DESTRUCTION OF MATERIALS BY SUPERSONIC PULSE CAPILLARY DISCHARGE PLASMA JETS

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The mechanism involved in the destruction of various materials under the action of supersonic plasma jets is considered. The fundamental reason for the destruction of metallic materials is their fusion and the subsequent removal of the liquid phase from the damaged area.

Plasma jets directed at the ambient atmosphere at supersonic speed [1–3] can be produced by means of strong-current pulse capillary discharges. The velocity of the vapors in the flame may exceed 10 km/sec for Mach numbers of 2–4. When supersonic plasma jets impinge on a fixed barrier they create a shock-compressed plasma region in front of that barrier [4, 5], and the interaction of the plasma with the barrier leads to intensive heating and the destruction of the latter.

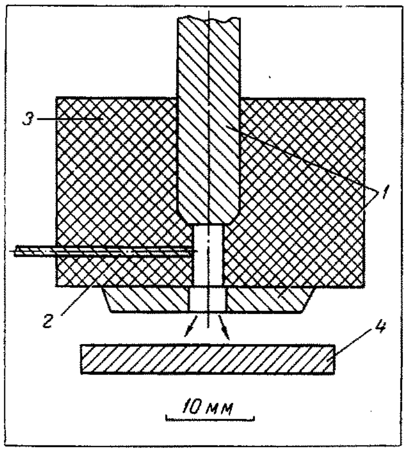

Fig. 1. Diagram of discharge device: 1) Main electrodes (iron); 2) keep-alive electrode; 3) dielectric cube; 4) body under investigation.

It was noted in [4] that the extent of destruction in various materials is not governed by their thermal or mechanical strength. The hypothesis was put forth that the principal factor responsible for loss of mass in various metals subject to the action of supersonic plasma jets is the fusion and subsequent ablation of the liquid phase by the free stream. However, no quantitative measurements confirming this viewpoint were carried out in [4].

Since the problem of the interaction of supersonic plasma jets with barriers is of interest to a number of branches of contemporary engineering, continued experimentation along this line would be desirable. In this paper we treat the fundamental quantitative relationships governing the destruction produced by the action of pulse-supersonic plasma jets in various metallic and nonmetallic substances, differing markedly in terms of their thermophysical and mechanical properties.

To achieve directed plasma jets we employed the discharge device depicted schematically in Fig. 1. The discharge took place within the cylindrical capillary ($\varnothing = 3.5$ mm, $h = 6$ mm) with an open base. The discharge regime was: $C = 200\ \mu F$, $L = 1\ \mu H$, $U = 3$ kV. The discharge was nearly aperiodic. The current amplitude value was 10–12 kA. The pulse duration was about 120 μsec. The studies were carried out in air at atmospheric pressure.

On discharge a plasma jet consisting of electrode materials and the products of the destruction of capillary walls are ejected from the open base of the discharge space. The velocity of the jet was measured by means of a high-speed photographic time-scan of the glow (with an SFR-2 camera). At a distance of approximately 10 mm from the outlet of the orifice, the jet velocity was approximately equal to 10 km/sec. The jet temperature, according to the data of [5], was approximately 10 000° K and the pressure within the jet was close to atmospheric. The Mach number under these conditions was 3–3.5.

The materials of the investigation exhibited flat surfaces and were positioned at a distance of 4.5 mm from the base of the discharge plate. Under these conditions, the jet impinged against the barrier at supersonic speed. The pattern observed in this case is shown in Fig. 2 which shows frames from the high-speed photography of the pulse jets ejected into open space from the capillary, as well as the jets impinging on the subject barrier. A shock-compressed plasma layer ($H = 1$ mm) is formed on the flat surface of the barrier; the temperature within the layer may rise to 15 000–20 000° K, while the pressure may involve tens of atmospheres [4, 5]. Convective and radiative flows are responsible for the heating of the subject surface, its destruction, and the subsequent removal of mass. As a result of the jet's action against the surface of the body, an erosion hole is formed. The photography of the erosion hole is shown in Fig. 2c for the case of lead. The mean heat flux to the surface of the streamlined body is determined from the magnitude of removed metal mass. This proved to be equal to $\sim 1 \cdot 10^{-5}\ \mathrm{cal/cm^2 \cdot sec}$. The heat accumulated by the material and expended on vaporization was not taken into consideration.

The dimensions and shape of the erosion markings were taken from the profiles of their cross sections, recorded by means of a clock-indicator which made it possible to determine the depth of damage to an accuracy of 0.01 mm. The mass losses were determined by weighing the test materials prior to and after the experiment, and also by calculating the volume of the erosion holes.

