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KINETICS OF SPALLATION RUPTURE IN THE ALUMINUM ALLOY AMg6M

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It is well known that the magnitude of rupture stresses depends on the duration of the loads, but the quantitative expression for this dependence remains unclear. Under conditions of spallation, in the presence of very short actions, magnitudes of tensile stresses in metals approaching the values of the theoretical tensile strength are achieved, as reported, for example, in [1]. However, the method used in [1] to study spallation phenomena, based on an analysis of samples remaining after the tests, could significantly overestimate the values of the rupture stresses attained [2]. In this respect, the most reliable and informative method is the method of determining the spallation strength from continuous records of the velocity profiles of the free rear surface of the samples w(t). In this work, we measured the profiles w(t) and determined the magnitude of the spallation strength of the aluminum alloy AMg6M in a wide range of characteristic durations of incident loading pulses. Based on the data obtained, the previously proposed [3] continuous model of rupture is modified and the calculations using the proposed kinetics of rupture are compared with the experimental data.

The samples studied were prepared from sheets 1.8-10 mm thick. The transverse dimensions of the samples were equal to 80-120 mm. The one-dimensional compression pulses in the samples were generated by striking an aluminum foil 0.19-0.40 mm thick with a velocity of 675 ± 15 m/sec or by detonating an explosive (explosion lens) in contact with the sample. The foil was hurled with the help of explosion setups similar to those described in [2]. The velocity profiles of the free back surfaces of the samples were recorded continuously with the use of capacitative sensors [4]. Depending on the required resolution and recording time, the diameter of the measuring electrode was 5-20 mm, and the distance between the electrodes and the surface of the sample was 1-6 mm, respectively.

The recorded changes in the velocity of the sample surface w with time t are shown by the solid lines in Fig. 1, where each curve was obtained by averaging data from two to five experiments. The loading conditions are indicated in Table 1. The use of capacitive sensors with a diameter of 5 mm ensures that the rise time of the velocity of the surface at the front of the shock wave is resolved at a level of 10-15 nsec. For shock waves whose amplitude is lower than 3 GPa, the recorded rise time is much greater than this limit, which agrees with the results of measurements performed with the use of laser interferometry [5].

The emergence of an elastic precursor with an amplitude of 0.37 GPa, which corresponds to a dynamic yield stress of σ_T = 0.18 GPa, at the surface is clearly evident in the profiles w(t). The emergence of a plastic shock wave and the head part of the incident rarefaction

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TABLE 1

No. of curve in Fig. 1	Conditions of loading	Sample thickness, m	V_{co} m/sec	Δw, m/sec	Δh, mm	$-\dot{w}_1$, 10^6 m/sec^2	σ*, GPa	10^5 ΔE, J/m^2
1	Explosion lens	10,0	685±15	75±15	4,7	66±5	0,57±0,1	—
2	Striker, δ = 0,40 mm	9,6	283±6	113±5	0,61	950±50	0,83±0,08	0,18
3	Striker, δ = 0,19 mm	4,4	285±5	160±5	0,34	2100±100	1,15±0,05	0,15
4	»	1,8	495±15	160±15	0,18	5500±1000	1,2±0,12	0,19

