Investigation of the main mechanical characteristics of plastics for three-dimensional printing of machine parts models

P V Dorodov¹, V V Kasatkin¹*, N Y Kasatkina¹, V A Petrov¹ and A A Litvinyuk²

¹FSBEI HE Izhevsk state agricultural Academy, 11, Studencheskaya St., Izhevsk, 426069, Russia
²FSBEI HE Udmurt state University, 1, Universitetskaya St., Izhevsk, 426034, Russia

*E-mail: kasww@mail.ru

Abstract. Today, new methods of manufacturing complex parts using three-dimensional printing are being introduced in engineering, including in the mechanical engineering of agricultural machinery. This technique is also used in the design of agricultural machinery at the stage of physical modeling of their structures to determine certain properties of the product as a whole and its individual parts (details) on the corresponding models. Physical modeling is used when it is difficult to perform full-scale tests of the product, as well as for economic reasons. The necessary conditions for physical modeling are the geometric and physical similarity of the model and kind. The presence of such proportionality allows us to recalculate the experimental results obtained for the model in kind by multiplying each of the determined values by a constant multiplier for all values of this dimension – the similarity coefficient. However, to study the physical characteristics of a product, it is necessary to take into account the mechanical properties of the material of its model. From various sources, you can find the main mechanical characteristics of plastic threads or samples made on a 3-D printer. Their values vary greatly depending on the model manufacturing technology. The paper presents the results of a study of the physical and mechanical properties of polylactide (PLA) and polyethylene terephlatate (PET-G), which are used in the manufacture of parts by three-dimensional printing. The specific strength of polymers was respectively: for PLA 65.6...12.2 kPa·m³/kg, for PET-G 36.7...95.4 kPa·m³/kg. Specific plasticity for PLA is equal to 60.3 %· cm³/kg, for PET-G – 468.2 %· cm³/kg. The specific plasticity for PLA is 608.3 %· cm³/kg, for PET-G – 468.2 %· cm³/kg. Mechanical properties are investigated and the obtained mechanical characteristics must be taken into account when calculating and physically modeling plastic products for three-dimensional printing.

1. Introduction

1.1. Relevance

Today, new methods of manufacturing complex parts using three-dimensional printing are being introduced in technology (figure 1). This technique is also used when designing at the stage of physical modeling of structures of machines and mechanisms, to determine certain properties of the product as a whole and its individual parts (details) on the corresponding models.
Physical modeling is a type of experimental study of an object or phenomenon based on its model, which has the same physical nature. Physical modeling is used when it is difficult to carry out full-scale tests of the product, when the size of the object of research or the values of its other characteristics (pressure, temperature, process speed, etc.) are too large (or small), as well as for economic reasons. Physical modeling is based on similarity theory and dimensional analysis. The necessary conditions for physical modeling are geometric similarity (similarity of form) and physical similarity of the model and kind: at similar points in time and at similar points in space, the values of variables that characterize phenomena for nature must be proportional to the values of the same values for the model. The presence of such proportionality makes it possible to recalculate the experimental results obtained for the model in kind by multiplying each of the determined values by a constant multiplier for all values of this dimension – the similarity coefficient [1]. A geometrically similar model of a real part can be made using three-dimensional printing, but to study the physical characteristics of the product, it is necessary to take into account the mechanical properties of the model material. From various sources, you can find the main mechanical characteristics of plastic threads or samples made on a 3-D printer: strength limits, relative residual elongation, modulus of elasticity. Their values vary greatly depending on the model manufacturing technology.

1.2. The aim of this work is to study the physical and mechanical properties of polylactide (PLA) and polyethylene terephthalate (PET-G), which are used in the manufacture of parts by three-dimensional printing.

The following tasks are set: to determine the mechanical characteristics of PLA and PETG samples under static tension, compression, and bending.

1.3. Methods of mechanical testing are regulated by state standards and laboratory studies of mechanical characteristics are carried out in accordance with them [2].

2. Results and discussions

Compression tests were carried out on an upgraded breaking machine MP-0,5-1 [3, 4], equipped with a loading device consisting of support plates with guides (figure 2).
Figure 2. Testing machine MP-0.5-1: a) General view; 1 – diagram of the apparatus; 2 – dynamometer; b) load device; 3 – test sample; 4 – support plates

The test was performed on a series of square-section samples with a side $h = 5.0...5.3$ mm ($h \times h \times h$ cubes), shown in figure 3.

Figure 3. Samples on compression: a) PLA before testing; b) PLA after the test across the layers; c) PLA after the test along the layers; d) PET-G prior to testing; e) PET-G after testing across layers; f) PET-G after test along the layers.

Compression diagrams (load – shortening relationships of the sample) were drawn on the diagram apparatus. Some of the resulting diagrams are shown in figure 4.
Figure 4. Compression charts: a) PLA across layers; b) PLA along the layers; c) PET-G across layers; d) PET-G along the layers.

The ordinate of point A on the scale of the diagram represents the load of the RP corresponding to the proportionality limit.

