ATTENUATION OF IMPACT-INDUCED PLANE SHOCK WAVES IN ALUMINUM

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This paper gives experimental data on the attenuation of the plane shock wave induced in aluminum by the impact of a thin aluminum plate (accelerated by explosion products to a velocity of 5.9 km/sec) and presents the corresponding calculations in the quasi-acoustic approximation. Measurements were made in the following range of relative distances from the impact surface $6 \leq X/\Delta \leq 190$, where X is the distance traveled by the shock wave and Δ is the thickness of the flying plate.

1. In the experiments we employed specimens of AD-1 aluminum 70 mm in diameter and from 3–15 mm thick and aluminum foil projectiles 60 mm in diameter and 0.08, 0.13, and 0.6 mm thick. The 0.6 mm projectiles, pressed into brass rings of the same thickness, were accelerated by a charge of composition B (50/50) 25 mm thick and 60 mm in diameter. As plane-wave generators we used explosive lenses composed of composition B (50/50) and a baratol filler. In the case of projectiles 0.08 and 0.13 mm thick the explosive lens and the main 12.5 mm charge of cast composition B (50/50) were separated from the 3 mm charge of pressed composition B (50/50) that accelerated the plate by a brass screen 3 mm thick. Introducing the screen made it possible to cut out the explosion products of the main charge and the lens and reduce the pressure of the explosion products behind the projectile at the moment of impact to 60 kbar. The shock wave passing through the screen was intense enough to excite detonation in the 3 mm charge within about 10^{-7} sec. The screen struck the specimen 7.5 μsec after the projectile and therefore did not affect the results.

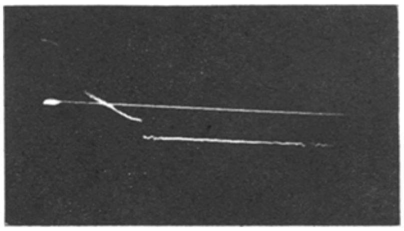

Fig. 1

The distortion and misalignment of the projectile on impact did not exceed 0.6 mm on a diameter of 50 mm, and the velocity was 5.9 ± 0.2 km/sec.

In the experiments the free surface velocity w was measured directly by the electrical contact and capacitive methods [1, 2]. In determining the shock front parameters from the results of the measurements it was assumed that the free surface velocity was equal to twice the particle velocity in the front.

The signal from the capacitive probe was fed to an OK-17M oscillograph, whose input resistance R was equal to the characteristic impedance of the cable.

An analysis of the operation of the capacitive probe showed that in this case the free surface velocity is given by the formula

$$w = \frac{V(t)\,h}{ERC}\left(1 - \int_0^t \frac{w\,dt}{h}\right)^2. \tag{1.1}$$

Here, V(t) is the probe output voltage, E is the emf of the source, h and C are the gap and capacitance of the measuring capacitor, respectively.

A typical oscillogram of the capacitive probe output voltage is presented in Fig. 1, where X/Δ = 187.

The signals from the contact probes were recorded on two IV-30M oscillographs with a time interval resolution of $\pm 5 \cdot 10^{-9}$ sec.

Both the capacitive and contact methods made it possible to obtain measurements with an error not exceeding ±5% in each experiment.

The results of the measurements are presented in the table.

2. In solving the problem of attenuation of a plane shock wave in the quasi-acoustic approximation we made the following assumptions.

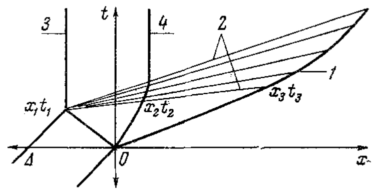

Fig. 2

The behavior of the material behind the shock front is the same as in a perfect liquid, in which rigidity, viscosity and heat conduction can be neglected. This assumption is usually well satisfied at pressures in the shock considerably in excess of the dynamic yield point of the material.

The entropy is constant everywhere, including the shock transition. The validity of this assumption at small compressions was demonstrated in [3]. As the isentropic equation of state we will use the shock adiabat of the material in the form of a linear relation between the wave velocity N and the particle velocity u

$$N = \alpha + \beta u\ . \tag{2.1}$$

In aluminum in the range up 1000 kbar [4–6]

$$N = 5.35 + 1.35\ u\,. \tag{2.2}$$

Moreover, we will use the equations at the front to relate the parameters of the material behind the front.

