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Computer Simulation of Normal and Oblique Impacts of Yawed Projectiles on Ceramic Targets

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Численное моделирование при ударе по нормали и под углом к поверхности преграды

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На основе метода конечных элементов исследовалась пространственная задача взаимодействия при ударе по нормали и под углом снаряда с керамической пластиной при скорости до 4000 м/с. Представлена усовершенствованная модель керамики AD995 Alumina, учитывающая температурное воздействие. Применяется также модель поврежденной среды, характеризующаяся возможностью моделировать возникновение и развитие трещины в условиях ударного нагружения. В процессе численного моделирования разрушения керамической пластины при высокоскоростном воздействии была использована кинетическая модель разрушения активного типа, разработанная ранее для моделирования разрушения различных материалов.

Ключевые слова: ударное нагружение, керамика, метод конечных элементов, модель разрушения.

Formulation of the Problem. A model of a damageable medium characterized by microcavities (cracks and pores) is used. According to [1], the total volume of the medium W consists of an undamaged part, which occupies the volume W_c and is characterized by the density ρ_c, and microcavities, which occupy the volume W_T. The density of the microcavities is assumed to be zero. The mean density of the damageable medium is related to the parameters introduced by the formula $\rho = \rho_c(W_c/W)$. The degree of damage of the medium is characterized by the specific volume of cracks $V_T = W_T/(W\rho)$. A set of equations describing time-dependent adiabatic motion of a compressible medium (in the case of both elastic and plastic deformation) and taking into account the growth and accumulation of microdamages consists of equations of continuity, motion, and energy, and the equation that describes the variation of the specific volume of cracks:

$$\rho\, dv_i/dt = \sigma_{ij,j}, \tag{1}$$

$$\partial\rho/\partial t + \mathrm{div}(\rho v) = 0, \tag{2}$$

$$dE/dt = (1/\rho)\sigma_{ij}\varepsilon_{ij}, \tag{3}$$

$$\frac{dV_T}{dt} = \begin{cases} 0 \text{ for } |P_c| \le P^* \text{ or } P_c > P^* \text{ and } V_T = 0, \\ -\operatorname{sgn}(P_c) K_4 (|P_c| - P^*)(V_2 + V_T) \\ \text{for } P_c < -P^* \text{ or } P_c > P^* \text{ and } V_T > 0, \end{cases} \tag{4}$$

where $P^* = P_k V_1/(V_T + V_1)$; ρ is the density; v_i are the components of the velocity vector; E is the specific internal energy, ε_{ij} are the components of the deformation-velocity tensor; $\sigma_{ij} = (P+Q)\delta_{ij} + S_{ij}$ are the stress-tensor components; P_c is the pressure in the continuous component of the substance; $P = P_c(\rho/\rho_c)$ is the mean pressure; Q is the artificial viscosity [2], and V_1, V_2, P_k, and K_4 are material constants obtained experimentally. Simulation of fracture was performed with the help of the kinetic model of fracture of active type, which defines the growth of microcracks that continuously change the material properties and cause the stress relaxation [3, 4]. Pressure in the undamaged substance is a function of the specific volume, internal energy, and specific volume of cracks, and in the whole range of loading conditions it is defined by the equation of state of the Mie–Gruneisen type according to the formula

$$P_c = \rho_0 a^2 \mu + \rho_0 a^2 [1 - \gamma_0/2 + 2(b-1)]\mu^2 +$$

$$+ \rho_0 a^2 [2(1-\gamma_0/2)(b-1) + 3(b-1)^2]\mu^3 + \gamma_0 \rho_0 E,$$

$$\mu = V_0/(V - V_T) - 1,$$

where γ_0 is the Gruneisen coefficient, V_0 and V are the initial and current specific volumes, a and b are constants of the Hugoniot adiabat, which is defined by the linear relation

$$D = a + bu_m,$$

where D is the shock-wave velocity and u_m is the mass velocity of the substance beyond the shock-wave front. Deviatoric components of the stress tensor are obtained from the following relation:

$$2G\left(\varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}\delta_{ij}\right) = \frac{dS_{ij}^0}{dt} + \lambda S_{ij},$$

where

$$\frac{dS_{ij}^0}{dt} = \frac{dS_{ij}}{dt} - S_{ik}W_{jk} - S_{jk}W_{ik}, \quad 2W_{ij} = \partial v_i/\partial x_j - \partial v_i/\partial x_j.$$

