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Impact of additive manufacturing temperature on strength of 3D printouts made of PLA and ABS

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Abstract:

The 3D printing technology is an example of innovative approach to the manufacturing technology. It finds further application fields, due to the rapid development of printers and the materials to be used. The article presents and describes the currently used additive manufacturing technologies called 3D printing, the materials used and the results of tensile strength tests of PLA and ABS prints. The process of preparing objects for 3D printing is presented and the testing methodology is described. Conclusions are formulated regarding the impact of printing nozzle temperature on the objects tensile strength. Standardized samples printed from ABS and PLA were tested. The summary also presents the possibilities of using objects made by 3D printing in practice.

Streszczenie:

Technika druku 3D jest przykładem innowacyjnego podejścia do zagadnień technologii wytwarzania. Znajduje ona kolejne obszary zastosowań, co jest możliwe dzięki szybkiemu rozwojowi drukarek oraz stosowanych materiałów. W artykule przedstawiono i opisano obecnie stosowane technologie druku przestrzennego potocznie określanego jako druk 3D, wykorzystywane materiały oraz wyniki badań wytrzymałości wydruków z PLA i ABS na rozciąganie. Zaprezentowano proces przygotowania elementów w technologii druku 3D oraz opisano sposób przeprowadzenia badania. Sformułowano wnioski odnośnie wpływu temperatury dyszy drukującej na wytrzymałość elementów na rozciąganie. Badania przeprowadzono na znormalizowanych próbkach wydrukowanych z ABS oraz PLA. W podsumowaniu przedstawiono również możliwości zastosowania obiektów wykonanych metodą druku przestrzennego w praktyce.

1. Introduction

Additive manufacturing technology, called 3D printing, is the process of creation of 3D objects, where 3D printers can be used. Their principle of operation is similar to operation of commonly used numerically controlled machine tools as their kinematic chains are of similar design. Additive manufacturing technology, in large simplification, consists in application of subsequent material layers into which the virtual model of the required part was previously divided [1, 2].

The beginnings of 3D printing back to the 1980s, but the dynamic development of this technology, caused by increased availability and reduced costs of materials and devices, is being observed now. 3D printing was first used by Charles Hull, who introduced the 3D printer developed in 1984, while in 1986 he obtained a patent. The 3Dprinter developed by Charles Hull used SLA technology for printing. SLA is the colloquial name of stereolithography, one of the technologies of 3D printing that uses a laser beam to locally harden the material (usually in the form of a special resin).

Development by Scott Crump a device for printing the objects in Fused Deposition Modelling (FDM) technology in 1988 was another breakthrough in 3D printing. FDM is recommended for melting thermoplastics, which are then applied to the 3D printer platform layer by layer. FDM technology is the most popular nowadays, mainly due to the fact that low-cost devices can be used.

Today, 3D printing is a technology for manufacturing not only plastic object. This process is realized by precise application and subsequent sintering or hardening of various materials. At present, it is possible to print not only using inorganic materials such as polymers, metals, wood-like materials, ceramics, concrete and resin, but also applying live tissues, i.e. stem cells, have been developed. It will allow, for example, to print the ear, and in the future, perhaps even entire human organs. Unfortunately, due to the complex structure of human organs, the vision of their printing remains distant [4, 5, 6, 7, 8].

Manufacturing of objects from inorganic materials is the basis of 3D printing. 3D printing is a very universal technology used in many industries. It is possible to make objects such as engine components, casting moulds, parts for airplanes and cars, but also the objects used in everyday life, e.g. decorative elements, gadgets, game figurines or even a functional coffee mug. This is due to the continuous development of this technology and the increasing number of types of materials used in this process [2, 3, 5, 6].

However, this technology is not suitable for mass production, because compared to injection moulds it is more time-consuming and therefore the cost of producing a single object is higher. 3D printing is used in applications, where there is a need to make individual unique component. Currently, the industry uses 3D printers to make prototypes, mock-ups, prostheses. With the development of 3D printing technology, it is possible to apply this technology in the mining industry. Due to the individual character of each machine used in underground mines, the 3D printing technology is ideal for making, for example, enclosures for intrinsically safe electronic equipment. At the KOMAG Institute, the 3D printing technology has been implemented comprehensively for manufacturing prototypes of mining machines and equipment which are tested then. Selection and purchase of components for 3D printers took place in parallel with the development of knowledge resources enabling the training of all participants in the 3D printing process. Training materials describing the possibilities of available 3D printers, guidelines describing the requirements for the preparation of 3D models for the printing process, potential problems and examples of applications from various fields are compiled in the form of an e-learning course prepared by experts from KOMAG [9, 10, 11, 12].

