

<https://doi.org/10.21122/2227-1031-2019-18-3-233-239>

UDC 620.172.242

Experimental Determination and Comparative Analysis of the PPH030GP, ABS and PLA Polymer Strength Characteristics at Different Strain Rates

M. Yu. Zalohin¹⁾, V. V. Skliarov²⁾, Ja. S. Dovzhenko²⁾, D. A. Brega³⁾

¹⁾Kharkiv National Automobile and Highway University (Kharkiv, Ukraine),

²⁾National Scientific Center “Institute of Metrology” (Kharkiv, Ukraine),

³⁾Kharkiv National Aerospace University “Kharkiv Aviation Institute” (Kharkiv, Ukraine)

Abstract. Nowadays the field of application of products made from polymer materials is constantly increasing. These products find their wide application in the most high-tech industries such as automotive, aerospace and medical industry. Modern trends in the development of the automotive industry predicts that 75 % of the total car mass will be replaced with polymer materials by 2020 and other industries demonstrate similar trends. Regarding to this information, engineering companies that design parts of the automotive industry should have polymer material characteristics over an entire range of deformations up to destruction for their performance prediction. However, strength characteristics of products from polymers are different and depend not only on a polymer grade but also on technology used for part production. Existing literature review on this problematic area is rather rare. The purpose of this paper is to determine and analyze mechanical characteristics of widely used PPH030GP polymer obtained by extrusion and ABS, PLA polymers applied while manufacturing samples using an additive method (3D-printing) depending on the rate of high-elastic deformation. All the samples have been made according to the requirements of GOST 11262–80 and subjected to uniaxial stretching on a tensile machine UIT STM 050/300 at different speeds of clamp expansion. According to experimental results, stretching diagrams in conditional coordinates σ – ε have been obtained up to the point of failure for different rates of clamp expansion. It has been shown that while using the additive method, a direction of layers and adhesion between them, which depends on 3D-print parameters, have a significant effect on the part strength. Printing settings are indicated in accordance with the selected mode and a 3D-printer model. As a result of data processing, strength characteristics of PPH030GP polymer and ABS and PLA polymers have been determined to a sufficient extent, depending on the direction of printing layers and rate of high-elastic deformation. These data can be used to calculate strength of products by numerical methods and a finite element method in various software products.

Keywords: polymer, stretching diagram, mechanical characteristic, strength, destruction, 3D-printing

For citation: Zalohin M. Yu., Skliarov V. V., Dovzhenko Ja. S., Brega D. A. (2019) Experimental Determination and Comparative Analysis of the PPH030GP, ABS and PLA Polymer Strength Characteristics at Different Strain Rates. *Science and Technique*. 18 (3), 233–239. <https://doi.org/10.21122/2227-1031-2019-18-3-233-239>

Экспериментальное определение и сравнительный анализ характеристик прочности полимеров PPH030GP, ABS и PLA при различных скоростях деформации

Канд. техн. наук, доц. М. Ю. Залогин¹⁾, канд. техн. наук В. В. Скляр²⁾, Я. С. Довженко²⁾, канд. техн. наук, доц. Д. А. Брега³⁾

¹⁾Харьковский национальный автомобильно-дорожный университет (Харьков, Украина),

²⁾Национальный научный центр «Институт метрологии» (Харьков, Украина),

³⁾Харьковский национальный аэрокосмический университет имени Н. Е. Жуковского (Харьков, Украина)

Реферат. Сегодня область применения изделий из полимерных материалов постоянно увеличивается. Такие изделия находят широкое применение в наиболее наукоемких отраслях, таких как автомобильная, аэрокосмическая

Адрес для переписки

Залогин Максим Юрьевич
Харьковский национальный
автомобильно-дорожный университет
ул. Ярослава Мудрого, 25,
61002, г. Харьков, Украина
Тел.: +375 057 707-37-69
zalohin@khadi.kharkov.ua

Address for correspondence

Zalohin Maksim Yu.
Kharkiv National
Automobile and Highway University
25 Yaroslava Mudrogo str.,
61002, Kharkov, Ukraine
Tel.: +375 057 707-37-69
zalohin@khadi.kharkov.ua

