QUANTITATIVE DESCRIPTION OF SPALL DAMAGE

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Experimental data relating to spalling effects in organic glass (Plexiglas) and the aluminum alloy AMg-6 obtained by the shock loading of the samples are presented in the form of an approximate analytical relationship between the degree of damage, the applied stress in the rectangular pulse, and the period of action of the latter.

When a solid body is subjected to severe, brief impacts of explosions, tensile stresses are developed and these lead to the rupture of the material. The experimentally observed degree of damage depends on the amplitude and duration of the applied load [1, 2]. With diminishing period of application of the load, the difference between the stress due to the formation of local centers of damage and the stress creating a spallation fragment increases.

In the present investigation, plates of various thicknesses made from the material under consideration were made to collide, and the threshold impact velocities corresponding to the two forms of damage were found: local damage in the form of pores or small isolated cracks, and spallation (the merging of local damage into a cleavage crack). The damage was recorded visually at a low optical magnification. The local damage encountered in Plexiglas had characteristic dimensions of 0.02-0.05 mm and in aluminum 0.05-0.10 mm. The damage recorded lay in the neighborhood of a plane at a distance equal to the thickness of the striker from the rear surface of the sample. No damage at the edge of the sample in the region embraced by lateral loading was taken into account. The plates had the form of a disk 50 mm in diameter. The pairs of aluminum plates were 3-5 and 5-10 mm thick and the Plexiglas plates 1-2, 2-4, and

TABLE 1

Degree of damage	Pairs of Plexiglas plates	v, m/sec	Pairs of aluminum AMg-6 plates	v, m/sec
No damage	1–2	67.5, 88, 92	3–5	255, 262
	2–4	77.5, 89.5	5–10	142, 145, 162, 170
	2.8–7	79, 83.5		
Local damage	1–2	95.5, 97.4, 104, 108, 114, 116, 127	3–5	290, 295, 335, 360
	2–4	89, 90, 102	5–10	180, 188, 193, 220, 237
	2.8–7	89, 95, 98.5		
Spalling	1–2	134, 147, 153	3–5	390, 465
	2–4	108, 125.5, 128	5–10	220, 265, 290, 305, 325
	2.8–7	101, 109, 131		

TABLE 2

Material	τ, μsec	v_1, m/sec	v_2, m/sec	σ_1, kbar	σ_2, kbar
Plexiglas	0.75	94±2	130±4	1.48±0.03	2.06±0.06
	1.49	89±1	105±3	1.41±0.02	1.66±0.05
	2.09	86±3	100±2	1.36±0.05	1.58±0.03
Aluminum AMg-6	0.68	275±15	375±15	21.4±1.2	29.2±1.2
	1.70	175±5	230±10	13.6±0.4	17.9±0.8

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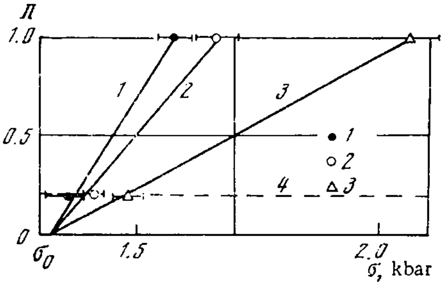

Fig. 1

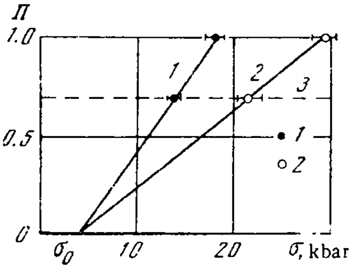

Fig. 2

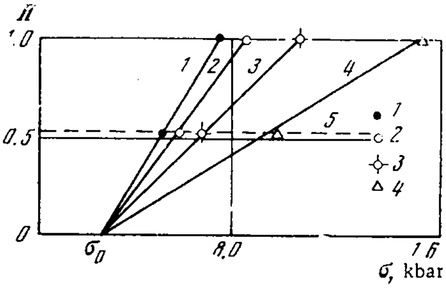

Fig. 3

2.8-7 mm. The direction of application of the load in the aluminum samples coincided with the direction of technological rolling.

The tensile stress σ and its period of action τ in the spallation cross section were calculated from the equations

$$\sigma = {}^1/_2 \rho c v$$

$$\tau = \begin{cases} 2(h_1 - h_2)/c, & h_1 < 2h_2 \\ 2h_2/c, & h_1 > 2h_2 \end{cases}$$

where ρ is the density of the material, c is the velocity of sound, v is the impact velocity, h_1 is the sample thickness, and h_2 is the thickness of the striker. In the calculations we used the following values of the constants: $\rho = 2.64$ g/cm^3, c = 5.92 g/cm^3 for aluminium; $\rho = 1.18$ g/cm^3, c = 2.68 km/sec for Plexiglas.

