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SITE OF ORIGINATION OF SHOCK WAVES ON EXPOSURE OF METAL TARGETS TO HIGH-CURRENT ELECTRON BEAMS

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We calculate the depth at which shock waves originate in metal targets on exposure to high-current electron beams with $E_0 = 1-5$ MeV, $i = 10^4-10^5$ A, $r_{beam} = 0.1-0.2$ cm.

On exposure of metal targets to high-current electron beams (HEB) a variety of physical processes occur in the material of the specimen, among which there are the melting of metals, evaporation, the passage of shock waves, and, as a consequence, the appearance of cracks and spalls. A possible reason for the appearance of shock waves in metal targets on passage of HEB is the formation of plasmons [1]. The objective of the present work is to determine the region or site of origination of shock waves (we mean the depth from the target surface at which the second compression wave overtakes the first) in metal targets under the action of HEB. This will make it possible to determine the dimensions of spalls (that is, their thickness).

Since initially the elementary compression waves that appear propagate in the target with the speed of sound, it is to be expected that the magnitude of the surface-layer acceleration will be close to the value of the derivative of the speed of sound [2]. From classical gas dynamics it is known that in a homogeneous medium a shock wave originates at a distance from the surface that is determined from the formula [3]

$$h = \frac{2c_0^2}{(j+1)\,a}, \tag{1}$$

where j is a coefficient whose value for solid bodies is close to 3–4; a is the acceleration of the surface layer of the medium acquired under the action of an electron beam.

Consequently, to find the coordinate h, it is necessary to find the value of a that, as was mentioned above, is equal to the derivative of the speed of sound:

$$a = \frac{\partial c}{\partial t}. \tag{2}$$

It is known that the speed of sound in solid bodies is determined by the formula

$$c = \sqrt{\left(\frac{E_{\text{elas}}}{\rho}\right)}, \tag{3}$$

Since the speed of sound depends on the density of the target material, it also depends on the change in the medium temperature under the action of the electron beam:

$$\rho = \rho_0 \left(\frac{\Delta p - p_0}{A} + 1\right)^{1/4}, \tag{4}$$

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TABLE 1. Actual Values of the Depth of Origination h of a Shock Wave Depending on the Parameters of the Beam and the Target Material

Target material	r_{beam}, cm	Beam current, A	Origination depth, mm
Aluminum	0.2	10^4	0.694
	0.2	$5 \cdot 10^4$	0.918
	0.1	10^4	0.632
	0.1	$5 \cdot 10^4$	0.714
Copper	0.2	10^4	0.592
	0.2	$5 \cdot 10^4$	0.734
	0.1	10^4	0.653
	0.1	$5 \cdot 10^4$	0.796

$$\Delta p = -\alpha k \Delta T, \tag{5}$$

where ρ_0 is the density of the target material before irradiation; k is the bulk modulus, which depends on E_{elas} and ν:

$$k = \frac{E_{elas}}{3(1 - 2\nu)}.$$

Generally, the coefficient A is a variable quantity that depends on the speed of collision of the fast electrons of the HEB with the atoms of the target, but if this speed does not exceed several kilometers per second, then we can neglect the increase in entropy in the collision and can consider A = const. In the general case the value of A is proportional to ρ_0 and to the speed of sound in the target at the instant of irradiation c_0 [4].

The temperature T in the region of irradiation by the electron beam is determined from the expression [5]

$$T = T_0 + \Delta T, \quad \Delta T = \frac{\Delta E}{c_p \rho_0 V}, \tag{6}$$

where T_0 is the temperature of the metal target before irradiation.

Then, taking into account that the energy release by the electrons of the beam is directly proportional to the current of the beam i, the duration of the action on the target τ, and the energy of the electrons in the beam E_0 and is inversely proportional to the electron charge e, we obtain the following expression for determining the speed of sound in solid bodies:

$$c = \sqrt{\left(\frac{E_{elas}}{\rho}\right)} A^{1/8} \left(A - p_0 - \frac{\alpha k E_0 i \tau}{c_p \rho_0 V e}\right)^{-1/8}, \tag{7}$$

Finally, using expressions (1)-(4) and (7), we obtain a formula for determining the distance from the target surface to the site of origination of the shock wave:

$$h = \frac{16 c_0^2}{A^{1/8} (j + 1)} \sqrt{\left(\frac{\rho_0}{E_{elas}}\right)} \frac{c_p \rho_0 V e}{\alpha k E_0 i} \left(A - p_0 - \frac{\alpha k E_0 i \tau}{c_p \rho_0 V e}\right)^{9/8}. \tag{8}$$

As an example of the calculation, we considered the action of a high-current beam of relativistic electrons with E_0 = 1–5 MeV, i exceeding 10^4 A [6], r_{beam} = 0.1–0.2 cm, and $\tau = 10^{-11}$–10^{-4} sec on a cylindrical axisymmetric target made of aluminum, copper, and iron. The pulse of the HEB was selected so that the heating at each point of the target exposed to the high-current beam would not exceed the melting temperature for the given material [5]. Results of calculation of values of h are presented in Table 1.

As seen from the table, on exposure of a metal target to a high-current beam of relativistic electrons a shock wave originates in the medium at a distance of approximately 0.3–0.4 of the electron mean free path in the given substance. The results obtained agree well with experimental data presented in [1].

NOTATION

A, experimental coefficient whose values are given in [4]; α, coefficient of volumetric thermal expansion of the target material; c_0, speed of sound in the given medium; c_p, specific heat; e, electron charge; E_0, initial energy of the beam electrons; E_{elas}, longitudinal-elasticity modulus of the target material; ΔE, energy release of the HEB in the specimen; h, depth of origination of the shock wave; i, current of the beam; j, coefficient; ν, Poisson coefficient; p_0, normal atmospheric pressure; r_{beam}, beam radius; p, density of the target material; T, temperature of the target; V, volume of the target region in which the temperature changes by ΔT under the action of the HEB (calculated by a procedure given in [5]); τ, pulse of the beam.

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