Mechanisms of surface formation at treatment with compression plasma flows

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Abstract. The mechanisms of the formation of the surface relief at treatment with intense plasma flows are considered in this paper. The main attention is paid to the formation of a wave-like relief of the surface. On the basis of the presented theoretical model for the formation of wave-like surface relief, it is shown that the inhomogeneous velocity field formed in the melt during its radial motion over the target surface leads to an increase in the elastic energy of the melt. It can be accompanied by the melt decomposition into separate fragments. If the elastic energy is sufficient to form a new surface the fragmentation of the melt takes place. The decomposition of the melt will not be observed if the time during which the elastic energy necessary for decay is stored is less than the characteristic hydrodynamic time. It is shown that the thinner ring of the melt is broken down into smaller fragments with the same difference in the velocities of the outer part of the melt and the inner one. As the velocity difference increases, the fragments become more elongated, which agrees well with the experimental data. Thus, the phenomenon observed in the experiment of the formation of the wave-like relief of the surface was explained.

1. Introduction

The treatment of different structural materials with intense plasma flows (with a power density of $10^6$-$10^9$ W/cm²) is one of the promising methods for improving their performance characteristics. Plasma treatment results in: an increase in microhardness [1], wear resistance; modification of the surface relief (smoothing or increase in roughness) [2-4]; improves the adhesion of the coating to the substrate [5]. It is also used for doping the surface [6]. There is also mass transfer of matter [7, 8].

It has been established experimentally that at treatment with compression plasma flows (CPF) [9], a surface relief modification is observed [2-4]. At a scale of 10 μm, the surface relief is smoothed [10], at scales of 100 μm or more, roughness and the formation of wave-like surface relief are observed [10]. It is noted in [11, 12] that there is no the formation of a wave-like relief of the surface [12] depending on the absorbed energy density and on the properties of the target material.

The growth of roughness and smoothing of the surface relief has been thoroughly studied. As it was shown in [13, 14] that under the influence of intense energy fluxes, two treatment modes can be distinguished: subcritical and supercritical. In the subcritical processing mode, the material remains in a condensed (solid or melt) state. The velocity of this surface is $1 \pm 10$ m/s and, as shown in [13], the microrelief is smoothed. The supercritical processing regime is characterized by the formation and intensive expansion of the plasma torch from the target material, the material surface velocity reaches
100–1000 m/s, which leads to the development of the Rayleigh-Taylor (RTI) and Richtmyer-Meshkov (RMI) instabilities, which results in the formation of craters on the treated surface. The transition from subcritical irradiation to supercritical radiation has a threshold character and is determined by the density of the absorbed energy and the thermodynamic properties of the substance. It was shown in [12, 13] that smoothing of the relief of the surface of the melt occurs due to the combined effect of surface tension forces and viscosity.

Since the surface layers of the target undergo a transition from solid to liquid state when the plasma target is exposed to the target surface, the Kelvin-Helmholtz instability develops [8], which is due to the formation of a radial plasma flow upon its braking on the surface being treated.

However, at the moment there is no complete description of the formation of a wave-like relief of the surface treated with intense plasma flows. The experimental fact of absence of wave-like relief for some substances (for example, for copper) is left without attention; there is no quantitative description of the wave-like surface relief. Therefore, the aim of this work is to study the mechanisms of the formation of wave-like relief.

2. The formation of wave-like relief

It is established experimentally [7, 10] and theoretically (based on the results of numerical studies) at compression plasma flows treatment the near-surface material layers melt while the melt moves along the target surface in the radial direction from the region of higher pressure which is caused by plasma flow to the lower pressure region. The motion of the melt along the surface of the solid part of the target is accompanied by its cooling and, as a result, deceleration. The inhomogeneous velocity field which is formed in the melt leads to deformation of the material and, correspondingly, to the growth of the elastic energy of the melt, which can cause the decomposition of the melt into separate fragments. If the elastic energy is sufficient to form a new surface there is the fragmentation of the melt. The decomposition of the melt is not be observed if the time during which the elastic energy is stored is less than the characteristic hydrodynamic time. The hydrodynamic time is defined as the ratio of the characteristic spatial formed fragment to the speed of sound – $c_s$.

Let us estimate the number of fragments on which the melt breaks. Since the problem is axisymmetric, it is convenient to consider the problem of breaking one ring into fragments. The surface area of one fragment is written in the form

$$
\Delta f = h \left( r_b + r_a \right)^2 \pi N^2 + 2 \left( r_b - r_a \right)
$$

$r_b$ – outer radius of the ring, $r_a$ – inner radius of the ring, $h$ – height of ring (melt), $N$ – number of segments in which melt decays. The characteristic hydrodynamic time can be determined as $t_h=(r_b-r_a)/c_s$.

The surface energy of a given fragment is written in the form $U_\sigma=\sigma \Delta f$, where $\sigma$ is surface tension coefficient.

