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The impact of a shock-compressed layer on the mass transfer of target material during processing compression plasma flows

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ABSTRACT

The paper describes the results of experimental and numerical research of the thickness of the molten bath and the surface erosion of a substance under the influence of compression plasma flows. It has been demonstrated that the formation of the shock-compressed layer affects the melted depth and the mass erosion from the surface of the treated target.

1. Introduction

High-temperature plasma flows generated by plasma accelerators are some of the most promising energy carriers for use in the field of radiation technologies for production and modification of materials, since they allow a combination of ultra-fast hardening, liquid phase alloying of the surface layer by the elements of the previously applied coating, and saturation of the surface by atoms of the plasma gas. Interaction of an intensive plasma stream with the material surface can be characterized by ultrafast heating processes (10^8 K/s) of the surface layer (to temperatures exceeding the melting temperature) and cooling, resulting in structural and phase changes of the surface layer [1]. Exposure to high temperatures is one of the reasons for the erosion of the material surface that can be used to analyze the behaviour of materials in the first wall of fusion reactors in the event of disruption of the plasma [2–5]. The main mechanisms of erosion can be ablation, including evaporation and boiling of the material [3,6], as well as the melt flow on the surface, accompanied by the formation of hydrodynamic instabilities and ejection of drops of the material [2–6].

A distinctive feature of compression plasma flows (CPF) generated by quasi-stationary plasma accelerators is the relatively large discharge duration (in the order of hundreds of microseconds), while maintaining high plasma parameters (plasma speed is 30–70 km/s, temperature of the plasma is 2–5 eV; the electron density is 10^{16}–10^{18} cm^{-3}) [7]. The shock-compressed plasma layer [7] is formed at the surface of the sample under the influence of supersonic compression stream; the position of its border is determined by the dynamic balance between the pressure of the compression flow and gas-kinetic (heat) expansion of the surface plasma. These high energy plasma parameters of the shock-compressed layer provide high-speed surface heating to temperatures above the melting point of almost any material.

The main parameters that determine the structure, element and phase composition of the surface layer, modified layer thickness, and weight of the material eroded from the surface, is the density of the absorbed energy in the surface layer [8,9]. At the moment, much (more than 10 years of research) empirical material has been collected on the modification of materials by compression plasma flows [8]. The theoretical studies [10,11] have made it possible to explain a number of experimentally observed facts. However, the current approach leaves a significant discrepancy between the results of numerical calculations and experimental data, such as the volume eroded from the treated surface material and the molten depth. For example, as noted at [12], the CPF, in terms of the energy emission, can be considered as a surface energy source and consequently [12] the molten depth is determined by the thermal conductivity and is equal to a few micrometers. Experimental data presented in this work, though, indicate that the molten depth can reach tens of micrometers, depending on the treatment mode. Mass erosion from the target surface, also measured in this work, is, in some cases, below the results of numerical calculations using BETAIN software package [13]. This discrepancy between numerical calculations and experimental data may be explained by the fact that the research [13] did not take into account the effect of plasma pressure on the dynamics of the near-surface layers of material.

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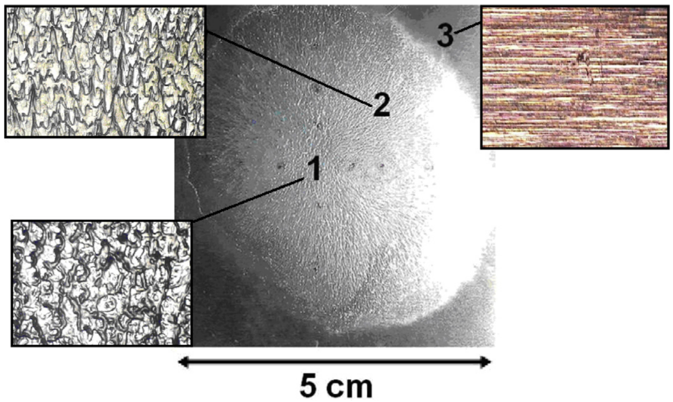

Fig. 1. View of the target after CPF treatment.

