CRATER FORMATION IN A METAL BY MEANS OF A HIGH-ENTHALPY PLASMA SHOCK

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UDC 662.215

Considerable attention has been devoted in recent years to a study of the local high-intensity pulses which act on a metal so as to form a crater on the metal surface that is ascribed to plastic flow, melting, or to the vaporization of the material. When explosive devices are used, among the foregoing we have to include the crater formation which occurs in high-velocity impact against a solid, the action of a stream of metal from a shaped charge, or from the deceleration of a jet of material produced in the explosion of a shaped charge [1-4].

The present study is devoted to an investigation of the crater formation in a metal when it is impacted by a high-enthalpy plasma cluster from an explosive plasma generator (EPG).

The experimental installation which we used here consists of an EPG and a metal target. Figure 1 shows a diagram of this installation: 1, the electronic detonator; 2, the explosive charge; 3, a metallic piston plate; 4, the working gas (air under normal conditions); 5, a hemispherical EPG compression chamber; 6, openings for the passage of the plasma; 7, protective shielding; 8, target. A wooden liner protects the target against a direct impact from the metallic compression chamber. The cylindrical targets have been fabricated from various metals and alloys and exhibit a diameter which is several times greater than the diameter of the crater that is formed. The crater is shown in Fig. 1 conditionally by a dashed line. A general description of the EPG can be found in [5, 6].

In our experiments we used a powder charge of 6ZhV ammonite with a mass of 0.3 kg. The mass of the working air in the compression chamber was 22 mg. The total plasma energy of 7 kJ was measured calorimetrically [7]. The calculated plasma temperature was $\sim 2 \cdot 10^4$ K (without consideration of the impurities from the walls). With the characteristic volume of 0.25 cm^3 the plasma pressure was on the order of 10 GPa. The radiant heat flux density from the plasma was $\sim 1\ GW/m^2$. This plasma pressure exceeds the plasticity threshold of all metals, while the heat flow density is sufficient to melt and vaporize the surface layer within tens of microseconds. These factors enable us to predict the formation of a crater under the action of an EPG plasma on the surface of a metal. The purpose of this study is to determine the characteristics of the crater and to establish the fundamental mechanism by which it is formed: this will either be plastic deformation of the metal or ejection of the metal in the liquid or gaseous phase.

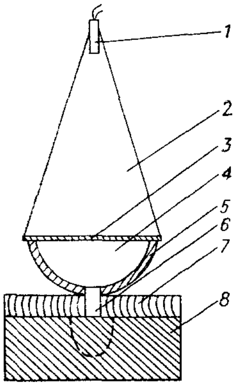

Fig. 1

Dnepropetrovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 30, No. 6, pp. 19-22, November-December, 1989. Original article submitted June 9, 1987; revision submitted August 3, 1988.

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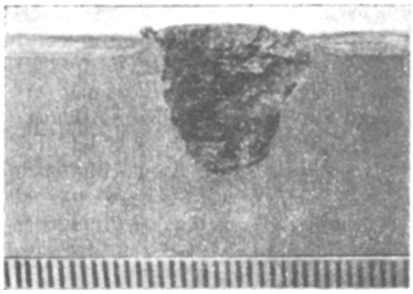

Fig. 2

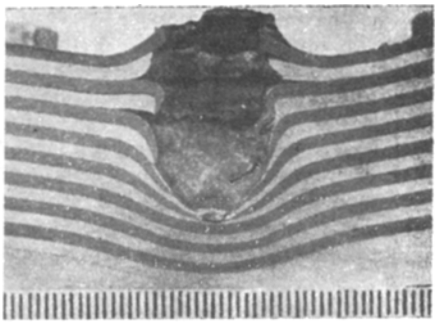

Fig. 3

In Fig. 2 we see a photograph of the axial cross section of a target made of St.45 with a crater formed by the impact of the plasma under the indicated conditions. The scale markings are 1 mm. The edge of the crater is surrounded by a characteristic rim which solidified in the motion of the metal, and this is a rim that is similar to that which appears about a crater in the case of a high-velocity impact [1, 2]. The ratio of the crater depth to its diameter for these metals ranges within the limits $h/d = 1\text{-}2$. We might take note of the fact that in the case of a solid high-velocity impact the crater is virtually hemispherical in shape, i.e., $h/d \approx 0.5$, while the cavity formed by the cumulative charge is markedly elongated ($h/d \gg 1$). Comparison of these data shows the correlation between the time of the action and the relative depth of the crater.

