ELASTIC COEFFICIENTS OF ALUMINUM AS FUNCTIONS OF THE DEGREE OF COMPRESSION IN A SHOCK WAVE

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The velocities of elastic relief waves in commercial aluminum (AD1) and aluminum alloy (D16) samples compressed by a shock wave were measured by the most direct method. Using these results together with the relationship for the three-dimensional velocity of sound as a function of the intensity of the sound wave (derived on the assumption that the shock adiabat and the one-dimensional release isentrope coincide when expressed in pressure/mass-velocity coordinates), Young's modulus, the shear modulus, and the Poisson coefficient are calculated for shock-compressed aluminum.

It was shown experimentally in [1] that the strength characteristics of the material largely determine the character and parameters of the relief wave traveling through a shock-compressed material and also the attenuation parameters of the shock waves. Also, two other papers [2, 3] were devoted to the creation of a method of determining the law of stress relaxation in a medium transmitting a plane elastoplastic compression or relief wave from a series of experimental pressure or mass-velocity profiles. In order to use this method it is necessary to know the way in which the elasticity coefficients depend on the pressure in the material compressed by the shock wave. These coefficients may be calculated from the equations of elastic theory if we know the velocity of longitudinal elastic waves and the "three-dimensional" velocity of sound at a given pressure. The three-dimensional (bulk) compression modulus and, correspondingly, the three-dimensional velocity of sound are calculated from the equation of state of the particular material; in order to determine the velocity of longitudinal elastic waves, additional measurements are required.

Measurements of the velocity of longitudinal elastic waves in shock-compressed metals were first carried out in [1] by the lateral-release method. The "overtaking-" release method was used in [4-9] to determine the velocity of elastic relief waves (equal to the "longitudinal" velocity of sound) for various pressures behind the leading edge of the shock wave. This method is based on a study of the attenuation of the elastic waves arising as a result of the impact of thin plates on the test material. In [10, 11] the velocity of elastic relief waves was determined by using pressure profiles obtained with the aid of Manganin sensors. In these papers the pressure profile was recorded in a certain section of the sample, together with the velocity of the striker. The velocity of the elastic relief wave was then determined from the measured time interval between the instants of arrival of the leading edges of the shock wave and the relief wave at the sensor, using data relating to the thickness of the striker, the velocity of the sound wave, and the degree of compression behind the leading edge of the shock wave.

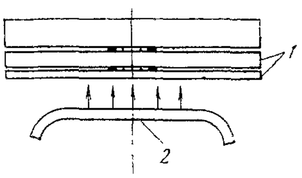

Fig. 1

Many measurements of the velocity of longitudinal elastic waves have been carried out in aluminum, copper, and iron for various pressures behind the leading edge of the shock wave. However, the results of these measurements are disconnected, insufficiently accurate, and in poor agreement

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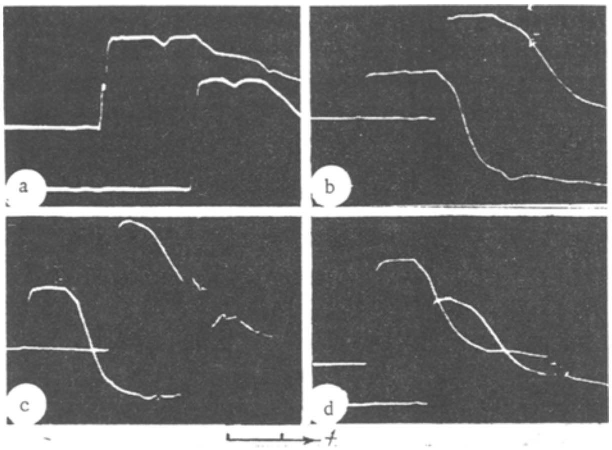

Fig. 2

with each other. In this paper we shall present the results of the most direct method of measuring the velocities of elastic relief waves in shock-compressed aluminum alloys AD1 and D16 for pressures of up to 300 kbar.

