# FAILURE IN MATERIALS ON LOADING WITH THE EXPLOSION OF A SHEET EXPLOSIVE CHARGE

V. K. Golubev, S. A. Novikov,
and L. M. Sinitsyna

UDC 532.593:620.172

Loading by detonating a sheet explosive charge is widely used in practice in explosive experiments. This includes, for example, hardening and explosive welding [1], and the investigation of spallation damage in metals [2-4]. Combining this simple method for loading with a calculation of the flow of the stressed material has provided comparative results on the spallation damage in a number of metals and polymers, which, in their turn, can be compared with results obtained with other conditions of pulsed mechanical loading (detonation of a block explosive, impact by a plate).

The setup of the experiments involving loading of plates by a detonation of a sheet charge of plastic explosive and the wave propagation that is realized with such a scheme are presented in [2]. The metal samples studied were cut out of corresponding rod-shaped materials and plastics were cut out of sheets. The dimensions of the stressed surfaces were chosen sufficiently large in order to eliminate the effect of lateral loading and the initial nonstationary loading zone on the process of spallation. The loading charge was initiated by a linear detonation wave generator consisting of a perforated plastic explosive [5]. After loading, the nature of the spallation damage was observed visually and the thickness of the spalled layer was measured.

The flow field in the detonation products and in the stressed materials was computed numerically by the method of characteristics. The computational method used is described in detail in [6, 7]. The expansion isentropes of the detonation products were assumed to follow a cubic polytropic curve, the equation of state of the materials investigated without taking into account the effects of strength and change in entropy along the shock-wave front were assumed to be known linear D—u relations between the wave and mass velocities, and, in addition, it was assumed that they could be extrapolated to negative pressures. In the calculations, we determined the maximum negative pressure p in a plane corresponding to fracture failure and the pressure gradient $\Delta p/\Delta l$ in the stretching pulse, whose shape in this case was nearly triangular. These parameters, characterizing the failure-inducing stretching pulse, were successfully compared in [8] in stressing a number of metals by detonating a block explosive.

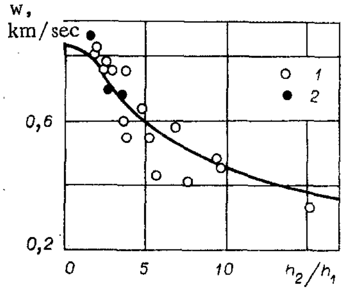

Fig. 1

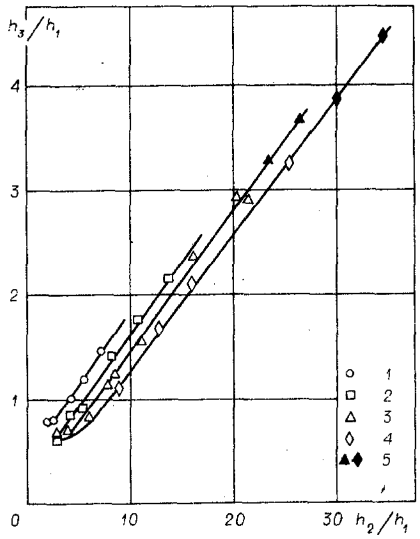

Fig. 2

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 112-118, March-April, 1981. Original article submitted January 31, 1980.