2. 3D printing technologies [2, 3]

These devices are used within the following technologies:

- FDM (FFF) – based on application of layer by layer of molten material.
- DLP – using the DLP projector for light-curing of resins.
- SLA – involving a laser beam to harden the photopolymer.
- SLM (DMLS) – a method consisting in printing metal components by local action of a laser beam on a metal powder.
- CJP - technology that uses gypsum powder to print objects, the method enables multi-colour printing.
- SLS – technology in which the objects are produced by sintering polymer powder using the laser beam.

2.1. Fused Deposition Modelling

FDM (Fused Deposition Modelling) or FFF (Fused Filament Fabrication) are the most commonly used 3D printing technologies. They consists in printing the objects by applying a molten thermoplastic, e.g. ABS, PET, PLA, HIPS layer by layer (Fig. 1). In this method, it is possible to use elastomers, e.g. TPU or TPE, to make not only hard objects but also flexible ones. The material is fed in the form of a filament, i.e. a line wound on an extruder spool. Then the material is heated and pressed through a nozzle of a diameter 0.3 mm to 0.8 mm. The melted filament in the form of a path of a thickness 0.05 to 0.4 mm is applied to the 3D printer table path by path and layer by layer until the entire object is printed (Fig. 2) [2, 9, 13].

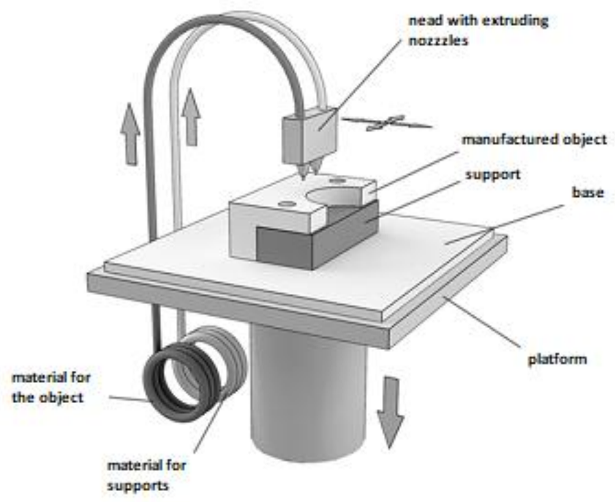

Fig. 1. Schematic diagram of FDM technology [2]

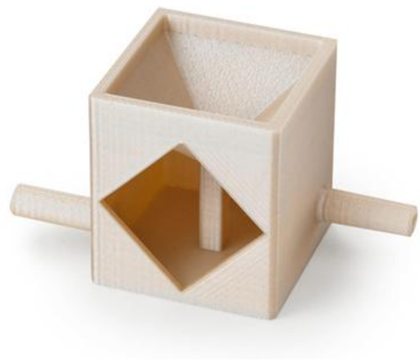

Fig. 2. Object manufacture in FDM technology [2]

3. Materials used in 3D printing technology

In different 3D printing technologies, different printing materials are used. A list of the most popular materials with a short description is presented in Table 1.

Table 1. Materials used in 3D printing [3, 5, 14]

Technology	Material	Description
FDM/FFF	PLA (Polylactide)	Used for large-size prints, it is characterized by low shrinkage after printing, it is possible to contact the objects with food.
	ABS (thermoplastic polymer acrylonitrile butadiene styrene)	Used in manufacturing the majority of prototypes
	Elastomers	Rubber-like materials used to print imitations of rubber objects, characterized by high flexibility.
	Nylon (Polyamide)	The material is popularly used in industry. It is characterized by high temperature and mechanical resistance. It also shows resistance to most chemicals.
	PET-G	Used for the production of, among others, bottles in the food industry. A material with high mechanical strength and resistance to grease and oils.
	SKU GRPHN-175	Conductive graphene filament for printing electrically conductive components. The filament can be used for EMI/RF shielding, capacitive sensors and enclosures for intrinsically safe equipment in the mining industry.
DLP	MakerJuice SF	Intended for manufacture of large-size objects
	MakerJuice G+	Material of higher mechanical strength.
	B9R-1	Resign for manufacturing precise components enabling melting after printing
SLS	DuraForm ProX	Strong and durable plastic, used for engineering applications, characterized by high mechanical strength. Powder made on the basis of PA12.

