EFFECT OF THE PRESSURE OF SHOCK COMPRESSION ON THE CRITICAL SHEAR STRESSES IN METALS

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The critical shear stresses σ_* behind the leading edges of shock waves were studied in aluminum at pressures of 300 and 650 kbar, copper at 240 and 550 kbar, and lead at 460 kbar by carrying out explosion experiments. The quantity in question was estimated by comparing the experimental data characterizing the fall in pressure at the leading edge of the shock wave (arising from load relaxation) with the results of calculations.

1. It was shown experimentally in [1, 2] that the value of the critical shear stresses σ_* in metals increased substantially with increasing hydrostatic pressure. In shock compression the magnitude of the critical shear stresses determines the amplitude of the elastic relaxation wave in the substance previously compressed by the shock wave. The change in the stressed state during shock compression and subsequent expansion of an infinite medium is illustrated schematically in Fig. 1, where ABC is the curve of shock compression (shock adiabatic), CDE is the curve of expansion, CD is the elastic section (expansion taking place in the elastic relaxation wave), DE is the section of plastic relaxation, and AF is the curve of hydrostatic compression.

The magnitude of the critical shear stresses σ_* at which the reverse transition from elasticity to plasticity takes place during the expansion of the shock-compressed material is associated with the amplitude of the pressure in the relaxation wave P_- in the following way:

$$\sigma_* = \frac{P_-}{2} \frac{1-2\mu}{1-\mu} \tag{1}$$

where μ is the Poisson coefficient of the material for the particular pressure of shock compression.

In calculating the compression of metals by strong shock waves, one frequently neglects the strength characteristics, simply considering the metal as a liquid (hydrodynamic theory). Allowance for the mechanical strength, i.e., for the elastic section on the expansion curve, substantially alters the yield (flow) picture during shock compression [3].

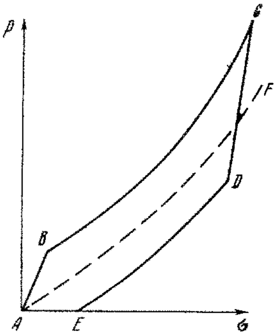

Fig. 1

It was first demonstrated experimentally in [4] that, when the pressure of the shock compression equalled 100 kbar, the role of the strength factor in aluminum was very considerable, the critical shear stresses being 28.5 kbar. This result was supported in [5] in experiments with aluminum alloys: For shock-compression pressures of 110 and 345 kbar the critical shear stresses were 8.6 and 22 kbar, respectively.* The results of some numerical computations allowing for the effect of elastic relaxation on the propagation and attenuation of elastic waves in solids were presented in [6].

*These values of the critical stresses were obtained from the values of pressure P_- determined in [5] for $\mu = 0.31$.

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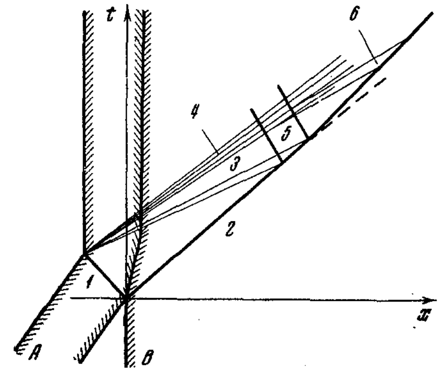

Fig. 2

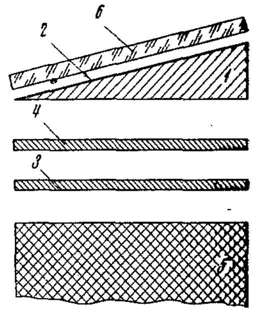

Fig. 3

As in [4,5], our present estimates of the value of σ_* were based on a comparison of the calculated and experimental relationships characterizing the fall in pressure at the leading edge of shock waves in metals, attributable to the overtaking wave of elastic relaxation.

