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Assessment of strength of elements produced using 3D printing technology

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Abstract. In some cases, 3D-printed products must be able to resist the stresses caused by their functionality. The design of bionic artificial hand is considered as a construction made using 3D printing technology, the strength of which must be assessed. The artificial limb is made using extrusion plastic printing. In order to assess the strength of the artificial limb, the experimental study of the samples made using 3D printing technology was carried out. The influence of three parameters on the strength characteristics of the samples was studied: the percentage of filling, the filling pattern and the direction of the material layering in the sample.

1. Introduction

The powerful possibilities of additive technologies make them relevant in the modern world of digital production [6, 12, 13, 22]. Nowadays their functionality has increased significantly from prototyping to structures that accept workloads [12, 13, 15, 19, 21, 25]. Moreover, it covers such high-tech spheres of production as aircraft construction, shipbuilding, mechanical engineering, instrument production and the field of medical engineering.

In particular, the technology of three-dimensional printing or 3D-printing, called FDM - printing (Fused Deposition Modeling) is of great interest. It is based on extrusion printing, the essence of the method of which is that under the influence of an extruder, the source material is heated to a predetermined temperature and squeezed out through a nozzle, forming the required product layer by layer in accordance with the electronic model. This technology is interesting for its simplicity in operation, the ability to create parts of almost any geometry complexity and availability for a wide range of users.

The spectrum ranges from industrial to household users. This is due to the offer on the market of 3D printers of any price category with different technical capabilities that determine different functionality. In this regard, this direction of 3D printing is rapidly developing and already covers various products, the reliability criteria of which include the criteria of strength and rigidity. This means that the issues of the assessment of the strength of such products are becoming relevant [13–15, 19, 20, 26].

In particular, in the field of medicine, additive technologies have become extremely popular in many areas [20–24] for example, in the production of implants, prosthetics, dentistry, etc. Here the prototype model should take into account its physical and mechanical characteristics along with the geometric parameters of the prototype. Therefore, the important aspect of 3D production is to ensure the strength and stiffness corresponding to the prototype.



2. Problem statement

The students of Irkutsk National Research University in the student innovation bureau “Aviator” are developing a bionic artificial hand for disabled people who have no wrist joint. Along with a wide functionality of the limb, one of the main advantages of the development is affordable price. It was decided to make the details of the limb using additive technology - plastic extrusion printing. For the production of the parts of the limb, inexpensive materials available to a wide range of consumers are proposed: ABS plastic, PetG plastic.

The performance characteristics of bionic artificial hand necessitate a responsible attitude towards its strength reliability. The design of the limb (Fig. 1) is a complex structure, the elements of which are simultaneously in different stress-strain states. Moreover, for an obvious reason, these states change during the operation of the limb. According to the classical theory of strength, the assessment of the parameters of the stress-strain state of a body requires knowledge of the mechanical characteristics of the material from which it is made [4]. At the same time, the theory is based on a number of hypotheses, principles and assumptions. Their performance has been proven experimentally. The important component of the theory is hypotheses about the properties of the material, in particular, about the homogeneity and continuity of the material within the volume of the studied body [3]. At the same time, they do not forget about the natural discreteness of the material. The schematization of the internal forces of a deformed body is based on this model of material properties.