0021-8944/81/2202-0236$07.50

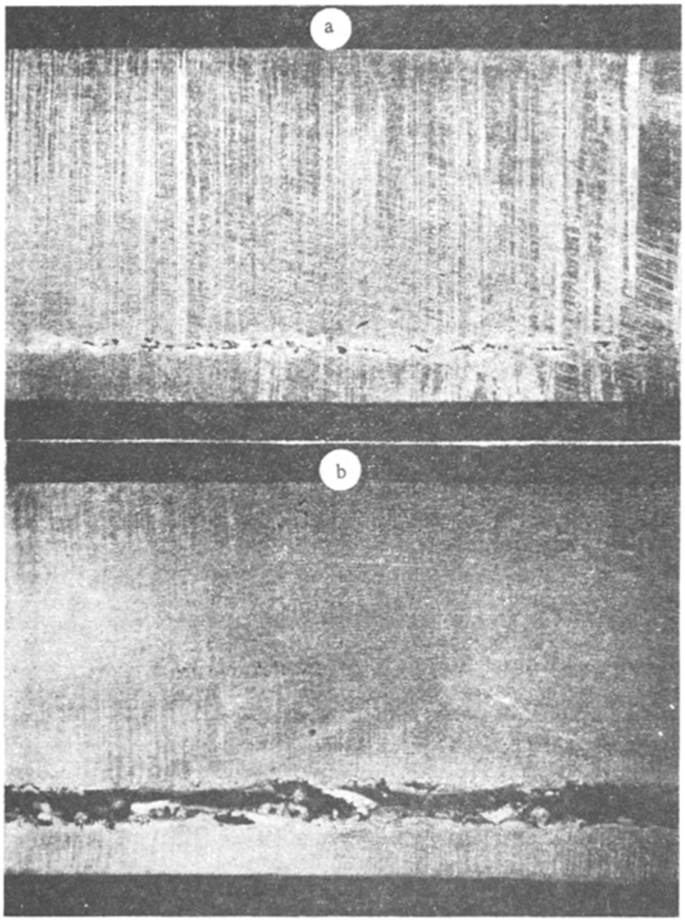

Fig. 3

Figure 1 shows the computed dependence of the velocity of the free surface of an aluminum plate loaded by the detonating sheet charge as a function of the dimensionless thickness of the plate $h_2/h_1$ ($h_1$ is the thickness of the explosive layer, $h_2$ is the thickness of the aluminum plate) and the results of measurements of the velocities of thin artificial spalls (AMts aluminum alloy 1 [2], AMg aluminum alloy 2 [3]). The satisfactory agreement between the computed and experimental results indicates the possibility of using the computational method used for plastic metals and polymers. In the case when metals that have significant shearing strength are stressed, the shock wave propagating through the material will be more intensely damped and the calculation can only estimate the upper limit for the amplitude of the shock wave reaching the free surface of the plate.

Figure 2 shows the results of experiments with Ad1 aluminum [$h_3$ is the thickness of the first spalled layer (the average value of the thickness determined by not less than 10 measurements), measured here for values of $h_2$ equal to 2 mm (1), 4 mm (2), 8 mm (3), 12 mm (4) and in the absence of visually observable separation (5)], indicating the existence of a scale effect for spallation of aluminum, also observed in experiments on the collision of aluminum plates [9, 10]. A similar effect was also observed for other materials investigated in this work. The values of $h_3$ obtained by linear extrapolation, corresponding in Fig. 2 to the absence of visually observable separation of layers, correspond to sections that are more susceptible to spallation. This is supported by a more detailed examination of microsections using a microscope. In Fig. 3a ($h_1 = 0.34$ mm, $h_2 = 8$ mm), a spallation damage zone that has already been completely formed is observed in the sample, although separation of layers, i.e., spallation, occurs only with subsequent increase in the load intensity [Fig. 3b ($h_1 = 0.37$ mm, $h_2 = 8$ mm)].

The starting data used in the calculations and the range of the measured values of $h_1$ and $h_2$ are presented in Table 1 ($\rho$ is the density, $c_0$ and $\lambda$ are the coefficients in linear D−u relations), and the results of a numerical analysis of the experimental data are presented in Fig. 4 (the numbers in Fig. 4 correspond to the numbers of the materials in Table 1) in the variables ($\sqrt[3]{\Delta p/\Delta l}$, p). The choice of variables stems from an attempt to systematize the results obtained using the energy criteria for spallation damage presented in [11], which consist of an energy balance equation for failure. In application to the results of the present work, the

TABLE 1

| No. | Material | $\rho$, g/cm$^3$ | $c_0$, km/sec | $\lambda$ | $h_1$, mm | $h_2$, mm | $\gamma_{\min}$, cm$^2$ |
|---|---|---|---|---|---|---|---|
| 1 | AD1 aluminum | 2,71 | 5,25 | 1,39 | 0,3—2,6 | 2—12 | 1,25 |
| 2 | D16 hardened aluminum alloy | 2,78 | — | — | 0,5—1,8 | 10 | 7,10 |
| 3 | D16 aluminum alloy (annealed) | — | — | — | 0,4—1,1 | 10 | 2,65 |
| 4 | AMts aluminum alloy [2] | 2,73 | — | — | 0,5—2,2 | 2—15 | 1,21 |
| 5 | AMg aluminum alloy [3] | 2,64 | — | — | 3—5 | 8 | 6,53 |
| 6 | M1 copper | 8,93 | 3,95 | 1,50 | 0,3—1,5 | 2—12 | 0,60 |
| 7 | NT2 nickel | 8,86 | 4,62 | 1,52 | 0,3—1,6 | 2—4 | 2,97 |
| 8 | PS1 lead | 11,3 | 2,03 | 1,52 | 0,3—0,5 | 8—12 | 0,11 |
| 9 | St. 3 steel | 7,85 | 4,57 | 1,49 | 0,3—1,6 | 2—4 | 3,30 |
| 10 | St. 3 steel [3, 4] | — | — | — | 3—5 | 5—40 | 9,15 |
| 11 | SCh 18-36 cast iron | — | — | — | 0,5—0,8 | 4 | 0,43 |
| 12 | 12Kh18N10Г steel | 7.80 | — | — | 0,8—2,6 | 2—4 | >35 |
| 13 | VT3, VT14 titanium | 4,51 | 5,22 | 0,77 | 0,8—2,6 | 2—4 | >47 |
| 14 | Teflon | 2,19 | 1,53 | 1,95 | 0,3—0,6 | 3—15 | 0,28 |
| 15 | Plexiglas | 1,18 | 2,59 | 1,51 | 0,3—0,9 | 10—20 | 0,15 |
| 16 | Polyethylene | 0,92 | 2,05 | 1,95 | 0,3—0,6 | 5—20 | 0,05 |
| 17 | PT Textolite | 1,36 | 2,65 | 1,49 | 0,3—0,5 | 10—15 | 0,05 |

