06

The effect of ultrasound frequency on the physical and mechanical properties of carbon fiber reinforced plastic formed using the layer-by-layer fusion bonding technology

© I.V. Zlobina[1,2], N.V. Bekrenev[1], D.O. Churikov[1]

[1] Gagarin Saratov State Technical University, Saratov, Russia
[2] National Research Center „Kurchatov Institute", Moscow, Russia
E-mail: irinka_7_@mail.ru

Received October 6, 2025
Revised November 22, 2025
Accepted November 27, 2025

A study was conducted to examine changes in strength and stiffness under three-point bending, tension, and impact loads of carbon fiber reinforced plastic (CFRP) produced using FDM technology after contact ultrasonic treatment. It was found that final ultrasonic treatment at 22 and 44 kHz increased stresses under three-point bending by 18.7 % and 8.6 %, respectively. Tensile stresses in the test specimens increased by an average of 12 % and 11 %, respectively, compared to the control specimens.

Keywords: carbon fiber, polyetheretherketone, physical and mechanical properties, shock absorption.

DOI: 10.61011/TPL.2026.03.63070.20517

In the context of a gradual transition to Industry 4.0, industrial production is characterized by a heavier reliance on polymer composite materials (PCMs) and additive technologies in the design of transport systems of various purposes and wind energy complexes and construction [1]. This is attributable to the higher specific strength of PCMs (compared to metals and single-component polymers) and the simplicity of technological implementation of 3D printing for fabrication of objects of a complex shape. Owing to their technical and cost availability, additive technologies utilizing non-metallic materials (FDM, LOM) are the most widespread [2]. Thermoplastic products fabricated by the specified methods have a significant drawback: low interlayer and shear strength, which is associated with the instability of temperature conditions in the printing area, strong temperature gradients between consecutive layers, and significant structural imperfection caused by the high viscosity of thermoplastic materials and poor wetting of the surface of reinforcing fibers by these materials.

The results of application of various types of electrophysical modification to PCMs have been reported in literature [3–6]. The influence of ultrasonic processes on the properties of products formed from composite filaments reinforced with continuous carbon fibers (CFs) has been little studied. The available data on ultrasonic modification of polymers [6] are indicative of fine prospects for the use of ultrasonic technologies for improving the physical and mechanical characteristics of PCM products formed by additive methods.

The aim of the present study is to examine the influence of ultrasonic vibration frequency on stresses and elastic moduli under three-point bending of specimens obtained using additive technologies, on stresses and relative elongation under tension, and on shock absorption.

Plane-parallel carbon fiber reinforced plastic specimens $70 \times 10 \times 2.5$ mm in size with $\pm 45^\circ$ fiber arrangement, which were formed by FDM (fused deposition modeling) from a filament based on CF-reinforced polyetheretherketone (PEEK), were used in experiments. A comparison was made between the properties of reference specimens and specimens subjected to contact ultrasonic treatment with resonant frequencies of 22 and 44 kHz. Since our research was focused on subsequent industrial implementation, the indicated frequencies were chosen as the ones that are used most often for technological purposes and are readily provided by series-produced modern Russian generators. Thermograms were recorded with a Flir E40 thermal imager in the process of ultrasonic treatment. Reference and test specimens were split into three groups of five units each. These PCM specimens were subjected to three-point bending, tension, and impact bending tests performed in accordance with GOST R 57866–2017, GOST 32656–2017, and RF patent 2730055 [7], respectively.

With processing at a frequency of 22 kHz, the temperature in the contact area was $32-40\,^\circ$C; at 44 kHz, the temperature was 13.7 % higher ($39.1-42.8\,^\circ$).

The results obtained in three-point bending and tension tests are presented in Figs. 1 and 2. The experimental stress–strain plots under bending (Fig. 1) are approximated by second-degree polynomials with a sufficiently high accuracy of 96–98 %.

Tension tests revealed that the average stresses of reference specimens, test specimens subjected to ultrasonic treatment at a frequency of 22 kHz, and test specimens treated at 44 kHz were 163, 182.7, and 181.07 MPa, respectively. The stress (load)–strain dependences obtained under tension for reference and test specimens are similar in nature.