и медицинская отрасли. Современные тенденции развития автомобильной промышленности прогнозируют к 2020 году 75 % общей массы автомобиля заменить полимерными материалами. Схожие тренды демонстрируют и другие отрасли. В связи с этим инженерным компаниям, проектирующим детали автомобильной промышленности, для прогнозирования их работоспособности необходимо иметь характеристики полимерных материалов во всем диапазоне деформаций – вплоть до разрушения. Однако прочностные характеристики изделий из полимеров различны и зависят не только от марки полимера, но и от технологии производства детали. Подробная информация в отечественной литературе встречается достаточно редко и в сжатом виде. Авторами статьи была поставлена задача определить и проанализировать механические характеристики широко применяемого полимера PPH030GP, полученного экструзивным методом, и полимеров ABS и PLA, применяемых при изготовлении образцов аддитивным методом (3D-печать) в зависимости от скорости деформации. Для этого были выполнены образцы согласно требованиям ГОСТ 11262–80 и подвергнуты одноосному растяжению на разрывной машине UIT STM 050/300 при разных скоростях раздвижения зажимов. По результатам экспериментальных исследований получены диаграммы растяжения в условных координатах σ – ε вплоть до момента разрушения для различных скоростей раздвижения зажимов. Показано, что при аддитивном методе значительное влияние на прочность изделия оказывают направление слоев и адгезия между ними, которая зависит от параметров 3D-печати. Параметры печати указаны в зависимости от выбранного режима и конструкции 3D-принтера. В результате обработки данных в достаточной мере определены прочностные характеристики полимеров PPH030GP, ABS и PLA в зависимости от направления слоев печати и скорости деформации. Эти данные можно применять для расчета прочности изделий численным методом и методом конечных элементов в различных программных продуктах.

Ключевые слова: полимер, диаграмма растяжения, механическая характеристика, прочность, разрушение, 3D-печать

Для цитирования: Экспериментальное определение и сравнительный анализ характеристик прочности полимеров PPH030GP, ABS и PLA при различных скоростях деформации / М. Ю. Залогин [и др.] // *Наука и техника*. 2019. Т. 18, № 3. С. 233–239. <https://doi.org/10.21122/2227-1031-2019-18-3-233-239>

Introduction

Nowadays, polymers have found wide application in various branches of science and technology, such as automobile and tractor design, medicine, oil and gas extraction, national economy, etc. [1]. According to experts from Research and Markets [2] and the information-analytical publication [3] in the automotive industry, in order to make cars more energy efficient, the use of polymer materials should be increased to 75 % of the total mass of the car by 2020. It should be noted that parts made of polymeric materials by the traditional method or made with additive technologies (3D-printing method) should operate in temperature range from plus 150 °C to minus 45 °C under a variety of loading conditions [4]. Due to this fact, engineering companies that design car parts should have strength characteristics for the materials under various loading conditions up to destruction for their performance prediction.

Unfortunately, the literary review showed scant information in this problematic scientific area [5–8]. For example, in [9–12], the authors pay special attention to the study of the polymer fibers strength from which the sample then 3D-printed. Either, in the works mentioned, there is no analysis of the influence of the load application velocity on the polymers strength characteristics. In the foreign literature, the analysis was performed without ta-

king into account the influence of the viscoelastic deformation [13–16].

Thereby, the authors of the article were aimed on experimental determination and analysis of the mechanical characteristics of the strength of widely used PPH030GP polymers obtained by the extrusion method and ABS, PLA polymers used for sample manufacturing by the additive method. The investigations were carried depending on the initial strain rate on the tensile machine with a maximum force of 5000 kg.

Experimental setup

To determine the mechanical characteristics of the polymers strength, it is vital to have an experiment in which the sample is subjected to uniaxial stretching until its destruction. Tensile tests were carried in accordance with the state standard GOST 11262–80 or international ISO 527. In this connection, 8 samples of the extensively used PPH030GP polymer and 6 polymer ABS and PLA samples produced by 3D-printing (3 samples for each material) were subjected to tensile testing to determine the strength characteristics according to GOST 11262–80. The geometrical parameters of the samples are shown in fig. 1.

