Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 5, 2000

ACCELERATION OF METAL PLATES BY A TANGENTIAL DETONATION WAVE

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UDC 534.222.2

The studies of the two-dimensional acceleration of metal plates that began in the 1960s at the Siberian Division of the Russian Academy of Sciences under the supervision of Academician M. A. Lavrent'ev in connection with explosion-welding works are reviewed briefly. Some new results concerning the use of industrial high-explosives (HE) *that operate under conditions of nonideal detonation are given.*

1. The Gurney scheme developed in the U.S.A. in the early 1940s is in widespread use for determining the acceleration velocity in explosions of flat, cylindrical, and spherical charges of different configuration [1]. The processes that accompany the acceleration are described within the framework of the instantaneous-detonation model, and the velocity distribution in the explosion products is assumed to be linear. Exact formulas for determination of the acceleration parameters for plates and shells of different geometry are obtained under these assumptions.

Upon acceleration of a plate by an HE layer opened at one side (Fig. 1a), the Gurney formula for the velocity of the plate has the form [2]

$$V = \sqrt{2E_G}\,\frac{r\sqrt{3}}{\sqrt{r^2+5r+4}}. \tag{1}$$

Here r is the ratio of the HE mass to the mass of the plate to be accelerated; the quantity E_G is called the Gurney energy and is a portion of the energy Q, namely, the heat of explosion that converts to the kinetic energy of the explosion products. We give here the Gurney formulas describing the acceleration for the cases shown in Fig. 1. We use the notation adopted in the Western literature [1].

For acceleration of two plates of different mass by an HE layer (Fig. 1b), we have

$$\frac{V}{\sqrt{2E_G}} = \Big[\frac{1+A^3}{3(1+A)} + \frac{NA^2}{C} + \frac{M}{C}\Big]^{-1/2}. \tag{2}$$

In the symmetric case of acceleration of two identical plates (Fig. 1b), Eq. (2) takes a simpler form

$$V/\sqrt{2E_G} = (M/C + 1/3)^{-1/2}. \tag{3}$$

Upon acceleration of a cylindrical shell by an inner charge (Fig. 1c) packed closely in the internal hollow, we have

$$V/\sqrt{2E_G} = (M/C + 1/2)^{-1/2}. \tag{4}$$

In the spherical case (Fig. 1d), the velocity formula takes the form

$$V/\sqrt{2E_G} = (M/C + 3/5)^{-1/2}. \tag{5}$$

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 0021-8944/00/4105-0824 $25.00

