

Shock compressibility and spall strength of textolite depending on fiber orientation

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THE EXPERIMENTAL STUDY OF SHOCK WAVE COMPRESSIBILITY and spall strength of an aramid fiber reinforced epoxy composite (textolite) for two fiber orientations was performed by the VISAR interferometer. The particle velocity profiles were obtained at velocities of the flyer plate from 0.65 to 5.05 km/s. The sound speed of textolite for the longitudinal direction is three times higher than that for transverse one, and as a result, the particle velocity profiles are different for two orientations. For the transverse direction of the fibers, a single shock wave is observed, while for longitudinal one, a two-wave configuration is recorded up to 20 GPa. Hugoniot parameters for both orientations of the fibers were found up to 35 GPa: D = 2.37 + 1.26 * u for transverse one and D = 1.45 + 2.05 * u - for longitudinal, where D is the shock wave velocity and u is the particle velocity. The spall strength of textolite is equal to 61 MPa for shocks traveling along the fibers, and this is almost twice higher than that for the transverse direction.

Key words: anisotropy, composites, aramid fiber, textolite, shock wave, Hugoniot, impact, compressibility, spall strength, VISAR.

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1. Introduction

POLYMER COMPOSITE MATERIALS ARE WIDELY USED in the automotive and aerospace industry, because their strength and fatigue properties per unit weight are higher than those of most metals and alloys. Their mechanical response varies greatly depending on the fiber compound, porosity, matrix, adhesion of the polymer filler and other microstructural features, depending on the method of manufacture. To predict the behavior of these materials, correct physical models are needed, based on experimental data obtained under the conditions most appropriate for numerical calculations. In this regard, shock-wave research methods have the indisputable advantage, which allow one-dimensional deformation of materials to be realized, which is strictly analyzed within the framework of the basic conservation laws.

A significant part of the work with shock wave experiments is devoted to the study of composite materials based on carbon, aramid and glass fibers [1-10]and Ultra High Molecular Weight PolyEthylene (UHMWPE) [11]. It has been shown, for example, [1, 2, 7] that in the pressure range of 10–15 GPa and less, a single shock wave typical of polymer materials is formed during the propagation of a compression pulse across the fibers, while a two-wave configuration is observed when moving along the fibers. At the same time, the Hugoniot data corresponding to the bulk compression for both directions are the same for the composite materials studied in [1, 2, 8], whereas for the carbon fiber from the work [7] there is a noticeable discrepancy: Hugoniot parameters for the longitudinal direction lie above those for the transverse one. A detailed study of the effect of orientation on the shock-wave properties of anisotropic composite materials was performed by the authors [6], who recorded the stress profiles during the propagation of a shock wave in a unidirectional composite when the normal to the surface of the wave front is directed at different angles to the reinforcing fibers. At 5 and 15 degrees, an elastic precursor is recorded, beyond which the shock wave propagates. In the case of 45 degrees, the elastic precursor is transformed into a plastic wave with a diffuse front, and at 90 degrees a single shock wave is recorded.

The anisotropy of the properties of composite materials is due to the orientation of the fibers, the grinding of which, as noted in [3] by the example of carbon fiber, results in the absence of a dependence of the shock compressibility on orientation. The authors of [3], using light-gas guns, conducted studies of composite materials reinforced by carbon fibers, up to 50 GPa and in the vicinity of 25 GPa, recorded a feature on Hugoniot, which, according to the authors, is associated with chemical decomposition of the composite under shock compression. Additional information on the thermodynamic properties of composite materials is provided by the results of studying the isentropic unloading of a sample after shock compression [4, 5, 12]. Using carbon fiber/epoxy resin and aramid fiber/epoxy resin as an example, it was shown [4] that shock-wave experiments provide the data necessary to construct the equation of state and the model of spall destruction of matter.

The process of fracture of heterogeneous anisotropic materials is quite complex and to identify the factors that have a decisive influence in each particular situation, various research methods are used. The authors of [13] implemented the process of pulsed destruction of a composite of carbon fibers/epoxy matrix using the Taylor cylindrical test. They observed the influence of the orientation of the fibers on the character of the dynamic fracture and noted the decisive role of the impact velocity of the sample with the target. An experimental study of the dynamic fracture of composites based on Kevlar fibers with a different initial structure was carried out in [14]. It is shown that for all samples the maximum strength is realized along the fibers. Moreover, the specific structure of the fibers, as well as various additives, have a significant impact on the character of the sample damage. In [15], when studying Kevlar samples with carbon nanotubes as a filler, it was shown that with the addition of 0.5% nanotubes, the threshold for the beginning of fracture increases by more than 30%. A qualitatively similar result was obtained by the authors of [16] in the study of the process of impact response of Kevlar composites with nanoclay containing an epoxy matrix.