The samples were tested on a UIT STM 050/300 tensile machine at the Metrology Institute at an ambient temperature of 22 °C and a relative humidity of 47 %.

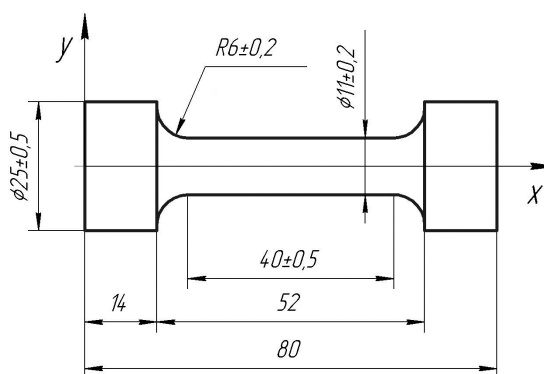


Fig. 1. Sample No 4:
geometry according to GOST 11262–80

It is known that the additive method for part production involves layer-by-layer deposition of molten material with a rolling head in order to completely reproduce the computer 3D-model [9]. Consequently, several strategies for the sample manufacturing are possible: application of material layers along and across the x axis (fig. 1). Detailed review of the creating process of a product using the 3D-printing method can be found in [10, 11]. However, such method of printing leads to anisotropy of material properties. In this case, the structural strength of a part made by the 3D-printing method will largely depend on the direction in which the force is applied – along or across the line direction of layers when printing. In this connection, two samples of ABS material were printed along the x-axis (fig. 1), and 1 sample was transverse. Also in the transverse direction were printed 3 samples from PLA material. For the analysis of the mechanical characteristics of the polymers, it was planned to conduct an experiment for 4 samples from the PPH030GP polymer with a quasistatic speed of 5 mm/min. In order to determine the dependence of the deformation rate on the strength characteristics for each next sample (of the remaining 4 samples of PPH030GP), the deformation rate was planned to be increased by one subsequent position in the software for the tensile machine.

Results and discussions

From the experimental results, the values of forces and the movements obtained by the UIT STM 050/300 sensor interpreted in a form of the tensile diagram in the “force-displacement coordinates”. However, in order to carry out theoretical

calculations for strength, the designer needs the values of the stresses and deformations of the material. That is why the test results were transformed according to expressions [5] and are represented in the stress-strain coordinates (fig. 2).

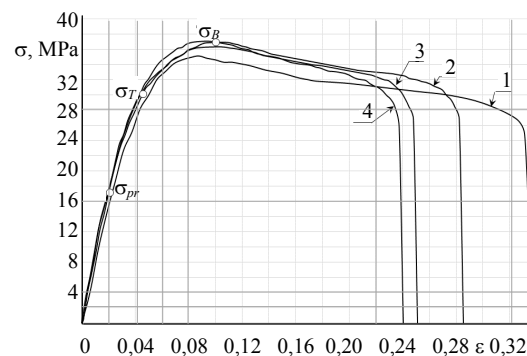


Fig. 2. Stretching diagram for polymer PPH030GP
at deformation rate of 5 mm/min

It should be noticed that such diagram is conditional and is characteristic only for the cylindrical sample depicted in fig. 1 [5]. To identify the characteristics of samples and tabular values, the article adopts the end-to-end numbering of curves in all figures. As can be seen from the stretching diagram (fig. 2), the elastic properties of the material appear on the linear part up to the proportionality limit σ_{pr} and can be described by the theory of elasticity based on Hooke's law [5, 12]. The magnitude of the elastic deformation does not exceed 2 %. The behavior of the material after the yield point σ_T indicates the presence of plastic deformations in the material and their concentrating in the most critical section of the sample. The subsequent increase in plastic deformation continues up to the ultimate strength σ_B and is accompanied by the formation of a neck. At the same time, the relative elongation of the sample reaches 10 %. The further behavior of the material exhibits nonlinear rheological properties typical for the amorphous-crystalline polymers and can be described by a nonlinear theory of viscoelasticity based on the Boltzmann heredity principle [17]. In this case, the energy of deformation is expended on the work of the micro cracks emergence inside the material, which are concentrators of considerable stresses and for the heat release. The nature of the destruction of polymers depends on their physical state during deformation and is a consequence of the action of various mechanisms [12]. To determine the rheo-

logical properties of the material, experiments were carried out with different deformation rates, the results of which are shown on fig. 3 and in tab. 1.

