Journal of Energy, Mechanical Engineering and Transport
Volume 1 (2024), Issue 2, 9-13

https://doi.org/10.51301/jemet.2024.i2.02

The influence of technological factors of 3D printing on the strength of standard details made of glass-filled polymer composite

G. Abilezova*, M. Isametova, R. Karpekov
Satbayev University, Almaty, Kazakhstan
**Corresponding author: abilezova_gazel@mail.ru*

Abstract. The article presents the results of the study of the influence of technological factors of 3D printing on the strength of standard details made of glass-filled polymer composite. A matrix of a three-factor experiment was compiled, where the temperature parameters of the extruder head, layer thickness and occupancy were taken as the factors of variation. Regression analysis of the experimental results was carried out, response surfaces were constructed. According to the results of mathematical processing, it was revealed that the factor– layer thickness - has the strongest effect on the strength of printed products. The maximum value of the tensile strength of the composite sample was in the sample printed with the parameters: the temperature of the extruder head is 2700, the layer thickness is 0.3 and the occupancy rate is 100%, the strength limit value reached 81 MPa.

Keywords: *3D printing, additive technologies, composite materials, strength, polymer and technological factors.*

1. Introduction

Due to the ability to easily adapt to any task and launch complex geometry products into production as quickly as possible at minimal cost, 3D printing is actively being introduced into various industries and is the focus of research attention around the world.

The increasing share of global consumption of composites in a wide variety of industries also causes an urgent need to involve composite materials, in particular glass fiber reinforced, in additive technologies. It is well known that the formation of the properties of polymer products is influenced not only by the structure of the material, but also by the method of processing. The experimental data accumulated to date on the use of polymer materials in additive technologies show that the properties of products obtained by 3D printing are significantly inferior to the properties of injection molding products, despite the fact that, unlike traditional processing methods, 3D technologies allow you to adjust a large number of printing parameters that can have a significant impact on the physical and mechanical properties of the printed object [1-3].

One of the factors significantly affecting the quality of parts produced by additive technology are residual stresses.

Despite the significant development of technologies and modeling, residual stresses are still poorly studied and difficult to determine, especially for anisotropic materials. This article will consider the influence of technological factors on the mechanical properties of products made by 3D printing technology [4-6].

2. Materials and methods

The TOTAL GF 10% composite material based on a polymer matrix was also selected as the second object of the study. Discrete glass fiber manufactured by ESUN with a length of 3 mm was used as inclusions (Figure 1).

Figure 1. Pictute of granules of TOTAL GF 10% composite material

To study the effect of printing modes on the properties of formed products made of filled polymer, composite polymer was used, previously obtained by mixing in the melt of the company «ESUN» with glass fiber, the content of glass fibers in the matrix was 10%. The material characteristics are given in Table 1.

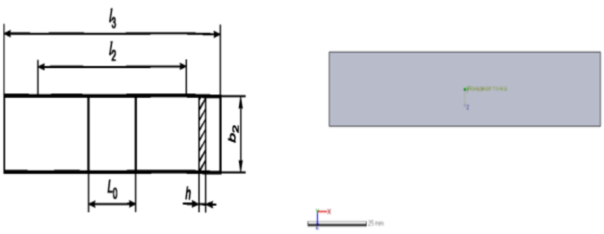
Composite samples were printed on a PioCreat G5 3D printer (Figure 2) FGF printing technology. The FGF method as a new stage of development in polymer extrusion, the principle of operation of the FGF printing method. The principle of movement of the extruder in an FGF 3D printer is the same as in a traditional FFF printer, however, composite granules are the consumable material instead of a filament. Additional components, such as a hopper and a screw extruder, are used for processing pellets. The screw in the extruder moves the pellets from the inlet of the feed system to the nozzle opening. Immediately before extrusion through the nozzle, the molten composite is subjected to high pressure due to the motor that rotates the auger.