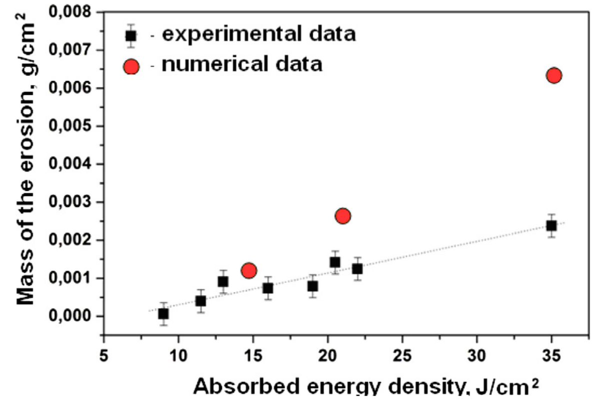

Fig. 2. The dependence of the mass of the erosion material at the unit surface area upon the absorbed energy density.

The goal of this work is the experimental and numerical study of the effect of a shock-compressed layer on mass transfer and its impact on the depth of the molten bath formed and mass of the erosion material from the surface of the sample.

2. Experimental method

The object of the study is steel samples of grade st.3. (0.2C, 0.2Si, 0.5Mn in wt.%, Fe-balance) with dimensions of 50×50 mm and thickness of 3 mm. The geometric dimensions of the samples were larger than the radius of the plasma flow, taking into account the radial scattering of the plasma along the surface of the sample.

The samples were exposed to the compression plasma flow generated in a gas-discharge magnetoplasma compressor of compact geometry (MPC CG) [7,11]. In the experiments, the initial voltage on the capacitor bank was 4 kV, discharge time ~100 microseconds. The velocity of compression plasma flow was $(4–7) \times 10^4$ m/s. The temperature and the concentration of electrons in the plasma compression flow were, respectively, 1–3 eV and $(4–7)\bullet 10^{17}$ cm^{-3}. Pressure was up to 15 MPa.

Target treatment by the plasma flow was conducted in “residual gas” mode, where the container under vacuum was filled with nitrogen (the working gas) up to a pressure of 400 Pa. The density of the energy absorbed by the surface of the sample, according to calorimetic measurements, was $W = 10–35$ J/cm^2. It should be noted that this density of the absorbed energy is averaged over the area of the sample, and it does not account for the energy dissipated by the evaporated matter.

Measurement of the sample weights before and after the exposure was conducted using the analytical laboratory balance VLA-200-M with measurement precision of ±0.2 mg. The state of the sample surface was analyzed using the scanning probe microscope Solver Pro and the profiler Proton-MIET, model 130.

Prior to treatment by the plasma flow, the steel samples of st. 3 were ground. The surface of the sample, as a result of grinding, had formed parallel grooves, the depth of which was approximately 1.5 µm.

3. Results and discussion

After samples treatment by the CPF, there was a visually noticeable change to the surface conditions, and the following areas can be identified (Fig. 1.): (1) the central region is the part of the sample surface where the plasma stream was normally directed; (2) the transitional region (the region between 1 and 3) is the part of the sample surface where the radial scattering of the plasma stream occurs; (3) the untreated area is the part of the sample where the surface was not affected by the treatment (the surface relief did not change).

Numerical analysis of the dependence of melted depth and the mass eroded from the material surface upon the absorbed energy density was performed using BETAIN_1D software package [13]. Action of the CPF on a substance was evaluated as heat flow, because the CPF is, in fact, a surface energy source. The calculations took into account the evaporation (ablation) of the material, the redeposition of the evaporated material was not taken into account.

Fig. 2 presents the results of numerical and experimental studies of the dependence between mass erosion and the absorbed energy density. The figure shows that the results of the numerical analysis are in good agreement with the experimental data only if the input energy densities are less than 20 J/cm^2. According to calculations, the ablation of the substance is not observed at an absorbed energy density of less than 15 J/cm^2.

Molten depth, determined experimentally for the absorbed energy density of $W = 20$ J/cm^2, is 20 µm (the depth of the melt was determined from the analysis of the cross section), while the numerically calculated values, determined only based on the thermal conductivity, do not exceed 5 µm.

