DISINTEGRATION OF CARBON STEEL BY HIGH-VELOCITY PLASMA JETS

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The disintegration of steel targets by high-velocity concentrated plasma jets is analyzed. The effects of carbon content, heat treatment, and specimen temperature on the disintegration pattern are revealed as a result.

Concentrated energy sources, among them high-velocity plasma jets, have recently found increasing applications in various methods of material treatment. According to [1, 2], the basic mechanism of metal disintegration by supersonic plasma jets is melting and subsequent sweep of the liquid layer by the oncoming plasma stream. In other words, material is removed by the jet immediately after the metal temperature has reached the melting point. It would be of interest to explore also other factors affecting the mechanism of metal disintegration by high-velocity jets, and this is the object of the following report.

The authors studied the effect of 30-35 km/sec plasma jets on steel targets. The plasma jets were generated here by discharges of a capacitor bank within a confined space, with the plasma products of resulting explosions fed into the narrow bore of a gun [3, 4]. The capacitor bank was rated for ~60,000 J energy at 5 kV.

The highest values of plasma jet parameters were measured directly at the gun throat. The mean density of plasma beams was estimated at 10^{-2} g/cm^3 on the basis of the mass of the bursting metal foil, the loss of electrode mass, and the loss of dielectric mass in the burst region. The mean power density of a plasma jet moving at an average velocity of 18-20 km/sec is of the order of $5 \cdot 10^{10}$ W/cm^2. The velocity parameters of a jet were measured by high-speed photorecording with a model SFR-1 apparatus the expansion of a plasma beam under vacuum. A jet acted on a target for 70 μsec. This time was measured by the length of the trace left by a plasma jet on a disk rotating at 16,000 rpm.

When a concentrated plasma jet acts on a metal target, it produces a crater as shown in cross section in Fig. 1. Characteristically, the crater depth is smaller at the center than around the periphery. This convexity relates to the flow pattern of a normally incident plasma jet at a solid barrier. At the center of the hearth the jet velocity is perpendicular to the plane of the target, which makes the removal of liquefied and vaporized material more difficult. Meanwhile, both the temperature and the pressure become highest here. The pressure causes the plasma together with liquefied and vaporized target material to expand radially into the free space. At the same time, sideways from the center there appears a large tangential velocity component parallel to the surface. It produces large friction forces between the expanding stream and the target, ensuring that most of the mass wear occurs around the hearth periphery and the crater will assume its peculiar shape.

In view of the different disintegration patterns at the periphery and at the center, we will analyze the effect of some factors which determine the hearth depth at both locations. Our concern here is, specifically, how the carbon content, the heat treatment, and the initial temperature of steel specimens affect their resistance to disintegration – the crater depth serving as a measure of this resistance. In our tests we used specimens of carbon steel in the shape of disks 12 mm thick with a base 50 mm in diameter susceptible to jet action. The carbon content varied from 0.2 to 1.2%. The specimens were initially annealed or hardened.

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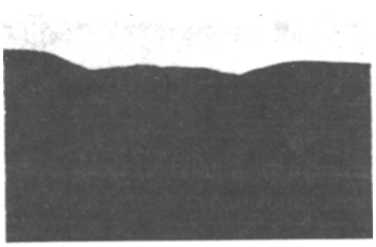

Fig. 1

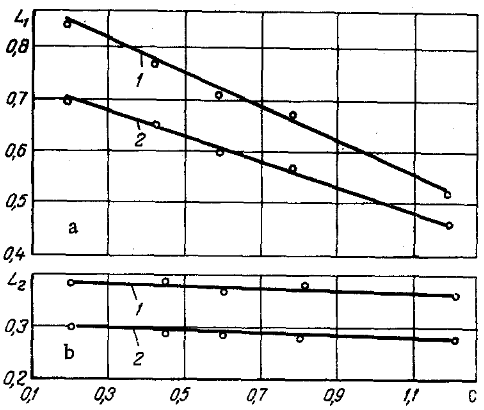

Fig. 2

Fig. 1. Profile view of a hearth produced by a plasma jet in a steel target.

Fig. 2. Crater depth (a) at the periphery L_1 (mm) and (b) at the center L_2 (mm), as function of the carbon content (%) in steel specimens.

The study has shown that the resistance to disintegration increases with a higher carbon content and depends on the heat treatment. Hardened specimens appear more resistant than annealed ones. The crater depth L_1 at the periphery is shown in Fig. 2a as a function of the carbon content in hardened and in annealed steel specimens. Evidently, the depth L_1 decreases with increasing carbon content and, moreover, the curve for hardened steel (2) lies below the curve for annealed steel (1). The effect of changes in the carbon content or in the heat treatment is much weaker at the hearth center. Here, according to the curves in Fig. 2b, the depth L_2 is not so much different for hardened and annealed specimens, respectively; it also decreases less with increasing carbon content. The difference between L_1 and L_2, however, is greater in annealed than in hardened specimens.