The effect of external condition of influence on the character of the composites damage is especially pronounced during spall fracture. Direct planar plate impact experiments were performed in order to study the spall behavior of UHMWPE composites [11]. Thus, a tensile strength of 50 MPa was measured for this material under highly dynamic conditions. In [17], it was shown that the spall strength of the investigated carbon fiber increases linearly from 39.2 MPa to 163.3 MPa with an increase in the strain rate from $22 \cdot 10^3$ 1/s to $122 \cdot 10^3$ 1/s. The spall strength is strongly dependent on the composite structure (number of plies, orientation, fiber material, matrix material, curing process) this has been evidenced at least by [18] in which authors evidenced that the spall strength on CFRP composite laminates decreases when the load duration increases. They obtained a spall strength a bit lower than 300 MPa for 8 plies [0°, 90°] for CFRP.

Thus, shock-wave methods are an important part in the study of the properties of composite materials. The data currently available testify to the pronounced individual response of these materials to a pulsed action. In such a situation, the actual task is the experimental study of composite materials based on fibers of different nature and detection of the general laws of their deformation and fracture under the shock wave action. The purpose of this work is an experimental study of the shock compressibility and spall strength of composite materials based on aramid fibers (textolite) with different orientation of the fibers relative to the shock wave propagation.

2. Materials tested and experimental details

Textolite is a composite material consisting of unidirectional aramid fibers and a matrix-epoxy resin. Fig. 1 (left side) shows a microphoto of the sample surface, which is normal to fiber orientation. The dark spots are the ends of the fibers, the light layers are epoxy resin. The structure of one of these fibers, which is a bundle of 400–500 individual fibers, is shown in Fig. 1 (right side). The character diameter of the individual fibers is about 10–15 microns, and their volume fraction in the textolite is 63–65%. ED-10 epoxy resin, which is an



FIG. 1. Microphotos of the sample surface which is normal to fiber orientation (left side) and fiber is a bundle of 400–500 individual fibers of 10–15 microns thick (right side).

analogue of DER-671, was used as a matrix. Shock-wave properties of this resin were studied in [19].

The density of the material tested is 1.265 g/cm^3 . To perform the shockwave experiments, samples of 3–10 mm in thick and 25–50 mm in diameter with two different fiber orientations (along and across the direction of impact) were prepared from a single block of textolite. The sound speed, measured by the ultrasonic method, across and along the fibers was 2.45 km/s and 7.10 km/s, respectively.

To study the shock compressibility of materials, calibrated explosive propellant charges were used to ensure flat throwing of aluminum flyer plates with the diameter of 70–100 mm and thickness of 0.4–10 mm, with velocities of 0.65–5.05 km/s. The loading of the samples was carried out through aluminum and copper plates. The scheme of the experiments is shown in Fig. 2. After the collision of the aluminum flyer plate (1) with the plate (2), a shock wave was formed in the plate, which loaded the sample tested (3). The shock wave parameters were determined by a VISAR laser interferometer [20] at its exit to the boundary with a water window (4). Water was used for preventing the comeback of the rarefaction wave from the sample free surface to avoid early spallation in this configuration. The change in the reflection index water under shock-wave loading influences on the VISAR measurements, which was taken into account by using the correction proposed in [21].

To reflect the laser beam, aluminum foil (5) with a thickness of 7 μ m was glued to the sample surface. The reflected beam was collected by a lens and directed to a laser interferometer. In each experiment, along with the particle



FIG. 2. The scheme of experiments to measure the parameters of shock compression of the sample: 1 – flyer plate; 2 – metal plate; 3 – sample; 4 – water window; 5 – aluminum foil; 6 – polarization gauge.

velocity, the shock wave velocity of the sample was measured. For this purpose, a polarization gauge (6) was placed between the plate and sample, which recorded the moment of the shock wave entering to the sample. A flat capacitor filled with the polarized PVDF film is a sensitive element of the gauge [22]. One of the electrodes of the capacitor was a plate (2), and as the second electrode, a copper



FIG. 3. Velocity profiles on the plate – water boundary.

foil with a thickness of 20 μ m was used. The error in determining the shock wave velocity does not exceed 1%.

