15. S. A. Abdukadyrov, "Influence of an elastic medium on resonance waves in a layer," Applied Problems of Strength and Plasticity. Static and Dynamics of Deformable Systems [in Russian], Izd. Gor'kii Univ., Gor'kii (1980).

ANALYSIS OF SPALL FRACTURE IN SPECIMENS CONTAINING POROUS SPACERS

N. N. Belov, V. A. Gridneva,
I. I. Korneeva, and V. G. Simonenko

UDC 539.375

Spall fracture can occur in metallic specimens under explosive and impact loading. It can be diminished or prevented entirely by using spacers of porous materials since they possess high energy absorption characteristics.

On the basis of numerical methods of the mechanics of a continuous medium, the influence of porous spacers on the spall fracture in cylindrical specimens subjected to explosive and impact loading is investigated in this paper.

1. The system of equations describing the behavior of a porous material in a two-dimensional axisymmetric formulation within the framework of the model of an elastic-plastic body has the form

$$\rho\dot{v} = \partial\sigma_z/\partial z + \partial s_{rz}/\partial z + s_{rz}/r,\ \rho\dot{u} = \partial s_{rz}/\partial z$$
$$+ \partial\sigma_r/\partial r + (2s_r + s_z)/r,\ \dot{V}/V = \partial v/\partial z + \partial u/\partial r + u/r,$$
$$\dot{E} = -pV + V[s_z\dot{e}_z + s_r\dot{e}_r + s_{rz}\dot{e}_{rz} - (s_r + s_z)\dot{e}_\varphi], \tag{1.1}$$
$$p = \frac{k_{0m}\left[1 - 0{,}5\Gamma_{0m}\left(1 - \frac{\alpha_0}{\alpha}V\right)\right]}{\alpha\left[1 - s_{0m}\left(1 - \frac{\alpha_0}{\alpha}V\right)\right]^2}\left(1 - \frac{\alpha_0}{\alpha}V\right) + \frac{\Gamma_{0m}E}{\alpha};$$
$$2\mu\dot{e}_r = \frac{D}{Dt}s_r + \lambda s_r,\ 2\mu\dot{e}_z = \frac{D}{Dt}s_z + \lambda s_z, \tag{1.2}$$
$$2\mu\dot{e}_\varphi = \frac{D}{Dt}s_\varphi + \lambda s_\varphi,\ \mu\dot{e}_{rz} = \frac{D}{Dt}s_{rz} + \lambda s_{rz}.$$

Here and below r, z are coordinates, u, v are velocity vector components along the r, z axes, σ_r, σ_z are stress tensor components, p is the pressure, s_r, s_z, s_{rz}, $s_\varphi = -(s_r + s_z)$ are stress deviator tensor components, E is the internal energy, $\dot{e}_r$, $\dot{e}_z$, $\dot{e}_{rz}$, $\dot{e}_\varphi$ are strain rate deviator tensor components, $V = \rho_{00}/\rho$ is the relative volume, $\rho_{00} = \rho_{0m}/\alpha_0$ is the initial density of the porous material, ρ_{0m} is the initial density of the host material under normal conditions, $\alpha = \rho_m/\rho$ is the porosity, α_0 is the initial porosity, ρ is the density, $\mu = \mu_{0m} \times (1 - \xi)\left(1 - \frac{6K_{0m} + 12\mu_{0m}}{9K_{0m} + 8\mu_{0m}}\xi\right)$ is the shear modulus [1], μ_{0m}, K_{0m} are, respectively, the shear modulus and the multilateral volume compression, Γ_{0m} is the Grüneisen coefficient, s_{0m} is a material constant, Y_{dm}, Y_{0m} are the dynamic and static yield points, $\xi = (\alpha - 1)/\alpha$ is the relative pore volume, D/Dt is the symbol of the Jahmann derivative; all quantities without the subscript m refer to the porous material.

The parameter λ in (1.2) is determined by using the Mises flow condition for a porous material in the form

$$s_r^2 + s_z^2 + s_{rz}^2 + s_r s_z = \frac{1}{3}\left(\frac{Y_{Dm}}{\alpha}\right)^2. \tag{1.3}$$

The specific expression for λ is not presented since in the numerical method proposed for the solution of the problem [2], a procedure is used that reduces the stress to a flow circle, which is equivalent to the complete relationships (1.2).