The arrangement of the experiments is indicated in Fig. 1. In each experiment we simultaneously recorded the pressure profiles in two cross sections of the sample 1 using an OK-33 double-beam oscillograph, after applying a shock load to the sample by means of the striker plate 2, initially accelerated to a high velocity. Knowing the distance between the sensors, and after determining the time intervals between the arrivals of the leading edges of the shock and relief waves at the first and second sensors from the oscillograms, we may find the velocity of the shock wave D and the Lagrange velocity of the elastic relief wave a_l. Using these data and the shock adiabat we calculated the pressure p, the degree of compression ρ/ρ_0, the mass velocity in the sample behind the leading edge of the shock wave u, and the "longitudinal" velocity of sound in Euler coordinates c_l.

In order to record the pressure profiles we used Manganin sensors [12-14]. The sensitive element of the sensor was made from a piece of Manganin wire 0.1 mm in diameter, which was bent into a zigzag and flattened in a press to a thickness of 0.02-0.03 mm. Leads constituting strips of copper foil 0.015 mm thick were spot-welded to the ends of the Manganin strip so obtained. After making the sensors these were vacuum-annealed at 150°C for 4 h.

Each sample consisted of three plates 120 mm in diameter with pressure sensors between them. The surfaces of the plates facing the sensors were polished. The sensors were separated from the sample by insulating Dacron or Teflon films 0.04-0.07 mm thick on either side of the sensor. The insulating films and sensors were bonded to the sample plates with vacuum grease, which also filled all cavities. The thickness of the plate facing the striker was 4-5 mm, the thickness of the second plate (base for measuring the velocity of the shock wave and the velocity of the leading edge of the relief wave) was 10-15 mm, and the third plate was 15 mm thick.

The shock waves were created in the samples by aluminum strikers 5 or 7 mm thick, accelerated by an explosion; the diameter of the flat part at the instant of collision was no less than 60 mm. The velocities of the strikers were 1.96 ± 0.05, 2.20 ± 0.07, 2.72 ± 0.1 km/sec. In order to reduce the pressure of the shock compression of the samples, in a number of experiments we used copper screens 4 or 5 mm thick, replacing the first plate of the sample. Measurements at pressures below 100 kbar were made by means of a powder gun. In these experiments the samples were compressed by a blow from an aluminum projectile 50 mm in diameter with a copper tip 4 mm thick.

Typical oscillograms of the experiments are presented in Fig. 2 in which (a) represents an oscillogram of the experiment on the AD1 sample, loaded to a pressure of 95 kbar by the impact of an aluminum projectile with a copper tip, (b) represents the loading of the AD1 sample to a pressure of 180 kbar by the impact of an aluminum plate 7 mm thick, while (c) and (d), respectively, represent the loading of AD1 and D16 samples to a pressure of 270-277 kbar by the impact of an aluminum plate 5 mm thick. In the experiments with the powder gun a "dip" was recorded at the top of the rectangular pressure pulse by both sensors (Fig. 2a). The appearance of a region of reduced pressure moving behind the leading edge of the shock

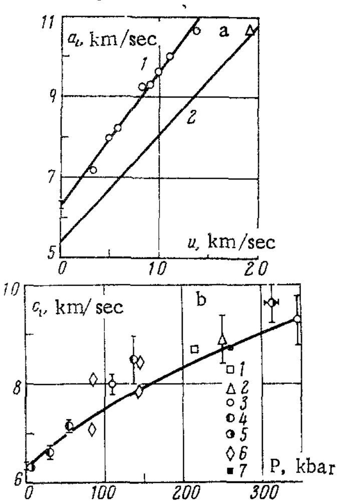

Fig. 3

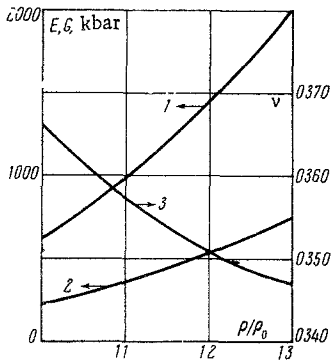

Fig. 4

wave is due to the reflection of the relief wave (arising as the shock wave passes through the insulation of the first sensor) from the interface between the aluminum sample and the copper tip of the projectile.

