Pulsed plasma jet interaction with a metal targets

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Abstract. The results of experimental studies of the interaction of plasma jets, created by a pulsed capillary discharge with an evaporating wall, with metal targets are presented. It is shown that the main mechanism of targets destruction is the material melting and the subsequent removal of the melt under the dynamic pressure of the plasma jet. The main sources of energy transmitted to the target are: the high-speed flow of high-enthalpy plasma created inside the capillary, and the fluxes of charged particles accelerated in the near-electrode layers. The energy transport provided by charged particles does not exceed \( \sim 0.1 \)–\( 0.2 \) of the total energy input onto the target. The enthalpy transport is capable to provide heat flux densities of \( \sim 5\)–\( 6 \) kW/mm\(^2\), an order of magnitude exceeding the values achievable in welding arcs.

1. Introduction

The interaction of plasma flows with different materials covers a wide range of scientific and practical problems and underlies numerous processes of plasma technology, metallurgy, plasma chemistry, modelling in experimental technique, etc. Special attention is paid to the study of the processes in the contact area of plasma and target, which are of fundamental importance in plasma physics.

One of the effective means for producing plasma flows with the required chemical composition and high specific parameters is a pulsed discharge in a capillary with an ablating wall [1]. Despite the large amount of experimental and theoretical research in this field, the number of papers devoted to the study of the interaction of plasma flows obtained in this way with various materials is very limited [2–4]. In these papers, the destroying impact of pulsed plasma jets on materials with different thermo- and electrophysical properties was studied. In [4], the heat release in a shock-compressed area, accompanied by melting and subsequent blowing off the melted film, was considered as the main reason of conductors destruction. In [3], the dominant role of this mechanism is questioned. The authors [3] also exclude the possibility of Joule heating of conductors due to closing of the discharge current portion on the target or excessive plasma potential, and note the insignificant influence of radiant energy transport on the target heating. At the same time, Joule heat release, as a possible mechanism for heating the thin metal foils when the discharge current flows through the target, is considered in [2]. It was shown that the discharge current can close through the target if the distance between the target and the capillary edge is not too large. This mechanism, however, cannot cause a noticeable heating of massive conductors, which, just like thin foils, are subjected to intense destruction upon the plasma jet impact.

According to the results obtained in [3], the fraction of energy expended on heating and subsequent destruction of conductors can reach up to 57\% of the energy input into discharge. This value is
quantitatively consistent with the fraction of energy released on the electrodes of the arc discharge, which value in welding arcs reaches up to 60-80% [5]. Therefore, it seems that the basic physical processes that regulate the energy balance in the contact area of a pulsed plasma jet with a target and in the near-electrode areas of the arc discharge have a common nature. Such processes include: the energy transport by the charged particles fluxes, heat conduction caused by temperature gradients between the plasma and target, forced convection, radiant heat exchange, chemical reactions on the target surface. In this paper, an attempt has been made to estimate the role and contribution of named mechanisms to the energy balance in the contact area of a plasma jet with a target.

2. The object and the methods of research
A capillary arrester, whose detailed description is given elsewhere [1], was used for plasma jets obtaining. A capacitive storage device with series-connected inductor is used as a discharge power source. The algorithm of power supply approximately corresponds to the sine half-wave. The experiments were conducted for two discharge modes, which, for definiteness, will be called as a short-pulse and a long-pulse discharge modes, at a fixed energy of a power source ($Q=85 \text{ J}$). The duration of the discharge pulse, the amplitude of the discharge current and the discharge power are the following: $t_p=1 \text{ ms}$, $I_m=350-450 \text{ A}$, $N_m=50-80 \text{ kW}$ in the short-pulse mode [6] and $t_p=9 \text{ ms}$, $I_m=50-60 \text{ A}$, $N_m=5-8 \text{ kW}$ in the long-pulse discharge mode [1]. The discharge was ignited by applying to the arrester’s electrodes of a high voltage pulse ($U\sim 60 \text{ kV}$, $t\sim 10 \mu\text{s}$), formed by an auxiliary power source. Capillaries made of polymethylmethacrylate (PMMA, chemical formula $(C_5H_8O_2)_n$), polytetrafluoroethylene (PTFE, chemical formula $(C_2F_4)_n$) and corundum ($\text{Al}_2\text{O}_3$) are used in our experiments, that is allow us to obtain the plasma jets with different chemical composition and thermal properties and permit to estimate the influence of these properties on the energy balance in the contact area.

