PARAMETERS OF NONUNIFORM SHOCKS IN ALUMINUM

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UDC 539.87

A method of recording the pressure profile and mass velocity behind the front of a two-dimensional shock excited in a flat plate by a load moving over its surface is described. Results obtained for the case of detonation of a layer of explosive on the surface of an aluminum plate are presented.

Let a load move with supersonic speed over the surface of a plate. Then a shock, whose front is inclined to the surface being loaded, originates in the plate. The diagram of the wave picture for a moving load is presented in Fig. 1. Such a loading can be accomplished, for example, in the propagation of a detonation in a layer of explosive material along the plate surface, in the collision of plates with a sufficiently small collision angle, and in other cases. The investigation of such nonuniform flows is of value in studying the equation of state of materials, in studying the scabbing phenomenon upon wave reflection from a free surface, for the dynamic strength of materials in a complex stress state, etc.

The motion behind the front of nonuniform waves is complex in nature. Analytical solutions have been obtained for some cases. For example, potentials which describe the flow caused by a moving flow are found in a linear formulation in [1, 2]. The problem of scabbing in a linearly elastic slab is examined in [3] for a given kind of loading.

An experimental method is described herein, which permits reproduction of the parameter distribution behind a shock front excited by a moving load in a material (in the domain AOB in Fig. 1). This method uses the principle of the Hopkinson rod as a basis. The known Hopkinson mechanical method [4] is used to measure the parameters of a plane one-dimensional shock. The load in the rod is produced by an explosion or by an impact on one of its ends. A set of plates is placed at the opposite end of the rod. The shock being propagated along the rod is reflected from the end as a rarefaction wave. Because of reflection of the waves the plates fly off from the end of the rod at different velocities. The profile of the mass velocity and pressure behind the front is reproduced by means of the velocities of the dispersing plates [5, 6].

A modification of the Hopkinson rod permitted determination of the shock parameters even in the case of two-dimensional flows. To do this, the sample of material to be investigated was taken as a flat packet of thin plates squeezed compactly together. A load moves over one of the packet surfaces and excites a shock therein. A fanlike dispersion of the plates occurs upon reflection of the wave from the free surface of the packet. The mechanism of their dispersal is the same as in the Hopkinson rod. Exactly as in the Hopkinson method, the velocity of the dispersing plates must be recorded. But the computational formulas to determine the shock parameters are rather modified.

The mass velocity and pressure distribution has been obtained by the method mentioned in an aluminum plate subjected to the detonation of a sheet charge. The tests were conducted according to the scheme shown in Fig. 2a, where 1 is the cassette with film, 2 is the installation, and 3 is the x-ray source, and in Fig. 2 in which the construction of the installation is given: 4 is the initiating unit, 5 is the layer of explosive, and 6 is the packet of plates. The plate is a packet of the size $4 \times 60 \times 120$ mm^3. It is composed of laminae 0.2 mm thick (20 pieces) or 0.6 mm thick (7 pieces). A 1-mm thick layer of charge is deposited on

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 147-152, July-August, 1971. Original article submitted July 30, 1970.

