EXPERIMENTAL INVESTIGATION OF THE MOTION OF CYLINDRICAL SHELLS UNDER THE ACTION OF THE PRODUCTS OF AN EXPLOSION IN A CAVITY

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An investigation was made of the motion of a cylindrical shell under the action of the products of an explosion in a cavity. An incompressible, nonviscous shell without strength was considered. The method of pulsed x-ray photography, with recording by the shadow method in a streak camera, was used to investigate the motion of shells made of alloy D16, brass, copper, and lead, with different degrees of filling of the cavity of the shells by the charge of explosive. The experimental and calculated results are compared. The agreement between the experimental results and calculation is satisfactory.

1. The method of pulsed x-ray photography, as well as photochronography, was used to investigate the behavior of round metallic cylindrical shells, with pulsed loading set up by the explosion of a cord-type charge of explosive inside [1]. The use of photochronometry in the present work makes it possible to obtain a continuous recording of the motion of the outer surface of a cylindrical shell, with a high-degree of accuracy.

The experiments were made using several kinds of cylindrical shells ($l \leq 3R_0$), made of aluminum alloy D16, lead, brass, and copper; R_0 is the radius of the inside surface of the shell.

Tests were made of eight series of cylindrical shells 1-8, data on which are given below.

No. of series	1	2	3	4
Material	alloy-16	alloy-16	lead	copper
R_0, mm	3	8	8	2.5—6
δ_0, mm	0.8	0.8—7.5	0.5—3.0	0.5—5.0
R_c, mm	3	8	8	2.5—6.0
No. of series	5	6	7	8
Material	brass	brass	brass	brass
R_0, mm	8	8	8	15
δ_0, mm	0.4—3.75	0.9—3.35	0.9—3.35	0.2—6.85
R_c, mm	8	6	3	15

Note. δ is the thickness of the shell; R_c is the radius of the charge of the explosive.

The pulsed loading was set up by the explosion of cylindrical charges of explosive, similar to that used in [2], with a density $\rho_C = 1.62$ g/cm^3 and a pressure at the Jouguet point $P_C = 301$ kbar.

The rate of motion of the surface of the cylindrical shells as a function of the time was recorded using photochronographic (under streak-camera conditions) and x-ray-graphic units. A typical x-ray photo and a typical photochronogram, obtained in experiments with different shells, are shown in Fig. 1. In Fig. 1, part a represents an x-ray photo of a lead shell ($R_0 = 8$ mm, $\xi_0 = 0.125$, $\alpha = 12.6°$, $v_p = 1.85$ km/sec); part b is a photochronogram

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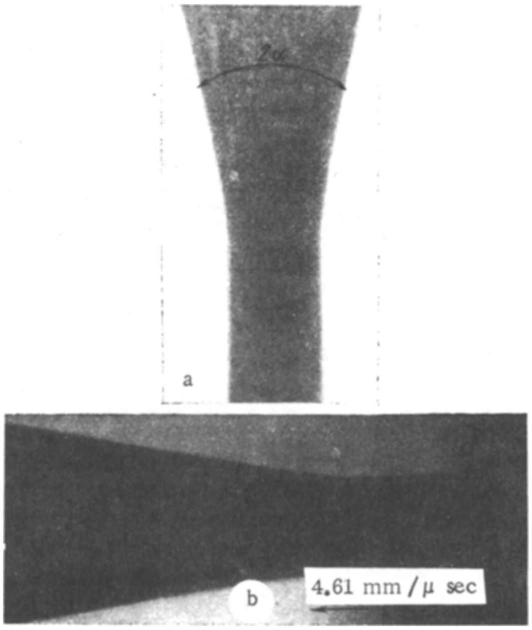

Fig. 1

of a shell made of aluminum alloy D16 (R_0 = 8 mm, ξ_0 = 0.85, α = 7°10', v_p = 1.05 km/sec. Here, $\xi_0 = \delta_0/R_0$, v_p is the velocity of the flight of the fragments).

Interpretation of the experimental results obtained makes it possible to construct the laws of the motion of a spherical shell with different ratios of the masses of the charge of explosive and the shell, and to determine the value of the radius at the moment of the fracture of the shell and the velocity of the flight of the fragments. Interpretation of the x-ray photos gives the dependence of the thickness of the shell on the time $\delta = f(t)$.

From an analysis of the dependences $\delta = f(t)$ it follows that, during the process of its motion, the material of the shell behaves like an incompressible liquid and satisfies the equation of continuity

$$\delta_0\,(2R_0 + \delta_0) = \delta\,(2R + \delta) \qquad (1.1)$$

where δ and R are the instantaneous thickness and inside radius of the shell.