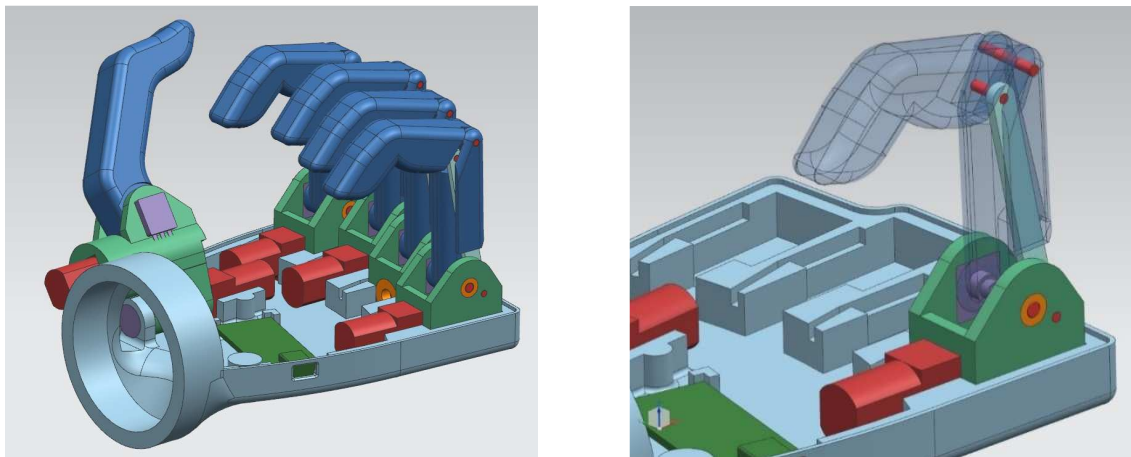


Figure 1. Design of bionic artificial hand

The combination of this theory, the information on the mechanical characteristics of materials and modern technologies for the automation of engineering calculations of structures allows carrying out the calculations of a structure of almost any complexity with a high degree of reliability of the results. However, the additive technology used for the production of the main parts of the structure of bionic artificial hand does not allow assessing the parameters of the stress-strain state of the structure, based on the classical theory of strength. Considering how the content of the volume occupied by the body is formed [1, 17], the application of hypotheses about the homogeneity and continuity of the material is queried. In this case, it is necessary to take into account the structure that is formed from the filament of the corresponding material [7]. At the same time, the solution to this problem is carried out not at the micro, but at the macro level. Since the assessment of the structural components is correlated with the categories comparable to the diameter of the extruder bore.

In order to assess the parameters of strength and stiffness of a product, it is necessary to know the mechanical characteristics of the filament materials, that is, the monofilament of the raw material. As a rule, the producer declares them. However, this information is insufficient to assess the strength and stiffness of the product itself. Practice shows that these characteristics of a filament and a product do not coincide. In particular, the strength of the product is lower than the strength of the monofilament

of the raw material [4, 7]. Moreover, the value of this deviation depends on the factors both reasoned by the printing mode and the structure that fills the volume of the product [5, 8–10, 14, 18].

There are enough thermoplastics available for non-industrial 3D printing. Moreover, practice shows that the same thermoplastic from different producers has different characteristics. The characteristics may differ even when they are produced by one and the same producer and from one and the same thermoplastic but differently colored. Since the colorant of the material can affect the characteristics of the plastic.

The information on the research of the parameters of the stress-strain state of 3D-printed products is not uniform and, accordingly, not systematized. As a rule, these studies are carried out on the basis of field tests. These are tests of the samples or finished products with the violation of integrity and fixation of the value of the corresponding parameter of the state of strength or stiffness at this stage and the use of the terminology relevant within the framework of the hypothesis of the homogeneity and continuity of the material [8, 10, 11, 18].

The specificity of the design of the artificial hand is such that full-scale experiments that provide information on the strength and stiffness of the structure under all possible loading methods are impossible. Apart from other reasons they are impossible only because the number of experimental samples due to the number of loading cases is large.

However, the guarantee of product reliability is essential. As a result, a deep analysis of the structure is required, containing a reliable calculation of strength and stiffness. Therefore, a correct description of the material behavior of the loaded structure is required. In this case, the experimental studies of the behavior of loaded samples are needed.

There is information on the strength characteristics of molded plastic samples, while the design of bionic artificial hand requires the characteristics of samples layer-by-layer printed on a 3D printer. At this stage of the creation of bionic artificial hand, the information on the behavior of materials under static loads is relevant. In order to obtain this kind of information, the samples were tested for axial tension.

3. Input data for the experiment

The sizes of the samples for testing for axial tension were taken in accordance with GOST 11262-2017 [16]. Figure 2 shows a standard sample of A type.

