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# VISCOSITY OF ALUMINUM AND LEAD IN SHOCKWAVE EXPERIMENTS

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Many engineering problems can be modeled within the framework of non-dissipative gasdynamic flows. However, some problems also involve large strains of various types of shells, and accounting for the elastoplastic properties of the materials becomes important if the characteristic pressures are too much greater than the yield point. By making such allowances, it is then possible to more accurately calculate the final strains and evaluate the heating of the shell due to dissipative forces. Also, dissipative losses due to viscous forces become important for high-speed flows characterized by high strain rates [1-6].

Heating due to viscosity is usually characterized by large discontinuities in the dissipation of kinetic energy into heat. The greatest local heating is realized near various physical discontinuities in the material being deformed, i.e., near foreign inclusions and cavities, at grain boundaries and slip planes, etc. Nonuniform heating of the material due to viscosity will obviously lower its strength characteristics and can thereby facilitate deformation along certain planes and directions [6]. Typical examples of the latter are the piercing of a shell by a fragment or the deep penetration of a barrier by microscopic particles. Such penetration has recently been the subject of intensive research [7]. At the same time, these examples also serve to illustrate the present state of fracture mechanics, which has as yet been unable to quantitatively describe such experiments [8-10].

It has long been known that dissipative processes are nontrivial in high-rate viscoplastic flows. For example, the authors of [1, 2] studied the dependence of the viscosity of several materials on compression and temperature behind a shock wave (compression range $\sigma \leq 2$, temperature $T \sim 10^4$ °C). The viscoplastic properties of the materials were also studied in [3, 11, 12] in tests involving the inertial collision of cylindrical shells (compression $\sigma \sim 1$, temperature $T \sim 10^3$ °C). The shells were accelerated and collided in these experiments as a result of energy supplied by an explosive. In this scheme, the parameters of the explosive charge and the shells can be chosen so that all of the initial kinetic energy of the shell is transformed into heat and the shells are left with a certain radius.

It has been established that the main physical processes which occur in the shell material are characterized by nonuniform heating of the shell material through the thickness. The greatest degree of heating is reached on the internal boundary of the shell, and the degree of nonuniformity of the heating increases toward the shell's center [11, 13]. This alters properties such as dynamic yield point and absolute viscosity.

The phenomena mentioned above are likely to be seen to some extent in any high-rate viscoplastic flow. Progress in systematically accounting for dissipative losses during intensive viscoplastic flows in different problems involving high energy densities is being slowed by the lack of adequately developed phenomenological models and corresponding data on material properties. In the present study, we continue to analyze the possibilities of the model of a viscoplastic medium. We focus our attention in particular on the dependence of absolute viscosity on the compression of the substance in the shock wave.

**1.** The physical pattern of high-rate deformation is locally complex [14-16]. The viscosity coefficient is not exactly constant for processes having different deformation laws — even within a narrow range of strain rates. In fact, depending on the scale of the phenomenon being examined, the investigation may either involve the associated flow of a large number of deformable crystals or may be restricted to viscous flow within one or several grains, i.e., it may be restricted to the viscosity of the actual crystalline structure due to the dynamic retardation of moving dislocations.

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TABLE 1

| Metal | $\dot{\varepsilon}$, $sec^{-1}$ | $p$, GPa | $\eta$, kPa·sec | Source |
|---|---|---|---|---|
| Aluminum | $\geq 10^3$ | — | 1,5 | [4] |
| | | 31 | 2±0,5 | |
| | | 68 | 10±4 | [2] |
| | $10^5$—$10^7$ | 105 | 7±2 | |
| | | 202 | $<2$ | |
| | 6,3 | 1,1 | 2,4 | |
| | 3,8 | 1,5 | 4,2 | [19] |
| | 8,3 | 2,0 | 2,3 | |
| | 11,0 | 4,0 | 2,0 | |
| | $10^3$ | 1,0 | 29,6 | [17] |
| | $4,4\cdot10^5$ | — | 0,8 | [20] |
| | $10^5$ | 3,6 | 3,1 | [14, 15, 21] |
| | | 5,5 | 8,5 | |
| | $10^2$—$10^3$ | 1,0 | 0,4 | [22] |
| | $1,2\cdot10^8$ | 35,0 | 0,075 | [16] |
| | $1,1\cdot10^8$ | 40,6 | 0,10 | |
| | $4\cdot10^4$ | 2,1 | 0,40 | [25] |
| | $6\cdot10^5$ | 3,7 | 0,10 | |
| | $7\cdot10^5$ | 8,7 | 0,05 | |
| | $10^7$ | 1,1—2 | 0,03 | [26, 27] |
| Lead | $\geq 10^3$ | — | 3,7 | [4] |
| | | 35 | 3,7±1,4 | |
| | | 41 | 15±2 | |
| | $10^5$—$10^7$ | 124 | $<30$ | [2] |
| | | 250 | $<13$ | |
| | $10^5$ | 0,1—2 | 5,7 | [14, 15] |
| | $10^7$ | 0,6 | 0,04 | [26, 27] |

On the other hand, several different effects may be realized, depending on the intensity of the shock load. Among these effects are an increase in the number of shears in the grains and subdivision of the latter into smaller blocks. An increase in the number of active slip planes in the grains and the activation of new systems that were not involved in the deformation process at lower pressures, an increase in the density of mobile dislocations, and other changes which increase the number of elementary interparticle bonds acting simultaneously also help determine the ratio of the rate of dislocation multiplication to the rate of dislocation pinning, i.e., in the general case the absolute viscosity of the material is dependent on the strain state and the strain rate, $\eta = \eta(\dot{\varepsilon}, p, T)$.

