Optimization of the Strength Characteristics of the Cellular Structure in Samples of Thermoplastic Polyester

V T Erofeev1,2, T F Elchishcheva3, E M Preobrazhenskaya3, M V Makarchuk3, V V Afonin1

1Faculty of Architecture and Civil Engineering, National Research Mordovian State University named after N.P. Ogarev, Bolshevistskaya str, 68, 430005 Saransk, Russia
2Research Institute "Materials Science"
3Tambov State Technical University, Sovetskaya str 106, 392000, Tambov, Russia

Email: fac-build@adm.mrsu.ru, elschevat@mail.ru,

Abstract. When making a prototype during design in industrial design, specialists use the data on the strength characteristics of filaments for extrusion provided by the manufacturer of equipment for FDM printing. It is likely that the strength characteristics of the product may deviate from the characteristics of the threads. The authors suggested that the samples of the cellular structure made on 3D printers from polylactide with an internal volume filling of 10% with the filament laying direction according to the standard settings of the equipment manufacturer during the experimental determination of strength characteristics will demonstrate values several times lower than the samples with filling the cell volume with polylactide by 100% and having in their geometry the same direction of laying the extrudable material. To confirm the hypothesis put forward by the authors, a study was carried out of the characteristics of products made of polylactide using the FDM printing method. A comparison is made of the relative change in some parameters of the samples (mass, elongation, and the force used to break the samples), the two devices for growing prototypes – 3D printers MakerBotReplicator 5 Gen and MakerBotReplicator Z18 in percentage terms. Recommendations are given on the optimal operation of equipment for 3D printing, depending on the goals set by the user. The results can be used to select equipment for printing and sample production technology, cell filling density and amount of material when creating a prototype using the additive method in industrial design.

1. Introduction
In the construction industry, various polymer composite materials based on thermosetting and thermoplastic binders are used. There are also products distinguished by pressing, vacuum, extrusion, and centrifugation technologies. A large number of works have been devoted to the experimental and theoretical substantiation of their preparation, the study of physical and mechanical properties, and durability. Under construction conditions, polymeric materials and products are manufactured using injection molding technology, formed in the factory [1-29, 31]. The use of additive technologies in prototyping in industrial design has become widespread. This technology involves the use of 3D printing by the FDM (FusedDepositionModeling) method - layer-by-layer filling with an extrudable
polymer melt. Manufacturers offer a wide variety of materials for use in 3D printing, their overview is given in Table 1. The materials presented differ in consumer and physico-mechanical properties used depending on the requirements for the prototype. The interconnection of technologies and strength characteristics of materials are scrutinized in some publications [30, 32, 33, 34].

Table 1. Popular materials used in 3D printing.

| International material designation | Tensile Strength, MPa | Extrudertemperature, °C |
|----------------------------------|----------------------|------------------------|
| ABS                              | 22.00                | 220-260                |
| ASA                              | 35.80                | 270-280                |
| HIPS                             | 62.00                | 220-260                |
| NYLON                            | 65.99                | 250-270                |
| PP                               | 25.50                | 254                    |
| PET                              | 50.00                | 120-160                |
| PLA                              | 57.80                | 210-240                |
| POM                              | 75.00                | 210-250                |
| SBS                              | 24.00                | 240                    |
| TPU                              | 40.00                | 180-220                |

In the manufacture of the prototype of the selected material by FDM-printing, users rely on the strength characteristics declared for this plastic by the manufacturer. However, the strength characteristics of the manufactured parts do not always correspond to the material properties of the filaments from which they are made. The structure of the part obtained by layer-by-layer deposition of an extrudable melt may differ in properties from unextruded filament.

Another important factor affecting the strength characteristics of the prototype is a feature of the technology. The volume of the product to save material and reduce printing time is filled in the form of a cellular structure. In the case of minimal filling of the volume of the prototype, you can get the shell of the prototype with an empty (unfilled) volume inside. Such a prototype will have low strength characteristics and may be deformed as a result of internal stresses in its design or a significant mass of the prototype.

