Research of polymers strength properties for 3D printing under normal conditions

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Abstract. An article is devoted to the study of the strength properties of interlayer adhesion and determination of Young's modulus by the ball instrumental indentation method for samples, made of various plastics using additive technology under normal conditions. This production method is chosen as the most appropriate for creating lightly stressed parts of complex geometry (up to 30 MPa) in the shortest possible time. One of the possible options for such products is full-size centrifugal wheels layouts of low power gas turbine units (up to 250 kW) for testing them in model conditions. It will ensure the work of the material in the elastic zone. The samples are considered, obtained by FDM method from various polymers such as: acrylonitrile butadiene styrene thermoplastic resin (ABS+), acrylonitrile butadiene styrene thermoplastic resin with addition of carbon fibers (ABS Carbon), nylon with addition of carbon fibers (Nylon Super Carbon), polyethylene terephthalate glycol (PETG) and a compound based on polylactide (PLA HP). Plastics, made by this method, have anisotropic properties. Therefore, in this work, the strength characteristics of the test samples interlayer adhesion under tension are determined.

1. Introduction
Currently, there are a large number of technologies that may be used to obtain a part with the required configuration. In this case, the main goal is to select the most effective of them in terms of economic and time costs [1]. If it is necessary to obtain prototypes, low stressed during operation (up to 30 MPa), an additive technology for manufacturing parts by FDM method is suitable. The selected technology serves to create complex products, required in power engineering industry. This work is dedicated to determining the strength properties of samples interlayer adhesion, made from various filaments using 3D printing. The performed research is a continuation of studies of the anisotropic properties of plastics [2–4].

The efficiency of the main device depends on the reliability of the units and parts included in it. Therefore, it is necessary to select for them such materials, the strength characteristics of which will ensure the uninterrupted operation of the setup under the required operating conditions, or will allow conducting a series of tests. Examples of such units are compressor and turbine impellers of high-
speed machines, which are often subject to significant stresses. Manufacturing impellers from metal is
time consuming and costly compared to polymer wheels, which can be created by 3D printing with
minimal investment. Such impellers cannot be used as a complete replacement for metal wheels, but
they are quite suitable for operation in model conditions. Therefore, a special test rig was created at
JIHT RAS for testing compressor and turbine wheels. It allows conducting experimental studies of
full-size models of impeller wheels, made of plastics, at reduced rotation speeds. The data of such tests
serve to verify the results of numerical calculations and develop a general methodology for designing.
This approach can be used to create gas pumping units in various industries.

To carry out such tests, it is necessary to know the accurate strength characteristics of the material.
There are a large number of different filaments for 3D printing on the market today. However, not all
of their strength properties have been studied. Parts, obtained by FDM method, have anisotropic
properties. Therefore, it is necessary to conduct tests to determine the strength characteristics of
polymer samples along all printing directions.

2. Objects and research methods
The research of the selected filaments properties was carried out in two stages. At the first stage, a
study of the tensile strength properties of polymers interlayer adhesion was performed. The method,
conditions for determining the properties of plastics, and preparation of samples for testing were
conducted in accordance with ISO 527-2:2012. Sample type 4 was chosen for testing, because it meets
the shape and size requirements for a 3D printer and a tensile testing machine “Instron 8801”.

Samples for strength studies were printed by layer-by-layer growth from following plastics: ABS+
(unpainted), ABS Carbon, Nylon Super Carbon (NSC), PETG and PLA HP. Three test samples were
prepared for each of the polymers. Parts, obtained using this method, have anisotropic properties.
Consequently, usage of plastic products, created by FDM method, requires the knowledge of the
properties of interlayer adhesion. For this purpose, samples were printed on the 3D printer in order to
determine their strength properties with a fill pattern of grid, which will be used for printing the
compressor and turbine wheels for full-scale tests (figure 1).

![Figure 1. Fill pattern of grid to determine samples strength properties of interlayer adhesion: 1 – contour lines; 2 – inner filling of contour.](image)

As shown in figure 1, the sample is printed layer by layer, each layer consists of 2 contour lines,
and the rest part has a zigzag filling. The lines thickness is 0.5 mm, and the thickness of the layer is
0.1 mm. When creating samples, the printing speed is 5 mm/s, and the extrusion speed is 0.25 mm³/s.