Table 1. Physical and mechanical characteristics of TOTAL GF 10% for FDM printing from the company «ESUN»

Indicator	TOTAL GF 10%
Sharpie Impact strength	11.5 kJ/m^2
Tensile strength along layers	75.4 MPa
Modulus of elasticity in tension along the layers	2.9 GPa
Flexural strength	98.2 MPa
Flexural modulus of elasticity	3.2 GPa
Maximum bending load	210 N
Tensile strength across layers	72.2 MPa
Modulus of elasticity in tension across layers	2.9 GPa
Maximum tensile load	4030 H
Compressive strength	80 MPa
Compressive modulus of elasticity	3.1 GPa
Maximum compression load	9800 N
Elongation coefficient	30%

Figure 2. PioCreat G5 Printer

For the research, samples were made (Figure 3) for testing with the dimensions given in Table 2 in accordance with GOST 11262-2017 (ISO 527-2:2012) 3D models were prepared in the COMPASS software.



a) b)

Figure 3. a) Sample type 1 GOST 11262— 2017 (ISO 527-2:2012); b) The GOST bar modeled in the COMPASS software

Table 2. Dimensions of Type 1 test samples

Dimensions	3 type (mm)
l_3 Total length	250
b_2 Head width	25
h Thickness	2

To study the effect of printing parameters on the mechanical properties of finished products, a matrix of a three-factor experiment was prepared. The research was carried out on various printed objects, varying the technological parameters one by one.

The following factors were taken as variable: the temperature of the extruder head, the percentage of filling and the thickness of the layer. Tables 3, 4 present the experiment planning matrix.

Here, the following factors were also taken as variable: the temperature of the extruder head, the percentage of filling and the thickness of the layer. Table 3, 4 shows the experiment planning matrix.

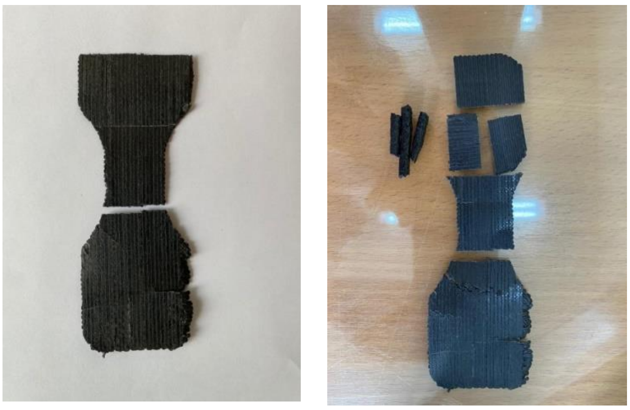
Table 3. Parameters of the experiment of layer-by-layer application of the TOTAL GF 10%

Parameters	Max	Min
Temperature, ^{0}C	290	270
Layer thickness, mm	0.3	0.1
Density filling, %	100	30

Table 4. Parameters of the 3 - factor experiment

№	Temperature, ^{0}C	Layer thickness, mm	Density filling, %	X1	X2	X3
1	+	+	+	290	0.3	100
2	-	+	+	270	0.3	100
3	+	-	+	290	0.1	100
4	-	-	+	270	0.1	100
5	+	+	-	290	0.3	30
6	-	+	-	270	0.3	30
7	+	-	-	290	0.1	30
8	-	-	-	270	0.1	30

When printing the TOTAL GF composite from 20% and 30% glass fiber fillings, the PioCreat G5 3D printer encountered difficulties and the printed samples were of very poor quality. Scientific facts explaining these phenomena are given in [7-9], the authors justify the defects of the printing process by the fact that the increase in solid inclusions and the decrease in binder leads to low adhesion of the matrix with the filler (Figure 4).



a) TOTAL GF 20% б) TOTAL GF 30%

Figure 4. Printed samples from a TOTAL GF a grade composite pellet a) 20% and b) 30%

Samples from the TOTAL GF 10% material had a satisfactory appearance on visual inspection, without any defects. Figure 5 shows 8 samples printed on this printer from TOTAL GF 10% composite material.

The eighth sample, when removed from the substrate, had a large warping, which indicates high residual stresses, and this assumption will have to be verified by conducting further experiments.

Tensile and bending tests of polymer composite materials.

The tests were carried out at a temperature of 230, at a speed of 20 mm /s on a WDW-50E breaking machine. Figure 6 shows photographs from the experiment.

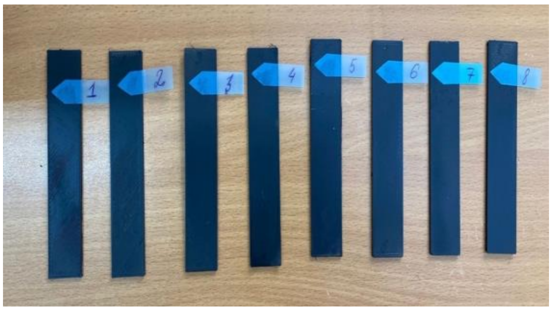


Figure 5. Printed 8 samples from a TOTAL GF 10% composite pellet

Figure 6. Formation of the neck at break

During the tests, it was noticed that the rupture occurs in all samples closer to the clamping devices, which indicates the heterogeneity and anisotropy of the structure of the printed details.