The additive technology user has a difficult choice to make. You should choose between saving the amount of material and printing time, however, this causes a decrease in the strength of the prototype. Another option is to manufacture a prototype with greater strength, but it will use up more material and spend more time. It can be assumed that polylactide (PLA) cellular samples printed with the manufacturer's recommended settings on a MakerBotReplicator 5 Gen printer with an internal 10% volume filling during tensile testing will demonstrate strength values several times lower than polylactide samples with cell volume filling 100%. The same statement, obviously, is true for samples having the same cellularity made with the MakerBotReplicator Z18 printer.

The results can be used to create a map showing the dependence of the strength characteristics of the prototype on the degree (percent) of the cellular structure, the type of plastic used and other 3D printing parameters, and in the end, to select the manufacturing technology and type of material when creating the prototype in industrial design.

It is obvious that when creating prototypes it is necessary to individually select the parameters of 3D printing depending on the goals and objectives of designers and engineers, taking into account material savings and reducing the mass of the resulting prototype.

Thus, it is relevant to study the strength properties of the product, made by additive technology with different filling of the cellular structure.

2. Research methods
Strength analysis samples were manufactured using additive technology on two 3D printers: MakerBotReplicator Z18 and MakerBotReplicator 5 Gen.

On each of the printers, samples were made in batches of six pieces in each batch with filling of the internal cellular structure of samples from 10% to 100% with a filling step of 10%. A total of 120 samples were manufactured. When growing samples, print settings recommended by the equipment manufacturer were applied. The printing material used was polylactide (PLA) polymer, a polyester of lactic (2-hydroxypropionic) acid \( \text{CH}_3\text{-CH(OH)}\text{-COOH} \).

The geometric dimensions of the samples: total length 150 mm, the distance between the wide parts with parallel sides 108 mm, the length of the narrow part with parallel sides 60 mm, the radius of the head 60 mm, the width of the wide part 20 mm, the width of the narrow part with parallel sides 10 mm, thickness 4 mm (GOST 33693-2015).

Studies of the strength characteristics of all manufactured samples were carried out on an MP-0.5-1 tensile testing machine.

3. Research results

On the tensile testing machine MP-0.5-1, the strength characteristics of the samples made of polylactide with various percent filling of the cellular structure were tested.

Using optical microscopy, the fractures of all samples subjected to tensile tests were studied. A typical view of fractures of samples with filling of the cellular structure by 10%, 50%, and 100% is shown in Fig.1.

![Figure 1](image)

**Figure 1.** Fracture of samples with 10% (a), 50% (b) and 100% (c) filling the mesh structure

The fracture surface of all samples is porous; the threads of the internally obtained samples are clearly visible. According to the degree of plastic deformation, the samples are fragile. The fracture of the samples under the influence of the applied load is flat with bevels.

The cellular structure is formed in the internal volume of the sample, and its external surface is filled with polymer by 100% (Fig. 1, a, b). An analysis of the samples made with the MakerBotReplicator 5 Gen 3D printer showed that the sample without filling the internal cellular structure has an average weight of 5.66 g, and at 100% filling the average weight of the sample is 10 g. Thus, approximately 4.34 g of the total mass of the sample is involved in the change in the percent filling of the cellular structure of samples from 0% to 100%. For samples made with the MakerBotReplicator Z18 printer, the mass value that changes when filling the mesh structure of the sample from 0% to 100% is 4.16 g. The data obtained show that prototypes manufactured using additive technology for each printer will have a minimum threshold strength.

The test results of the strength characteristics of samples made of polylactide with filling the cellular structure of the sample from 0% to 100% on a tensile testing machine MP-0.5-1 are summarized in table 2.