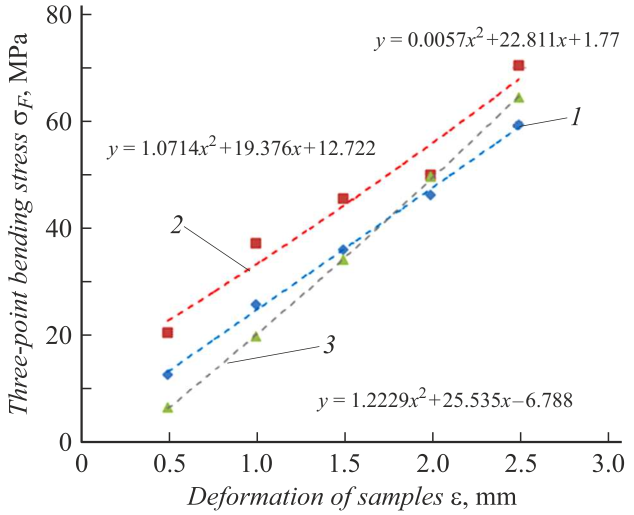

Figure 1. Stress–strain plots for reference (*1*) and test (*2* — subjected to ultrasonic treatment at a frequency of 22 kHz, *3* — at a frequency of 44 kHz) specimens.

Differences characterizing the mechanisms of influence of ultrasound were revealed upon visual inspection of failure areas of the studied specimens (Fig. 3). Individual long and short bundles of consolidated fibers are visible in the failure area of the reference specimen (Fig. 3, *a*). Sections of fibers of different lengths are seen at the points of fracture of test specimens (Figs. 3, *b, c*); the break edge is kinked.

The failure area is 1.5–2 times smaller in extent than that of the reference specimens.

The data obtained by applying shock loads are presented in the table.

The effect of ultrasonic modification of specimens formed by FDM from composite filaments and consisting of continuous CFs and PEEK depends significantly on the ultrasound frequency. It was found that finishing ultrasonic treatment at frequencies of 22 and 44 kHz contributes to a 18.7 and 8.6 % increase in stresses under three-point bending, respectively. In comparison with the reference specimens, tensile stresses of the test specimens processed at frequencies of 22 and 44 kHz increased by 12 and 11 % on the average, respectively, while the strain remained unchanged. The effect of shock damping was found to be suppressed under exposure to high-frequency ultrasound: the impact force transmitted through the specimen was reduced by 23 and 10.8 %, respectively, which is consistent with the data from other studies into shock damping by polymer structures [8].

The above results may be attributed to the following processes occurring in the monolayer binder under exposure to ultrasound. Compressive plastic strain induced by a contact impact of ultrasound on the surface of a monolayer manifests itself in a reduction of the specimen thickness. Owing to the noted increase in temperature and the influence of high pressures caused by the dynamic force, the magnitude of which is approximately 4 times greater than the static concentrator pressing force [9], the thermoplastic polymer of the outer filament shell diffuses into discontinuities present in a bundle of reinforcing fibers, voids between individual filament tracks in the layer are filled, and they are subjected to additional mutual welding. At the same time, cyclic loading with a large number of cycles (22,000 and 44,000 per second) is conducive to micro-ruptures in the thermosetting matrix combining the reinforcing fibers into bundles. These competing processes proceed simultaneously, inducing different kinds of damage to specimens depending on the quality of preliminary impregnation and consolidation of bundles. At the same time, ultrasonic welding of adjacent filament tracks neutralizes the indicated negative phenomena.

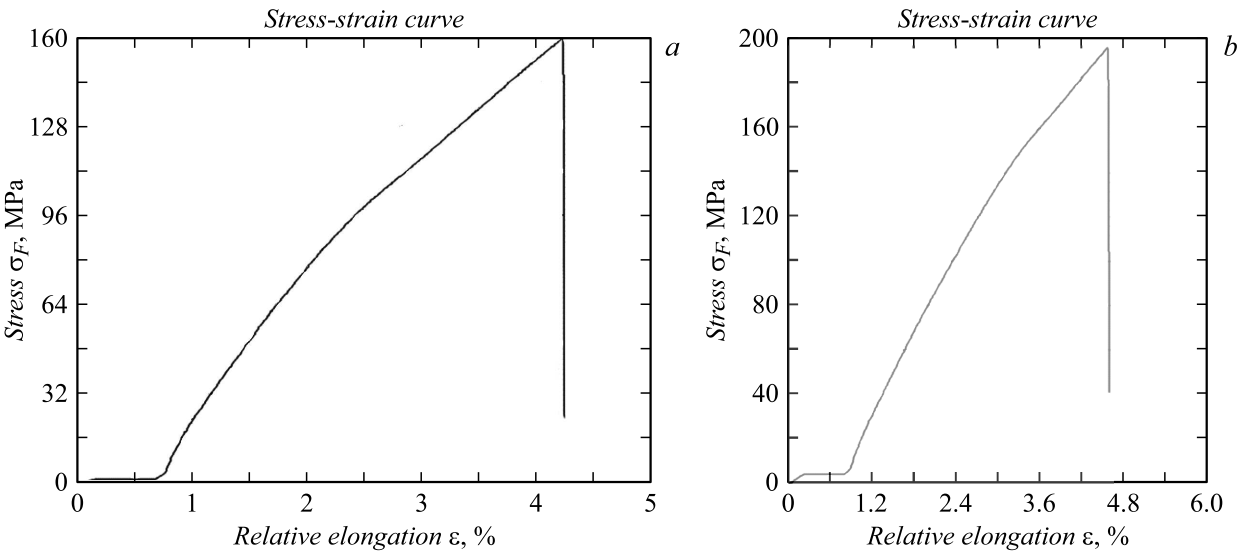

Figure 2. Typical stress–strain plots obtained under tension for reference (*a*) and test (*b*) specimens.