3. Results and discussion

Tensile strength along the layers (tear) composite material TOTAL GF 10%.

Graphs of the stress-strain relationship at break are shown in Figure 7. Photos of torn samples before and after are shown in Figure 7.

Dimensions of the sample: width – 25 mm, thickness – 2 mm, length – 250 mm and working length at break – 75 mm. The speed is 2.00 mm/min. The material is TOTAL GF 10%.

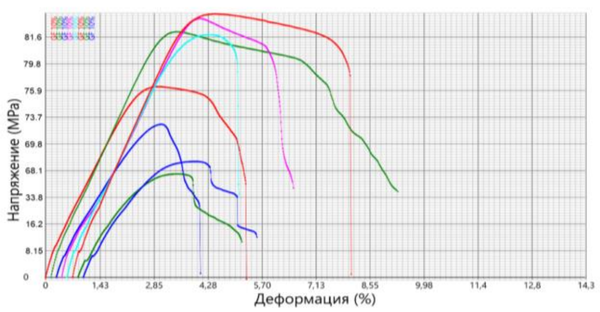
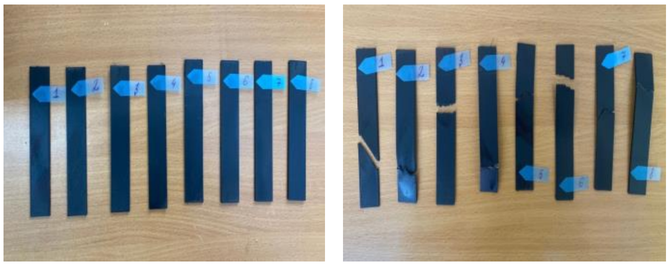


Figure 7. The dependence of the load on displacement for samples from TOTAL GF 10% at break (the first red stripe is sample No. 1, the first green stripe is sample No. 2, the first blue stripe is sample No. 3, the pink stripe is sa ple No. 4, the blue stripe is sample No. 5, the second red stripe is sample No. 6, the second green stripe is sample No. 7, the second blue stripe is sample No



а) б)

Figure 8. a) samples after 3D printing b) samples after stretching along the layers (break)

The data on the results of the experiment are summarized in Table 5.

Table 5. Breaking stress along TOTAL GF 10% layers

№ samples	Combination of factors			Breaking stress, MPa
	Temperature, ^{0}C	Layer thickness, mm	Density filling, %	
1	290	0.3	100	96.3
2	270	0.3	100	101.8
3	290	0.1	100	92.5
4	270	0.1	100	98.2
5	290	0.3	30	91.6
6	270	0.3	30	93.6
7	290	0.1	30	77.5
8	270	0.1	30	78.7

The table shows that the sixth, fifth, fourth and second samples have high indicators. In the second and fourth samples, the filling density is 100%, and the layer thickness is 0.3 and 0.1 mm, respectively. At this moment, the fifth and sixth have a filling density of 30%, and a layer thickness of 0.3 mm. The first and third samples show the average voltage values at a filling density of 100%. Here, the lowest values are in the seventh and eighth samples of 77.5 and 78.7 MPa, respectively. These samples have a layer thickness of 0.1 mm. According to the values, it can be concluded that the thickness of the layer matters most when it breaks.

According to the data obtained, Table 6 was compiled. Planning matrices for processing the results of TOTAL GF 10%.

The mathematical processing of the regression analysis experiment was carried out in the following order:

1) variables are encoded;

2) planning matrices are completed in coded variables considering paired interactions and supplemented with a column of average response values;

3) the coefficients of the regression equation are calculated;

4) the calculated coefficients are checked for significance, previously determining the variance of reproducibility, and the regression equation in the encoded variables is obtained;

5) the obtained equation is checked for adequacy;

6) interpretation of the received model is carried out;

7) the regression equation in natural variables is written out.

