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MODELING OF FRACTURED MATERIAL BY FINITE-SIZE DISCRETE PARTICLES

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The impact processes of solids are generally accompanied by fracture, the type of fracture depending on the properties of materials of bodies, the shape of a projectile, the impact velocity, and on the relative geometric dimensions of bodies. In the general case, some combination of fracture types is observed [1, 2]. It is possible to make one of the fracture types predominant by choosing the parameters of colliding bodies. For example, fracture of a plastic-puncture type occurs when a pointed projectile made of hardened steel penetrates into a soft target [3]. Spalling is observed when a thin plate hits a target of finite thickness [4]. The interaction of a solid cylinder with a flat front section leads to shear fracture of the target with knocking-out of a plug.

In the numerical solution of problems of high-speed impact of bodies being deformed, the fracture processes can be simulated by one of the following techniques:

(1) The fractured medium remains continuous, and the stress tensor is corrected using the functional relations [6, 7];

(2) An explicit separation of macroscopic fracture surfaces by adding the difference-grid nodes so that these surfaces pass over the cell boundaries; the limiting case is splitting of the fractured region of the body into fragments containing one or several difference cells [8–10];

(3) An alternative method of explicit separation of macroscopic fracture surfaces is the local reconstruction of the destroyed cell; this method is more general, because there are no limitations related to the cell boundaries of a difference grid [4];

(4) The medium is assumed to consist of discrete particles of regular shape and different sizes, and the particles interact according to certain laws; deformation of such a medium can be followed by the change of the neighbors and also by the formation of new links [11, 12].

In the present paper, we propose a continuum-discrete approach for representation of the medium in numerical simulation of high-speed impact processes with allowance for fracture [13–15]. An approach using a similar concept was used in [16, 17].

The Lagrangian approach is widely used to describe unsteady processes in the mechanics of deformed solids. This approach involves direct calculations of the motion of the free boundaries of bodies and of the contact surfaces between the interacting bodies, and there is no artificial overflow of materials between the regions containing different materials, which allows one to trace the history of any material particle.

Equations of the Prandtl–Reuss elastoplastic model and the formulation of the problem of collision of deformed bodies were considered in detail in [18–20]. Since the interaction of bodies causes fracture of materials, the model should be supplemented by a number of fracture criteria which were chosen as the maximum tensile and compressive (for brittle materials) strains and stresses, the maximum shear strains, the internal energy, and the damage parameter $\chi = 1 - \rho/\rho_0$ for $\rho < \rho_0$:

$$|\varepsilon_1| < \varepsilon_*, \quad |\sigma_1| < \sigma_*, \quad |\gamma_1| < \gamma_*, \quad e < e_*. \tag{1}$$

Here ε_1 and γ_1 are the maximum extension and shear strains, σ_1 is the maximum tensile stress, and ε_*, σ_*, γ_*, and e_* are the limiting strength characteristics of the material. If the current value of the corresponding

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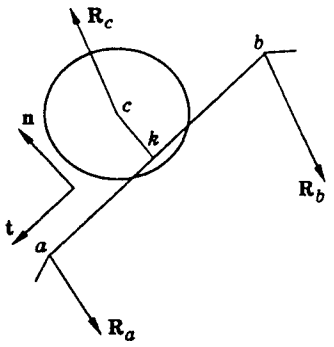

Fig. 1

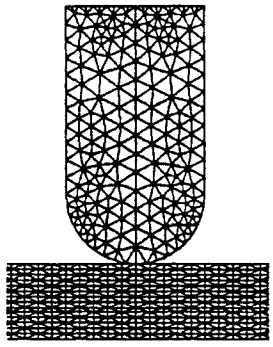

Fig. 2

function exceeds any of these criteria, the medium in this material particle is in a damaged state which is understood as the medium's state resistant only to bulk compression. A particular case of such a material can be liquid. The parameter χ characterizes the ability of a damaged medium to remain continuous in bulk expansion when the substance density becomes lower than the initial one and amounts to a few percent (if $\chi > \chi_*$, then the medium is considered completely destroyed).

All constants in the initial equations and the initial and boundary conditions are assumed to be specified. A modified Wilkins's method is used for numerical solution of the problems of collision of bodies [15, 18]. The following quantities are known in each cell of the difference grid: current density of the material, stress and strain-rate tensors, and specific internal energy. The velocity coordinates are referred to the difference-grid nodes. The computational algorithm is implemented in such a way that if at least one of the criteria (1) is satisfied in a cell of the computational grid, the equation of state of the material changes in this cell, the cell itself being marked as damaged.

