ACCELERATING PLATES TO HYPERSONIC VELOCITIES: APPARATUS

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UDC 621.791.1

Frequently in the solution of various problems at the engineering and physical level it is required to accelerate plates to high velocities.

Nowadays, in the totality of known techniques [1-7], the cheapest and simplest in terms of technical implementation is the technique of accelerating a plate by the products of the detonation of a high-explosive charge on its surface. The velocity of the accelerated plate is enhanced by the use of so-called buffer systems, where a set of plates with sharply different acoustic stiffnesses is placed between the charge and the driver plate [8-10].

The maximum velocity that can be acquired by a plate in contact with a high-explosive charge (or a plate in a buffer system) is equal to the velocity of ejection of the explosion products. The latter velocity is approximately equal to the detonation rate D. At velocities greater than 5-6 km·sec^{-1} (~0.7D) the efficiency of the charge—plate system falls off rapidly, and these velocities can be taken as the limiting values.

The velocity of the plate can be further increased by artificially increasing the pressure in the explosion products. It is generally known [7] that, besides the normal regime, the hydrodynamic theory of detonation also predicts a regime of supercompressed detonation waves, which can materialize when the charge is struck by a striker traveling at a velocity of several kilometers per second. Moreover, the hydrodynamic theory of detonation predicts the existence in the detonation wave of an elevated-pressure zone called the chemical peak zone. For condensed high explosives the width of the chemical peak zone varies in the range 0.5-2.0 mm [11, 12]. Of course, the elevated pressures in the chemical peak zone can affect the acceleration of a plate when the thickness of the latter l_2 is commensurate with or smaller than the width a of the chemical peak zone. The acceleration of a thin plate by explosion products is accompanied by a wavelike transfer of energy back and forth between the plate and the explosion products, with a characteristic transfer-wave period $2l_2U^{-1}$ (U is the shock velocity in the plate). Two cases of interaction between the chemical peak and the plate are conceivable.

1. If $l_2 \gg a$, the chemical-peak shock wave decays over the thickness of the plate, and the velocity of the latter is determined by the Chapman—Jouguet constant. In coordinates of the pressure p and the particle velocity u, the acceleration process corresponding to this case is shown in Fig. 1, in which curves 1-3 represent the shock adiabats of the plate, the first compression of the charge, and the striker; curves 4 and 5 the unloading isentropes of the charge; and curve 6 the reflection isentropes of the explosion products. The state of the plate upon reflection of the detonation wave from it is determined by the point A; the plate acquires a velocity $V_0 \approx 2u_A$. The velocity of the plate in subsequent transfer waves has values V_1, V_2, etc. The maximum calculated velocity of the plate in this case is equal to the detonation rate, but in practice (because of the finite charge dimensions) is always smaller.

2. If $l_2 \leqslant a$ and the striker has a velocity V_+, then the shock adiabat 2 for the first compression of the cold charge (Fig. 1) is decisive in the first stage of the acceleration process, because for a certain period of time the charge does not undergo any appreciable changes. The plate is loaded to the state B, acquiring a velocity $V_0' \approx 2u_B$ (Fig. 1). In the next acceleration stage the state of the plate is determined by an intermediate state between those at the chemical peak and at the Chapman—Jouguet point (V_1', V_2', etc.). It is clear that in such a situation the plate can be accelerated to larger velocities in comparison with the first case. Thus, by creating a supercompressed detonation regime and utilizing the chemical peak zone it is possible to accelerate thin plates to velocities exceeding the

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 86-90, March-April, 1982. Original article submitted May 6, 1981.

