Study of the tensile strength of a polymer composite material based on ABS-plastic and impregnated in epoxy resin with different types of hardener

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Annotation. This article examines the study of strength properties of polymer composite material, based on 3D-printed frame produced by FDM technology. The printing material is ABS plastic (acrylonitrile butadiene styrene). After the printing samples frames were soaked in pure epoxy resin with various hardeners. Subsequent curing went in two modes. After that, tensile tests were performed. The strength of impregnated, non-impregnated (clean frame) samples and samples made of pure resin was compared. Tests have shown that the strength of impregnated samples exceeds the strength of non-impregnated ones, but obtained strength value of impregnated samples were far from the expected theoretical values. It was found that low strength is associated with poor quality of the impregnation.

Key words: 3D-printing, additive technologies, FDM, ABS plastic, epoxy resin, composite material, mechanical properties, tensile strength

1. Introduction
Modern high-performance agriculture requires the creation of new progressive machines [1]-[5]. Their creation is impossible without the development of new materials and new efficient technologies for manufacturing machine parts. One of the most promising technologies for manufacturing parts today is additive technologies [6]-[13]. The most common 3D printing technology at the present time is FDM technology (Fused Deposition Modelling, figure 1). The main problem of this technology related with anisotropy of product properties and its lower mechanical characteristics compared to the characteristics of products produced by standard manufacturing methods. The essence of the technology is to lay the molten polymer filament in layers. As a result, the layers are often not well glued together. In addition, the use of engineering group plastics with obviously higher strength properties is limited due to their poor technological properties for processing with FDM printing. The price of these plastics is also quite significant.
One of the ways to improve the strength characteristics of products printed on a 3D-printer using FDM technology can be vacuum impregnation in a polymer compound with high mechanical properties [14], [15]. The method is related to the vacuum infusion technology used to create fabric-based composites [16]-[20]. Such processing can allow gluing the product layers together, thereby reducing the anisotropy of properties, as well as using compounds with high mechanical properties to increase the strength of parts to a level comparable to the properties of engineering plastics. At the same time, as the base of the part (the frame that produces the geometry) can be used technologically cheap general-purpose plastic. As a result of such processing a composite material is formed in the structure of the part, which mechanical properties are higher.

2. Materials and methods
In this study, the samples had a standard form for tensile tests according to GOST 11262-2017 “Plastics. Tensile test method” (figure 2).

The frame of the samples was printed on a 3D-printer Picaso 3D Designer X PRO and was made of ABS plastic (acrylonitrile butadiene styrene). Printing was performed with 33% filling in the form of a simple grid with an angle in the crosshairs of 90° (figure 3a). In the printing process for the samples varied the stacking direction of the layers: along the axis of the sample and across the axis of the sample, figure 3b.

After printing, the samples were impregnated in epoxy resin compound ED-20 grade with the content of epoxy groups from 20 to 22.4 %. The impregnation was carried out using a vacuum system presented on the figure 4. It was used two types of hardeners: triethylenetetramine (TETA) and polyethylene polyamine (PEPA). Both are primary aliphatic amines for cold curing epoxy resins at room temperature. The expected breaking tensile stress with TETA hardener is 88 MPa, with PEPA hardener – 50 MPa.
Mixing was carried out using an automatic agitator in the proportion of 1 part of the hardener to 10 parts of the base by weight. Before impregnation, the components separately and the compound in the mixture were degassed.

![Figure 3. Parameters for printing wireframes on a 3D-printer: a – internal filling, 33%; b – the stacking direction of the layers in the printing process](image)

![Figure 4. Impregnation of 3D printed parts with polymer compound: 1 – chamber; 2 – transparent lid; 3 – pressure gauge; 4 – polymer compound; 5 – impregnated part; 6 – release valve; 7 – shut-off valve; 8 – vacuum pump](image)

After impregnation, the samples were cured in two different modes: one-stage – at room temperature for 5 days, two-stage – 24 hours at room temperature, then 5 hours at 90 °C. Additionally, for comparison of the properties it was manufactured samples from a clean resin with the same curing modes is as follows. There were three samples in each batch.

Tensile tests were carried out in accordance with GOST 11261-2017 “Plastics. Tensile test method” on the test machine Zwick/Roell Z050. The loading speed was 50 mm/min.

### 3. Results and discussion

According to the results of the tensile test, it can conclude that all samples are destroyed brittle, which is confirmed by the appearance of the fracture and absence of the yield point on the resulting stretch diagram.