When a target is nonuniformly heated in depth, a convective flow can appear. The following two types of convection are possible in a conducting material: thermocapillary convection and thermogravitational convection (which is caused by the acceleration of an irradiated medium). As shown in [10], at heating metal target by low-energy high-current electron (LEHCEB) beams thermocapillary convection develops while the role of thermogravitational one is negligible.

Thermocapillary convection can develop when there is temperature gradient directing into target from free surface. Energy release of CPF is surface source differed from energy release of LEHCEB. Therefore the temperature gradient pointing to opposite direction, to free surface, makes stabilizing effect on volume flow. Therefore, the role of thermocapillary convection in this problem is negligible.

The discrepancy between the experimental results and the numerical calculations can be explained by the fact that the numerical calculations do not take into consideration the effect of the shock-compressed layer on the dynamics of material during the CPF treatment. Based on the above, it can be suggested that during the action of CPF on the target, its near-surface layers change from solid to liquid state, and then, due to the pressure of the shock-compressed layer on the target, the molten bath is displaced from the Area 1 to Areas 2 and 3. If the geometric dimensions of the target are less than the diameter of the plasma stream (the geometrical dimensions of the Areas 1 and 2), the molten bath will be displaced beyond the target. Experimental studies have shown that the evaporated mass for samples with linear dimensions smaller

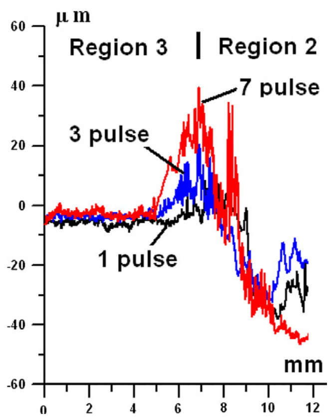

Fig. 3. The surface profile of the sample after the CPF treatment.

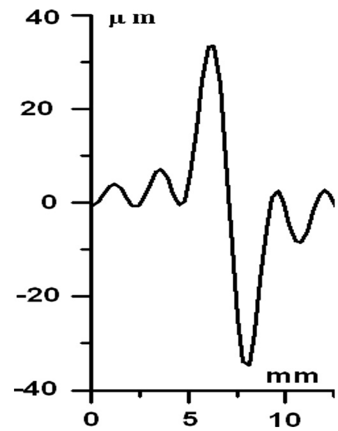

Fig. 4. The surface profile of the sample after the CPF treatment. Numerical calculation. N = 1.

than the diameter of the plasma flow is an order of magnitude larger than for samples with linear dimensions larger than the diameter of the plasma flow.

Displacement of the material leads to the exposure of the deeper layers of the target, which are subject to the CPF action. This dynamic of the target heating explains the deeper melting of the target comparing to the thermal conductivity alone. After action of the CPF on the target is completed, a part of the displaced melt returns to the Area 1 due to the surface tension forces while the molten bath still exists.

If the shock-compressed layer displaces the melt beyond the target, then the part of the melt, which has not returned to the Area 1 by the moment of crystallization, forms an "influx" of the melt on the untreated area.

Fig. 3 shows the profile of the target surface for the $W = 20\,J/cm^2$, plotted by the profiler (track length of 12 mm) after CPF treatment with different pulse numbers (N = 1, 3, 5, 7). The Figure confirms that an untreated part of the surface (Area 3) is observed for 0–4.5 mm. A "parapet" of about 40 µm in height is observed in Area 2 from 4.5 to 8 mm. The height of the "parapet" depends on the number of pulses, this supports the proposed hypothesis. Next to it, there is the depression with the depth of up to 45 µm. This profile pattern is typical for all the samples studied.

Thus, it has been experimentally discovered that the shock-compressed layer displaces melt to on the border between areas 2 and 3.

In order to confirm the proposed mechanism of surface profile formation shown in Fig. 3, numeric modelling of the shock-compressed layer influence on the dynamics of the melt has been carried out. To accomplish this, the melt (with a thickness of h) was assumed to be an incompressible fluid. Action of the CPF on the molten bath was replaced by the action of a corresponding pressure field.