| Table 2. Results of testing the strength characteristics of samples made on 3D printers MakerBotReplicator Z18 and MakerBot Replicator 5 Gen |
| % sample | No sample | weight / g | mm | MPa | weight / g | mm | MPa |
|----------|-----------|------------|----|-----|------------|----|-----|
| 10       | 1         | 5.56       | 5  | 9.69| 6.18       | 9  | 13.056|
|          | 2         | 5.62       | 5  | 10.557| 6.18       | 9.5 | 12.852|
|          | 3         | 5.64       | 6  | 10.812| 6.18       | 7  | 13.77 |
|          | 4         | 5.62       | 5.5| 10.404| 6.14       | 9  | 13.056|
|          | 5         | 5.24       | 7  | 9.69 | 6.18       | 7.5| 10.71 |
|          | 6         | 5.56       | 6  | 9.69 | 6.16       | 8  | 12.852|
| 20       | 1         | 6.24       | 5.5| 6.63 | 6.64       | 7  | 12.036|
|          | 2         | 6.18       | 4  | 5.61 | 6.67       | 6  | 12.648|
|          | 3         | 6.14       | 6  | 8.67 | 6.62       | 5.5| 10.71 |
|          | 4         | 6.18       | 4  | 5.61 | 6.62       | 6  | 10.098|
|          | 5         | 6.16       | 4  | 4.386| 6.62       | 7  | 8.67  |
|          | 6         | 6.16       | 3.5| 4.896| 6.6        | 4  | 9.18  |
| 30       | 1         | 6.6        | 5.5| 11.526| 7.1        | 8  | 14.076|
|          | 2         | 6.6        | 5.5| 11.118| 7.1        | 6.5| 10.608|
|          | 3         | 6.6        | 5  | 9.69 | 7.1        | 7  | 13.26 |
|          | 4         | 6.6        | 6  | 11.628| 7.1        | 4  | 13.26 |
|          | 5         | 6.6        | 4.5| 9.18 | 7.2        | 5  | 11.974|
|          | 6         | 6.6        | 3.5| 12.342| 7.1        | 5  | 12.056|
| 40       | 1         | 7.06       | 6  | 9.078| 7.6        | 7  | 11.73 |
|          | 2         | 7.06       | 5.5| 7.548| 7.55       | 6  | 11.016|
|          | 3         | 7.04       | 4  | 5.814| 7.3        | 6.5| 11.526|
|          | 4         | 7.08       | 5.5| 7.65 | 7.45       | 6  | 10.2  |
|          | 5         | 7.08       | 6.5| 8.772| 7.31       | 5  | 8.67  |
|          | 6         | 7.08       | 5  | 6.324| 7.52       | 6  | 9.18  |
| 50       | 1         | 7.58       | 8  | 13.974| 8.1        | 9  | 13.056|
|          | 2         | 7.53       | 8  | 13.056| 8.1        | 8  | 14.688|
|          | 3         | 7.55       | 8  | 14.076| 8.2        | 8  | 13.872|
|          | 4         | 7.53       | 8  | 12.648| 8.1        | 8  | 16.32 |
|          | 5         | 7.56       | 7  | 12.24| 8.2        | 8  | 14.076|
|          | 6         | 7.53       | 8  | 12.852| 8.1        | 8  | 14.28 |
| 60       | 1         | 8          | 5  | 7.446| 8.64       | 7  | 11.832|
|          | 2         | 8          | 8  | 11.22| 8.6        | 7.5| 11.628|
| %   | No sample | weight / g | mm | MPa  | weight / g | mm | MPa  |
|-----|-----------|------------|----|------|------------|----|------|
| 3   | 8         | 5          | 7.548 | 8.62 | 5          | 8.67 |
| 4   | 8         | 6          | 8.67  | 8.64 | 7          | 11.73 |
| 5   | 8         | 5          | 7.446 | 8.52 | 7          | 12.75 |
| 6   | 7.96      | 6          | 9.996 | 8.56 | 7          | 12.648 |
| 70  | 1         | 8.46       | 9    | 15.912 | 9.2       | 8.5 | 17.238 |
|     | 2         | 8.42       | 8    | 14.994 | 9.14      | 8   | 18.462 |
|     | 3         | 8.44       | 8.5  | 15.3  | 9.22       | 8.5 | 16.32 |
|     | 4         | 8.46       | 11   | 16.83 | 9.22      | 10.5| 18.564 |
|     | 5         | 8.44       | 8    | 14.688 | 9.24      | 10  | 18.87 |
|     | 6         | 8.44       | 8    | 15.912 | 9.18      | 8.5 | 19.89 |
| 80  | 1         | 8.76       | 9    | 16.524 | 9.42      | 8   | 19.482 |
|     | 2         | 8.78       | 8    | 16.932 | 9.48      | 9.5 | 20.706 |
|     | 3         | 8.82       | 7    | 17.85 | 9.44      | 8   | 19.074 |
|     | 4         | 8.76       | 7    | 17.34 | 9.5       | 12  | 16.116 |
|     | 5         | 8.76       | 6.5  | 18.054 | 9.48      | 10.5| 18.258 |
|     | 6         | 8.78       | 9    | 18.513 | 9.48      | 9   | 19.686 |
| 90  | 1         | 9.35       | 6    | 10.914 | 9.5       | 9   | 18.054 |
|     | 2         | 9.3        | 8    | 16.014 | 9.72      | 8.5 | 18.564 |
|     | 3         | 9.3        | 7    | 13.77 | 9.64      | 9   | 14.79 |
|     | 4         | 9.3        | 6    | 11.526 | 9.58      | 9   | 17.34 |
|     | 5         | 9.3        | 7    | 15.3  | 9.78      | 8.5 | 17.136 |
|     | 6         | 9.2        | 8    | 16.83 | 9.74      | 9   | 18.36 |
| 100 | 1         | 9.65       | 15   | 21.573 | 9.7       | 7   | 22.95 |
|     | 2         | 9.68       | 14   | 22.236 | 9.8       | 7   | 21.114 |
|     | 3         | 9.65       | 11   | 22.185 | 10.2      | 8   | 20.91 |
|     | 4         | 10.04      | 15   | 21.522 | 10.06     | 8   | 23.46 |
|     | 5         | 9.78       | 9    | 19.125 | 10        | 8   | 21.93 |
|     | 6         | 9.66       | 12   | 20.4  | 9.9       | 7   | 22.44 |