Experiments were carried out for three operation modes of the target (figure 1): the cathode, anode, and isolated body modes. In the first two modes, the target served as one of the arrester electrodes, and in the third mode it was under floating potential. Targets were placed opposite the capillary, perpendicularly or at different angles of inclination with respect to the jet axis. The typical distance between the target and the capillary outlet was $z=(5-10) \text{ mm}$ and could vary depending on the problem to be solved. Thin foils, sheet blanks, fine-mesh grids made of metals with different thermophysical properties (nickel, copper, steel, aluminum and lead) were used for targets fabrication.

![Figure 1. Principal electrical schemes for the target’ operation modes: (a) anode mode, (b) cathode mode, (c) isolated body mode, (1) pulsed power source, (2), (4) arrester electrodes, (3) capillary, (5) plasma jet, (6) target.](image)

The following parameters were measured in experiments: the discharge current and voltage drop, the target electrical potential, and the target mass loss. Based on these data, the energy deposited into
The discharge was determined, and estimates of the energy release in the contact area were obtained. The interaction process was recorded by MotionPro N3 high-speed video camera.

3. The results of research

3.1. The picture and the main parameters of the target destruction process

The analysis of video recording and condition of the destroyed targets shows that the substance is carried away from the surface mainly because the target melting and subsequent blowing off of the melt under the plasma jet dynamic pressure. At the first moments of time, the melt appears in the center of the contact area, where the plasma temperature, according to the results of spectral measurements [1,6], reaches maximum values - of the order of $T \approx 1.5-2$ eV. At the further times moments, the melting zone expands, and the melt is pushed out to the periphery of the crater, where it partially solidifies, and partially removed under the dynamic pressure of the plasma jet. Depending on the target thickness and discharge pulse parameters, the plasma jet impact leads to the formation of the through hole or crater (figure 2). The process of destruction and final condition of the affected area do not depend on target polarity.

![Figure 2](image)

**Figure 2.** The results of plasma jet impact on metal targets: (a) nickel foil, $\delta=0.2$ mm, (b) steel sheet, $\delta=6$ mm, (c) lead sheet, $\delta=3$ mm.

The target begin to melt with a certain time delay after contact with the plasma jet, which is necessary for heating the surface to the melting point and depends on the discharge parameters and the thermophysical properties of the target [7]

$$t_{\text{delay}} = \frac{\pi \lambda_w c_p (T_f - T_\infty)^2}{q_w^3},$$

(1)

where $q_w$ - heat flux density, $\lambda_w$ - thermal conductivity coefficient, $c_p$ - specific heat capacity of the target material, $\rho$ - density, $T_f$ - melting point, $T_\infty$ - initial target temperature).

In the range of the studied discharge parameters, the time of heating the target to the melting point is a small fraction (less than 20%) relatively discharge pulse duration. In some cases (for targets with a smooth surface), it was possible to establish the start of melting using the video recording data for this purpose. So, for a target made of nickel foil with a thickness of $\delta=0.2$ mm, the time of heating the contact spot to the melting point is approximately $t_{\text{delay}}(T_f) \approx 200$ $\mu$s for the short-pulse discharge mode and $t_{\text{delay}}(T_f) \approx 2$ ms for the long-pulse one. Substituting these values into equation (1), one can estimate the heat flux density averaged over the time interval $[t_0, t_{\text{delay}}(T_f)]$ ($t_0$ is the moment of contact of the plasma jet with the target), that gives $q_{w_0}(t_{\text{delay}}(T_f)) = 1.7$ kW/mm² for the short-pulse discharge mode and $q_{w_0}(t_{\text{delay}}(T_f)) = 0.55$ kW/mm² for the long-pulse one. The surface heating time to the boiling point $T_b$ for the indicated values of the heat flux density, in accordance with (1), turns out
to be of the order of the discharge pulse duration, \( t_{del}(T_b) \leq \tau_p \), for both discharge modes. In fact, since after the beginning of the target melting the heat flux density continues to rise up to the middle of the discharge pulse (according to the power source algorithm), the boiling point in the contact spot is reached only a little later than the melting point due to the inverse proportionality of the heating time to the second degree of heat flux density. For example, in accordance with (1), only a twofold increase in the heat flux density is necessary to reach a boiling point over the same period of time, that is more than ensured by heat fluxes provided by enthalpy transport (see Section 3.2). The heating of the contact area to a boiling point is evidenced by clear signs of evaporation, which are observed over most of the discharge pulse, in particular: intense atomic and ionic lines of the target material recorded in the plasma emission spectra near the contact spot, as well as plasma jets emanating from the contact spot and directed perpendicular to the target surface. Overheating of the surface above boiling point under experimental conditions seems unlikely due to the continuous removal of the melt from the heat supply zone under the dynamic pressure provided by oncoming plasma jet. Therefore, when making estimates, it seems appropriate to take the boiling point as the temperature of the target surface.

