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Influence of 3D Printing Parameters by FDM Method on the Mechanical Properties of Manufactured Parts

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ABSTRACT

The manufacturing of machine parts with additive methods (AM) is of significant importance in modern industry. The development of 3D printers and all 3D printing technology is impressive. The ability to make parts quickly and relatively cheaply with AM gives excellent opportunities in terms of e.g., shortening the production preparation time. Proper selection of printing parameters allows for a significant reduction of printing time and production costs. Unfortunately, this has different consequences. Due to the course of the printing process and the parameters that can be set, the same product produced with different parameters has different mechanical properties – mainly different strength. This paper presents the impact of 3D printing parameters on the strength of manufactured parts. Strength tests were carried out on samples made in accordance with DIN EN ISO 527-1:2019. The samples were printed in technology FDM from three different materials, i.e. PLA (completely biodegradable), PETG (recycled material) and Smart ABS (material with minimal shrinkage). The tested samples were made in three levels of print filling – 10, 30 and 60% and with different types of filling – line, mesh and honeycomb. A series of static tensile tests were carried out to determine the strength of the samples produced with different printing parameters. Thanks to the obtained test results, it is possible to select the optimal printing parameters depending on the forecast load of the manufactured parts.

Keywords: 3D printing, line, honeycomb, PLA, ABS, PETG, 3D printing strength, additive methods.

INTRODUCTION

From the beginning of the existence of human civilization, man strove to simplify everyday activities as much as possible. The motives could be different, as the proverb says: "Necessity is the mother of invention". Often you can also come across a similar and quite funny term, replacing the word "need" with "laziness". While creating new inventions, Homo sapiens often needed to create new tools. More durable, more precise with a more complicated shape [1, 2]. At some stage in human history and development, the burden of production was shifted onto computers. Precisely programmed systems that control complex apparatus, making movements so precise and fast that the production of products in this way has become more attractive and more profitable. Machines controlled in this way are now called CNC machines (Computerized Numerical Control). Constructed by Joseph Marie Jacquemart in 1805, the tying machine became the basis for the future automation of production in many industries, as well as part of the industrial revolution [1, 3, 4].

CNC machines are an unprecedented human achievement that enabled the development of technology, which is now known as "3D printing" or "additive manufacturing" (AM). Launched at the end of the 20th century, it made it possible to produce models with complex shapes in a short time and at low cost. Initially used for prototyping, in recent years it has gained considerable popularity in the industry for making finished products. The rapid development of 3D printing technologies, partly due to the expiration of patents related to it, has resulted in a significant reduction in the cost of the machines themselves, now called "3D printers". This decrease is so large that 3D printing, mainly using the material extrusion method called FDM / FFF (Fused Deposition Modeling / Fused Filament Fabrication), has also become affordable on the consumer market [5–7]. The ever-growing popularity of the field of 3D printing in the industry requires rethinking the entire production process. Starting from new design tools, developing better and better materials, ending with qualified personnel [8–10].

Despite such difficulties and the need for large changes, the report of the analytical company Wohlers' Associates predicts that the global 3D printing market will reach a value of USD 15.8 billion in 2020, thus forecasting an increase in this value to USD 35.6 billion in 2024 [11].

Each branch of industry uses different materials with strictly defined properties. Materials used in traditional manufacturing methods are seldom used in additive manufacturing methods. This makes it necessary to develop new material solutions. As a result, the value of the 3D printing materials market alone is forecast at USD 5.78 billion in 2026 [11, 12].

No material is perfect, so it is very important to select the appropriate material properties before starting the production process. The ability to interfere with the internal structure of 3D printed models (e.g., filling density, print structure) makes it difficult to clearly define the strength properties of the final product. This gives great opportunities to test the strength of 3D printed models.

3D printing is primarily generation methods, building a given element using layers of material stacked on top of each other. The orientation of the parts in relation to the base of the device affects the printing direction of individual layers. Changing the angle of the model arrangement changes the orientation of the layers that will make up the finished part. This, in turn, can lead to a change in certain strength properties of the finished product. 3D printing (AM) means a process that includes creating a real, three-dimensional object from a prepared 3D-CAD model [2,13].