Then, if the cell marked as damaged is located at the computational-domain boundary and the damage criterion reaches a critical value, the material of this cell is replaced by discrete particles whose radius is calculated from the condition of inscription of one or several particles in the cell. The mass of this cell is distributed over the discrete particles. Only one layer of the boundary cells can be transformed to discrete particles during one time step, because it is assumed that the velocity of the fracture-wave front does not exceed the velocity of disturbance propagation in the medium. Thus, under certain conditions in the course of interaction, the bodies can be split into fragments or even become "worked out," i.e., they can be completely replaced by a system of discrete finite-size particles.

The representation of the vector of the forces acting upon a material particle as a sum $\mathbf{F} + \mathbf{R}$ is a key point in the difference equations of motion. Here $\mathbf{F}$ is determined in terms of the stress-tensor components, while $\mathbf{R} = 0$ for the internal nodes and is calculated for the boundary nodes [20, 21]. This allows one to use a single algorithm for calculation of the contact boundaries between the continuous material, between the particles and the intact medium, and also between the discrete particles.

For each elementary act of interaction, calculations are carried out in two stages. At the first stage, the vector $\mathbf{R} = 0$, and the intermediate positions of the particles and of the boundary nodes are determined. The positions for which the no-slip condition can be violated are then found. The second stage of calculations can be demonstrated by the example of a discrete particle and the continuous-material boundary (Fig. 1). If, for the intermediate position of a particle c and the nodes of the boundary section ab, the distance from the particle center to the section is smaller than the particle radius, the equations of equilibrium and momenta relative to the point k (Fig. 1) are written for the normal components of the vectors $\mathbf{R}_c$, $\mathbf{R}_a$, and $\mathbf{R}_b$. Substituting these relations into the condition of equality of the normal velocity-vector components at the point k, we find the normal components of the reacting-forces vector. With a friction law specified, a similar procedure can be used to calculate the tangential component of these forces [20].

Since the discrete particles are assumed to be incompressible, their motion is determined only by $\mathbf{R}$. If a particle interacts with a set of particles, the force vectors are summed over the entire set. Thus, introduction

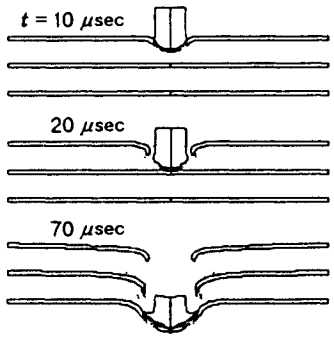

Fig. 3

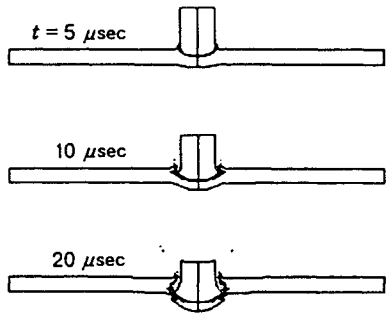

Fig. 4

of the force **R** allows one to develop a uniform algorithm for solving the equations of motion of material particles.

The approach described above was implemented on KRUG24 software intended for solution of a class of problems of impact interaction of elastoplastic bodies in the two-dimensional case.

As an example, let us consider the solution of the problem of penetration of a lead bullet through aluminum targets. A similar problem was studied experimentally in [22] for a system of aluminum plates with different thickness, strength properties, and gaps between them. The initial data for computations were taken from [22]. The lead bullet was assumed to be nondestructible and to have a mass of 11 g, a radius of 0.278 cm, and a spherical forebody. The velocity range was 350–390 m/sec. The parameters that characterize the material properties were as follows: $\rho_0 = 11.34$ g/cm^3, $K = 50$ GPa, $\mu = 5.7$ GPa, and $Y_0 = 0.03$ GPa for lead and $\rho_0 = 2.7$ g/cm^3, $K = 73$ GPa, $\mu = 24.6$ GPa, $Y_0 = 0.28$ GPa, $\varepsilon_* = 0.4$, and $\chi_* = 0.03$ for an aluminum alloy 6061-T6.

Figure 2 shows the initial difference grid in the bullet and in some part of the target. For numerical solution of this problem, a series of methodical computations was performed to find out the effect of the grid parameters. In these computations, a further increase in the number of cells of the difference grid was found not to lead to a noticeable change of the final result and increases only the computation time. Besides, it was found that one particle for one cell is sufficient when the destroyed material is replaced by discrete particles.