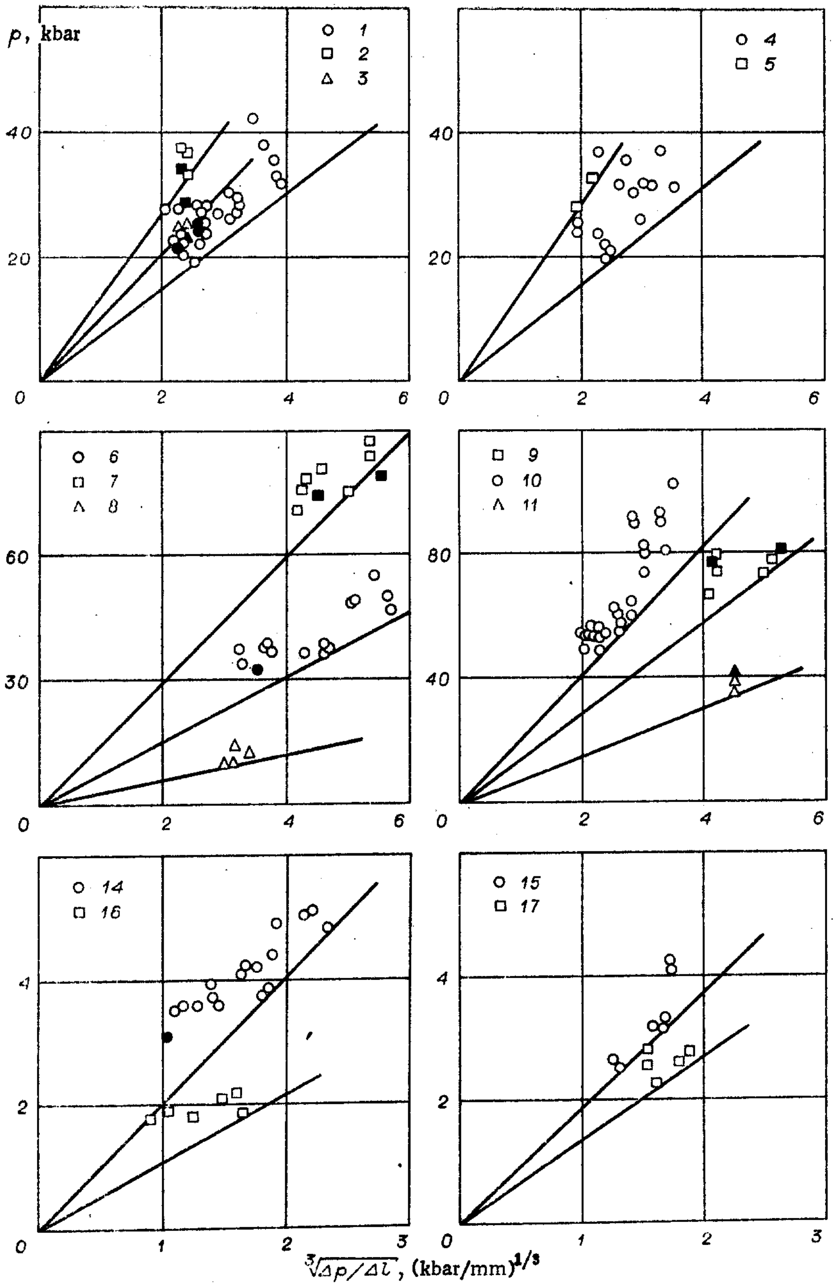

Fig. 4

TABLE 2

| Material | Results of the present work | Loading by detonating a block charge | Loading by plate impact | Material | Results of the present work | Loading by detonating a block charge | Loading by plate impact |
|---|---|---|---|---|---|---|---|
| Aluminum | 1,3 | 1,7[8] | 15[13] | Lead | 0,1 | 1,4— | 1,6 — |
| Copper | 0,6 | 4,4 — | 24 — | St. 3 steel | 3,3 | | 32 — |
| Nickel | 3,0 | 9,2 — | 40 — | Plexiglas | 0,15 | | 0,65 [10] |

energy criterion for spallation has the form $p^3/(\Delta p/\Delta l)=6\rho c_0^2\gamma$, i.e., the stored elastic energy in the stretching pulse is equal to the work $\gamma$ expended on separating the spalled layer.

