AN EXPERIMENTAL STUDY OF SHOCK-WAVE DAMPING IN STEEL

M. M. Boiko, V. A. Letyagin, and V. S. Solov'ev

UDC 534.22.2

Using a capacitive sensor [1], the propagation of shock waves in steel specimens, produced by contact detonation of a plane wave charge of an explosive material, is studied. Monotonic damping of the shock-wave maximum pressure with increase in distance from the contact surface was observed. The propagation velocities of the first and second shock waves were calculated. Calculations were conducted with the use of the known velocity of an elastic wave and the experimentally determined time intervals for emergence of the wave at the free surface of plates of varying thicknesses. The experiments showed that up to thicknesses $x_1/h \approx 1.35$ (x_1, specimen thickness; h, charge height) the shock wave in steel propagates in the form of three steps, which further degenerate into two.

In the study of D. Bancroft [2] the complex structure of shock waves in steel was discovered, using contact sensors. The profile of shock-wave pressures arising from the blow of a plane striker in steel have been studied by D. Hughes [3]. A detailed analysis of the first and second shock waves in Armco iron, using a capacitive sensor, was performed by Taylor [4]. A series of works by S. A. Novikov, A. G. Ivanov, and others was dedicated to the study of compression shock waves in iron and steel [5-8]. An optical method was used for the same purpose in Peyre's work [9]. In the works mentioned, it was noted that in the pressure range 130-360 kbar the pressure impulse in iron and steel propagates in the form of two successive compression waves which carry the basic pressure and a preliminary elastic wave of significantly lower amplitude.

In this study an experimental investigation was made of damping in steel specimens of shock waves produced by detonation upon the surface of a trinitrotoluene charge of diameter d = 50 mm and height h = 10 mm. Damping of the shock waves was produced by wave discharges, driving the waves from the direction of the charge. The detonation was initiated with a plane-wave lens, in a manner such that the time difference for emergence of the detonation wave at the limit of the division with the steel bar did not exceed 0.1 μsec. The inert lenses used had little effect on the load profile, this being evaluated by their deterioration. The signal from the capacitive sensor was recorded by an OK-17M oscillograph. The relationship between pressure profile in the shock wave and specimen thickness (x_1) was established. The specimens were cut from a single rod of St. 3, the material being employed in the state supplied. The oscillogram of the signal obtained with explosive loading of a disc of thickness x_1 = 6.6 mm, and the change in velocity of the free surface of the disk, obtained after processing of the oscillogram, are shown in Fig. 1a, b (marker frequency is 4 MHz; 1) elastic wave, 2, 3) first and second shock waves). Oscillogram processing was done by the formula

$$W(t) = V(t)\,\delta \Big/ \left[C_0ER\left(1 + \frac{1}{C_0ER}\int_0^t V(t)\,dt\right)^2\right] \tag{1}$$

where W(t) is the velocity of the disk free surface, V(t) is the amplitude of the signal taken from the sensor, δ and C_0 are the initial distance between plates of the measurement capacitor and its capacitance, E is the voltage of the potential source, and R is the input impedance of the oscilloscope.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 101-104, March-April, 1972. Original article submitted June 14, 1971.