The typical velocity profiles at the plate/water boundary determining the compression pulse entering the sample are shown in Fig. 3. In these experiments the flyer plates (1) and plates (2) (Fig. 2) were made of aluminum. Velocity W and thickness h_i of the flyer plate, and the plate thickness h_t are given in Table 1. The designations of the experiments in Fig. 3 and in Table 1 are the same.

Table 1. Parameters of experimental setup.

No	W, $\rm km/s$	h_i, mm	h_t, mm
1	1.13	7	4
2	2.5	10	4
3	4.6	2	2

3. Experimental results

3.1. Particle velocity profiles and Hugoniot parameters of textolite

The results of the experiments and the parameters of the experimental setups are given in Table 2 and Figs. 4–6. The following values are in Table 2: h_s is the sample thickness, W and h_i are the velocity and thickness of the aluminum flyer plate, h_t is the plate thickness (the material is indicated), D, u and Pare the shock wave velocity, particle velocity and pressure in the sample. The designations of the experiments in Figs. 5, 6 and in Table 2 are the same.

The pressure and particle velocity in the textolite were calculated by analyzing the wave interactions in the P - u plane and the Lagrange diagram. An example of calculation for experiment 1 from Table 2 is shown in Fig. 4. After



FIG. 4. P-u (left side) and Lagrange diagram (right side) demonstrating wave interactions in the experimental configuration. On the Lagrange diagram, the S1 and 1 symbols indicate the areas in which the parameters are implemented, similarly marked on the P-u diagram.

No	h_s , mm	W, $\rm km/s$	h_i, mm	$h_t, mm/material of plate$	D, km/s	u, km/s	P, GPa		
Transverse orientation of fibers									
1	9.30	1.13	7	$5.5/\mathrm{Cu}$	3.04	0.62	2.38		
2	9.40	1.13	7	4.0/Al	3.46	0.88	3.83		
3	3.10	2.5	10	$5.5/\mathrm{Cu}$	4.05	1.37	7.02		
4	8.80	2.5	10	4.0/Al	4.83	1.83	11.20		
5	3.20	3.3	5	2.0/Al	5.33	2.40	16.18		
6	3.13	5.05	2	2.0/Al	6.67	3.55	29.95		
Longitudinal orientation of fibers									
7	7.60	1.13	7	$5.5/\mathrm{Cu}$	2.70	0.62	2.10		
8	4.40	1.13	7	4.0/Al	3.27	0.89	3.68		
9	7.61	2.5	10	8.0/Cu	4.23	1.36	7.40		
10	7.71	2.5	10	4.0/Al	5.10	1.81	11.70		
11	7.20	3.3	5	2.0/Al	6.26	2.29	18.20		
12	5.10	5.05	2	2.0/Al	8.33	3.34	35.30		

Table 2. Parameters of the experimental setups and experimental results.

the collision of an aluminum flyer plate with a copper plate the shock waves propagate into the copper and aluminum, and the parameters of these waves are determined by the point S1 of intersection of the Hugoniots of Cu and Al (Fig. 4, left side). When the shock wave enters the boundary with the textolite, a rarefaction wave is reflected in the copper plate, and a shock wave is formed in the sample, the pressure and velocity in which are determined by the intersection of the copper unloading isentrope and Rayleigh line $P = \rho_0 Du$ (point 1 in Fig. 2 left side). It is assumed that the copper isentrope coincides with the symmetrical reflection of Hugoniot [23]. Hugoniots of aluminum and copper were used in the line D-u relations [24]: for Al, D = 5.38 + 1.34u km/s; for Cu, D = 3.89 + 1.52u km/s. The accuracy of pressure and particle velocity determination is $\pm 2.5\%$.