The considerable scatter in the results obtained (Fig. 4) indicates that the results cannot be uniquely represented in the form of clear-cut dependences $p(\Delta p/\Delta l)$, as was done in [8]. The magnitude of the parameter $\gamma$ can thus change significantly and arbitrarily in experiments conducted with specimens prepared from the same material. Thus, for AD1 aluminum and Teflon, for which a considerable number of experiments were performed, the magnitude of the parameter $\gamma$ varies over the ranges 1.3-7.1 and 0.3-1.1 J/cm$^2$, respectively. In order to compare the materials studied, it is apparently useful to choose the lower value of the parameter $\gamma$, which can be determined for each of the materials, thereby fixing the limits of the spallation damage zone and conserving the continuity in Fig. 4. The magnitude of the minimum effective failure energy $\gamma_{\min}$ will in this case characterize the necessary but not sufficient conditions for spallation of the materials investigated under analogous or compatible conditions of pulsed mechanical loading. The values obtained for the magnitude of $\gamma_{\min}$ are presented in Table 1. It should be noted that the titanium and 12 Kh18N10T steel samples with thickness up to 4 mm did not withstand spallation, while the estimated values of $\gamma_{\min}$ for these materials were determined under the arbitrary assumption of a weakest average cross section of the specimen ($h_3=h_2/2$). In order to create the conditions for pulsed mechanical loading of the materials, we used a plastic explosive of density 1.52 g/cm$^2$ and a detonation velocity of 7.8 km/s. In carrying out the numerical analysis of the experimental results of [2-4], calculations were performed for the explosives used in these works.

Let us point out some of the properties of the visually observed failure in the materials investigated. For the metals, with the exception of St. 3 steel and cast iron, the external appearance of the failure surface is dull and stringy, which indicates the viscous nature of spallation in these materials. In reflected light, reflections from the spallation surfaces can be seen on the failure surface of St. 3 and cast iron, which indicates the brittle nature of the failure. The more coarse and even appearance of the failure surface for polyethylene, less coarse for Teflon, and quite even for Plexiglas and Textolite, which fails along the binder layers, should be noted. When the shock wave that reaches the free surface has a sufficiently high intensity, a clearly expressed double spallation was observed in Plexiglas and Textolite, and, in addition, the thickness of the second spalled layer exceeded, by not less than a factor of 2, the thickness of the first layer, while in Teflon and polyethylene a zone in which layers of the material were separated was observed behind the spalled layer. For aluminum, on the other hand, the second spalled layer had approximately half the thickness of the first layer. The observed effects are explained in [12] from the point of view of a kinetic approach and are apparently related to the difference in the spallation mechanisms in brittle and ductile materials.

It is useful to compare the results obtained in the present work with the results obtained under different conditions of pulsed mechanical loading. Under impact loading by a plate, the shape of the stretching pulse is nearly rectangular, while under loading by detonating a sheet charge and a block charge it is nearly triangular. The energy criterion for these cases is written in the form $p^2 l=2\rho c_0^2\gamma$ and $p^2 l=6\rho c_0^2\gamma$ respectively ($l$ is the length of the stretching pulse, and in the present work $l=h_3/\cos(\arcsin(c_0/D))$, where D is the detonation velocity of the explosive charge). The values of $\gamma_{\min}$ obtained by plate impact, detonating a block explosive, and those obtained in the present work by detonating a sheet explosive charge are presented in Table 2. One can see the difference in the values of the effective failure energy determined in this manner, which is apparently related more to the change in the scale of the system than to a change in other parameters of loading (loading intensity, form of the load-deformed state, and others). This is also indicated, for example, by the increase in the quantity $\gamma_{\min}$ to 9 J/cm$^2$ for St. 3 [3, 4] with a loading method similar to that used in this work and an increase in the scale of the system and the decrease in the magnitude of $\gamma_{\min}$ for aluminum 6061-T6 to 1 J/cm$^2$ [14] under loading by plate impact and a decrease in scale. Such considerable coupling of the effective spallation energy of materials with the scale of the system appears to stem from the fact that the initial stage of the failure process, nucleation and development of pores, in the case of a viscous material or cracks in the case of a brittle failure, occurs in a volume whose characteristic size is comparable to the size of the loading stressing pulse [15]. Thus, it may be assumed that the energy absorbed initially is proportional to the scale of the system, while the energy absorbed in the final stage, when the damage coalesces into a mainline crack, depends on the scale to a much lesser extent. This is also indicated by the more weakly manifested scale effect (see Fig. 2), compared with the purely energetic effect [11], in the presence of spallation, also observed in other works [9, 10, 14].