The parameter λ is equal to 0 in the case of elastic deformation. In the case of plastic deformation, it can be found using the von Mises yield criterion:

$$S_{ij}S_{ij} = 2/3\sigma^2.$$

Here G is the shear modulus and σ is the dynamic yield strength. These parameters are obtained with the help of the following relations:

$$G = G_0[1 + cP/(1+\mu)^{1/3} + d(T-300)]V_3/(V_T + V_3) \text{ when } T \le T_m,$$
$$G = 0 \text{ for } T > T_m,$$

$$\sigma = \sigma_0[1 + cP/(1+\mu)^{1/3} + d(T-300)](1 - V_T/V_4)$$
$$\text{when } T \le T_m \text{ and } V_T \le V_4,$$
$$\sigma = \sigma_p \text{ when } V_{TK} \le V_T \le V_4 \text{ and } T \le T_m,$$
$$\sigma = 0 \text{ when } T > T_m \text{ or } V_T > V_4 \text{ or } \sigma_{sw} \le p_{fr}.$$

Here T_m is the substance melting temperature, σ_{sw} is the stress in a shock wave, c, d, V_3, and V_4 are material constants defined experimentally. The temperature is calculated according to [5]:

$$T = (E - E_{0x})/c_p = [E - E_0 - E_1\mu - (-E_1 + E_2)\mu^2 -$$

$$-(E_1 - 2E_2 + E_3)\mu^3 - (-E_1 + 3E_2 - 3E_3 + E_4)\mu^4]/c_p,$$

$$E_0 = -300c_p, \quad E_1 = \gamma_0 E_0, \quad E_2 = (a^2 + \gamma_0^2 E_0)/2,$$

$$E_3 = (4ba^2 + \gamma_0^4 E_0)/16, \quad E_4 = (-2\gamma_0 ba^2 + 18b^2a^2 + \gamma_0^4 E_0)/24,$$

where c_p is the specific heat, and E_{0x} is the cold component of the specific internal energy.

To investigate the effects of fracture and temperature in a ceramic target during oblique impact of yawed projectiles in the range of velocities up to 4000 m/s, a number of simulations were performed. The interaction of a steel cylinder 7.6 mm in diameter and 50.8 mm in height with a 10 mm thick AD995 plate was modeled. The model parameters for AD995 ceramics were adjusted using the data from plate impact experiments. The characteristics of the AD995 plate employed in computations were [6] as follows: $\rho_0 = 3890$ kg/m^3, $\sigma_0 = 4.7$ GPa, $G_0 = 160.0$ GPa, $V_1 = 1.46 \cdot 10^{-6}$ m^3/kg, $V_2 = 0.875 \cdot 10^{-7}$ m^3/kg, $V_3 = 5.83 \cdot 10^{-5}$ m^3/kg, $V_4 = 1.75 \cdot 10^{-4}$ m^3/kg, $K_4 = 0.5$ (m·s)/kg, $P_k = 0.45$ GPa, $a = 7700$ m/s, $b = 1.3$, $c = 10560$ m/s, $T_m = 2327$ K, $V_{TK} = 1.0 \cdot 10^{-5}$ m^3/kg, $d = 1.6 \cdot 10$ K, $c_p = 775.2$ J/(kg·K), $\gamma_0 = 1.32$, $\sigma_p = 0.3$ GPa, $p_{fr} = -8.8$ GPa.

The characteristics of the steel were: $\rho_0 = 7850$ kg/m^3, $\sigma_0 = 1.01$ GPa, $G_0 = 79$ GPa, $V_1 = 9.2 \cdot 10^{-6}$ m^3/kg, $V_2 = 5.7 \cdot 10^{-7}$ m^3/kg, $V_3 = 2.55 \cdot 10^{-5}$ m^3/kg, $V_4 = 6.37 \cdot 10^{-5}$ m^3/kg, $K_4 = 0.54$ (m·s)/kg, $P_k = -1.5$ GPa, $a = 4400$ m/s, $b = 1.55$, $c = 206$ GPa, $d = 1.6 \cdot 10$ K, $c_p = 446.7$ J/(kg·K), $\gamma_0 = 1.91$.