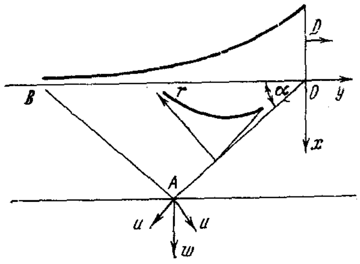

Fig. 1

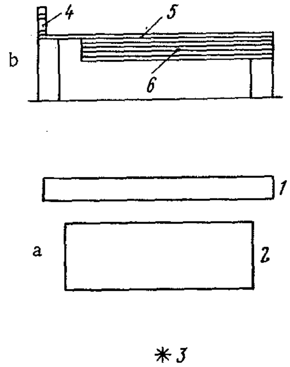

Fig. 2

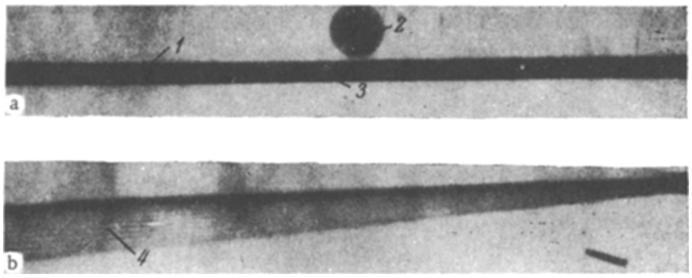

Fig. 3

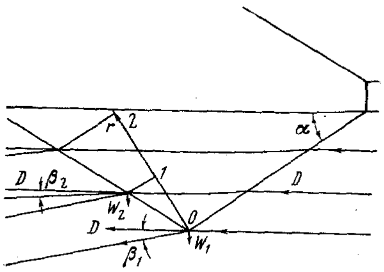

Fig. 4

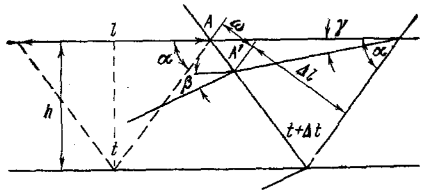

Fig. 5

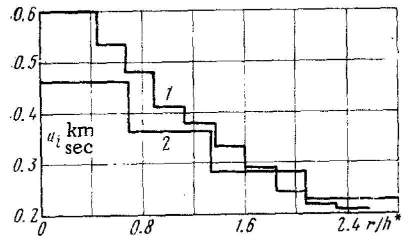

Fig. 6

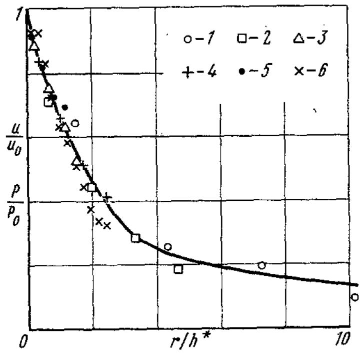

Fig. 7

TABLE 1

$\overset{*}{h}$	$n \times h$	w_i	r_i/h^*	u_i	u_0	$u_i/u_0 = p_i/p_0$
0.25	7×0.6	0.28	1.44	0.23	0.35	0.65
		0.11	4.33	0.09		0.25
		0.07	7.26	0.07		0.19
		0.04	10.19	0.03		0.09
0.5	7×0.6	0.36	0.66	0.29	0.40	0.73
		0.22	1.99	0.18		0.44
		0.14	3.33	0.11		0.28
		0.09	4.68	0.07		0.18
1.0	7×0.6	0.57	0.34	0.46	0.55	0.84
		0.45	1.01	0.36		0.66
		0.35	1.70	0.28		0.52
		0.28	2.38	0.23		0.41
1.6	7×0.6	0.66	0.22	0.54	0.60	0.89
		0.56	0.66	0.45		0.75
		0.47	1.10	0.38		0.63
		0.39	1.54	0.32		0.52
2.1	7×0.6	0.79	0.17	0.64	0.70	0.92
		0.71	0.50	0.58		0.82
		0.63	0.84	0.51		0.73
		0.60	1.18	0.49		0.70
1.0	20×0.2	0.74	0.11	0.60	0.65	0.92
		0.74	0.33	0.60		0.92
		0.66	0.55	0.54		0.82
		0.58	0.77	0.47		0.72
		0.51	1.00	0.41		0.64
		0.47	1.24	0.38		0.58
		0.41	1.48	0.33		0.51
		0.36	1.72	0.29		0.45
		0.30	1.96	0.24		0.37
		0.27	2.20	0.22		0.34
		0.26	2.44	0.21		0.32

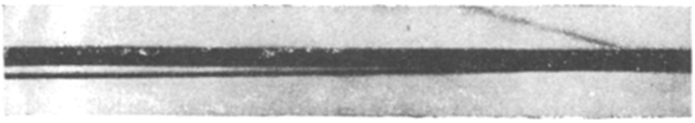

Fig. 8

one side of the packet. The installation was fastened near a source of pulsed x radiation. The detonation was initiated simultaneously along the whole width of the explosive layer by the impact of a steel plate. Delivery of the x-ray pulse is accomplished at the required time, and the phenomenon was determined at a definite stage of development. An x-ray pattern of one of the tests is presented in Fig. 3, where 1 is the layer of charge, 2 is a scale element, 3 is a packet of 20 plates, and 4 is the frame of the dispersing plates.

The instantaneous location of the dispersing plates was recorded in the test. The plate velocities and, therefore, the mass velocity and pressure profile behind the shock front can be determined from it. In the weak-wave approximation the fronts of the incident and reflected waves are rectilinear and inclined to the surface at an angle $\alpha = \arcsin (c/D)$. Here c is the velocity of the waves in the material and D is the rate of detonation of the high explosive.

The mass velocity in the shock front and the velocity increment in the rarefaction wave are equal in absolute value and directed along the normal to the fronts (Fig. 1). In this case the plate velocity is related to the mass velocity and pressure by the relationships

$$u = w / 2 \cos \alpha, \qquad p = \rho c w / 2 \cos \alpha$$

Therefore, knowledge of the plate velocities, the wave velocity in the material, and the rate of detonation of the explosive is necessary to determine the pressure and mass velocity. The rate of detonation of the explosive used in the tests was measured in advance and equalled 7.5 km/sec. The density of the material was 2.65 g/cm^3. The reason for the selection of the magnitude of the wave velocity in aluminum is presented below.

The method of determining the plate velocities by means of the x-ray patterns is clear from an examination of the flow in a coordinate system coupled to the detonation front (Fig. 4).

