$$X_0 = \rho_2^0 r \left\{\left[\frac{F_2(\gamma)}{T_2(\gamma)} - \frac{F_1}{T_1}\right] + \left[\frac{F_2(r)}{T_2(r)} - \frac{F_2(\gamma)}{T_2(\gamma)}\right] + \rho_2^0 r U_2(\gamma)\left[\frac{1}{T_3(\mu)} - \frac{1}{T_2(r)}\right] + \rho_2^0 r \left\{\frac{\left[\mathbf{v}_2'(r,\gamma,\mu,\xi) - \mathbf{v}_1\right]^2}{2T_2(r)} - \right.\right.$$
$$- \frac{\left[\mathbf{v}_2'(r,\gamma,\mu,\xi) - \mathbf{v}_2(r)\right]^2}{2T_2(r)} + \frac{J_2(r)\left[\boldsymbol{\omega}_2'(r,\gamma,\mu,\xi) - \boldsymbol{\omega}_1\right]^2}{2T_2(r)} -$$
$$\left. - \frac{J_2(r)\left[\boldsymbol{\omega}_2'(r,\gamma,\mu,\xi) - \boldsymbol{\omega}_2(r)\right]^2}{2T_2(r)}\right\} + \left\{\frac{\rho_2^0 r \varkappa \varepsilon_0}{2\rho_2 T_2(r)}\left[\mathbf{E}_1^2 + \mathbf{E}_2^2(r) + \mathbf{E}_3^2(\mu)\right] + \right.$$
$$\left.\left. + \frac{\rho_2 \varkappa \mu_0}{2\rho_2 T_2(r)}\left[\mathbf{H}_1^2 + \mathbf{H}_2^2(r) + \mathbf{H}_3^2(\mu)\right] + \frac{\rho_2^0 r}{T_2(r)}\left[\mu_0 \mathbf{m}_2(r)\mathbf{H}_2^*(r) + \mathbf{p}_2(r)\mathbf{E}_2^*(r)\right]\right\}\right\}. \quad (6.3)$$

The experimental studies [6, 7] demonstrated the dependence of the refinement process in an EMF on the strength of the disperse-phase particles, the energy of the fragmenting bodies, and the energy of the electromagnetic field. This finding is consistent with the structure of the equations (6.2), (6.3) obtained here for the driving forces.

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TEMPERATURE DEPENDENCE OF THE DYNAMIC STIFFNESS OF MATERIALS

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Several investigations have examined the effect of temperature on the cleavage strength of structural materials. In connection with certain technical problems encountered in realizing intensive shock loading and performing the necessary measurements, in conditions of high temperature, the authors of [1] did not consider the effect of the temperature of preheating on the form of the equation of state, while it was argued in [2] that the reduction in pressures and tensile stresses due to changes in the properties of materials at high temperatures is negligible.

Here, we derive a formula to evaluate dynamic stiffness for a material from its known coefficient of thermal expansion and we propose an empirical method of obtaining this formula for any material by studying the cleavage fracture which takes place in the collision of cold and hot specimens in a gas gun. We also compare calculations and experimental results for aluminum alloy AMg6.

In experimentally studying the temperature dependence of the cleavage strength of materials by the method of high-speed collision of a striker with a hot target made of the test material, it is necessary to determine the following slightly increasing function of temperature

$$f(T) = \frac{Z_0}{Z_T} = \frac{(1 + 3\alpha T) C_0}{(1 + 3\alpha T_0) C_T} \simeq (1 + 3\alpha \Delta T) \frac{C_0}{C_T} \simeq \frac{C_0}{C_T}, \quad (1)$$

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where we have introduced notation for dynamic stiffness (impedance) $Z = \rho C$, the temperature difference $\Delta T = T - T_0$, the coefficient of linear expansion α, and the velocity of the longitudinal plane elastic wave in the material $C = [E(1-\nu)/\rho(1+\nu)(1-2\nu)]^{1/2}$. The quantities ρ, E, and ν are the density, elastic modulus, and Poisson's ratio. The zero subscript denotes values at a temperature of 20°C.

It is known that the elastic modulus decreases with heating. Thus, it is $0.86E_0$ for aluminum alloy AK-4 at 200°C [3] and $0.82E_0$ at 250°C. Experimental estimates we obtained for the velocity of ultrasonic waves showed that velocity decreased by about 13% at 200°C and by about 16% at 250°C. Due to the limited thermal resistance of the piezoelectric transducers, standard flaw detectors cannot be used to obtain direct ultrasonic measurements at high temperatures.

