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PHENOMENOLOGICAL MODEL OF PUNCH-THROUGH

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At this time the most widespread method for analyzing the punch-through process, based on a numerical procedure for solving the problem posed under any assumptions about the constitutive equations of the medium and, as a rule, without considering fracture processes (e.g., [1]), yields results that are not always convenient from the practical viewpoint. In particular, these results are difficult to compare with experimental data in which the critical punch-through velocities are most often recorded (e.g., [2, 3]). In the probable future, when crack generation and development criteria and the constitutive equations of a medium become sufficiently reliable under high-speed loading conditions, numerical methods will permit the efficient solution of practical problems. However, at this time there is a need for simple models to describe the punch-through process. The model proposed is an example of this kind of phenomenology.

It is shown in [2] that in those cases when punch-through is accompanied by the recovery of a "plug," the main contribution to the resistance against inserting the impactor is from plastic deformation or brittle fragmentation of a comparatively thin cylindrical layer. In this case, at least if plastic deformation occurs, it is evident that the resistance to the impactor motion should depend on the velocity v of the impactor.

Let us assume that the quantity F for a given impactor-obstacle pair depends only on v. (It is clear that this assumption is invalid when the impactor is near the obstacle surface, hence, we consider only obstacles of sufficiently great thickness.) Let us approximate this dependence by a power-law function

$$F(v) = -Kv^n,$$

where K and n are constants.

If $v = v_0$ for $x = 0$ (x is the coordinate in the direction of impactor motion and the origin is on the frontal surface of the obstacle), then

$$v_0^{2-n} - v^{2-n} = k(2-n)x,$$

where $k = K/m$ and m is the impactor mass.

For an obstacle thickness h we have the critical velocity $v_0 = v_*$ of the impactor so that $v = 0$ for $x = h$:

$$v_* = k(2-n)h.$$

For $v_0 > v_*$ we have the velocity v_1 of impactor taking off from the obstacle so that

$$\tilde{v}_0^{2-n} - \tilde{v}_1^{2-n} = 1,$$

where $\tilde{v} = v/v_*$.

The result obtained (which corresponds, for $n = 0$, to the condition of constancy of the energy absorbed by the obstacle, and is sometimes [4] taken as being sufficiently evident) turns out to be wonderfully simple: the curve $\tilde{v}_1(\tilde{v}_0)$ is independent of the obstacle thickness. This simplicity requires convincing experimental confirmation.

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TABLE 1

No. of curve in Fig. 1	Obstacle material	Notation of points in Fig. 1	d, mm	v_*, m/sec	h, mm
I	AMg-6	1	6,37	250	1,97
		2	6,37	350	3,00
		3	6,37	405	4,00
		4	10,3	228	3,37
II	VT-14	1	6,37	240	1,00
		2	6,37	335	1,43
		3	6,37	423	2,05
III	Copper MCh	1	6,37	300	1,50
		4	10,3	220	1,50

TABLE 2

Material	n	
	punch-through	direct experiment
AMg-6	0,35	0,3 [6]
VT-14	0,31	0,1 [7]
Copper MCh	0,37	0,6 [8]

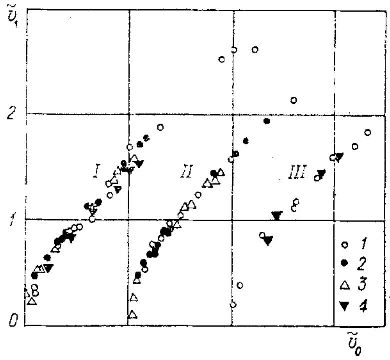

Fig. 1

An experiment was posed by the method and on the apparatus described earlier [2], except that the apparatus was provided with a second unit to measure the velocity v_1 with an appropriate modification of the method. The results of the experiment on punching through an obstacle of copper, aluminum AMg-6 and titanium VT-14 alloys by steel balls are represented in Fig. 1 (the conditions for the experiment and the notation of the points are presented in Table 1).

