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FRONT STRUCTURE OF A WEAK SHOCK WAVE IN DENSE COMPOSITES

B. R. Gafarov, A. V. Utkin, S. V. Razorenov,
A. A. Bogach, and E. S. Yushkov

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The structure of the compression-pulse front in a heterogeneous energy material with a characteristic size of granules of 100–300 μm *and its inert simulator with a particle size of 3–5 mm is studied experimentally. Shock waves with an amplitude of the order of* 0.1 GPa *were initiated by a* 20-g *explosive charge. The velocity of the free surface of the samples or the velocity on the boundary with a water window was recorded by a VISAR laser interferometer. It is shown that the variation in the mass rate in an energy material is of oscillating character, which is explained by the heterogeneous structure of the samples. Oscillations were not observed in a finely dispersed simulator. In addition, it is shown that the viscoelastic Maxwell model is suitable for averaging the description of the evolution of the compression pulse in the studied materials.*

Introduction. The properties of dense polymers under shock-wave loading are of great interest owing to important engineering applications [1–3]. In particular, among this class of media are energy materials (EM) of the elastomeric binder–crystalline oxidizer type with a volumetric content of the oxidizer of up to 70%, for which data on the shock-wave compressibility and the thresholds of ignition and spalling fracture [4–7] are available. However, data on the rheological properties of these materials are scarce in the literature, although it is impossible to perform numerical modeling of the processes of propagation, interaction, and damping of compression and tension pulses in actual structures without these data. Therefore, dissipation [6] is often ignored or simplified material models with estimated values of the viscosity [2] are used.

The greatest success was achieved for composite materials with properties periodically varying in space (see, e.g., [8, 9]). The distinctive feature of these media is the disperse properties which lead to expansion and smoothing of compression pulses even when the initial components are in an elastic state. The general wave energy is redistributed in such a way that the effect of damping is observed. In an averaged description of the evolution of shock waves in heterogeneous materials, this effect can be taken into account within the framework of a homogeneous viscoelastic medium. This was shown in [10], where the results of a numerical calculation of the propagation of a shock wave in a viscoelastic layered system are approximated by a shock wave propagating in a homogeneous medium described by Maxwell's relaxation model. The characteristic relaxation time was determined with the use of the front structure of a stationary shock wave.

The goal of the present work is to study experimentally the front structure of two heterogeneous materials with different particle sizes of a filler and to analyze the possibility of using the relaxation model to describe the results.

Scheme of Experiments. The object of our study is an EM consisting of polybutadiene rubber filled with ammonium perchlorate and HMX with a characteristic size of granules of 100–300 μm and finely dispersed aluminum. The density of the material ρ_0 is equal to 1.87 g/cm^3; its shock adiabat was found in [4, 7] and corresponds to the generalized shock adiabat of condensed substances [11]:

$$D = 2.1 + 2.0\,u,$$

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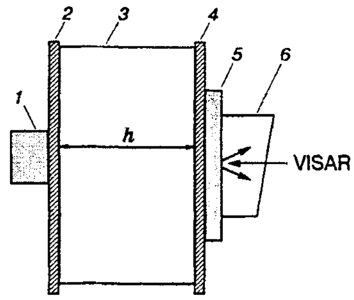

Fig. 1

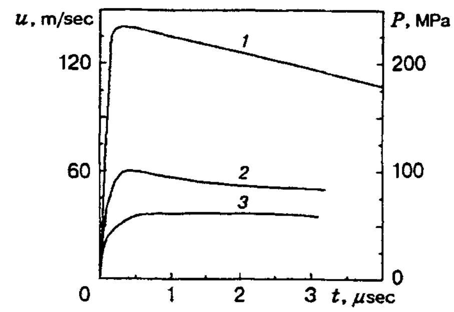

Fig. 2

where D is the velocity of the shock wave and u is the mass rate (in km/sec). The sound velocity C_e measured by an ultrasonic method is close to the first coefficient in the shock-adiabat equation. The porosity of the material is a hundredth fractions of a percent, and the filling with crystalline components is at the level of dense packing. Therefore, contact interaction between the particles in the crystal phase is possible in this composite under shock-wave loading.

