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CALCULATION OF A SHOCK ADIABATIC CURVE FOR SYNTACTIC FOAM TAKING INTO ACCOUNT PRESENCE OF GAS COMPONENT LOCALIZED IN HOLLOW MICROSPHERES

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Abstract. Calculation method for shock adiabatic curves of syntactic foam are considered. The comparison results of the calculated and experimental data are given. The satisfactory consent of these data is shown. Influence of gas components on dynamic compressibility of syntactic foam is received when initial gas pressure is more 50 bar.

1. Introduction

Composites based on hollow microspheres (HMS) and called syntactic foams (SF) have found wide application in the making of constructions elements of aircraft and submarines [1, 2]. Their production requires materials having high specific deformation-strength characteristics. The SF advantage becomes predominant at high volumetric HMS content (>50 %). Syntactic foams are exposed to a wide range of loads (including non-stationary loading) when they are working in such constructions. In addition, highly porous materials containing multi-component HMS are used as protective layers of the aircraft under mechanical and thermal actions of radiations and particles fluxes [3]. Prediction of parameters of wave processes developing in SF under non-stationary actions requires knowledge of SF shock-wave characteristics (in particular the shock adiabatic curve (SAC)) [4, 5].

Additive approximation [6] is often used when calculating of SAC for multicomponent mixtures can also be true in the absence of the thermal pressure component which increases with an increase of medium porosity and cannot be ignored for shock compression of highly porous materials. The Zeldovich's model [7] of full pore collapse at any pressure other than zero does not allow to consider the presence of gas localized in the pores and a more detailed description for the process of pore collapse is required. But HMS contain a gas of high density in some cases [8, 9] and the gas component can influence on the SAC.

The HMS strength (on the order of hundreds of bar) is low compared to the pressure behind the shock wave (SW) and SF can be considered as a mixture of materials of the walls of destroyed microspheres and binder and gas contained in HMS before their destruction. The contribution of the gaseous component of the porous mixes was considered in [10-12].

2. Calculation of shock adiabatic curve for porous heterogeneous medium

A mixture of solid particles of matter and gas is a special case of a porous heterogeneous medium. The calculation of its SAC is based further on a one-velocity model of the continuous medium (the validity of the one-speed approximation for SW propagated in heterogeneous material is discussed in [13]). In addition, it is assumed that temperature and pressure have to be equal between material components behind the SW front. Equality of pressures and temperatures can occur if the SW front is localized in a porous heterogeneous medium and is realized in a narrow region but this region is sufficient to establish a partial thermodynamic equilibrium (for temperature and pressure) [11].

The components of a ternary mixture (solid particles and gas) is labeled with the indices: 1, 2 are components of solid particles (from materials of destroyed HMS walls and resin matrix in our case); *g* is gas. The Mie-Gruneisen equation is used to describe the behavior of matter (electronic components of pressure and energy are assumed to be small; the heat capacity are considered as constant; *i*=1,2,*g*):

$$P_i = P_{xi}(\rho) + \Gamma_i(\rho)\rho c_{vi}(T - T_0), \qquad E_i = E_{xi}(\rho) + c_{vi}(T - T_0), \qquad E_{xi} = \int_{\rho_0}^{\rho} P_{xi}(\rho)/\rho^2 d\rho, \qquad (1)$$

where P, E, T are, respectively, the pressure, specific internal energy and the temperature; P_x, E_x are cool components of the pressure and specific internal energy; ρ, ρ_0 are current and initial (for conditions $T = T_0$, P=P_0) densities; the $\Gamma(\rho)$ is Gruneisen coefficient.

Used equations of state (EOS) (1) are normalized so that specific internal energy is equal to zero when $\rho = \rho_0, T = T_0$. Such normalization simplifies the equations for the energies change at the SW front propagating in an unperturbed environment under normal conditions. We have for the van der Waal's gas (μ is molecular mass of gas)

$$P_{xg}(\rho) = -\frac{a}{\mu^2}\rho^2, \quad \Gamma_g(\rho) \equiv (\gamma - 1)\frac{1}{1 - (b/\mu)\rho}, \quad E_x(\rho) = -\frac{a}{\mu^2}(\rho - \rho_0),$$

where γ is the adiabatic constant; a, b are der Waal's constants.

To calculate SAC we write for the SW front the equations of conservation of mass fluxes (for each of the solid and gas components of the mixture separately) and the momentum conservation equation and also equation of change of internal energy (for i=1,2,g):

$$\rho_{i0}\eta_{i0}\, D = \rho_i\eta_i\, (D - U), \qquad (2)$$

$$P_0 + \sum_i \rho_{i0}\eta_{i0}\, D^2 = P + \sum_i \rho_i\eta_i\, (D - U)^2, \qquad (3)$$

$$\sum_i m_i E_i = -\frac{1}{2}(P + P_0)\sum_i m_i\left(\frac{1}{\rho_i} - \frac{1}{\rho_{i0}}\right), \qquad m_i = \frac{\rho_{i0}\eta_{i0}}{\sum_i \rho_{i0}\eta_{i0}}, \qquad (4)$$

where η_i, m_i are volume and mass fractions of the mixture components; D is the SW velocity; U is the mass velocity behind the SW.