The movement of the target material in the formation of the crater is clearly impressed into the cross section of the target, which is made up of a series of layers of steel and aluminum with a thickness of 1.5 mm (Fig. 3). The bent plates show that the two upper plates move in the direction of the free surface, i.e., in the direction of the impact, in the latter stages of the crater formation, while the deeper plates move in the same direction as the impact. The pronounced residual deformation of the metallic plates indicates the presence of loads, at the instant of impact, which exceed the limit of elasticity. The shape of the crater and the residual deformation of the target layers, which come about as a result of the plasma impact (Figs. 2 and 3), turned out to be similar to those which are observed in the case of a high-speed impact with a solid striker mechanism [2].

We have established the fact that a portion of the target mass is lost: the weight of the target after the experiment is reduced. In the case of steel targets a volume of material corresponding approximately to 10% of the crater volume is lost. Thus, a portion of the target material is ejected in the formation of the crater; however, this is not the fundamental mechanism of crater formation.

We have determined the relationship between depth and the loss of material by weighing the plates making up the layered target, shown in Fig. 3. Figure 4 shows the lost mass M as a function of the plate number n (we begin counting the plates from the target surface). Curves 1 and 2 pertain, respectively, to the steel and aluminum plates. The experimental results give evidence to the effect that the ejection of material is significantly reduced as depth increases.

Figure 5 shows the experimentally determined relationship between the reciprocal $1/V$ of the crater volume V and the Brinell hardness B of the target (the target materials are as follows: 1, copper; 2, an AMts aluminum alloy; 3, St.45; 4, 9KhS alloy; 5, VT3-1 titanium alloy). The hardness of the targets was measured prior to the experiment and the temperature of the targets prior to the experiment was found to be 15-20°C. The crater volume was established by filling it with water from a burette. The reproducibility of the results was verified by means of six identical tests involving steel targets and proved to be ~15%.

The relationships shown in Fig. 5 can be represented by the formula $V = C(E/B)$, where C is a constant and E is the energy of the plasma. We find an analogous relationship in the case of a high-speed impact with a solid body [1]. The difference is to be found in the numerical value of the constant: $C = 0.2$ in our case and $C = 0.4$ in the case of the high-speed impact. Thus, with the impact of a plasma cluster approximately 20% of its energy is expended on the formation of the crater, while in the case of the high-speed impact by a solid material approximately 40% of the striking mechanism's energy is spent.

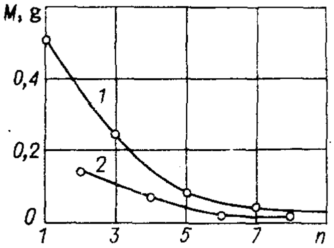

Fig. 4

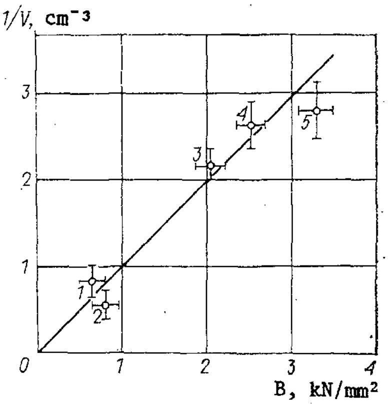

Fig. 5

The surface of the crater wall exhibits irregular unevenness (see Fig. 2). We assume that these irregularities are a consequence of the familiar Taylor instability of the accelerating boundary between two media of different densities, in this particular case, the boundary between the plasma and the metal, although we cannot exclude the possibility that the irregularities are simply a consequence of the nonuniformities in the dynamic thrust of the plasma jet.