Many 3D printing methods may differ in the way the material is applied, or in the type of material used to complete the printing. Despite this, the 3D printing process can be simplified to four basic steps:

- preparation of a three-dimensional model to be produced (CAD software, 3D scan, artistic programs, e.g. Blender);
- file conversion to the format used in 3D printing – STL;
- proper 3D printing process;
- post-processing, e.g. removal of supports, grinding of imperfections, etc.

Since 1984, many different methods of 3D printing have been developed. Some of them use the same material hardening process others use different materials. Table 1 shows the division of additive manufacturing (AM) methods due to the process that takes place in the 3D printer and the basic materials used in a given method.

The paper presents the results of strength tests of standardized samples made of thermoplastic polymers popular in the FDM technique. The modern use of 3D printers covers almost all industries. From its beginnings, when only the capabilities of the technology were tested in Rapid Prototyping or Reverse Engineering, to the modern industrial application of products manufactured using the additive method (e.g. Rapid Tooling). Over time, however, despite the fact that in 2018 prototyping accounted for almost half of the share in the global 3D printing market, the production of final parts or entire devices amounted to over 37% of the global market. Market predictions indicate that over time, the production of functional parts using additive techniques will constitute an increasing share of the 3D printing market [2, 5, 14]. 3D printing products can successively create an important place in modern industry. 3D prints are used in the aviation, machinery, automotive and even medical industries. It is in the medical industry that 3D printing technology covers newer and newer areas. There are already known applications in dentistry for the production of personalized dental models as well as preoperative and intraoperative measures (orthopedics, jaw surgery, etc.) [12, 13, 15].

Table 1. 3D Technologies [1, 15–19]

Process	Technology	Materials
Light polymerization	Stereolithography (SLA)	Photopolymers
	Digital light processing (DLP)	
Extrusion	Fused deposition modeling (FDM) Fused filament fabrication (FFF)	Thermoplastics, low melting point metals, food materials etc.
	Robocasting or direct ink writing (DIW)	Ceramic materials, metal alloys, ceramic-metal mixtures, ceramic composites, metal composites
Powder bed	Selective laser sintering (SLS)	Thermoplastics, metal and ceramic powders
	Selective heat sintering (SHS)	Thermoplastic powders
	Selective laser melting (SLM)	Titanium, chrome-cobalt alloys, aluminum, stainless steel
	Powder Bed and Inkjet head 3D Printing (3DP)	Most metal alloys, gypsum, powdered polymers
	Electron-beam melting (EBM)	Most metal alloys
	Direct metal laser sintering (DMLS)	Most metal alloys
Wire	Electron beam freeform fabrication (EBF3)	Most metal alloys
Lamination	Laminated object manufacturing (LOM)	Paper, metal foils, plastic foils

The analysis of the literature showed that the mechanical properties of products produced in the FDM technology on 3D printers were insufficiently determined. Papers [8, 10, 19] mention the ABS material, often used for printing, but did not take into account the change in the degree of filling of the printed objects or the type of filling. Our work shows the influence on the strength properties of not only various materials (ABS, PLA and PETG), but also various degrees of filling in the print (10, 30 and 60%) and the types of filling (line, honeycomb and grid) of the manufactured objects.

MATERIALS AND METHODS

In the FDM technology thermoplastic polymer materials are mainly used. The following polymer materials were used in the research.

ABS (acrylonitrile-butadiene-styrene) is a low-cost engineering thermoplastic that is easily machined, fabricated and thermoformed [2]. This thermoplastic material has excellent chemical, stress and creep resistance. ABS offers a good balance of impact, heat, chemical and abrasion resistance, dimensional stability, tensile strength, surface hardness, rigidity and electrical characteristics. ABS is considered a food grade thermoplastic, and can be safe for use in food processing. ABS plastic remains hard, rigid and tough even at low temperatures. It is available in fire-retardant, heat-resistant and palatable grades. Impact strength varies by grade. See the chart below for ABS yield strength, Young's modulus (ABS elasticity), tensile yield strength of ABS plastic, mechanical properties of ABS plastic, and other properties [10]. The tests used samples made of improved ABS, the so-called Smart ABS with less thermal shrinkage. Material specially designed for 3D printing.