The computations have shown that the best agreement with experimental data on the residual bullet velocity is achieved using the first criterion from (1) in the fracture model. The value of ε_* was found from the computations of penetration through one plate 1 mm thick and was used in subsequent calculations. It should be noted that $\varepsilon_* = 0.4$ lies in the range of tabular values of the limiting tensile strain for aluminum alloys, which is indicated in various handbooks.

Three target configurations were chosen for analysis: a monolithic target 3 mm thick, three 1-mm-thick contact plates, and a system of three spaced-apart plates, each 1 mm thick. The initial impact velocity was $U_0 = 355$ m/sec.

The process of the bullet–target interaction depends considerably on the type of a target. For example, a typical feature of damage of a target with spaced-apart layers is the fact that piercing of the first layer occurs like plug knocking-out. The bullet with the attached plug then contacts the next layer where the process is repeated. For a large number of layers, the remnants from the previous layers are accumulated ahead of the bullet, and the layers adjacent to the bullet are gradually destroyed completely. Finally, when the bullet penetrates through the entire target, it brings out, ahead of it, the partially intact fragments of the layers. Piercing through a spaced-out target is illustrated in Fig. 3.

When the bullet penetrates through a monolithic target, at the first stage the fracture process is localized above the bullet forebody. After that, a zone of target-material fracture arises at the projectile periphery which grows up to the back surface. This results in the formation of a plug whose thickness is slightly smaller than the target thickness. Figure 4 shows the calculated results for the case of penetration through a monolithic target for different time moments.

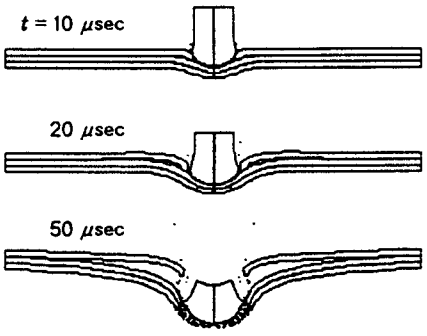

Fig. 5

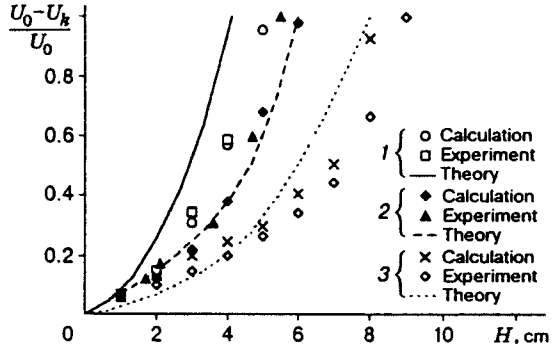

Fig. 6

A specific feature of penetration through a target of three contact layers is the fact that fracture occurs primarily in the first layer. The subsequent layers undergo strong deformation, and the layers are separated. In these layers, fracture begins at the symmetry axis where the region of maximum tensile strains is located. The process of interaction for this case is shown in Fig. 5 for different time moments.

In Fig. 6, the calculated results are compared with the theoretical and experimental ones [22] in the coordinates $(\Delta U/U_0, H)$ for the alloy 6061-T6. Here U_0 is the initial bullet velocity, and ΔU is the loss of velocity in penetrating through a target of total thickness H. Figure 6 shows data for three types of targets: a target with contact layers (1), a monolithic target (2), and a target with spaced-apart layers (3). The theoretical curves and the experimental points are taken from [22]. One can see that the calculated results are in good agreement with experimental ones. In particular, the experimentally observed fact that the target with contact layers has the highest resistance was confirmed.

Thus, the proposed model of fracture and the computational method allow one to calculate effectively the processes of interaction of deformed bodies within the framework of the Lagrangian approach. This is confirmed not only by qualitative but also quantitative agreement between the calculated and experimental results.