The kinetic equation describing the compression of a porous material can be obtained from the solution of the equilibrium problem for a spherical pore subjected to an applied pressure [3]

Tomsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 115-120, July-August, 1988. Original article submitted February 4, 1987.

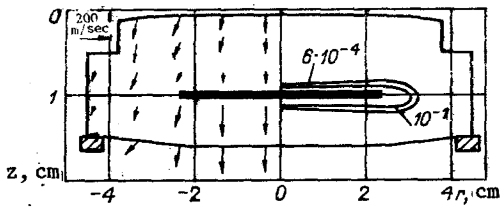

Fig. 1

$$p=\begin{cases}\dfrac{4\mu_{0m}(\alpha_0-\alpha)}{3\alpha^2(\alpha-1)} & \text{for } \alpha_0\geqslant\alpha\geqslant\alpha_1,\\ \dfrac{2}{3}Y_{0m}\left\{1-\dfrac{2\mu_{0m}}{Y_{0m}}\left(\dfrac{\alpha_0-\alpha}{\alpha}\right)+\ln\left[\dfrac{2\mu_{0m}}{Y_{0m}}\left(\dfrac{\alpha_0-\alpha}{\alpha-1}\right)\right]\right\} & \text{for } \alpha_1>\alpha\geqslant\alpha_2,\\ \dfrac{2}{3}Y_{0m}\ln\left(\dfrac{\alpha}{\alpha-1}\right) & \text{for } \alpha_2>\alpha\geqslant\alpha_{00}>1,\end{cases}$$

$$\alpha_1=\frac{2\mu_{0m}\alpha_0+Y_{0m}}{2\mu_{0m}+Y_{0m}},\quad \alpha_2=\frac{2\mu_{0m}\alpha_0}{2\mu_{0m}+Y_{0m}}. \tag{1.4}$$

Pore growth in a plastically deformed material can be computed by means of the equation [4]

$$\dot{\alpha}=(\alpha-1)\left[\frac{3n}{2\eta_0}|\Delta p|\frac{\alpha}{1-\left(\dfrac{\alpha-1}{\alpha}\right)^n}\right]^{1/n} \text{ for } \Delta p=p+\frac{a_s}{\alpha}\ln\left(\frac{\alpha}{\alpha-1}\right)<0, \tag{1.5}$$

where α_{00} is the residual porosity in a continuous material ($\alpha_{00}\approx 1.0006$), and a_s, η_0, n are material constants whose numerical values are presented in [4].

Investigation of the behavior of a porous material subjected to brief pulse loads reduces to solving the system of equations (1.1)-(1.5) under the appropriate initial and boundary conditions. The initial conditions correspond to the fact that the specimen material is in the undeformed state up to the action of the load. The boundary conditions on the free surfaces of the specimen under investigation are that the normal and tangential stress vector components equal zero as does the normal component of the velocity vector at sites of its fastening to a ring support.

Spall fracture in specimens is considered as a process of pore growth in a plastically deformed material. When the critical porosity (a relative pore volume of 0.3) is reached in an element of material, disturbance of the continuity of the material occurs and the stresses therein are taken equal to zero.

2. As experimental data [5] show, spall fracture is formed in a target during the impact of a steel disc (0.5 cm thickness, 7.6 cm diameter) on a steel target (1 cm thickness and 9 cm diameter) at velocities above 215 m/sec. Presented in Fig. 1 at the time 6 μsec is the fracture pattern in the target for a 320 m/sec impact velocity, where isolines of the relative pore volume are displayed by lines by which the degree of target fracture can be judged; the domain of ruptured material is blackened. The limit porosity is reached in one series of cells at the center of the target perpendicular to the impact direction. A mainline crack is formed in this domain of the material.

