Study of the shock-wave compressibility of heterogeneous anisotropic materials

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Abstract. Investigation of shock-wave compressibility of three anisotropic materials (carbon fibre reinforced plastic, textolite and kevlar) was performed by a VISAR laser interferometer. Two of these composites consist of the same aramid fibers (textolite and kevlar) and two of them have the same structure (CFRP and kevlar). The structure of compression pulse and shock wave velocity of materials were obtained in each experiment. The shock wave structure in tested composites significantly depends on the fibers orientation - a two-wave configuration is recorded in almost the entire range of studied pressures when shock wave propagates along the fibers. Hugoniot parameters of anisotropic materials were obtained in the coordinates of the shock wave velocity \( D \) – particle velocity \( a \) for two orientations of the fibers. Hugoniot of kevlar, textolite and CFRP with perpendicular orientation of the fibers are parallel to each other. For kevlar and CFRP, the shock wave compressibility almost does not depend on the fibers orientation relative to the direction of the shock wave propagation. In textolite with parallel orientation of the fibers, the shock compressibility is determined by the properties of unidirectional aramid fibers, and Hugoniot for two directions differ significantly.

1. Introduction
Composite reinforced plastics based on fibers of various nature are used in many areas of science and technology, such as automotive, aerospace, sport industry, military, and understanding how such materials behave under high pressure is very important. Reinforced polymer composites have high temperature resistance, fold characteristics and their strength and fatigue properties per unit weight are higher than most metals and alloys. The mechanical properties of anisotropic heterogeneous materials depend on the fiber compound, structure, adhesion of polymer filler, porosity, binder. There are many papers devoted to the study of shock-wave compressibility of composites based on different fibers such as carbon, glass, aramid, filled with various polymers [1-21]. In our work, we try to find common laws in shock compressibility of three composite materials, two of which based on the same aramid fibers with the same composition but have different structure (textolite and kevlar) and two other the same structure, but based on fibers of different nature (carbon fibre reinforced plastic (CFRP) and kevlar).

2. The scheme of experiments
Shock waves in investigated composites were initiated by aluminum impactors, accelerated by explosion products to velocities \( W \) from 1.1 to 3.3 km/s [22]. The thickness of impactors varied from 5.0 to 10.0 mm. The samples were loaded through base plates made from aluminum or copper, which thickness varied from 2.0 to 5.5 mm. The scheme of experiments is shown in Fig. 1. After the collision of impactor (1) with the base plate (2), a shock wave was formed in the plate, which loaded the sample (3).
shock wave parameters were determined by a VISAR laser interferometer [23] at its exit to the boundary with an optical window (4). Water was taken as window and used for preventing the comeback of the release wave from the sample free surface to avoid early spallation in this configuration. The change in the reflection index of the water under shock-wave loading influences on the VISAR measurements, which was taken into account by using of the correction proposed in [24]. To reflect the laser beam, aluminum foil (5) of 7 µm thickness was used, which was glued to the sample surface. The reflected beam was collected by a lens and directed to VISAR. In each experiment, the shock wave velocity of the sample was measured using a polarization gauge (6), which was placed between the metal plate and the sample. The gauge recorded the moment when the shock wave entering to the sample [25]. The error in determining the shock wave velocity does not exceed 1%.

![Fig. 1. The scheme of experiments to measure the parameters of shock compression of the sample: 1 - impactor; 2 – base plate; 3 - sample; 4 – optical window; 5 – aluminum foil; 6 – polarization gauge.](image)

3. Experimental results

3.1. Investigated composite materials and their particle velocity profiles

Studied composites – kevlar, textolite and CFRP consist of aramid and carbon fibers and a matrix - epoxy resin. Kevlar and textolite are based on the same aramid fibers but have different structure. Kevlar consists of plies of woven fibers filled with epoxy resin, whereas textolite has unidirectional fibers. The density of studied samples is 1.26 - 1.27 g/cc. CFRP consists of plies of woven carbon fibers filled with epoxy resin and has the same structure as kevlar, the density of this composite is 1.55 g/cc. For all the materials, the character diameter of the fibers is about 10 - 15 µm, and their volume fraction in the composites is approximately 60 - 63%. To perform the shock-wave experiments, samples with the thickness of 4-7 mm and diameter of 40-50 mm were prepared from a single block of each composite.

