Room temperature testing of PLA plastics

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Abstract. Polylactide plastic (PLA) prototypes are studied by means of additive technology to determine their strength properties in case of tension along the grain. In this article, testing of PLA and its compound PLA HP was carried out. Mechanical properties (yield limit, Poisson’s ratio, Young’s modulus) are determined. Analysis of results related to comparison of PLA and PLA HP was realized. Plastic is also studied using microscope for determination of adhesion influence on strength characteristics.

1. Introduction
Progress doesn’t stand still, and every day technologies’ improving of parts production occurs. One of them is 3D-printing technology or additive technology, which allows to get products of different materials in the shortest possible time.

Traditional methods of parts formation are connected with lathe work of a massive billet or a casting/die forming. Lathe work produces big lack of material, while casting implies increasing cost of producing process. Additive technologies involve producing of whole three-dimensional objects of any complexity, using different kinds of 3D-technologies, and completely replace expensive traditional methods.

One of the most common method of additive production is Fused Deposition Modeling (FDM). In this technology polymer thread is brought to an extruder and melted there. Using this melted thread, physical model is formed according to section configuration of a virtual CAD-model [1].

Nowadays, a lot of different polymers for 3D-printing are presented, but their strength characteristics in accordance with infill shapes of a model are absent. This leads to necessity of mechanical tests, which will allow to predict essential product behavior in exploitation conditions.

2. Preparing for mechanical tests
Objects of mechanical tests are specially printed test prototypes using FDM method (fig. 1a and 1b).
These prototypes were fabricated according to dimensions specified in GOST 11262-80 (fig. 2a) and with a zigzag infill shape (fig. 2b).

FDM method allows to print using different kinds of plastics. In the global market the most common of them are ABS [3] and PLA. To carry out mechanical tests, PLA plastic in pure form and compound based on PLA - PLA HP were chosen.

Prototypes for mechanical tests are printed in sets of five pieces with following parameters: Infill density of an object – 100%. Infill pattern of an object – zigzag. Quantity of lines in a wall is 3. Width of a line is 0.4 (mm). Height of a layer is 0.2 (mm).

Before PLA and PLA HP material tests lengths and widths of a prototype bodies are measured. Table 1 shows data only for PLA prototypes. According to these measures area of a cross section $F_0$ is calculated.

| № of prototype | $b_1$ (mm) | $b_2$ (mm) | $b_3$ (mm) | $h_1$ (mm) | $h_2$ (mm) | $h_3$ (mm) | $F_0$ (mm$^2$) |
|----------------|------------|------------|------------|------------|------------|------------|----------------|
| 1              | 6.17       | 6.15       | 6.17       | 1.90       | 1.85       | 1.91       | 11.63         |
| 2              | 6.00       | 6.00       | 6.08       | 1.97       | 1.96       | 1.94       | 11.79         |
| 3              | 6.13       | 6.17       | 6.24       | 1.91       | 1.86       | 1.94       | 11.76         |
| 4              | 5.95       | 6.02       | 5.94       | 1.92       | 1.91       | 2.09       | 11.78         |
| 5              | 6.05       | 6.16       | 6.13       | 1.94       | 1.96       | 1.97       | 11.96         |
3. Mechanical test
Mechanical tests are realized in room temperature using electromechanical testing machine Instron 5982 produced in 2010. Recording of parameters was made with sampling frequency equaled 0.1 (s). Measurement accuracy equals ± 0.5 (%). Elastic compliance $k$ is 4.8. Every prototype preloads to the value of 2 (MPa) to make clearance adjustment in a wedge clamp of testing machine before tests begin.

Data array with following parameters – axial tensile force $P$ and absolute elongation of a prototype body $\Delta l$ is a result of mechanical tests.

It is convenient to use diagrams with axes «Stress - Relative deformation» for researching properties of materials [2]. To determine value of stress let’s use an equation:

$$\sigma = \frac{P}{F_0}$$

To determine relative elongation of a prototype, let’s use this equation:

$$\varepsilon = \frac{\Delta l}{l} \times 100$$

In figure 3a stress-strain diagram of five PLA plastic prototypes is presented. It is shown, that PLA is instable and it has wide data spread within one test. In figure 3b stress-strain diagram of five PLA HP plastic prototypes is presented. It is shown, that all prototypes have similar results on the breaking stage.

