Experimental study of dynamic properties of porous materials under shock-wave loading

A N Zubareva$^{1,2}$, V P Efremov$^3$, V M Mochalova$^{1,2}$ and A V Utkin$^1$

$^1$ Institute of Problems of Chemical Physics of the Russian Academy of Sciences, Academician Semenov Avenue 1, Chernogolovka, Moscow Region 142432, Russia.
$^2$ State Scientific Center of the Russian Federation “Institute for Theoretical and Experimental Physics”, National Research Center “Kurchatov Institute”, Bolshaya Cheremushkinskaya 25, Moscow 117218, Russia
$^3$ Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia

E-mail: zan@ficp.ac.ru

Abstract. The paper presents new experimental data on properties of porous media under shock-wave loading. We considered materials with different nature of porosity. The porosity in the silicone rubber and the epoxy resin was produced by glass microspheres filler. Open porosity was realized in a fibrous material made from glass fibers with corundum. It was shown that two-wave configuration was formed in materials with closed porosity. Such structure of the pulse with a precursor was not observed in samples with open porosity. As a result of analysis of experimental data, Hugoniots for the investigated materials were obtained.

1. Introduction

Research of shock-wave processes provides information on thermodynamic and rheological properties of materials in a wide range of pressures and temperatures under conditions of high strain rates. Investigation of shock compression features of porous materials is of particular interest, since the experimental study of the same material at different densities can significantly expand the area of thermodynamic states accessible by pulse loading [1–3].

At high pressures, shock compression of porous media is described by the Zel’dovich model [4], according to which the total pore collapse occurs practically at zero pressure, after which the compression of the matrix begins. Characterization of porous materials under pulse loading at low pressures is more complicated. Under such conditions, pore collapse kinetics has a significant influence on the structure of the compression pulse and the nature of its propagation. In particular, this can lead to the manifestation of anomalous properties of the material, which is expressed in a “blurring” of the compression pulse front [5]. Determining the physical causes of anomalous compressibility is relevant due to the need for constructing models that adequately describe a behavior of materials under shock-wave loading. The task is complicated by the fact that even for a particular substance the kinetics of pore collapse is not universal. It depends on the distribution of pore sizes, on pore geometry, properties of the free surface, etc. Characteristic features of pore collapse should also appear depending on whether the porosity is closed or open, which can influence the propagation of shock waves through the material. Thus, the purpose of
Figure 1. Photo of sample microstructure: a) silicone rubber with microspheres at fracture. Scale bar = 120 µm; b) fibrous material at a depth of 3 mm.

this work is an experimental study of characteristics of the structure of the compression pulse front that appears in this case.

Samples of several materials with different nature of porosity were selected as objects of study. As a material with closed porosity, rubber and epoxy resin were used. The porosity in them was created by the addition of glass microspheres with an average size of about 80 µm and a shell thickness of 1 µm. Figure 1a shows a photograph of the microstructure of the silicone rubber sample with the density of $\rho_0 = 0.55 \text{ g/cm}^3$. Open porosity was realized in a material consisting of fibers with a diameter of several microns (figure 1b). The material of the fibers is a $2\text{Al}_2\text{O}_3$–$3\text{SiO}_2$ compound. The density of the samples was equal to 0.32 g/cm$^3$.

2. Experimental scheme
The experiments were conducted using calibrated explosive projecting devices (figure 2). A shock wave in a studied sample was created by an aluminum flyer plate 1 with a diameter of 70–100 mm and a thickness of 0.4–10 mm, which was accelerated by the explosion products to velocities from 0.7 to 1.5 km/s [6]. Loading of the sample was carried out through aluminum or copper shield plate 2. Shock wave parameters in the sample 3 were determined by the VISAR laser interferometer at the border with water window 4. Aluminum foil 5 with a thickness of 7 µm was glued to the surface of the sample to reflect the laser probing beam. Geometrical relations between the experimental assembly parameters provided one-dimensional loading conditions during the registration of the process.

In each experiment, the shock wave velocity in the sample was measured along with the particle velocity. For this purpose, a polarization sensor 6 on the border of screen–sample was placed, which captured the time of entering of the shock wave into the sample. The moment of the exit of the shock wave from the sample was determined by the VISAR interferometer signal. Since a signal from the sensor and a signal from interferometer are on different recording channels, preliminary experiments were conducted to determine the desynchronization delay between them which proved to be less than 30 ns. This correction must be taken into account if the characteristic propagation time of a shock wave through the sample is about 100 ns, but in our experiments, the time of wave propagation exceeded 2 µs, so the measured disagreement time had not resulted in a significant error in the determination of shock wave velocity.
3. Experimental results and discussion

3.1. Silicone rubber and epoxy resin with glass microspheres

The volume ratio of silicone rubber and glass microspheres in investigated samples was equal to 100/39 which corresponds to a density of 0.55 g/cm$^3$. An important physical characteristic of a sample in the shock-wave research is the speed of sound under normal conditions. It was measured using the ultrasonic method and found to be equal to $C_{l0} = 1.77 \pm 0.01$ km/s. The thickness of samples in all experiments was the same and equal to 4 mm. The diameter of samples was 40 mm.

