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EXPERIMENTAL ESTIMATION OF THE ULTIMATE STRAINS OF DYNAMICAL RUPTURE OF CYLINDRICAL SHELLS

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The question of the ultimate strains of cylindrical shells expanding under the action of detonation products (DP) of condensed explosives (CE) is discussed in [1-4]. Realization of the rupture criteria [2, 5] in application to rigidly plastic cylindrical shells is examined in [4].

The simplest estimation of the influence of a scale factor on the rupture radius of a shell loaded by a pressure pulse and storing some elastic energy to be expended entirely in rupture is presented in [6]. A modification of this approach that takes account of the dynamics of the shell loading process, its thickness, the plastic properties of the shell material, the type of CE loading, and the presence of tensile stress zones varying over the thickness as a shell expands under the action of DP, can be realized by applying the Taylor dependence [1]

$$y = \delta Y / p, \tag{1}$$

where y is the thickness of the stretched zone measured from the shell outer surface, δ is the shell running thickness, Y is the dynamic yield point of the shell material, $p = p_0(a_0/a)^{2k}$ is the running pressure on the shell inner surface, $p_0 = \rho_0 D^2/2(k + 1)$ is the pressure of instantaneous detonation, ρ_0 is the CE density, D is the detonation velocity, k is the DP isentropy index, and a_0 and a are the initial and running inner radii of the shell.

Long cylindrical shells ($L_0/a_0 > 12$, L_0 is the shell length) whose internal cavity is filled with a CE charge initiated at the point of endface surface symmetry were subjected to explosive loading. By use of a high-speed optical device, values of the relative outer fracture radius b_f/b_0 (b_0 is the initial outer radius of the shell, and b_f is the rupture radius) found by the outbreak of DP on the outer surface, were determined. Certain results of the experiment are presented in Fig. 1 for medium carbon steel at successive times 1) t = 11.2; 2) 22.4; 3) 28.8; 4) 35.2 μsec.

We shall consider the development of rupture to be the propagation of a separation crack. Since only the tensile zone that expends the stored energy on rupture can be subjected to unloading, the store of this energy equals the quantity

$$E_1 = A\varepsilon_1 \frac{2b - y}{2} y L_0, \tag{2}$$

where ε_1 is the specific volume energy in the stretched zone expended on rupture (the development of the separation crack), $(2b - y)/2 = R_y$ is the mean radius of the tensile zone, and A = const.

Taking account of (1), the dependence (2) has the form

$$E_1 = A \frac{Y}{p} \delta b L_0 \left(1 - \frac{y}{2b}\right) \varepsilon_1.$$

Moreover, $\varepsilon_1 \sim Y^2/E$, and $Y \sim (\varepsilon_1 E)^{1/2}$, i.e., $\varepsilon_1 Y \sim \varepsilon_1^{3/2} E^{1/2} = B$, and then

$$E_1 = \frac{C}{p} \delta b L_0 \left(1 - \frac{y}{2b}\right), \tag{3}$$

where C = AB = const.

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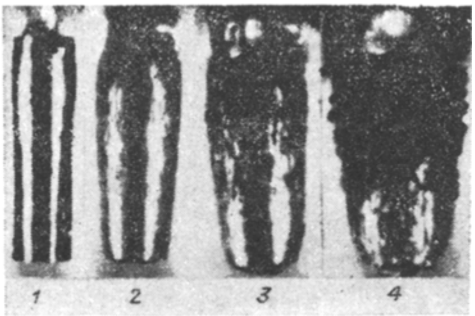

Fig. 1

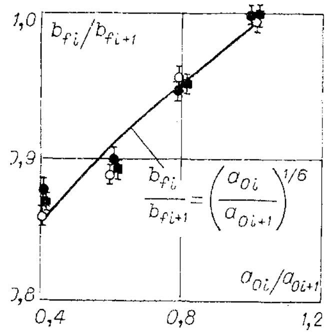

Fig. 2

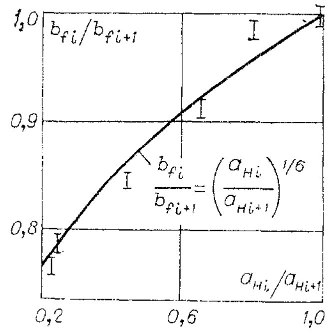

Fig. 3

The energy

$$E_2 = K\varepsilon_2\delta L_0, \tag{4}$$

is necessary for material rupture, where ε_2 is the rupture energy expended in the formation of unit free surface area, and K = const.