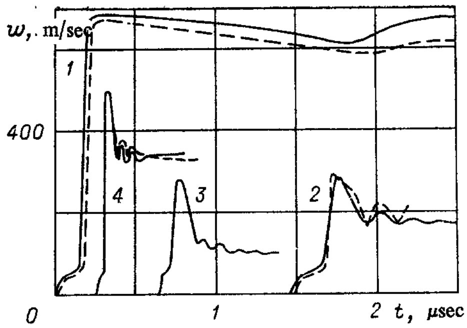

Fig. 1

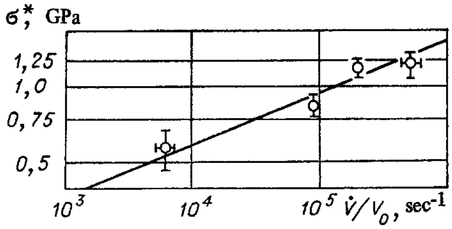

Fig. 2

wave on the surface is fixed immediately following the elastic precursor. The reflection of the compression pulse from the free surface is accompanied by the appearance of tensile stresses in the sample, which lead to its fracture. As a result of the drop in the tensile stresses accompanying fracture, a compression wave appears (spallation pulse). The damped oscillations of the velocity of the surface are associated with repeated reflections of the spallation pulse from the sample surface and the rupture zone. It is evident from the profiles presented that appreciable retardation of the spalled plate continues for approximately 0.2 μsec against the background of oscillations of the velocity of the surface. This is evidently the characteristic time required for the completion of the process of rupture of the sample under these conditions.

The tensile stresses in the spallation surface σ* were determined from the profiles w(t) from the difference Δw of the velocity at the first maximum and the first minimum [6, 7]:

$$\sigma^* = (1/2)\rho_0 c_0 (\Delta w + \delta w),$$

where ρ_0 = 2.61 g/cm^3 is the density of the material; c_0 is the volume velocity of sound, taken as the average value of 5.3 km/sec for aluminum alloys; δw is a correction which takes into account the fact that the front of the spallation pulse, propagating along the stretched material with the velocity of the longitudinal elastic wave c_l = 6.4 km/sec, overtakes the unloading part of the starting compression pulse, which has a velocity of c_0. Taking into account the gradients of the velocity in the incident pulse $\dot{w}_1$ and at the front of the spallation pulse $\dot{w}_2$, the quantity δw is estimated, as is easily shown, by the expression

$$\delta w = \left(\frac{h}{c_0} - \frac{h}{c_l}\right)\frac{|\dot{w}_1 \dot{w}_2|}{|\dot{w}_1| + \dot{w}_2},$$

where h is the thickness of the spalled plate, determined from the period of reverberation of the spallation pulse in it: $h = (1/2)c_l \Delta t$. The values found for the spallation strength of the alloy are presented in Table 1. The table also gives the values of the rupture work, estimated from the magnitude of the loss of kinetic energy of the spalled plate ΔE in the process of its separation from the sample [8]. The error in the determination of the rupture work is equal to ~20%; within these limits, the value of ΔE is practically the same for all three conditions of loading.

The appearance of a minimum on the profile $w(t)$ can be interpreted as an indication that the rate of growth of the crack or pore volume $\dot{V}_c$ reaches the rate of deformation in the unloading part of the incident pulse $\dot{V} \approx -(1/2)\dot{w}_1/\rho_0 c_0$; for this ratio of velocities, part of the incident pulse is screened [9]. Judging from the relation of the times of the first and subsequent oscillations of the velocity of the surface, the rupture is not appreciably delayed, and the values obtained for the rupture stresses practically correspond to the onset of rupture.

The measurements of the spallation strength are presented in Fig. 2 in the form of the dependence of the rupture stresses σ^* on the rate of deformation in logarithmic coordinates. Within the limits of error of the measurements, the experimental data are described by the relation

$$\sigma^* = 0.093(\dot{V}/V_0)^{0.2}, \tag{1}$$

whence the dependence of the initial rate of rupture on the stress can be represented in the form

$$\dot{V}_c = 1.45 \cdot 10^5 \sigma^5 V_0, \tag{2}$$

where σ is measured in GPa; $\dot{V}_c$ is measured in $cm^3 \cdot g^{-1} \cdot sec^{-1}$; and, V_0 is the specific volume of the continuous material in the absence of pressure.