During the experiments, weight measurements of the target were carried out before and after interaction with the plasma jet. The accuracy of weight measurements is 0.1 mg, so the error in determining the mass loss for minimum recorded values \( \Delta m=1 \) mg does not exceed 10%. The results of the mass loss measurements were used to estimate the energy spent on the target destruction

\[
Q_{\text{destr}}(\Delta m) = Q_f + Q_b = \Delta m (c(T_s - T_\infty) + L_f) + m_b L_b,
\]

where \( \Delta m = m_f + m_b \) – the total mass loss, including melted mass \( m_f \) and vapor-phase mass \( m_b \); \( c \) - the heat capacity of the target material (for simplicity, we accept the equality of the heat capacities of the solid and liquid phases); \( L_b \) and \( L_f \) - the specific heats of evaporation and melting; \( T_s \) - the surface temperature at the vapor-liquid interface (it is assumed \( T_s = T_b \); \( T_\infty \) - the ambient temperature.

The first term in the right-hand side of equation (2) corresponds to the energy \( Q_f \) spent on heating the total mass of the removed substance \( \Delta m \) to the boiling point and on its melting, the second term is the energy \( Q_b \) spent on evaporation of the mass \( m_b \). To estimate the ratio of these energies, \( Q_b/Q_f \), one can use the continuity equations (in the stationary approximation) for the vapor and liquid phases

\[
\frac{m_b}{\rho_b \tau_d} = \rho_f v_b \quad (3a)
\]

\[
\frac{m_f}{\rho_f \tau_d} = \rho_s v_f \quad (3b)
\]

from whence

\[
\frac{m_b}{\Delta m} = \frac{v_b}{v_b + v_f} \quad (4)
\]

where \( v_b \) and \( v_f \) – the velocities of the phase boundaries "melt-vapor" and "solid-melt"; \( F_b \) and \( F_f \) – the surface area of the melt zone at the boundary "melt-vapor" and "melt-solid"; \( \rho_f, \rho_s \) – the mass density of the substance in the liquid and solid phases, respectively. Hereinafter, we accept for simplicity \( F_b = F_f \) and \( \rho_f = \rho_s \).

The velocity of melt-vapor boundary can be estimated by the Hertz-Knudsen equation [8]

\[
\rho_f v_b(T_s) = \frac{1}{\alpha} \sqrt{\frac{m_p}{2 \pi k T_s}} p_{\text{sat}}(T_s),
\]

where \( p_{\text{sat}}(T_s) \) is the saturated vapor pressure, which is determined from Clapeyron-Clausius equation

\[
p_{\text{sat}}(T_s) = p_b \exp \left[ \frac{\mu m}{k} \left( \frac{1}{T_b} - \frac{1}{T_s} \right) \right]
\]

Here \( T_b \) – boiling temperature at normal pressure \( T_b = 10^5 \) Pa; \( \alpha \) – accommodation factor (\( \alpha \approx 1 \)); \( m_p \) – effective mass of the vapor particles.
Estimates of the velocity of the “melt-solid” phase boundary were made using the continuity equation (3b) by substituting the measured values of the mass loss $\Delta m$ (instead of the melted mass $m_f$) and affected surface area of the target. The estimates obtained in such a way agree satisfactorily with the propagation velocity of the heat flux averaged over the discharge pulse duration

$$v_f \approx \sqrt{a/\tau_p},$$

(7)

where $a$ is a thermal diffusivity.

The estimates made on the basis of relations (2) and (4), taking into account (5) and (7), show that for targets made of aluminum, copper, steel, nickel, and lead, which were used in our experiments, the mass fraction of vaporized substance (at $T_s = T_b$) is $m_b/\Delta m = 0.02-0.07$, and the ratio of the energy spent on evaporation to the energy spent on heating and melting the target is $Q_b/Q_f = 0.09-0.26$. In fact, these values are overestimated approximately by an order of magnitude. The reason is that the relation (5) was obtained under assumption that all evaporated atoms are evacuated from the surface into surrounding space and do not return [8]. Equation (5) is applicable for relatively low surface temperatures when the saturated vapor pressure does not exceed $p_{sat} < 100$ Pa [8]. For higher surface temperatures, a significant fraction of atoms flow back to the surface due to collisions, and, therefore, the net rate of substance evaporation under these conditions is approximately an order of magnitude less than that given by (5) [9–12]. Therefore, the second term in equation (2), corresponding to the energy spent on evaporation, can be neglected.