At the second stage, tests were carried out to determine the Young’s modulus. Plastics were
selected for testing, which did not show a strong discrepancy in the results for three samples, when
tested on the tensile testing machine “Instron 8801”, and polymer rupture occurred in the area of the
sample test section. For these polymers, samples were prepared on the 3D printer by FDM method with 100% filling (figure 2). After that, Young's modulus was determined experimentally according to GOST R 56232-2014. The tests were implemented on “NanoScan-3D” equipment.

![Figure 2. Samples for determining the Young's modulus: 1 – PETG, 2 – PLA HP, 3 – Nylon Super Carbon.](image)

3. Results and discussion
Strength tests for defining the properties of interlayer adhesion were carried out at the Institute of National Research University "MPEI" at the department of Metal Technology. The tensile tests of samples were implemented using the servo-hydraulic testing system “Instron 8801” under normal conditions. The parameters report rate was taken equal to 0.1 s, and the measurement error was ± 0.5%. Figure 3-7 shows the tensile test results for cylindrical and flat samples. Cylindrical samples represent the adhesion strength of the layers during fusion (interlayer adhesion). Flat samples show the strength characteristics of the material along the layer, when adhesion does not affect the strength [4]. Figure 8 shows the dependence "stress-relative elongation" for researching polymers, averaged over the test results for defining the interlayer adhesion.

![Figure 3. ABS+ strength properties: a) Interlayer adhesion strength properties, b) Strength properties comparison for interlayer adhesion (cylindrical sample) and along the layer (flat sample).](image)
Figure 4. ABS Carbon strength properties:
a) Interlayer adhesion strength properties, b) Strength properties comparison for interlayer adhesion (cylindrical sample) and along the layer (flat sample).

Figure 5. Nylon Super Carbon strength properties:
a) Interlayer adhesion strength properties, b) Strength properties comparison for interlayer adhesion (cylindrical sample) and along the layer (flat sample).

Figure 6. PETG strength properties:
a) Interlayer adhesion strength properties, b) Strength properties comparison for interlayer adhesion (cylindrical sample) and along the layer (flat sample).
According to figures 3–8, ABS Carbon shows a strong discrepancy in the results for the three tested samples, and, presumably, this is due to carbon inserts in the form of a fine powder. In addition, ABS Carbon and ABS + (unpainted) ruptured outside of the sample test section, where elongation is determined. Thus, these plastics are not suitable for products operated at stresses in the region of 30 MPa, since they are extremely unstable. The interlayer strength properties of PETG and Nylon Super Carbon are superior to the tensile strength along the layer. The opposite is true for PLA HP. According to the test results (figures 3–8), PETG, PLA HP and Nylon Super Carbon show satisfactory results. The strength properties of interlayer adhesion and the strength characteristics of the material, when loaded along the layer, exceed the stress of 30 MPa. Therefore, Young's modulus for these polymers using the NanoScan-3D equipment by the ball instrumental indentation method was determined (figure 9).
Figure 9. Dependence of force on displacement, obtained by the ball instrumental indentation method.

In the course of research, plastics were selected for the use as responsible products, loaded up to 30 MPa. Strength properties for PETG, PLA HP and Nylon Super Carbon polymers are shown in table 1.

Table 1. Strength properties for interlayer adhesion and along the layer

| Polymer | Yield strength σy, MPa | Tensile strength σt, MPa | Experimental Young's modulus, MPa | Elongation at fracture δ, % |
|---------|------------------------|--------------------------|---------------------------------|-----------------------------|
| PETG    | 20.82                  | 47.58                    | 2236                            | 4.55                        |
| PLA HP  | 28.55                  | 43.34                    | 2786                            | 3.42                        |
| NSC     | 15.95                  | 38.87                    | 1975                            | 13.77                       |