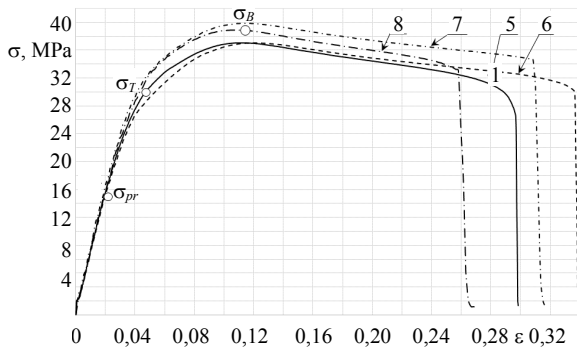


Fig. 3. Stretching diagram for polymer PPH030GP at different deformation rates: 5 – 10 mm/min; 6 – 20 mm/min; 7, 8 – 50 mm/min

It should be noted that the rise in the rate of deformation by 100 % increases the tensile strength σ_B by 5.25 %, and the increase in velocity by 1000 % increases the tensile strength by 9.5 %. As can be seen from fig. 3 the elastic properties of the material σ_{pr} and σ_T have not changed due to increased rate of deformation, since their value does not depend on the rate of deformation [5, 12]. Experimental results for polymer PPH030GP are summarized in tab. 1.

The elastic modulus E , the shear modulus G and the bulk modulus of elasticity K were calculated from the following expressions:

$$E = \frac{\sigma_{pr}}{\varepsilon}; \tag{1}$$

$$G = \frac{E}{2(1+\mu)}; \tag{2}$$

$$K = \frac{E}{3(1-2\mu)}, \tag{3}$$

where μ – Poisson's ratio.

The Poisson ratio was determined from the well-known expression [5]

$$\mu = \frac{\varepsilon_{\perp}}{\varepsilon_{\parallel}}, \tag{4}$$

where ε_{\perp} – residual deformation after the sample rupture in the transverse direction; ε_{\parallel} – residual deformation after the sample rupture in the longitudinal direction.

Samples of ABS polymer were printed with the following parameters: the diameter of the nozzle of the extruder was 0.4 mm; the height of the layers is 0.3 mm; thread diameter – 1.75 mm; the plastic feed rate is 0.95; the temperature of the extruder is 230 °C; the table temperature of the first layer is 100 °C; printing speed – 40 mm/s; filling of the sample – 100 %.

The layers of molten material were applied at an angle of 45° to the longitudinal axis of the sample.

Then, the samples were tested for one-axis stretching, the results were summarized in the form of dependence of the sample internal stress on deformation at different strain rates (fig. 4).

Table 1

Mechanical strength parameters of PPH030GP polymer

Sample number	σ_{pr} , MPa	σ_T , MPa	σ_B , MPa	ε_p , %	ε , %	E , MPa	G , MPa	K , GPa	μ	v , mm/min	S_k , mm ²
1	18.6	29.95	34.60	33.1	6.25	743.80	249.6	12.390	0.499	5	95.033
2	17.53	31.96	36.90	28.2	5.50	876.53	295.1	9.740	0.485		95.033
3	18.50	32.07	36.90	24.8	4.10	853.20	284.8	14.200	0.498		95.033
4	17.00	31.40	36.25	23.7	4.20	850.70	285.3	15.750	0.491		94.860
5	17.58	31.70	38.85	29.6	4.25	882.50	297.9	7.740	0.481	10	95.033
6	17.47	28.70	39.06	33.6	7.50	857.50	290.1	6.496	0.478	20	95.033
7	18.73	34.33	41.85	30.8	4.90	937.68	315.3	12.020	0.487	50	95.033
8	17.56	35.02	40.90	25.8	5.50	876.90	293.1	36.500	0.496		95.033

ε_p – relative deformation of the sample at the moment of failure; ε – deformation of the sample after the failure; S_k – area of the sample in the critical cross-section.