In this system the flow has the velocity D equal to the rate of detonation of the explosive, ahead of the shock front. After the fronts have passed, the flow has the velocity components D and w_i so that $w_i/D = \tan \beta_i$. Here i is the number of the plate counting from the free surface.

Therefore, the formulas to determine the mass velocity and pressure as a function of the coordinate r behind the shock front are

$$u^i = D \operatorname{tg} \beta_i / 2 \cos \alpha, \qquad p_i = {}^1/_2 \rho D^2 \operatorname{tg} \alpha \operatorname{tg} \beta_i$$

The quantities to be recorded experimentally here are the angles β_i between the plate positions at the initial instant and during dispersion. Because of the finite plate thickness, the values obtained for u_i and p_i are average values in the segments 0-1, 1-2, etc., measured from any point of the front along its normal. As is seen from Fig. 5, the length of these segments equals 2h cos α approximately, where h is the thickness of one plate in the packet. At time t let the shock front pass through the point A. The rarefaction wave reaches the point A after

$$\Delta t = l / D = 2h / D \operatorname{tg} \alpha$$

During this time the shock traverses a path segment

$$\Delta r = c \, \Delta t = 2h \cos \alpha$$

The segment lengths determined in this manner do not take account of the motion of the material behind the shock front. A correction for the displacement of the plate surfaces up to the time of rarefaction wave arrival thereon can also be introduced within the scope of the weak wave approximation. From a geometric analysis of the picture portrayed in Fig. 5, it follows that the correction to the first segment behind the shock front equals

$$\omega_1 = 4h \cos \alpha \operatorname{tg} \gamma_1 / (\operatorname{tg} \alpha + \operatorname{tg} \gamma_1)$$

Since tan $\gamma \approx 0.5$ tan β, then we have for the segment length

$$\Delta r_i = 2h \cos \alpha \, [1 - \operatorname{tg} \beta_i / (\operatorname{tg} \alpha + 0.5 \operatorname{tg} \beta_i)$$

The wave velocity c, whose magnitude is assumed constant, enters into the computational formulas for the pressure and mass velocity. It is known [7, 8] that there exists some variation in the velocity of a wave excited by the detonation of an explosive layer on the surface of an aluminum plate as it is propagated in the material. The results in these papers permit us to establish that the deviation of the wave velocity from the value used in the computations 5.9 km/sec is approximately ±5%.

Data characterizing the formulation of experiments to determine the parameters behind a shock front, and also the results obtained are presented in the table. The charge layer thickness h* in mm, the number n of plates of thickness h in mm comprising the packet, the plate velocity w_i in km/sec, the coordinates of the middle of the segments r_i/h^*, the mass velocity in the front u_0 and behind the front u_i in km/sec are indicated therein, so that for p_i we have $p_i/p_0 = u_i/u_0$.

As an illustration, two histograms are given in Fig. 6. In these tests the packet of plates was loaded by a h* = 1 mm thick layer of explosive, where the plates were h = 0.2 mm thick in case 1, and 0.6 mm thick in case 2.

As should have been expected, the spatial resolution of this method depends on the thickness of the plates in the packet. The segment length to which the mean value of the wave parameters are ascribed equals $2h\sqrt{1-(c/D)^2}$. For a given c/D, the resolution is determined by the plate thickness h.

It is seen from the table that the parameters near the shock front (determined by means of the first plates) differ for different explosive thicknesses. This can be the result of a change in the rate of explosive detonation as the charge thickness varies. Moreover, a rougher averaging of the parameters over the plate thicknesses also exerts some effect. Hence, the parameter distribution behind the shock front will differ in tests with different explosive thicknesses. The dependence generalizing the results of all the tests has been obtained by representing the data in dimensionless form. The ratio of the running value of the parameter (the mass velocity or pressure) to its value in the shock front is plotted along the ordinate axis in Fig. 7. The points 1, 2, 3, 4, 5 correspond to tests with plates h = 0.6 mm thick, and the point 6 to h = 0.2 mm plates. The values h* = 0.25, 0.5, 1.0, 1.6, 2.1, 1.0 correspond to the points 1, 2, ..., 6. The front parameters for each test were determined by means of histograms analogous to Fig. 6.

As an illustration of the use of the results obtained, the dynamic strength of the material is estimated. A 0.65-mm scab (Fig. 8) was formed on a 4-mm plate of the aluminum alloy AMg-6 subjected to an explosion of a 0.32-mm thick explosive layer. The pressure behind the shock front at a distance of twice the scab thickness, multiplied by the cosine the slope of the shock to the plate surface, was determined from Fig. 7. It was $0.6\ p_0 \approx 35$ kbar. This quantity also characterizes the dynamic strength of the material at a discontinuity under explosive loading conditions.

In conclusion, the authors are grateful to E. I. Silkin, A. N. Tkachenko, and N. I. Shishkin for interest manifested in the research.

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