Figure 2 gives the dependence of the relative decrease in the thickness of the shell at the moment of fracture $\varepsilon = \delta_0/\delta$ on the initial relative thickness. In Fig. 2 and the following figures the following notation is adopted: 1) Pb ($R_0 = R_c$ = 8 mm); 2) alloy D16 ($R_0 = R_c$ = 8 mm); 3) alloy D16 ($R_0 = R_c$ = 3 mm); 4) Cu ($R_0 = R_c$, $2.5 \le R \le 6$ mm); 5) brass ($R_0 = R_c$ = 8 mm); 6) brass (R_0 = 8 mm, R_c = 6 mm); 7) brass (R_0 = 8 mm, R_c = 3 mm); 8) brass ($R_0 = R_c$ = 15 mm).

As can be seen from Fig. 2, shells made from different metals form a single empirical dependence $\varepsilon(\xi_0)$.

In the interval $0 \le \xi_0 \le 0.2$, the value of ε rises from 0 to ~0.35, and then, further, with $\xi > 0.2$, the value of ε rises only weakly. This is in agreement with data for steel round cylindrical shells.

From the moment of fracture, and further on during flight, the thickness of the fragments does not change. Therefore, knowing the thickness of the shell at the moment of fracture, we can determine the radius R at which the fracture of the shell takes place,

$$(R_1 / R_0)_* = 1 / (1 - \varepsilon) + \xi_0\varepsilon\,(2 - \varepsilon) / 2\,(1 - \varepsilon) \qquad (1.2)$$

The values of $(R_1/R_0)_*$ were determined from experimental data on the radius of the outer surface of the shell, bringing in expression (1.1). Figure 3 shows the values of $(R_1/R_0)_*$, determined in this fashion, as a function of the initial relative thickness of the shell.