PLA (polylactide acid or polylactide) – it is a fully biodegradable polymer belonging to the group of aliphatic polyesters [10]. It is obtained from renewable raw materials (e.g. cornmeal). Polylactide is mainly used for biomedical purposes, incl. for the production of dental implants and resorbable surgical threads. There are plans to use polylactide as a replacement for polyolefins and other polymers derived from non-renewable raw materials. Disposable bottles and dishes are also made of polylactide, and they decompose within 75-80 days. However, a barrier to mass applications is the cost of production and processing of this polymer. Today, it is also used as a filament (printing material) in home and professional 3D printers (in the FDM technique).

PETG (poly (ethylene terephthalate) – is a polyethylene terephthalate enriched with glycol. This additional component reduces thermal shrinkage and increases the impact strength of PETG models [8]. The filament made of PETG is characterized by the ease of 3D printing similar to PLA, while its mechanical strength is very similar. The filament made of polyethylene terephthalate enriched with glycol has a Young's modulus ranging from 2000 to even 3000 MPa, and its yield point is from 45 to 65 MPa. As a result, models printed in 3D with PETG show good elasticity. The soft outer surface (in relation to the surfaces of models made of ABS and PLA) makes the models printed in 3D made of

PETG more susceptible to abrasion than other popular thermoplastics used in the field of 3D printing. Additional advantages of the filament made of PETG are: shiny and relatively smooth surface of printed models (sometimes too transparency) and virtually zero gas emissions during the 3D printing process. The disadvantages of PETG as a filament in the field of FDM 3D printing are poor high-angle printing characteristics without the use of a support material.

The table below shows the parameters of the filaments of the materials used for printing the samples.

For strength tests, shapes and sizes of samples are compliant with the DIN EN ISO 527-1:2019 [20]. The samples were printed with various types and degrees of filling. Due to the type of filling, samples were made with Grid, Honeycomb and Lines filling (Fig. 1). Due to the degree of filling, samples were made with 10%, 30% and 60% filling. In the process of selecting the parameters of the printing process for individual materials, the basic features of the printout, which have the greatest impact on the mechanical strength of the obtained prints, were established. These parameters are presented in Table 3.

The samples were subjected to a static tensile test. The test parameters: initial force – 0.1 MPa, stretching speed – 1 mm/min, test speed – 50 mm/min, distance fixing – 110 mm. The tests were based on the DIN EN ISO 527-1:2019 standard.

Figure 1. Types of sample filling (30% filling, view for 60% of the print) a) honeycomb, b) grid, c) line

RESULTS

Strength tests – a static tensile test was carried out in the Zwick/Roell Z010 testing machine. The tests were made on the same samples made in accordance with DIN EN ISO 527-1:2019 [20]. In the first stage, static tensile tests were carried out for samples made of PLA with grid, line and honeycomb filling and the filling degree of 10, 30 and 60%. The averaged test results are shown in Table 4.

Table 2. Sample materials [1, 15–19]

Atribut	Value		
	Smart ABS	PLA	PETG
Filament nominal diameter	1.75	1.75	1.75
Color	Coral	Tropical green	Stellar blue
The average value of the filament diameter	1.752	1.733	1.742
Filament ovality	0.2%	0.3%	0.4%
Standard deviation of the filament diameter	5.0 μm	11.9 μm	7.4 μm
Recommended extruder temperature	230–255 °C	185–215 °C	230–255 °C
Recommended temperature of the heated bed	100 °C	0–45 °C	60–80 °C

Table 3. Printing parameters

Parameter	Value		
	PLA	PETG	Smart ABS
Extruder temperature during printing	205°C	235°C	235°C
Temperature of the heated bed	60°C	70°C	80°C
Material flow	96%	98%	94%
The percentage of blowing on the material	100%	35%	0%
Retraction value	0.2 mm	0.5 mm	0.4 mm
Retraction speed	40 mm/s	40 mm/s	20 mm/s
Printing speed	70 mm/s	70 mm/s	70 mm/s
Extrusion path width	0.4 mm	0.4 mm	0.4 mm