Results of Numerical Calculations. Computations have been made for the yaw up to 100. Figure 1 shows configurations of the projectile and plate during interaction at the impact velocity 4000 m/s for the obliquity 45° and yaw 10° at 10 s. In this case, the computation evidences that the process of perforation is observed and completed within 15 μs.

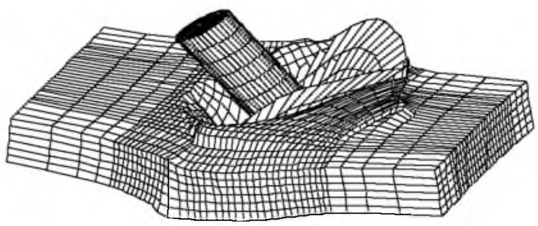

Fig. 1. Penetration processes at the impact velocity 4000 m/s for the obliquity 45° and yaw 10°.

Figure 2 shows the histories of resistance force components during penetration at the impact velocity 4000 m/s for the 45° obliquity. The curves show that at the initial moment the vertical components of resistance forces are larger. Beyond 6 μs, the horizontal components of the resistance forces are larger for both angles of the yaw.

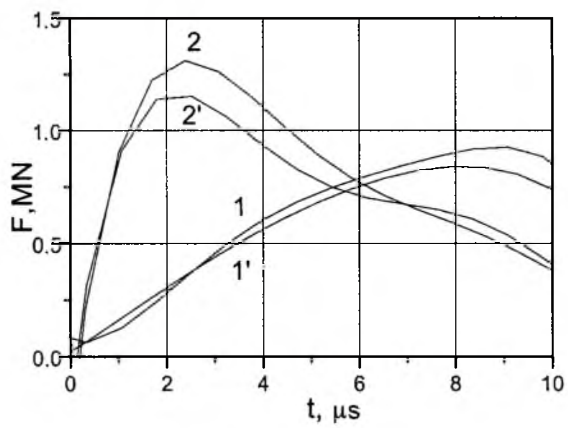

Fig. 2. Histories of resistance force components during penetration at the impact velocity 4000 m/s for the obliquity 45°: (*1*) F_2, yaw = 0°; (*1'*) F_2, yaw = 10°; (*2*) F_3, yaw = 0°; (*2'*) F_3, yaw = 10°.

We investigated the histories of temperature near the contact surface in the target and projectile. The results obtained show that the temperature effects are important for the impact velocity range over 4000 m/s and they are more pronounced for the ceramic target. To further investigate the ceramic model, the contours of specific volume of cracks were generated. The computations show that the maximum damage occurred in the bottom of the ceramic target near the impact axis for both angles of the yaw and only for the 10° yaw in the surface layer of the ceramics near the leading edge of the projectile-target interaction region. The effect of the yaw on fracture was clearly pronounced.

In conclusion it may be said that the results of numerical simulations using the shock-wave-propagation-based finite-element code revealed that both temperature effects and fracture of ceramics are important at the velocity 4000 m/s. We established the stages in the penetration process, the surfaces and contours of temperature and specific volume of cracks for various instants of time. The results show that the temperature effects in ceramic targets are clearly pronounced for the impact velocity 4000 m/s. It was revealed that during the second stage of penetration the values of the horizontal components of the resistance forces are larger than the values of their vertical components. This results in the normalization of the vector velocity of the projectile mass center during the second stage of the penetration process at the 45° obliquity.

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Резюме

На основі методу скінченних елементів досліджувалася просторова задача взаємодії при ударі по нормалі та під кутом снаряда з керамічною пластиною при швидкості до 4000 м/с. Представлено удосконалену модель кераміки AD955 Alumina, яка враховує температурну взаємодію. Використовується також модель пошкодженого середовища, для якої характерна можливість моделювання виникнення і розвитку тріщини в умовах ударного навантаження. У процесі числового моделювання руйнування керамічної пластини при високій швидкості було використано кінетичну модель руйнування активного типу, яку розроблено раніше для моделювання руйнування різних матеріалів.

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