Measurements of energy absorbed in metal foils during their exposure to plasma jet at the Plasma Focus facility

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Abstract. The work presents the results of estimating the energy absorbed in metal foils (copper, aluminium, and vanadium) during their exposure to the high-speed (>10⁷ cm/s) plasma jets generated in a plasma focus facility. The absorbed energy was calculated under assumption that the plasma jet power is not too high, which allowed us to neglect the loss of material due to evaporation. In this case, when the foils were exposed to the single plasma jet, the amount of absorbed energy was determined using data on the mass of the molten metal layer and the ablated melt mass. The energy absorbed in the Al, Cu and V foils calculated in this way turned out to be ~6.5, 5 and 2.1 J, respectively, which is considerably less than the plasma jet energy, which is of the order ~100 J.

1. Introduction

When studying the processes of interaction between the pulsed plasma jet and the solid surfaces in the plasma focus facilities, there is a problem of determining the energy absorbed in the target. Measurements of the plasma jet energy using the calorimetric methods, and the optical and X-ray spectroscopy [1] partially solve this problem, but they cannot provide information on what part of the plasma jet energy is absorbed in the target. At the same time, for calculating the surface temperature, ablation of the target material, and other parameters that characterize the plasma-surface interaction, it is necessary to know exactly the energy absorbed in the target. Usually, when the metal targets are exposed to the laser radiation, high-power pulsed flows of charged particles and high-energy plasma jets, the calculations of the absorbed energy are reduced to solving the nonlinear heat conduction equation [2–5]. Under certain simplifying assumptions, the problem can be solved numerically, which allows determining the thickness of the molten metal layer and the heating time before the melting starts. Then, according to the well-known formulas, the amount of energy absorbed in a metal target [6] is determined. In some cases, the energy absorbed in the target is determined from data on the radiance temperature measured by the optical high-speed pyrometers [7]. In [8], the thermal effects in the thin Al, Fe, V and W plates exposed to the plasma flows at the PF-4, PF-60, PF-1000 plasma focus facilities were estimated. The heat conduction equation was solved numerically under assumption of the complete plasma energy absorption and without allowance for the ablation of the liquid melt mass.

In this paper, the model for calculating the energy absorbed by metal foils is proposed based on the experimentally measured molten layer mass and the ablated melt mass. This model was used to
determine the amount of energy absorbed by metal foils (Al, Cu and V) exposed to the pulsed plasma jets at the PF-4 plasma focus facility (Lebedev Physical Institute).

2. Experimental technique
The experiments were performed at the PF-4 plasma focus type facility (LPI) with the Mather-type electrode geometry [9, 10]. The storage capacity of the facility was 48 μF at a charging voltage of up to 12 kV, which provided energy of 3.5 kJ in the electric discharge. The plasma jet duration was less than 100 ns. Argon at a pressure of ~1 Torr was the working gas in the PF discharge chamber. The foil was exposed to the single plasma jet. The foil samples were installed at a distance of 3 cm from the anode of the facility. In the experiment, the \(20 \times 20 \text{ mm}^2\) metal foils (Al, Cu and V) were used with thicknesses from 50 to 350 μm. The foil surface was sanded with fine abrasive paper. The samples were etched in a weak solution of nitric acid, degreased in alcohol, and then washed with the distilled water. After the foils were exposed to plasma, they were cut into two halves using the electric-spark cutting in order to determine the thickness of the molten layer. The sample halves were poured with the Wood alloy in a special fixture, and then their ends were polished. The EVO-40 scanning electron microscope (Germany) was used to determine the thicknesses of the molten metal layers. The ablated molten metal mass was determined by weighing the foils before and after their exposure to plasma using the VLR-200 analytical balance.

Figure 1 shows (a) the scheme for the metal foils (targets) processing and (b) the image of the sample holder for three targets. The foils were rigidly attached to the sample holder by diaphragms made of the X18H10T-type steel with aperture diameters of ~15 mm. In the sample holder, the corresponding apertures with a diameter of ~15 mm were made for the free bending of the foils. The sample holder was attached to the steel rod, using which the holder was introduced into the vacuum chamber of the PF-4 facility.

![Figure 1](image-url)

Figure 1. (a) Scheme for the foil processing by plasma at the PF-4 facility, and (b) the image of the sample holder for 3 targets: (1) metal disk of the sample holder; (2) steel rod; (3) foil; (4) metal diaphragm; (5) and (6) the anode and cathode of the PF facility, respectively.

The aperture diameter (~15 mm) was chosen so that it corresponded to the size of the region exposed to the plasma (~20 mm) in order to obtain the fairly uniform plasma energy distribution on the foil surface. Under the effect of plasma jet, the foil deformations occur. The deformed foil takes the form of a spherical segment with the radius R (Fig. 2).
Figure 2. Duralumin plate after its exposure to plasma at the PF-4 facility. The deformation region with a diameter of ~20 mm and the melting region can be seen. The distance from the sample to the anode is ~3 cm.