In the samples of epoxy resin and glass microspheres, the volume ratio of components was equal to 100/52. The density of the samples was 0.56 g/cm$^3$. The thickness of the samples varied in the range of 6.5–7.5 mm.

Typical velocity profiles at the sample–water window boundary obtained by VISAR laser interferometer are shown in figure 3. In this case, the experimental conditions were the same: 7 mm aluminum flyer plate accelerated to the velocity of 1.13 km/s impacted the 5.5 mm copper shield plate.
Velocity profiles for the two investigated materials are similar. The difference between them is of purely quantitative nature, due to differences in shock-wave properties of matrix materials. A complicated structure of the shock wave front was observed for both materials.

First, the precursor wave propagates ahead of the shock wave, i.e. the two-wave configuration is formed which is most clearly expressed at low pressures. For example, for the porous rubber, the amplitude of the first wave (precursor) reaches 20 m/s (see figure 3a). The velocity of its propagation (1.62 km/s), that was determined by the polarization sensor (see figure 2), is much greater than the speed of the second wave (0.92 km/s). In the porous epoxy resin the amplitude of the precursor reaches 30 m/s (see figure 3b) and its propagation velocity equals to about 2.4 km/s. The emergence of the first wave is primarily due to the closed porosity of the samples, so the matrix material forms a conductive path in which the propagation velocity of disturbances is considerably greater than the shock wave velocity in the porous medium. The speed of the second wave increases sharply with increasing pressure while the velocity of the first wave is practically constant. This leads to the disappearance of the two-wave configuration in the porous rubber at a pressure of about 1 GPa and in the porous epoxy resin at a pressure of more than 2 GPa.

Second, the heterogeneous structure of the investigated samples leads to a significant oscillation of velocity profiles behind the shock jump. Since the oscillations are not smoothed by the passage of a shock wave through the 7 µm aluminum foil which is used to reflect the probe laser beam, it means that the spatial size of inhomogeneities is greater than the thickness of a foil, i.e. not less than 10 µm. This estimate correlates to the size of glass microspheres which determine the characteristic size of inhomogeneities.

Third, the wave profiles have a feature that is associated with the registration technique. In all experiments, an additional velocity jump is recorded after 1 µs after the second wave comes to the water window border. It is due to the fact that the shock compressibility of samples is higher than that in water. Therefore, after a shock wave comes to the border with water, it is reflected back into the sample, after which it is again reflected by the shield plate and returns to the water border as a shock wave. The circulation time decreases with the increase of pressure.

As a result of processing of the experimental data, Hugoniots were obtained for the investigated materials. They are presented in figure 4 in the coordinate system of shock wave velocity \(D\) and particle velocity \(u\). The experimental points for the first (red points) and the second (black points) waves are shown. Hugoniot for the second wave is well approximated by a linear dependence \(D(u)\) if particle velocity is greater than 0.5 km/s, which corresponds to a pressure that exceeds 0.3 GPa. The ratio of \(P = \rho_0 Du\) is used for the pressure calculation. For the construction of \(D-u\) dependence for the precursor wave, particle velocity was taken as the same as for the second wave, which is obviously incorrect. Therefore, the red points can not be considered as a shock Hugoniot for the first wave. However, such a representation of the data is convenient because it clearly shows that a two-wave configuration exists below the intersection point of the Hugoniots. Note that for a precursor wave in the porous rubber (figure 4a) there is a slight decrease in the velocity of its propagation with the increase of pressure in the second wave. Perhaps this reflects the physical nature of the phenomenon, but since the effect is not much greater than the experimental error, there is no serious ground for the discussion of it.

3.2. Fibrous material with open porosity
The density of the investigated samples was 0.32 g/cm³. Their thickness in all experiments was the same and was equal to 10 mm. Their diameter was about 100 mm. Typical velocity profiles which were obtained under the same loading conditions as for samples with a closed porosity (figure 3) are shown in figure 5a. Two velocity profiles correspond to two different experiments with a different thickness of aluminum foil for reflecting the probe laser beam: red color marked the dependence obtained at the 7 µm thickness, black—with the 200 µm thickness. It can be
Figure 4. Shock Hugoniots of samples: a) porous rubber; b) porous epoxy resin. The lines are an approximation.