Spallation phenomena in AMg6 aluminum were studied previously [10, 11] by observing the samples remaining after the tests and by determining the threshold collision velocities, for which the first indicators of rupture or complete spallation appear. In this case, in [10], the formation of rupture was observed under stresses of 1.3-1.55 GPa (threshold collision velocities of plates 1-3 and 2-5 mm thick equal to 180-230 m/sec); total cleavage was observed under stresses of 1.5-1.8 GPa (the threshold collision velocities were 210-265 m/sec). At the same time, in [11], the onset of spallation was observed under normal initial conditions only at a stress of 3 GPa, though a loading pulse with the longest duration was used in this work. Both sets of data greatly exceed the values of the spallation strength obtained from the velocity profiles of the sample surfaces. This disagreement is apparently primarily attributable to the absence of objective criteria for establishing rupture thresholds. We can also point out the effect of the conditions of conservation and the edge effects, which are usually ignored, on the determination of the threshold collision velocities.

The reliability of the method used to determine the fracture stresses by recording the motion of the surface of the sample is convincingly confirmed by observations of the appearance of the spallation pulse in experiments in which the amplitude of the starting load was increased from low values to values exceeding the spallation strength of the sample [12, 13]. When the rate of rupture depends strongly on the stress, as in (2), it is hardly possible to talk about the possibility of significant overstresses, so that the values of the spallation strength obtained in [10, 11] must be recognized as being too high. Nevertheless, the disagreement between the results of different methods of studying spallation phenomena indicates that the physical mechanism of generation and development of ruptures under the given conditions requires further study.

The relation (1) can be used to estimate the possibility of initiation of rupture and the thickness of the spalled plate for nearly triangular profiles of the loading pulses. For calculations of ruptures in cases of arbitrarily varying load, the continuous-kinetic approach [14], which describes rupture as a continuous process of accumulation of damage in the material, is the most promising approach. A simple kinetic relation describing the rate of growth of the specific volume of cracks or pores $\dot{V}_c$ as a function of the effective stress σ and the degree of rupture V_c attained is proposed in [3]:

$$\dot{V}_c = K_1\left(|\sigma| - \sigma_0 \frac{a}{V_c + a}\right)(V_c + V_{c0})\,\mathrm{sign}(\sigma) \quad \text{for} \quad |\sigma| > \sigma_0 \frac{a}{V_c + a}, \tag{3}$$

where σ_0 is the initial rupture threshold; V_{c0} is the specific volume of potential fracture foci; K_1 is a constant which is inversely proportional to the viscosity of the material; and, a is a constant which determines the drop in the threshold stress as the rupture increases and has a value of the order of $0.01V_0$. In the numerical modeling of the experiments, the relation (3) agrees well with the measurements when the characteristic duration of the starting loading pulse changes approximately by an order of magnitude. The experiments presented in this work encompass two orders of magnitude in the rate of deformation, and the accuracy of relation (3) in describing the data obtained turns out to be inadequate. This should be expected, because it is clear that, in reality, a spectrum of foci of ruptures, initiated at different levels of stress, exists in the material. In this connection, the constant V_{c0} in relation (3) is replaced by the expression

$$V_{c0} = K_2\sigma^n. \quad (4)$$

Since with the substitution of (4) into (3) the initial rate of rupture is equal to

$$\dot{V}_c = K_1 K_2 \sigma^{n+1},$$

the relation (2) can be used to determine the constant n and the product K_1K_2. The choice of values of the coefficients K_1 and K_2 remains quite arbitrary, but experience in performing calculations of spallation ruptures using (3) with V_{c_0} = const shows that good agreement with experimental data is achieved with a value of $K_1 \sim 10^{-1}$ m·sec/kg. The value of the rupture strength σ_0 falls between the true rupture stress under static conditions and the spallation strength; in this work, it was estimated by linearly extrapolating the experimental results on the spallation strength to a zero rate of deformation.

