ACCELERATING PLATES TO HYPERSONIC VELOCITIES: AIR-DRAG INSTABILITY

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The acceleration of plates to velocities of ~10 km·sec^{-1} in air by the method described in [1] involves the unfavorable effect of instability. The onset and development of instability can, in the final analysis, cause the accelerated plate to lose compactness.

In the acceleration process the plate almost always has an initial disturbance of some form or other, which is induced by the nonideal quality of the accelerator used. In the slowing-down process of the plate in air the acceleration is directed from the lower-density air to the higher-density plate, and the presence of the initial disturbance at the plate can lead to the development of a Taylor disturbance (gravitational instability) [2].

When the plate flying through air interacts with a barrier, added conditions can set in for the development of instability. For example, when a plate flies into a barrier, the air shock moving ahead of the plate is reflected from the barrier and impinges on the interface between the plate and the compressed air. If the plate has a surface disturbance and the intensity of the reflected shock impinging on it is sufficiently great, growth of the disturbance will be observed [3].

We have investigated the flight of aluminum and copper plates with a diameter of 60 mm and thickness of 0.3 mm; the initial velocities were 8-11 km·sec^{-1}. The plates were accelerated in a two-stage scheme, which is described in detail in [1]. In the first series of tests a steel striker with a diameter of 60 mm and thickness of 1.5 mm was accelerated by means of a high explosive charge to a velocity of 5.64 km·sec^{-1} (stage I) and loaded a copper spacer with a thickness of 4 mm (stage II), on the other side of which there was an aluminum plate with a thickness of 0.3 mm (flight tracer). In the second series of tests the copper spacer was replaced with a high-explosive layer having a thickness of 3 mm. Both series of plate-acceleration tests were conducted in an airspace bounded by the plate on one side and by a Plexiglas spall plate on the other. In the tests the width of the airspace was varied from 10 to 50 mm. In some tests the space between the driver plate and the spall plate was evacuated to a pressure of ~1 hPa.

The shape of the surface of the striker or driver plate was recorded from the luminescence of the air shock moving in the spall plate space or ahead of the driver plate, respectively, with the use of an SFR-3M apparatus operating as a slit-aperture streak camera. In recording the shape of the striker surface the spall plate was set up in the position of the spacer with the driver plate (stage II). The surface of the spall plate facing the striker was darkened, and the spall plate had two slit openings with widths of 0.5 and 1.0 mm, which were spaced 5 mm apart. Figure 1a shows a photochronogram of a test to record the shape of the striker surface, illustrating the fact that in the flight of the striker toward stage II its surface has a disturbance of almost sinusoidal shape.

In recording the shape of the driver plate surface the Plexiglas spall plate had transparent surfaces. In this way it was possible to observe the evolution of the shape of the disturbance on the surface of the plates. The photochronograms of the flight of an aluminum plate over travel paths of 10, 20, 30, and 50 mm (Figs. 1b-e, respectively) indicate that at the time t_0 corresponding to the start of motion of the plate the latter has an initial disturbance induced by the disturbance of the striker in its flight toward stage II (Fig. 1a). At the time t_1 corresponding to impingence on the spall plate of the air shock moving ahead of the driver plate, an air shock reflected from the spall plate is formed. This event increases the intensity of luminescence of the compressed air. The time t_2 at which luminescence vanishes in the photochronograms corresponds to the moment of impact of the driver plate on the spall plate and the loss of transparency by the latter.

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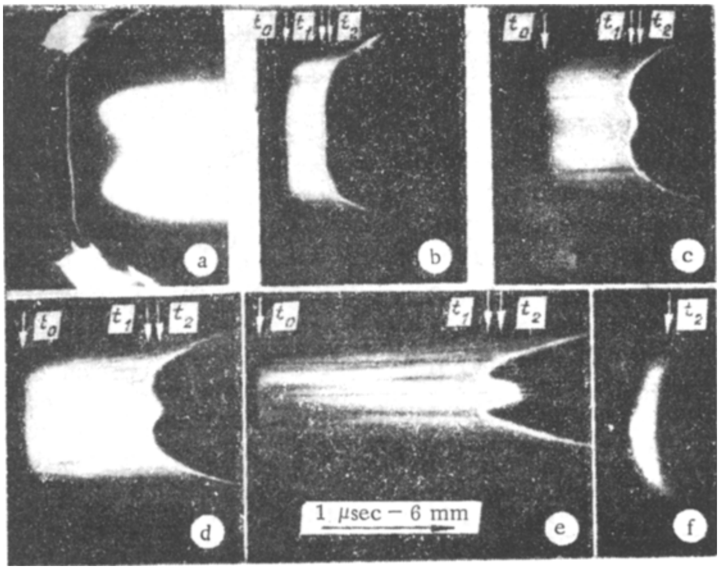

