MATHEMATICAL MODELLING OF CRACK DEVELOPMENT IN CERAMICS UNDER CONTACT LOADING

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ABSTRACT

Failure kinetic model of active type, used earlier for the calculation of various metal behaviour, is used for numerical modelling of ceramic failure at high velocity impact. The variation of constants, included in the model, allow to describe the properties of high-modulus composite materials, produced out of ceramics and metallic binder. The calculation of cylinder metal bodies interaction with ceramic plates, carried out with the finite elements method, describe the interaction peculiarities and development character of plate failure at high velocity impact. The peculiarities of arising and spreading of damages, leading to crack net formation and ceramics failure under high velocity impact conditions have been investigated.

KEYWORDS

Ceramic, high velocity impact, failure kinetic model, finite elements method.

INTRODUCTION

Ceramic materials posses high hardness and wear resistance. These properties characterize, in particular, the refractory oxides of aluminum, beryllium, zirconium, chromium and others. The creation of new generations of ceramic materials, able to work in a wide range of loading conditions, require the investigation of materials, stable to possible random transient loads during operation. The contact loading is one of the most known cases of force interaction of construction elements. If, in the case of plastic materials, such actions lead to the arising of local plastic deformations which have, as a rule, small influence on strength, then in solid brittle materials similar actions may cause local failures, decreasing disastrously their supporting power. The experiments show that the ceramic plates failure at dynamic impact interaction occurs due to ~~arising~~ and subsequent spreading of net of cracks in subsurface regions, leading to fragmentation of material. In present paper, the investigation of axially symmetrical problems of metal striker interaction with ceramic plate in velocity range up to 1000 m/s. The kinetic model of active type is used to describe the failure in ceramics, sharp drop of strength properties in attaining the critical value of crack specific volume is specified in this model.

MATHEMATICAL MODELS

The model of damaged medium is used in calculations, it is characterized with possibility of crack formation (Seaman et al., 1977). Undamaged medium part W_c, characterized by density ρ_c, and crack, occupying the volume W_*, in which the density is supposed to be equal to 0, constitute the total medium volume W. The mean density of damaged medium is connected with input parameters by relation $\rho = \rho_c W_c / W$. The degree of medium damage is characterized by crack specific volume $V_T = W_* / (W\rho)$. The system of equations, describing non-stationary adiabatic movements of compressible medium with regard for crack development is as follows:

$$\dot{\rho} = -\rho(v_{,z} + u_{,r} + u/r),$$
$$\rho\dot{u} = S_{rr,r} + S_{rz,z} + (S_{rr} - S_{\theta\theta})/r - P_{,r},$$
$$\rho\dot{v} = S_{rz,r} + S_{zz,z} + S_{rz}/r - P_{,z},$$
$$\rho\dot{E} = P\dot{\rho}/\rho + S_{zz}v_{,z} + S_{rr}u_{,r} + S_{\theta\theta}u/r + S_{rz}(u_{,z} + v_{,r}), \qquad (1)$$
$$\dot{V}_T = 0 \quad \text{at } |P_c| \le P_* \text{ or } (P_c > P_* \text{ and } V_T = 0),\quad P_* = P_k V_1/(V_1 + V_T),$$
$$\dot{V}_T = -\mathrm{sign}(P_c)\, K_4(|P_c| - P_*)(V_2 + V_T)$$
$$\text{at } P_c < -P_* \text{ or } (P_c > P_* \text{ and } V_T > 0).$$

Here r, θ, z are the axis of cylinder coordinate system (z is axis of symmetry), S_{rr}, S_{zz}, $S_{\theta\theta}$, S_{rz} - components of stress deviator, u, v - radial and axial components of velocity vector, E - specific internal energy, P and P_c - mean pressure and pressure in undamaged substance component, V_1, V_2, P_k, K_4 -constants of failure model of active type. Pressure in undamaged substance is the function of specific volume, internal energy and crack specific volume

$$P_c = \sum_{n=1}^{3} K_n\left(\frac{V_0}{V - V_T} - 1\right)^n \left[1 - \frac{K_0}{2}\left(\frac{V_0}{V - V_T} - 1\right)\right] + K_0\rho_0 E, \qquad (2)$$

where K_0, K_n, ρ_0 are material constants, V_0 and V are initial and current volumes. Coefficients K_n are expressed through material constants a, b out of relation D = a + bu according to Gust (1982). Mean pressure in medium is determined according to formula $P = P_c\,\rho/\rho_c$. Components of stress deviator are found out of relations:

$$2G(v_{,z} + 1/3\,\dot{\rho}/\rho) = \overset{\nabla}{S}_{zz} + \lambda S_{zz},$$
$$2G(u_{,r} + 1/3\,\dot{\rho}/\rho) = \overset{\nabla}{S}_{rr} + \lambda S_{rr}, \qquad (3)$$
$$2G(u/r + 1/3\,\dot{\rho}/\rho) = \overset{\nabla}{S}_{\theta\theta} + \lambda S_{\theta\theta},$$
$$G(u_{,z} + v_{,r}) = \overset{\nabla}{S}_{rz} + \lambda S_{rz}.$$

Parameter λ = 0 for elastic material and $\lambda \geqslant 0$ when plastic deformation is present. In these relations G is shear modulus, σ is dynamic flow stress and index ∇ indicates derivative according to Jaumann. Shear modulus and dynamic flow stress were supposed to be dependent on attained damage level

$$G = G_0 V_3/(V_3 + V_T),$$
$$\sigma = \sigma_0(1 - V_T/V_4), \quad (V_T < V_T^K), \qquad (4)$$
$$\sigma = \sigma_p, \quad (V_T^K < V_T < V_T^p),$$
$$\sigma = 0, \quad (V_T > V_T^p).$$

The problem of steel cylinder interaction with ceramic plate is under consideration. For equations from (1) to (4) the problem is stated with initial (when t=0) and predetermined boundary conditions on surfaces. Problem statement is characterized by lack of initial internal stresses and loads on free surfaces during all the process. Sliding conditions are realized on contact surface between cylinder and ceramic plate. The relations of finite elements method used for the solution of the stated problem are reported in Gorelsky et al. (1992).