On the basis of these data, one may conclude that the resistance of metals to disintegration by high-velocity plasma jets depends not only on the melting point and other thermal characteristics of the metal. Indeed, with a higher carbon content the melting point of steel drops only slightly; the thermophysical properties of steel are also almost unaffected by hardening. The test data can be interpreted with the assumption that the resistance of metals to ablation is determined by their mechanical strength, mainly by their resistance to plastic flow.

This hypothesis is confirmed, first of all, by an increase in the mechanical strength of steel as a result of hardening and a higher carbon content; secondly, the effect of these factors is manifested mainly at the crater periphery, where the appreciable wear of mass may be attributed to large friction forces between the plasma stream, the liquid phase, and the solid target material. In the case of very fast and dense plasma jets, the stresses may become sufficiently high to cause plastic flow in the solid phase. The more intensive disintegration at the crater periphery may then be attributed to the flow and the wear of solid metal.

One can test the possibility of such a mechanism by estimating the viscous forces generated in the liquid as the latter flow along the solid surface. This force is, per unit area,

$$\tau = \eta \frac{\Delta v}{\Delta z}.$$

Let us assume that solid material at the solid–liquid interface will begin to flow swept by the liquid as soon as the viscous force τ becomes equal to the critical shear stress τ_0 at which plastic flow of the solid occurs. From this we estimate the thickness of the liquid layer capable of sweeping away solid material:

$$\Delta z_0 = \eta \frac{\Delta v}{\tau_0}.$$

A gas jet and liquid droplets carried by it leave the hearth in a target at a velocity of ~10 km/sec, as the separate tracks of droplets on the photograms in our high-speed test with the SFR-1 cinematograph indicate. We may, then, estimate the velocity of the liquid to be 10 km/sec at the liquid–gas boundary and zero at the liquid–solid boundary. The viscosity of molten steel is $\eta = 2 \cdot 10^{-2}$ P [5] and τ_0 will be taken as equal to the yield point of steel or ~10^9 dyn/cm^2. With these values, we have $\Delta z_0 \sim 0.2\ \mu$.

A metallographic examination of a crater cross section has confirmed this estimate. The white unetched zone emerging as a result of crystallization from the liquid phase [6] indicates what the thickness of the liquid layer may be at various locations within the hearth region. The analysis has shown that the white zone is ~50 μ thick at the crater center, but less than 1 μ thick or more often so small as to be undetectable at the crater periphery (where the crater is deepest). This indicates, in accordance with the given estimate, that conditions are realized under which wear of solid target material can occur.

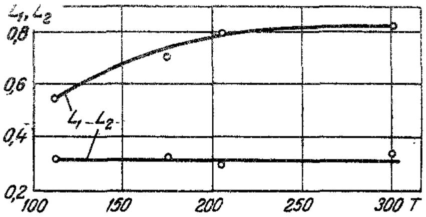

Fig. 3. Crater depth (a) at the periphery L_1 (mm) and (b) at the center L_2 (mm), as a function of the initial temperature T (°K) of steel specimens.

Apparently, this applies only to the case of very fast and dense plasma jets, when the rate of mass wear is so high that the film of molten metal between the target and the plasma stream becomes very thin. Contrariwise, the velocity gradient would not be sufficiently high to ensure a sweep of solid mass.

As this mechanism becomes effective, the role of the mechanical strength of the target becomes obvious. The higher the resistance to plastic flow τ_0 is, the higher a velocity gradient $\Delta v/\Delta z$ is required to attain that stress level τ_0.

Into this conception of the process fit also the data pertaining to the effect of the initial specimen temperature. The crater depths L_1 and L_2 in annealed specimens are shown in Fig. 3 as functions of the temperature. We see that L_1 decreases with lower temperatures, a drop in the temperature being known to increase the resistance to plastic flow. At the same time, L_2 is almost independent of the temperature, within the spread of test values, inasmuch as the friction forces are less effective at the crater center.

NOTATION

L_1	is the crater depth at the periphery;
L_2	is the crater depth at the center;
τ	is the viscous force (per unit area);
η	is the dynamic viscosity;
$\Delta v/\Delta z$	is the velocity gradient;
τ_0	is the critical shear stress;
Δz_0	is the thickness of liquid layer under which flow stress is produced in the solid phase.

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