Fig. 1

TABLE 1

Series No.	Test No.	Stage II: spacer, material	Stage II: spacer, thickness, mm	Stage II: plate*, V_0, km/sec	Stage II: medium	Flight space: Δ, mm	Flight space: Δt_0, μsec	Flight space: Δt_2, μsec	Flight space: t, μsec	Flight space: λ, mm
I	1	Cu	4,0	7,8	Air, standard conditions	10	0,04	0,04	1,3	~25
	2	»	4,0	7,8		20	0,04	0,13	2,7	~25
	3	»	4,0	7,8		30	0,04	0,17	4,1	~25
	4	»	4,0	7,8		50	0,06	0,60	7,7	~25
II	5	HE	3,0	10,8	The same	10	0,05	0,05	0,9	~25
	6	»	3,0	10,8		20	0,05	0,10	1,9	~25
	7	»	3,0	10,8		30	0,05	0,17	2,8	~25
	8	»	3,0	10,8		50	0,05	0,27	4,6	~25
	9	»	3,0	10,3		20	0,04	0,07	2,0	~25
III	10	Cu	4,0	7,8	Vacuum ~1 hPa	20	—	<0,05		
	11	HE	3,0	10,8		30	—	<0,05		

*Material of the driver plate, aluminum in all tests except No. 9, copper in No. 9, thickness 0.3 mm.

In the tests with evacuated spaces (Fig. 1f, width of space 20 mm) the same recording procedure was used. At a pressure of ~1 hPa, luminescence in the air shock moving ahead of the aluminum driver plate is not recorded until the density of the air ahead of the plate attains a definite value. The time t_2, as above, corresponds to the moment of impact of the driver plate on the spall plate.

The tests with an airspace are typified by the fact that at the time t_0 the disturbance of the plate practically coincides in magnitude and phase with the disturbance of the striker. Over a travel path shorter than 10 mm the disturbance of the investigated plate reverses its phase, and the amplitude of the disturbance increases with time during the subsequent motion of the plate (Figs. 1b–e). In the tests with evacuated spaces having widths of 20 and 30 mm, growth of the initial disturbance is not observed.

The results of the tests are summarized in Table 1, in which V_0 denotes the initial velocity of the driver plate, Δ is the width of the space, Δt_0 and Δt_2 are the amplitudes of the disturbance at the time t_0 at which the plate starts to move and the time t_2 of impact of the driver plate on the spall plate, $t = t_2 - t_0$, λ is the wavelength of the initial disturbance of the plate, and HE denotes high-explosive material.

TABLE 2

Test No.	$G \cdot 10^{-10}$, $cm^{-2} \cdot sec$	t_*, μsec	$k_+ = e^{\|\omega\| t}$	$k_- = \frac{\Delta t_2}{\Delta t_0}$	$\frac{k_-}{k_+}$	Test No.	$G \cdot 10^{-10}$, $cm^{-2} \cdot sec$	t_*, μsec	$k_+ = e^{\|\omega\| t}$	$k_- = \frac{\Delta t_2}{\Delta t_0}$	$\frac{k_-}{k_+}$
1	2,4		1,3	1,0	0,8	5	2,0		1,2	1,0	0,8
2	2,4		1,9	3,3	1,7	6	2,0		1,5	2,0	1,3
3	2,4	9	2,7	4,3	1,6	7	2,0	6	1,9	3,4	1,8
4	2,4		6,6	10,0	1,5	8	2,0		2,7	5,4	2,0
						9	1,3		1,5	1,8	1,2

The phase reversal of the disturbance over a travel path shorter than 10 mm is evidently attributable to the dynamic nonunformity of the system used to accelerate the investigated plates. Thus, if a wave with a disturbed profile emerges at the surface of a plane-parallel plate accelerated by a detonation or shock wave, then centers of reduced pressure will exist behind the leading parts of such a wave, and centers of elevated pressure will exist behind the lagging parts. As a result, the parts of the driver plate situated under the lag zones of the detonation or shock front will acquire greater velocities at the initial time and surge forward.