It was noted in [4] that many metals are characterized by a constant value of the ratio of the coefficient of thermal expansion to the relative temperature coefficient of the elastic modulus $\alpha \Big/ \frac{d \ln E}{dT} \approx -0.04$. It follows from this that we can obtain a law which is close to exponential for the reduction in elastic modulus with heating

$$E(T)/E_0 \simeq \exp\left[-25 \int_{T_0}^{T} \alpha(T)\, dT\right]. \tag{2}$$

Using the value $\alpha \approx 22 \cdot 10^{-6}$ K^{-1} for alloy AK-4 [3], at T = 200°C we can use (2) to find $E(T)/E_0 = 0.89$. This value agrees quite well with the data from [3] cited above. Assuming that the Poisson's ratio is athermal in the elastic region, we will express the temperature dependence of dynamic stiffness (1) as an exponential law for the increase in the function

$$f(T) \simeq \exp\left[12.5 \int_{T_0}^{T} \alpha(T)\, dT\right] \approx \exp(2.9 \cdot 10^{-4} \Delta T), \tag{3}$$

where the last equality corresponds to aluminum alloys at the above-indicated value of α. When Eq. (3) is used, it is necessary to consider the difference in α for different alloys and the possible changes in α with heating.

The main goal of our investigation was to develop an empirical method involving cleavage fracture to obtain data on the relation f(T). The collision of cold thick specimen and a striker at the velocity V_0 cleaves a section of the thickness $\delta_0 = h_1$ from the specimen under the influence of the tensile stress $\sigma_0 = (1/2)Z_0V_0$ over the period of time $\tau_0 = 2h_1/C_0$ (h_1 is the thickness of the striker). The impact of a cold target of the thickness H_2 at the velocity V_2 against a hot thin striker cleaves a section of the target of the thickness $\delta_2 = h_1 f(T)$ from the action of the stress $\sigma_2 = Z_0V_2/[1 + f(T)]$ over the period of time $\tau_2 = 2h_1 f(T)/C_0$. With an arbitrary time dependence of cleavage strength at room temperature $\psi(\tau) = \sigma(\tau)/\sigma(1)$, where $\sigma(1)$ is the cleavage strength with a period of tension τ = 1 µsec, we obtain the basic functional relations $\Phi(f) = \varphi(T)$, $\Phi(f) = (1+f)\psi(f\tau)/\psi(\tau_0) - 1$, $\varphi(T) = 2V_2(T)/V_0 - 1$ to determine the temperature dependence f(T) from empirically established critical rates of cleavage in a cold target with a cold ($V = V_0$) and a hot ($V = V_2$) striker. In the special case of a time dependence in the form of Zhurkov's relation $\psi(\tau) = 1 - A \log\tau = 1 - 0.0315 \times \log\tau$, for aluminum alloys we have $\Phi(f) = f - A/(1 - \log\tau_0)\cdot(1 + f)\log f \approx f - 0.0315(1+f) \times \log f \approx f$, i.e., we obtain the simple formula $f(T) = V_2(T)/V_0 - 1$ to find the temperature dependence of the dynamic stiffness of the material (at $A \ll 1$) from measured critical velocities $V_2 \geqslant V_0$ of cleavage in a cold target in a collision with a hot striker at different temperatures.

Additional information is obtained from experiments involving the collision of stepped specimens (Fig. 1), when cleavage in thick half-disks is possible not only for the cold projectile, but also for the hot stationary striker of the thickness $\delta_1 = h_2/f(T)$. This cleavage is the result of action of the stress $\sigma = Z_0V_1/[1 + f(T)]$ over the period of time $\tau = 2h_2/C_0$. Thus, the cleavage δ_2 which occurs in the cold projectile is greater – and the cleavage taking place in the hot stationary striker δ_1 is less – than in the collision of cold specimens. This qualitative effect has been observed in experiments with stepped specimens of aluminum alloy AMg6. However, due to the insufficient distinctness of the boundary of the cleavage crack, we found it difficult to qualitatively determine the weak dependence f(T) from the relations $f(T) = \delta_2(T)/h_1 = h_2/\delta_1(T)$ in the case being considered.

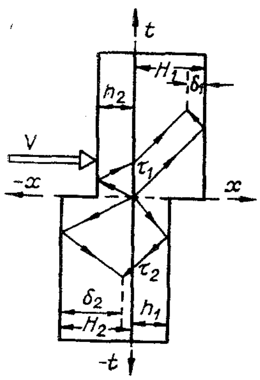

Fig. 1

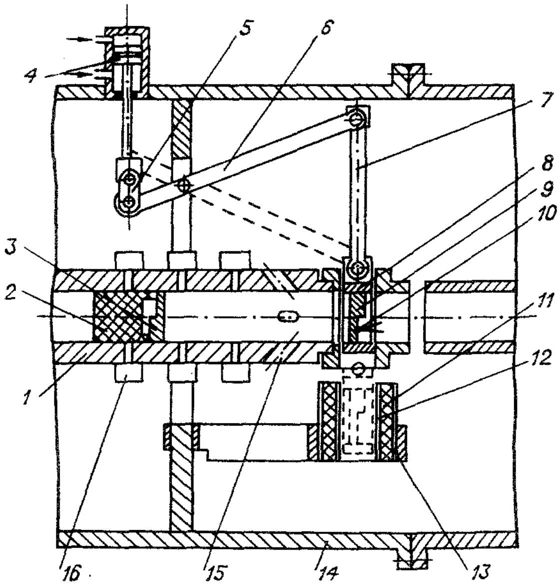

Fig. 2

Experiments were conducted using a gas gun similar to that described in [5]. Figure 2 presents a diagram of the set-up of the tests. The specimens were plane or stepped disks with a diameter of 48 mm and a thickness $2h_{1,2} = H_{1,2} = 8$ mm.