It can be seen from the graph that the deformation curves of the samples with longitudinal arrangement of the layers (No 10 and 11) have a small area of plastic deformations concentrated in the neck region. For sample No 9, there is no formation of plastic deformations. This is explained by the fact that the strength characteristics of the part are more affected by the adhesive component of strength, rather than the behavior of the material itself in the layers. The dispersion of the ultimate strength values can reach a value up to 70 %. Which is also confirmed by other studies [9–11].

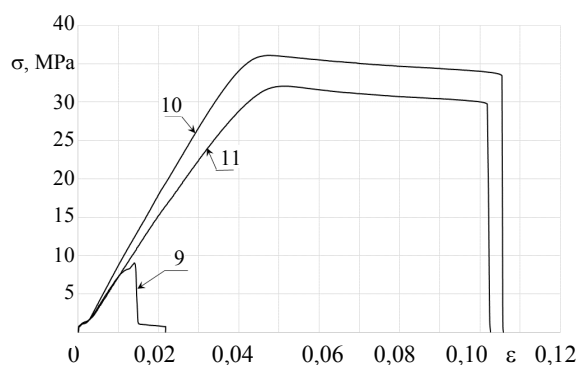


Fig. 4. Stretching diagram for 3D-printed ABS polymer sample at different strain rates: 9 – 5 mm/min; 10 – 2 mm/min; 11 – 5 mm/min (sample No 9 has been printed across x axis; samples No 10, 11 – along x axis (fig. 1))

Samples from the PLA polymer were printed with the following parameters: the diameter of the nozzle of the extruder was 0.2 mm; the height of the layers is 0.1 mm; thread diameter – 1.75 mm; the plastic feed rate is 1; the extruder temperature is 245 °C; the temperature of the table of the first layer is 55 °C; speed of printing – 20 mm/s; filling the sample – 100 %.

Processing data from a discontinuous machine, gives the expansion diagrams at different deformation rates depicted in fig. 5.

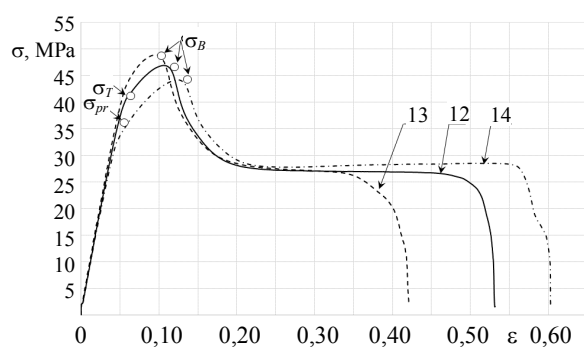


Fig. 5. Stretching diagram of sample made by 3D-printing from PLA polymer, at different strain rates: 12 – 10 mm/min; 13 – 20 mm/min; 14 – 2 mm/min

Thus, elastic properties of the material are clearly traced in the deformation diagrams up to 5 % of the deformation of the sample. A further increase in deformation of up to 10 % leads to a concentration of plastic deformations and the appearance of a neck. The decrease in stresses by exponential dependence with simultaneous increase in deformation unambiguously indicates the viscous flow behavior of the material up to the point of failure.

It should also be noted that at a strain rate of 2 mm/min, the energy of deformation is partially expended on the temperature change in the neck formation region, which in turn, leads to hardening of the material by 2.5 % (fig. 5, curve No 14). Besides, in sample No 14, the characteristic difference was the formation of a second neck with a plastic deformation of 58 %.