What is responsible for the development of the initial disturbance of the driver plate? The results of the tests with evacuated spaces (Fig. 1f) indicate that the presence of dynamic nonuniformity on the part of the plate-accelerating system does not promote growth with time of the amplitude of the initial disturbance. The nature of the disturbance at the times t_1 and t_2 evinces the fact that the air shock moves parallel to the surface of the flying driver plate and that the shape of the disturbance of the air shock front is similar to the shape of the disturbance of the contact boundary between the plate and the air. This consideration fosters the conclusion that the growth of the disturbance of the plate—air contact boundary with time is not associated with the instability that could be realized when the motion of the driver plate is retarded by the spall plate.

To asertain the possibility of development of the disturbance by the Taylor (gravitational) instability mechanism we carried out gasdynamical calculations of the acceleration of plates in air, using a computer. In the calculations we considered the air to be an ideal gas with an adiabatic exponent of 1.3. From the results of the calculations we determined the acceleration G imparted by the air to the driver plate during slowing-down of the latter by air drag for the time interval $(t_1 \ldots t_0)$.

In the linear approximation [4] the growth of the disturbances is determined by the exponential term $e^{|\omega| t}$. The quantity $|\omega|$ is called the instability exponent and is represented by the relation

$$|\omega| = \sqrt{kG(\rho_1 - \rho_2)/(\rho_1 + \rho_2)},$$

in which $k = 2\pi\lambda^{-1}$ is the wave vector and ρ_1 and ρ_2 are the densities of the two media having a common interface. In an unstable regime the interval of observation within which the linear approximation remains valid for a sinusoidal disturbance is given by the expression $t_* \leqslant \omega^{-1} \ln (0.1\lambda/\Delta t_0 V_0)$. The exponential growth of the disturbances also expresses the Taylor gravitational instability in a rigorous mathematical formulation [2]. The results of the calculations are given in Table 2. Also shown are the results of a comparison of the calculated values k_+ and experimental values k_- of the disturbance growth rate.

A comparison of the results of the calculations and the experiments shows that the linear approximation qualitatively describes the development of disturbances on the investigated plates by the Taylor instability mechanism. In the quantitative respect the numerical and experimental results differ by a factor of 1.5–2. This discrepancy can be attributed, first, to the neglect of the influence of the above-mentioned dynamic nonuniformity in the calculations; this factor can affect the initial stage of flight of the plate. Second, the character of the photochronograms indicates that with the passage of time jets begin to form on the surface of the plates, probably due to the nonlinearity of the processes of development of gravitational instability of the plate—air contact boundary in connection with air drag on the plate. This fact has been mentioned by Emmons et al. [5] and Ott [6] in explaining the deformation of a sinusoidal disturbance by the onset of higher harmonics that are not present in the initial disturbance but are induced by the nonlinearity of the process.

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CALCULATION OF SHOCK ADIABATS IN SOLIDS

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A knowledge of shock adiabats of solid is required in problems dealing with the behavior of matter under shock loading. The calculation of pressure on the shock adiabat p_H as a function of volume V is usually carried out with equations of state the parameters of which are related to experimental [1] or theoretical [2] characteristics of the highly compressed material, with model representations of the Gruneisen coefficient $\gamma(V)$ [1, 3]. At the same time, many materials of practical interest such as metal alloys, mining ores, and ceramics have been studied insufficiently at high pressures, complicating use of this traditional approach. In connection with this, it is of significant interest to determine the laws of shock loading with the aid of reliable and easily measurable characteristics of the undeformed material. In the present study shock adiabats of a wide range of materials will be calculated using as experimental parameters the adiabatic modulus of omnidirectional compression K_S and the thermochemical internal energy E_0.

To specify the pressure on the isentrope p_S semiempirical equations corresponding to the Morse formula are used:

$$p_S = \frac{2E_0\alpha}{3V_0} x^{-2/3} [\exp 2\alpha (1 - x^{1/3}) - \exp \alpha (1 - x^{1/3})] \tag{1}$$

together with a modified Lennard–Jones formula

$$p_S = \frac{E_0 n (n-1)}{V_0} [x^{-1} - 1] x^{-n}, \tag{2}$$

where $x = V/V_0$; V_0 is the specific volume of the undeformed material. The parameters α and n are expressed in terms of the modulus of omnidirectional compression K_S and energy E_0, using the formulas Equations (1), (2) reliably describe the behavior of materials over a wide range of hydrostatic deformations [4]. In considering shock loading the dependence of shock velocity D on mass velocity of the material U is approximated by a quadratic relationship

$$D = a + bU + cU^2. \tag{3}$$

To determine the parameters a, b, c, an approach based on the relationships between the first, second, and third derivatives of $p_H(V)$ and $p_S(V)$ at the point V_0 is used [5, 3]:

(4)

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