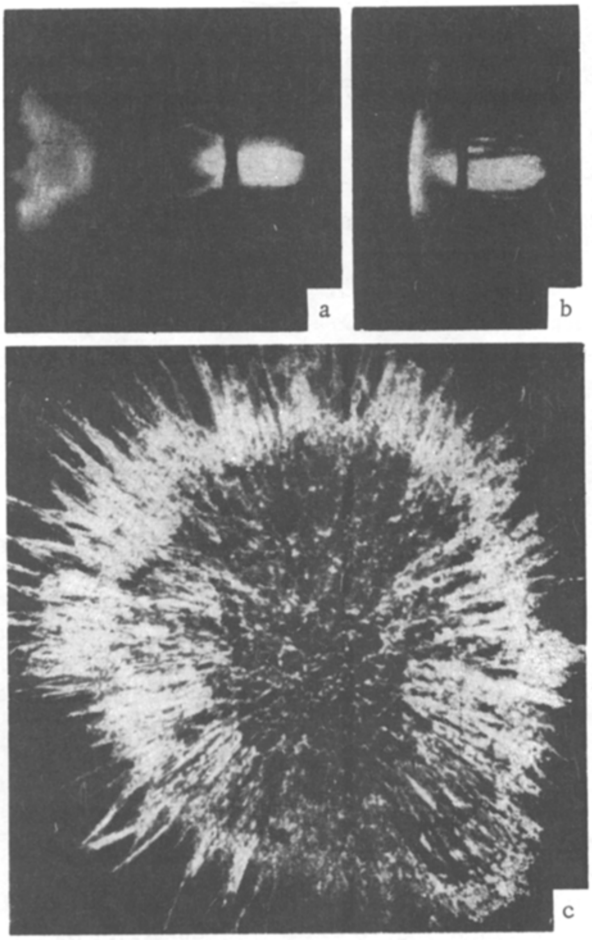

Fig. 2. Separate high-speed photography frames (125 000 frames/sec) of a free-flowing jet (a) impinging on a flat barrier (b), photography of erosion hole on a lead plate (c).

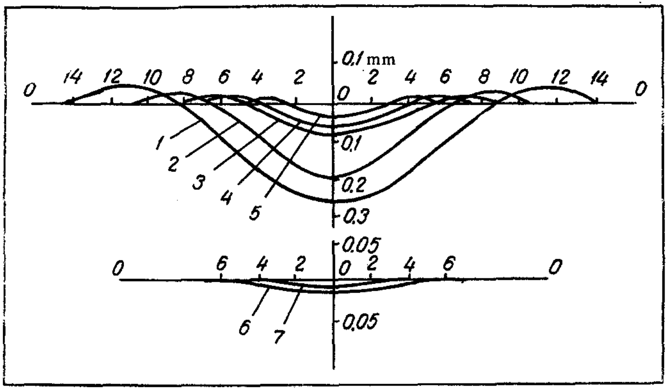

Fig. 3. Profile of erosion holes forming in various metals and nonmetals under the action of supersonic jet: 1) Sn; 2) Al; 3) Cu; 4) Ni; 5) W; 6) plastic; 7) paper.

The profile of the erosion markings left as a result of a single pulse are shown in Fig. 3. The data on the volume of the erosion holes, as well as those on weight losses in the test materials, are given in the table. Here we also find the fundamental thermophysical constants of the subject materials. Figure 4 shows the mass of removed metal as a function of the melting point under the given conditions of the experiment, which is a straight line on a semilogarithmic scale.

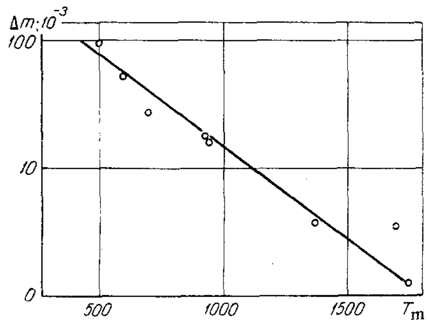

Fig. 4. Dependence of metal mass entrainment (g) on fusion temperature (° K).

Our attention is drawn to the fact that all of the metals, including even so refractory a metal as tungsten, are more markedly affected by plasma jets than any of the studied nonmetals. The profile of textolite, micarta, and paper are virtually coincident with the curve for their surfaces prior to the experiment and the volumes of erosion holes and the mass of material ejected from the holes were therefore not calculated.