We see from the pressure profiles in Fig. 2b-d that the separation of the relief wave into elastic and plastic waves with a zone of stress relaxation between them is quite clearly recorded.

In determining the time intervals between the arrivals of the leading edges of the shock and relief waves at each sensor from the oscillograms, we allowed for the displacement of the oscillograph beams relative to one another along the x axis, the nonlinearity of the sweep, and the fact that the x and y axes corresponding to the deviation of the oscillograph beams were not quite perpendicular to one another. The velocities of the shock and relief waves were calculated after allowing a correction for the thickness of the sensor insulation.

The results of the measurements are shown by the circles in Fig. 3a in coordinates of the Lagrange velocity of the elastic relief wave a_l and the mass velocity of the material behind the leading edge of the shock wave u. Each point was obtained by averaging three to six independent measurements. The values of the mass velocity exceeding 0.7 km/sec were calculated from the velocity of the shock wave, using the shock adiabat of the samples. For shock waves of lower intensity the values of the mass velocity were calculated from the measured pressure behind the leading edge of the shock wave, in view of the fact that the velocity of the leading edge of the shock wave could not be measured accurately enough. For commercial aluminum AD1 and Duralumin D16 we used a shock adiabat in the form

$$D = (5.34 + 1.36u)\ \text{km/sec}. \tag{1}$$

The data presented in [15] for the case of the alloy 2024 (which has a composition similar to that of D16) at pressures up to 1000 kbar may be described by an expression of this kind. This expression is also obtained for the shock adiabat of commercial aluminum on using the three-dimensional velocity of sound under normal conditions, averaged over the results presented in [16-19], and experimental data regarding the shock compressibility at pressures up to 1 Mbar given in [20].

The error in the determination of a is no greater than ±2.5%; for u it amounts to ±0.075 km/sec. The experiments revealed no difference in the velocities of the elastic waves for the D16 and AD1 alloys within the limits of experimental error.

We see from Fig. 3a that the relationship between the Lagrange velocity of the elastic relief waves and the jump in mass velocity in the shock wave may be closely approximated by the linear expression (straight line 1)

$$a_l = (6.30 + 3.36u)\ \text{km/sec}. \tag{2}$$

Figure 3b shows the "longitudinal" velocity of sound in Euler coordinates as a function of the shock-compression pressure for commercial aluminum AD1, obtained from Eq. (2) using the shock adiabat of aluminum (1) and the conservation laws of the shock wave. The analogous relationship for D16 is displaced by 2.7% to the right along the pressure axis on account of the difference in the initial densities (2.71 g/cm³ for AD1 and 2.785 g/cm³ for D16). The same figure illustrates some published data taken from [21], 1; [4], 2; [5], 3; [11], 4; [6], 5; [10], 6; [7], 7. The values of the longitudinal velocity of sound given in the literature in general lie above the relationship obtained in the present investigation. A possible reason for this discrepancy lies in the fact that the thickness of the striker projected by the explosion at the instant of impact may differ from the initial thickness.

In the present investigation we determined the thickness of the striker at the moment of impact from the measured velocities of the shock and elastic relief waves and the durations of the compression pulses (measured from the instant at which the leading edge of the shock wave reached the sensor to the instant

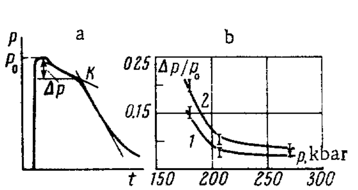

Fig. 5

at which the leading edge of the elastic relief wave arrived). We found that at the moment of collision the thickness of the striker was, as a rule, 5÷10% smaller than the original. The thinning of the striker occurs because of its deformation during acceleration. In those strikers which we were able to find after the experiment, the surface facing the explosive charge was very inhomogeneous and covered in hillocks; this also constituted a reason for the reduction in the effective thickness of the striker at the instant of collision. The point obtained in [7] by means of a light-gas gun corresponds to the relationship derived in the present investigation.