The second material that we studied, namely, the inert simulator of the EM which has the same binder but is filled with fine-disperse aluminum and chalk with a characteristic size of granules of 3–5 μm and total volume portion of the order of 50%, had the same density and shock adiabat as the EM.

To generate compression pulses of small amplitude (of the order of 0.1 GPa), an experimental setup shown schematically in Fig. 1 was used. Shock waves were initiated by charge 1 of an A-IX-1 explosive substance. The diameter of the charge was 20 mm, and its weight was 20 g. The charge was placed on an aluminum plate 2 of thickness 2 mm. The shock-wave parameters were varied by varying the thickness h of water layer 3 between the explosive substance and sample 5 to be examined; the latter was separated from water by Plexiglas 4 of thickness 2 mm. The transverse size of the setup was 150 mm.

The EM samples and its simulator in the form of a round plate were 90 mm in diameter and 20 mm thick. The front structure was determined using the velocity of the free surface of the samples or the velocity of the boundary with a water window 6. The velocity was recorded by a VISAR laser interferometer [12] with the interferometer constant equal to 80.8 m/sec. This allowed us to perform measurements with an accuracy of ± 2 m/sec and a time resolution of approximately 5 nsec. For the reflection of a laser beam from the studied surface, the latter was made even by epoxy resin to which an aluminum foil of thickness 7 μm was stuck. The total thickness of the coating did not exceed 150 μm, which corresponded to the roughness of the material due to its structure. The dynamic rigidity of epoxy resin is approximately 12% smaller than the rigidity of the EM. Therefore, this reflecting layer will not cause marked distortions in the shape of the front, which is supported by the analysis of the results given below. The beam of the interferometer was focused on a spot of about 100 μm in size, which coincides with the characteristic size of the filler granules. One can expect a scatter of data in the experiments because of the small area of averaging over the surface.

Experimental Results. Preliminary experiments were carried out to determine the dependence of the amplitude of compression pulses on the distance to the explosive substance. In these experiments, the mass rate behind the shock-wave front in water was recorded. For the reflection of a laser beam in water, an aluminum foil of thickness 100–200 μm was placed at a fixed distance from the charge h. The results obtained in the P measurement for $h = 50$, 100, and 150 mm are shown by curves 1–3 in Fig. 2. One can see that, for $h > 100$ mm, the water pressure does not exceed 100 MPa (curves 2 and 3), which allows one to obtain compression pulses of required amplitude in the samples. The thick aluminum foil ensured reliable recording of the mass rate, but simultaneously smeared the front. Therefore, the experimentally measured width of the jump greatly exceeds the width of the shock-wave front in water.

The formed shock wave is divergent. Generally speaking, this should be taken into account in the interpretation of experimental data. However, one can expect that this will not lead to a significant change