Spall fracture in the target can be averted if a porous spacer is used. Let us consider the process of steel impactor interaction with a two-layer target consisting of a steel sheet and a sheet of porous iron with the relative pore volume 0.25 (α_0 = 1.34). It is seen from computations that the shock wave in the target is reflected into the steel sheet in the form of an unloading wave upon reaching the interfacial surface of the materials, whereupon the compressive stress level therein is reduced from 4-1.5 GPa. The intensity of the shock being propagated over the porous sheet is inadequate to total compression of the material. Interference of the unloading waves being propagated from the impactor free surface and the material interfacial surface results in the appearance of a domain of tensile stresses at the center of the steel sheet, however their level is insufficient for fracture formation. Pore growth occurs in the target in only a small domain at the contact surface with the impactor. All these features are traced well in Fig. 2 where the mass velocity field and the isolines of the relative pore volume in the impactor and the target are presented at the time 5 μsec.

The fracture pattern in the target containing the porous spacer depends strongly on the impact velocity, the magnitude and location of the porous spacer, and the relative volume of

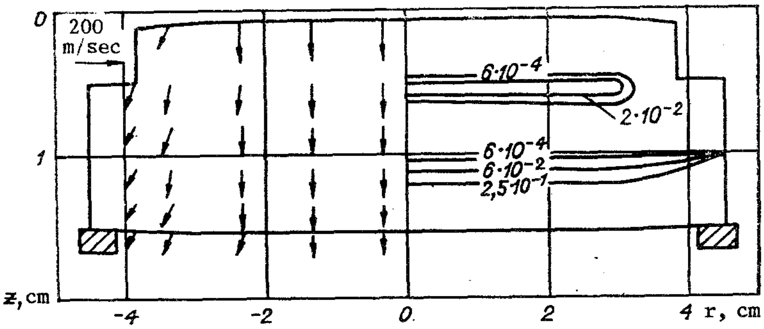

Fig. 2

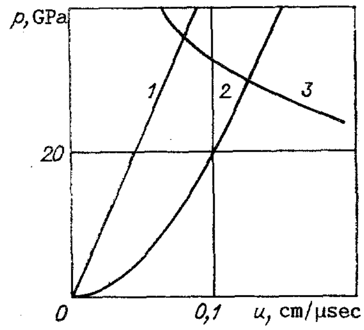

Fig. 3

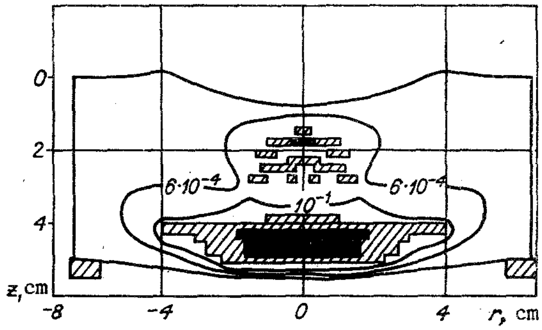

Fig. 4

the pores therein, as computations performed within the framework of one-dimensional deformation showed [6].

3. We examine the influence of porous spacers on the spall fracture in metal discs subjected to explosive loading by cylindrical superposed HE charges. In order to simplify the solution of the problem, the action of the detonating charge on the metal disc is replaced by the action of a pressure pulse

$$p(r, z, t) = p_0\left(1 - \frac{t}{T_0}\right)\left[1 - 0.5\left(\frac{r}{r_0}\right)^2\right],$$

where $T_0 = 2I_s/(\pi p_0 r_0^2)$ is the time of detonation product action on the disc, $I_s = 0.8(h/r_0)^{1/3}\rho_{0H} r_0^3 D_H$ is the total impulse transmitted to the disc by the detonation products [7], D_H is the detonation wave velocity, h, d = $2r_0$ are the HE charge height and diameter, and ρ_{0H} is the charge density.

A shock whose intensity depends on the HE charge characteristics occurs during detonation product interaction with a metal disc. As regards the detonation products, a reflected shock is propagated over it whose initial intensity is determined by the dependence [8]

$$u = \frac{D_H}{m+1}\left[1 - 2\sqrt{m}\frac{k-1}{\sqrt{(m+1)k + (m-1)}}\right].$$

Here $k = 4p/(\rho_{0H} D_H^2)$, m is the polytropic index, and u is the mass velocity.

The solution of this equation in conjunction with the shock adiabatic equation for the disc material completely determines the solution of the problem of finding the initial pressure p_0 on the separation boundary. The method of constructing the porous material adiabat is presented in [6].