	PA 12 (polyamide PA12)	The material was created by pulverizing PA12 polyamide, used to make structural components and tools. Used in the automotive and aviation industries. Allows tinting in any colour.
SLM	Stainless steel	EU 1.4542 X5CrNiCuNb16-4 steel – Used for manufacture of machines components
	Martensitic steel	EU 1.2709 X3NiCoMoTi 18-9-5 steel – Often used in the aviation industry. Enables printing the components such as gears, pressure moulds and components of pressing machines.

ABS and PLA are the most popular materials used in FDM printing. ABS is a plastic material of a density 1.05 g / cm^3. Printouts made of ABS are characterized by high hardness, which makes them scratch-resistant. The material has good insulating properties and has a satisfactory resistance to fats, oils, greases and diluted acids. The disadvantage of ABS is its low resistance to acids and UV radiation. ABS objects are printed by melting the material at a temperature of 230^{o}C-270^{o}C at the temperature of the 3D printer table in the range of 40^{o}C - 80^{o}C [3, 5].

PLA (polylactic acid) is a thermoplastic and biodegradable polyester, made from renewable raw materials. Sugar beet or corn is most commonly used for the production of PLA. Production of 1 kg of PLA uses approx. 2.5 kg of corn kernels of a moisture content approx. 15%. Time of PLA decomposition, ranging from several months to several years is its advantage. For this reason, it is possible to use the components made of PLA in medicine for example. The material has very good organoleptic properties and objects made of PLA may come into contact with food. PLA requires a lower temperature of the printing head in the range of 190^{o}C-220^{o}C. Slight and almost imperceptible shrinkage is the PLA advantage. PLA is a material much easier for 3D printing than ABS [3, 5].

4. Testing the strength of samples made of PLA and ABS

Number of profiles (samples) were made to analyse the strength of 3D printout. The shape and individual dimensions comply with the EN ISO 527-1:2012- Plastics - Determination of tensile properties - Part 1: General principles [15]. The graphic model of the sample was made in accordance with the above-mentioned standard in the Autodesk Inventor program. Then the 3D model was exported to the .stl format, which is necessary to create a file with instructions for the 3D printer. In the next step, the printing instructions were entered to the Anet A8 device. During one printout, 3 samples were made, and each printout was done with a different printing head temperature. PLA samples were printed with head temperatures of 190^{o}C, 195^{o}C, 200^{o}C, 205^{o}C and 210^{o}C at the printing table temperature of 55^{o}C, while ABS samples with temperatures of 230^{o}C, 235^{o}C, 240^{o}C, 245^{o}C and 250^{o}C at a table temperature of 110^{o}C. The main parameters are presented in the Table 2.

Table 2. Basic parameters of 3D printing [15]

Layer height	Wall thickness	Thickness of bottom/top	Infill	Printing rate	Filament diameter
0.2 mm	1 mm	1 mm	50%	60 mm/s	1.75

Where:

- Layer height - parameter specifying the height of a single layer applied by the device,
- Wall thickness - parameter defining the thickness of printout walls that are exposed outside the model,
- Thickness of bottom/top - parameter specifying the thickness of the walls printed directly on the heatbed (bottom) and thickness of the parts that are exposed to the outside of the model, facing up towards the nozzle (top),
- Infill - parameter defining the degree of filling the internal structure of the 3d print,
- Printing rate - parameter defining the speed of movement of heatbed and the printing nozzle-parameter defining speed of movement of the heatbed and printing nozzle,

- Filament diameter - parameter describing the diameter of material used in the form of a filament.

The 60% filling value was selected because during the strength tests of 3D printed samples with different filling, it was shown that there was no significant difference in the strength of samples with 30% -70% filling [4].

Fig. 3 shows a 3D printing station consisting of a 3D printer and a PC. The Anet A8 printer does not require a direct connection to the computer during printing. The use of a PC makes it much easier to supervise the correctness and parameters of 3d prints. Fig. 4 shows ready-made 3D prints. Black samples were made of ABS, while pink ones were made of PLA. In order to identify the samples, they were individually described and sorted according to the material and printing temperature

Fig. 3. Stand for 3D printing [3]

Fig. 4. The printed objects [3]

The tensile strength of the materials was tested in the static tensile test. This test is based on the axial stretching of a standard sample with a constant rate until it breaks. The test should take place at room temperature, i.e. about 25°C. The tested sample (profile), was made in accordance with the relevant standards. The test was carried out on a tensile testing machine called a ripper which during the test recorded the correlation between the tensile force and increase in the sample length. The ripper used for the static tensile test is constructed on the basis of a modified hydraulic system with a double-acting cylinder (Fig.5).