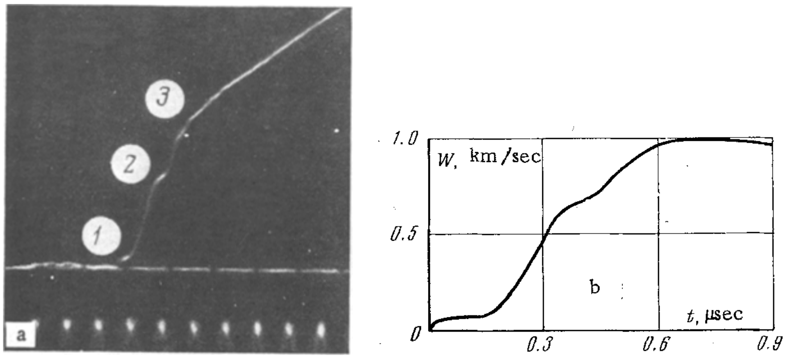

Fig. 1

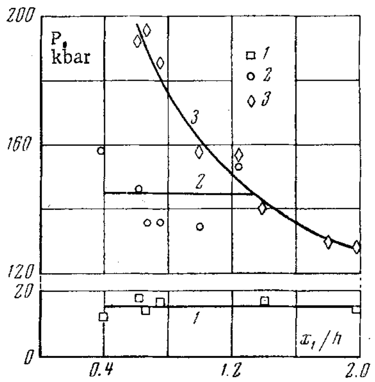

Fig. 2

Calculations were conducted on a digital computer with time step of $5 \cdot 10^{-8}$ sec. Pressure was calculated from free surface velocity by the law of preservation of impulse $P = \rho UD$, where $U = W/2$, P is the shock-compression pressure, and ρ is the density of the material. Inasmuch as the compression has a discontinuous character, every step must have its own value of shock wave velocity D with consideration of the fact that every subsequent pulse propagates in a material which is already in motion.

To determine the velocity of the elastic wave D_{10} in [5], multistep sensors were used. Direct measurement of the velocities of the second and third shock waves relative to the flow before their front D_{21} and D_{32} is quite complicated. Therefore, we will employ only the value D_{10}, and the velocities D_{21} and D_{32} will be calculated using, as in [3], the simple relationships evident from x–t diagrams of the process of shock-wave propagation in a disc:

$$D_{21} = (-B + \sqrt{B^2 - 4AC})/2A \quad (A = t_2,\ B = D_{10}t_2 - x_1 + 2U_1t_1,\ C = -(x_1 - U_1t_1)(D_{10} + U_1) \tag{2}$$

where t_1 and t_2 are the times from application of pressure to emergence of the elastic and first shock wave at the free surface, and U_1 is the mass velocity behind the front of the elastic wave. Therefore, if $D_{21} \gg U_1$ and t_2 is little different from t_1, then

$$D_{21} \approx x_1/t_2 - U_1 \tag{3}$$

With this supposition

$$D_{32} \approx (-B + \sqrt{B^2 - 4AC})/2A$$

$$A = t_3,\ B = D_{21}t_3 - x_1 + 2U_2t_2,\ C = -(x_1 - U_2t_2)\ (D_{21} + U_2) \tag{4}$$

where t_3 is the time from pressure application until emergence of the second shock wave, and U_2 is the mass velocity behind the front of the first shock wave.

It is assumed in Eqs. (2-4) that each succeeding pressure increase propagates in an already moving medium.

Table 1 presents the results of the experiments by which the velocity of the first shock wave was determined, with $t_1 = x_1/D_{10}$, $t_2 = t_1 + \Delta t_{21}$. The time value for emergence of the wave Δt_{21} was determined from the oscillogram. The elastic wave velocity $D_{10} = 6.01$ km/sec was taken from the data of L. V. Al'tshuler [10].

As follows from Table 1, with a probability of 0.95, $D_{21} = (5.27 \pm 0.04)$ km/sec. The pressure impulse corresponding to the point of phase transition propagates with this velocity. In calculating the velocity D_{21} the mass velocity behind the front of the elastic wave was taken from the oscillogram and was equal to $U_1 =$

TABLE 1

x_1, mm	Δt_{21}, μsec	D_{21}, km/sec	x_1, mm	Δt_{21}, μsec	D_{21}, km/sec
4.0	0.10	5.10	10.0	0.25	5.18
4.5	0.10	5.26	10.0	0.25	5.18
5.7	0.10	5.36	10.0	0.20	5.32
6.2	0.15	5.21	12.2	0.35	5.08
6.2	0.15	5.21	12.5	0.25	5.32
6.2	0.15	5.21	12.5	0.25	5.32
6.7	0.15	5.24	13.7	0.30	5.27
7.2	0.20	5.11	14.0	0.30	5.28
7.5	0.20	5.12	14.5	0.35	5.22
7.5	0.20	5.12	18.1	0.40	5.25
9.7	0.20	5.30	19.8	0.45	5.22
9.7	0.20	5.30	19.8	0.45	5.23
10.0	0.25	5.18	22.0	0.50	5.25

TABLE 2

x_1, mm	D_{21}, km/sec	$2U_1$, km/sec	$2U_2$, km/sec	$2U_3$, km/sec	Δt_{32}, μsec	D_{32}, km/sec
4.0	5.27	0.050	0.760	1.060	—	—
6.2	5.27	0.074	0.700	1.000	0.35	3.81
6.7	5.27	0.060	0.650	0.990	0.25	4.13
7.5	5.27	0.070	0.650	0.920	0.20	4.28
10.0	5.27	—	0.638	0.816	0.30	2.71
12.2	5.27	—	—	—	0.35	2.34
12.5	5.27	—	0.750	0.780	0.40	2.68
13.7	5.27	—	—	—	0.30	2.59
14.0	5.27	0.070	0.674	—	—	—
18.1	5.27	—	0.624	—	—	—
19.8	5.27	—	0.612	—	—	—