(b) Strength properties along the layer [4]

| Polymer | Yield strength σy, MPa | Tensile strength σt, MPa | Estimated Young's modulus, MPa (error between exp. and est. Young's modulus) | Elongation at fracture δ, % |
|---------|------------------------|--------------------------|-------------------------------------------------|-----------------------------|
| PETG    | 21.85                  | 38.52                    | 1809 (19.1%)                                    | 5.93                        |
| PLA HP  | 32.72                  | 52.69                    | 3176 (12.3%)                                    | 2.85                        |
| NSC     | 14.72                  | 34.41                    | 1246 (36.9%)                                    | 12.29                       |

The obtained test results may be summarized as follows:

- PETG withstands the tensile load along the layer of sample σt = 38.52 MPa (elongation at fracture δ = 5.93%), which is less than the strength characteristics of interlayer adhesion σy = 47.58 MPa (elongation at fracture is δ = 4.55%).
- PLA HP is the most durable plastic in comparison with PETG and Nylon Super Carbon. It has ultimate strength along the layer and interlayer adhesion σt = 52.69 MPa and σy = 43.34 MPa, respectively. The tensile strength along the layer is greater than the strength properties of the interlayer adhesion. Elongations at fracture for stretching along the layer is δ = 2.85%. The value of elongation for interlayer adhesion is equal to δ = 3.42%.
- Nylon Super Carbon has tensile strength along the layer σt = 34.41 MPa and interlayer adhesion σy = 38.87 MPa. The interlayer adhesion strength is greater than the tensile strength along the layer. Elongation at fracture under tension along the layer is δ = 12.29%, with interlayer adhesion equal to δ = 13.77%.
As shown in table 1, the difference between the values of Young's modulus, determined from the relationship [4] and experimentally, reaches 37%. These results indicate that, perhaps, the stiffness coefficients of the tensile testing machine were incorrectly taken into account or an error was made when calculating a slope of a load-displacement curve. In addition, Hooke's Law works for ideal samples. However, plastics, obtained by the FDM method, have anisotropic properties. Also, microfractures from heat shrinkage may present in them. Hence, we can conclude that experimental studies are needed to obtain more accurate results.

Young's modulus data from the filament supplier, for which the study was conducted, was compared with the experimental results. According to data from the site “u3print.com”, polymers have the following Young's modulus: PETG (1422 MPa), PLA HP (2169), NSC (1738 MPa). When compared with the data from table 1, the following error is obtained: PETG (36%), PLA HP (22%), NSC (12%).

Conclusions
After the conducted research, it can be concluded that it is necessary to take into account the anisotropy of properties for polymers, obtained by FDM method. The plastics ABS+ (unpainted), ABS Carbon, Nylon Super Carbon, PETG and PLA HP have been investigated. Only PETG, PLA HP and Nylon Super Carbon show satisfactory test results. These materials can be used to create parts of complex geometry that experience low loads (up to 30 MPa) during their operation. HP PLA is the most durable from the test results. However, this polymer absorbs moisture over time, which leads to a loss of its strength properties. Therefore, this material is suitable for short-term tests. For instance, it is determination of gas-dynamic properties at the special test rig of JIHT RAS for testing compressor and turbine wheels under model conditions. When comparing experimental results with estimated and third-party data of Young's modulus, the error reaches the value of 37%. Therefore, it is necessary to carry out strength tests to determine the precise characteristics of the polymers.

References
[1] Borisov Yu A., Belova O V and Volkov-Muzylev V V 2018 Naukograd Nauka Proizvodstvo Obshchestvo 16(2) 56–59 [In Russian]
[2] Vendland L E, Volkov-Muzylev V V, Demidov A N and Borisov Yu A 2019 Journal of Physics: Conference series 1359 012107
[3] Volkov-Muzylev V V, Vendland L E, Borisov Yu A and Demidov A N 2019 AIP Conference Proceedings 2141 040001
[4] Vendland L E, Volkov-Muzylev V V, Demidov A N, Borisov Yu A and Gavrilova Yu A Research of plastics strength properties for 3D printing under normal conditions 2021 AIP Conference Proceedings (to be published)