Figure 3 shows a solution, by a graphical method, for the problem of finding the initial pressure p_0 on the surface of monolithic and porous steel obstacles during the explosion of a cylindrical HE charge (α_0 = 1.34, ρ_{0H} = 1.65 g/cm³, D_H = 7655 m/sec, m = 3) lines 1 and 2 are shock adiabats of the continuous and porous iron, 3 is the secondary expression adiabat of the detonation products.

The fracture pattern in a steel disc (12.7 cm diameter, 5.08 cm height) subjected to the action of an impulsive load simulating a contact explosion of a cylindrical HE charge (d = h = 5.08 cm, ρ_{0H} = 1.65 g/cm³, D_H = 7655 m/sec) is presented at the time 20 μsec in Fig. 4. The geometric dimensions of the steel disc and the applied HE charge are taken the same as

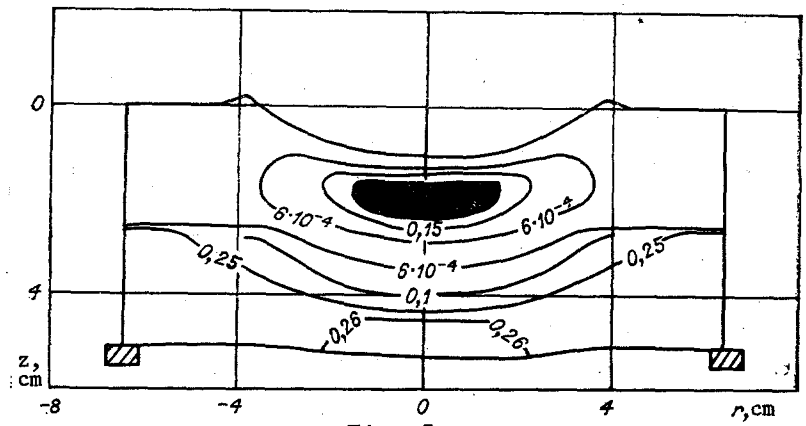

Fig. 5

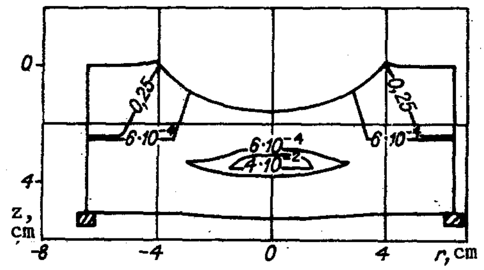

Fig. 6

in [9]. The shaded zones are the material domains in which the relative pore volume is greater than 0.15. Two fracture zones were formed in the disc. The main fracture domain is parallel to the rear surface of the disc. The second fracture zone is under a crater. It appeared because of interference of the unloading waves being propagated from the contact surface and the free facial surface of the disc. Both fracture zones are observed in experiment [9].

Shown in Fig. 5 are the fracture and isolines of the relative pore volume in a two-layer disc at the time 20 μsec. The first sheet of the disc is steel, while the second is porous iron with a relative pore volume of 0.25.

Interaction of opposing unloading waves being propagated from the free facial surface of the steel sheet and from the interfacial surface of the materials resulted in the formation of a fracture domain at the center of the steel sheet. The shock being propagated over the porous material first compresses it. Its intensity drops during propagation so that the porous material remains practically uncompressed behind the shock front in the last times. Having reached the free rear surface of the porous layer it is reflected in the form of unloading waves whose interference with the unloading waves being propagated from the free surface of the steel sheet results in an increase in the relative pore volume at the disc rear surface.

Figure 6 illustrates the fracture and isolines of the relative pore volume in a two-layer disc at the time 21 μsec, where the first sheet is porous iron while the second is steel. The shock intensity in the porous layer is sufficient for compression of the central part of the porous material layer to a continuous material. Material domains adjoining the free side surface of the porous layer and the crater edge remained uncompressed. Fracture did not occur in this modification of the computation. Only a small domain of material in which insignificant growth of the porosity occurred as a result of interference of the opposing unloading waves being propagated from the free facial and rear surfaces of the disc, was formed at the center of the disc.