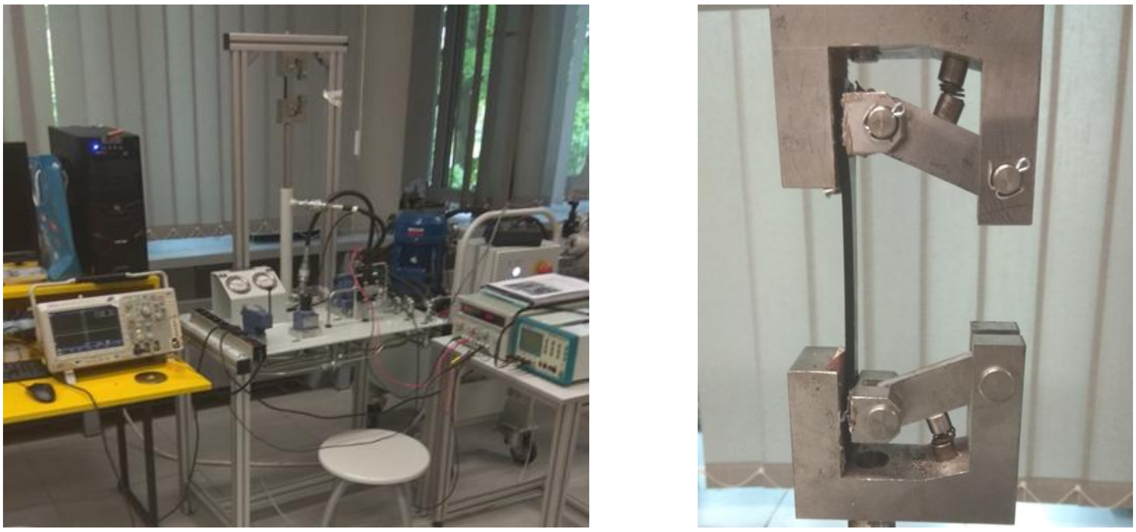

Fig. 5. Laboratory test stand of the ripper [3]

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The method consists in indirect pressure measurement in the chamber using PT5402 sensor.

The hydro-electric transducer converts the pressure in the range 0-100 bar into the current in the range 4-20 mA. A 330 Ω resistor was plugged into the measuring circuit, so it was possible to measure the voltage drop across this element by an oscilloscope. Then, each of the printed object underwent the static tensile test. The direction of the tensile force during the static tensile test was parallel to the layers of the printed objects.

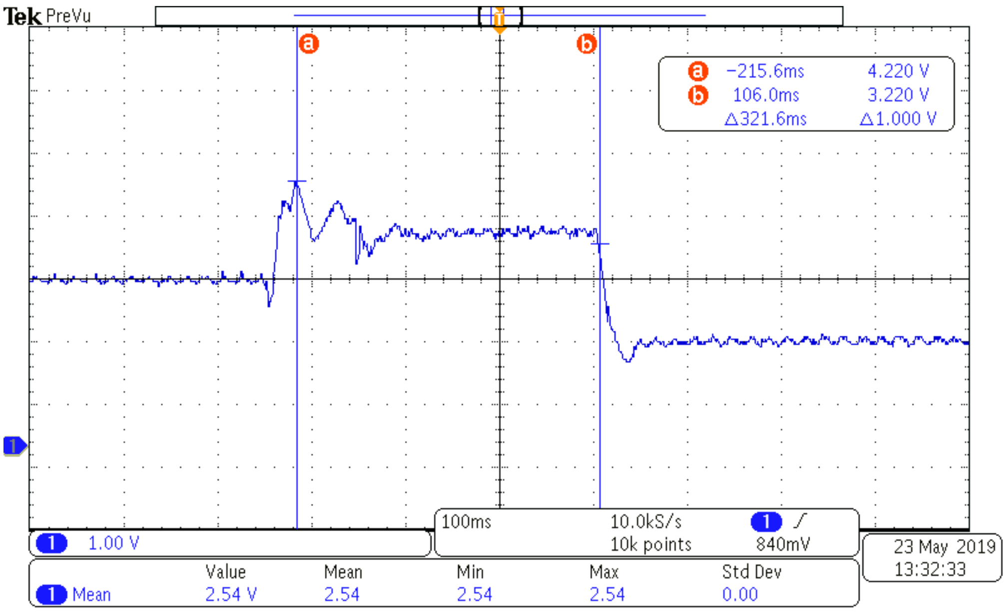

Fig. 6. Oscilloscope displays during testing sample no.2 made with ABS printed with the nozzle temperature 200°C [3]