The degree of destruction is not identical for the individual metals. The maximum erosion-hole volume is found with tin (32.1 mm^3), while tungsten shows the minimum (0.7 mm^3). The divergence in the degree of destruction for these metals amounts approximately to 1.5 orders.

As we can see from the table, in terms of the degrees of destruction the metals are arranged approximately in accordance with their melting points. The magnitude of the erosion-hole volume increases as T_m of the metals decreases. The only noticeable deviation is seen in the case of zinc. For the time being, the reasons for this are not clear.

No close relationship between T_b and the degree of destruction is found. This is particularly evident, for example, in one pair of metals (tin-copper). Their boiling points are approximately identical (for Cu T_b = = 2583° K, for Sn T_b = 2609° K), while their degrees of destruction diverge substantially. The erosion-hole dimensions in the case of tin are greater by a factor of 10 than the dimensions of the erosion hole in a copper plate.

Analysis of the derived data is in agreement with the hypothesis proposed in [4] that the fundamental factor responsible for metal destruction is fusion and subsequent removal of the liquid phase from the damaged area. Removal of the liquid phase is a result of removal of matter by the plasma flow spreading ra-

Degree of Destruction in Various Metals by a Supersonic Plasma Jet

Metals	T_m, °K	T_b °K	Depth of damage, mm^3	Volume of hole, mm^3	Loss of mass, mg	
					by hole volume	by weighing
Sn	505	2609	0.28	32	235	90
Pb	600	2003	0.26	27	300	50
Zn	692	1181	0.095	6.7	47	27
Mg	924	1323	0.25	24.7	42	18
Al	933	2603	0.21	8.8	24	16
Cu	1355	2583	0.085	3	31	3.5
steel	1671	2723	0.09	4.5	28	4.9
Ni	1725	3273	0.07	1.55	13	1.2
W	3653	5643	0.03	0.7	1.4	0.6

dially, as well as a result of the strong pressures exerted by the shock-compressed plasma layer on the fused metal volume.

Since the main loss of material in a substance subject to streamlining by a supersonic plasma jet occurs in the liquid phase, it becomes clear why the studied nonmetals which are destroyed at high temperatures as a result of the sublimation process will experience a reduction in the degree of destruction.

The weight losses determined from the calculated volumes of the erosion holes, as well as by weighing, turn out not to be identical. This descrepancy is associated with the above-indicated unique features of the mechanism of metal destruction. A portion of the fused metal in the liquid phase is shifted from the hole to the peripheral zones or to an undamaged part of the surface, cooling there. An embankment of cooled metal forms about the hole in this case, with rays extending over the undamaged surface (Fig. 2c).

The "eroding series" (a) of metals determined in this paper from the action of a supersonic plasma jet corresponds basically to the "eroded series" (b) for the case in which electrodes are destroyed by pulse discharge [7]:

a) Sn, Pb, Zn, Mg, Al, Fe, Cu, Ni, W;

b) Pb, Sn, Zn, Ni, Cu, Fe.

The metals in these series are listed in descending order of erosion stability. The correspondence between the series provides a basis for the assumption that the destruction mechanism is similar for the two cases. This agrees also with [8], in which it has been demonstrated that the fundamental ejection of electrode substance in the case of pulse discharge takes place in the liquid phase as a result of the pressures developed at the electrodes [9, 10]. However, the factor responsible for the development of such pressures is, apparently, not the same in the two cases.

REFERENCES

1. L. I. Grechikhin and L. Ya. Min'ko, ZhTF, **32**, 1072, 1962.
2. N. N. Ogurtsova, I. V. Podmoshenskii, and V. M. Shelmina, Opt. i spektr., **15**, 743, 1963.
3. M. A. Sultanov and L. I. Kiselevskii, TVT, **4**, 40, 1966.
4. M. A. Sultanov and L. I. Kiselevskii, TVT, **4**, 375, 1966.
5. V. N. Snopko and L. I. Kiselevskii, ZhPS [Journal of Applied Spectroscopy], **5**, 148, 1966.
6. V. N. Snopko and L. I. Kiselevskii, ZhPS [Journal of Applied Spectroscopy], **5**, 421, 1966.
7. N. V. Zitka, Czechoslov. phys. journal, **3**, 241, 1953.
8. N. V. Afanas'ev and S. N. Kapel'yan, Vestsi AN BSSR, ser. fiz.-tekhn. navuk [Belorussian], no. 2, 1965.
9. I. G. Nekrashevich, Sbornik nauchnykh tr. FTI AN BSSR, Izd-vo AN BSSR, no. 1, 1954.
10. I. G. Nekrashevich and I. A. Bakuto, IFZh, **7**, 3, 1960.

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