TEMPERATURE DEPENDENCE OF THE FRACTURE STRENGTH OF GLYCERINE

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Under high-speed loading, liquids lose the flow properties that they have under normal conditions and behave like solids, exhibiting brittleness [1, 2]. The study of fracture of liquids with the help of shock waves with weak intensity makes it possible to determine the magnitude of the critical tensile stresses (σ_p), obtained as a result of interference of loading waves at a free surface (fracture method) [3]. Thus, recently there appeared works in which the quantity σ_p was determined in the acoustic approximation at room temperature: in water [4, 5], ethyl alcohol [4, 5], glycerine [5-8], and mercury [9].

The effect of temperature on σ_p for glycerine was investigated in [10]. Shock waves were excited in glycerine with the help of a pulsed electron beam with energy fluxes varying from 80 to 1500 kJ/m^2. Let us assume that the shape of the loading pulse remains close to triangular as the flux of the irradiation energy changed. The quantities σ_p were computed in the acoustical approximation according to the formula

$$\sigma_p = 0.5\ \rho c(v_0 - v_1), \tag{1}$$

where ρ and c are the density and bulk velocity of sound for glycerine, respectively; v_0 and v_1 are the values of the velocities of the free surface at the instant the shock front reaches the surface and at the time when it attains the first minimum in the velocity, respectively. A laser interferometer was used to record the velocity of the free surface. The values of σ_p as a function of temperature T obtained in [10] according to formula (1) are shown in Fig. 1 (○ points) and are approximated by two curves, which (in the opinion of the authors of [10]) concern different fracture mechanisms. In the temperature range below 262°K, fracture has a brittle character (curve 1), and it is accompanied by the formation and growth of cracks; in the temperature range above 262°K (curve 2), the fracture is viscous, and is accompanied by the formation and growth of bubbles.

This is not the only interpretation of the experimental data. Thus, in examining the transition from brittle fracture to viscous in [10] it is noted that the temperature of vitrification of glycerine, when such a transition would be expected, is significantly less than 262°K and equals, according to [11], 180°K. The data for T < 262°K are approximated quite arbitrarily. The experimental values can be described smoothly by a curve decreasing with increasing T (Fig. 1, curve 3) with a characteristic resonant peak in the temperature range from 240 to 280°K. We note that it is in this particular region that a sharp change (dispersion) in the velocity of sound (Fig. 1, curve 5) and increased absorption are observed [10]. This circumstance indicates the possibility of relaxation phenomena in glycerine, arising with the propagation of weak shock waves just as with the propagation of ultrasound [3]. Not taking into account the anomalously high attenuation in the liquid with reflection of the loading pulse from the free surface could lead to overestimated values of σ_p, computed according to formula (1). We will demonstrate this.

Let us determine the magnitude of the rupture stresses in the same approximation as in [10] but taking into account damping (σ^*_p). In determining σ^*_p, we will take into account the fact that at small distances, which interest us, the loading pulse damps out without changing its shape.†

Thus, if we start with a loading pulse with a front that appears at the free surface (t = 0), then after it transverses a distance x = ct, the values of the mass velocities and pressures decrease by a factor $\exp(-\alpha x)$, where α is the damping coefficient. The quantity σ^*_p

†We are interested in the damping of the front part of the pulse with an extent of ~2δ, which determines the stress developed in the fraction surface. For this reason, the formal decrease in the amount of motion in examining damping of the entire pulse should not disturb us, since it is a result of the acoustic approximation adopted.

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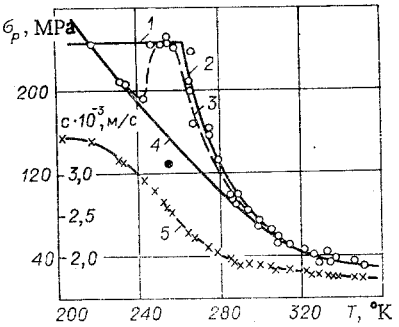