Dependence plots are constructed for average indicators of mass (Fig. 2), elongation (Fig. 3) and strength (Fig. 4) of samples as a percentage of the filling of the cellular structure. The weight of samples made with the MakerBot G5 printer is on average 0.55 g (8%) larger than the mass of samples made with the MakerBot Z18 printer. The change in mass occurs in proportion to the change in the filling of the cellular structure and averages: 0.38 g for samples made with a MakerBot G5 printer, and
0.41 g for samples made with a MakerBot Z18 printer. It should be noted that the change in mass in each batch of samples occurred uniformly without a significant dispersion of values (Table 2).

Figure 2. The dependence of the average mass of samples produced on printers MakerBot Z18 and MakerBot G5 from the percentage of filling cells

The elongation of samples made with the MakerBotZ18 and MakerBot G5 printers occurs nonlinearly (Fig. 3). The nature of the change in the elongation curves of the samples correlates with the nature of the change in the curves of their tensile strength (Fig. 4). In the batch of samples with the same cell filling, a scatter of the measurement results is observed (Table 2), which may be due to the modes and algorithm of polylactide stacking during printing.

The nature of the change in the tensile strength of samples made on MakerBot Z18 and MakerBot G5 printers is similar (Fig. 4). The characteristic values are the tensile strength for the filling values of the cellular structure of the samples 10%, 50% and 100%.

Figure 3. The dependence of the average elongation of samples to the moment of rupture of the percentage of filling cells
For all the samples studied, in the filling interval of the cellular structure above 10% and below 50%, a decrease in the tensile strength is observed in comparison with the strength of the samples with a filling of 10%. Therefore, the manufacture of prototypes with a filling of the cellular structure of 20%, 30% and 40% is irrational.

In the filling interval of the cellular structure above 50% and below 100%, a drop in the tensile strength for a filling value of 60% is observed. The strength value is lower than the strength of the sample with a filling of the cellular structure of 50%. Also, a drop in the tensile strength is observed at a filling value of 90% compared with filling samples by 70%, 80% and 100%. When the cellular structure is filled with 20%, 30%, 40%, 60% and 90%, a significant drop in the tensile strength of the studied samples occurs.

To analyze the operating parameters of printers, we plotted the dependence of changes in indicators (in relative%) — mass, elongation, and the force used to break the samples, samples made on a MakerBotG5 printer compared to samples made on a MakerBotZ18 printer (Fig. 5). Depending on the indicator, which is taken as the basis for the study (mass, elongation, tear strength) and the required level of filling of the samples, a different approach is possible in choosing a printer for 3D printing, as shown below.