(32.4 ± 5.6) m/sec. The velocity of the second shock wave D_{32} was determined by Eq. (4). Necessary experimental data and results of calculation are shown in Table 2. In the calculations an average mass velocity for the first shock wave $U_2 = (327 \pm 27)$ m/sec was used, since up to $x_1/h = 1.35$ it was not observed to be damped.

On the basis of experimental measurements of mass velocities and calculated shock-wave velocities, profiles of the pressure impulse in steel specimens were found for thicknesses $0.4 \le x_1/h \le 1.98$. The change in shock-wave pressure with increase in specimen thickness is shown in Fig. 2 [1) elastic-wave pressure, 2) first-shock-wave pressure, 3) maximum shock-compression pressure]. The pressure at each step was calculated from the pressure at the previous one:

$$P_{10} = \rho_{00} U_1 D_{10} \tag{5}$$

$$P_{21} = \rho_{10}(U_2 - U_1) D_{21} \tag{6}$$

$$P_{32} = \rho_{21}(U_3 - U_2) D_{32} \tag{7}$$

$$\left(\rho_{10} \approx \rho_{00},\ \rho_{21} \approx \rho_{00} \frac{D_{21}}{D_{21} - (U_2 - U_1)}\right)$$

where ρ_{00}, ρ_{10}, and ρ_{21} are the densities of the undisturbed material, that behind the elastic wave, and that behind the first shock wave.

As the experimental measurements and calculations based thereon show, the maximum shock-compression pressure in the steel samples over the thickness range studied $0.4 \le x_1/h \le 1.98$ monotonically decreases with increase in thickness. It was discovered that up to $x_1/h \approx 1.35$ the pressure profile in the steel specimen has a three-step character. Over the range studied, the experimental conditions insured unidimensionality, and therefore significant change in elastic pressure $P_{10} = 15$ kbar did not occur. The pressure of the phase transition $P_2 = 145$ kbar (in [7], 147 kbar) up to a thickness $x_1/h = 1.35$ also did not change.

LITERATURE CITED

1. A. G. Ivanov and S. A. Novikov, "The capacitive-sensor method for registration of instantaneous velocity of a moving surface," Pribory i Tekh. Éksperim., No. 1, 135 (1963).
2. D. Bancroft, E. L. Peterson, and S. Minchall, "Polymorphism of iron at high pressure," J. Appl. Phys., 27, No. 3,291 (1956).

3. D. S. Hughes, L. E. Gourley, and M. F. Gourley, "Shock-wave compression of iron and bismuth," J. Appl. Phys., 32, No. 4, 624 (1961).
4. J. W. Taylor and M. H. Rice, "Elastic-plastic properties of iron," J. Appl. Phys., 34, No. 2, 364 (1963).
5. A. G. Ivanov, S. A. Novikov, and V. A. Sinitsyn, "A study of elastic-plastic waves in iron and steel with explosive loading," Fiz. Tverd. Tela, 5, No. 1, 269 (1963).
6. S. A. Novikov, I. I. Divnov, and A. G. Ivanov, "Structure of shock compression waves in iron and steel," Zh. Éksperim. i Tekh. Fiz., 47, No. 3, 814 (1964).
7. S. A. Novikov, I. I. Divnov, and A. G. Ivanov, "Phase transition in steel under shock compression," Fiz. Metallov i Metalloved., 21, No. 2, 252 (1966).
8. S. A. Novikov, I. I. Divnov, and A. G. Ivanov, "Failure of steel, aluminum, and copper under explosive loading," Fiz. Metallov i Metalloved, 21, No. 4, 608 (1966).
9. C. Peyre, J. Pujol, and J. Thouwenin, "Experimental method for analysis of the structure of a shock wave in a solid," Proc. 4th Sympos. (Internat.) Detonat., White Oak, Maryland, 1965, Washington (1967).
10. L. V. Al'tshuler, "Use of shock waves in high pressure physics," Usp. Fiz. Nauk, 85, No. 2, 197 (1965).