Fig. 1

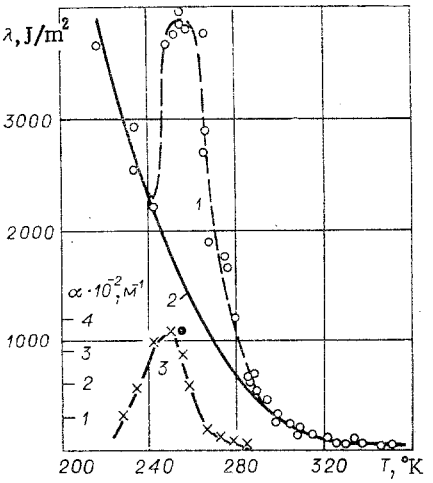

Fig. 2

in the section $x = \delta$ at time $t = \delta/c$ is computed as the difference between the amplitude of the reflected pulse and the value of the stress of the incident pulse:

$$\sigma_p^* = \sigma_0 \exp(-\alpha\delta) - \sigma_0(1 - 2\delta/l)\exp(-\alpha\delta) = 2\sigma_0\delta[\exp(-\alpha\delta)]/l, \quad (2)$$

where σ_0 is the amplitude of the incidence pulse at $t = 0$, which corresponds to a velocity for the free surface of v_0. Let us express the experimentally measured value v_1 in terms of v_0, δ, and α. Since v_1 is the velocity of the free surface at the time $t = 2\delta/c$, taking into account damping, we have

$$v_1 = v_0(1 - 2\delta/l)\exp(-2\alpha\delta). \quad (3)$$

Solving Eqs. (2) and (3) simultaneously taking into account $\sigma_0 = 0.5\,\rho c v_0$, we obtain the relation

$$\sigma_p^* = 0.5\rho c[v_0\exp(-\alpha\delta) - v_1\exp(\alpha\delta)], \quad (4)$$

which, as could be expected, transforms into (1) for $\alpha\delta \ll 1$.

Let us estimate the value of α for glycerine in the region of the resonant peak. For strongly viscous liquids, of which glycerine is an example, the dispersion in the velocity of sound and the anomalously high absorption associated with it are determined by their microscopic nonuniform structure [12]. For these liquids, the damping coefficient, referred to the frequency ν, depends on the product of the frequency and the viscosity η:

$$\alpha/\nu = f(\nu\eta), \quad (5)$$

and in addition, for glycerine, $\ln\eta = a + b/T^3$, where $b = 2.098\cdot10^8$ [10]. Experimental data on the damping of ultrasound in glycerine as a function of T for $\nu = 22.3$ mHz obtained in [13] are presented in [12]. According to Fig. 3 in [10], the duration of the loading pulse in the vicinity of the resonant peak equals ~1 μsec. For such a pulse, the principle harmonic will be $\nu \sim 1$ mHz. Setting $\nu\eta \sim \nu\exp(b/T^3) = \text{const}$ in (5) and using the experimental data in [13], let us transform from the function $\alpha_1(T_1)$ for $\nu_1 = 22.3$ mHz to a similar function $\alpha_2(T_2)$ for $\nu_2 = 1$ mHz:

$$\alpha_2 = \alpha_1\nu_1/\nu_2 \text{ and } T_2 = b^{1/3}[\ln(\nu_1/\nu_2) + b/T^3]^{-1/3}.$$

The function $\alpha(T)$ found in this manner for $\nu = 1$ mHz is shown in Fig. 2 (curve 3), from which it follows that the maximum value of 350 m^{-1} is attained for T = 250°K, while for $T \leq 220$°K and $T \geq 280$°K the value of α decreases by more than a factor of 10. Since $\delta \sim 8\cdot10^{-4}$ m, in the entire temperature range, with the exception of the range 220-270°K, $\alpha\delta \ll 1$ and Eq. (4) can be replaced by Eq. (1). Unfortunately, there are no data in [10] on v_0 and v_1, and only the differences are presented. However, for T = 255°K, where a maximum is observed in σ_p, the values of v_0 and v_1 can be found from Fig. 3 of [10]. They equal, respectively, 210 and 60 m/sec. Substituting the values of these velocities, $\alpha = 350$ m^{-1} and $\delta = 8\cdot10^{-4}$ m in [4] taking into account Eq. (1), we obtain $\sigma^*_p \approx 1.9\cdot\sigma_p \approx 130$ mPa (Fig. 1, ● points). The values $\sigma^*_p \approx 130$ mPa and T = 255°K, together with the experimentally measured values of σ_p for $T \leq 220$°K and $T \geq 270$°K, provide a basis for assuming that the actual function $\sigma_p(T)$ has a smoothly decreasing behavior (Fig. 1, curve 4) while the maximum in σ_p recorded in [10] is a result of