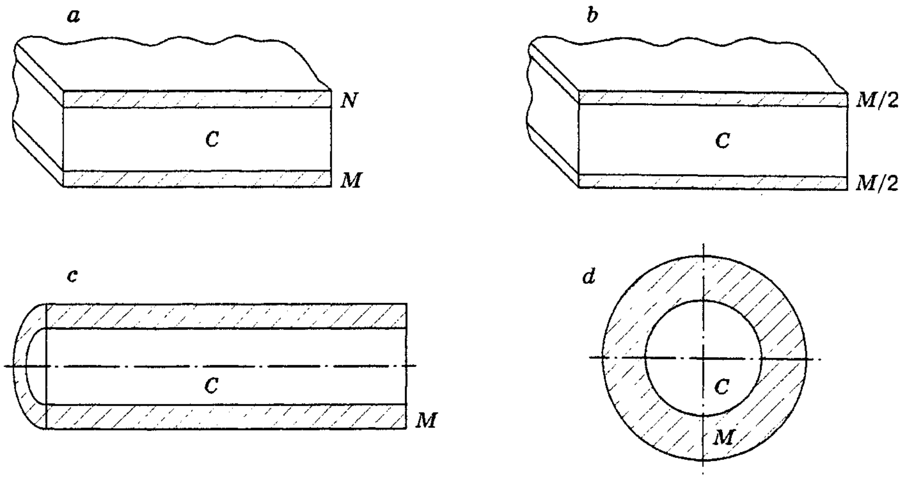

Fig. 1

TABLE 1

HE No.	Type of HE	ρ_0, g/cm^3	D, km/sec	Q, kcal/g	γ	$\sqrt{2E_G}$, km/sec	E_G/Q	k	Charge size
1	TNT [1]	1.63	6.93	1.09	2.50	2.37	0.61	3.09*	—
2	RDX [1]	1.77	8.70	1.51	2.64	2.83	0.64	3.23*	—
3	RDX [4]	1.0	6.0	0.80	2.44	2.29	0.73	2.80*	—
4	PETN [1]	1.76	8.26	1.49	2.54	2.93	0.69	2.98*	—
5	HMX [1]	1.89	9.11	1.48	2.77	2.97	0.72	3.22*	—
6	Compound V [1]	1.717	7.98	1.20	2.71	2.71	0.72	3.12*	—
7	6ZhV ammonite [5]	1.0	4.2	0.81	1.90	1.83	0.49	2.50	Diameter 50 mm
8	TNT [4]	1.0	5.0	0.437	2.31	1.58	0.7	3.31	—
9	6ZhV ammonite and ammonium nitrate (1 : 1) [6]	1.0	3.0	0.40	1.92	1.53	0.7	2.20	Layer thickness 20–40 mm
10	Ammonium nitrate [7]	1.0	5.0	1.00	2.00	2.93	0.7	2.29	Layer thickness 200 mm

Note. The calculated values are asterisked.

In Eqs. (2)–(5), C is the HE mass, M and N are the masses of the elements to be accelerated, and $A = (1 + 2M/C)/(1 + 2N/C)$. Carrying out special experiments on the measurement of the maximum velocity of the bodies accelerated according to the schemes depicted in Fig. 1, one can determine the Gurney energy E_G for various HE. To determine the acceleration velocity of the cylinder, the technique described by Kury et al. in [3] is widely used currently.

The Gurney formulas are attractive for acceleration-velocity calculations, because they are straightforward and allow one to estimate the parameters of various explosive devices. Table 1 lists the values of the detonation-wave and Gurney-energy parameters for some HE.

The heat of explosion Q was calculated from the known formula

$$Q = D^2/(2(\gamma^2 - 1)), \tag{6}$$

where γ is the polytropic exponent of the explosion products immediately behind the detonation-wave front and D is the detonation velocity. The quantity γ can be calculated if the detonation velocity and one more detonation-front parameter, for example, the mass velocity of the explosion products U or the detonation pressure P_D [4, 5], are known. These quantities and the initial density of the explosive charge ρ_0 are related

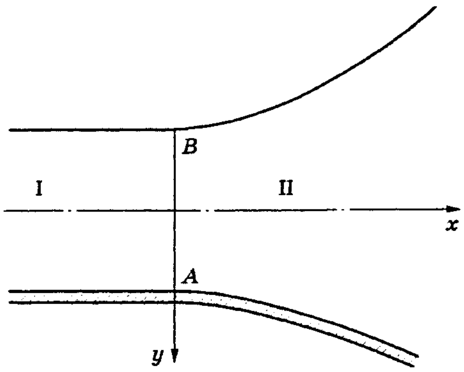

Fig. 2

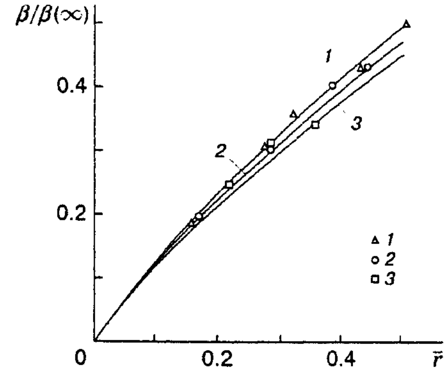

Fig. 3

by relations which make it possible to calculate the quantity γ:

$$P_D = \rho_0 D^2/(\gamma + 1); \tag{7}$$

$$U = D/(\gamma + 1). \tag{8}$$

In particular, for HE Nos. 1–6 (see Table 1), the quantity γ was calculated from Eq. (7), and the quantities D and U were measured [6]. For HE Nos. 3, 7, and 8, the quantity γ was calculated from Eq. (8), and the quantities D and U were measured. For HE No. 10, the quantity γ was calculated from formulas for the detonation parameters of mixed HE given in [7]. It is noteworthy that in the case of low-speed HE Nos. 3, 7–10, the detonation parameters usually depend on the charge sizes, and the characteristics of the ideal detonation front for these HE are not the exactly determined quantities. The dependence of the detonation characteristics on the size and shape of the particles, the method of mixing the composite HE, the compressibility of the material of the plate to be accelerated, etc., complicates the experimental determination of the ideal-detonation parameters for these HE [8]. The quantity k was calculated from formula (6) with the Gurney energy used instead of the heat of explosion Q:

$$E_G = D^2/(2(k^2 - 1)). \tag{9}$$

For HE Nos. 3, 7, and 9 (see Table 1), the quantity k was found by solving the two-dimensional problem of a plate accelerated by an HE layer [9].

2. Deribas and Kuz'min [9] gave the solution of the two-dimensional stationary problem of acceleration of an incompressible plate that consists of elements not connected to one another. This problem was solved earlier by Taylor [10]. Figure 2 shows schematically the acceleration of a plate by an HE layer. In the coordinate system connected with the detonation wave AB, the motion is considered stationary, because the plate and charge lengths are unbounded. The coordinate origin is on the plate, the y^* axis is perpendicular to the plate, and the distance along the vertical is measured in the thicknesses of the charge. The nonreacting HE is in region I, and the explosion products are in region II. The explosion products are regarded as a polytropic gas:

$$P = \rho^k. \tag{10}$$

The polytropic exponent k is assumed to be constant in the entire region of scatter of the explosion products. The Prandtl–Mayer centered rarefaction wave is at the point of intersection of the detonation wave with the free surface. Based on the analytical solution and the numerical calculations performed in [9], Kuz'min [11] proposed a formula that determines the position of the plate:

$$\beta = \sqrt{(k+1)/(k-1)}\,(\pi/2)\bar{r}, \qquad \bar{r} = r/(r + a + b/y), \qquad y = y^*\delta_0. \tag{11}$$

Here β is the angle of slope of the plate, r is the ratio between the HE and plate masses, a and b are constants, k is the polytropic exponent, and δ_0 is the charge thickness. The experimental data on the acceleration of metal plates by the charges of loose RDX ($\rho_0 = 1.0$ g/cm^3), 6ZhV ammonite, and a mixture of 6ZhV with granulated ammonium nitrate (1 : 1) for different r were processed according to this formula. The angle β was found by the rheostat technique described in [12]. Processing of the data obtained in many experiments allowed us to determine the constants a and b, which are the same for all the HE examined, and the polytropic exponent k: $a = 2.71$, $b = 0184$, and $k = 2.8$, 2.5, and 2.2 for RDX, 6ZhV ammonite, and a mixture of 6ZhV and granulated ammonium nitrate (1 : 1), respectively.

Figure 3 shows experimental (points) and calculated (curves) dependences $\beta/\beta(\infty)(\bar{r})$; the latter were obtained from Eq. (11). Points 1–3 refer to experimental data for loose RDX, 6ZhV ammonite, and a mixture of 6ZhV and granulated ammonium nitrate (50 : 50), respectively. Curves 1–3 correspond to $k = 2.8$, 2.5, and 2.2. It is noteworthy that in all the experiments, the detonation of the charges used was not ideal. It follows from Table 1 that the values of k from (11) can be calculated from formula (9). Here the ratio between Q and E_G is in the same limits as for highly brisant HE, for which the detonation is close to ideal detonation. To determine the Gurney energy experimentally, it is necessary to use the relation between the angle β and the velocity of the plate V obtained in [10]:

$$V = 2D \sin(\beta/2). \tag{12}$$

We note that in the two-dimensional problem of a plate accelerated by sliding detonation, the polytropic exponent of the explosion products can be determined by measuring the angle of scatter of the gases from the free surface of the charge, as is done in [13]. The values obtained for k differ slightly from those calculated from formula (11).