 0021-8944/82/2302-0238$07.50

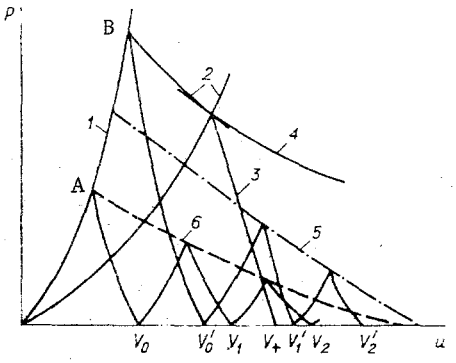

Fig. 1

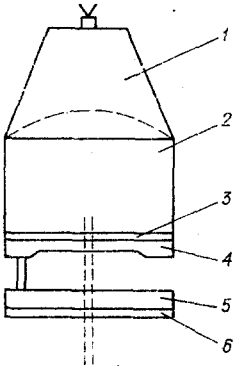

Fig. 2

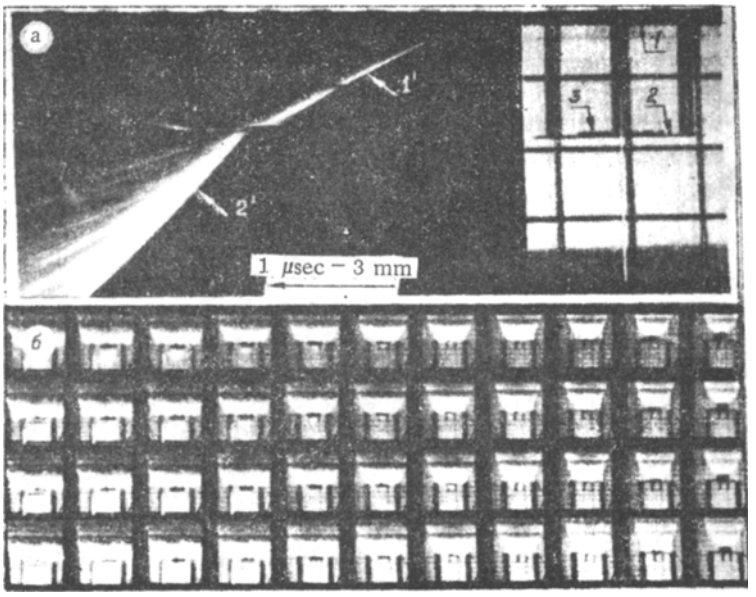

Fig. 3

normal detonation rate. We have implemented this idea in a two-stage plate-accelerating mechanism containing a high-explosive charge in each stage.

A schematic diagram of the experimental two-stage mechanism is shown in Fig. 2. The plane-shock generator 1 initiates the main charge 2. Acting through the Plexiglas plate 3, the main charge accelerates the steel striker 4 (stage I) over a travel path of 86 mm. The striker drives the second stage consisting of the high-explosive (Plexiglas in individual tests) layer 5 and the accelerated thin plate 6.

The travel velocity of the plate will depend on the material, the thickness and velocity of the striker, the thickness of the explosive layer, and the thickness and material of the plate. We have carried out a series of experiments and calculations to determine these dependences.

In the experiments we measured continuously the relations between the travel path and time of the striker and the plate by means of an SFR-3M apparatus operating as a high-speed streak camera (the projection of the SFR-3M slit is conditionally represented in Fig. 2 by two dashed lines). The evolution of the processes taking place in the explosive mechanism was monitored by a second SFR-3M apparatus operating as a slow-motion recorder at a framing rate of 10^6 frames$\cdot$sec^{-1}.

A typical slit-streak photograph is shown in Fig. 3a. The velocities of the striker 1 and the plate 2 (here the number 3 refers to the explosive layer) were calculated from the photochronograms on the basis of slopes of the light boundaries 1' and 2', respectively, averaged for a 50 mm travel path. Figure 3b illustrates the nature of the evolution of the striker and plate acceleration processes.

TABLE 1

No.	Stage I		Stage II						μ	φ_+	φ_-
	striker		spacer			plate					
	l_1, mm	V_+, km/sec	material	l_2, mm	E, kJ/cm	material	l_2, mm	V_-, km/sec			
1	1,5	5,64	HE	3,0	1,72	Al	0,1	11,6	0,02	0,09	0,06
2	1,5	5,64	»	3,0	1,72	»	0,3	10,7	0,05	0,23	0,21
3	1,5	5,64	»	3,0	1,72	»	0,92	9,5	0,15	0,60	0,45
4	4,0	3,80	»	3,0	1,72	»	0,3	7,8	0,07	0,34	0,28
5	1,5	6,20	»	3,0	2,70	»	0,3	12,8	0,05	0,26	0,21
6	1,5	5,64	»	3,0	1,72	Cu	0,1	11,2	0,05	0,27	0,21
7	1,5	5,64	»	3,0	1,72	»	0,3	10,3	0,16	0,71	0,46
8	1,5	5,64	»	3,0	1,72	»	0,5	9,1	0,28	0,91	0,59
9	1,5	5,64	»	3,0	1,72	»	1,0	6,8	0,55	1,0	—
10	1,5	5,64	»	1,0	0,57	»	0,3	10,3	0,20	0,74	0,51
11	1,5	5,64	»	5,0	2,85	»	0,3	10,0	0,14	0,62	0,43
12	1,0	6,14	»	3,0	1,72	»	0,3	10,0	0,22	0,82	0,54
13	1,5	6,20	»	3,0	2,70	Pb	0,3	11,3	0,2	0,83	0,51
14	1,5	6,20	»	3,0	2,70	»	1,0	6,6	0,66	0,98	—
15	1,5	5,64	»	3,0	1,72	Ta	0,3	8,5	0,31	0,88	0,66
16	1,5	5,64	Plexiglas	3,0	—	Al	0,15	9,9	0,03	0,11	0,11
17	1,5	5,64	»	3,0	—	»	0,92	8,6	0,16	0,49	0,50
18	1,5	5,64	»	3,0	—	Cu	0,1	9,9	0,06	0,23	0,25
19	1,5	5,64	»	3,0	—	»	0,5	7,0	0,3	0,59	0,61