Experimental results for composites when shock wave propagates across the fibers are shown in Figure 2. A comparison of particle velocity profiles at the composite – water boundary are presented for kevlar and textolite. All the experiments were performed with Al impactors with the thicknesses of 7 mm (W=1.13 km/s) and 10 mm (W=2.50 km/s). Aluminum base plates with the thickness of 4 mm were used in all experiments. Numbers near velocity profiles indicate the velocity of impactors. In experiments, a velocity jump is recorded, behind which the oscillations are observed relative to a certain average value, due to the heterogeneous structure of composites. These 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 materials, determined by the thickness of the fibers. Velocity profiles for CFRP with perpendicular orientation of the fibers are similar to those for
textolite and kevlar. At the same speed of impactor, the profiles have approximately the same amplitude of particle velocity. We observe the differences in the size and period of oscillations, the arrival of the release wave, which is related to the structure of the sample, the size of the fibers, the thickness of the sample.

![Figure 2](image1.png)

**Fig. 2.** Particle velocity profiles in kevlar and textolite with transverse orientation of the fibers. Numbers indicate the velocity of the Al impactor.

Figure 3 shows the particle velocity profiles for all investigated composites – kevlar, textolite and CFRP - when shock wave propagates along the fibers. All experiments were performed under the same conditions. Aluminum impactors of 7 mm in thick (W=1.13 km/s) and copper base plates with a thickness of 5.5 mm were used. For all composite materials with parallel orientation of the fibers, a two-wave configuration is recorded. This is due to a high sound speed of materials along the fibers. The velocity of propagation of disturbances along the fibers is higher than the shock wave velocity, that results in the formation of precursor. The profiles differ in the duration of the release wave and precursor, its amplitude, as well as in the oscillations size, which is related to the size of heterogeneities, the structure, the thickness of the samples, and the speed of sound along the fibers in the studied composites.

![Figure 3](image2.png)

**Fig. 3.** Particle velocity profiles for kevlar, textolite and CFRP with parallel orientation of the fibers. Speed of aluminum impactor is W=1.13 km/s.
Figure 4 illustrates how the velocity profiles in kevlar change as the incoming pressure pulse increases. The two-wave configuration is observed until the propagation velocity of the shock wave exceeds the velocity of the first wave, which is almost the same as the speed of sound at zero pressure (5.2 km/s), and the two-wave configuration is observed up to the pressure of 17 GPa. When this pressure is exceeded, we record particle velocity profiles similar to the case of wave propagation perpendicular to the fibers. In our experiments, the maximum investigated pressure in kevlar was approximately 18 GPa. Thus, in this composite, the two-wave configuration is observed in almost the entire studied pressure range. In textolite, the sound speed along the fibers is higher than that of kevlar, and it is close to 7 km/s. Therefore, we observe the two-wave configuration up to a shock compression pressure of about 20 GPa, that is in the entire studied range of pressures. In CFRP, the situation is similar to textolite, since the speed of sound along the fibers exceeds 9 km/s, and the two-wave configuration is observed up to maximum pressure obtained in our experiments.

![Graph](image)

**Fig. 4.** Particle velocity profiles for kevlar with parallel orientation of the fibers. Aluminum impactors and metal plates.