The experimental results are, as is seen, stacked sufficiently well within the framework of a single curve $\tilde{v}_1(\tilde{v}_0)$, even as the diameter d of the ball-impactor changes. Hence, it can be assumed that the quantity n in the power-law approximation F(v) is determined only by the obstacle material, i.e., the dependence of a certain characteristic stress (for instance, the yield point σ_*) on the strain rate $\dot{\varepsilon}$. In such a case the characteristic dimension $a(v = \dot{\varepsilon}a)$ should be the thickness of the plastically deformable or spalled cylindrical layer [2] observable during punch-through. The real values of the quantity a are on the order of 1 mm; therefore, at the velocities 10^2–10^3 m/sec the quantities $\dot{\varepsilon}$ are on the order of 10^5–10^6 sec^{-1}. This makes difficult the comparison of quantities obtained in experiments on punch-through with direct measurements of the dependence $\sigma_*(\dot{\varepsilon})$: the majority of experimental results of this kind are constrained to the strain rates 10^4–10^5 sec^{-1} [5]. Nevertheless, the comparisons presented in Table 2 qualitatively indicate the reasoning presented.

Conditions of the experiments from whose data the quantities in Table 2 have been determined are presented in [6-8]. Polycrystalline aluminum at room temperature was used in [6], the characteristic stress σ_* corresponds to 20% plastic deformation, $\dot{\varepsilon} = 10^5$–$1.2 \cdot 10^5$ sec^{-1}; technically pure titanium at room temperature was used in [7], and the quantity σ_* corresponds to 0.2% plastic deformation and $\dot{\varepsilon} = 5 \cdot 10^2$–$5 \cdot 10^3$ sec^{-1}; copper at room temperature was used in [8] and σ_* corresponds to 5% deformation, while $\dot{\varepsilon} = 5 \cdot 10^3$–$5 \cdot 10^4$ sec^{-1}.

The simple formula obtained above for the critical punch-through velocity v_* as a function of the obstacle thickness h should be corrected, taking into account that F = 0 for x = 0 and x = h.

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ESTIMATION OF THE TEMPERATURE ON THE HUGONIOT ADIABAT BY USING THE "MIRROR IMAGE" RULE

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Existing methods of computing the temperature of a solid body compressed by a shock, which require tedious calculations, are approximate to some degree or other. This is associated both with the inaccuracies in giving the potential and the magnitudes of its governing coefficients and with the selection of the equation of state. In practical computations, the approximation $\Gamma/V = \Gamma_0/V_0$ is often used, where Γ is the Grunhausen coefficient, V is the volume, and the subscript zero refers to the initial state of the substance [1, 2], and the "mirror image" rule also. The foundation for this rule is the law for doubling the mass flow rate of a substance u_H in an unloading wave [3, 4] which has been established experimentally for not too high pressures p_H in the shock.

In many papers [4-7], the agreement between the unloading isentrope and shock compressibility curve in p–u-coordinates is used to evaluate just one of the Riemann integrals governing the shape of the isentrope on the p–V plane. This procedure permits giving an estimate of the magnitude of the volume increment of the material because of the irreversible shock heating after unloading to zero pressure:

$$\Delta\hat{V}_{\text{res}} = \hat{V}_{\text{res}} - V_0 - \int_0^p \left(\frac{du_H}{dp}\right)^2 dp - \Delta V_H. \tag{1}$$

However, within the framework of the same "mirror" approximation, it is possible to write a second Riemann integral also for the energy E:

$$\Delta\hat{E}_{\text{res}} = \hat{E}_{\text{res}} - E_0 = \Delta E_H - \int_0^p p\left(\frac{du_H}{\partial p}\right)^2 dp. \tag{2}$$

Since (1) and (2) for the residual parameters are formally equivalent, the question occurs as to which describes the thermodynamics of shock compression best.

Both the true and the "mirror image" residual quantities admit of expansion in Taylor series at low pressures. For deviations of these parameters it is possible to obtain

$$\Delta V_{\text{true}} - \Delta\hat{V}_{\text{res}} \sim p^3 \sim \Delta V_{\text{true}},\ \Delta E_{\text{res}} - \Delta\hat{E}_{\text{res}} \sim p^4,$$

from which it follows that the "mirror" approximation for the energy (2) best describes the thermodynamics of shock compression. The use of (1) results also in substantial inaccuracies in computing the shape of the "mirror" isentropes [7].

It is possible to arrive at the same deduction by comparing the thermodynamic consequences of the integrals (1) and (2) with the extensively used approximation Γ/V = const. As in [8], the thermodynamic equality

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