Therefore, it follows from the above that porous spacers protect specimens under explosive loading well if they are on their facial surface.

LITERATURE CITED

1. J. N. Johnson, "Dynamic fracture and spallation in ductile solids," J. Appl. Phys., 52, No. 4 (1981).

2. M. L. Wilkins, "Computation of elastic-plastic flows," in: Computational Methods in Hydromechanics [Russian translation], Mir, Moscow (1967).
3. M. M. Carrol and A. C. Holt, "Static and dynamic pore-collapse for ductile porous materials," J. Appl. Phys., 43, No. 4 (1972).
4. N. N. Belov, A. I. Korneev, and A. P. Nikolaev, "Numerical analysis of fracture in slabs subjected to impulsive loads," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1985).
5. A. G. Ivanov, O. A. Kleshchevnikov, et al., "Spall in steel," Fiz. Goreniya Vzryva, No. 6 (1981).
6. N. N. Belov, A. I. Korneev, and V. G. Simonenko, Investigation of the Influence of Interlayers from Porous Material on Spall Fracture of Metallic Slabs [in Russian], Dep. in VINITI Dec. 12, 1985, No. 8859-B85, Moscow (1985).
7. E. P. Shubin, "On regularities of the change in a pressure pulse on an obstacle surface near a HE charge," Fiz. Goreniya Vzryva, No. 3 (1965).
8. F. M. Baum, L. P. Orlenko, K. P. Stanyukovich, et al., Physics of Explosion [in Russian], Nauka, Moscow (1975).
9. G. Reinhart, "Certain experimental data on the stress caused by an explosion," Mekhanika, No. 4 (1953).

EQUATIONS OF ISOTROPIC DEFORMATION OF GAS-SATURATED MATERIALS WITH ALLOWANCE FOR LARGE STRAINS OF SPHERICAL PORES

V. A. Buryachenko and A. M. Lipanov

UDC 539.4

We will examine a composite medium consisting of a homogeneous isotropic matrix and spherical pores saturated with gas. The character of location of the pores is assumed to be statistically uniform. The effective-field method was used in [1-3] to obtain equations of state of gas-saturated porous media with the assumption of small strains of the pores and the medium as a whole [1]. In the case of large general strains, it is natural to examine methods of solution involving the use of successive approximations [4], such as was done in in an examination of composite media by the method of conditional functions [5]. The latter method is based on the assumption that the stress field is uniform within each component of the composite – an assumption which leads to large errors in evaluating the effective parameters of linearly elastic media compared to the effective-field method [1, 2]. The authors of [6, 7] analyzed arbitrarily large strains for the special case of isotropic deformation of a material with spherical pores and an incompressible matrix, using a cellular model to perform the analysis. Here, we solve a similar problem with allowance for the effect of gas pressure in the pores, and we make use of the ideas behind the effective-field method [1, 2] in doing so. The usefulness of this method has been proven in studies of linear problems for micro-inhomogeneous media.

1. Physical Model. In a number of cases of practical importance, it is of interest to study the volumetric deformation of rubber-like materials with a low ($\leqslant 1\%$) porosity. For the sake of determinateness, we will describe the strain properties of the matrix with a Mooney potential [4]. The authors of [1] showed that in linear problems of gas-saturated porous media, the effects of binary interaction of inclusions are unimportant for spherical pores in an incompressible matrix in the case of low porosity. Here, the effective bulk modulus is determined by the solution of the linearly elastic problem of a single inclusion in a matrix with a certain effective stress field specified at infinity. Thus, it is acceptable to make use of the cellular model in [6, 7]. This model presumes equivalent strain properties for a porous medium and a thick-walled spherical shell and equality of the ratio of the volumes of the pore and spherical element to the porosity of the composite medium being modeled. Here, we will use the positive ideas behind the effective-field method and we will place the spherical element in a matrix with a prescribed effective stress field at infinity which differs from the acting stress field. We find the parameters of this field by the self-consistent effective-field method [1, 3]. The method makes it unnecessary to postulate the relationship between the relative dimensions of the spherical element and the porosity of

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 120-124, July-August, 1988. Original article submitted March 24, 1987.