3.2. **Hugoniot states for kevlar, textolite and CFRP**

From the obtained experimental data, Hugoniot states of kevlar, textolite and CFRP were plotted. They are shown in Figure 5 in the coordinates of the shock wave velocity $D$ and the particle velocity $u$. The particle velocity was calculated using the known velocity of aluminum impactor and measured in experiment value of $D$. The experimental data for kevlar with transverse orientation of the fibers (filled circles) can be approximated by the linear dependence of $D = 2.53 + 1.45 u$, km/s (solid line in Figure 5). Hugoniot of Kevlar with parallel orientation of the fibers is close to that for transverse direction. The experimental data for textolite with transverse direction of the fibers (grey circles) are approximated by the linear dependence of $D = 2.17 + 1.45 u$, km/s (grey line in Figure 5). Unlike kevlar in textolite, Hugoniots for two directions of the shock wave propagation are different and Hugoniot parameters (grey triangles) can be approximated by the dependence of $D = 1.45 + 2.05 u$, km/s (grey dashed line). Hugoniot of CFRP when shock wave propagating across the fibers is $D = 1.70 + 1.43 u$, km/s (dotted line in Figure 5). In the same way as in kevlar, the shock wave compressibility of CFRP with parallel orientation of the fibers is close to that for transverse direction. We can see from the experimental results (Fig. 5), that Hugoniots of all investigated composite materials with transverse orientation of the fibers are almost parallel to each other and differ only in the first coefficient determined by the sound speed of the composite. The angle of inclination of Hugoniot is determined by the thermal properties of the material, and most likely the properties of epoxy resin, which is a common binder in all these materials, are the most significant in this direction of the fibers.
Fig. 5. Hugoniot states of kevlar (filled circles), textolite (grey circles) and CFRP (empty circles) for the shocks propagating across the fibers. Grey triangles are Hugoniot states for textolite with parallel orientation of the fibers.

4. Conclusion
In our experiments, we tried to find some common laws in shock-wave compressibility of three composite materials based on aramid and carbon fibers. For all investigated in this work composites, the two-wave configuration is observed in almost the entire investigated range of pressures when the shock wave propagates along the fibers. Despite the difference in the nature of the fibers and the structure of the materials, in all the studied composites consisting of the same binder and the volume fraction of fibers, Hugoniot with a perpendicular orientation of the fibers are parallel to each other, which can be explained by the thermal properties of the binder polymer.

It should be noted that for kevlar and CFRP having the same structure - plies of woven fibers filled with epoxy resin – Hugoniots for two orientations of the fibers are close to each other. This means that the shock wave compressibility in these materials almost does not depend on the fibers orientation relative to the direction of the shock wave propagation. But in textolite consisting of unidirectional fibers, Hugoniot for two directions differ significantly, what means that the shock-wave compressibility of material is determined by the properties of unidirectional aramid fibers in the case when shock wave propagates along the fibers. Due to the features of the materials structure, although the volume fraction of fibers in all composites is approximately the same, the number of fibers in kevlar and CFRP at parallel orientation is much less than in textolite. And in this case, shock-wave compressibility is most likely mainly determined by the properties of the epoxy resin as well as for the perpendicular direction. However, what is the minimum volume fraction of the fibers in the composite required for the shock compressibility of the material to be determined by its full composition, we will try to find in further studies with anisotropic heterogeneous materials containing a larger number of fibers.

Acknowledgement
This work was performed in accordance with the state task, state registration No 0089-2019-0001 (experiments with textolite) and supported by government contract “Investigation of thermophysical properties of substances under compression to record high pressures and magnetic fields” (experiments with kevlar and CFRP).
References

[1] Dattelbaum D M, Coe J D, Rigg P A, Scharff R J and Gammel J T 2014 Shockwave response of two carbon fiber-polymer composites to 50 GPa J. Appl. Phys. 116 194308.

[2] Millett J C F, Bourne N K, Meziere Y J E, Vignjevic R and Lukyanov A 2009 The Effect of Orientation on the Shock Response of a Carbon Fibre - Epoxy Composite Compos. Sci. Technol. 67 3253.

[3] Riedel W, Nahme H and Thoma K 2003 Equation of State Properties of Modern Composite Materials Modeling Shock, Release and Spallation AIP Conf. Proc. Shock Compression of Condensed Matter vol 706 pp 701-4.

[4] Alexander C S, Key C T and Schumacher S C 2013 Dynamic response and modeling of a carbon fiber—epoxy composite subject to shock loading J. Appl. Phys. 114 223515.

[5] Homae T, Shimizu T, Fukasawa K and Masamura O 2006 Hypervelocity Planar Plate Impact Experiments of Aramid Fiber-reinforced Plastics J. Reinf. Plast. Compos. 25 1215-21.

[6] Bordzilovskii S A, Karakhanov S M and Merzhiievskii L A 1997 Shock-wave structure in a unidirectional composite with differently oriented fibers Combust., Explos. Shock Waves (Engl. Transl.) 33 354-9.

