Experimental study of spall strength of silicon rubber with microspheres under shock-wave action

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Abstract. In this work, porous media are studied using silicone rubber with glass microspheres as an example. There were investigated three types of silicone rubber samples featuring different concentrations and sizes of microspheres: non-porous silicone rubber, porous silicone rubber with calibrated glass microspheres and porous silicone rubber with glass microspheres having a wide range of sizes. The density of the samples was 0.99, 0.55 and 0.48 g/cm\textsuperscript{3}, accordingly. Investigating spall strength under pulse tension shows that the destruction beginning threshold of the samples in question is quite low. For the non-porous sample, it is around 30 MPa, for the porous ones it is an order of magnitude lower. The spall plate does not come off the sample after the beginning of destruction. The ability of the free surface velocity to change in such a way is typical for materials with a low destruction threshold.

1. Introduction
Investigation of spall phenomena occurring when a shock wave reflects from the free surface of a body \cite{1,2} provides unique data on strength properties of materials within submicrosecond range. The most detailed studies applying this approach were carried out for metals, alloys and polymers \cite{1–3}. Unique results were obtained for liquids \cite{4–7}, the destruction kinetics of which is determined by the homogeneous theory of nucleation. Elastomers \cite{8}, including those containing various fillers \cite{9}, have been studied significantly less. There is almost no data on spall fracture of porous materials which are used more and more widely in different areas of science and technology. The goal of this work is to conduct an experimental study of spall strength of a sample porous material represented by silicone rubber with the addition of glass microspheres.

2. Experimental scheme
We studied three types of samples of silicone rubber featuring different concentrations and sizes of microspheres: non-porous silicone rubber (S0), porous silicone rubber with calibrated glass microspheres (S1) and porous silicone rubber with glass microspheres featuring a wide size range (S2). The main characteristics of the samples are given in table 1, where one can find...
Table 1. Main characteristics of silicone rubber samples.

| Samples | \(\rho_0\) (g/cm\(^3\)) | \(c_0\) (km/s) | \(\alpha/S\) | Ø (µm) | \(\delta\) (µm) |
|---------|-----------------|-----------------|-------------|--------|-------------|
| S0      | 0.99            | 1.17            | 0/100       | —      | —           |
| S1      | 0.55            | 1.77            | 39/100      | 80     | 1           |
| S2      | 0.48            | 1.10            | 50/100      | 20–150 | 1–2         |

Figure 1. Scheme of experimental assembly: 1—flyer plate; 2—shield plate; 3—sample; 4—Al foil.

The initial density \(\rho_0\), measured sound speed \(c_0\), the ratio of glass microspheres filler to rubber by volume \(\alpha/S\), characteristic diameter of microspheres Ø and shell thickness \(\delta\).

The scheme of experiments for studying spall strength of materials is given in figure 1. The shock waves in the samples were created by aluminum flier plates being 70 mm in diameter and 0.4–2 mm thick, which were accelerated by explosion products up to the speed of 0.7 km/s. The samples were loaded either directly by the flier plates or through aluminum and copper shield plates. The free surface velocity of the samples was registered with a VISAR laser Doppler interferometer. To reflect the probing radiation, aluminum foil, 7 µm thick, was glued onto the sample surface. The geometrical relations between the parameters of the experimental assembly provided one-dimension loading conditions during the whole period of the process registration.

3. Experimental results
The parameters of the experimental assemblies and the results of the experiments for studying shock compressibility of the samples are given in table 2 and in figures 2–4. Table 2 shows the material and thickness of the shield plate \(h_b\), the thickness of the flier plates \(h_i\) and of the
Table 2. Parameters of experimental assemblies and results of experiments.