It is assumed that all values are known before the SW front. Then ten unknown quantities $D, U, T, P, \rho_i, \eta_i$ (*i*=1,2,*g*) are included in the non-linear system of five equations (2)-(4) and three EOS for the mixture components and obvious condition $\sum \eta_i = 1$. This fact allows us to find mixture SAC in the form of dependence of the kinematic variables $D = D(U)$ or the dependence $P(U)$ or shock compressibility $P = P(\sigma_\Sigma)$ ($\sigma_\Sigma = \rho_\Sigma / \rho_{\Sigma 0}$ is the degree of mixture compression, ρ_Σ is the mixture density on the whole).

The solution of the nonlinear equations system is searched numerically. With this purpose the system is reduced to a single nonlinear equation ($\sigma_2 = \rho_2 / \rho_{20}$ is the degree of compression of the second component). The mixture pressure can be expressed as a function of compression degrees if you use the equality of the pressures in the components *i* and *j* (we have two independent equations in our case)

$$P_{xi}(\sigma_i) + \Gamma_i(\sigma_i)\rho_{i0}c_{vi}(T - T_0) = P_{xj}(\sigma_j) + \Gamma_j(\sigma_j)\rho_{j0}c_{vj}(T - T_0).$$

Next, we find the temperature increment and substitute it in the EOS of *i*-component. The result is (it is obviously that we shell find equivalent equation by substitution temperature increment in the EOS of *j*-component)

$$P=\frac{P_{xi}(\sigma_i)-\alpha_{ij}(\sigma_i,\sigma_j)P_{xj}(\sigma_j)}{1-\alpha_{ij}(\sigma_i,\sigma_j)},\qquad \alpha_{ij}(\sigma_i,\sigma_j)=\frac{\Gamma_i(\sigma_i)}{\Gamma_j(\sigma_j)}\frac{\sigma_i}{\sigma_j}\frac{\rho_{i0}c_{vi}}{\rho_{j0}c_{vj}}. \tag{5}$$

Here the compression degrees $\sigma_i=\rho_i/\rho_{i0}$ are used in (5) instead of densities ρ_i since initial densities are considered as known. It is convenient and is used also in subsequent equations. We get from (4) and EOS of mixture components (1) (here temperature is excluded as well):

$$2\sum_i\rho_{i0}\eta_i\left(E_{xi}(\sigma_i)-\frac{P_{xi}(\sigma_i)}{\Gamma_i(\sigma_i)\rho_{i0}\sigma_i}\right)=(P+P_0)\sum_i\eta_{0i}\left(1-\frac{h_i(\sigma_i)}{\sigma_i}\right),\qquad h_i=\frac{2}{\Gamma_i(\sigma_i)}+1, \tag{6}$$

The mixture pressure is determined from (6)

$$P=2\sum_i\rho_{i0}\eta_i\left(E_{xi}(\sigma_i)-\frac{P_{xi}(\sigma_i)}{\Gamma_i(\sigma_i)\rho_{i0}\sigma_i}\right)\left(\sum_i\eta_{i0}\left(1-\frac{h_i(\sigma_i)}{\sigma_i}\right)\right)^{-1}-P_0. \tag{7}$$

The basic nonlinear equation for determining the compression degree σ_2 is found from (5) (for i=1, j=2) and (7)

$$\frac{P_{x1}(\sigma_1)-\alpha_{12}(\sigma_1,\sigma_2)P_{x2}(\sigma_2)}{1-\alpha_{12}(\sigma_1,\sigma_2)}-2\sum_i\rho_{i0}\eta_{i0}\left(E_{xi}(\sigma_i)-\frac{P_{xi}(\sigma_i)}{\Gamma_i(\sigma_i)\rho_{i0}\sigma_i}\right)\left(\sum_i\eta_{i0}\left(1-\frac{h_i(\sigma_i)}{\sigma_i}\right)\right)^{-1}-P_0=0. \tag{8}$$

Unknown compression degrees σ_1,σ_g are present in this equation. Therefore, the calculation of the left part (8) is done as follows. The lot of values $\{\sigma_1\}$ is set. Next, the pressure of the mixture P is found for each of these values from equation (5) with i=1, j=2 and given σ_2

$$P=\frac{P_{x1}(\sigma_1)-\alpha_{12}(\sigma_1,\sigma_2)P_{x2}(\sigma_2)}{1-\alpha_{12}(\sigma_1,\sigma_2)},\qquad \alpha_{12}(\sigma_1,\sigma_2)=\frac{\Gamma_1(\sigma_1)}{\Gamma_2(\sigma_2)}\frac{\sigma_1}{\sigma_2}\frac{\rho_{10}c_{v1}}{\rho_{20}c_{v2}}.$$