The specimen 3, secured to an accelerating piston made of foam plastic 2, was accelerated in the barrel of gas gun 1 with a bore of 50 mm. The specimen 9, placed in a holder 8, was heated with the plunger of the pneumatic drive 4 in its upper position. The specimen was heated by radiation from two Nichrome coils 12 with a combined power of 1.2 kV·A (10 A, 60 V). The coils were mounted on heat-resistant insulators 11 in a housing 13. Heating and collision took place in a vacuum chamber 14. Gas was removed from the chamber through the hole 15. Specimen temperature was monitored by means of a thermocouple 10 up to the moment of collision of the specimens. The time taken to heat the specimen to 400°C was about 30 min. The nonuniformity of temperature over the specimen thickness at the moment of loading was no greater than 1 K. After the required specimen temperature was reached, the high-pressure chamber was filled with gas until attainment of the pressure needed to ensure the prescribed velocity of the piston 2. The piston was lowered by feeding gas into the cavity above the plunger 4 through an electropneumatic valve. Acting through a system consisting of a connecting rod 5, rocker arm 6, and tie rod 7, the descending piston raised the holder from the heater until the axis of the specimen 9 was aligned with the axis of the gun barrel. When this occurred, a limit switch was activated which sent a signal for the gun to be discharged. We measured collision velocity on three bases in each test. The velocity was measured with the transducers 16 in a special photoelectric system. The error of velocity measurement was no greater than 2%. After the collision, the specimens were recovered on the foam-plastic piston in a braking barrel (not shown in the figure). After being extracted from this barrel, the specimens were cut along their diameters. Metallographic sections were prepared and an MI-1 tool microscope was used to determine whether or not a cleavage crack was present.

Figure 3 shows experimental data in the coordinates T, $f(T) = 2V/V_0 - 1$ with allowance for the value $V_0 = 173$ m/sec. The data was obtained in a series of tests involving the collision of specimens at room temperature. Curve II shows the relation (3), while empirical curve I is drawn between the experimental points 1 (in the presence of cleavage) and 2 (in the absence of cleavage), with qualitative allowance for the degree of development of the cleavage crack in the cold target. Point 3 corresponds to the limit of observation of the cleavage crack. It is evident that theoretical relation (3) for dynamic stiffness agrees satisfactorily with the experimental data, since calculations with (3) for the maximum temperature of 500°C give values of f(T) which are about 4% lower than the experimental values.

With allowance for the above-derived relation f(T), in Fig. 4 we show the temperature dependences of the critical cleavage velocities in cold V_2 and hot V_1 stepped specimens ($V_1 \leqslant V_0 \leqslant V_2$). The comparison with experimental data presented in the figure (the values of the experimental points 1 and 2 being the same as those in Fig. 3 and points 3 corresponding

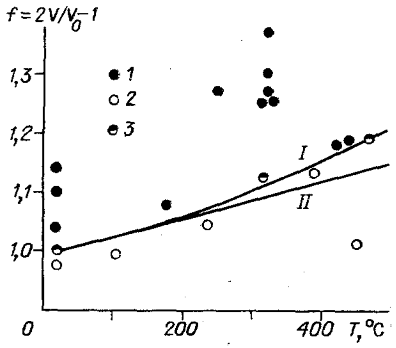

Fig. 3

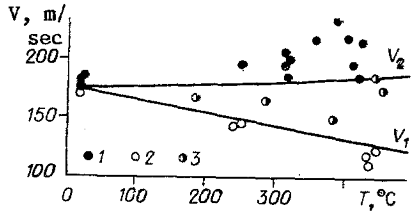

Fig. 4

to cleavage only in the hot specimen) shows that theoretical formulas can be used to calculate critical velocities

$$\frac{V_1}{V_0} = \frac{1+f(T)}{2}\left\{1 - \frac{A}{1 - A\lg\tau_0}\left[(7+\lg\tau_0)\frac{\Delta T}{T} + \frac{T}{T_0}\lg\frac{h_2}{h_1}\right]\right\} \approx \frac{1+f(T)}{2}\left(1 - 0.22\frac{\Delta T}{293}\right),$$

$$\frac{V_2}{V_0} = \frac{1+f(T)}{2}\left[1 - \frac{A}{1 - A\lg\tau_0}\lg f(T)\right] \approx \frac{1+f(T)}{2},$$

which were used to construct the curves of V_1 and V_2 in Fig. 4.

Thus, to evaluate the temperature dependence of the dynamic stiffness of metal, we can take Eq. (3) as a first approximation. As shown in the example for alloy AMg6, the formula is satisfactorily accurate. Additional information on the relation in question is given by the proposed experimental method, which can be used both with metals and with arbitrary materials.

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