![Stress-strain diagrams of prototypes a) PLA, b) PLA HP.](image)

4. Calculation of testing results
To determine mechanical properties (conventional yield limit, Poisson’s ratio, Young’s modulus), overall dimensions of prototypes are measured again after tests [3].

| № of prototype | $b_1'$ (mm) | $b_2'$ (mm) | $b_3'$ (mm) | $h_1'$ (mm) | $h_2'$ (mm) | $h_3'$ (mm) | $l'$ (mm) |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|----------|
| 1              | 6.26        | 6.22        | 6.23        | 2.01        | 1.98        | 1.98        | 44.31    |
| 2              | 6.12        | 6.10        | 6.12        | 1.93        | 1.97        | 1.98        | 41.90    |
| 3              | 6.19        | 6.16        | 6.17        | 1.97        | 1.92        | 1.95        | 45.21    |
| 4              | 6.21        | 6.20        | 6.26        | 1.91        | 1.92        | 1.95        | 44.97    |
| 5              | 6.29        | 6.30        | 6.31        | 2.06        | 1.88        | 1.92        | 43.83    |

There aren’t any yield lines in plastic stress-strain diagrams. It means, that it is necessary to calculate conventional yield limit $\sigma_{0.2}$:

$$\sigma_{0.2} = \frac{P_{0.2}}{F_0}$$
where $P_{0.2}$ – load value, related to absolute elongation $\Delta l_{0.2}$, when relative residual elongation $\delta_{0.2} = 0.2$ (%) occurs in prototype:

$$\Delta l_{0.2} = \delta_{0.2} l$$

Tensile strength $\sigma_{pc}$ can be calculated using an equation:

$$\sigma_{pc} = \frac{P_{\text{max}}}{F_{0}}$$

where $P_{\text{max}}$ – maximum load value.

Due to deformation of solid, dimensions change, and this process is characterized by Poisson’s ratio.

$$\mu = \frac{b' - b}{b} \times \frac{l}{l'} - \frac{l}{l'}$$

where $l$ – length of a prototype before deformation, $l'$ – length of a prototype after deformation, $b$ – shear dimension of a prototype before deformation, $b'$—shear dimension of a prototype after deformation.

Young’s modulus describes the resistance of materials to tension in elastic deformation. It can be determine as stress and elongation ratio:

$$E = \frac{\sigma l}{\Delta l} k = tg \alpha,$$

where $\alpha$ – tangent line angle of arrival to stress-strain diagram.

5. Analysis of testing results

Calculated results of average values of PLA and PLA HP mechanical properties are presented in table 3.

| Prototypes | $P_{0.2}$ (N) | $\sigma_{0.2}$ (MPa) | $\sigma_{pc}$ (MPa) | $\mu$ | $E$ (MPa) |
|------------|---------------|---------------------|---------------------|-------|-----------|
| PLA        | 444.50        | 38.22               | 45.59               | 0.320 | 2004.48   |
| PLA HP     | 504.77        | 38.99               | 52.70               | 0.134 | 3168.48   |

Magnitude of conventional yield limit for two types of plastic are similar, but PLA HP has higher maximum value of load. PLA has higher value of Poisson’s ratio, than PLA HP has. It means, that PLA HP is more brittle material. Young’s modulus of PLA is 40% lower than PLA HP – PLA is more plastic.

Comparison of PLA and PLA HP in elastic range is shown in fig. 4.

![Figure 4. Comparison of PLA and PLA HP in elastic range.](image-url)
Average displacements relatively to average stress-strain diagram of PLA and PLA HP accordingly are presented in fig. 5a and 5b. It is clearly shown, that PLA plastic is less stable and it has up to 10 (%) wide data spread, while PLA HP stably shows one characteristic with no more 4 (%) displacement from an average value.

![Figure 5. Average stress displacement of plastics a) PLA, b) PLA HP](image)

Reasons for PLA plastic instability can be seen by means of microscope (fig. 6a and 6b). Due to 50-fold magnification it is shown that PLA HP plastic is steady with high adhesion between sticks, while PLA plastic has a defect – an adhesion between sticks is minimal or it is absent, which affects on instability of stress characteristics.

![Figure 6. Layers before plastic breaking a) PLA, b) PLA HP with 50-fold magnification.](image)
Fig. 7. Breaking place of plastics a) PLA, b) PLA HP with 50-fold magnification.

Conclusions

PLA and PLA HP plastic prototypes are fabricated for tests on 3D-printer with a definite infill shape using FDM method. Stress-strain diagrams are created.

Strength characteristics of PLA and PLA HP plastic are got. Conventional yield limits $\sigma_{0.2}$ for PLA and PLA HP are similar and they equal 38.22 (MPa) and 38.99 (MPa) accordingly. Tensile strength $\sigma_{tc}$ of PLA HP is 7.11 (N) higher than PLA’s one. Poisson’s ratio $\mu$ showed, that PLA is less brittle plastic, then PLA HP. Young’s modulus of PLA HP is 40 (%) higher than PLA, in other words, PLA HP is less plastic.

Plastic was researched by means of microscope. Investigations exhibited, that adhesion of PLA is much worse than adhesion of PLA HP.

Considering results of this research, it can be concluded, that PLA plastic isn’t intended for production operations, because it has wide data spread in parameters, instable adhesion between sticks and unsatisfying strength characteristics.

References

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