To describe the nonlinear dynamics of the boundary between the two media (plasma-melt) in the approximation of the potential flows of incompressible fluids, the approach described in [14,15] has been used. Let the boundary plasma-melt be described by the equation $z = Z(x,\ t)$, where $Z(x,\ t = 0) = 0$. Axis z is pointed inside the target, the boundary between the melt and the solid phase – $z = H = -h$.

The system of equations describing the potential flow of an incompressible fluid has the standard form:

$$\nabla^2 \varphi(x, z, t) = 0, \tag{1}$$

$$\frac{\partial \varphi(x, Z, t)}{\partial t} + \frac{\upsilon^2(x, Z, t)}{2} + G(x, Z, t) + \frac{P(x, Z, t)}{\rho} = 0,$$
$$\upsilon_x(x, H, t) = \upsilon_z(x, H, t) = 0 \tag{2}$$

$$\frac{\partial Z}{\partial t} + \upsilon_x(x, Z, t)\frac{\partial Z}{\partial x} = \upsilon_z(x, Z, t), \tag{3}$$

where φ is velocity potential, $G(x, Z, t) = -g(t) Z(x, t)$ - is external field potential, where $g(t)$ - is acceleration of the free surface resulting from its plasma heating, $P(x, Z, t) = P_0(x, t) + \sigma K(x, t)$, $P_0(x, t)$ – is pressure of the compression plasma flow onto the melt, σK– is Laplace pressure, $K(x, t)$ – is surface curvature, σ - is surface tension. Bernoulli's equations (2) are the boundary conditions for the Laplace Eq. (1). The kinematic condition (3) means there is no liquid flow through the free surface.

The local transformations method [14,15] was used to solve the system (1)–(3), this permits description of the evolution of the liquid surface without calculating the flow in its entirety. The method is based on mapping of a complex area occupied by liquid, into an area with plane boundaries. Since the proposed transformations do not change the form of the Laplace equation for the velocity potential, one can find its analytic solution that permits establishment of the relation between the flow function and potential for the liquid surface. This relation allows approximated inverse transformations to the old variables, but only for the surface of the liquid.

Iron was used as the material, its mass density, surface tension and viscosity are listed in [16] for the molten iron temperature of 1800 K. At the initiation time, the melt surface was without any disturbances, i.e. absolutely smooth. Pressure on the melt surface and the linear dimensions of the system were set in accordance with the experimental conditions, results obtained are shown in Fig. 2. In the calculations, the dynamics of the system was traced for 200 μs, which is equal to the time of melt existence, the pressure of the shock-compressed layer is taken into account for the duration of the CPF action on the target (80 μs, the first 20 μs surface layers are in the solid state).

Calculations indicate that for the times of the CPF action the development of capillary waves occurs on the surface of the target; after CPF is completed the amplitude of the disturbances increases due to development of Richtmyer–Meshkov instability till crystallization.

Fig. 4. represents the calculated profile of the target surface after CPF treatment. The figure shows that an undulating profile forms as the result of the substance exposure to CPF. It is also evident that due to the pressure of the shock-compressed layer, a "parapet" is formed (Area 2), which was also observed experimentally. Amplitude of the observed surface disturbances at the crystallization time varies from 10 to 40 µm depending on parameters such as the plasma flow pressure, and the lifetime of the molten

bath, which coincides with the depth of the melt observed experimentally.

4. Conclusion

The work includes an experimental and numerical study of the effect of a shock-compressed layer on the mass transfer, the thickness of the molten bath, and erosion of material from the surface of the sample.

It has been shown that due to the pressure exerted by the shock-compressed layer upon the target, the molten bath is displaced from the centre of the treatment spot to the periphery. If the geometric dimensions of the target are less than the diameter of the plasma stream, the molten bath is displaced beyond the target. This approach provides the explanation for the experimentally determined values of the melt thickness and weight of the eroded material.

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References

[1] B.A. Kalin, V.L. Yakushin, V.I. Vasiliev, S.S. Tserevitinov, Use of high temperature pulsed plasma fluxes in modification of metal materials, Surf. Coat. Technol. 96 (1997) 110–116.