TABLE 1

Liquid	$\frac{dp}{dt}\cdot 10^{-14}$, $N/m^2 \cdot sec$	$\delta \cdot 10^5$, m	$\lambda \cdot 10^{-3}$, J/m^2	$\gamma \cdot 10^3$, J/m^2
Glycerine [10]	1,85	44	0,46	64
Water [4]	1,39	61	0,58	73
Alcohol [4]	1,03	9,2	3,5	22
Mercury [9]	375	7	5,4	472
Plastic [4]	2,32	262	10	

not taking into account the anomalously high damping with interference of load-relief waves in the vicinity of the fracture. Such pseudoresonant peaks in $\sigma_p(T)$ with fracture, especially with a decrease in the duration of the loading pulse, can also be expected in other viscous liquids, such as triacetin, butanediol, hexatriol [12], rosin [14], and others.

In the course of carrying out the experiments at different temperatures [10], the energy flux in the electron beam varied by a factor of ~20, therefore, the σ_p data concern different times for which the material is under the load τ or different durations of the loading pulse l. However, it is known that for solids the magnitude of σ_p depends on τ [15-17]. Apparently, a similar dependence can also be expected for liquids. This can explain the differences in the values of σ_p obtained for glycerine at room temperature by different authors: 6.3 mPa [6], 25 mPa [7], 48 mPa [5], 60 mPa [8], and 85 mPa [10]. In order to obtain more complete characteristics of the failure of the material, other than σ_p, it is convenient to use the energy approach [18-20] and change over to a description of the strength of the material in terms of the specific work λ expended on rupturing the material with fracture, where $\lambda \sim \sigma_p^2 l =$ const. In the case of loading by a triangularly shaped pulse, in the acoustic approximation, the fracture criterion has the form [21]

$$\lambda = \sigma_p^2 \delta / 6\rho c^2 \tag{6}$$

or [19]

$$\lambda = 2\delta^3 \sigma_0^2 / 3\rho c^2 l^2. \tag{7}$$

Using the experimental data for $\rho(T)$, $c(T)$, and $\sigma_p(T)$ [10], taking into account the corrections to σ_p (Fig. 1, curve 4) and assuming that the quantity δ decreases linearly with temperature between its extreme values from $13.6 \cdot 10^{-4}$ to $1.8 \cdot 10^{-4}$ m, we obtain from formula (6) $\lambda(T)$ for glycerine (Fig. 2, curve 1 neglects damping, while curve 2 takes into account damping). As follows from Fig. 2 (curve 2), as the temperature increases, the quantity λ smoothly decreases; solid bodies, copper and steel [21], the aluminum alloy AMG-6 [22], behave similarly.

The available data on fracture [4, 9] permit determining λ according to Eq. (7) for many other liquids at room temperature and for given load conditions (see Table 1, where dP/dt is the rate of change of pressure of the incident load pulse, γ is the coefficient of surface tension). In comparison with metals, the values of λ for liquids are 1-2 orders of magnitude lower. Thus, for copper $\lambda = 3 \cdot 10^4$ J/m^2, while for soft steel $\lambda = 9 \cdot 10^4$ J/m^2 [19-21].

In conclusion, we note that the values of λ obtained for liquids due to the simplifying assumptions made must be viewed as approximate, requiring further refinement.