By formula (1)
the proportionality limits were calculated \( \sigma_p \), the value of which was: for PLA \( \sigma_p = 32.0...34.5 \, MPa \) (across layers), \( \sigma_p = 30.9...36.0 \, MPa \) (along the layers); for PET-G \( \sigma_p = 29.5...30.7 \, MPa \) (across layers), \( \sigma_p = 25.1...25.7 \, MPa \) (along the layers). At a density of PLA \( \rho = 1085 \, kg/m^3 \) and PET-G \( \rho = 1132 \, kg/m^3 \) their specific characteristics are found: for PLA \( \sigma_p/\rho = 29.5...31.8 \cdot kPa\cdot m^3/kg \) (across layers), \( \sigma_p/\rho = 28.5...33.2 \cdot kPa\cdot m^3/kg \) (along the layers); for PET-G \( \sigma_p/\rho = 26.1...27.1 \cdot kPa\cdot m^3/kg \) (across layers), \( \sigma_p/\rho = 22.2...22.7 \cdot kPa\cdot m^3/kg \) (along the layers).

The shape of the samples after the test (figure 3 b, c, e, f) indicates that the material is elastic-plastic, but there are no yield points on the compression diagrams, so the conditional yield strength \( \sigma_{0.2} \) was determined with a residual strain value of 0.0002\( h \). The ordinate of the point \( B \) in the scale of the diagram represents the load \( P_{0.2} \), corresponding to the conditional yield strength \( \sigma_{0.2} \), which was also calculated using the formula (1). Based on the results of the study, we have the following values: for PLA across layers \( \sigma_{0.2} = 33.2...35.6 \, MPa \) (\( \sigma_{0.2}/\rho = 30.6...33.0 \cdot kPa\cdot m^3/kg \)), along the layers - \( \sigma_{0.2} = 32.1...37.3 \, MPa \) (\( \sigma_{0.2}/\rho = 29.6...34.4 \cdot kPa\cdot m^3/kg \)); for PET-G across layers \( \sigma_{0.2} = 33.4...34.7 \, MPa \) (\( \sigma_{0.2}/\rho = 29.5...30.6 \cdot kPa\cdot m^3/kg \)), along the layers - \( \sigma_{0.2} = 28.9...29.5 \, MPa \) (\( \sigma_{0.2}/\rho = 25.5...26.0 \cdot kPa\cdot m^3/kg \)).

When testing samples across the layers, a characteristic maximum was observed (figure 4 a, c). The ordinate of the point \( C \) in the scale of the diagram represents the load \( P_b \) corresponding to the ultimate strength \( \sigma_b \). When testing samples along the layers, their destruction did not occur, they only flattened, so the conditional strength limit was calculated for absolute deformation of the sample equal to \( h/3 \). At the scale of the compression diagram, abscissae corresponding to \( h/3 \) were deposited (see figure 4 b, d), and the positions of the point \( C \) are determined, along the height of which the conditional destructive loads are found \( P_b^0 \). For the test samples, the tests showed: for PLA across the layers \( \sigma_b = 79.5...89.3 \, MPa \) (\( \sigma_b/\rho = 73.3...82.3 \cdot kPa\cdot m^3/kg \)), along the - \( \sigma_b = 71.2...80.0 \, MPa \) (\( \sigma_b/\rho = 65.6...73.7 \cdot kPa\cdot m^3/kg \)); for PET-G across layers \( \sigma_b = 52.5...54.7 \, MPa \) (\( \sigma_b/\rho = 46.4...48.3 \cdot kPa\cdot m^3/kg \)), along the - \( \sigma_b = 41.5...42.3 \, MPa \) (\( \sigma_b/\rho = 36.6...37.4 \cdot kPa\cdot m^3/kg \)).

A series of flat-shaped samples with a working length of \( l_0 = 75.0 \, mm \) and a rectangular cross-section with an area of \( F_0 = 43.8...44.3 \, mm^2 \) were subjected to the tensile test (figure 5), which were clamped in the grippers of the MP-0.5-1 (figure 6).

\[
\sigma_l = \frac{P_l}{h^2}
\]

(1)
Figure 6. Tensile test: 1 – the grips of the machine; 2 – investigated sample.

Stretching diagrams were drawn on the diagram apparatus, some of which are shown in figure

Figure 7. Stretch charts: a) for PLA; b) for PET-G.

Studies have shown that both materials have a brittle fracture when stretched. After processing the experimental data, the following mechanical characteristics were obtained: for PLA $\sigma_b = 40.2...40.3 \text{ MPa} (\sigma_b/\rho = 37.0...37.1 \cdot \text{kPa} \cdot \text{m}^3/\text{kg})$, average relative residual elongation $\delta = 0.66 \%$; for PET-G $\sigma_b = 27.8...28.7 \text{ MPa} (\sigma_b/\rho = 24.6...25.4 \cdot \text{kPa} \cdot \text{m}^3/\text{kg})$, $\delta = 0.53 \%$. 
Bending test. The samples were tested for bending according to the design scheme of a pivotally supported beam loaded in the middle by a concentrated force (figure 8).

