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DESIGN OF MACHINE FOR 3D PRINTING OF POLYETHYLENE TEREPHTHALATE GLYCOL COMPOSITES WITH CONTINUOUS CARBON FILAMENT FOR MANUFACTURE OF AEROSPACE PRODUCTS

At present time, technologies and materials, designed for 3D printing are of great interest. Due to lack of the well-known polymeric materials with high stress-strain properties the modern science and technology is targeted at strengthening of available polymers by filling them with carbon nanotubes, microspheres, discontinuous and continuous fibers, as well as 3D printing devices.

In order to create optimal solution for 3D printing by polyethylene terephthalate glycol composites with continuous carbon fiber an improved 3D printer design was proposed with revised design of extruder and modified components, which will allow to accomplish assigned task. Owing to new extruder design and use of materials, recommended in this scientific paper, one may obtain a carbon plastic with strength characteristics, which exceeds 3-3.7 times the characteristics of unfilled polymeric material. [dx.doi.org/10.29010/085.2]

Keywords: *3D printer; 3D print; composites; polyethyleneterephtalate glycol; carbon plastic.*

1. Introduction

State-of-the-art additive technologies for manufacture of products from polymeric composite materials (PCM) allow to automatize execution of manufacturing operations and significantly expand the list of components, made from PCM in aerospace technology. Among additive technologies, which have found application in serial manufacture of parts from PCM the following aspect has become most widely spread – automatic fiber positioning (for manufacture of nonrotational awkward-shaped parts), filament winding (for manufacture of parts in the form of rotation bodies) and 3D print (for manufacture of small-size nonloaded parts).

In recent years, improvement of materials for 3D print and 3D printer design allowed to manufacture products with higher strength, that, however, is not enough for aerospace products. As an example, for carbon plastic based on carbon fiber Tenax-E IMS65 (Toho Tenax, Japan) and epoxy polymeric matrix ЭДТ-69У (Compositservis, Ukraine) the elasticity modulus in tension is 140 GPa, whereas ONYX filament certified values, with discontinuous carbon fibers and ABS resin as polymeric matrix, produced by Mark Forged company, are 24 GPa [1], that does not allow to apply this material in components, which are under high load. Based on the sources [2, 3] it is known that there are designs for continuous carbon fiber 3D printing devices, using PLA resins, as a polymeric matrix. Unmodified carbon plastic, obtained in the work [2] has modulus of elasticity in tension 64 GPa. The work [3] presents modulus of elasticity in flexure, which was 30 GPa. Owing to printing head design feature the binder content in carbon plastic is 70-55% by volume.

Due to insufficient physical mechanical parameters of products, printed by 3D printer, using the filament with discontinuous fibers there is a need for search of solutions for printing by filament with continuous fibers.

The objective of the scientific paper is: selection of optimal solutions for building 3D printer by simulation melting method, using continuous carbon fiber as a filler and using polyethylene terephthalate glycol (PET-G) as polymeric matrix.

2. Design part

2.1. Recommended materials for 3D printing

2.1.1 PET-G polymeric matrix

PET-G resin is polyethylene terephthalate with added glycol (according to PET-G international designation). PET-G has high impact strength and does not crystallize when heated, has a low shrinkage coefficient, does not absorb moisture. The filament certified values [4] are shown in Table 1.

Table 1

PETG resin characteristics

Parameter	Units of measure	Value
Tensile elongation	%	228
Ultimate tensile strength	MPa	49
Flexural strength	MPa	68
Modulus of elasticity in tension	GPA	23.27
Izod impact strength	kJ/m^2	8
Density	g/cm^3	1.23

2.1.2. Carbon filler

Carbon yarn IMS 65 E23 24K 830 tex, produced by Toho Tenax, is recommended to be used as carbon filler. The yarn IMS 65 E23 24K 830 tex is compatible with thermoplastic binders, such as polyetherketone, polyethyleneterephthalate and polyamide. The rest of yarn certified values [5] are shown in Table 2.