Table 6. Experiment matrices for processing the results of TOTAL GF 10%

№	Temperature, ^{0}C	Layer thickness, mm	Density filling, %	X1	X2	X3	Y Breaking stress, MPa	Y Module, MPa
1	+	+	+	290	0.3	100	76.3	2190
2	-	+	+	270	0.3	100	81.8	2260
3	+	-	+	290	0.1	100	72.5	2194
4	-	-	+	270	0.1	100	83.2	2180
5	+	+	-	290	0.3	30	81.6	2214
6	-	+	-	270	0.3	30	83.6	2293
7	+	-	-	290	0.1	30	77.5	2033
8	-	-	-	270	0.1	30	78.7	2055

After determining the coefficients and checking the resulting equation for adequacy according to the Fisher criterion. The interpretation of the resulting model was carried out, equation 1:

The TOTAL GF break is 10%. Regression equation:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3, \quad (1)$$

The values of the regression coefficients are summarized in Table 7.

Table 7. Values of regression coefficients

b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{123}
76.900	-2.425	3.925	1.550	3.550	-2.625	-3.325	0.750

According to Equation 1, the response surface of the tensile strength function of the samples from technological factors was constructed (Figure 9).

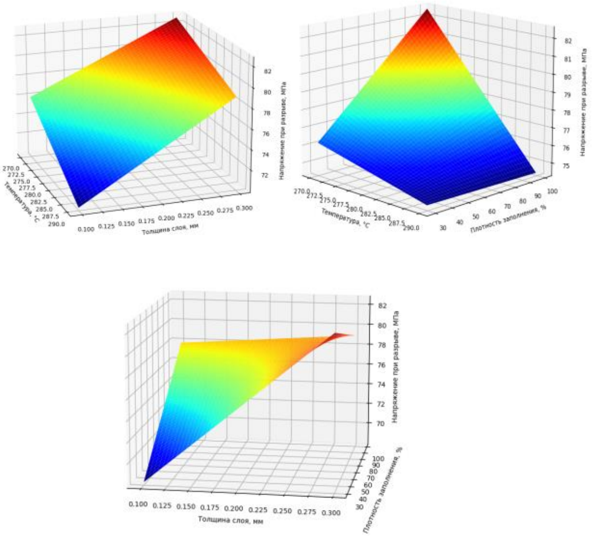


Figure 9. The surface of the response of the operating tension under tension

According to equation (1), it is obvious that the factor x2 – the thickness of the layer - has the strongest influence, since it has the largest coefficient in absolute value. After it, according to the strength of the influence on the response (stress at break), there are: the double interaction of two factors x1x2 - a combination of factors of layer thickness and temperature of the extruder head; factor x1 – the temperature of the extruder head. Since the coefficients at x2 and x3 are positive, the response increases with an increase in these factors, i.e. the tensile strength increases. The coefficients at x1, x1x3 are negative, which means that with a decrease in the factor x1 and the listed interactions, the response value will increase, and with an increase it will decrease.

4. Conclusions

To identify the influence of the technological parameters of 3D printing, such as layer thickness, fillability and temperature of the extruder head, a three-factor experiment was conducted, the processing of the experiment showed the influence of technological factors filling density, temperature and layer thickness on the mechanical characteristics of the glass-filled composite material. According to the derived regression equations and the constructed response surfaces, it can be seen that the factor– the thickness of the layer - has the strongest influence, since it has the largest coefficient in absolute value. The maximum value of the tensile strength of the composite sample was in the sample printed at the parameter of the extruder head 2700, the layer thickness is 0.3 and the occupancy rate is 100%, the value of the tensile strength reached 81 MPa.

Acknowledgements

The research is funded by the Ministry of Education and Science of the Republic of Kazakhstan PTF BR18574141 «Comprehensive multi-purpose program to improve energy efficiency and resource conservation in energy and mechanical engineering for the industry of Kazakhstan» according to Contract No. 27-PTF-23-24.

References

[1] Kondrashov, S.V., Pykhtin, A.A., Larionov, S.A. & Sorokin, A.E. (2019). Ispol'zovanie tekhnologicheskikh rezhimov FDM-pechati i sostavlenie materialov na fiziko-mekhanicheskie kharakteristiki FDM-modelei. *Trudy VIAM, Kompozitsionnye materialy, 10(82)*

[2] Vasil'ev, V.V. (1988). Mehanika konstrukcij iz kompozi-cionnyh materialov. *Retrieved from:* https://lib-bkm.ru/10930

[3] Molodcov, G.A., Bitkin, V.E. (2000). Formostabil'nye i intellektual'nye konstrukcii iz kompozicionnyh materialov. *Retrieved from*: https://www.studmed.ru/molodcov-g-a-bitkin-v-e-i-dr-formostabilnye-i-intellektualnye-konstrukcii-iz-kompozicionnyh-materialov_828ff08c012.html