| Experiment number | Sample | Shield plate material and thickness, $h_s$ (mm) | Flier plate material and thickness, $h_i$ (mm) | Spall strength, $\sigma$ (MPa) | Strain rate, $\dot{\varepsilon}$ (1/s) |
|-------------------|--------|-----------------------------------------------|-----------------------------------------------|-------------------------------|-----------------------------------|
| 1                 | 3      | PMMA, 6.5 Al, 0.4                            |                                               | 17.4                          | $2.2 \times 10^5$                 |
| 2                 | 6      | —                                             | Al, 0.4                                       | 31.3                          | $4.5 \times 10^5$                 |
| 3                 | 3      | PMMA, 1.0 Al, 0.4                            |                                               | 23.2                          | $3.6 \times 10^5$                 |
| 4                 | 4      | Cu, 2.5                                     |                                               | 1.3                           | —                                 |
| 5                 | 4      | Al, 2.0                                     |                                               | 1.6                           | —                                 |
| 6                 | 2      | Al, 2.0                                     |                                               | 6.4                           | —                                 |
| 7                 | 4      | Cu, 2.5                                     |                                               | 3.2                           | —                                 |
| 8                 | 4.9    | —                                             | Al, 0.4                                       | 4.2                           | —                                 |
| 9                 | 2.6    | —                                             | Al, 0.4                                       | 3.3                           | —                                 |
| 10                | 2.7    | Cu, 2.0                                     |                                               | 2.8                           | —                                 |

samples $h_s$ respectively, as well as the calculated spall strength $\sigma$ and the strain rate in the unloading part of the pulse $\dot{\varepsilon}$. Figures 2–4 show the obtained profiles of the free surface velocity, which are labelled in accordance with the numbers of the experiments in table 2.

Figure 2 shows the experimental results for the silicone rubber S0. The shock wave entering the free surface causes an abrupt increase of the surface velocity up to the value $W_0$ equal to doubled mass velocity in the shock wave. Then one can observe a velocity decrease caused by a rarefaction wave propagating after the shock jump. The interaction between the falling rarefaction wave and the one reflected from the free surface leads to stretching and destruction of the material, which, in their turn, cause relaxation of tension stresses and formation of a compression wave, which enters the free surface as a spall pulse. As a result, a local minimum $W_m$, which is marked with vertical arrows in figure 2, is formed on the velocity profile. The spall strength calculated by the formula $\sigma = 0.5\rho_0c_0(W_0 - W_m)$ is given in table 2.

Changing the free surface velocity as in silicone rubber (see figure 2) is typical for elastomers [8,9]. The velocity fluctuations, caused by the circulation of waves in the spall plate, fade quickly, being practically imperceptible in experiment 3. Besides, when destruction begins, the average velocity keeps decreasing for some time, thus indicating viscous nature of the said destruction. For almost all known materials, the spall strength increases together with the increase of strain rate in the unloading part of the pulse $\dot{\varepsilon} = 0.5c_0dW/dt$. A similar pattern is also observed in silicone rubber. Doubling the strain rate in experiment 2 in comparison to experiment 1 almost doubles the spall strength. Determination error of silicon rubber spall strength depends on the measurement error of the wave profiles and is 2%. For the materials containing microspheres, this error is about twice that much, but it does not exceed 5%.

Free surface velocity profiles for porous silicone rubber with calibrated glass microspheres (S1) are shown in figure 3. In order to exclude mutual intersections, profiles 4 and 7 have a time shift of 2 $\mu$s and of $-1$ $\mu$s respectively. First of all, it should be noted that, unlike in silicone
rubber (see figure 2), a clearly visible two-wave structure is formed in the samples S1. The emergence of the first wave is related to the high concentration of the filler, glass microspheres, which convey disturbances at a significantly higher velocity than the sound speed in the matrix. The second wave moves more slowly and is behind the first one. Moreover, its front is blurred; for example, the blurring is over 2 \( \mu \)s in experiment 4. In this case, the front widens while it propagates through the sample. It is obvious if we compare experiments 5 and 6 which have the same conditions of shock-wave action, while the former sample is twice as thick as the latter. Such evolution of compression pulses is also characteristic of substances with anomalous compressibility. A detailed study of shock-wave compressibility, the nature of compression pulses propagation and the pressure range, where the two-wave configuration can exist, is conducted in the paper [10].