The degree of compression of the gas is determined from equation (5) for i=g, j=1 as the pressure P is already known

$$\frac{P_{x1}(\sigma_g)-\alpha_{g1}(\sigma_g,\sigma_1)P_{x1}(\sigma_1)}{1-\alpha_{g1}(\sigma_g,\sigma_1)}=P,\qquad \alpha_{g1}(\sigma_g,\sigma_1)=\frac{\Gamma_g(\sigma_g)}{\Gamma_1(\sigma_1)}\frac{\sigma_g}{\sigma_1}\frac{\rho_{g0}c_{vg}}{\rho_{10}c_{v1}}. \tag{9}$$

Then we find the compression degree σ_2 by numerical solution of (8) $F(\sigma_2)=0$ with known σ_1,σ_g. Other required values are easily determined since degrees of compression of all mixture components $\sigma_1,\sigma_2,\sigma_g$ are already known. In the result, we obtain SAC having parametric form, where the parameter is compression degree σ_1 defined earlier as the lot of values $\{\sigma_1\}$. For example, the kinematic dependence $D=D(U)$ is calculated in the form $D=D(\sigma_1),\ U=U(\sigma_1)$.

Determination of the compression degree σ_g is not required and equation (9) is not solved if there is no gas in the pores. Then the contributions of a gas component is equal to zero in all the equations given above except (4), (6)-(8). In particular, the gas contribution $\eta_{g0}\left(1-h_g(\sigma_g)/\sigma_g\right)$ is not approaching zero in the main equation (8) and is equal to the value of the initial volume content of pores η_{p0} ($\eta_{g0}\to\eta_{p0}$).

3. The shock adiabatic curve and dynamic compressibility of syntactic foam

Equations of states for of materials of HMS and binder EPC (epoxy-polyamide composition) were used in simplest form [11,12] for syntactic foam also. The initial volumetric contents of components (1 is SiO_2, 2 is EPC) were taken equal to $\eta_{10}=10{,}4\%$, $\eta_{20}=23{,}7\%$ that corresponds to a known initial SF density 0.56 g/cm3 at a relative HMS thickness $h/R=1/20$.

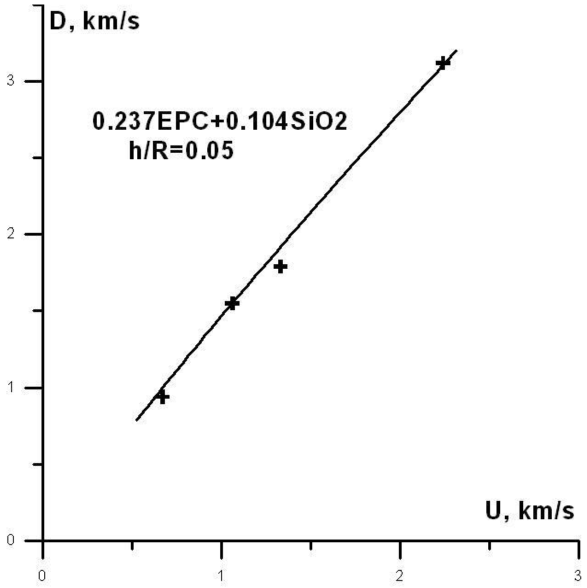

Fig. 1. Shock adiabatic curve.

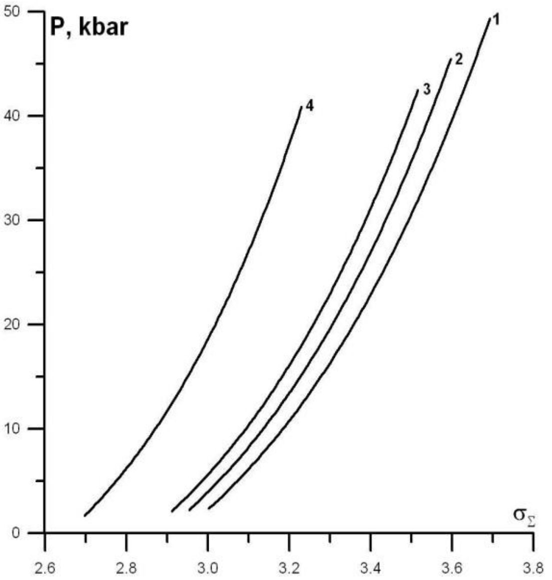

Fig. 2. Dynamic compressibility.

The results of the comparison of the calculated and experimental (crosses) data for the SF shock adiabatic curve $D-U$ are presented in figure 1. Experimental data obtained by the authors using the shock-wave method [5]. Dynamic SF compressibility are given in figure 2 for different initial gas pressures localized in HMS (1 is $P_{p.}$=0, 2 is $P_{p.}$=50bar, 3 is $P_{p.}$=100 bar, 4 is $P_{p.}$=500 bar).

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