Let’s write the total energy of the melt ring as

$$
e = N(U_\sigma + T)
$$

$T$ – kinetic energy of the ring. Let’s write the elastic energy per unit volume for the ring in the following form

$$
e_e = \frac{K(V - V_0)^2}{2V_0}
$$

where $K$ – coefficient of volume compression, $V_0$, $V$ are initial and final volumes. As $\varepsilon_e=\varepsilon$, then we can find the number of fragments on which the ring breaks:

$$
N = \pi \left( r_a + r_b \right) \left( \varepsilon_e - \frac{\tau}{2\sigma} - \frac{1}{r_b - r_a} \right), \text{ where } \tau = \frac{\rho v^2}{2}
$$

– kinetic energy per unit volume.
3. Results

Fragmentation of the melt, and as a consequence the formation of a wave-like topography of the surface, can be clearly seen in figure 1. In figure 1 the surface of the target from steel-3 is represented after the action of CPF with the density of absorbed energy $W=10 \text{ J/cm}^2$. In the figure, the wave-like topography of the surface is clearly visible, and also the figure shows a transverse $\lambda_2$ and a longitudinal $\lambda_1$ scales. To compare experimental and theoretical studies an iron melt at $T=1800 \text{ K}$ was considered. Surface tension coefficient, the density, coefficient of volume compression for these conditions were taken from [15].

The number of fragments on which the melt breaks was determined, as well as the ratio of the transverse fragment size to the longitudinal $\lambda_2/\lambda_1$ from the experiments [10, 12]. According to [10], $\lambda_2/\lambda_1$ is about 0.4-0.6. The number of fragments into which the melt decomposes is $N=100-300$ fragments. A comparison was made on these two parameters.

![Figure 1](image)

**Figure 1.** The surface of steel-3 sample after CPF treatment $W=10 \text{ J/cm}^2$. The scale is 1 mm.

The numerical values of the number of fragments and the ratio $\lambda_2/\lambda_1$ were obtained using the model described above. It should be noted that, according to numerical studies [8], as well as according to the data of [12], the melt velocity along the target surface is 0.1-1 m/s. Therefore, all our results must fit within this speed range.

In figure 2, the dependence of the ratio of the transverse dimension of the fragment to the longitudinal dimension ($\lambda_2/\lambda_1$) on the difference in the velocities of the outer part of the melt and the internal one is presented. Figure 3 shows the dependence of the number of fragments on which the melt decays from the difference in velocities. In figure 2, the dashed line indicates the area into which data obtained theoretically and experimentally should fall. The results are given for different ring thicknesses and for $r_0=1 \text{ mm}$. There are the following notations in figures 2 and 3. (a), (b), (c) and (d) correspond to the ring thicknesses of 0.1, 0.5, 1 and 2 mm, respectively; 1, 2, 3, 4, and 5 corresponds to the energy densities of 10 [10], 15 [10], 20 [12], 57 [12], and 46 J/cm$^2$ [12], respectively.

As it can be seen from figure 3, the thinner ring breaks down into smaller fragments with the same difference in the velocities of the outer part of the melt and the inner that. As the velocity difference increases, the fragments become more elongated. This agrees well with the experimental data [10, 12]. This figure also demonstrates a good agreement of the simulation data with the experimental data for the number of fragments, as well as for the ratio of the transverse dimension of the fragment to the longitudinal dimension.
According to experiments [10, 12], there is no fragmentation of the melt at processing with intense plasma flows on a copper target due to the high thermal conductivity of copper. The characteristic thermal diffusivity of copper $\chi = H^2/\chi$ ($H$ is the thickness of the melt, $\chi$ is the coefficient of thermal diffusivity) is $\sim 5$ times smaller than for iron. For a 5-μm melt the characteristic hydrodynamic time of copper is comparable to its thermal diffusivity $\sim 0.2$ μs, and for an iron target one is $t_\chi \sim 1.1$ μs. Thus the copper melt does not have time to break up into fragments.

4. Conclusion
In this paper a model for the formation of a wave-like topography of a surface under the influence of intense plasma flows has been developed.

On the basis of the presented model, it is established that the inhomogeneous velocity field formed in the melt during its radial motion over the surface of the target leads to an increase in the elastic energy in the melt which can be accompanied by the decomposition of the melt into separate fragments. If the elastic energy is sufficient to form a new surface, the fragmentation of the melt is occurred. The decomposition of the melt will not be observed if the time during which the elastic
energy necessary for decay is stored is less than the characteristic hydrodynamic energy. Thus, at processing of a copper target with intense plasma flows, the fragmentation of the melt is not observed.

It is shown that the thinner ring of the melt is broken down into smaller fragments with the same difference in the velocities of the outer part of the melt and the inner one. The fragments of the decomposing melt become more elongated with an increase in the velocity difference. This is in good agreement with the experimental data [10, 12].

Thus the phenomenon of the formation of a wave-like topography of the surface observed in the experiment was explained theoretically.

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