REFERENCES

1. M. A. Meyers and C. T. Aimone, "Dynamic fracture (spalling) of metals," *Prog. Mater. Sci.*, **28**, 1–96 (1983).
2. "Hypervelocity impact" (Proc. Symposium, 1989), *Int. J. Impact Eng.*, **10**, Nos. 1–4 (1990).
3. A. I. Gulidov, V. M. Fomin, and N. N. Yanenko, "Numerical simulation of penetration of bodies in an elastoplastic approximation," in: *Problems of Mathematics and Mechanics* [in Russian], Nauka, Novosibirsk (1983), pp. 71–81.
4. A. I. Gulidov and I. I. Shabalin, "Numerical simulation of a curved spalling crack in plate collision," in: *Numerical Methods for Solving the Problems of Elasticity and Plasticity Theory*: Materials 9th All-Union Conf., Novosibirsk (1986), pp. 117–121.
5. A. I. Gulidov, V. M. Fomin, and I. I. Shabalin, "Numerical simulation of shear fracture," in: *Mechanics of Rapid Processes* [in Russian], Novosibirsk (1984), pp. 48–51.
6. A. B. Kiselev, "Dynamic fracture criterion in impact interaction of elastoplastic bodies," *Vestn. Mosk. Univ, Ser. 1, Mat. Mekh.*, No. 6, 46–51 (1986).
7. G. Maenchen and S. Sack, "The TENSOR code," in: *Methods of Computational Physics*, B. Alder, S. Fernbach, and M. Retenberg (eds.), Academic Press, New York (1964), Vol. 3, pp. 181–210.
8. Y. M. Chen and M. L. Wilkins, "Stress analysis of crack problems with a three-dimensional, time-dependent computer program," *Int. J. Fracture*, **2**, No. 4, 607–615 (1976).
9. L. D. Berholf, I. D. Buxton, B. J. Thorue, et al., "Damage in steel plates from hypervelocity impact. II. Numerical results and spall measurement," *J. Appl. Phys.*, **6**, No. 9, 3779–3783 (1975).

10. A. D. Resnyanskii and L. A. Merzhievskii, "Application of the moving-grid technique in problems of solid-body fracture," in: *Dynamics of Continuous Media* [in Russian], Novosibirsk, **64**, 150–157 (1984).
11. G. R. Johnson, R. A. Stryk, and J. G. Dodd, "Dynamic Lagrangian computation for solids, with variable nodal connectivity for severe distortion," *Int. J. Numer. Meth. Eng.*, **23**, 509–522 (1986).
12. J. M. Ting, B. T. Corkum, C. R. Kauffman, et al., "Discrete numerical model for soil mechanics," *J. Geomech. Eng.*, **115**, No. 3, 379–398 (1989).
13. A. M. Gladyshev, A. I. Gulidov, V. M. Kovenya, et al., "Explosive throwing, aerodynamics, and solid-body impact. Numerical experiment," in: *Simulation in Mechanics* [in Russian], Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, Novosibirsk, **5**, No. 2, 7–19 (1991).
14. A. M. Gladyshev, A. I. Gulidov, G. A. Sapozhnikov, et al., "Application of the principles of discrete-continuous representation of a medium in problems of high-speed interaction of bodies," *Simulation in Mechanics* [in Russian], Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR. Novosibirsk, **7**, No. 4, 36–51 (1993).
15. A. I. Gulidov and I. I. Shabalin, "A method of free elements. Application to solution of the problems of fracture of elastoplastic bodies in the course of impact interaction," Preprint No. 9-94, Inst. Theor. and Appl. Mech., Russian Acad. Sci., Novosibirsk (1994).
16. C. R. Johnson, R. A. Stryk, T. J. Halmquist, et al., "Recent EPIC code development for high velocity impact: 3D element arrangements and 2D fragment distributions," *Int. J. Impact Eng.*, **10**, 281–294 (1990).
17. V. V. Bashurov and S. K. Buruchenko, "Simulation of high-speed penetration problems in Lagrangian coordinates," *Mat. Model.*, **4**, No. 6, 37–42 (1992).
18. M. L. Wilkins, "Calculation of elastoplastic flows," in: B. Alder, S. Fernbach, and M. Retenberg (eds.), *Methods of Computational Physics*, Vol. 3, Academic Press, New York (1964).
19. K. P. Stanyukovich (ed.), *Physics of Explosion* [in Russian], Nauka, Moscow (1975).
20. A. I. Gulidov and I. I. Shabalin, "Numerical realization of the boundary conditions in dynamic contact problems," Preprint No. 12-87, Inst. Theor. and Appl. Mech., Sib. Div., USSR Acad. Sci., Novosibirsk (1987).
21. A. I. Gulidov, "Organization of the computational process and of the data structure for numerical solution of the problems of mechanics of deformed media," in: *Simulation in Mechanics* [in Russian], Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, **5**, No. 3, 127–141 (1991).
22. I. Marom and S. R. Bodner, "Projectile perforation of multi-layered beams," *Int. J. Mech. Sci.*, **21**, 489–504 (1979).