Thus, the effective failure energy obtained in experiments on fracturing, revealed in [16], while significant in measurements for comparing the spallation conditions of different materials under identical loading conditions, characterizes the properties of the loading system more than the intrinsic properties of the material. The value of the failure energy that characterizes the properties of the material can be determined if the scale of the system is decreased or the available results are somehow extrapolated to conditions under which failure is localized in a zone with a characteristic size of the order of the size of a grain. In this sense it is of interest to compare the effective spallation energy to the propagation energy of a single crack $G_{1c}$ obtained under conditions of plane deformation. The values of $G_{1c}$ presented in [17] for 7075-T6 aluminum, low-alloy steels, and Plexiglas, are 0.8, 1, and 0.07 J/cm$^2$, respectively, and apparently are extreme values for the quantity $\gamma$ for decreasing scale.

## LITERATURE CITED

1. A.A. Deribas, Physics of Hardening and Explosive Welding [in Russian], Nauka, Moscow (1972).
2. E. V. Menteshov, V. P. Ratnikov, et al., "Action of the explosion of a sheet charge on an aluminum plate," Fiz. Goren. Vzryva, No. 2 (1967).
3. A. P. Rybakov, E. V. Menteshov, and V. P. Shavkov, "Action of the explosion of a sheet charge on metallic plates," Fiz. Goren. Vzryva, No. 1 (1968).
4. A. P. Rybakov, "Spallation in steel loaded by the explosion of a sheet charge and by plate impact," Prikl. Mekh. Tekh. Fiz., No. 1 (1977).
5. R. Shall, "Physics of detonation," in: Physics of Fast Processes, Vol. 2 [Russian translation] Mir, Moscow (1971).
6. J. O. Erkman, "Explosively induced nonuniform oblique shocks," Phys. Fluids, 1, No. 6 (1958).
7. Yu. M. Privalov, V. R. Solonenko, and B. A. Tarasov, "Action of a sliding detonation on a compressable wall," Fiz. Goren. Vzryva, No. 3 (1976).
8. B. R. Breed, C. L. Mader, and D. Venabl, "Technique for the determination of dynamic tensile strength characteristics," J. Appl. Phys., 38, No. 8 (1967).
9. B. M. Butcher, L. M. Barker, D. E. Munson, and C. D. Lundergan, "Influence of stress history on time-dependent spall in metals," AIAA Journal, 2, No. 6 (1964).
10. B. A. Tarasov, "Quantitative description of spallation damage," Prikl. Mekh. Tekh. Fiz., No. 6 (1973).
11. A. G. Ivanov, "Spallation in the quasiacoustic approximation," Fiz. Goren. Vzryva, No. 3 (1975).
12. V. S. Nikiforovskii, "Kinetic nature of brittle failure in solids," Prikl. Mekh. Tekh. Fiz., No. 5 (1976).
13. S. A. Novikov, V. K. Golubev, Yu. S. Sobolev, and V. A. Sinitsyn, "Effect of temperature on the magnitude of spallation-inducing stresses in metals," in: Applied Problems in Strength and Plasticity [in Russian], No. 11 Gork. Gos. Univ., Gor'kii (1979).
14. L. J. Cohen and H. M. Berkowitz, "Time-dependent fracture criteria for 6061-T6 aluminum under stress-wave loading in uniaxial strain," Int. J. Fracture Mech., 7, No. 2 (1971).
15. T. W. Barbee, L. Seaman, R. Crewdson, and D. Curran, "Dynamic fracture criteria for ductile and brittle metals," J. Mater., 7, No. 3 (1972).
16. Yu. I. Fadeenko, "Temporal criteria for failure in dynamics of a solid body," in: Dynamic Problems in the Mechanics of Continuous Media [in Russian] No. 32, Gidrodinam. Sib. Otd. Akad. Nauk SSSR, Novosihirsk (1977).
17. B. L. Auerbakh, "Some physical aspects of failure," in: Failure, Vol. 1 [Russian translation], Mir, Moscow (1973).