3. Model for the absorbed energy calculations

To determine the energy absorbed in the foils, the volume of the spherical segment with and without the thin melt layer was calculated. The difference in volumes made it possible to determine the melt volume. Next, the melt mass was found, and taking into account the ablation of the liquid metal mass, the energy spent on melting the metal was determined. To calculate the absorbed energy, we used the model shown in Fig. 3.

Figure 3. The model for calculating the energy absorbed in the metal foil after it is exposed to plasma: $R_1$ and $R_2 = R_1 + \tau$ are the radii of the spherical segment without and with the melt layer, respectively; $\tau$ is the thickness of the molten metal layer; $w$ is the foil deflection; $d$ is the foil thickness; $h_1 = w$ and $h_2 = h_1 + \tau$ are the heights of the spherical segment; $2a_1 = 15$ mm and $2a_2$ are the diameters of the spherical segment base without melt and with molten metal, respectively.

Using the expression for the spherical segment volume [11] (Fig. 4), we determined the melt volume (formula 1) and then the mass $\Delta m$ of the molten layer (formula 2). Using the known molten metal mass and taking into account its ablated mass $m_x$, we determined the absorbed energy (formulas 3). When calculating the absorbed energy, we assumed that the loss of melt mass associated with the metal evaporation is small. The energy losses on metal thermal conductivity were not taken into account in view of the short times of the plasma–foil surface interaction (<100 ns) [9, 10].
The energies spent on the foil deformations and the kinetic energy of the particles acquired during the molten metal expansion also were not taken into account.

\[ V = \frac{1}{3} \pi h^2 (3R - h), \quad a^2 = h(2R - h) \]  \hspace{1cm} (1)

\[ \Delta V = V_2 - V_1 \quad \Delta m = \rho \Delta V \quad M = \Delta m + m_x \]  \hspace{1cm} (2)

\[ Q = M <C_p> \quad Q_n = \Delta HM \quad \Sigma Q = Q + Q_n \]  \hspace{1cm} (3)

Here, \( V \) is the volume of the spherical segment with the radius \( R \); \( \Delta m \) is the mass of molten metal layer with the thickness \( \tau \); \( m_x \) is the ablated molten metal mass; \( M \) is the total molten metal mass; \( <C_p> \) is the average metal specific heat in the temperature range from \( T_0 \) to \( T_{pl} \) \[12\]; \( Q \) is the energy absorbed by the melt with the mass \( M \); \( T_0 \) is the foil temperature (300K); \( 2a \) is the base diameter of the spherical segment with the radius \( R \); \( h \) is the height of the spherical segment; \( \rho \) is the metal specific density; \( Q_n \) is the latent heat of melting of metal with the \( M \) mass; \( \Delta H \) is the enthalpy of melting \[6\]; and \( \Sigma Q \) is the total energy absorbed in the molten metal layer with the thickness \( \tau \).

4. The results on the experimental and calculated absorbed energy

The experimental part of the work on determining the absorbed energy was reduced to determining the thickness of the molten metal layer, the ablated metal mass, and the foil deflections. Figures 5a, 5b, and 5c show the Al, Cu, and V foils after exposing them to the single jet of Ar plasma, as well as images of the foil cross sections obtained using the EVO-40 scanning microscope.
Figure 5. Foil cross sections after exposing them to the single Ar plasma jet: (a) Al, (b) Cu and (c) V. The peculiarity amplitudes (see Fig. 6) on the derivatives of the PF facility discharge current were 90 (Al), 80 (Cu) and 110 (V), respectively (in arbitrary units).

The peculiarity is a short peak on the discharge current derivative recorded by the magnetic field sensor at time of the maximum plasma compression at the OZ axis of the PF facility (Fig. 6). Using data on the peculiarity amplitude measurements, we can estimate the plasma jet energy in arbitrary units.

Figure 6. Discharge current derivative. The arrow indicates the peculiarity.

The melt layer thicknesses on the Al, Cu and V foil surfaces were found to be: ~5 μm (Al), ~8 μm (Cu) and ~1 μm (V). The melt thicknesses were determined by averaging their values in the center and at the edge of foil region exposed to the plasma with allowance for the relief inhomogeneity (Fig. 5). The melt layer thickness considerably varies over the foil surface, which is associated with the inhomogeneous energy distribution in the plasma jet and the molten metal motion under the action of the high-speed plasma flow. The measurement results for the ablated melt mass and the calculated energies absorbed in the foils are shown in Table 1.