Table 2

IMS 65 E23 24K 830 tex characteristics

Parameter	Units of measure	Value
Linear density	tex	830
Density	kg/m^3	1780
Ultimate tensile strength	MPa	6000
Modulus of elasticity in tension	GPa	290
Fiber diameter	мкм	5.0
Relative elongation	%	2.0

2.2. 3D printer structural schematic

3D printer structural schematic includes units as follows:

- computer – controls the device by means of dedicated software;

- controller – generates commands for drivers: step motors; filament and fiber feed roll motors; fiber and polymeric filament cutter drive;

- step motor driver – processes and transmits signals to step motors;

- filament and fiber feed roll motor driver – processes and transmits a signal to roll motors;

- fiber and polymeric filament cutter driver – processes and transmits a signal to fiber and polymeric filament cutting device;

- power-supply unit – serves as alternating-current source;

- heating element – heats the filament;

- forced cooling system – reduces the temperature at the inlet of extruder guide tube;

- voltage converter – converts 12 V to 5 V;

- step X motor – sets X carriage in motion;

- step Y motor – sets Y carriage in motion;

- step Z motor – sets Z carriage in motion;

- filament feed roll motor – sets filament feed rolls in motion;

- fiber feed roll motor – sets fiber feed rolls in motion;

- fiber and filament cutter drive – sets fiber and polymeric filament cutter drives in motion;

- 0X sensor – microswitch, locates initial point in X-coordinate;

- 0Y sensor – microswitch, locates initial point in Y-coordinate;

- 0Z sensor – microswitch, locates initial point in Z-coordinate.

2.3 Extruder design

3D printer extruder, designed for printing by continuous carbon fiber along direct and curvilinear trajectory, is shown in Figure 1. PET-G filament and carbon yarn are fed into extruder guide tube, where under the influence of temperature PET-G from glassy phase state turns into viscous flow state and mixes with carbon yarn. Forced cooling radiator is at the inlet of extruder guide tube (to ensure PET-G glassy state at the inlet of extruder). For uniform and unhindered extrusion of PET-G melt and carbon yarn it is proposed to use a conical nozzle with round die hole. During extrusion process, PET-G melt with carbon yarn sticks to the heated platform (table) surface for printing, ensuring in this way constant tension and feed of the carbon yarn. Owing to carbon filament and polymeric matrix cutting device, extruder allows to position PET-G melt and carbon yarn according to schematic, shown in Figure 2 that ensures lesser content of PET-G in resin (50-55% by volume) and increases physical and mechanical characteristics of end product.

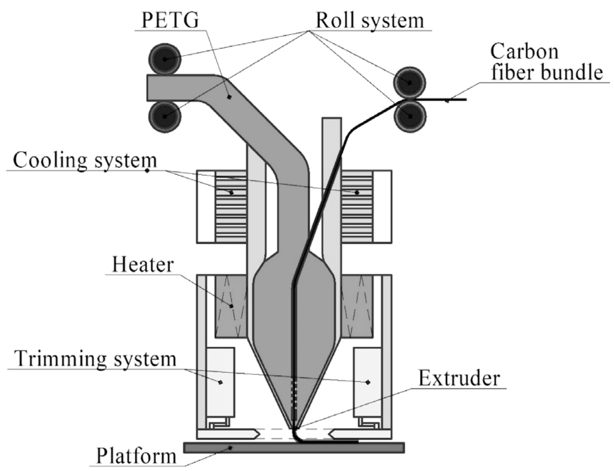

Fig. 1. Schematic of 3D printer extruder designed for printing by continuous carbon fiber along the direct and curvilinear trajectory

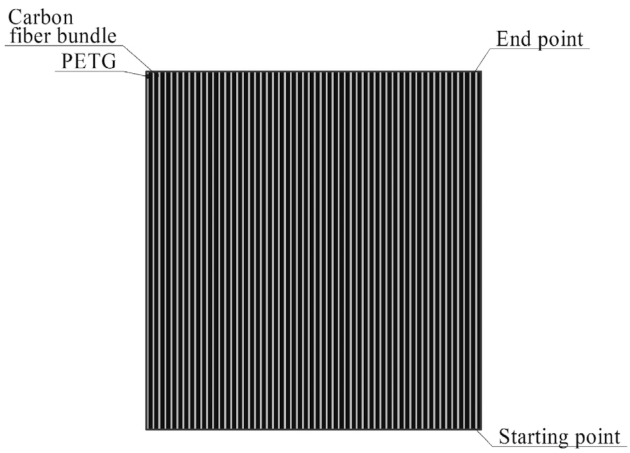

Fig. 2. Layout of carbon fiber and melt of PET-G resin

3. Theoretical calculations of the composite physical mechanical characteristics

PCM mechanical properties are defined by stress-strain properties of the filler and polymeric matrix, its correlation and bond strength at boundary line [6]. Having analyzed the data of Table 1 and Table 2 one may calculate theoretical values of ultimate tensile strength and modulus of tension in carbon plastic with one-directional reinforcing fiber, taking into account that polymeric matrix-to-filler relationship is 50:50 % by volume. The calculations are performed according to the formulas:

$$\sigma_{\text{теор}} = (\sigma_{\text{в}} V_{\text{в}}) + (\sigma_{\text{п}} V_{\text{п}}) \qquad (1)$$

$$\sigma_{\text{теор}} = \left(6000 \cdot \left(\frac{50}{100}\right)\right) + \left(49 \cdot \left(\frac{50}{100}\right)\right) = 3024{,}5,\ \text{MPa} \qquad (2)$$

$$E_{\text{теор}} = (E_{\text{в}} V_{\text{в}}) + (E_{\text{п}} V_{\text{п}}) \qquad (3)$$

$$E_{\text{теор}} = \left(290 \cdot \left(\frac{50}{100}\right)\right) + \left(23{,}27 \cdot \left(\frac{50}{100}\right)\right) = 156{,}635,\ \text{GPa} \qquad (4)$$

Where $\sigma_{\text{в}}$ and $E_{\text{в}}$ – ultimate tensile strength and modulus of elasticity in tension of fiber; $\sigma_{\text{п}}$ and $E_{\text{п}}$ – ultimate tensile strength and modulus of elasticity in tension of polymeric matrix; $V_{\text{в}}$ and $V_{\text{п}}$ volume content of fiber and polymeric matrix

Based on the source [7], it is known that theoretical calculations of ultimate tensile strength and modulus of elasticity in tension, as well as practical test results can be different by 45-55%. Based on the above, the values of composite stress-strain properties, given in Table 3, were predicted.

Table 3

Predicted values of the composite stress-strain properties

Parameter	Units of measure	Value
Ultimate tensile strength	MPa	1360.8-1663.2
Modulus of elasticity	GPa	70.5-86.15

4. Application areas of PET-G composites with continuous fiber

The obtained predicted material characteristics are indicative of its applicability in the following areas:

- for manufacture of launch vehicle spacecraft component elements;
- in the manufacture of civil, cargo and military aircrafts;
- printing of unmanned aerial vehicle components.

5. Conclusions

The research paper analyzes design of 3D printer, intended for printing PET-G by composite with continuous carbon fiber. As a result of design an optimal printing head configuration was presented, where carbon fiber is coated with binder melt. The printing head combines classical 3D printer and the device for making filled polymeric filaments, whereby it makes the cost of end product cheaper. Owing to polymeric filament cutting device, integrated into printing head and optimum configuration of extruder die an expected binder content in carbon plastic is achieved and is 50%.

The research paper also discusses theoretical calculations of the composite predicted stress-strain properties. Elasticity modulus of PET-G composite with continuous filament is 3-3.7 times higher than in PETG resin, and ABS resin, filled with discontinuous fibers, 1.1-1.3 times higher than in PLA resin, filled with continuous fiber and 0.5-0.4 times lesser than in carbon plastic with epoxy binder.

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ПРОЕКТ УСТРОЙСТВА ДЛЯ 3D-ПЕЧАТИ ПОЛИЭТИЛЕНТЕРЕФТАЛАТГЛИКОЛЕВЫХ КОМПОЗИТОВ С НЕПРЕРЫВНЫМ УГЛЕРОДНЫМ ВОЛОКНОМ ДЛЯ ИЗГОТОВЛЕНИЯ ИЗДЕЛИЙ АВИАКОСМИЧЕСКОГО НАЗНАЧЕНИЯ

В настоящее время большой интерес вызывают технологии и материалы, предназначенные для трехмерной печати. В связи с отсутствием известных полимерных материалов с высокими упругопрочностных характеристиками современная наука и техника нацелена на упрочнение имеющихся полимеров путем наполнения их углеродными нанотрубками, микросферами, дискретными волокнами и непрерывными волокнами, так же устройствами для трехмерной печати.

С целью создания оптимального решения для 3D-печати полиэтилентерефталатгликолевыми композитами с непрерывным углеродным волокном предложена усовершенствованная конструкция 3D-принтера с измененной конструкцией экструдера и доработанными узлами, которые позволят достичь возложенной задачи. Благодаря новой конструкции экструдера и использованию рекомендуемых в данной статье материалов возможно получить углепластик с прочностными характеристиками, которые превышают характеристики ненаполненного полимерного материала в 3-3,7 раза. [dx.doi.org/10.29010/085.2]

<u>Ключевые слова:</u> *3D-принтер; 3D-печать; композиты; полиэтилентерефталатгликоль; углепластик.*

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