In order to calculate the isentropic elasticity coefficients, it is essential to know not only the longitudinal, but also the three-dimensional, velocity of sound. The latter may be calculated to a fair accuracy on the assumption that the shock adiabat and the uniform-unloading (release) isentrope coincide on being expressed in coordinates of p – u [22]. In this case

$$(dp/du)_S = \rho c = (dp/du)_H = \rho_0 (c_0 + 2bu) \tag{3}$$

Here $(dp/du)_S$ and $(dp/du)_H$ are, respectively, the derivatives along the isentropic and shock adiabat; c_0 and b are the coefficients of the shock adiabat in the linear form $D = c_0 + bu$ (c_0 is the three-dimensional velocity of sound at zero pressure); ρ_0, ρ are the initial density and the density of the compressed material. From Eq. (3) we obtain a linear relationship between the velocity of sound in Lagrange coordinates a and the mass velocity of the material behind the leading edge of the shock wave:

$$a = c_0 + 2bu \tag{4}$$

For aluminum we obtain

$$a = (5.34 + 2.72u)\ \text{km/sec}. \tag{5}$$

We see from Fig. 3a that Eq. (5), represented by the straight line 2, agrees satisfactorily with the experimental point of [1] (indicated by a triangle).

If we know the values of the "three-dimensional" and longitudinal velocities of sound behind the leading edge of the shock wave, by using the equations of elasticity theory we may calculate the isentropic elasticity coefficients of the compressed material:

$$c/c_l = a/a_l = [(1+\nu)/3(1-\nu)]^{1/2} \tag{6}$$
$$K = \rho c^2, \quad E = 3K(1-2\nu), \quad G = E/2(1+\nu)$$

Here ν is the Poisson coefficient, K is the bulk compression modulus, E is Young's modulus, G is the shear modulus, ρ is the density, related to D and u by the equation $\rho = \rho_0 D/(D-u)$. If the Poisson coefficient is constant, as proposed in [4, 8, 23], while a_l and a depend linearly on u, the equation $d(a/a_l)/du = 0$ should be satisfied, from which we see that the second coefficient in the equation $a_l = a_{l0} + du$ equals

$$d = 2ba_{l0}/c_0 \tag{7}$$

In the case of aluminum, for b = 1.36, c_0 = 5.34 km/sec, a_{l0} = 6.3 km/sec this gives d = 3.21, i.e., 4.5% below the experimental value.

Figure 4 represents the isentropic Young's modulus (curve 1), the shear modulus (curve 2), and the Poisson coefficient (curve 3) of commercial aluminum AD1 as functions of the degree of compression ρ/ρ_0 of the material behind the leading edge of the shock wave, calculated by means of Eqs. (1), (2), (5), and (6). For the D16 alloy Young's modulus and the shear modulus are 2.7% higher than for AD1; the Poisson coefficients of AD1 and D16 are equal.

It is interesting to compare the effect of strength on the release process in the AD1 and D16 alloys, (the initial strengths differ considerably). The strength properties of the compressed material cannot be characterized exactly by reference to the pressure profile. For a rough estimate in the present investigation we determined the proportion of the nonhydrodynamic part of the relief wave relative to the total amplitude of the release wave. As the characteristic point distinguishing the nonhydrodynamic part of the wave we took the point K (Fig. 5a). Figure 5b shows the relative proportion of the nonhydrodynamic part of the relief wave as a function of the pressure behind the leading edge of the shock wave for alloys AD1 (curve 1) and D16 (curve 2). We see that alloy D16 (stronger in the original state) remains stronger behind the leading edge of the shock wave, while the proportion of the nonhydrodynamic part of the relief wave falls with increasing pressure behind the leading edge of the shock wave for both alloys.

It is interesting to examine the generality of our conclusion as to the linearity of the relationship between the Lagrange longitudinal velocity of sound and the jump in the mass velocity u in the shock wave. Experimental data for copper taken from [1, 7, 9] may be described to an accuracy of ±1% by the equation $a_l = (4.65 + 3.26u)$ km/sec for $u \leq 2$ km/sec.

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