Figure 5 shows the particle velocity profiles at the textolite – water boundary when shock wave propagates across, and in Fig. 6 – along the fibers. For textolite with a transverse direction of the fibers, after the shock wave reaches the boundary with water, a velocity jump is recorded, behind which pronounced oscillations are observed relative to a certain average value, due to the heterogeneous structure of the material tested (Fig. 5). Note that the velocity profiles entering the sample (Fig. 3) are smooth. Oscillations are without any periodic structure; nevertheless, there is a characteristic oscillation period of the order of 100 ns. This value correlates with the size of the heterogeneities in the material tested, which is determined by the thickness of the fibers. The characteristic time of perturbation reverberation is proportional to twice the size of heterogeneities



FIG. 5. Particle velocity profiles in textolite with transverse orientation of the fibers.

divided by the sound speed equal to 2.45 km/s in the transverse direction, i.e. it has the same order of magnitude as the oscillation time.

The velocity profiles in textolite at the shock wave propagation along the fibers are shown in Fig. 6. A significant feature, in contrast to transverse orientation of the fibers, is the formation of a two-wave configuration. The amplitude of the first wave is about 100 m/s and it is observed up to a shock compression pressure of about 20 GPa. It is due to a high speed of sound disturbances along the fibers, equal to 7.1 km/s. Therefore, the two-wave configuration is observed



FIG. 6. Particle velocity profiles in textolite with longitudinal orientation of the fibers. The profile 8 is shifted in time by 0.5 μ s to eliminate the intersection with the profile 9.

until the propagation velocity of the second wave exceeds this value, which is realized in experiment 12.

As a result of processing the experimental data, Hugoniot parameters of textolite were constructed for the shock propagating along and across the fibers. They are shown in Fig. 7 in the coordinates of the shock wave velocity D and the particle velocity u. The particle velocity was calculated using the known velocity of flyer plate and measured value of D. In the pressure range studied, the experimental data for textolite with transverse direction of the fibers (filled circles) are approximated by the dependence of D = 2.37 + 1.26 * u km/s (dashed line in Figure 7). When the shock wave propagates along the fibers, the experimental data (solid triangles) are approximated by the dependence of D = 1.45 + 2.05 * u km/s (solid line in Figure 7). The measured values of the speed of sound for two orientations of the fibers (u = 0) are also given. The dash-dotted line represents the approximation of the experimental data of the authors [4], empty circles – the experimental data from [5]. It should be noted that Hugoniot of textolite for longitudinal orientation of the fibers agrees well with the results of [4, 5].



FIG. 7. Hugoniot parameters of textolite for the shocks traveling along (solid line) and across the fibers (dashed line).

The result of intersection of Hugoniots for two orientations of the aramid fibers relative to the direction of the shock wave propagation is unexpected and indicates a complex rheology of this material. In particular, this means that textolite cannot be approximated by a homogeneous medium model, the "longitudinal velocity" which depends on the direction, as for example, for metals. Correct modeling of behavior of textolite under the shock wave action is possible only within the framework of a two-component anisotropic medium.

3.2. The spall strength of textolite

The study of the spall strength provides information on the initial stage of material fracture under pulsed tension [25]. The scheme of experiments on the study of the spall strength of textolite is similar to that shown in Fig. 2, but the water window (4) was absent, and the sample was unloaded into the air. The shock waves were created by an aluminum flyer plate of 0.4 mm in thick, accelerated to velocity of 650 m/s, by collision directly with the sample. The thickness of the samples in experiments with transverse and longitudinal orientations of the fibers is h = 3.1 mm and 3.7 mm, respectively. The transverse dimensions were large enough to ensure one-dimensional motion throughout the time period required for the measurements.

Figure 8 illustrates the measured velocity profiles of a free surface for textolite with transverse and longitudinal fiber orientations. Both orientations are characterized by a strong blurring of the shock wave front, but for the transverse direction of the fibers (dashed line in Fig. 8), the velocity almost linearly increases with time, whereas for the longitudinal direction (solid line) a clearly pronounced two-wave configuration is formed. The amplitude of the first wave is about 90 m/s, which agrees well with the data shown in Fig. 6.



FIG. 8. Velocity profiles of free surface for shocks traveling along (solid line) and across (dashed line) the aramid fibers.