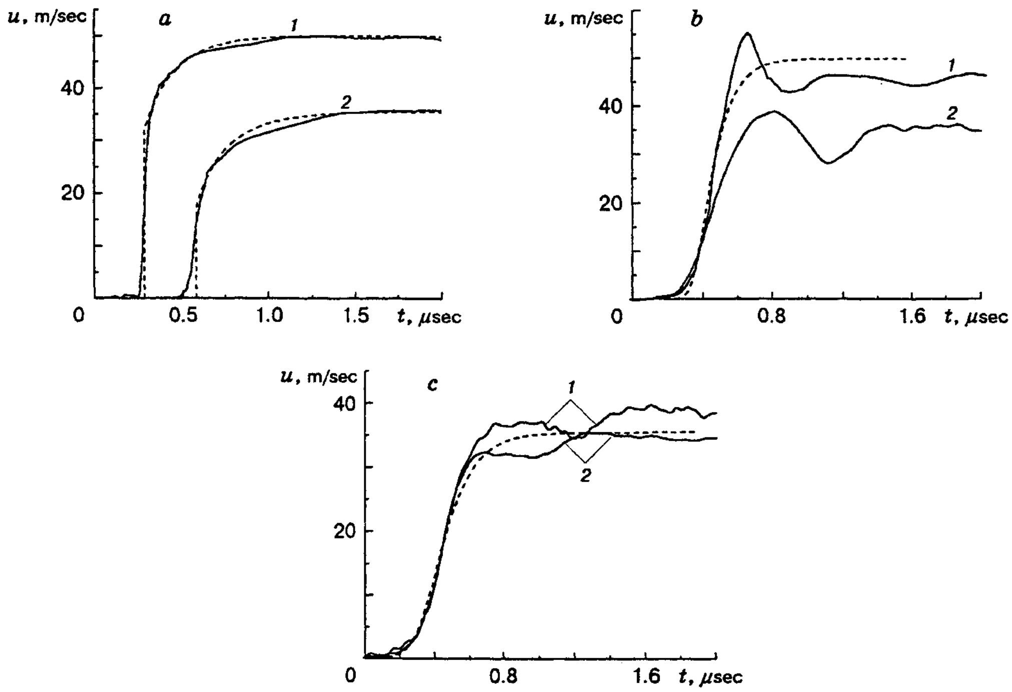

Fig. 3

in the structure of the shock-wave front compared with one-dimensional loading.

Figure 3 shows the experimental results for the EM and its simulator. For water thickness $h = 100$ and 150 mm, the velocity of the free surface of the simulator is shown by solid curves 1 and 2 in Fig. 3a. At the moment when the shock wave reaches the free surface, the velocity increases abruptly for 30–50 nsec and then reaches slowly a finite magnitude for approximately 1 μsec. The profile structure is similar to the front structure recorded in polymers [13], the behavior of which is viscoelastic under loading below the dynamic yield point [14]. In this case, the specific features that are due to the heterogeneous structure of the material were not observed, because the size of the focal spot on which the velocity was averaged over the surface was one order of magnitude larger than the characteristic size of the inhomogeneities.

A different structure of the front was recorded in the EM. The velocity of the free surface of the sample (curve 1) and the unloading rate into water (curve 2) are shown by solid curves in Fig. 3 under the same loading conditions ($h = 100$ mm). In contrast to the simulator, in this case, one can observe the slow s-shaped increase in the velocity from zero to the maximum value for approximately 0.4 μsec. The distinctive feature is the formation of a characteristic peak whose amplitude exceeds the finite velocity. Evidently, this peak is due to the internal structure of the EM and is connected with the fact that the velocity is averaged over the area of the focal spot whose size is of the order of the size of the inhomogeneities. The profile is qualitatively reproduced from experiment to experiment, which is seen from comparison of both dependences. Only the displacement of the velocity peak in time and the variation in its duration are observed. The averaged velocity profile can be constructed by this scheme only if there are many experimental dependences obtained under the same loading conditions.

After the wave reaches the free surface, a rarefaction wave propagates in the depth of the sample; the presence of the velocity peak leads to the occurrence of tensile stresses, which can cause spallation of the internal layers of the EM [15]. This explains the damping oscillations of the velocity on curve 1 after the peak. This assumption is supported by experimental data (curve 2), when tensile stresses do not occur under unloading into water and after the first peak the velocity increases and reaches monotonically a finite value without any oscillations. Therefore, the velocity of the free surface can be regarded as a mass rate inside the sample only before the moment when the first minimum on curve 1 is reached. The minimum velocity is determined by the magnitude of the spalling strength rather than the oscillation amplitude. The spalling strength can be found from the difference between the maximum and minimum values of the velocity and is equal to (23 ± 2) MPa, which is in agreement with known results [7]. The duration of the peak makes it possible to estimate the thickness of a spalling plate, which is approximately 0.5 mm and is 3–4 times greater than the thickness of the layer of epoxy resin, i.e., the fracture occurs in the internal layers of the EM rather than at the boundary of the reflecting layer. Spallation causes not only overestimation of the minimal, but also underestimation of the finite velocity, whose magnitude (curve 2 in Fig. 3b) is equal to (49 ± 2) m/sec. This coincides with the data for the simulator (curve 1 in Fig. 3a) obtained in similar conditions.