LITERATURE CITED

1. M. Kornfel'd, Elasticity and Strength of Liquids [in Russian], Gostekhizdat, Moscow (1951).
2. J. Frenkel', Kinetic Theory of Liquids, Peter Smith.
3. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, Academic Press.
4. A. N. Dremin, G. I. Kanel', and S. A. Koldunov, "Investigation of fracture in water, ethyl alcohol, and Plexiglas," in: Combustion and Explosion [in Russian], Nauka, Moscow (1972).
5. A. P. Rybakov, "Investigation of fracture phenomena in condensed bodies," in: Critical Phenomena. Physicochemical Transformations [in Russian], Izd. Akad. Nauk SSSR, Chernogolovka (1978).
6. T. H. Bull, "The tensile strengths of liquids under dynamic loading," Phil. Mag., 1, Ser. 9, No. 2 (1956).

7. D. C. Erlich, D. C. Woolen, and R. C. Crewdson, "Dynamic tensile [sic] of glycerol," J. Appl. Phys., 42, No. 13 (1971).
8. G. A. Carlson and K. W. Henry, "Technique for studying dynamic tensile failure in liquids: application to glycerol," J. Appl. Phys., 44, No. 5 (1973).
9. G. A. Carlson, "Dynamic tensile strength of mercury," J. Appl. Phys., 46, No. 9 (1975).
10. G. A. Carlson and H. S. Levine, "Dynamic tensile strength of a glycerol," J. Appl. Phys., 46, No. 4 (1975).
11. W. Kauzman, "The nature of the glassy state and the behavior of liquids at low temperatures," Chem. Rev., 43, No. 2 (1948).
12. M. A. Isakovich and I. A. Chaban, "Wave propagation in highly viscous liquids," Zh. Eksp. Teor. Fiz., 50, No. 5 (1966).
13. R. Piccerelly and T. A. Littovitz, "Ultrasonic shear and compressional relaxation in liquid glycerol," J. Acoust. Soc. Am., 29, No. 9 (1957).
14. B. A. Belinskii and L. M. Lazarenko, "Absorption and dispersion of ultrasound in a mixture of abietic acid," Akust. Zh., 21, No. 3 (1975).
15. G. Nahmaini, "Experimental investigation of scabbing produced in mild steel plates by plane stress waves," in: Les Ondes de Detonation, Paris (1961).
16. Yu. I. Tarasov, "Investigation of the dependence of the failure time on the tensile load for steel and copper," Dokl. Akad. Nauk SSSR, 165, No. 2 (1965).
17. L. V. Al'tshuler, S. A. Novikov, and I. I. Divnov, "Relation of critical failure stresses to failure time with explosive loading of metals," Dokl. Akad. Nauk SSSR, 166, No. 1 (1966).
18. A. G. Ivanov and V. N. Mineev, "Scale criteria for brittle failure of structures," Dokl. Akad. Nauk SSSR, 220, No. 3 (1975).
19. A. G. Ivanov, "Fracture in the quasiacoustic approximation," Fiz. Goreniya Vzryva, No. 5 (1979).
20. A. G. Ivanov and V. N. Mineev, "Scale effects in failure," Fiz. Goreniya Vzryva, No. 5 (1979).
21. M. A. Ivanov, "Temperature dependence of the specific work of failure in copper and steel," Fiz. Goreniya Vzryva, No. 4 (1979).
22. Yu. V. Bat'kov, S. A. Novikov, et al., "Effect of the temperature of a sample on the magnitude of the failure stresses with fracture in AMG-6 aluminum alloy," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1979).

EFFECT OF A CAMOUFLET EXPLOSION ON FILTRATION CHARACTERISTICS OF A BRITTLE MEDIUM

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At the present time, explosions are finding increasing use in the national economy. In particular, they are widely used for increasing the production of oil and gas wells. Here, there is great interest in the filtration properties of the medium surrounding the explosion. It should be noted that the theoretical study of filtration properties of media is especially important, since their experimental study is very difficult.

However, at the present time, there are practically no works in which the filtration characteristics of media after an explosion are computed on the basis of the physical picture of the action of a camouflet explosion on the surrounding rock. Thus, e.g., in [1] an attempt is made to describe phenomenologically using a single function, the coefficient of permeability of the medium after a camouflet explosion both in the pulverization zone and in the zone of radial fracturing. But the results of this work do not agree satisfactorily with the experiments [2], since in the investigation concrete mechanisms for dynamic action of the explosion on the medium were not taken into account.

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