According to the data of [13], in the velocity interval 5-15 km·sec^{-1} the front of the air shock leads the projectile by 5-10%. In each specific situation the velocities of the striker and the plate were calculated with a correction for their lag behind the air shock with the use of tables [13]. The error of measurement of the striker and plate velocities from the photochronograms did not exceed ±10%. In isolated experiments the explosive mechanism of Fig. 2 was evacuated to p ≈ 1 hPa. The flight velocity of the plate, measured by the electrical contact method, coincided with the velocity determined by the photochronographic method within the experimental error limits.

The density of the accelerated plates was estimated from the velocity of motion of the free surface of a barrier struck by the plate. The barriers in this work were made of materials having a lower acoustic stiffness than the plate. The thickness of the barrier was chosen so as to prevent attentuation of the shock wave in the barrier and to have the mass of the barrier equal to that of the driver plate. In the experiments the velocity of the free surface of the barrier was in good agreement with the same quantity determined analytically, provided that the density of the flying driver plate was taken equal to its initial value. We also performed x-ray tests using copper and aluminum plates. The tests indicated that the plate travels compactly, at least over a filming path of 17 mm.

Numerical calculations were carried out in the hydrodynamic approximation and without regard for the possible influence of nonhydrodynamic shock attenuation; in the investigated pressure range, however, these assumptions did not produce appreciable errors.

The results of the experiments and the calculations are summarized in Table 1. Also shown are the initial characteristics of the mechanism. In the table l_1, l_2, and l_3 are the thicknesses of the striker, the driver plate, and the spacer, respectively, V_+ and V_- are the velocities of the striker and the plate, E is the internal energy of the high-explosive layer (HE) or of the spacer per unit surface area, μ is the mass of the plate relative to the total mass of the spacer (explosive layer) plus the striker, and φ_+ and φ_- are the measured and calculated ratios of the kinetic energy of the accelerated plate to the sum of the kinetic energy of the striker and the internal energy of the spacer (explosive layer).

It follows from the table that the mechanism can be used to accelerate thin metal plates with a thickness of less than 1 mm to velocities of 7-12 km·sec^{-1}. With the use of such plates it is possible to create in a copper barrier, for example, pressure pulses with amplitudes of 300-600 GPa and durations of 15-350 nsec. In terms of shock intensity, this result is an order of magnitude greater than the pressure developed in a copper barrier by a contact explosion.

It is seen that the velocity of the plate is determined mainly by the velocity of the striker, the ratio between the masses of the plate and the striker, and the material of the spacer in stage II (explosive or inert material). The velocity of the plate depends slightly on the mass of the spacer. For a ratio l_3/l_1 = 1-3 the velocity of the plate is constant, and for $l_3/l_1 > 3$ the velocity of the plate decreases due to pressure unloading on the side of the striker. A comparison of the experimental values φ_+ with the calculated values φ_- shows that with the use of an inert (Plexiglas) spacer in stage II these values agree within 5% error limits and under optimal conditions ($\mu \approx 0.3$) are equal to $\varphi_\pm \simeq 0.6$. The situation is otherwise when the spacer in stage II is a high explosive. The coefficient of energy transfer to the plate from the striker and the explosive spacer for $\mu \approx 0.3$-0.6 is $\varphi_+ \simeq 0.95$ which is ~35% higher than the calculated value φ_- . We recall that the experimental circumstances were always such that the width of the chemical peak zone was greater than the plate thickness and in the calculations we used the equation of state of the explosion products without regard for the kinetics of the chemical reaction (chemical peak). Of course, the presence of the chemical peak and the additional energy associated with it were disregarded. This consideration is clearly the most probable cause of the low calculated velocities in comparison with those measured in the experiments.

In conclusion we note that the investigated mechanism makes it possible to: increase the rate of deformation of materials to 10^{10} sec^{-1}, which brings the loading conditions significantly closer to the maximum possible 10^{12} sec^{-1} dictated by the oscillations of the atoms in the lattice; increase the pressure in the material to ~1 TPa without resorting to convergent detonation waves [3]. The experimental study of the process of acceleration of thin plates can be used to obtain information about the state of a high explosive in the chemical peak zone and to plot the expansion isentropes of the explosive from the state intermediate between the chemical peak and the Chapman–Jouguet point.*

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*Rapid advances have been made in recent years in the laser method of generating short pressure pulses (see, e.g., [14]). However, the relatively low intensity level of the shock wave (small areas loaded by the laser beam and a high electromagnetic noise level) complicate and limit the possibilities of the laser for general applications.