We have carried out a metallographic study of the cross section of the crater wall in St.45 (etched in a 4% solution of nitric acid in alcohol). The microsections clearly show two layers in which the burning plasma exerts an intense thermal effect. The crater surface is covered with a light layer of a cooling melt without any distinguishable crystal structure (its thickness at various points in the crater ranges from 10 to 100 μm). The calculated estimate yields a cooling rate for the melted layer in excess of 10^5 K/sec due to the rapid removal of heat into the depth of the cold metal. With such high cooling rates an amorphous metal is usually formed, and this might be assumed under the conditions being considered here. The volume of the remaining layer of the melt amounts to less than 1% of the crater volume.

In the crater walls, within the light layer, we find a multiplicity of micropores. These pores are, apparently, a consequence of the escape of metal vapors during the volumetric effervescence of the layer of superheated metal that is attributable to the sharp reduction in plasma pressure. The possibility of such a process has been indicated in [8]. In addition to the pores at the surface of the crater walls, at certain points we find microcracks for whose appearance no cause has yet been established. Beneath this layer of cold melt we find a layer of hardened metal with an elevated microhardness (its thickness is ~50 μm). This hardened layer is also a result of the heating of the surface by the plasma and its subsequent cooling by removal of heat to the cold metal, but the peak temperature and the cooling rate are lower than in the first layer. The formation of such melt and tempered layers in the steel walls had been observed earlier in the passage of plasma from an EPG through a tube and in the filling of its cavity [9].

Beneath these two layers thermally affected by the plasma we find the original material, distinguished in the microsections only by some elongation of the crystals in a direction approximately parallel to the crater wall. With increasing distance from the crater the elongation of the crystals is reduced. The presence of such a microstructure gives evidence of the plastic metal flow which has occurred.

The described phenomenon of crater formation through impact of a high-enthalpy plasma is yet another example of the intense impact action on metal that leads to the destruction of the metal surface. All of these established facts make it possible for us to maintain that in this case the basic mechanism for the formation of a crater is the plastic flow of the metal subjected to the action of the high plasma pressure. The thermal effect of the plasma is seen primarily in the appearance of layers in which the crater walls are subjected to a thermal effect.

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A MIXED AEROSOL—PARTICLE CHARGE. THE ASYMPTOTE AND INTERPOLATION FORMULAS FOR THE ELECTRIFICATION CURRENT

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UDC 532.584:537.24

In the electrohydrodynamic flows of weakly ionized aerosols particles may undergo electrification due to a combination of ion charges [1]. With a low disperse-phase concentration we can limit ourselves in the description of this process to a study of the charge of a single particle. The present study is devoted to an investigation of a mixed charge, where diffusion significantly affects ion motion in the electric field generated by external forces in the vicinity of the particle. In studying this mixed charge, as a rule, we can neglect the motion of the gas relative to the particle. In extreme cases in which neither the diffusion of the ions nor the external electric field have been taken into consideration, the problem of the unipolar charge of a spherical particle in a nonmoving weakly ionized gas has been solved in [2, 3]. The solution of the problem with respect to the influence exerted by a weak external electric field on the diffusion charge of the particle has been derived in [4]. In the present paper we examine the opposite case of a strong external electric field. We have used the method of joined asymptotic expansions [5] to find the distribution of ions in the vicinity of the particle as well as an expression for the electrification current, which refines the familiar solution [2]. These results are subsequently used in the construction of an approximate interpolation formula for the global electrification current. We note that the conventional summation of the limit expressions [2, 3] to calculate the electrification current in the case of a mixed charge produces major errors. Comparison with the results from a numerical solution of the problem on a computer shows that the constructed interpolation formula provides good approximation in the case of arbitrary values for the electric Peclet number Pe_E.

1. In disperse media consisting of a weakly ionized gas and dispersed particles, the latter may become charged by capturing the charge of the ions. Given a sufficiently small particle concentration, in order to study this phenomenon we will examine the electrification of a single ideally conducting spherical particle in a unipolar charged gas. Without loss of generality for the results, we will assume the ion charge to be positive. Let the ion concentration and the particle radius a be sufficiently small and we will assume the external electric field to be uniform at distances of $\sim a$.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 30, No. 6, pp. 23-28, November-December, 1989. Original article submitted March 23, 1987; revision submitted July 8, 1988.

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