The spallation destruction of the samples S1 causes the same specific features to show up on the velocity profiles, as in silicone rubber (see figure 2). However, the velocity minimum, that is formed when the spall pulse enters the free surface (marked with vertical arrows in figure 3), is less pronounced, while being completely absent in experiment 4 (therefore, for this experiment, the table shows the spall strength value estimated with the minimal velocity recorded during the experiment). The complex structure of the shock-wave front greatly complicates spall strength determination. In particular, the emergence of a two-wave configuration reflects the presence of several values of sound speed in the investigated medium, and the spall pulse propagation velocity remains unclear. For example, in elastic-plastic media, it is necessary to know the volume and longitudinal velocities of sound [11]. For the samples S1, the value \( c_0 \) (given in table 1) could serve as an alternative for the longitudinal velocity. The first wave of the compression pulse propagates at this particular velocity. However, in this case a similar analogy cannot be used, because the microspheres are destroyed by compression, and the propagation velocity of small disturbances decreases. Therefore, spall strength was calculated by the same formula and using

**Figure 2.** Free surface velocity profiles in the experiments with silicone rubber (samples S0). The profile numbers 1, 2, 3 are labelled in accordance with the numbers of the experiments in table 2.
Figure 3. Free surface velocity profiles in the experiments with the porous samples S1. The profile numbers 4, 5, 6, 7 are labelled in accordance with the numbers of the experiments in table 2.

the same sound speed as for the silicone rubber S0. Table 2 shows the values which were obtained this way, them being by an order of magnitude less than those in the samples S0. It is impossible to evaluate the strain rate in this case.

Figure 4 shows free surface velocity profiles for the porous silicone rubber S2. Profiles 8 and 9 have a time shift of 2 µs each. They have the same qualitative specific features as those of the samples S1. In particular, in this case a two-wave configuration is formed, too. However, the first wave does not have a clear front, and its amplitude increases monotonously over time. Probably, such nature of velocity change is caused by the size distribution of microspheres, as the patterns of pressure increase in the first wave are determined by the kinetics of pore collapse and the compression damage initiation threshold of the pores, which both depend on the pore size. In the paper [10] it is noted, for example, that in the samples S2 the destruction of microspheres begins at 10 MPa, whereas in the samples S1 it happens at 30 MPa.

The spallation destruction of the samples S2 has the same qualitative features and occurs approximately at the same tension stresses as those of the samples S1. The vertical arrows in figure 4 indicate the location of the velocity minima that are due to the exit of the spall pulse to the free surface. The above-mentioned issues of σ determination, one of which is uncertainty of spall pulse propagation velocity, stay on. Therefore, in this case, too, spall strength is calculated using the same formula and the same sound speed as for the silicone rubber S0. It should be noted that in the samples S2 the front of the spall pulse is practically not formed, which is especially clearly seen in experiments 8 and 9. Only in experiment 10, after the onset of fracture of the sample, insignificant velocity fluctuations associated with the circulation of waves in the spall plate are observed. This is probably due to the large damage to the spall plate, which leads to intense attenuation of the waves.
Figure 4. Free surface velocity profiles in the experiments with the porous samples S2. The profile numbers 8, 9, 10 are labelled in accordance with the numbers of the experiments in table 2.

4. Conclusions
The results of the study of spall strength of porous silicone rubber demonstrate the possibility to use the methods of physics of shock waves for this purpose. A minor decrease in free surface velocity occurring when it reaches its maximum clearly indicates the destruction of the material. In this case, spall strength accurate evaluation is complicated not by the samples porosity, but by the method of its creation with the help of the microspheres which are destroyed by the compression wave. The latter circumstance leads to a change in the dynamic properties of the primary material. As it was already noted, during compression, this change is demonstrated by the dependence of the structure of the first wave on the size distribution of the microspheres. During stretching, the spall pulse propagation velocity becomes unclear.

It should be noted that for silicon rubber, wave profiles repeatability during the experiments under the same conditions stays within the velocity measurement error and is approximately 2%. In the materials containing microspheres the repeatability of the experiments decreases, mainly due to the velocity oscillations following the shock jump. In this case, the front structure, the maximum velocity values and the profile features associated with spall fracture are repeated with the error of about 5%.

Nevertheless, even for the materials having such a complex structure as that of the samples S1 and S2, it is possible to obtain reliable information on the character of the materials destruction under pulse tension under shock-wave action. In particular, it is shown that the addition of microspheres reduces spall strength of the silicone rubber by an order of magnitude.

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