After analyzing known estimates of the absolute viscosity of metals obtained by various methods (uniaxial compression of cylindrical shells [17, 18], introduction of a nondeformable striker with a conical head into a barrier [19], collapse of cylindrical shells by the energy from an explosion [12, 20], collision of plates in the explosive-welding regime [14, 15, 21], study of the decay of an elastic precursor [22] or the rate dependence of resistance to deformation [23, 24], measurement of the width of the front of a shock wave [16, 25], study of the laws governing the propagation of small perturbations [1, 2] and the kinetics of cleavage fracture [26, 27]), we conclude that absolute viscosity may vary by several orders of magnitude for the same given metal, depending on the test conditions.

Table 1 shows experimental data taken from the above-cited sources for aluminum and lead (these being the metals that have been studied the most) within a broad range of compressions. The data confirm the conclusion just made.

Unfortunately, the limitations of existing experimental methods sometimes preclude accurate determination of the explicit dependence of $\eta$ on kinematic parameters such as strain rate $\dot{\varepsilon}$ or thermodynamic parameters such as pressure and temperature. Nonetheless, these parameters are interrelated in shock-wave experiments. Thus, with allowance for conservation laws, the relationship $\dot{\varepsilon} = \frac{u}{\lambda} = \frac{\sigma - 1}{\sigma}\frac{c_0}{\lambda}$ exists for a weak shock wave with a front of the width $\lambda$. In the case of a strong shock wave, with the linear relation $D = c_0 + bu$, strain rate is determined by the expression $\dot{\varepsilon} = \frac{\sigma - 1}{b - \sigma(b - 1)}\frac{c_0}{\lambda}$, where $\sigma = \rho/\rho_0$; $\rho_0$ and $\rho$ are the density of the substance ahead of and behind the shock front; D and u are the velocity of the front and the mass velocity of the substance behind the front at the pressure p.

TABLE 2

| Metal | $p$, GPa | $\sigma$ | $T$, K | $\eta_e$ | $\eta_c$ | $\eta_0$ | $A$ | $B$ | $C$ | $D$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | kPa·sec | | | K | | | |
| | — | 1 | 293 | 1,5 | 1,5 | | | | | |
| | 31 | 1,26 | 630 | 2±0,5 | 2,8 | | | | | |
| Aluminum | 68 | 1,42 | 1600 | 10±4 | 12,6 | 0,91 | 3360 | 3218 | 8,82 | 1,41 |
| | 105 | 1,56 | 3500 | 7±2 | 8,2 | | | | | |
| | 202 | 1,83 | 10 100 | <2 | 3,2 | | | | | |
| | — | 1 | 293 | 3,7 | 3,7 | | | | | |
| | 35 | 1,36 | 1400 | 3,7±1,4 | 4,8 | | | | | |
| Lead | 41 | 1,38 | 1700 | 15±2 | 12,7 | 0,66 | 3799 | 3295 | 34,29 | 1,37 |
| | 124 | 1,65 | 7000 | <30 | 3,0 | | | | | |
| | 250 | 2,06 | 20 000 | <13 | 1,9 | | | | | |

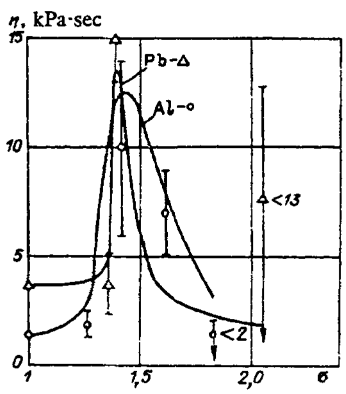

Fig. 1

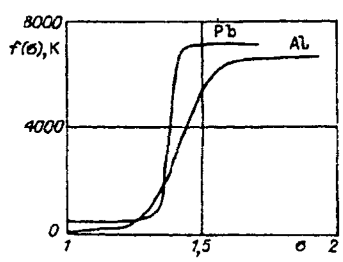

Fig. 2

Since temperature T behind a shock front is also unambiguously determined by the intensity of the wave when the equation of state is known and since it is convenient to work with independent thermodynamic variables when performing calculations for actual systems on the basis of elastoviscoplastic models [3], we used experimental results [2] obtained by a single method with $\dot{\varepsilon} = 10^5$-$10^7$ sec$^{-1}$ to analyze the relation for the viscosity coefficient behind the shock front in the form $\eta = \eta(\sigma, T)$. We used data obtained in [4] with $\dot{\varepsilon} \geq 10^3$ sec$^{-1}$ to extrapolate $\eta = \eta(\sigma, T)$ to the compression $\sigma = 1$. These data are close to the results reported in [14, 15, 21] for aluminum and lead at $\sigma = 1.04$ and $\dot{\varepsilon} = 10^5$ sec$^{-1}$.

