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3D-printed polyether ether ketone samples mechanical properties estimation

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Abstract
This paper is dedicated to study of mechanical characteristics (tensile limit, elasticity modulus and relative elongation) of samples made of polyether ether ketone by additive method FDM (FFF). The paper includes results of mechanical tests on tension of sample party and comparison to results of other authors. Conclusions on reasons of the results obtained are made.

Introduction

Modern trends of technical development show growing usage of new materials having high specific strength properties and unique technological properties [1-5]. One of such materials is high temperature structural polymer polyether ether ketone (PEEK), which has gained widespread use in different manufacturing industries due to its unique set of properties [6-10]. Chemical structure of this polymer consists of phenylene rings connected in-series with ester and carbonyl groups by pair bonds and provides high strength and flexibility of a material, and retaining these properties during heating up to remarkably high temperature (about 300 °C). Among other issues the material is flame resistant and gives few smoke and toxic substances while burning. In spite of high cost, this set of properties makes PEEK a high demand material for aircraft, machine, instrument and other industries. PEEK is used for manufacturing of sealing washers, bearings, sensors bodies, coils and other details contacting fuel, lubricant and cooling fluids.

Polyether ether ketone is a thermoplastic polymer, and it makes it possible to use PEEK in a FDM (FFF) 3D-printing, which is based on depositing of polymer material layer by layer in accordance to advance prepared program. Usage of additive technologies for details manufacturing allows to reduce their cost while piece or low volume production; in comparison to CNC milling resulting in 90% of initial material becoming metal chips, 3D-printing allows to cut expenses on raw materials. Obvious advantages of 3D-printing as a method of details manufacturing make processing of polyether ether ketone by FDM (FFF) methods a subject of researchers focus in recent years [11-15].

In spite of the benefits, details manufacturing by FDM (FFF) methods has a number of shortcomings, one of which is degradation of mechanical characteristics of 3D-printed components in comparison to components manufactured by traditional methods (casting and extrusion). The purpose of this paper is estimation of mechanical properties of samples made of polyether ether ketone by 3D-printing.

Materials and methods

Tension testing is the most universal among other kinds of testing, because allow to define mechanical properties of a material on each stage of its deformation (from elastic deformation to destruction). In this paper mechanical characteristics of the material at tension are defined according to the standard ASTM D638-14 “Standard Test Method for Tensile Properties of Plastics”. Sample of type 4 (fig. 1) was chosen for testing as recommended by the standard as suitable for estimation of properties of materials of different nature during comparative tests. Samples testing were carried out on electromechanical universal tensile testing machine TIME WDW-50E equipped with longitudinal deformation sensor.

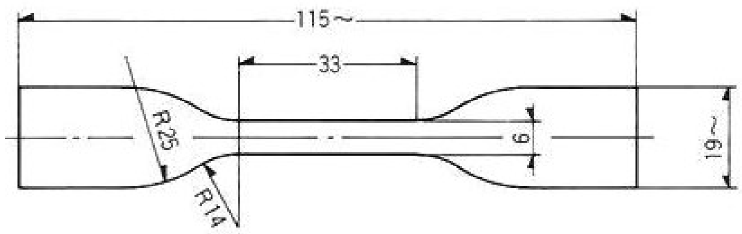

Figure 1. Sample of type 4 by standard ASTM D638-14, thickness is 4 mm

Subject of the research is 3D-printing filament made of granules Victrex® PEEK 381G manufactured by Russian-based company U3Print. Samples of this material were manufactured by FDM (FFF) method on high temperature 3D-printer TotalZAnyForm 950 PRO HOT+ at modes shown in table 1.Printing was implemented on polycarbonate list of 0.8mm thickness with the use of vacuum table and 20 minutes long preliminary heating of the camera. Geometry of laying of the layers is as follows: periphery walls of one-layer thickness along the whole perimeter of the sample, 100% inner filling, laying of layers at angles of 45°, -45°.

Table 1. Printing modes parameters for samples tension testing

Parameter	Value
Polymer type	PEEK
Extruder bore diameter	0.7 mm
Layer height	0.25 mm
Layer thickness	0.75 mm
Supply coefficient	100
Extruder temperature	450 °C
Camera temperature	290 °C
Printing speed	40 mm/c

Results and discussion

Tensile testing results for a party of 3 samples of the material under research are shown in table 2. As it can be concluded from testing results scattering of obtained values of tensile limit and elasticity modulus is not high and only 10% of average value. Relative elongation is varied more widely – from 3.0 to 5.5 %. Average value of tensile limit is about 67 MPa, while elasticity modulus – about 3.2 GPa.

Table 2. Mechanical properties of samples according to testing results

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№ образца	Tensile limit (σ_B), MPa	Elasticity modulus (E), GPa	Relative elongation (δ), %
1	68.0	3.2143	3.0
2	64.7	3.4354	3.4
3	68.0	3.1428	5.5
Average value	66.9	3.2641	3.96

Figure 2 shows machine diagram of tension of sample №1 having a form typical for all three tested samples. As it can be seen on the figure, yield plateau is absent on the diagram, what allows to make a conclusion about brittle destruction of samples. This conclusion corresponds to the data on relative elongation which is not high and is about 4% on average.