Figure 5. a) Velocity profiles for samples with open porosity at different thicknesses of reflective aluminum foil; b) shock Hugoniot for samples with open porosity. Solid line is approximation.

seen that the thick foil leads to a smoothing and almost complete disappearance of oscillations. It means that the spatial size of inhomogeneities less than 200 µm, which corresponds to the size of voids that are seen in the photographs of the sample microstructure (figure 1b). Increasing the thickness of the foil leads not only to a smoothing of oscillations but also to the significant change in the structure of compression pulse front. If using the 7 µm thin foil, clearly expressed shock jump is registered, followed by the velocity peak, after which its additional increase is observed. As a result of the averaging happening in the thick foil, the velocity in the compression pulse increases smoothly for approximately 0.5 µs. Such a character of the change of the front structure of the registered pulse at the variation of the scale of averaging is typical for heterogeneous media [7, 8].

In this case, as in the previous experiments, after approximately 1 µs after wave comes to the water boundary and additional velocity jump is registered, which is caused by the higher shock compressibility of the sample compared to water. The most interesting, however, is the absence of the precursor, which had been previously observed in materials with closed porosity (figure 3). Obviously, this is a consequence of the structure of fibrous materials that do not form conductive paths along which small perturbations could propagate before the compression wave front.
Figure 5b shows the shock Hugoniot of the studied material, which was obtained by processing the experimental data. It is well approximated by a linear dependence of $D$ on $u$. It should be noted that in the absence of phase transitions, with the increase of porosity the Hugoniot of a material moves closer to the $D = u$ dependence. The resulting shock Hugoniot (figure 5b) is less than 20% different from that ultimate value.

4. Summary
The studies show a strong dependence of compression pulse structure in porous materials on the nature of porosity. A distinguished feature of materials with closed porosity (silicone rubber and epoxy resin with microspheres) is the formation of two-wave configurations in them. In this case, the difference between the results which were obtained for samples made from different materials has a purely quantitative nature. In particular, the disappearance of the precursor wave for the rubber occurs at about 1 GPa, which is significantly lower than for the epoxy resin at the pressure of approximately 2 GPa. In materials with the open porosity the similar structure of compression pulse with a precursor wave is not observed. The different structures of shock waves, in this case, depend on the existence of conductive paths in the matrix material at closed porosity and their absence at open porosity.

A common result for all investigated materials is the presence of oscillations on the registered velocity profiles. There are due to the heterogeneous structure of samples in which a characteristic size of inhomogeneities is defined by a pore size. It is shown that using the foil for reflecting the probe laser beam the thickness of which exceeds the size of the heterogeneities allows for averaging the oscillations and obtaining the smoothed velocity profiles. It should be noted that under averaged description the evolution of shock waves in heterogeneous materials is well approximated by a shock wave propagating in a homogeneous medium described by the Maxwell relaxation model [9, 10].

Based on the experimental data analysis, the Hugoniots for the investigated samples were obtained, which are well described by a linear dependence of $D$ on $u$ at particle velocities above 0.5 km/s.

References
[1] Bushman A V, Lomonosov I V, Fortov V E, Khishchenko K V, Zhernokletov M V and Sutulov Y N 1993 JETP Lett. 58 620–624
[2] Efremov V P, Ostrik A V, Potapenko A I and Fortov V E 2000 Probl. At. Sci. Technol. 1 152–154
[3] Ostrik A V and Potapenko A I 2001 Konstr. Kompoz. Mater. 1 48–53
[4] Zel’dovich Ya B and Raizer Yu P 1967 Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena vol 1 (New York: Academic Press)
[5] Landau L D and Lifshitz E M 1987 Course of Theoretical Physics. Vol. 6. Fluid Mechanics 2nd ed (Oxford: Butterworth–Heinemann)
[6] Kanel’ G I, Razorenov S V, Utkin A V and Fortov V E 1996 Shock Wave Phenomena in Condensed Matter (Moscow: Yanus-K)
[7] Christensen R M 1979 Mechanics of Composite Materials (Mineola, NY: Dover)
[8] Mun F 1975 Composite Materials: Shock and wave propagation in composite materials vol 7 (New York: Academic Press)
[9] Gafarov B R, Utkin A V, Razorenov S V, Bogach A A and Yushkov E S 1999 J. Appl. Mech. Tech. Phys. 40 501–506
[10] Barker L 1971 J. Compos. Mater. 5 140–162