The dashed lines in Fig. 1 show the profiles w(t) obtained by numerical modeling of the experiments performed using the kinetics of rupture in the form (3) and (4). The calculation was performed by a ripple-through finite-difference method using the "cross" scheme with separation according to physical processes. In view of the fact that the amplitudes of the loads being modeled are relatively low, the shock adiabat of aluminum was used as the equation of state. The total specific volume of the material V was represented by the sum $V = V^{(p)}_{con} + V_c$ and the pressure in the continuous component V_{con} was assumed to be equal to the average over the cross section. In the case of loading by an explosion lens, a triangular velocity profile of the left boundary was used in the calculation, and in the remaining variants the collision of plates was calculated. The resistance to deformation was described by a model of an elasto-viscoplastic body with a nonlinear viscosity η, defined by the expression

$$\eta = \eta_0 \exp[-(|\tau| - \tau_y)/\tau_0(1 + \alpha\varepsilon)],$$

where τ is the maximum shear stress; τ_y is the shear stress at the static yield limit; $\varepsilon = \int_{V_0}^{V} \frac{dV}{V}$ is the deformation; α is the hardening constant; and τ_0, η_0 are constants of the material. For stresses $|\tau| < \tau_y$, the material behaves elastically. The pressure dependence of the elastic moduli was constructed under the assumption that Poisson's coefficient is constant [15]. It was assumed that the yield stress, the shear modulus, and the coefficient of viscosity decrease proportionally to the rupture strength as the rupture increases, i.e.,

$$\tau_y^{\text{eff}} = \tau_y a/(a + V_c), \quad \eta^{\text{eff}} = \eta a/(a + V_c), \quad G^{\text{eff}} = G(p)\, a/(a + V_c).$$

The data presented in Fig. 1 were obtained by calculations with the following material constants: $K_1 = 10^8$ GPa^{-1}·sec^{-1}, $K_2 = 1.5 \cdot 10^{-3}$ GPa$^{-4}/\rho_0$, $\sigma_0 = 0.5$ GPa, $a = 10^{-2}/\rho_0$, $\eta_0 = 10^5$ kg·m^{-1}·sec^{-1}, $\tau_y = 0.065$ GPa, $\tau_0 = 5$ MPa, $\alpha = 10$. A comparison of the experimental and computed data shows that the proposed phenomenological model of rupture gives a satisfactory description of the observed spallation phenomena in a wide range of rates of deformation.

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VORTEX FORMATION ACCOMPANYING THE ACTION OF A LASER PULSE ON POLYMERS

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The action of laser radiation on different materials is commonly studied from the point of view of the gas-dynamics of the ejection of products of evaporation or decomposition for short pulses with high energy density [1-4]. These questions have been studied to a lesser extent for radiation densities currently used to study the mechanism of ignition of solid fuels [5-6].

In this work, we study the hydrodynamics of outflow of the products of decomposition of polymers under the action of laser radiation with energy fluxes $q < 10$ kW/cm^2. The targets consisted of samples of polymethylmethacrylate (PMMA) and ebonite with dimensions slightly exceeding the characteristic size of the irradiation spot.

The experiments were performed in air at $T = 293$°K and $p = 10^5$ Pa in a closed chamber with a volume of $0.1 \times 0.1 \times 0.3$ m^3, equipped with windows for observations and for injecting the laser radiation. The beam from a continuous laser with a wavelength of $\lambda = 10.6$ μm (or $\lambda = 1.06$ μm) was focused from above onto the surface of the material being studied with a spherical mirror; when the mirror was displaced, the diameter of the irradiation spot varied in the range 1-4 mm. The duration of the irradiation pulse was fixed by a mechanical shutter to within 0.2 msec and the density of the incident flux was adjusted in the range 20-10^4 W/cm^2 by changing either the output power of the laser or the diameter of the irradiation spot.

The flow of the products of decomposition was visualized by the laser-knife method [7] in the stroboscopic regime. For this, the beam from a helium–neon laser was transformed by a system of cylindrical lenses into a plane-parallel beam and was interrupted by an obturator

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