Assuming all the stored energy E_1 expended in rupture ($E_2 = E_1$), we have in conformity with (3) and (4)

$$b_f = \frac{K}{C}\frac{\varepsilon_2 p}{1-y/2b_f}.$$

Since $y/2b_f \ll 1$ is a small parameter, we have $1/(1 - y/2b_f) \simeq 1 + y/2b_f \simeq 1$ and

$$\frac{b_f}{b_0} \simeq \frac{K}{C}\frac{\varepsilon_2 p}{b_0}.$$

Any of the material rupture characteristics (G_{1c}, J_{1c}, a_H, etc.) can be taken as the quantity ε_2. Let $\varepsilon_2 = a_H$, a_H is the impact viscosity of the material. Also taking into account that $b_0 = a_0/(1 - 2\delta_d)$, $p = \rho_0 D^2(a\ /a)^{2k}/2(k + 1)$, we obtain

$$\frac{b_f}{b_0} \simeq N\frac{a_H}{a_0}(1-2\delta_d)\,\rho_0 D^2\left(\frac{a_0}{a_f}\right)^{2k}, \tag{5}$$

where $\delta_d = \delta_0/2b_0$ is the relative shell wall thickness, δ_0 is the initial wall thickness, and $N = k/2C(k + 1)$ = const.

Moreover

$$\left(\frac{a_0}{a_f}\right)^{2k} = \left[\frac{b_0(1-2\delta_d)}{b_f(1-2\delta_{dj})}\right],$$

where $(1 - 2\delta_d)/(1 - 2\delta_{dt}) = 1 - 2(\delta_t - \delta_{dt})/(1 - 2\delta_{dt})$; $\delta_{df} = \delta/2b_f$ is the relative shell wall thickness at the time of rupture.

In comformity with the experimental data $0.1 < \delta_{df} < \delta_d$, i.e., $\delta_d - \delta_{df} \simeq 0.05$ and $(1 - 2\delta_d)/(1 - 2\delta_{df}) \simeq 1$ to 12% accuracy. Then (5) has the form

$$\left(\frac{b_f}{b_0}\right)^{1+2k} \simeq N\frac{a_H}{a_0}(1-2\delta_d)\,\rho_0 D^2$$

or

$$\frac{b_f}{b_0} \simeq \left[N\frac{a_H}{a_0}(1-2\delta_d)\,\rho_0 D^2\right]^{1/(1+2k)}. \tag{6}$$

Since shear rupture processes, the influence of rupture by separation on the stress–strain state, the influence of shocks, compression and rarefaction waves and their interaction were not taken into account in deriving (6), the powers of the factors in the right side of (6) should be determined from experimental results, i.e.,

$$\frac{b_f}{b_0} \sim \left(\frac{a_H}{a_0}\right)^{\alpha}(1-2\delta_d)^{\beta}(\rho_0 D^2)^{\gamma}. \tag{7}$$

Processing the results of a multifactor experiment conducted on 52 elongated steel cylinders results in the dependences

$$b_f/b_0 \sim (1/a_0)^{1/6},\ b_f/b_0 \sim (a_{\text{н}})^{1/6},\ b_f/b_0 \sim (\sqrt{\rho_0}D)^{1/2},$$
$$b_f/b_0 \sim (1-2\delta_d)^{1/2}. \quad (8)$$

Results of experimentsl confirming the first two dependences of the system of proportional relationships (8) are shown as examples in Figs. 2 and 3. Experimental data for steel 20 (circles), steel 60 (points), and steel 45X (squares) in the normalized state are superimposed in Fig. 2. The cylindrical models had a relative wall thickness of $\delta_d = 0.177$ and were loaded by DP of phlegmatized hexogene. The minimal initial inner radius of the shell was $a_0 = 6.5$ mm, while the maximal was 15.5 mm. Processing the results of each experiment was performed on 10 measurements of the rupture radius b_f/b_0 for a successive series of models under the condition $a_{0i} \leqslant a_{0i+1}$, where i is the index of the experiment.

The argument in Fig. 2 is the shock viscosity of the cylindrical shell material from steel 60, 45X, and 35 with different heat treatment, loaded by the DP of TH 50/50. The shell inner radius is $a_0 = 10$ mm, the relative wall thickness $\delta_d = 0.13$, and the minimal value of the shock viscosity $a_H \simeq 200$ kJ/m^2. The results of each experiment were processed on 10 measurements of the rupture radius for a successive series of models under the condition $a_{Hi} \leqslant a_{Hi+1}$.

Substitution of the system of proportional relations (8) into (7) and appropriate determination of the proportionality factor by least squares result in the dependence

$$b_f/b_0 \simeq 0.0019(a_{\text{н}}/a_0)^{1/6}(1-2\delta_d)^{1/2}(\sqrt{\rho_0}D)^{1/2}, \quad (9)$$

where a_H is in kJ/m^2, a_0 in mm, ρ_0 in kg/m^3, and D in m/sec.

A comparative estimate of the magnitude of the outer rupture radius found in conformity with (9) with respect to the experimental values shows that the error in the calculation does not exceed 15% and lies within the limits of measurement error.

Analysis of the experimental results showed that the main factors governing the ultimate strains (rupture radius) of the steel cylindrical shells loaded by detonation products of a CE are the scale effect a_0, the material plasticity a_H, the relative wall thickness δ_d, and the kind of loading body ($\rho_0 D^2$ is a quantity proportional to the detonation pressure). The relationship (9) obtained maps the process phenomenology qualitatively correctly, while quantitative results do not contradict the data of experimental investigations and take account of the scale effect during rupture.

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