The results of estimates of the target destruction energy calculated by formula (2) (neglecting the second term in the right side) and the ratio of this energy to the energy deposited into the discharge, $Q_{destr}/Q_{dis} = \int_0^{\tau_d} U_d(t)I(t)dt$, where $U_d(t), I(t)$ – voltage drop and discharge current, respectively, are presented in table 1. Here, estimates of the heat flux density to the target surface are also presented

$$q_w(\Delta m) = Q_{destr}(\Delta m)/(F \tau_p)$$

(8)

where $F$ – the area of the contact spot, which was determined by the sizes of the hole or crater made in the target. The results of estimations are presented for the three types of targets (the nickel foil with a thickness of $\delta = 0.2$ mm, the lead sheet with a thickness of $\delta = 3.2$ mm, the three-layers steel mesh with wire diameter of $d = 0.2$ mm and mesh sizes of 1 mmx1 mm), depending on their polarity and capillary discharge mode (the long-pulse ($\tau_d = 9$ ms) and short-pulse ($\tau_d = 1$ ms) modes). For a target made of a three-layer steel mesh, the results of estimates are also presented for the case when the plasma jet stoichiometry is determined by the PTFE ablation products (chemical formula (C$_3$F$_4$)$_n$).

The following specific features attract attention. Firstly, despite the fact that all the experiments, whose results are presented in the table 1, were carried out under the same conditions (fixed discharge parameters, distance to the target and atmospheric pressure), estimates of the energy parameters based on the measured values of the mass loss significantly differ as for various types of targets and discharge modes. Thus, the fraction of the energy spent on heating and melting the target increases from its minimum values of $Q_{destr}(\Delta m)/Q_{dis}=0.044-0.12$, typical for the long-pulse discharge mode, to maximal values of $Q_{destr}(\Delta m)/Q_{dis}=0.17-0.42$, typical for the short-pulse mode. Secondly, the estimates of the heat flux density based on the results of mass loss measurement are noticeably lower than the estimates based on the measurement of the heating time of target to the melting point, $q_w(\Delta m) < q_w(t_{mel})$, and cannot explain the heating of the target to the boiling point, whose obvious signs are present in both discharge modes.

The noted features are the consequence of the fact that estimations of the destruction energy based on results of weight measurements do not take into account the mass of the melt remaining on the target surface and the heat losses in the target body. The efficiency of the melt removing to a great extent depends on the dynamic pressure of the incident flow, which differs significantly for supersonic and subsonic plasma jets obtained in the short-pulse [6] and long-pulse [1] discharge modes, respectively. For this reason, a significant fraction of the molten mass, which in some cases reaches...
more than 90% of the total mass of the melt, remains on the target surface being displaced to the crater periphery under the low dynamic pressure produced by a subsonic plasma jet, while the strong dynamic pressure of a supersonic plasma jet provides removing of more than 60% of the melted mass. Therefore, the estimates of the target destruction energy and the heat flux density, based on the results of mass loss measurements, are much underestimated, especially for the long-pulse discharge mode.

Table 1. The results of evaluation of the energy parameters characterizing the interaction of plasma jet with a target.