2. In order to determine the critical shear stresses behind the leading edge of the shock waves, we studied the attenuation of the pressure at the leading edge of the shock wave produced by the impact of a plate of the same material on the test sample. To describe the method, let us consider the successive reduction in the pressure at the leading edge of the shock wave arising from its interaction with the wave of elastic relaxation in x, t (path–time) coordinates, as indicated in Fig. 2, where A is the striking plate and B is a semiinfinite sample.

When the plate strikes the sample, two shock waves 1 and 2 are formed in the sample. A relaxation wave 3, overtaking the leading edge of the compression shock wave, is formed when the shock wave 1 is reflected in the plate from the free surface of the latter. The metal first relaxes in the elastic relaxation wave 3 and then in the plastic relaxation wave 4 until zero pressure is reached (these correspond to the curves CD and DE in Fig. 1). The velocity of the elastic relaxation wave is greater than the velocity of the plastic wave. When the elastic relaxation wave interacts with the shock wave, the pressure at the leading edge of the wave falls by an amount determined by the amplitude of the elastic relaxation wave, i.e., by the magnitude of the critical shear stresses. A weak elastic compression wave 5 propagates to the left along the sample. Then this wave interacts with the plastic relaxation wave, and an elastic relaxation wave 6 again propagates to the right, overtaking the leading edge of the shock wave, and so on. The process is repeated until the pressure at the leading edge of the shock wave falls to zero.

Thus the pressure at the leading edge of the shock wave falls in jumps as the wave passes through the sample. The velocity of the material (mass velocity) changes correspondingly – i.e., the velocity u behind the leading edge of the shock wave; so does the velocity of the free surface w as the shock wave passes out through it.

3. In our experiments we studied samples of the aluminum alloy D1, copper M1, and lead in the as-supplied state (without additional heat treatment). The experimentally measured quantity was the velocity of the free test-sample surface w.

The arrangement of the experiment is illustrated in Fig. 3, where 1 is the sample, 2 is a foil, 3 and 4 are plates of test material, 5 is an explosive charge with a plane detonation wave, 6 is a block of organic glass recording the flight of the foil by a photochronographic method. The $w = w(x)$ relationship was determined in experiments with samples prepared in the form of wedges. The use of samples shaped in this way yielded the $w = w(x)$ relationship over the whole range $0 < x < h$ in each of the experiments (where h is the maximum sample thickness). The shock wave in the sample was excited by the impact of a plate 4 made of the same material, 2 mm thick. In order to eliminate the influence of the pressure from the explosion products on the propagation of the shock wave in the sample, a second similar plate 3 was placed between the striker plate and the explosive charge, and this was accelerated by the explosion.

When the plates collided, the plate 4 acquired a velocity equal to that of the plate 3, while the latter started moving much more slowly. An air gap of 5 mm was allowed between the explosive charge and the

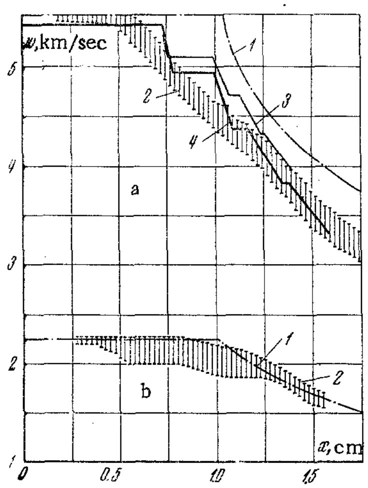

Fig. 4

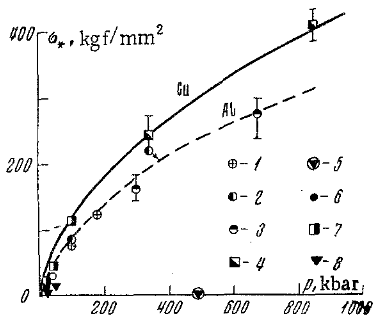

Fig. 5

plate 3 to eliminate chipping. The velocity at which the plate 4 struck the sample was measured in special experiments. The velocity was varied by using explosive charges of different compositions. In order to measure the velocity of the free surface we used photochronographic and electrical-contact methods, such as were described, for example, in [7]. In this way we recorded the time intervals between the instant at which the shock wave emerged at the free surface and that at which it reached the contacts (or the block of organic glass when using the photochronographic method), situated at 3–4 mm from the sample surface. In order to eliminate the influence of chipping on the experimentally measured velocities, an aluminum film 2 some 0.2 mm thick was fitted firmly to the surface of the aluminum samples 1. The correction for the change in the velocity of the free surface associated with chipping in the experiments with copper samples was based on experimental data [8].