Solid curves 1 and 2 in Fig. 3c show the velocity of the free surface of the EM for a water layer with $h = 150$ mm in two experiments. As for the compression pulse of a greater amplitude, the slow (of the order of 0.4 μsec) increase in the velocity is first observed, and then a velocity peak is formed. However, this peak is less pronounced than in the high-pressure experiments (solid curves in Fig. 3b), and its amplitude is smaller than the finite velocity. In this case, the rarefaction wave reflected from the free surface does not cause spallation of the sample. Satisfactory reproduction of the experiments is observed (curves 1 and 2 in Fig. 3c): the position of the peak and its width are somewhat shifted in time. The finite velocities obtained after averaging of both dependences coincide, within the accuracy of experiment, with the experimental data for the simulator (curve 2 in Fig. 3a) and is equal to (37 ± 2) m/sec.

There are no specific features connected with the thickness of the reflecting layer on the experimental dependences; therefore, the results given in Fig. 3 are the structure of the shock-wave front in the studied materials.

Discussion of Experimental Data. It has already been mentioned that the resulting velocity profiles are qualitatively similar to those occurring in a viscoelastic material. For these media, the front structure of the steady-state shock wave was examined in many studies [10, 14, 16, 17]. The distinctive feature of these media is the existence of instantaneous and equilibrium impact adiabats: in impact loading the substance first reaches an instantaneous shock adiabat and then relaxes to an equilibrium state. Therefore, the stationary compression wave consists of a shock jump and a subsequent monotone increase in the parameters to the amplitude value. This front structure observed in experiments with a simulator (Fig. 3a) exists until the shock-wave velocity is greater than the instantaneous sound velocity C_i. If $C_e < D < C_i$, the shock jump is not formed, and the parameters increase monotonically, as occurs with the EM at the initial moment (Fig. 3b and c).

We consider the possibility to apply the viscoelastic Maxwell model to a description of experimental data.

In the Maxwell model, in the case of a plane strain state, the stress σ and the strain ε are connected by the relation

$$\dot{\sigma} + \frac{\sigma - \sigma_e}{\tau} = G_i \dot{\varepsilon} \tag{1}$$

in the direction of the wave propagation, where σ_e is the equilibrium value of the longitudinal stresses, τ is the relaxation time, and G_i is the instantaneous-strain modulus determined via the curve of instantaneous strain $\sigma_i - \varepsilon$ ($G_i = d\sigma_i/d\varepsilon$) (the dot denotes derivative with respect to time t). For a stationary shock wave, all the parameters are the functions of one variable; therefore, it is convenient to use the mass rate as this variable:

$$\sigma = \rho_0 D u, \qquad \varepsilon = u/D. \tag{2}$$

We also assume that σ_i and σ_e can be written in the form

$$\sigma_e = \rho_0 (C_e + bu) u, \qquad \sigma_i = \rho_0 (C_i + bu) u, \qquad b = 2. \tag{3}$$

Substituting (2) and (3) into (1), to determine u we obtain an ordinary differential equation whose solution has the form

$$\frac{t - t_0}{\tau} = -\left(1 + \frac{C_i - C_e}{D - C_e}\right) \ln (u_e - u) - \frac{D - C_i}{D - C_e} \ln u, \tag{4}$$

where t_0 is the integration constant and u_e is the equilibrium value of the mass rate equal to $(D - C_e)/b$. For