[7] Micheli D, Vricella A, Pastore R, Delfini A, Giusti A, Albano M, Marchetti M, Moglie F and Primiani V M 2016 Ballistic and electromagnetic shielding behaviour of multifunctional Kevlar fiber reinforced epoxy composites modified by carbon nanotubes Carbon 104 141-56.

[8] Hereil P L, Allix O and Gratton M 1997 Shock behaviour of 3D carbon-carbon composite J. Phys. IV 7(C3) 529-34.

[9] Zaretsky E, DeBotton G and Perl M 2004 The response of a glass fibers reinforced epoxy composite to an impact loading Int. J. Solids Struct. 41 569-84.

[10] Katz S, Zaretsky E, Grossman E and Wagner H D 2009 Dynamic tensile strength of organic fiber-reinforced epoxy micro-composites Compos. Sci. Technol. 69 1250-5.

[11] Pacheco A H, Dattelbaum D M, Bruce O E, Bartram B D and Gustavsen R L 2014 Hugoniot-based equations of state for two filled EPDM rubbers J. Phys.: Conf. Ser. 500 182015.

[12] Bushman A V, Efremov V P, Lomonosov I V, Utkin A V and Fortov V E 1990 Shock-wave compressibility and equation of state for carbon fiber under high density energy Teplofiz. Vys. Temp. 28 1232.

[13] Bushman A V, Efremov V P, Kanel G I, Lomonosov I V, Utkin A V and Fortov V E 1992 Shock compressibility and equation of state of an organoplastic at high energy densities Soviet J. Chem. Phys. 11 587.

[14] Mochalova V M, Utkin A V, Rykova V E, Endres M and Hoffmann D H H 2019 Shock compressibility and spall strength of textolite depending on fiber orientation Arch. Mech. 71 417.

[15] Lässig T, Bagusat F, Pfändler S, Gulde M, Heunoske D, Osterholz J, Stein W, Nahme H and May M 2017 Investigations on the spall and delamination behavior of UHMWPE composites Compos. Struct. 182 590-7.

[16] Lukyanov A A 2012 Modeling the effect of orientation on the shock response of a damageable composite material J. Appl. Phys. 112 084908.

[17] Frias C, Parry S, Bourne N K, Townsend D, Soutis C and Withers P J 2015 On the high-rate failure of carbon fibre composites AIP Conf. Proc. Shock Compression of Condensed Matter vol 1793 p 110011-1.

[18] Yang S, Chalivendra V B and Kim Y K 2017 Fracture and impact characterization of novel auxetic kevlar®/epoxy laminated composites Compos. Struct. 168 120-9.

[19] Taraghi I, Fereidoon A and Taheri-Behrooz F 2014 Low-velocity impact response of woven Kevlar/epoxy laminated composites reinforced with multi-walled carbon nanotubes at ambient and low temperatures Mater. Des. 53 152-8.

[20] Reis P N B, Ferreira J A M, Zhang Z Y, Benenmeur T and Richardson M O W 2013 Impact response of Kevlar composites with nanoclay enhanced epoxy matrix Composites B 46 7–14.
[21] Wenbo Xie, Wei Zhang, Licheng Guo, Yubo Gao, Dacheng Li, Xiongwen Jiang 2018 The shock and spallation behavior of a carbon fiber reinforced polymer composite Composites B 153 176–83.
[22] Kanel G I, Razorenov S.V, Utkin A V and Fortov V E 1996 Shockwave Phenomena in Condensed Media (Moscow: Yanus-K) 248.
[23] Barker L M and Hollenbach R E 1972 Laser interferometer for measuring high velocities of any reflecting surface J. Appl. Phys. 43 4669-75.
[24] Utkin A V, Kanel' G I and Fortov V E 1989 Empirical macrokinetics of the decomposition of a desensitized hexogen in shock and detonation waves Combust., Explos. Shock Waves (Engl. Transl.) 25 625-32.
[25] Mochalova V M, Utkin A V, Pavlenko A V, Malyugina S N and Mokrushin S S 2019 Pulse Compression and Tension of Epoxy Resin under Shock-Wave Action Tech. Phys. 64 100-5.