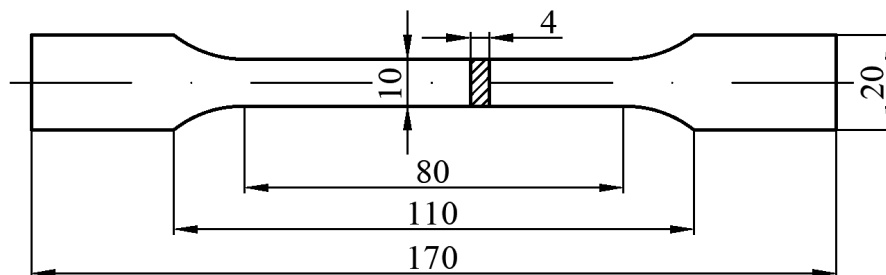


Figure 2. Sample of A type

The samples were made from PetG thermoplastic, produced by ABS Maker. The samples were printed on Anycubic Chiron printer with a print speed of 50 mm / sec, a working table temperature of 75 ° C and a nozzle temperature of 220 ° C. We tested the samples printed with two filling patterns: lines inclined at an angle to the longitudinal axis of the sample (Fig. 3, a) and triangles (Fig. 3, b). In the first case, the direction of the printing filaments periodically changed from layer to layer. Accordingly, the layers were attached to each other point wise, namely, in the limited areas of contact of the printing filaments. The location of these zones can be schematically characterized as the position of intersection points of the directions of printing filaments. In the second case, the structure of each layer can be characterized as a uniform grid with triangular cells. Moreover, the position of

each triangle does not change from layer to layer. Therefore, the layers are not attached to each other point wise, but along the entire path of the printing filament of a layer.

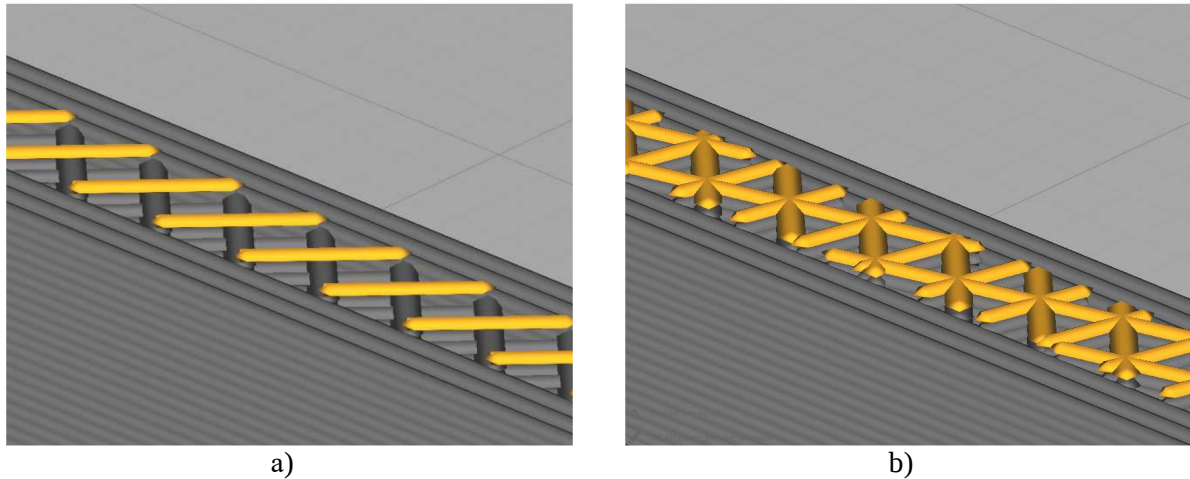


Figure 3. Filling patterns

The above mentioned analysis of the structure of the arrangement of the filaments when filling the sample volume allows assuming that the behavior of externally identical samples may differ under the action of the same loading scheme with different filling patterns.

Moreover, we can assume that it will differ for externally identical samples with the same filling pattern, but with a different direction of layer formation. In one case, the layers are formed in the direction of the minimum cross-sectional size of the sample, in the other case, in the direction of the maximum cross-sectional size of the sample (Fig. 4). Here, there is different amount of material in the cross sections of the samples. Within the framework of the theory of axial tension-compression, this factor determines different parameters of strength for externally identical samples. Therefore, the tests were carried out with two types of samples, printed flat (Fig. 4, a) and standing on the edge (Fig. 4, b).

10 samples were printed for each position, filling density and filling pattern. The tests were carried out on INSTRON 5982 tension testing machine for static testing with a loading rate of 1 mm / min.