$D > C_i$, a shock wave, in which the mass velocity varies jumpwise from zero to $u_i = (D - C_i)/b$, is formed. Its further increase is described by relation (4), in which t_0 can be chosen in such a way that $u = u_i$ for $t = 0$. If $C_e < D < C_i$, the velocity profile is s-shaped, and u vanishes as $t \to -\infty$ and tends asymptotically to u_e as $t \to +\infty$. The integration constant is chosen arbitrarily and determines only the displacement in time. In a more general formulation for a nonlinear viscoelastic model and with allowance for the quadratic dependence of the shock-wave velocity on u, the problem was solved by Schuler [14].

For $C_i = 2.12$ km/sec and $\tau = 0.15$ μsec (dashed curves in Fig. 3a), the calculated stationary wave profiles for the simulator agree well with the experimental data. The velocity of the free surface was assumed to be equal to the double mass rate.

It is noteworthy that the Maxwell model gives the averaged velocity distribution, whereas, for the EM, the measurements were carried out at local points. The consequence of the locality of measurements is, in particular, the characteristic peak on the velocity profile. This distribution of dynamic parameters is typical of heterogeneous media. The problem of the propagation of a nonstationary wave in a periodic laminated system perpendicular to the planes of stacking of the layers was solved analytically by Peck and Curtman [18]. It was shown that the compression-pulse profile is oscillating, and the characteristic stress relaxation, which indicates the resonance behavior of the medium, occurs. These conclusions were supported experimentally by Whittier and Peck [19] and Lundergan and Drumheller [20]. The influence of the nonperiodicity of the layers on the character of wave damping was investigated by Christensen [21]. Qualitatively similar results were obtained for pulse propagation in three-dimensional periodic media [22].

The problem of wave propagation in heterogeneous media was solved numerically in [10, 20, 23]. Of greatest interest is the study by Barker [10], where the averaging of the wave profile over the thickness of one period of a layered composite was shown to suppress the resonance effect; the averaged profile is well described by the viscoelastic model. The disordering of the layered system also led to a decrease in the amplitude of oscillations. It is noteworthy that the averaging of the wave profiles obtained in a given cross section of the sample for a different character of its disordering also gave the front structure predicted by the viscoelastic model.

Our experiments do not allow one to find the averaged profile of the mass rate for the EM. Therefore, based on the results of [10], we shall describe the front structure of PM by Maxwell's relaxation model with a view to obtaining only a satisfactory approximation of the averaged width of the front. The calculation results obtained with the use of Eq. (4) for $C_i = 2.18$ km/sec and $\tau = 40$ nsec are shown by dashed curves in Fig. 3b and c. Although these curves do not describe the resonance peak, they show the mean width of the front quite satisfactorily. This is true, in particular, for small-amplitude experiments, where the calculated profile coincides, within the accuracy of experiment, with the velocity profile obtained by averaging curves 1 and 2 in Fig. 3c.

Within the framework of the relaxation model of a homogeneous medium, the difference between the front structures of the simulator and the EM is connected with the difference between their instantaneous shock adiabats, although their equilibrium adiabats coincide. In our experiments, the wave velocity of the simulator is greater than the instantaneous sound velocity and smaller in the EM. Therefore, a shock jump is formed in the simulator, and a slow increase in the velocity of the compression wavefront is observed in the EM. It is easy to allow for this feature in the extension of the results of modeling of shock-wave processes in the simulator to the EM. Since the relaxation times in them differ almost fourfold, this can cause a marked difference in the rate of damping of compression pulses.

Thus, it has been shown that the viscoelastic model is valid in averaging the description of the evolution of a compression pulse in the studied materials, but does not allow one to describe local stresses to take into account the effects connected with the resonance behavior of the medium. Generally, this is not important, especially in the solution of applied problems, when the average quantities are of the greatest interest.

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