.

There are 8 electrodes of the anode (copper rods 8 mm in diameter 14 mm long) screwed in the front flange), an electrode of the cathode (a frustum with diameters 30 mm and 60 mm 50 mm long with an axial orifice (diverter)) made of copper inside the vacuum chamber (a discharge chamber of the facility).

The cathode isolator is made of fluorine plastic 4. The front flange has a hole ½ inch in diameter to supply the plasma generating gas.

The CPF generating facility operates as follows. Air is evacuated from the vacuum chamber with a vacuum pump up to 100 Pa, then the chamber is filled with the plasma generating gas up to the required pressure (from 500 Pa to 2 kPa). The plasma generating gas is filled from a balloon through a gear reducer. The pressure inside the discharge chamber is controlled with vacuum meters. The facility can operate with various plasma generating gases and their mixtures at different pressures. The arc discharge is initiated in the discharge chamber with the controlled ignitron IRT-6. The ignitron is switched on with an impulse lasting 10-20 µs with 2 kV voltage from a discharge control device between the cathode and the discharge control electrode. When the ignitron is switched on, high voltage is supplied from accumulating capacitors to electrodes housed in the discharge chamber.
3. Investigation of the CPF generating facility parameters
The discharge current was taken with a current meter based on the Rogovski belt principle. The discharge current shape and impulse parameters were measured with an oscillograph Rigol DS1052E in control sockets of a high-voltage rectifier and are shown in Fig.1a. The voltage level in accumulating capacitors was taken with a kilovoltmeter, while the voltage shape was recorded with an oscillograph (Fig.2b) in control sockets of the high-voltage rectifier.

![Figure 1. Oscillograms of the discharge current (a) and voltage (b).](image)

The CPF velocity was measured using a passing-over time method. For this two pairs of electrodes were placed at l=30 cm, a pair of electrodes were s=1 cm apart. The plasma flow, passing over the pair of electrodes, closed it. The corresponding oscillograms are illustrated in Fig.2. The first pair closure corresponded to -5V. The second pair was closed at +12V. As it can be seen in the Figure, the total time of closure of the electrodes is approximately 100 µs, and time within which the plasma flow passes over a 30-cm distance amounts to 20 µs. Thus, the impulse duration results in 100 µs (at nominal voltage 4.2 kV), and the plasma flow velocity amounts to 15 km/s.

![Figure 2. Measuring the plasma flow velocity and impulse duration.](image)
In the course of the experiment specifications of the designed CPF generating facility were defined. The facility parameters are summarized in Table 1.

**Table 1.** The facility parameters

| Parameters                                      | Value                      |
|------------------------------------------------|----------------------------|
| Plasma generating gas                          | Nitrogen, hydrogen, argon, air |
| Capacity of the accumulating capacitor         | 1200 µF                    |
| Voltage of the accumulating capacitor          | 2…5 (10) kV                |
| Stored energy, maximum value                   | 15 kJ                      |
| Discharge current                              | 50…120 kA                  |
| Impulse duration of discharge current          | up to 120 µs               |
| Plasma velocity of the compressive flow        | 15…30 km/s                 |
| Length of compressive plasma flow              | 8…12 cm                    |
| Plasma flow diameter                           | 1…2 cm                     |
| Pressure in vacuum chamber                     | from 40 Pa to 101.3 kPa    |
| Pump output                                    | 72 l/min                   |
| Water rate (to cool the ignitron)              | 72 l/min                   |

**4. Experimentally studied CPF interactions with a substance**

The experimental facility was used for experiments with modified surfaces of samples. For the experiment we took samples from steel 3 (50x50 mm in section, 3 mm thick) and glass (100x100 mm in section, 3 mm thick). The geometry sizes of the samples were selected so that they exceeded the plasma flow diameter with due account to the plasma scattering in radial direction along the surface.

After processing we visually observed a non-treated area; an area where the plasma flow falls normally, the area is featured by the formation of craters and the increased surface relief; an area where the plasma flow scatters radially along the surface, the area is featured by a wavy relief elongated in direction of the plasma flow scattering.

Fig. 3 presents the surface of steel 3 before and after it was treated with the CPF. The initial roughness was Ra=1 µm, upon treatment with the CPF at density of the absorbed energy 20 J/cm² it can be noted that the surface roughness increased, in accordance with the profilometry data it reached the value Ra=10 µm.

The foreign inclusions can be also noted in Fig. 3 upon the sample treatment. The foreign inclusions appeared since the cathode material got damaged and precipitated as drops on the sample. The regime of the plasma generator was observed when relative positions of the cathodes and anodes became unsymmetrical.

In Fig. 4 similar results are given for the CPF treated glass. Before the CPF treatment the glass surface was smooth, upon the treatment the surface damage can be visually seen as a system of cracks with rounded edges due to melting. The craters, which surfaces are free of cracks, were also observed.
5. Conclusion
The experimental facility generating CPF was made and its parameters were investigated. The investigation of parameters of the facility showed the following parameters of compressive plasma flows: impulse duration of up to 120 µs, discharge current of 50-120 kA, speed of plasma flow of 15-30 km/s. By contrast to the available facilities, parameters of the developed facility can be adjusted in a wide range of voltage from 2 kV to 10 kV, its design permits generating CPF in horizontal and vertical positions.

The surface modifications caused by the CPF treatment were experimentally explored. It was shown that upon the CPF treatment a system of cracks with rounded edges due to melting appeared on the glass surface.

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