When comparing the performance of samples obtained by printing on a MakerBotG5 printer with the performance of samples printed on a MakerBotZ18 printer, it was found that the greatest difference in the mass of samples is observed at 10% cell filling and amounts to +11.2%, the smallest difference is at 90% cell filling and is 3.9%. The MakerBotG5 printer at all levels of cell filling shows an increase in sample mass compared to the MakerBotZ18 printer. The average increase in sample mass at all cell fill levels on the MakerBotG5 printer is 6.9%. Therefore, in the manufacture of the prototype without special requirements for its elongation and strength, but with maximum requirements for polymer savings, it is advisable to use the MakerBotZ18 printer at all levels of cell filling.

A comparison of printers in terms of elongation of samples prior to rupture showed that the greatest difference in elongation of samples is observed at 10% cell filling and is +44.3%, as well as at 100% cell filling and is minus 40.5%. At the same time, the MakerBotG5 printer at cell filling levels from 10% to 90% shows higher elongation rates of the samples compared to the MakerBotZ18 printer. However, from a fill level of 80% to a fill level of 100%, the elongation rate of the MakerBotG5 printer samples is reduced. In this case, the elongation rate of MakerBotZ18 samples

Figure 4. The dependence of the average force applied to break the samples, the percentage of filling cells
increases from a cell filling level of 90% to a cell filling level of 100%. Thus, in the manufacture of the prototype with filling cells over 90%, it is advisable to organize the printing of samples on a MakerBotZ18 printer. The smallest difference in elongation of samples made on different printers is observed at 50% and 70% cell filling and is, respectively, + 2.5% + 2.9%. Therefore, when filling cells of 50% and 70%, it is possible to use Z18 and MakerBotG5 printers for printing samples.

A comparison of printers in terms of the applied force for breaking samples showed that the largest difference in the applied force is observed at 20% cell filling and is + 99.8%, as well as at 40% cell filling and is + 56.4%. The MakerBotG5 printer at all levels of cell filling has higher rates of applied force to break samples compared to the MakerBotZ18 printer. The smallest difference in the magnitude of the applied force for breaking samples made on different printers is observed at 50%, 80% and 100% cell filling and is, respectively, + 9.3%, + 7.6% and + 4.3%. Thus, in the manufacture of a prototype with requirements for filling the cells of 50%, 80% and 100%, it is possible to organize printing of samples on both the MakerBotG5 printer and the MakerBotZ18 printer. At other fill levels, printing on a MakerBotG5 printer is advisable.

4. Conclusions

To determine the strength characteristics of polylactide products grown on 3D printing equipment, samples were prepared with filling the internal cellular structure of samples from 10% to 100%. Samples were weighed and subjected to tensile tests. The results of the experiments are listed in the table, as well as expressed graphically. Analysis of the data showed the following:

- prototypes manufactured using additive technology for each type of printer will have a minimum threshold strength;
- the change in mass in each batch of samples is homogeneous without significant variation in values;
- the nature of the change in the elongation curves of the samples is similar in nature to the curves of the tensile strength of the same images. In batches of samples, significant
differences in measurement results are observed. It was not possible to establish the reason for such differences, this instability can be associated with the modes and algorithm of material stacking. It is a prospect for further research;

- in the filling interval of the cellular structure of more than 10%, but below 50%, a drop in the tensile strength is observed for all studied samples in comparison with the strength of samples with a filling of 10%. Therefore, the manufacture of prototypes with a filling of the cellular structure of 20%, 30% and 40% is irrational;
- when the cellular structure is filled with 20%, 30%, 40%, 60% and 90%, a significant drop in the tensile strength of the studied samples occurs.

The analysis of relative indicators for two printers showed:

- in the manufacture of the prototype without special requirements for its elongation and strength, but with maximum requirements for polymer savings, it is advisable to use the MakerBot Z18 printer at all levels of cell filling;
- the smallest difference in the elongation of samples made on different printers is observed when the cells are filled with 50% and 70%; therefore, at these levels it is possible to use both printers to print samples;
- the smallest difference in the magnitude of the applied force for breaking samples made on different printers is observed when the cells are filled with 50%, 80% and 100%. At these cell fill levels, it is possible to print samples on both printers. At other levels, printing on a MakerBot G5 printer is advisable.

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