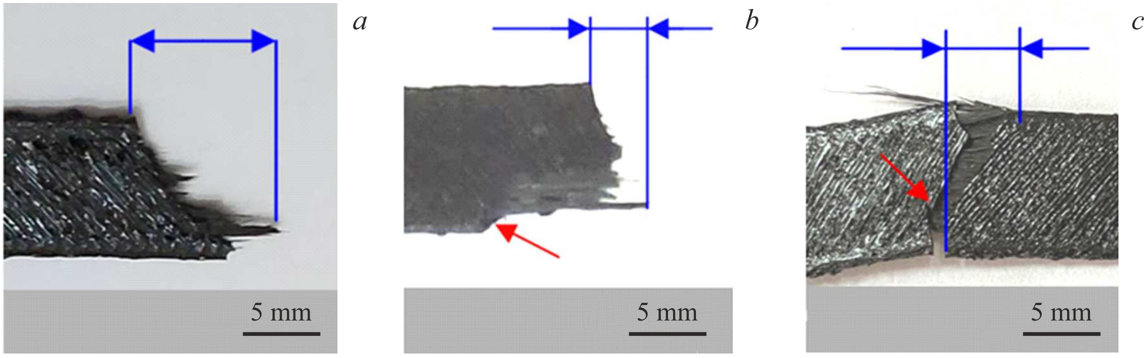

Figure 3. Pattern of tensile failure: *a* — reference specimen, *b* and *c* — test specimens after ultrasonic treatment at a frequency of 22 and 44 kHz, respectively. Inclined arrows point at the characteristic fracture areas of a specific group of specimens. Horizontal arrows indicate the extent of the failure area typical of a given group of specimens.

Parameters of response of the specimens to shock loads

Specimen type	Transferred force, N	Duration of pulsed force impact, ms
Reference	0.31	9.03
After ultrasonic treatment at a frequency of 22 kHz	0.27	6.67
Test parameter/ reference parameter	0.87	0.74
After ultrasonic treatment at a frequency of 44 kHz	0.34	2.50
Test parameter/ reference parameter	1.11	0.28
Metal	0.88	7.05

Acknowledgments

Equipment provided by the Chemical and Analytical Research Center at Kurchatov Institute was used for analytical studies.

Funding

This study was supported by the Russian Science Foundation (grant 23-79-00039).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] E.N. Lapteva, O.V. Nazarochkina, Mashinostr. Komp'yut. Tekhnol., No. 5, 11 (2019) (in Russian). DOI: 10.24108/0519.0001500

[2] I. Gibson, D. Rosen, B. Stucker, *Additive Manufacturing Technologies. 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing* (Springer, New York, 2014).

[3] *Microwave processing of materials* (National Academy Press, Washington, 1994). DOI: 10.17226/2266

[4] Yu.S. Arkhangel'skii, *Spravochnaya kniga po SVCh-elektrotermii* (Nauchn. Kniga, Saratov, 2011) (in Russian).

[5] I.V. Zlobina, N.V. Bekrenev, Izv. Sarat. Univ. Nov. Ser. Fiz., **22** (2), 158 (2022) (in Russian). DOI: 10.18500/1817-3020-2022-22-2-158-169

[6] V.N. Studentsov, I.V. Pyataev, Russ. J. Appl. Chem., **87** (3), 352 (2014). DOI: 10.1134/S1070427214030173.

[7] I.V. Zlobina, N.V. Bekrenev, *Sposob ispytaniya polimernykh kompozitsionnykh materialov na soprotivlenie povrezhdeniyu pri udarnom vozdeistvii*, RF Patent 2730055 (applied on February 14, 2020; published on August 14, 2020) (in Russian).

[8] V.M. Chernyshev, *Dempfirovanie kolebanii mekhanicheskikh sistem pokrytiyami iz polimernykh materialov* (Nauka, M., 2009) (in Russian).

[9] A.I. Markov, *Ul'trazvukovoe rezanie trudnoobrabatyvaemykh materialov* (Mashinostroenie, M., 1968) (in Russian).

Translated by D.Safin