[2] V.I. Tereshin, I.E. Garkusha, A.N. Bandura, Influence of plasma pressure gradient on melt layer macroscopic erosion of metal targets in disruption simulation experiments, J. Nucl. Mater. 313–316 (2003) 685–689.

[3] A. Hassanein, V. Belan, I. Konkashbaev, L. Nikandrov, V. Safronov, A. Zhitlukhin, V. Litunovsky, Modeling and simulation of melt-layer erosion during plasma disruption, J. Nucl. Mater. 241–243 (1997) 288–293.

[4] G.V. Miloshevsky, A. Hassanein, Modelling of Kelvin–Helmholtz instability and splashing of melt layers from plasma-facing components in tokamaks under plasma impact, Nucl. Fusion 50 (2010) 115005–115016.

[5] B. Bazylev, G. Janeschitz, I. Landman, A. Loarte, N.S. Klimov, V.L. Podkovyrov, V.M. Safronov, Experimental and theoretical investigation of droplet emission from tungsten melt layer, Fusion Eng. Des. 84 (2009) 441–445.

[6] N.S. Klimov, V.L. Podkovirov, A.M. Giltuhin, V.M. Safronov, D.V. Kovalenko, A.A. Moskacheva, I.M. Poznayk, Razgibanie volfama pri vozdeystvii intensivnovo potoka plazmi (in Russ.). Voprosi atomnoy nauki I tehniki, Ser. Termoyaderniy Sintez. 2 (2009) 52–61.

[7] V.V. Uglov, V.M. Anishchik, V.V. Astashynski, V.M. Astashynski, S.I. Ananin, V.V. Askerko, E.A. Kostyukevich, A.M. Kuz'mitski, N.T. Kvasov, AL. Danilyuk, The effect of dense compression plasma flow on silicon surface morphology, Surf. Coat. Technol. 158–159 (2002) 273–276.

[8] V.V. Uglov, N.N. Cherenda, V.M. Anishik, V.M. Astashynski, N.T. Kvasov, in: Modifikaziy materialov kompressionnimi plazmennimi potokami (in Russ), BGU, Minsk, 2013, p. 248.

[9] N.N. Cherenda, V.V. Uglov, A.K. Kuleshov, V.M. Astashynski, A.M. Kuzmitski, Surface nitriding and alloying of steels with Ti and Nb atoms by compression plasma flows treatment, Vacuum 129 (2016) 170–177.

[10] K.A. Talala, A. Ya Leyvi, A.P. Yalovets, Vestnik YURGU, Seria «Matematika. Mehanika. Fizika» 7 (34) (2012) 186–190.

[11] V.M. Astashinski, A.Ya. Leyvi, V.V. Uglov, N.N. Cherenda, A.P. Yalovets, X-ray, Synchrotron and Neutron Techniques, J. Surf. Invest. 8 (3) (2014) 519–523.

[12] A.Ya. Leyvi, V.M. Astashinski, N.N. Cherenda, V.V. Uglov, A.P. Yalovets, Izvestija vysshih uchebnyh zavedenij, Fizika 57 (12) (2014) 294–298 in Russ.

[13] A.P. Yalovets, A.E. Maer, in: Proceedings of 6-th International Conference on Modification of Materials with Particle Beams and Plasma Flows, Tomsk, 2002, pp. 297–299.

[14] N.B. Volkov, A.E. Maĭer, A.P. Yalovets, Nonlinear dynamics of the interface between continuous media with different densities Technical Physics, Russ. J. Appl. Phys. 48 (3) (2003) 275–283.

[15] A.Y. Leivi, A.P. Yalovets, V.S. Krasnikov, The liquid-phase mass transfer of material in the film–substrate system exposed to intense energy flows, High Temp. Mater. Processes 17 (1) (2015) 15–24.

[16] F. Velichiny, Spravochnik, Pod. redakciej I.S. Grigor'eva, E.Z. Mejlihova, Jenergoatomizdat, M., (1991) 1234 (in Russ).