Table 1. Energies absorbed in metal foils during their exposure to the single Ar plasma jet.

| Metall | $\rho$, g/cm$^3$ | d, mm | $T_{pl}$, K | $<C>$, J/kg·K | $\Delta H$, kJ/Mol | $U$, arb. units | $\Delta m \cdot 10^{-3}$, g | $m_0 \cdot 10^{-3}$, g | $W$, J | $J/cm^2$ |
|-------|-----------------|------|-------------|----------------|-------------------|---------------|-----------------|-----------------|-----|--------|
| Al    | 2.7             | 0.32 | 934         | 1040           | 10.8              | 90            | 5.1             | 1.0             | ~6.5| 3.7    |
| Cu    | 8.93            | 0.24 | 1356        | 455            | 13                | 80            | 7.8             | 0.25            | ~5  | 2.8    |
| V     | 6.1             | 0.164| 2220        | 688            | 17.6              | 110           | 1.1             | 0.15            | ~2.1| 1.2    |
5. The discussion of the results

Table 1 shows that, at the peculiarity amplitudes of 80–110 arbitrary units, the energies absorbed in metal (Al, Cu, and V) foils are \(\sim 6.5, 5\) and \(2.1\) J, respectively. The corresponding energy densities are \(3.7, 2.8\) and \(1.2\) J/cm\(^2\), respectively. At the comparable plasma jet energies, the melt mass ablation and the molten layer thickness strongly depend on the metal melting temperature and heat capacity. It can be seen in Table 1 that, as the melting temperature increases, the absorbed energy decreases. The higher absorbed energy density measured for the Al foil may be due to the presence of the refractory Al\(_2\)O\(_3\) oxide film and the considerably higher heat capacity. Another reason may be the considerable melt overheating (higher than the melting point of Al) that is confirmed by the higher mass loss and the presence of microcracks in the melt region (Fig. 5). The calculated absorbed energies are in good agreement with the results of [4]. For example, when metals were exposed to the high-power electron pulses with energies of \(\sim 10–20\) keV and pulse durations of \(\sim 0.8\) μs, the α-Fe melting was observed (the melting point is 1810 K) at an energy density of \(\sim 2.2\) J/cm\(^2\) per pulse. The melting of Ti was observed (the melting point is 1944 K) when the samples were exposed to the high-intensity ion flows (H\(^+\), C\(^+\), and O\(^+\)) with energies of \(\sim 50–350\) keV and pulse durations of \(\sim 0.4\) μs at the threshold energy density of \(\sim 5\) J/cm\(^2\). In [2], it was shown that when processing of the metal plates (Cu, W, Pt, etc.) with the ruby laser radiation \((\lambda = 0.6943\) µ\) in the Q-switching mode, the energy flux density threshold for surface destruction and melting was found to be \(\sim 2.5 \times 10^7\) W/cm\(^2\). This value is consistent with the results of this study. Namely, for plasma jet duration of \(\sim 100\) ns, the energy flux density, at which the melting of the Al, Cu, and V foils was observed, was \(\sim 3.7 \times 10^7\), \(2.8 \times 10^7\), and \(1.2 \times 10^7\) W/cm\(^2\), respectively. In [8], when the Al foils with a thickness of 74–160 μm were treated by the neodymium laser radiation \((\lambda = 1.04\) µ\) with an absorbed energy of \(\sim 3\) J/cm\(^2\). Thus, despite the difference in the mechanisms for generation of the high-power radiation flows at different facilities, the threshold absorbed energies for the metal foil melting correspond to the known data. This allows concluding that the model proposed for calculating the absorbed energy and the assumptions made are quite correct. We note that, in the case under consideration, the energy determination is complicated by the insufficient determination accuracy of the molten metal layer thickness. In addition, if the ablation of metal particles is high, the error of determining the melt layer thickness may increase. When calculating the molten layer volume (Fig. 3), the volume of the spherical sector cut off by the cylindrical aperture was not taken into account. Estimates show that the error in determining the absorbed energy can be 20–30%. We note that the absorbed energy is a small part of the total plasma jet energy and cannot provide information on the total plasma energy. For these purposes, the calorimetric and other methods can be used [1]. Under the effect of the pulsed plasma jets, the rather strong deflections of metal foils (of \(\sim 1\) mm or more) were observed. The kinetic and potential energies of the foil deformations can be high and, probably, comparable to the absorbed energy. However, these issues are beyond the scope of this work.

6. Conclusions

When the metal foils (Al, Cu and V) are exposed to the single argon plasma jet, the absorbed energies were determined to be \(\sim 6.5, 5\) and \(2\) J, respectively. The corresponding energy densities, at which melting of the metal was observed, were \(3.7, 2.8\) and \(1.2\) J/cm\(^2\), respectively. These values are in good agreement with the data presented in other works, describing the studies at different facilities on the sample processing by the high-intensity energy flows. It was found that, at the PF-4 plasma focus facility, when the amplitudes of the peculiarity on the current derivative are \(\sim 100\) arb. units, the density of the energy absorbed in metals can reach \(\sim 4\) J/cm\(^2\) per pulse.

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