| Material | Type          | Polarity | $Q\text{dis}$ | $\tau_d$ | $t_{det}(\tau_f)$ | $\Delta m$ | $Q_{\text{dest}}(\Delta m)$ | $q_{\text{dest}}(\Delta m)$ | $q_{\text{det}}(\tau_f)$ | $q_{\text{rad}}(\Delta m)$ | $\Delta m$ | $Q_{\text{dis}}$ |
|----------|---------------|----------|---------------|----------|--------------------|------------|-----------------------------|-----------------------------|--------------------------|-----------------------------|------------|----------------|
| Ni       | foil, $\delta=0.2$ mm | cathode | 51            | 1        | 0.2                | 1.5        | 2.25                        | 0.044                       | 0.55                     | 0.062                       |            |                |
|          |               | anode   | 58            | 9        | 2.0                | 10         | 16.5                        | 0.29                       | 1.7                      | 1.5                          |            |                |
| Pb       | plate, $\delta=3.2$ mm | cathode | 60            | 1        | 44                 | 10.6       | 0.17                        | 0.17                       | 0.88                     | 1.1                          |            |                |
|          |               | anode   | 57            | 1        | 55                 | 13.3       | 0.23                        | 0.23                       | 1.1                      |                              |            |                |
| Steel    | 3 layers of mesh | cathode | 57            | 1        | 13.5               | 20.6       | 0.36                        | 0.36                       | 1.85                     |                              |            |                |
|          |               | anode   | 56            | 1        | 15.5               | 23.6       | 0.42                        | 0.42                       | 2.15                     |                              |            |                |
| Steel    | 3 layers of mesh | cathode | 50            | 9        | 3                  | 4.6        | 0.09                        | 0.09                       | 0.13                     |                              |            |                |
|          |               | anode   | 44            | 9        | 3.5                | 5.3        | 0.12                        | 0.12                       | 0.15                     |                              |            |                |

a Estimation by the formula (2);
b Estimation by the formula (3)
c Estimation by the formula (1)

Other discovered features, which will be discussed below, are: an explicit dependence of the energy parameters on the target polarity, as well as on the incoming flow enthalpy depended on the plasma jet chemical composition.

3.2. Main sources and mechanisms of energy transfer

Energy exchange on the target surface, ultimately, determines the amount of heat flux density $q_p$, which provides heating, melting and evaporation of the substance. The main processes that regulate the energy balance in the contact spot are: energy transfer by charged particle fluxes $q_p$, radiation fluxes from the plasma onto the target $q_{\text{rad}}^\ell$, and from the target into the plasma $q_{\text{rad}}^w$. In the general case, the energy balance in the contact area can be represented as

$$q_p = q_p + q_{\text{rad}}^\ell - q_{\text{rad}}^w + q_{\text{etc}}$$

(9)

Here $q_{\text{etc}}$ takes into account another possible energy transfer mechanisms, in particular: the heat conduction flux from the plasma to the target, convective heat exchange forced by the plasma jet dynamic pressure, chemical reactions on the target surface, etc.

As a rule, radiation fluxes emitted from the surface and plasma do not influence significantly on the energy balance in the contact region. For example, the radiation flux density emitted from the target surface heated to $T = 3134$ K (boiling point of iron) does not exceed $q_{\text{rad}}^w < 10$ W/mm², which is less than 1% of the total heat flux density. However, in the temperature range $T = 1-2$ eV recorded in the axial zone of the plasma jet [1,6], the fraction of the energy transferred by the radiation flux from plasma to the contact region can be noticeable enough. The radiation flux density in the range of the indicated temperatures can reach up to $q_{\text{rad}}^\ell = \varepsilon_\sigma T^4 = 30 - 500$ W/mm² (for the grey factor of $\varepsilon \sim 0.03$), which makes it necessary to evaluate this mechanism in each specific case.
The energy transfer by charged particles is determined by the ion and electron fluxes from plasma onto the surface and by the flux of emitted electron into the plasma. The ratio between these fluxes is different for the cathode, anode and isolated body [13–15], that allows us to use this circumstance to estimate the contribution of mentioned mechanism into the energy balance. Experiments have shown that, ceteris paribus, the mass loss is always greater in the case when the target being under anode potential, than when the target being under cathode or floating potential (see figure 1 and table 1). In the latter two cases, the mass loss is about the same.

It should be noted, that since the distance between the target and the capillary outlet in these experiments did not exceed $z < 10$ mm, it was not possible to realize a stable regime of an isolated body (see figure 1). Under these conditions, almost immediately after the plasma jet contacts the target, the discharge switches to a cascade arc mode, consisting of two spatially separated sections, one of which coincides with the plasma jet, and the second section, which provides the discharge current closure, arises between the target and the external electrode (figure 3). In this case, the anode or cathode mode - depending on the polarity of the arrester' electrodes - is established in the contact area of target and plasma jet. In our experiments, the polarity of the arrester’ electrodes was such that the cathode mode was established in the contact area. This circumstance, apparently, was one of the reasons that the measured mass loss of targets both being under the floating and cathode potential was approximately the same.

![Figure 3](image)

Figure 3. Transition of the discharge to the cascade arc mode during the plasma jet interaction with a metal target initially being under the floating potential: (1) internal electrode,(2) capillary, (3) arrester housing, (4) plasma jet, (5) contact area, (6) external electrode, (7) section of the cascade arc, providing the closure of discharge current, (8) metal target.