After reaching the maximum value, the velocity of the free surface begins to decrease, which is caused by the rarefaction wave from the back side of the flyer plate. The interaction of the incident and reflected from the free surface rarefaction waves results in the appearance of tensile stress inside the sample and its fracture [25]. This process is accompanied by the relaxation of tensile stresses and the formation of a shock wave entering to the free surface of the sample in the shape of a spall pulse. As a result, a minimum is recorded on the velocity profile, indicated in Fig. 8 by vertical arrows. The velocity difference ΔW between its maximum value and this minimum allows determining the spall strength σ , which for an elastic-plastic body is calculated by the equation of [26]: $\sigma = \rho_0 * C_0 * C_l * \Delta W / (C_0 + C_l)$, where C_0 and C_l - bulk and longitudinal sound speed at zero pressure.

With the transverse orientation of the aramid fibers, both values of the sound speed coincide and are equal to 2.45 km/s, therefore the spall strength is equal to 37.2 MPa. For longitudinal orientation of the fibers, the formation of a two-wave configuration can be considered by analogy with an elastoplastic medium and assume that the sound speed measured at zero pressure, equal to 7.1 km/s, coincides with C_l . Then the bulk speed of sound should be close to the first coefficient of Hugoniot in the D - u coordinates (Fig. 7), that is, $C_0 = 1.45$ km/s. As a result, the value of spall strength with longitudinal orientation of the fibers is $\sigma = 61$ MPa.

It should be noted that the fracture of textolite with longitudinal orientation of the fibers is characterized not only by a higher value of spall strength, but also by a more complex character of the destruction process itself. Figure 8 illustrates that on the velocity profile, a kink is observed, marked by a double arrow, and only then, after some time, a spall pulse is formed. The appearance of a kink means the initiation of the process of fracture, but the growth rate of the pores is less than the critical value, which is necessary for the formation of spall pulse [27]. In this case, the tensile stress continues to increase, and the maximum value of that was determined above. Figure 9 shows the characteristics for a plate impact configuration that produces fracture damage with a kink in the velocity profile in front of the spall pulse. After collision, shock waves are formed in the flyer plate and the textolite, which are reflected from the free surfaces by centered rarefaction waves C_+ and C_- . When these rarefaction waves intersect, they cause tensile stresses to arise. Damage occurs at some intersection (initiation of fracture) and when information about this phenomenon returns to the free surface of textolite, a kink in the velocity profile is produced. The spall strength is realized later at the spall surface and as result a spall pulse is formed on the profile of free surface velocity [27]. In the area between the spall surface and the surface of initiation of fracture, the textolite is destroyed, but the tensile stress is less than the spall strength.

As noted above, spall strength of materials depends on the strain rate. Under the conditions of spall fracture, the strain rate is determined based on the velocity



FIG. 9. Scheme of spall failure, Lagrange diagram (left side) of the shock and rarefaction waves transitions and the resulting free surface velocity history (right side).

gradient of a free surface before the spall pulse (or before a kink in the velocity profile, Fig. 8): $\dot{\varepsilon} = (dW/dt)/2C_0$ [28]. For experiments with textolite, the results of which are shown in Fig. 8, the value of tensile strain rate is equal to ~ $6 \cdot 10^4$ 1/s.

4. Conclusions

The obtained experimental data show that the shock-wave properties of textolite depend on the orientation of the fibers relative to the direction of the shock wave. In the transverse orientation, a single shock wave is formed, whereas in the longitudinal orientation, a two-wave configuration up to 20 GPa is observed. At the same time, Hugoniot depends on the orientation of the fibers and the difference between them increases with increasing pressure. This result is fundamentally different from the data of [2] for CFRP, in which the divergence of Hugoniots is significant only at low pressures. With an increase in the amplitude of the wave, Hugoniots approach each other and, at P higher than 10 GPa, within the limits of the measurement accuracy, they coincide. Such a behavior is analogous to the behavior of an anisotropic elastoplastic body, as suggested by the authors of [2] in modeling for CFRP. The spall strength of textolite also depends on the orientation of the fibers. With pulsed tension along the fibers, it is almost twice as high as in the perpendicular direction. It should be noted that the measured values of σ are close to the results of [17] for CFRP. The tensile strain rate for textolite (Fig. 8) also corresponds to the measurements of the authors [17]. The close values of the spall strength for composites with fibers of different nature are probably due to the fact that the destruction is initiated at the interface of the fibers with the matrix. Therefore, σ is determined primarily by the strength of this compound, and not the strength of the individual components of a composite material.

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