Figure 8. Bending test: 1 – the base plate of the load device; 2 – indenter; 3 – investigated sample; 4 – centering supports.

For a series of samples with a working span length of $l = 63...65 \, mm$ and a diameter of $d = 10.0...10.1 \, mm$ (figure 9), load-deflection relationships were constructed using a diagram apparatus, some of which are shown in figure 10.

Figure 9. Bending patterns: a) PLA before and after the test; b) PET-G before and after the test.
Figure 10. Load-deflection diagrams: a) for PLA; b) for PET-G.

The ordinate of point A on the scale of the diagram represents the load of the $P_p$ corresponding to the proportionality limit.

By formula

$$\sigma_l = \frac{8P_l l}{\pi d^3}$$

the limit of proportionality $\sigma_p$, which was for the studied materials, is calculated $\sigma_p$.

$\sigma_p = 65.4...67.3 \text{ MPa}$ (for PLA $\sigma_p/\rho = 60.4...62.0\cdot \text{kPa}\cdot\text{m}^3/\text{kg}$; for PET-G $\sigma_p/\rho = 57.8...59.4\cdot \text{kPa}\cdot\text{m}^3/\text{kg}$).

If we consider the hypothesis of flat sections to be valid up to failure, then the ultimate strength $\sigma_b$ can be found by the formula (2) at $P = P_{\text{max}}$ (ordinate of point C in figure 10). Studies of a series of samples showed: for PLA $\sigma_b = 136.1...140.2 \text{ MPa}$ ($\sigma_b/\rho = 125.4...129.2\cdot \text{kPa}\cdot\text{m}^3/\text{kg}$); for PET-G $\sigma_b = 104.9...108.0 \text{ MPa}$ ($\sigma_b/\rho = 92.7...95.4\cdot \text{kPa}\cdot\text{m}^3/\text{kg}$).

The results of the research are summarized in a table that shows the specific mechanical characteristics of polymers, carbon steel, and gray cast iron to analyze the structural efficiency. Mechanical properties (strength and ductility) can be evaluated using dimensionless parameters:

$$\gamma(\sigma_b) = \frac{\sigma_b}{\rho(\text{polymer})}; \gamma(\delta) = \frac{\delta}{\rho(\text{metal})}.$$  

3. Conclusion

In order to prevent the appearance of residual deformation and loss of load-bearing capacity of models, the calculated stresses must be limited to the smallest value of the proportionality limit: for PLA $\sigma \leq 30 \text{ MPa}$, for PET-G $\sigma \leq 25 \text{ MPa}$.

The specific strength of the polymers was respectively: for PLA $65.6...129.2 \text{ kPa}\cdot\text{m}^3/\text{kg}$, for PET-G $36.7...95.4 \text{ kPa}\cdot\text{m}^3/\text{kg}$. PLA strength rating compared to steel $\gamma(\sigma_b) = 0.91...1.50$, with cast iron – $\gamma(\sigma_b) = 0.68...0.89$. Assessment of the strength of the PET-G in comparison with steel $\gamma(\sigma_b) = 0.68...0.84$, with cast iron – $\gamma(\sigma_b) = 0.49...0.50$. 
The specific plasticity for PLA is 608.3 %·cm³/kg, for PET-G – 468.2 %·cm³/kg. Evaluation of PLA plasticity in comparison with steel $\gamma(\delta) = 0.15…0.53$, with cast iron $\gamma(\delta) = 8.3…22.5$. Evaluation of PET-G plasticity in comparison with steel $\gamma(\delta) = 0.12…0.40$, with cast iron $\gamma(\delta) = 6.4…17.3$.

| Characteristic and structural efficiency | Material and type of resistance | PLA | PET-G | Carbon structural steels | Grey cast iron |
|----------------------------------------|-----------------------------|-----|-------|------------------------|---------------|
|                                        | Compression | Stretching | Bending | Compression | Stretching | Bending | Compression, Stretching, Bending | Compression |
| Tensile strength $\sigma_b$, MPa       | 71.2-82.3   | 40.2-40.3 | 136.1-140.2 | 41.5-54.7 | 27.8-28.7 | 104.9-108.0 | 340-1100 | 500-1400 |
| Yield strength $\sigma_{0.2}$, (MPa)   | 32.1-37.3   | -       | -       | 28.9-34.7 | -       | -       | 210-950  | -      |
| Relative elongation (shortening) $\delta$, % | 0.66       | 0.53       | 9.0 – 31.0 | 0.2 – 0.5 |
| Density $\rho$, kg/m³                  | 1085        | 1132       | 7800     | 6800 - 7400 |
| Specific strength $\Sigma_d$ $\rho$, kPa·m³/kg | - | -       | -       | 36.7 | 24.6 | 92.7 | 43.6 – 141.0 | 73.5 – 189.2 |
| Specific plasticity $\delta \rho$, %·cm³/kg | 608.3     | 468.2     | 1153.8 | 27.0 – 73.5 |

Mechanical properties are studied and the obtained mechanical characteristics should be taken into account when calculating [2-4, 6-10] and physical modeling of plastic products [11, 12].

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