3. Let a projectile of thickness Δ with initial velocity w_0 strike a target of the same material at t = 0 at the point x = 0 (Fig. 2). The resulting shock waves move in both directions from the impact surface at identical velocities M_1 relative to the material ahead of the front. The shock wave in the projectile, having reached its free surface at the point (x_1, t_1), is reflected in the form of a centered simple rarefaction wave with straight C_+ characteristics. The rarefaction wave overtakes the shock front in the target, which leads to attenuation.

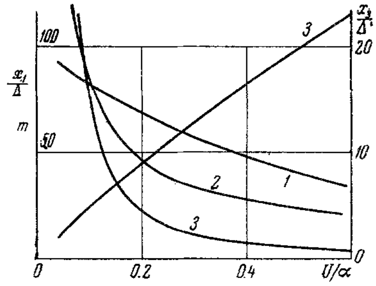

Fig. 3

We will denote the parameters of the material in the flow region bounded by the rarefaction wave front and the shock front by the subscript 1. In view of the symmetry of the problem, the initial velocity of the material at the projectile-target boundary $u_1 = w_0/2$. The other parameters behind the front are given by the formulas

$$N_1 = \alpha + \beta u_1, \quad p_1 = \rho_0 N_1 u_1,$$

$$c_1 = [\alpha + (\beta - 1)u_1]\ (1 + 2\ \beta u_1/\alpha)^{1/2},$$

$$\rho_1/\rho_0 = N_1/(N_1 - u_1). \qquad (3.1)\ \text{(cont'd)}$$

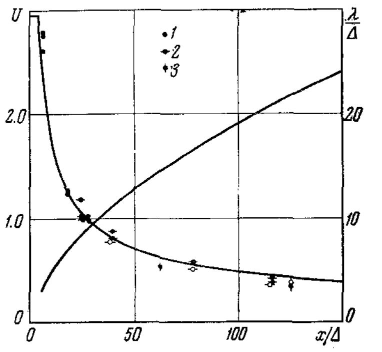

Fig. 4

Here, c is the speed of sound. The coordinates of the point (x_1, t_1) are given by the expressions

$$t_1 = \frac{\Delta - w_0 t_1}{N_1 - w_0}, \quad \text{or} \quad t_1 = \frac{\Delta}{N_1},$$

$$x_1 = -\Delta + w_0 t_1 = -\frac{\Delta (N_1 - w_0)}{N_1}. \qquad (3.2)$$

The rarefaction wave front is propagated at a velocity $u_1 + c_1$ and reaches the target-projectile boundary at the point (x_2, t_2),

$$t_2 = t_1 + \frac{\Delta \rho_0}{\rho_1 c_1} = \frac{\Delta (c_1 + N_1 - u_1)}{c_1 N_1},$$

$$x_2 = u_1 t_2 = \frac{\Delta u_1}{c_1 N_1}(c_1 + N_1 - u_1). \qquad (3.3)$$

The coordinates of the point (x_3, t_3) at which the shock front in the target is overtaken by the first C_+ characteristic are

$$t_3 = t_2 + \frac{x_3 - x_2}{u_1 + c_1} = \frac{\Delta (c_1 + N_1 - u_1)}{N_1 (u_1 + c_1 - N_1)},$$

$$x_3 = N_1 t_1 = \frac{\Delta (c_1 + N_1 - u_1)}{u_1 + c_1 - N_1}. \qquad (3.4)$$

In constructing a solution in the region where the C_+ characteristics overtake the shock front we employ the method described in [3].

By definition,

$$dX/dt = N(t). \qquad (3.5)$$

The equation of the C_+ characteristics is

$$x - x_1 = (u + c)\ (t - t_1). \qquad (3.6)$$

We differentiate this expression with respect to u along the trajectory of the front X(t)

$$\frac{d(X - x_1)}{du} = \frac{d(u + c)}{du}(t - t_1) + (c + u)\frac{dt}{dX}\frac{dX}{du}. \qquad (3.7)$$

Substituting (3.5) and (3.6) into (3.7), we obtain

$$\frac{d(X - x_1)}{X - x_1} = N\frac{d(c + u)}{(N - c - u)(u + c)} =$$

$$= \frac{d(c + u)}{c + u} + \frac{d(c + u)}{N - c - u}.$$

Integration gives

$$\ln kX = \ln \frac{u + c}{u + c - N} - \int \frac{dN}{u + c - N}. \qquad (3.8)$$

Here, k is a constant of integration.