[4] Petrovich, D.M. (2022). Formirovanie i harakter ostatoch-nyh naprjazhenij v dispersno-napolnennyh polimernyh kompozitah s chastichno kristallicheskoj strukturoj. *Retrieved from:* https://cyberleninka.ru/article/n/formirovanie-i-harakter-ostatochnyh-napryazheniy-v-dispersno-napolnennyh-polimernyh-kompozitah-s-chastichno-kristallicheskoy

[5] Birger, I.A. (1963). Ostatochnye naprjazhenija. *Retrieved from:* https://lib-bkm.ru/11346

[6] Chernyshev, G.N. (1996). Ostatochnye naprjazhenija v deformiruemyh tverdyh telah. *Retrieved from:* https://lib-bkm.ru/13055

[7] Mathieu, F., Hild, F. & Roux, S. (2012). Identification of a crack propagation law by digital image correlation. *International Journal of Fatigue, 36(1), 146–154.* https://doi.org/10.1016/j.ijfatigue.2011.08.004

[8] Carroll, J., Abuzaid, W., Lambros, J. & Şehitoğlu, H. (2013). High resolution digital image correlation measurements of strain accumulation in fatigue crack growth. *International Journal of Fatigue, 57, 140–150.* https://doi.org/10.1016/j.ijfatigue.2012.06.010

[9] Zhang, R. & He, L. (2012). Measurement of mixed-mode stress intensity factors using digital image correlation method. *Optics and Lasers in Engineering, 50(7), 1001–1007.* https://doi.org/10.1016/j.optlaseng.2012.01.009

3D басып шығарудың технологиялық факторларының шыны толтырылған полимерлі композиттен жасалған стандартты бұйымдардың беріктігіне әсері

Ғ. Әбілезова*, М. Исаметова, Р. Карпеков
Satbayev University, Алматы, Қазақстан
**Корреспонденция үшін автор: abilezova_gazel@mail.ru*

Аңдатпа. Мақалада 3D басып шығарудың технологиялық факторларының шыны толтырылған полимерлі композиттен жасалған стандартты өнімдердің беріктігіне әсерін зерттеу нәтижелері келтірілген. Үш факторлы эксперименттің матрицасы жасалды, онда экструдер басының температура параметрлері, қабаттың қалыңдығы және толтырылуы өзгермелі факторлар ретінде қабылданды. Эксперимент нәтижелеріне регрессиялық талдау жүргізілді, жауап беттері салынды. Математикалық өңдеу нәтижелері бойынша басып шығарылған өнімдердің беріктігіне әсер ететін фактор – қабаттың қалыңдығы анықталды. Композиттік үлгіні жырту кезіндегі максималды беріктік мәні параметрлерде басылған үлгіде болды: экструдер басының температурасы 2700, қабаттың қалыңдығы 0.3 және толтырылуы 100%, беріктік шегі мәні 81 МПа-ға жетті.

Негізгі сөздер: *3D басып шығару, аддитивті технологиялар, композициялық материалдар, беріктік, полимер және технологиялық факторлар.*

3D печати на прочность стандартных изделий из стеклонаполненного полимерного композита

Ғ. Әбілезова*, М. Исаметова, Р. Карпеков
Satbayev University, Алматы, Казахстан
**Автор для корреспонденции: abilezova_gazel@mail.ru*

Аннотация. В статье представлены результаты по исследованию влияния технологических факторов 3D печати на прочность стандартных изделий, из стеклонаполненного полимерного композита. Была составлена матрица трехфакторного эксперимента, где за факторы варьирования принимались параметры температуры экструдерной головки, толщина слоя и заполняемость. Был проведен регрессионный анализ результатов эксперимента, построены поверхности отклика. По результатам математической обработки выявлено что наиболее сильное на прочность напечатанных изделий из влияние оказывает фактор– толщина слоя. Максимальное значение прочности при разрыве композитного образца было в образце, напечатанном при параметрах: температура экструдерной головки 2700, толщина слоя 0.3 и заполняемость 100%, значение предела прочности достигло 81 МПа.

Ключевые слова: *3D-печать, аддитивные технологии, композитные материалы, прочность, полимер и технологические факторы.*

Received: 25 February 2024
Accepted: 15 June 2024
Available online: 30 June 2024