Based on the results of the experiments, a non-linear dependence of the change in the strength σ_B of PLA on the initial strain rate was also established. Thus, with an increase in the deformation rate by a factor of 5, the ultimate strength σ_B increases by 6.3 %, and with an increase in speed by a factor of 10, the tensile strength σ_B increases by 10.2 %. To analyze the strength characteristics of ABS and PLA polymers, the results of the processing of experimental data are summarized in tab. 2. Due to obtained data, it is seen that the tensile strength of the PLA polymer is 18 % higher than that of ABS at the same strain rate without regard for layers orientation. If the limiting values of the strength of the samples whose layers are disposed transversally will be taking into consideration (fig. 4 and 5, curves No 9 and No 13), the difference will be substantial and reach a ratio of 5-fold.

The fracture surface obtained after rupture of polymers PPH030GP and ABS has a classical and inherent form of all brittle materials, depicted in fig. 6 and 7.

The carried research have shown that the rate of deformation of polymers affected the strength characteristics. In addition, the strength of the parts obtained by the additive method is influenced by the direction of the layers (fibers) and their adhesion to each other. The degree of influence of the adhesive component depends on the parameters and operating mode of the 3D-printer.

Analysis of the test results showed that the samples made of PLA polymer by the additive method have pronounced viscoelasticity properties. Strength characteristics of this material exceed the characteristics of ABS by 28 % and the polymer PPH030GP by 18 %, which significantly expands its application for various purposes.

Mechanical properties of ABS and PLA polymers

Sample number	σ_{pr} , MPa	σ_T , MPa	σ_B , MPa	ε_p , %	ε , %	E , MPa	G , MPa	K , MPa	μ	v , mm/min	S_k , mm ²
9	9.05	–	–	–	–	646.63			0.495	5	88.247
10	34.01	–	36.1	10.5	2.50	852.47	284.30	142.1	0.491	2	86.590
11	28.90	–	32.1	10.1	1.50	719.92	240.10	120.0	0.490	5	98.520
12	37.32	40.64	46.9	52.5	47.5	743.41	247.82	123.9	0.488	10	97.640
13	39.14	42.79	48.9	42.1	38.0	779.72	260.10	129.9	0.496	20	97.640
14	33.70	35.10	44.0	55.1	47.5	674.20	224.80	112.3	0.492	2	97.640

ε_p – relative deformation of the sample at the moment of failure; ε – deformation of the sample after the failure; S_k – area of the sample in the critical cross-section.

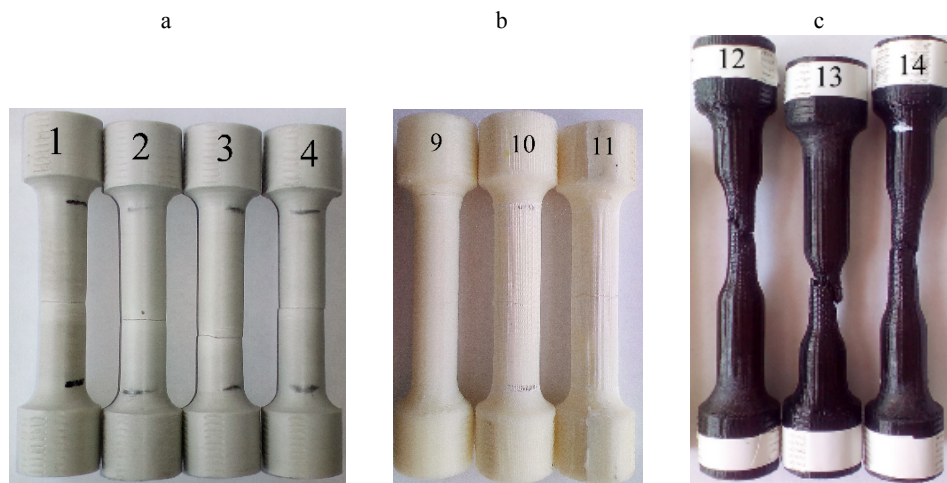


Fig. 6. Samples appearance after rupture: a – PPH030HP; b – ABS; c – PLA (samples 5, 6, 7, 8 are identical to 1, 2, 3, 4)