To determine the integral on the right-hand side of (3.8), we express u and c in terms of N with relations (3.1). After this we obtain

$$k(X - x_1) = \frac{(u + c)c}{(u + c - N)^2}\left(\frac{2\beta}{\beta - 1}\frac{N - u}{\alpha}\right)^{1/2} \times$$

$$\times \exp\left\{-\left(\frac{\beta + 1}{\beta - 1}\right)^{1/2} \operatorname{arc\,tg}\left[\frac{\beta - 1}{\beta + 1}\left(\frac{c}{N - u}\right)\right]^{1/2}\right\} = f\left(\frac{u}{\alpha}\right). \qquad (3.9)$$

Using the condition at the intercept point (x_3, t_3), where $u = u_1$, to determine k from (3.9), we obtain

$$\frac{X - x_1}{\Delta} = \frac{x_3 - x_1}{\Delta}\frac{f(u/\alpha)}{f(u_1/\alpha)} = mf(u/\alpha). \qquad (3.10)$$

The curves in Fig. 3 represent x_1/Δ, x_3/Δ, m, $f(u/\alpha)$ as functions of u/α for aluminum (curves 1–4, respectively).

The length λ of the shock wave is equal to the distance at a fixed moment of time between the front and the last C_+ characteristic, whose equation is

$$x - x_1 = \alpha\ (t - t_1).$$

When $X > x_3$

$$\lambda = \Delta mf\left(\frac{u}{\alpha}\right)\left(1 - \frac{\alpha}{u_* + c_*}\right), \qquad (3.11)$$

where $u_* + c_*$ is determined at the front using expressions (3.2) and (2.1).

The time of action of the shock wave $\tau_+ = \lambda/\alpha$. Then at a given instant of time the parameters of the material behind the front are determined by the expression

$$u + c = (u_* + c_*)\left[1 - \frac{\xi}{\Delta mf(u_*/\alpha)}\right],$$

$$\xi = X - x, \quad 0 \leqslant \xi \leqslant \lambda. \qquad (3.12)$$

At a given point x = X the dependence of the flow parameters on time τ, reckoned from the instant of arrival of the front at that point, is determined by the formula

$$u + c = (u_* + c_*)\left[1 + \frac{\tau(u_* + c_*)}{\Delta mf(u_*/\alpha)}\right]^{-1}. \qquad (3.13)$$

Formulas (3.12), (3.13) make it possible to calculate all the parameters of the material behind the shock front if they are expressed by means of equation of state (2.1) in terms of the parameter u + c.

X / Δ	Δ, mm	w, km/sec	u, km/sec	p, kbar
Contact method				
6	0.6	5.56	2.78	685
6	0.6	5.53	2.76	680
6	0.6	5.20	2.60	625
17.8	0.6	2.48	1.24	235
17.8	0.6	2.52	1.26	240
27.9	0.6	1.98	0.99	179
27.9	0.6	2.04	1.02	186
24.2	0.13	2.36	1.18	222
24.9	0.13	2.12	1.02	195
24.9	0.13	2.02	1.01	183
39.8	0.13	1.74	0.87	154
39.8	0.13	1.58	0.79	138
78	0.13	1.16	0.58	96.2
116	0.13	0.85	0.43	69
116	0.13	0.85	0.43	69
116	0.13	0.81	0.41	65.5
62.2	0.08	1.07	0.535	88
125	0.08	0.664	0.332	52
125	0.08	0.74	0.37	58.5
Capacitive method				
38.5	0.13	1.53	0.765	132
78	0.13	1.02	0.51	83.2
115	0.13	0.75	0.385	61
125	0.08	0.785	0.392	62.2
125	0.08	0.73	0.365	57.6
187	0.08	0.635	0.318	50
187	0.08	0.63	0.315	49.5

4. For the impact of a plate accelerated to a velocity of 5.9 km/sec the initial parameters of the shock wave in the aluminum

target are u_1 = 2.95 km/sec, N_1 = 9.333 km/sec, and c_1 = 10.07 km/sec.

In this case

$$X/\Delta = 1.076\ f(u/\alpha) - 0.3676\ . \tag{4.1}$$

The curves in Fig. 4 represent u and λ/Δ as functions of X/Δ. The same figure shows the experimental data determined by the contact and capacitive methods—solid and open circles, respectively. Figures 1, 2, and 3 denote the data obtained with projectiles 0.6, 0.13, and 0.08 mm thick, respectively. Correct to the experimental error, the experimental data are in agreement with the calculated values. Therefore we conclude that our assumptions concerning the liquid behavior of the material and the constancy of the entropy in the investigated range of relative shock wave intensities $0.065 \leq p/\rho_0\alpha^2 \leq 1$, $p/\sigma > 10$, where σ is the dynamic yield stress of the material, are correct. Hence it would appear possible to use quasi-acoustic calculations to determine the shock front parameters in other solids not employed in this research with an accuracy sufficient for practical purposes.

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