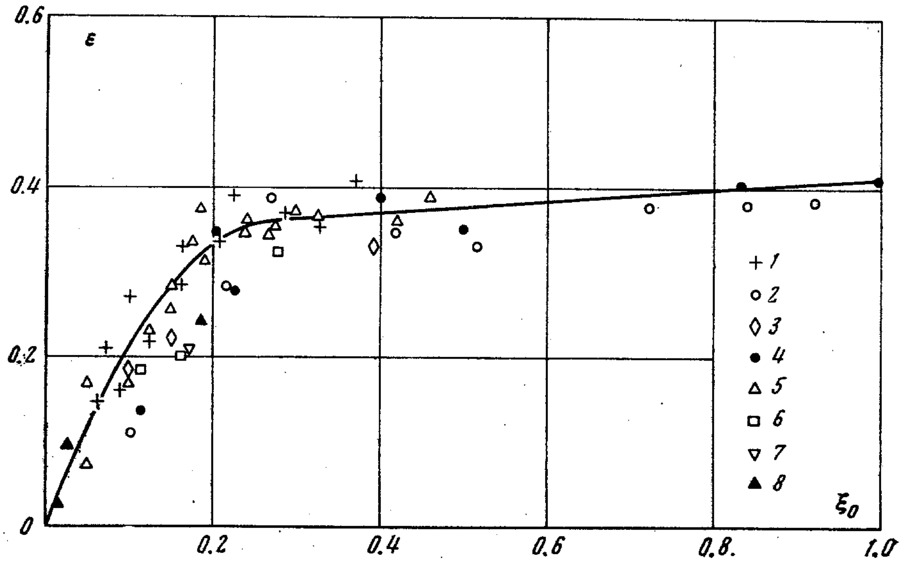

Fig. 2

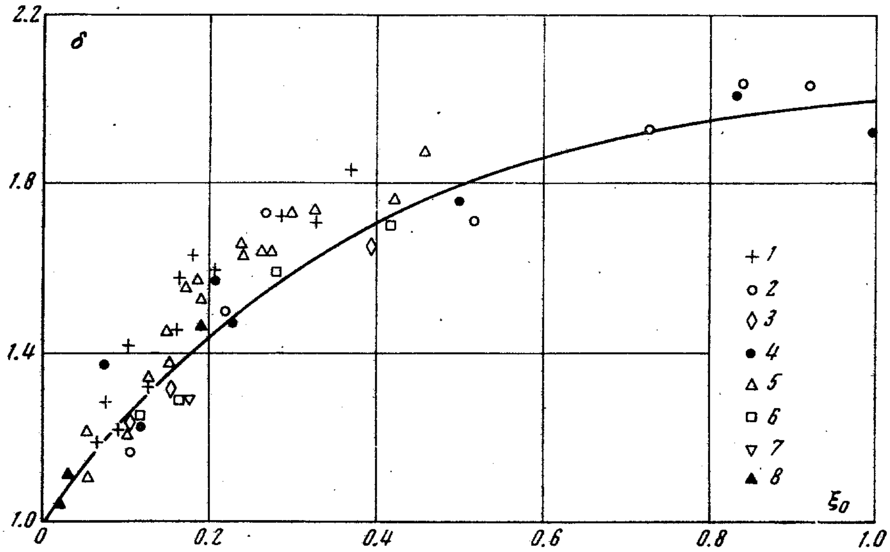

Fig. 3

Experimental results from the measurements of the velocity of the shell at the moment of fracture (the velocity of the fragments) are shown by the curve of Fig. 4. Along the axis of ordinates are plotted the values of v_p, and, along the axis of abscissas, the parameter $\varkappa = \xi_0\rho/\rho_0$, which is the dimensionless mass of the shell. The value of the velocity with $\varkappa = 0$, i.e., for a cylindrical charge of explosive without a shell, obtained in an experiment with frame-by-frame recording, in a photochronograph, of the process of the flight of the explosion products with the detonation of a cylindrical charge of explosive (R_c = 8 mm). Under these circumstances, a value α = 23°C was obtained, which corresponds to v_p = 3.57 km/sec.

2. With the consideration of the deformation of metallic cylindrical shells under the action of the pressure of the explosion products on the inner surface, we assume the material of the shells to be incompressible. The error of such an assumption is not great in the range of pressures attained in metals with the explosion of an explosive in contact with them. The postulation of incompressibility corresponds to the neglect of wave processes and to the consideration of inertial motion.

An explosive substance detonates before the shell is set into motion. This means that, at the start of the motion of the shell, the space inside it is filled with gas at high pressure. The products of the detonation constitute a polytropic gas with the index γ.

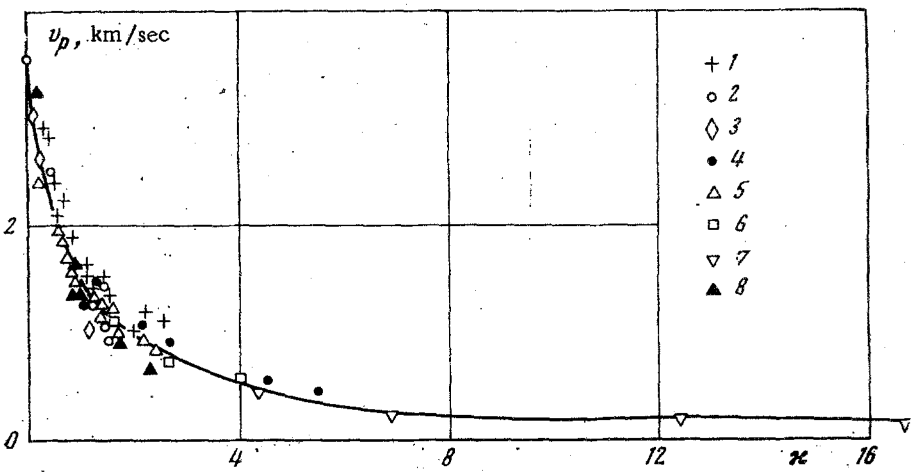

Fig. 4

We assume the cylindrical shells to be infinitely long, and all the motions to be axisymmetric and identical for all the orthogonal transverse cross sections of the shells. This assumption reduces the problem under consideration to the problem of the one-dimensional motion of an incompressible cylindrical shell.

With an equation of state of the combustion products $p = A\rho_g{}^{\gamma}$, where A = const, the pressure of the explosion products inside the shell varies in accordance with the law ($p = p_0\nu^{-2\gamma}$), and the equation of motion of a cylindrical shell assumes the form

$$\ddot{\nu} = \frac{M}{R_0^2}\nu^{-(2\gamma-1)}$$
$$M = Rp_0 / \rho\xi_0(\xi_0 + 2);\ p_0 = p\nu^{2\gamma},\ \dot{\nu} = d\nu / dt \qquad (2.1)$$

Integrating Eq. (2.1), we obtain the law of the one-dimensional motion of a shell

$$v^2 = N[1 - \nu^{-2(\gamma-1)}], \qquad N = \frac{2p_0}{\gamma - 1}[\rho\xi_0(\xi_0 + 2)]^{-1} \qquad (2.2)$$

Expression (2.2) holds if γ remains constant during the process of the expansion of the explosion products. In actuality, the adiabatic process of the expansion of the explosion products can be divided into two phases. According to [3], the pressure at the point of transition is equal to $p = p_1 = 2$ kbar. With $p_c > p > p_1$, we will designate $\gamma = \gamma_1$, and, with $p < p$, $\gamma = \gamma_2$.