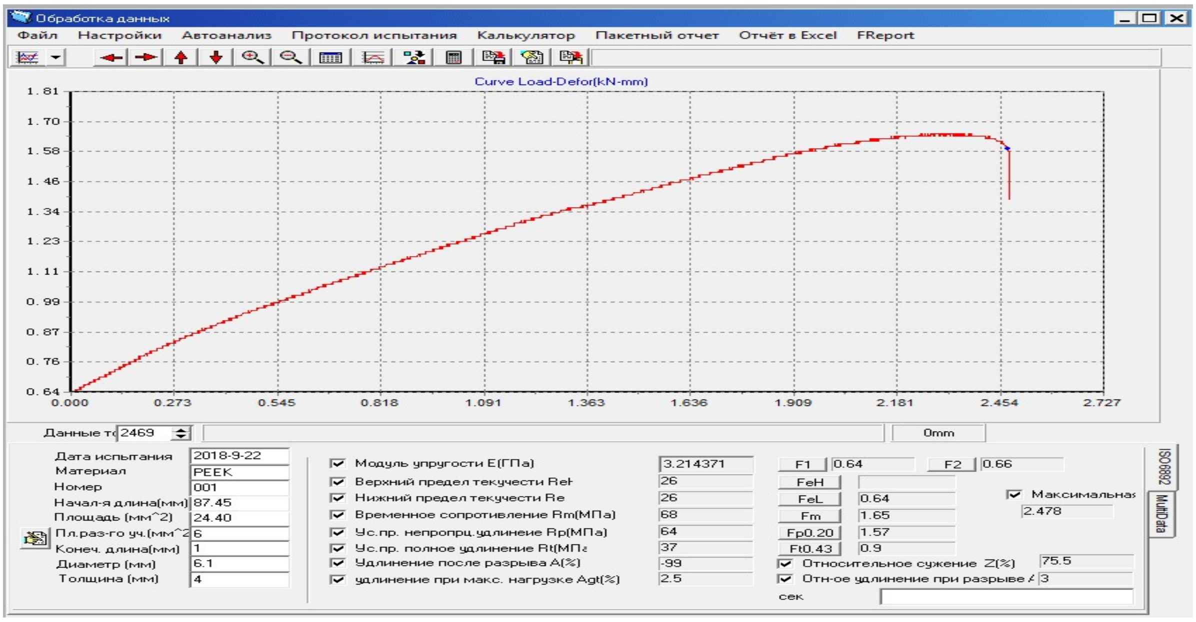

Figure 2. Machine diagram of tension of sample №1 in coordinates of kN-mm

Obtained experimental results were compared to data from different sources (table 3). It can be seen that tensile limit of samples obtained in this paper is 1.3 times lower than PEEK samples manufactured by pressure casting. Values of relative elongation is one order lower (4% in opposite to 34%).Degradation of strength properties of 3D-printed sample is caused by usage of FDM (FFF) technology, which produces samples consisting of layers having low adhesion relative to each other. Interlayer adhesion can be regulated in certain limits by speed of extruder and thickness of layers: those parameters influence spreading speed of heat from bore to material and, consequently, adhesion of layers. It appears that authors of papers [17] and [18] managed to find printing modes providing better interlayer adhesion of the tested material, at which point experimental data obtained in those papers are closer to characteristics of cast sample than those obtained in this paper. On the contrary, authors of papers [19] and [20] don't show corresponding parameters of printing modes, which causes mechanical characteristics of samples to be remarkably different from those of cast samples.

Table 3. Mechanical properties of samples made of PEEK according to different sources

	Manufacturing method and sample properties						
	Current experiment	Pressure casting[16]	FDM (FFF), filling 100%, laying of layers $+45^0/-45^0$ [17]	FDM (FFF), filling 100%, laying of layers 0^0 [18]	FDM (FFF), filling 100%, laying of layers 90^0 [18]	FDM (FFF), filling 100%, laying of layers $+45^0/-45^0$ [19]	FDM (FFF), filling 60 % [20]
Tensile limit (σ_B), MPa	66.9	100.0	98.9	82.6	72.9	~50	39.1
Elasticity modulus (E), GPa	3.2	3.7	3.9	3.8	3.5	~3	0.5
Relative elongation (δ), %	4.0	34.0	~50	110.0	2.9	~2-3	10.4

Conclusions

Therefore, polyether ether ketone as kind of aromatic polyarylene ether ketones are important polymeric material in applications, and different spheres of manufacturing industry show growing interest in it every year. Conducted research showed that strength of samples manufactured by FDM (FFF) 3D-printing technology is about 1.3 times lower than cast samples strength, what most likely caused by specificity of the technology involving creating details layer by layer. However, literature sources analysis showed existence of possibility of sample printing modes correction tending to improve their mechanical properties. Further it is planned to conduct research involving different sorts of polymers of polyetether ether ketone for 3D-printing.

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