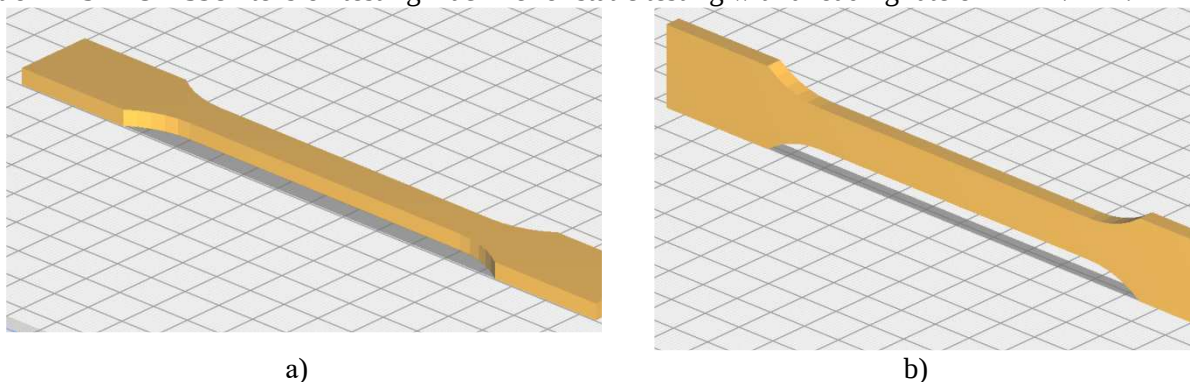


Figure 4. Position of samples when printing

4. Research results

Table 1 and Figure 5 shows the results of tension tests of the samples with the considered filling patterns (Fig. 3), the samples were printed with 60% filling density. The following designations are adopted in the tables of the article:

$N_{\max}$ - maximum effort, N;

$N_{\max}^{\text{aver}}$ - average maximum effort, N;

Δl - absolute elongation at maximum load, mm;

Δl^{aver} - average value of absolute elongation at maximum load, mm.

The abscissa shows the absolute elongation values at the moment of loading the samples. We mentioned above that 10 samples were printed for each filling pattern, but at the time of testing, some samples were destroyed outside the working area and were selected.

Table 1. Characteristics of samples with different filling patterns

Filling pattern	No. sample	N_{max}	N_{max}^{aver}	Δl	Δl^{aver}
Triangular	2	1212	1196±(60)	3,2	3,1±(0,2)
	4	1214		3,2	
	6	1086		2,5	
	8	1237		3,3	
	9	1230		3,2	
Linear	1	1285	1378±(69)	3	3,4±(0,2)
	2	1383		3,4	
	3	1369		3,5	
	5	1474		3,8	

According to Table 1 and Figure 5, the value of the average maximum tension force endured by the samples with a linear filling pattern exceeded by 13% the value of the average maximum tension force for samples with triangular elements. As for the stiffness characteristics, the average value of absolute elongation at maximum load for the samples with a linear pattern was 9% higher than for the samples with triangular filling. Perhaps the differences in strength and stiffness characteristics were associated both with the nature of the attachment of layers to one another during printing and with their structure, as it was mentioned earlier.

In further experiments, all the samples were printed with a triangular filling pattern as the sample with the most stable mechanical properties during testing. Let us consider the results of the experiments with different position of the samples during printing (flat and standing on the edge (Fig. 4)).