Figure 5 shows the average results of the obtained values of the ultimate strength for samples made of pure epoxy resin. It can see that the use of a two-stage curing mode leads to a significant increase in strength compared to the curing mode at room temperature for 5 days. Samples cured at elevated temperatures have a strength twice as high as those that cured at room temperature for both types of hardener used. The strength does not depend on the type of hardener: in both cases, the maximum strength values were about 45 MPa. The obtained strength values are consistent with the expected values.
only for the PEPA hardener. In the case of TETA hardener, the declared strength is twice as high as that obtained in real tests. The reduced strength index in this case can be caused by an incorrectly selected proportion between the base and the hardener, since the properties of epoxy resins are very sensitive to this parameter.

**Figure 5.** Results of tensile testing of pure epoxy resin samples with various hardeners and curing modes

The results of tests of impregnated 3D-printed samples with 33% filling and different directions of laying plastic layers during printing are at the figure 6. This figure also shows the strength values of non-impregnated frames with a similar geometry. The tensile diagram corresponds to the tensile diagram of the epoxy resin sample and the fracture of the samples is also brittle.

**Figure 6.** Results of tensile testing of impregnated 3D-printed samples: a – frames with the layers of plastic along the axis of the sample; b – frames with the layers of plastic across the sample axis

As seen in figure 6, the strength of the impregnated samples compared to the non-impregnated ones increased with all variants of impregnation, but the increase in strength is not as significant as expected. Knowing the strength of a pure resin and a pure 3D-printed frame it is possible to estimate the theoretical strength of the composition using the law of additivity which is widely used to evaluate the mechanical properties of composites. The calculation is using the formula 1:

\[
\sigma = V_{fr} \sigma_{fr} + V_{resin} \sigma_{resin},
\]

where \(V_{fr}=0.33\), \(V_{resin}=0.67\) – volume fractions of the frame and resin, respectively; \(\sigma_{fr}, \sigma_{resin}\) – the strength of the frame and resin, respectively.

To calculate theoretically strength, we will take the maximum strength value obtained experimentally as the resin strength (46.1 MPa, which corresponds to the use of TETA hardener and two-stage curing mode, figure 5), and as the value of the frame strength the corresponding experimental values of the
strength of pure ABS with 33% filling (figure 6). Then the theoretically strength of a composite based on along type frames can be calculated using the formula 2 as

$$\sigma_{\text{along}} = 0.33 \cdot 7.20 + 0.67 \cdot 46.1 \approx 33.3 \text{ MPa},$$  

and the strength of a composite based on cross-type frames can be determined as

$$\sigma_{\text{across}} = 0.33 \cdot 4.37 + 0.67 \cdot 46.1 \approx 32.3 \text{ MPa}.$$  

According to the test results, it can be observed that the closest to the calculated value was the result for a batch of samples based on a cross-type frame and impregnated in a compound with a TETA hardener and curing at an elevated temperature (21.4 MPa, figure 6b). The remaining impregnated samples showed much lower strength. To determine the reason for the low strength, the samples were additionally subjected to visual inspection. It was found that there is no resin in the fractures of the predominant part of the samples (figure 7). Thus, the low strength properties of the samples are probably related to the poor quality of impregnation of the test batch of materials.

![Figure 7](image.png)

**Figure 7.** Fractures of tested specimens: a – samples type along; b – samples type across

### 4. Conclusions

Based on the obtained results, it can be concluded that all types of investigated samples cured using two-stage mode (24 hours at room temperature, then 5 hours at 90 °C) show higher strength properties. In a series of the along type samples the highest strength was observed in the case of impregnation in a compound based on ED-20 resin with a PEPA hardener followed by a two-stage curing mode at elevated temperature – 10.24 MPa against the original strength of empty frame 7.20 MPa. Although in relative terms such increase is quite significant (about 40 %), in absolute terms the increase in strength is quite small, because the expected theoretical strength was 33.3 MPa. In a series of the across type samples the highest strength value was observed on samples impregnated in a compound based on ED-20 resin with a TETA hardener followed by a two-stage curing mode at elevated temperature – 21.40 MPa against the original strength of empty frame 4.37 MPa. The theoretically strength in this case was 32.3 MPa. Difference between the theoretically and experimental properties is explained by poor quality of impregnation: tested samples had a many void in investigated fractures.

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