Then the recorded electrical parameters were converted into force values. The transformations were made using the formula (1).

$$F = \frac{(U - 1{,}32) \cdot 10^5}{0{,}0528} \cdot S \tag{1}$$

where:

F – force during the tensile static test, N

U – voltage drop across the resistor, V

S – surface area of the piston (424,1mm2 $=0{,}4241 \cdot 10^{-3} m^2$)

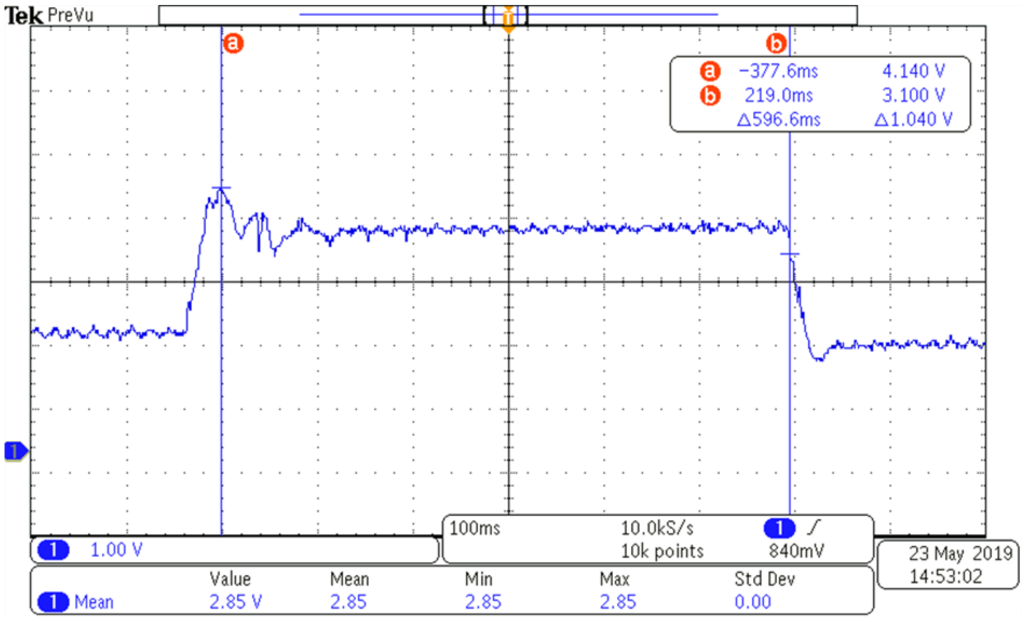

Fig. 7. Oscilloscope displays during testing sample no.2 made with ABS printed with the nozzle temperature 240°C [3]

During the static tensile test, the following waveforms were obtained, shown in the oscillograms Fig.6 and Fig.7. The waveforms shown are typical for hard and durable plastics. On the basis of the obtained results, individual force values were calculated using the formula (1). The values of the forces are presented in Table 3.

Table 3. Results from testing the ABS and PLA samples [3]

Material	**Temp.** [°C]	$F_{0.2}$ **[N]**	F_M **[N]**	**Material**	**Temp** [°C]	$F_{0.2}$ **[N]**	F_M **[N]**
PLA	190	2318.08	1622.12	ABS	230	2350.20	1611.41
	195	2478.69	1536.46		235	2243.13	1643.54
	200	2339.49	1461.52		240	2275.25	1482.93
	205	2393.03	1525.76		245	2221.72	1568.59
	210	2285.96	1632.83		250	2296.67	1670.30

$F_{0.2}$ – the force generating permanent deformation equal to 0.2% of initial length of a profile
F_M – the highest force recorded in the sample after exceeding the yielding point. [16]

Then, based on the obtained results, the tensile strength of the objects was calculated according to the formula (2).

$$R_M = \frac{F_M}{S_0} \tag{2}$$

where:
R_M – tensile strength, MPa
F_M – maximum force during the tensile static test, N
S_0 – the sample cross-section surface area before test, mm^2 [9,17]

The results are presented in Table 4.