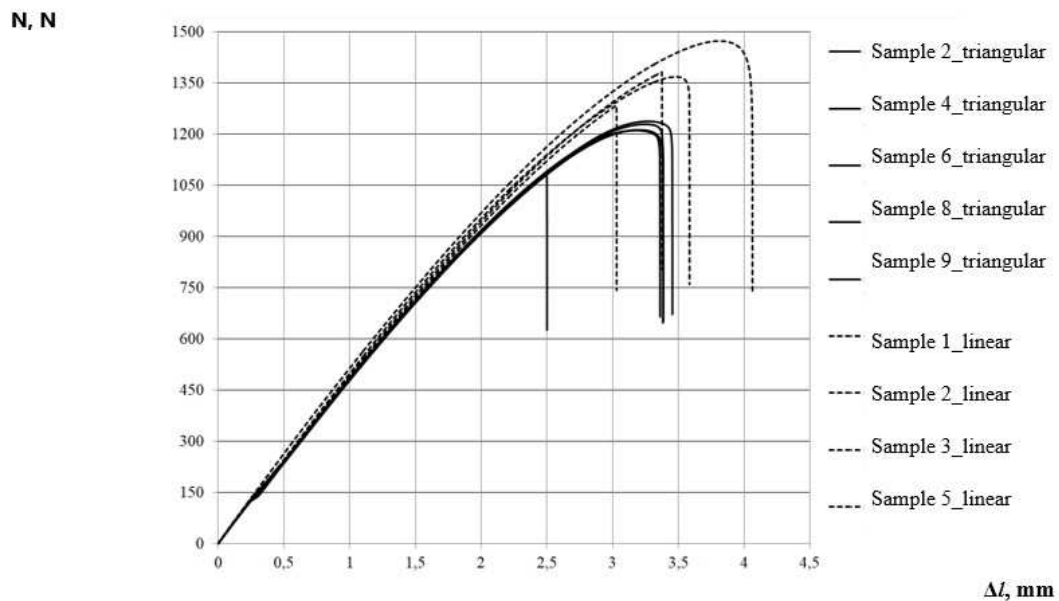


Figure 5. Tension diagrams of the samples with different filling patterns

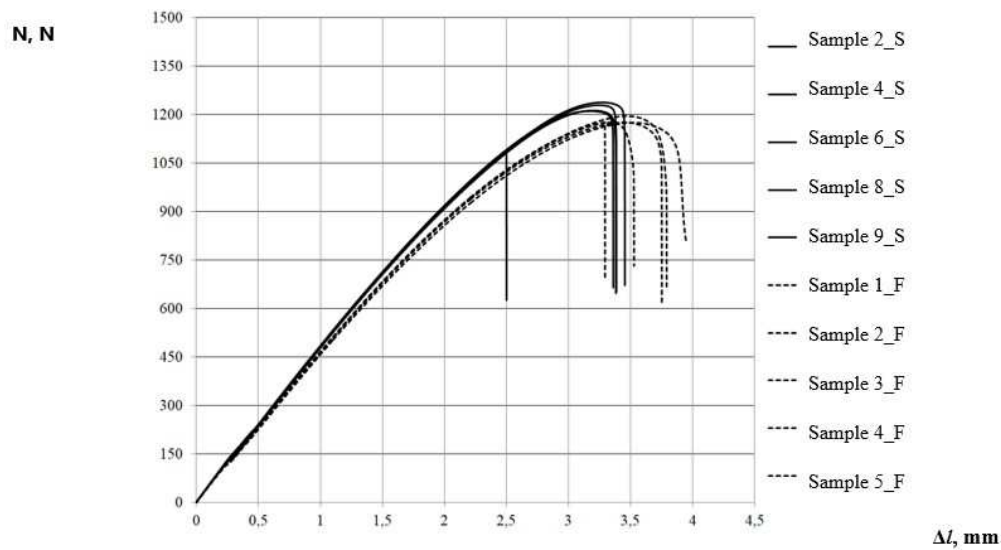


Figure 6. Tension diagrams of the samples with different position of samples when printing

According to Table 2 and Figure 6, the position of the samples when printing does not affect the characteristics of the samples, since the deviation between the values of tension forces when printing flat and standing is 1%. However, the stiffness characteristic when printing samples flat is 9% higher when printing standing on the edge.

In order to assess the influence of the filling density of the samples, we also conducted tests, the results of which are shown in Table 3 and Figure 7.

Table 2. Characteristics of the samples with different position of samples when printing

Position of samples	No. sample	$N_{\max}$	$N_{\max}^{\text{aver}}$	Δl	Δl^{aver}
Standing on the edge	2	1212		3,2	
	4	1214		3,2	
	6	1086	1196±(60)	2,5	3,1±(0,2)
	8	1239		3,3	
	9	1230		3,2	
Flat	1	1177		3,5	
	2	1197		3,5	
	3	1177	1181±(59)	3,3	3,4±(0,2)
	4	1176		3,5	
	5	1177		3,3	

Table 3. Characteristics of the samples depending on the % of filling

Filling density of the samples	No. sample	$N_{\max}$	$N_{\max}^{\text{aver}}$	Δl	Δl^{aver}
60%	2	1212		3,2	
	4	1214		3,2	
	6	1086	1196±(60)	2,5	3,1±(0,2)
	8	1237		3,3	
	9	1230		3,2	
100%	1	1391		3,1	
	3	1299		2,9	
	6	1350	1378±(69)	3,1	3±(0,2)
	8	1427		3	
	9	1424		3,1	

