The influence of ultrasound on physico-mechanical properties of composite materials reinforced with carbonaceous fibers in the formation process

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Abstract. The process of reinforcement in the ultrasonic field of structural elements from ABS plastic composite structures containing carbon fibers was studied. The fact of formation of an adhesive-strong interface of "composite-plastic" under the action of ultrasound on the sample during the curing of the composite is established. It is shown that ultrasonic action causes the formation of a homogeneous morphology of the surface and structure of the composite layer, as well as a change in the ratio of the strength parameters of the material. In tensile tests, an increase in strength of 18 % was found with a certain decrease in the elongation.

1. Introduction
The development of modern technology and its production is characterized by a wide use of non-metallic composite materials [1] and digital technologies, one of the directions of which are three-dimensional printing technologies, or additive technologies [2]. Among the various methods of three-dimensional printing, the most common are the technologies of selective laser sintering of products from metal powders and layer-by-layer fusing with polymer filament. However, composite materials are characterized by pronounced anisotropy of physico-mechanical characteristics, determined by the type and orientation of the reinforcing components [3]. Objects made of polymeric materials, obtained on the basis of additive technologies, are characterized along with significant heterogeneity of the structure by instability of properties from product to product and from installation to installation [2], which limits the scope of this technology by rapid prototyping and making models for foundry production. At the same time, the possibilities of additive technologies make it possible to strengthen reinforcement of objects from polymeric materials by introducing composite structures containing, for example, carbon fibers. However, to increase the strength of such products, it will be of great importance to have an adhesive interaction between the reinforcing composite and the polymer base. At the same time, due to the insignificant strength of the polymer structure for compression, which does not allow the use of significant loads in pressing the composite, it is very difficult to obtain a uniform impregnation of the composite with a binder. It is known that ultrasonic vibrations generated in liquid media contribute not only to the development of cavitation processes, but also to a significant intensification of capillary effects [4, 5].

2. Formulation of the problem
The purpose of our research was to study the possibility of improving the uniformity of impregnation of a composite based on an epoxy matrix filled with carbon fibers, as well as improving its contact interaction with a plastic substrate in an ultrasonic field.

3. Research methods and equipment
In the experiments we used samples of dimensions 120x40x4.5 mm from the thermoplastic ABS, obtained by three-dimensional printing using FDM technology from a 1.75 mm thick thread with a depth of 3 mm filled with carbon plastic. We used the 3D printer Felix 3.1 Single Extruder for printing. The cavity was layer-by-layer filled with carbon fiber produced by LLC Balakovo Carbon Production (Balakovo, Saratov Region) and epoxy resin ED-20 with PEP hardener. 10 samples were prepared and 5 samples after filling with a composite were subjected to ultrasound through the lower surface of the sample using a piezoceramic transducer (Figure 1).

![Experimental setup (a) and the loading scheme of the sample (b)](image)

**Figure 1.** Experimental setup (a) and the loading scheme of the sample (b) 1 – sample filled with a composite, 2 – source of ultrasonic vibrations

The converter was supplied with power from the designed by our technical task in the SSTU ultrasonic generator with a programmable frequency range from 20 to 60 kHz with the ability to fine-tune the joystick with an accuracy of 10 Hz. The resonant frequency of the converter was 23600 Hz, the amplitude of the oscillations was regulated from 5 to 15 µm by varying the generator voltage from 120 to 200 V. The processing was carried out at the attained maximum ultrasound intensity in the demonstration mode at an amplitude of 12 µm. After curing, the control and ultrasonically generated samples were subjected to tensile tests on a tearing machine IR-5082-100 with computer processing of the results. The surface of the composite layer and its contact area with plastic was examined with a digital microscope Digital Microscope 2.0 MP 1000X (GAOSUO, China) with an increase in x500, displaying on the laptop screen.

### 4. Results and discussion

The test results are shown in FIG. 2 and in the table. It can be seen that the curing of the composite structure with ultrasound influence causes a change in the ratio of the force parameters characterizing the process of deformation and destruction of the sample. With an insignificant increase in the maximum destructive load, loads corresponding to the elastic limit of the material increase significantly (by 14–18 %). In this case, the yield strength is reduced by 70 % and the duration of plastic deformation of the sample decreases. This corresponds to a twofold decrease in the relative elongation.
Figure 2. Loading schedules of samples: with a composite structure (a) cured under normal conditions, with a composite structure cured by ultrasonic vibrations (b)
Table 1. Mechanical characteristics of the control and ultrasound-generated samples obtained during the tensile tests.

| Sample                        | Parameter | \( F_{m}, \) kN | \( F_{eh}, \) kN | \( F_{el}, \) kN | \( F_{p}, \) kN | \( F_{t}, \) kN | \( A, \% \) |
|-------------------------------|-----------|------------------|------------------|------------------|----------------|----------------|-------------|
| Control sample                |           | 0.9              | 0.7              | 0.7              | 0.7            | 0.17           | 7.5         |
| After ultrasound processing   |           | 0.95             | 0.83             | 0.8              | 0.8            | 0.1            | 5.0         |
| Parameter change              |           | +5 %             | +18 %            | +14 %            | +14 %          | - 70 %         | - 50 %      |

At the same time, the maximum modulus of elasticity increases by almost 20 %. The spread of the values of all the listed parameters for the control sample was from 25 to 35 %, for samples formed with ultrasound – did not exceed 12 %.

The obtained results can be explained by analyzing the micrographs of the formed composite material (Figures 3 and 4). On all control samples, the separation of the reinforcing structure from the thermoplastic substrate is clearly visible. Apparently, almost separate perception of the tensile load by the substrate and the composite caused a decrease in some force parameters of the deformation of the control sample and especially its elastic modulus in comparison with the treated one, since the peeling of the reinforcing structure is of a random nature and the number of bond points is different for different samples. In the structure of the reinforcing composite, there are seen separate voids, not filled with a binder. The surface is characterized by a highly heterogeneous morphology. These results are apparently explained by the poor wettability of the carbon fibers and the incomplete flow of the binder into the gaps between them in the absence of evacuation or surface pressure.

The contact zone "composite-plastic", formed under conditions of ultrasonic influence, is solid. Clear penetration of the binder into the structure of the plastic substrate is seen. The local penetration of the binder through the entire layer of the substrate to the external surface contacted with the ultrasonic radiator was visually determined. The structure of the composite is more uniformly filled with a binder, there are practically no voids. The morphology of the surface has a smooth, wavy, repetitive appearance, which is connected to acoustic currents in the uncured composite.

Figure 3. The contact zone "composite-plastic" (a), the microstructure of the composite layer (b) and the morphology of the surface (c) of the control sample.
Figure 4. Contact zone "composite-plastic" (a), microstructure of the composite layer (b) and morphology of the surface (c) of the sample formed under influence of ultrasound

5. Conclusion
The noted features may be the reason of an increase in the elasticity modulus of the samples and a decrease in the relative elongation due to the joint perception of the load by both the plastic of the substrate and the composite, as well as an increase in the uniformity of the strength characteristics and an increase in the parameters determining the increase in the elastic limit. To optimize the elastoplastic characteristics of composite materials formed under conditions of ultrasonic influence, it is advisable to conduct studies on the selection of the frequency range and intensity of ultrasound, taking into account the wave properties of the substrate materials and reinforcing fibers, as well as the cavitation threshold of the binder.

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