4. The yield (flow of material) behind the leading edge of the shock wave was calculated with due allowance for interaction with the overtaking waves of elastic relaxation by using the known equations of state of these metals presented in [9]. The experimental and calculated $w = w(x)$ relationships for aluminum with P = 680 kbar and lead with P = 460 kbar are given in Fig. 4a and b respectively. The shaded regions 2 are determined by the scatter of the experimental data in each series of similar experiments. The broken curves 1 are the calculated relationships for $\sigma_* = 0$ (hydrodynamical theory); continuous lines 3 and 4 (Fig. 4a) are the calculated relationships for $P_- = 70$ kbar and $P_- = 100$ kbar. In carrying out the calculations, as in [4], no allowance was made for the change in the Poisson coefficient with pressure; the values of μ were taken as equal to 0.31, 0.34, and 0.44 for aluminum, copper, and lead respectively.*

We note that on none of the experimental curves is there a sudden fall in the velocity of the free surface. This is evidently because in the expansion of shock-compressed metals the transition from elasticity to plasticity takes place along a smooth curve and not a curve with a sharp break (CDE in Fig. 1). We should expect this kind of behavior of the metals on passing from elasticity to plasticity from the results of [10].

Three or four similar experiments were carried out for each metal with the same relative velocity of the striker plate.

As the critical shear stress corresponding to a particular pressure behind the leading edge of the shock wave, we took that value of σ_* for which the computed $w = w(x)$ relationship best described the experimental data.

As the error in determining σ_* from the comparison between calculation and experiment, we took the interval between the values of σ_* for which the calculated $w = w(x)$ curves touched the upper and lower boundaries of the shaded region.

We see from Fig. 4b that the experimental $w = w(x)$ relationship for lead closely follows the calculated curve based on the hydrodynamic theory ($\sigma_* = 0$).

The following table represents the estimated values of σ_* so obtained and also the corresponding pressure amplitudes in the elastic relaxation wave P_- (kbar) for a shock-wave pressure P (kbar) in the three test metals:

	P	σ_*	P
Al	300—680	17—29	60—100
Cu	340—860	25—41	90—150
Pb	460	0	0

*Allowance for the dependence of the Poisson coefficient on the pressure in the shock wave may change the value of σ_* slightly.

5. Comparison between the calculated and experimental results shows that strength plays an important part in the range of shock compression pressures studied for aluminum and copper (up to 680 and 860 kbar respectively).

The values of σ_* here obtained for the materials under consideration are shown in relation to the pressure behind the leading edge of the shock wave in Fig. 5: the points 3, 4, 5 correspond to aluminum, copper, and lead. The same figure illustrates the results of analogous measurements carried out earlier for aluminum [4, 5] (points 1 and 2). The figure also presents data relating to the effect of hydrostatic pressure on the value of σ_* in aluminum, copper, and lead: points 6 and 8 for aluminum and lead [1] and point 7 for copper [2]. The aluminum data fall closely on a common curve.

As the pressure of the shock compression increases, so does the temperature behind the leading edge of the shock wave. The effects of these two factors, temperature and pressure, on the critical shear stresses are directly opposed. It is evident that for a shock-compression pressure corresponding to the melting of the metal the value of σ_* will be practically zero. Thus the $\sigma_* = \sigma_*$ (P) relationship should have a maximum for shock compression.

According to the results of various theoretical and experimental investigations [11, 12], aluminum melts behind the leading edge of a shock wave for pressures of 1050-2020 kbar, copper for 2050-2550 kbar, and lead for 410-1240 kbar.

The fact that according to our experiments the value of σ_* for lead at a pressure of 460 kbar was practically zero confirms its melting behind the leading edge of the shock wave at this pressure.

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