3. Kiselev [14] used another approach because of significant difficulties encountered in the calculation of the acceleration process under conditions of nonideal detonation [14]. The solution of a number of practical problems calls for a more careful study of the initial phase of acceleration of the plate. It follows from Eq. (11) that at the beginning of the acceleration, for $y = 0$ the angle of slope is $\beta = 0$, and, according to Eq. (12), the initial acceleration velocity is $V = 0$.. We note that in deriving Eq. (11) in the formulation of the problem from [9], the plate to be accelerated was a set of incompressible elements that were not connected to one another, each element having a finite mass. The results of dedicated experiments, the technique of which was expounded in [14], showed that at the initial moment of acceleration, the angle β is different from zero and its value can be determined with sufficient accuracy if the compressibility of the plate material is taken into account and the (P–U) diagram of the accelerated material and the detonation-wave parameters of the accelerating charge are used. As a result, at the initial moment $\beta(0)$, the angle of slope is determined from the formula

$$\beta(0) = 2 \arcsin(U/D), \tag{13}$$

which is similar to (12) and where U is determined from the equation

$$\rho_1 U(A_1 + B_1 U) = \frac{\rho_0 D}{\gamma + 1}\Big[1 - \frac{(\gamma^2 - 1)U}{2\gamma D}\Big]^{2\gamma/(\gamma-1)}. \tag{14}$$

Here the left side refers to the shock adiabatic curve of the material of the plate to be accelerated and the right side refers to the pressure of the detonation products in a one-dimensional unloading wave [15].

After the acceleration terminates, the plate acquires the velocity V_∞ and rotates at the angle $\beta(\infty)$ determined by the Gurney formula (1) and relation (12):

$$\beta(\infty) = 2 \arcsin\Big(\frac{\sqrt{2E_G}}{2D}\,\frac{r\sqrt{3}}{\sqrt{r^2 + 5r + 4}}\Big). \tag{15}$$

The initial $\beta(0)$ and finite $\beta(\infty)$ values of the angle of rotation are determined from formulas (14) and (15), respectively. In [13, 14], formulas for the determination of the intermediate values of the angle of slope were derived. The following dependence of pressure on time behind the detonation-wave front was obtained in [13]:

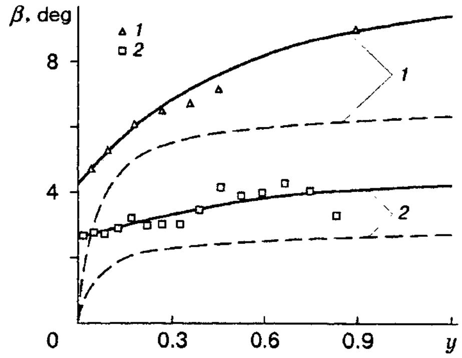

Fig. 4

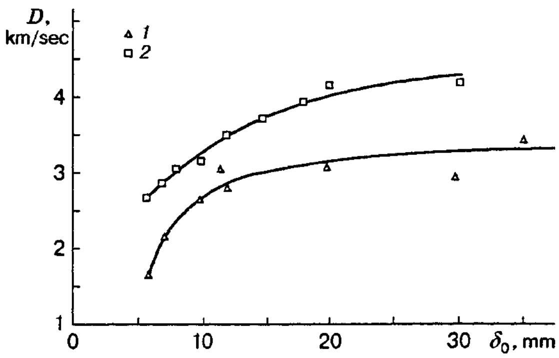

Fig. 5

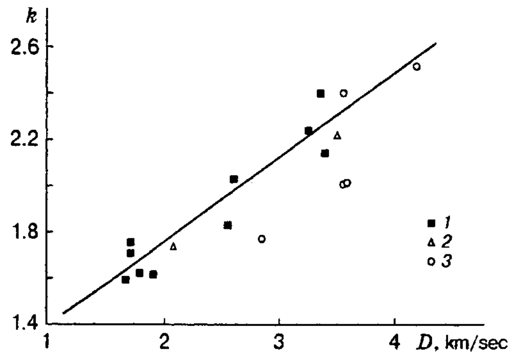

Fig. 6

$$P(t) = P_D \exp(-t/\tau).$$

Here τ is the characteristic time which depends on the type of HE, the charge thickness, and boundary effects and P_D is the pressure at the detonation front. In addition, the dependence of the angle of slope on time was obtained by Vacek [13]:

$$\beta = \beta(\infty)(1 - \exp(-t/\tau)). \tag{16}$$

Here the finite angle of slope $\beta(\infty)$ is determined with the use of the detonation-front parameters and the quantity τ:

$$P_D\tau/(D\delta_1\rho_1) = \beta(\infty). \tag{17}$$

Here δ_1 and ρ_1 are the thickness and density of the accelerated plate, respectively. Using relation (7) for P_D, from (17) we have

$$\beta(\infty) = \rho_0 D\tau/(\rho_1\delta_1(\gamma + 1)) \tag{18}$$

or

$$\beta(\infty) = (r/(\gamma + 1))(D\tau/\delta_0). \tag{19}$$

Kiselev [14] derived a formula for the angle of slope as a function of the path of acceleration, which is similar to (16):

$$\beta(y) = \beta(0) + (\beta(\infty) - \beta(0))(1 - \exp(-\zeta y)). \tag{20}$$

Here $\beta(0)$ is determined from relations (13) and (14), and $\beta(\infty)$ is given by formula (15) or (17), because one can obtain an expression for the quantity τ in terms of the Gurney energy from (19). As for the parameter ζ in

(20), it was shown in [14] that this parameter can depend on the properties of HE; however, as a comparison with the experimental data shows, one can set $\zeta = 2$ in the first approximation.

Figure 4 shows the experimental (points) and calculated (curves) dependences $\beta(y)$ for aluminum ($\delta_1 = 5$ mm) and copper ($\delta_1 = 4$ mm) plates accelerated by a charge of 6ZhV ammonite ($\delta_0 = 6$ mm and $\rho_0 = 1.0$ g/cm^3). Points 1 and curves 1 refer to the aluminum plate, and points 2 and curves 2 to the copper plate. The solid and dashed curves refer to the calculation by Eq. (20) for $k = 2.5$ and Eq. (11) for $k = 2.5$, respectively. One can see from Fig. 4 that the calculation results obtained by means of Eq. (20) agree well with the experimental results.

4. To use Eq. (20) for a particular HE, it is necessary to know its density, the detonation-front parameters (in particular, the velocity D), the polytropic exponent γ, and the Gurney energy or the quantity k, which determines the angle of slope from Eq. (11). If the dimensionless parameter $D\tau/\delta_0$ is known, one can use Eq. (18). The values of the Gurney energy and the polytropic exponent k are listed in Table 1. To determine the initial angle, it is necessary to know the shock adiabatic curve of the accelerated material and to solve Eq. (14) numerically. If the initial site of acceleration is not so important for analysis of the acceleration process, one can use Eq. (11) for approximate estimates. In determining the acceleration parameters, cases where HE charges operating under conditions of nonideal detonation are used for acceleration are the most difficult. Here all the detonation-wave parameters (D, γ, E_G, and k) depend on the charge sizes, in particular, on its thickness δ_0. Therefore, every charge is as a matter of fact the new HE, and its parameters should be found experimentally. Since this is precisely the case that occurs in such applications as explosion welding and explosive compaction, the available experimental data on D and k of some ammonium-nitrate HE can be used for estimating the acceleration parameters.

Figure 5 shows experimental dependences of the detonation velocity D on the charge thickness δ_0 [6]. Points 1 and 2 refer to a mixture of 6ZhV ammonite and granulated ammonium nitrate (1 : 1) and 6ZhV ammonite, respectively. Figure 6 shows the experimental dependences $k(D)$ [6]. In this figure, points 1–3 refer to 15GH3 rocky ammonite produced in Poland, a mixture of 6ZhV ammonite and granulated ammonium nitrate (1 : 1), and 6ZhV ammonite, respectively. The calculated curve was obtained from Eq. (11) (the angle β was measured). Using these dependences, one can determine the acceleration parameters for widely used explosive compounds.

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