Another feature found in the experiments is the different condition of the cathode' and anode' contact areas, indicating the different distribution of the discharge current in these areas (figure 4). A distinctive feature of the cathode contact area is the formation of cathode spots (figure 4(a)), through which, apparently, almost the entire discharge current is closed. Cathode spots arise and move on the periphery of the contact area, and do not penetrate into the zone occupied by the melt. Such pattern is observed on all targets, whose melting points turn out to be insufficient to provide the thermionic emission necessary to maintain the discharge current. This fact suggests that, at least until the surface temperature of the melt reaches the temperature necessary to provide the required emission current, the processes caused by the flow of discharge current do not influence on the energy balance in the melted zone. A different situation occurs when the target being under the anode potential (figure 4(b)). In this case, the discharge current flows through the melt that provides its additional heating.

Estimates of the heat flux densities to the target under the cathode and anode polarity, made on the basis of mass loss data, are presented in figure 5. The difference between the heat flux densities to the anode and cathode in the short-pulse mode is of $\Delta q = q_a - q_c = 30 - 200$ W/mm², which is
quantitatively agrees with those that obtained in welding arcs [5], where the charged particles fluxes serves as the main energy source. This value represents a small fraction (approximately $\Delta q / q_a \approx 0.1$-0.2) of the total energy expended to the target destruction. The transfer of the rest energy is obviously provided by other processes, the most probable among which are the following: thermal conduction flux caused by the temperature difference between the plasma and the target, forced convection flux, radiation flux from plasma, chemical reactions on the target surface. The energy source for the first two processes is a high-speed flow of highly ionized plasma created inside the capillary, whose enthalpy, depending on plasma chemical composition and the discharge power, can reach up to $h = 100-200$ MJ/kg [16]. This assumption is confirmed by the experimental results, according to which the heat flux density is twice higher when the PMMA ablation products determine plasma composition, compared to the case when the plasma composition is determined by PTFE or corundum (figure 5).

![Figure 4](image)

**Figure 4.** Images of the contact areas being under the (a) cathode and (b) anode potential: (1) cathode spots, (2) zone, occupied by the melt. The closure of the discharge current to the target being under the cathode potential occurs through cathode spots that arises at the periphery of the contact area and do not penetrate into the zone occupied by the melt.

![Figure 5](image)

**Figure 5.** Heat flux densities on the targets being under the cathode and anode potentials depending on the discharge power and chemical composition of plasma-forming substance.
The temperature dependences of the heat flux density, which can be provided by enthalpy transport, $q_h = \rho h v$ ($\rho$ and $v$ are the flow mass density and velocity), are presented for some substances in figure 6. These dependences were calculated using the data on thermophysical properties of plasmas of various chemical composition [16], assuming $v = c/\sqrt{T/m}$ is the speed of sound in a plasma. It can be seen that at atmospheric pressure in the temperature range of $T = (15-22)$ kK recorded in the axial zone of the plasma jet [1,6], the heat flux density reaches up to $q_h \sim 6$ kW/mm$^2$ when the PMMA decomposition products determine plasma stoichiometric composition. The heat flux density is about two times lower if the ablation products of PTFE or corundum serve as plasma-forming substance. These estimates are more than an order of magnitude greater than the heat flux densities that are achieved in welding arcs.

4. Conclusions
The main mechanism of metal targets destruction exposed by a plasma jet is the combined impact of the heat flux and dynamic pressure of the plasma jet. The dynamic pressure plays an important role in the destruction of meltable materials, providing removal of the melt from the contact area.

According to the estimations and obvious signs of target evaporation observed experimentally, the temperature in the contact spot reaches the boiling point. Surface overheating above the boiling point seems unlikely due to the continuous removal of the melt under the dynamic pressure provided by the plasma jet. The mass fraction of the evaporated substance at boiling temperatures does not exceed 7% and does not influence significantly on the total energy balance in the contact spot.

The main sources of energy transmitted to the target are: the high-speed flow of high-enthalpy plasma created inside the capillary, and the fluxes of charged particles accelerated in the near-electrode layers. The energy transport provided by charged particles constitutes a small fraction (~0.1–0.2) of the total energy expended to the target destruction. The enthalpy transport is capable to provide heat flux densities of ~5-6 kW/mm$^2$, an order of magnitude exceeding the values achievable in welding arcs.

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