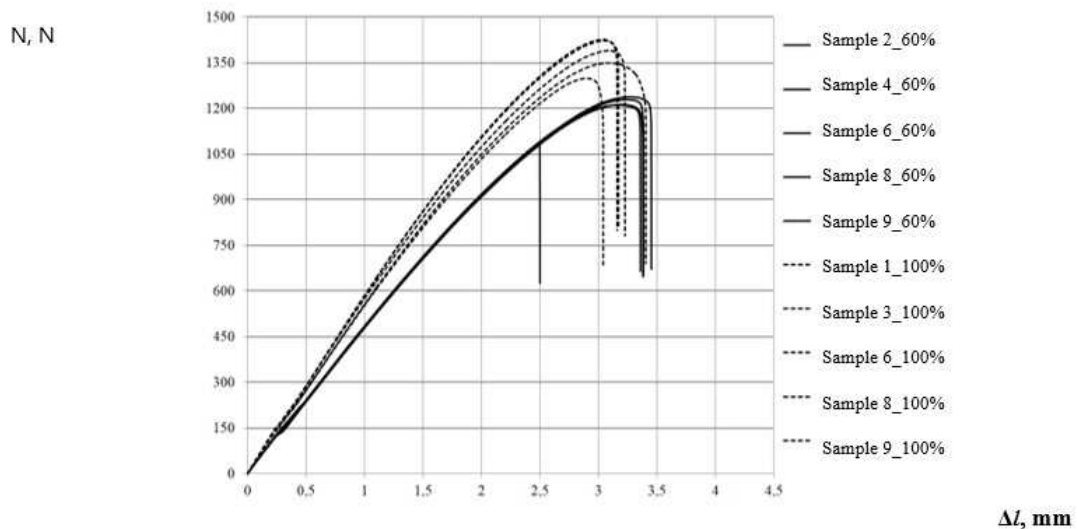


Figure 7. Tension diagrams of the samples at different filling densities

Thus, according to Table 3 and Figure 7, the average maximum tension force maintained by the samples with a filling density of 100% exceeds by 13% the average tension force for the samples with a filling density of 60%. At the same time, the mean value of absolute elongation at maximum load differs by only 3%, which is included in the confidence interval.

5. Conclusion

In this article, the authors studied three parameters of influence on the strength and stiffness characteristics of the samples: sample filling pattern, percentage of sample filling, direction of layering in the sample (the position of the samples when printing). Moreover, each influence parameter had two values, which were shown in Table 4. It summarized the results of all experiments, presented through the average values of the corresponding parameters of strength and stiffness.

Table 4. Experiment results

	Value of influence parameters			
	Inclined lines	Triangles	Triangles	Triangles
Filling pattern				
Filling percentage	60%	60%	60%	100%
Layering direction in the sample	Edge	Edge	Flat	Edge
Average maximum effort, N	1378±(69)	1196±(60)	1181±(59)	1378±(69)
Average absolute elongation at maximum load, mm	3,4±(0,2)	3,1±(0,2)	3,4±(0,2)	3,0±(0,2)

The experimental results allow assuming that with two equal parameters of influence (filling pattern and direction of layering), the strength characteristics of the samples depend on the density of their filling (60% and 100%), namely, with the increase in density, the maximum load endured by the samples increases. In addition, it affects strength characteristics and filling pattern (printing with lines or triangles) when the other two influence parameters are the same. However, the location of the samples during printing, that is, the direction of layering (standing on the edge or flat), with the other two equal parameters, does not affect the value of the average maximum tension force.

Regarding the stiffness characteristics of the samples, the experiments showed a significant effect of the filling patterns and the position of the samples when printed on the average absolute elongation.

The filling density with two equal parameters does not affect the specified characteristic (Table 4). Moreover, during the tests it was found that the samples printed with a linear pattern and a filling density of 60% and the samples printed with a triangular pattern and a filling density of 100% have equal values of the average tension force endured by the samples. A similar situation is observed for the characteristic of stiffness (Table 4). That is, it can be assumed that in order to achieve the required strength and stiffness characteristics several influence parameters should be combined in a certain way provided that the filament is saved.

It is necessary to note that the volume of experiments carried out during the preparation of this article does not allow making unambiguous conclusions about the strength and stiffness of the samples. As a result, at the moment it does not allow assessing the strength of a bionic artificial hand (Fig. 1). However, the results of the experiments make it possible to see some trends in the development of this topic and require further research with a large number of samples.

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