MODEL CALCULATIONS

The interaction of steel cylinder with 0.0076 m in diameter and 0.0254 m in height with ceramic plate with 0.010 m in thickness was modelled in calculations. The density of cylinder material was predeterminated to be 7850 kg/m^3 and the one of the plate to be 3430 kg/m^3. In relations (3) and (4) strength constants and equation of state constants (2) for ceramics were taken from Gust and Royce (1971); Wilkins (1978). Calculation results are given in the figures. Fig. 1 presents configurations of striker and plate during interaction with initial velocity 600 m/s.

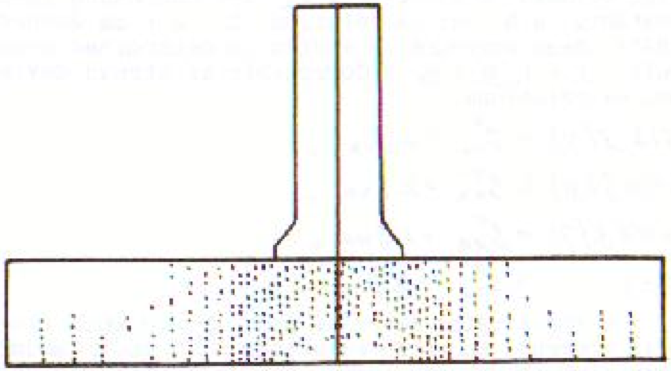

Fig. 1. Chronogram of interaction of striker with ceramic plate with initial velocity of 600 m/s in 4 μs after contact.

As it follows from Fig. 1 the deformation of plate is negligible in comparison with the striker. Fig. 2 illustrates the peculiarities of failure development in ceramics at impact with velocity of 1000 m/s: distributions of isolines of crack spe-

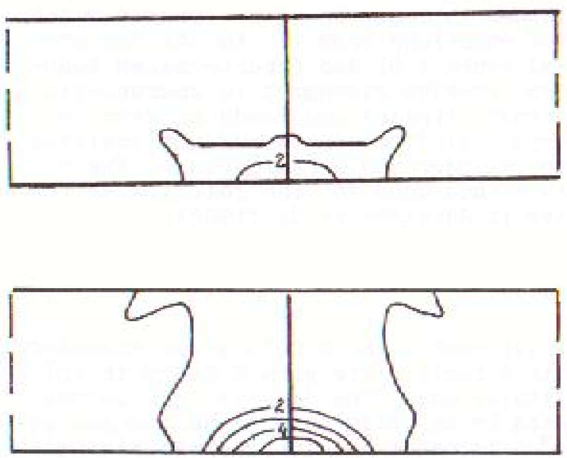

Fig. 2. Distribution of isolines of crack specific volume in ceramic plate after 2 and 4 μs after interaction with velocity of 1000 m/s.

cific volume at time moments of 2 and 4 μs are given there. Damaged regions configurations speak about significant distin

ctions of damage development in ceramics in comparison with peculiarities of metallic plates failure investigated in Dremin et al. (1986). In contrast to metals where damage zone is formed in some distance from reverse surface leading to the formation of chipping-off plate the failures in ceramics are initiated on reverse surface directly. Fig. 2 shows that main cracks are firstly spreading deep into the plate in separate directions and then continuous failure front is formed. Kinetics of damage development with impact velocities of 600 and 1000 m/s is illustrates in Fig. 3 where plots of crack volume

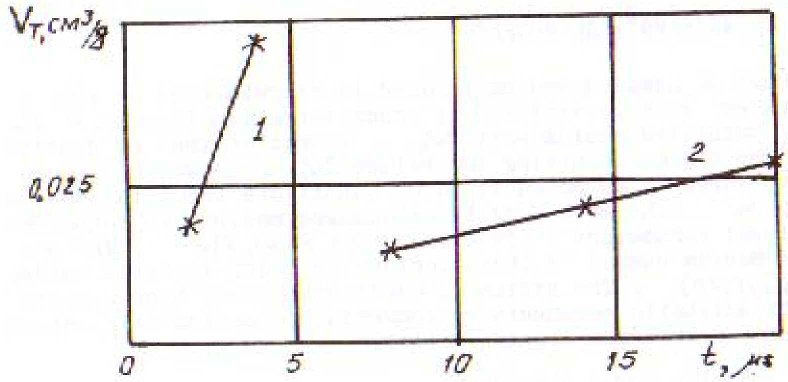

Fig. 3. Values of crack specific volume against time at axial point of reverse plate surface with impact velocity 1000 m/s (1) and 600 m/s (2)

against time in axial point of reverse plate surface are given. The curves reflect the fact that with the growth of interaction intensity the damage velocity is increasing greater in ceramics in comparison with metals.

CONCLUSIONS

The calculations show that the given material model allows to describe the failure of high modulus composite materials, produced out of ceramics and metallic binder in conditions of impact-wave loading.

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