2. For high-rate flows, the use of a viscoplastic model requires us to know how the dynamic yield point changes with temperature and compression. This dependence is most naturally represented as a function of the type [3]

$$Y(\sigma, T) = Y_0 \exp\left(E_a(\sigma)/T\right)$$

($Y_0$ is the yield point and $E_a$ is the activation energy).

Although there are several approximations for the viscosity coefficient, we prefer to use the data in [2, 10]. Here, the dependence of the viscosity coefficient on temperature and the degree of compression of a solid behind a shock front has the following form (Frenkel—Eyring formula)

$$\eta(\sigma, T) = \eta_0 \sigma \exp\left(E_a(\sigma)/T\right), \qquad (2.1)$$

Proceeding on the basis of qualitative considerations, the authors of [1] obtained the following for work connected with viscous motion in the formation of vacancies

$$f(\sigma) = E_a(\sigma) = A + B\sigma^m.$$

However, numerical calculations have not yielded physically acceptable values for the constants A and B. For example, activation energy becomes negative for aluminum when $\sigma \leq 1.13$. More detailed analysis of the compressibility of different hard materials and data from shock-wave experiments showed [28] that the dependence of activation energy on compression may be more complicated than was indicated in [1].

It follows from the physical significance of $E_a(\sigma)t$

$$E_a(\sigma) > 0 \quad \text{at} \quad \sigma > 1,$$

that this is a monotonically increasing function.

Inverting Eq. (2.1)

$$f(\sigma) = T(\ln\eta/\sigma - \ln\eta_0), \tag{2.2}$$

calculating f at points of $(\sigma, T, \eta)_i$ for any fixed $\eta_0$ (scale factor), and varying $\eta_i$ within the empirical error, we find that the function $f(\sigma)$ has the form of steps. This allows us to seek its analytic representation in the form

$$f(\sigma) = A + B\,\mathrm{th}\,[C(\sigma - D)]$$

with the restriction $A > B$, $\sigma \in [1, 2]$.

Numerical values of the parameters $\eta_0$, A, B, C, and D are found from the condition of the minimum of the function (least squares method):

$$\Phi(\eta_0, A, B, C, D) = \sum_i (\eta_c(\sigma_i, T_i) - \eta_e(\sigma_i, T_i))^2$$

($\eta_c$ and $\eta_e$ are the calculated and experimental values of the viscosity coefficient, respectively). The following relation can be proposed for the initial values of A, B, C, and D and, thus, the values assigned for their approximate range of variation: $A - B = f(\sigma_1)$ (asymptote of $f(\sigma)$ from the left), $A + B = f(\sigma_5)$ (asymptote of $f(\sigma)$ from the right), $D \simeq \sigma_2$ (value of $\sigma$ corresponding to the middle of the section on which $f(\sigma)$ increases abruptly), $f'(D) = BC$ (the slope of the curve $f = f(\sigma)$ at point D), where $f(\sigma_1)$, $f(\sigma_2)$, $f(\sigma_5)$ are determined by (2.2).

We used Box's method to find $\eta_0$, A, B, C, and D [29]. Table 2 shows values of the parameters obtained from calculations performed to determine the dependence of the viscosity coefficient on temperature and compression. The table also compares calculated and experimental values of the viscosity coefficients of lead and aluminum for the state behind the shock front.

Figures 1 and 2 show the relationship between the effective activation energy and the viscosity coefficient behind the shock front for the metals examined here.

**3.** The satisfactory description of empirical data on the dynamic viscosity of aluminum and lead is nonetheless preliminary, since the data have a relatively substantial error and number of experimental points is small. An analysis of the theoretical data indicates the possibility of fusion of the metals behind the shock front (Fig. 1). Meanwhile, the nontrivial dependence of the viscosity coefficient on the intensity of the shock wave (Fig. 2) can probably be attributed to competition between thermal processes and processes connected with compression of the material.

The results obtained here agree qualitatively with the results reported in [24, 30], where a local increase in viscosity and a subsequent decrease were seen for aluminum at $\dot{\varepsilon}_n > 10^5$ sec$^{-1}$. Qualitatively similar are the dependences of dynamic yield point [31] and technical cohesive strength [32] on the compression of the material behind the shock front. Although the viscosity coefficients of aluminum and lead were found for the state behind the front, the data in [4, 14, 15, 21] suggest that these relations might remain valid for extrapolations outside the shock wave.

It would be useful to conduct further experiments both for methodological reasons and to refine the relation $\eta = \eta(\sigma, T)$ — including for other metals.

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