Table 4. Results of tensile strength for ABS and PLA [3]

Material	Temp. [^{o}C]	R_M [MPa]	Material	Temp [^{o}C]	R_M [MPa]
PLA	190	39.37	ABS	230	41.21
	195	36.49		235	41.37
	200	37.82		240	37.09
	205	38.48		245	39.79
	210	41.45		250	41.77

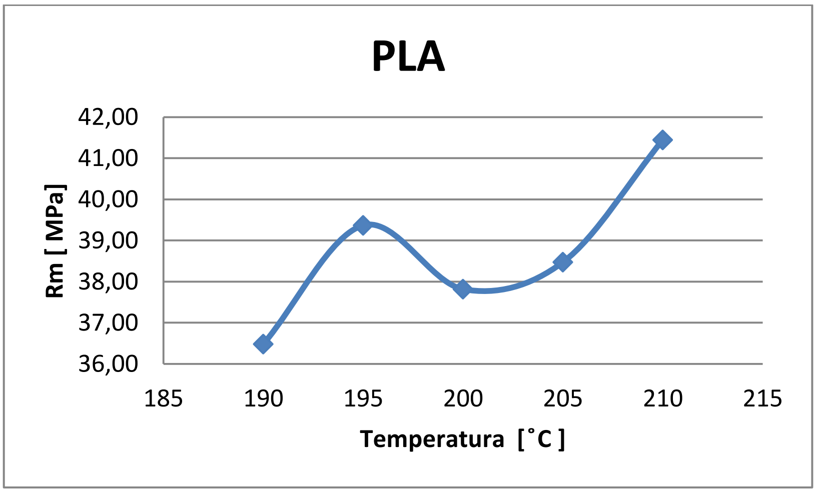

Fig. 8. Relationship between tensile strength and temperature of 3D printing for PLA samples [3]

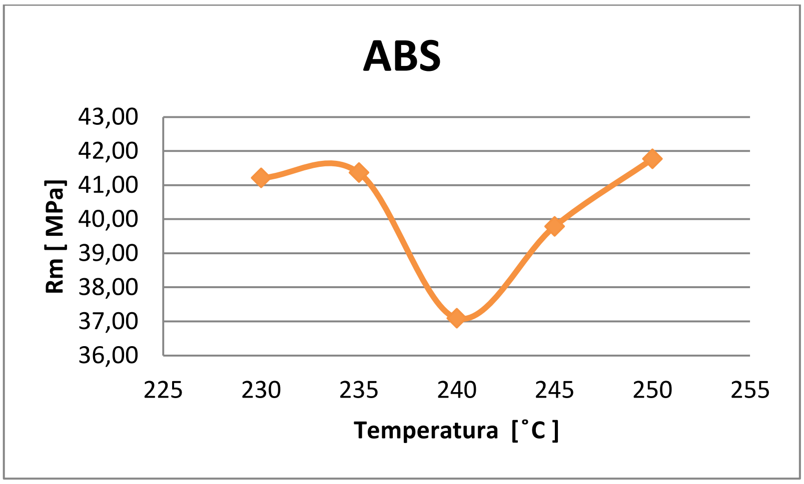

Fig. 9. Relationship between tensile strength and temperature of 3D printing for ABS samples [3]

The highest tensile strength in the case of PLA elements was 41.45 MPa, obtained for the printing temperature of 210^{o}C (Fig. 8), while in the case of ABS samples it was 41.77 MPa printed at 250^{o}C (Fig. 9). Tests have confirmed that ABS is the more durable material. The highest value of stresses in both cases was measured for samples printed with the highest temperatures in the tested compartments.

5. Conclusions

The 3D printing technology enables the production of elements from many types of materials. Due to the rapid development of this method, it is possible to obtain better and better results of quality and durability. Another advantage of 3D printing is the ability to make the objects that cannot be made with other technologies. The disadvantage of this technology is the speed of making 3D printouts, so this method is not suitable for the production of a large number of components. 3D printing is used mainly in the production of prototypes and low number of components. The increasing popularity of this technology is related to the availability of low-cost 3D printers, thanks to which 3D printing is available to a large number of users. [5, 18, 19]

Static tensile test of the manufactured objects enabled determining their tensile strength and the yield point. The objects made of ABS had much better tensile strength than objects made of PLA. The highest tensile strength was obtained for ABS equal to 41.77 MPa for samples printed at 250oC, while for PLA fittings it was 41.45 MPa for samples printed at a temperature of 210oC. The lowest strength was obtained for PLA samples printed at 195oC - 36.49 MPa, while for ABS samples printed at 235oC it was 37.09 MPa.

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