In the case of incomplete filling of the cavity of the shell by the charge of explosive ($R_c < R_0$, R_c is the radius of the charge of explosive), two cases are possible. The pressure at the start of the motion of the shell $p_c > p_0 > p_1$ or $p_0 < p_1$. With $p_0 \leq p_1$, in expression (2.2) we must set $\gamma = \gamma_2$. In this case, the quality p_0 is defined as

$$p_0 = \left(\frac{R_c}{R_0}\right)^{2\gamma_2} p_c^{\gamma_2/\gamma_1} p_1^{(1-\gamma_2/\gamma_1)} \qquad (2.3)$$

With $p_c > p_0 > p_1$

$$v^2 = K\left[1 - \left(\frac{p_c}{p_1}\right)^{(\gamma_2-1)/\gamma_1}\left(\frac{R_c}{R_0}\right)^{2(\gamma_2-1)}\right] + v_*^2$$
$$K = \frac{2p_1}{\gamma_2 - 1}\left(\frac{p_c}{p_1}\right)^{1/\gamma_1}\left(\frac{R_c}{R_0}\right)^2\frac{1}{\rho\xi_0(\xi_0 + 2)} \qquad (2.4)$$
$$v_*^2 = \frac{2p_c}{\gamma_1 - 1}\left(\frac{R_c}{R_0}\right)^{2\gamma_1}\left[1 - \left(\frac{R_1}{R_c}\right)^{(\gamma_1-1)/\gamma}\left(\frac{R_0}{R_c}\right)^{2(\gamma_1-1)}\right]\frac{1}{\rho\xi_0(\xi_0 + 2)}$$

In the case of incomplete filling of the cavity of the shell by the explosive, formulas (2.4) are valid with the substitution of $R_c = R_0$ and p_0 in place of p_c.

The character of the motion of metallic cylindrical shells under the action of the explosion of a charge of explosive in a cavity is affected by the viscosity and the strength. Taking account of the elasticoplastic behavior of a metallic shell under such conditions leads to a need for the numerical solution of differential equations. Equations

(2.2) and (2.4) show how the velocity of the shell changes with its motion, but do not determine the moment of the cessation of the action of such a mechanism of the motion. The existence of a finite tensile strength in real shells limits the action of these equations.

The motion of a shell under the action of the combustion products takes place until it breaks down as a result of the passage of cracks over the thickness of the shell. After the fracture of the shell, the fragments fly away at the constant velocity which the shell had at the moment of fracture. In the remaining cases, over the whole range from the start of the motion up to fracture of the shell $\gamma = 3$.

The values of the radius of the inner surface at the moment of R_1, using (2.2) and (2.4), can be used to determine the calculated values of the velocity. These values relate to the internal surface. In the experiments, velocities were obtained which relate to the external surface at the moment of fracture of the shell. From the equation of continuity (1.1) it follows that

$$v_+ R_+ = vR \qquad (2.5)$$

Here the plus sign relates to the external surface. The quantities without subscripts relate to the internal surface. Therefore, with the experimental results we shall compare values obtained using (2.2) and (2.4), taking account of (2.5). A comparison between the calculated and experimental values shows that a model of an incompressible, nonviscous liquid without strength, for lead and aluminum alloy D16, gives a deviation toward the high side of 8%, and toward the low side of 1%. For brass and copper, this model gives a systematic increase of 30% on the average.

In the case of complete filling of the cavity in the shell there is a tangential drop of the front of the detonation front to the contact boundary between the explosive and the shell. It is shown in [4] that, under these circumstances, the pressures arising at the contact boundary are lowered considerably down to a value less than p_c. Evaluations showed that, in the case under consideration, the pressure will have the following values: for alloy D16 p_0 = 160 kbar, for lead p_0 = 175 kbar, for brass p_0 = 190 kbar, for copper p_0 = 200 kbar.

With the decomposition of an explosion at the boundary between the explosive and the shell, into the material of the shell there passes a shock wave which, by virtue of the character of the cylindrical motion, has a pressure at the front decreasing with time, and a falling profile of the pressure behind the front. Therefore, the velocity imparted by the shock wave on arrival at the outer surface of the shell can be neglected.

In the case of incomplete filling of the cavity of the shell by the charge of explosive, the explosion products fly away and are braked at the wall of the shell. At the moment when the cavity of the shell is filled by the expanding explosion products, they can be characterized by mean values of the density and the pressure. Values of p_0, evaluated from existing values of the initial radius of the internal surface R and the radius of the charge of explosive R_c, are found equal to 50 kbar and 1.6 kbar, respectively, for R_c = 6 and 3 mm and R_0 = 8 mm. The shock wave forming with the braking of the explosion products at the wall will be weak.

In the case of brass shells with R_0 = 8 mm, R_c = 3 mm, $p_0 < p_1$, and with the start of the motion of the shell, $\gamma = \gamma_2 = 1.3$. It must be taken into consideration that the calculated values include the error in determination of ν. The systematically high calculated values of the velocity for brass and copper are possibly connected with a high estimate of p_0.

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