The results of individual experiments are shown in Table 1. Table 2 gives the threshold values of the velocity v_1 and the corresponding stress σ_1 associated with the formation of local damage and also v_2 and σ_2 associated with spalling. The values of v_1 and v_2 were determined as the arithmetic means between the extreme values in the columns of Table 1. The error in measuring the velocity was $\sim 1\%$. Table 2 shows that σ_1 and σ_2 are monotonically decreasing functions of τ, where

$$\sigma_2(\tau_1) > \sigma_1(\tau_1), \quad \sigma_2(\tau_1) - \sigma_1(\tau_1) > \sigma_2(\tau_2) - \sigma_1(\tau_2)$$

if $\tau_2 > \tau_1$.

We shall seek the function Π describing the degree of damage on the basis of the following assumptions: 1) there exists a stress σ_0 such that for $\sigma < \sigma_0$ no damage occurs, whatever the period of action of the load, i.e., σ_0 is the static tensile strength under conditions of one-dimensional strain; 2) the observed local acts of damage are not the original ones, i.e., damage occurs for $\sigma_0 < \sigma < \sigma_1$. We assume further that the dependence of Π on σ may be described by a linear law; then

$$\Pi = (\sigma / \sigma_0 - 1)\,(\sigma_2(\tau) / \sigma_0 - 1)^{-1} \tag{1}$$

Substituting $\sigma = \sigma_1(\tau)$ into (1), we find the estimated values of σ_0 and Π_1 for each pair of values of τ. For Plexiglas the mean values obtained from three pairs of τ values are $\sigma_0 = 1.32$ kbar, $\Pi_1 = 0.2$. For aluminum, using one pair of τ values, $\sigma_0 = 4$ kbar, $\Pi_1 = 0.69$. Equation (1) is shown in Figs. 1 (Plexiglas) and 2 (aluminum) for the values of the constants indicated.

In Fig. 1, line 1 corresponds to $\tau = 2.09\ \mu$sec, 2 to $\tau = 1.49\ \mu$sec, 3 to $\tau = 0.75\ \mu$sec, 4 to $\Pi = 0.2$; in Fig. 2, 1 to $\tau = 0.68\ \mu$sec, 2 to $\tau = 0.68\ \mu$, 3 to $\Pi = 0.69$. If the value of σ_0 is known in advance, a more precise construction of the function $\Pi(\sigma)$ may be made.

The graphical construction of the function

$$a(\tau) = (\sigma_2(\tau) / \sigma_0 - 1)^{-1}$$

shows that for Plexiglas there is a linear relationship $a = \alpha\tau$ ($\alpha = 2.5\ \mu\text{sec}^{-1}$), while for aluminum $a = \alpha\tau^{2/3}$ ($\alpha = 0.21\ \mu\text{sec}^{-2/3}$). We have

$$\Pi = \alpha\tau^n (\sigma / \sigma_0 - 1) \tag{2}$$

with the above constants.

Using the above method, we analyzed experimental data relating to spalling effects in beryllium No. 50A [2]. The degree of damage in these experiments was determined from a study of photographs of the test samples. In Fig. 3 [1) τ = 0.79 μsec, 2) τ = 0.394 μsec, 3) τ = 0.201 μsec, 4) τ = 0.043 μsec, 5) Π = 0.52] the data are referred to σ_0 taken as being equal to the Hugoniot elastic limit (2.5 kbar [2]). Experiment agrees with this construction. The initial stage of damage mentioned in [2] corresponds to $\Pi = 0.52$. In Eq. (2) n = 0.35.

Equation (2) approximately describes the dependence of the damage received on the parameters of an incident stress wave of rectangular profile. The possibility of using this equation to estimate the accumulation of damage with time during the rupture process depends on the satisfaction of the constant stress condition, which was regarded as prespecified in [1]. In the earlier stage of the rupture process, before the formation of macroscopic defects in the form of pores [$\Pi < (0.2-0.5)$], when the medium still retains continuity, we may regard the density of the material and the velocity of sound as constant. The stress in the zone of rupture will then be constant for a rectangular wave. At the stage of macroscopic rupture (the development and merging of the pores, with the formation of a spallation crack), when continuity is infringed and the pores serve as local sources of relaxation waves, the assumption as to the constancy of the tensile stress in the rupture zone is less justified.

The resultant values of the index in (2) ($n \leq 1$) do not correspond to the avalanche-like mechanism of increasing damage, which would appear to be the most probable for cases in which the tensile stress remains constant during rupture, and for which $n > 1$ ($\partial\Pi/\partial t \sim t^{n-1}$).

LITERATURE CITED

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2. L. Davison and A. L. Stevens, "Continuum measures of spall damage," J. Appl. Phys., 43, No. 3 (1972).