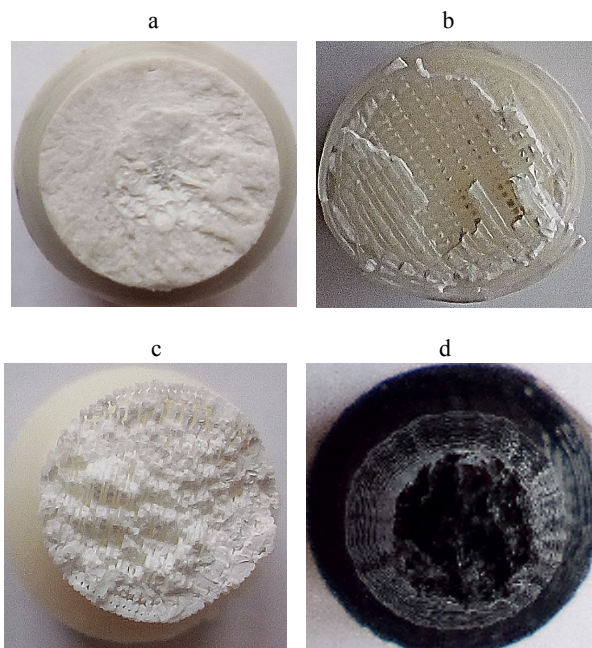


Fig. 7. The surface of rupture: a – PPH030GP; b, c – ABS; d – PLA

Eventually, it should be noted that due to the results of the experimental study of the polymer strength parameters, carried out by various methods, the use of these materials in the automotive industry is positively advisable. There is a whole list of aggregates and systems, where the parts require the replacement of steel material with polymer [18]. So, for example, the pistons of the clutch cylinders are made of plastic by the traditional method, followed by mechanical work.

An essential advantage of the additive method is the creation of complex shape parts. These include the body of cylinders and units, working at low loads. The disadvantage of the additive method is the high cost of manufacturing the part. To date, the cost of printing varies in the range of 0.10–0.25 dol. for gram depending on the selected material, which somewhat limits the scope of its use.

CONCLUSIONS

Ultimately, strength characteristics of polymers PPH030GP, ABS and PLA were determined and

analyzed in the article, depending on the rate of deformation. Overall, the following conclusions can be made:

1) strength characteristics of the polymer have both elastic and viscous-flow properties. It was found that the modulus of elasticity E of PPH030GP polymer ranges from 937 to 743 MPa and on average is 860 MPa, which is 8.5 % more than ABS and 14.8 % higher than PLA;

2) additive methods of manufacturing products create a part with a significant anisotropy of properties, which depends on the direction of layers and printing parameters of the 3D-printer. It is established that in the case of applying a force that coincides with the direction of the printing layers, the strength limit increased up to 4 times for samples from ABS polymer. For the PLA polymer, this ratio approaches 5;

3) the effect of deformation rate on the ultimate strength of ABS polymer was determined. Thus, an increase in the deformation rate by 100 % raises the tensile strength by 5.25 %, and an increase in the deformation rate by 1000 % increases the tensile strength by 9.5 %;

4) the effect of strain rate on the ultimate strength for PLA polymer has also been established. Thus, when the strain rate is increased by a factor of 5, the tensile strength σ_B increases by 6.3 %, and with an increase in speed by a factor of 10, the tensile strength σ_B is increased by 10.2 %;

5) it has been defined that the ultimate tensile strength of the PLA polymer is 18 % higher than that of ABS and 22 % higher than that of the polymer PPH030GP at the same strain rate without taking into account the orientation of the sample layers;

6) the obtained values of the strength parameters of polymers can be used to calculate the parts strength by the numerical method and the finite element method in various software products.

Acknowledgment

The authors of the article express their gratitude to the director of the “Aplast” company V. Chukhalov for providing samples from the homo-polymer PPH030GP, as well as to the director of the company “Energouchet” Ph. D. A. Stetsenko and Engineer Yu. Glova for providing samples from polymers PLA and ABS.

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Received: 03.05.2018

Accepted: 14.08.2018

Published online: 30.05.2019