Table 4. The average tests results for static tensile test for PLA

Probe	E_t	σ_m	ε_m	SD $\sigma_{\varepsilon m}$	σ_b	ε_b	b	h
	[MPa]	[MPa]	[%]	[-]	[MPa]	[%]	[mm]	[mm]
Grid 10%	1492	28.31	2.53	0.025	28.31	2.53	10	4
Grid 30%	1611	30.04	2.48	0.038	30.04	2.48	10	4
Grid 60%	1941	36.58	2.52	0.018	36.58	2.52	10	4
Line 10%	1537	30.19	2.51	0.018	29.54	2.50	10	4
Line 30%	1731	34.62	2.54	0.015	32.87	2.53	10	4
Line 60%	2058	40.15	2.50	0.011	39.99	2.49	10	4
Honeycomb 10%	1601	32.15	2.49	0.014	32.15	2.48	10	4
Honeycomb 30%	1838	35.57	2.55	0.035	35.57	2.55	10	4
Honeycomb 60%	2168	41.69	2.54	0.012	41.58	2.54	10	4

The following Figures 2-4 show example plots of the dependence of the elongation of the tested PLA samples on the tensile force.

In the next stage, static tensile tests were carried out for samples made of PETG with grid, line and honeycomb filling and the filling degree of 10%, 30% and 60% (Figs. 5-7). The averaged test results are shown in Table 5.

In the next part of the work, static tensile tests were performed for samples made of Smart ABS with grid, line and honeycomb filling and the filling degree of 10%, 30% and 60% (Figs. 8-10). The averaged test results are shown in Table 6.

DISCUSSION

During the research, it turned out that the process of their destruction was different. The type of sample break changed with not only the change of material, but also the type of filling and the size of the filling had a great influence.

In the case of PLA samples (Fig. 11), it can be seen that the breakage of the samples with grid filling and 10% filling density occurs near the throat of the sample (Fig. 11a) with a clear loss of a fragment of the material of the tested sample. The break is definitely plastic.

As the filling density increases, the character of the crack is close to the brittle one, the break is replaced in a part of the constriction without any loss of sample material.

In the case of samples with mesh filling, the highest tensile strength was demonstrated for samples with a filling density of 60%. This value averaged 36.8 MPa, with the elongation of the samples about 2.5%. The tensile modulus reached the average value of 1941.1 MPa. The samples with 10% filling were characterized by the lowest strength. In this case, the tensile modulus averaged

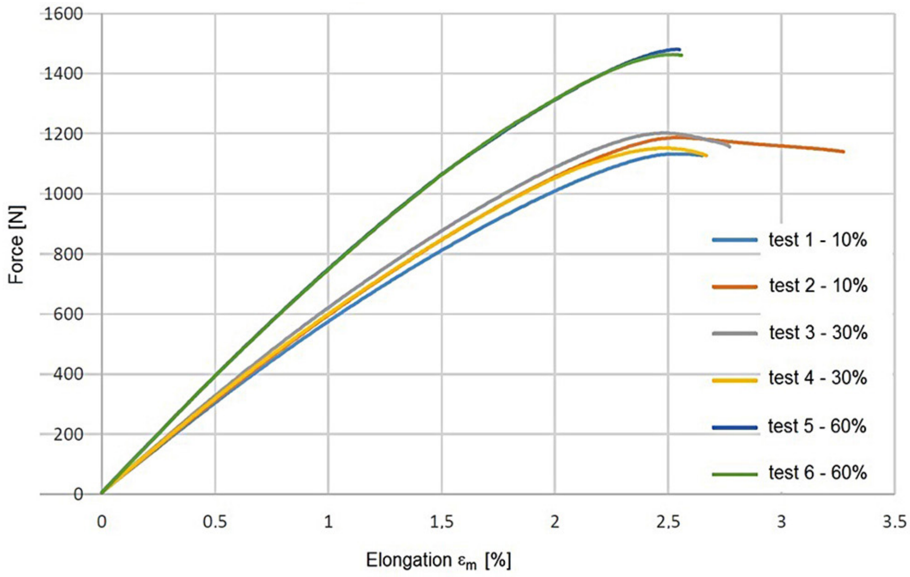

Figure 2. Dependence of elongation on tensile force for PLA, filling method – grid

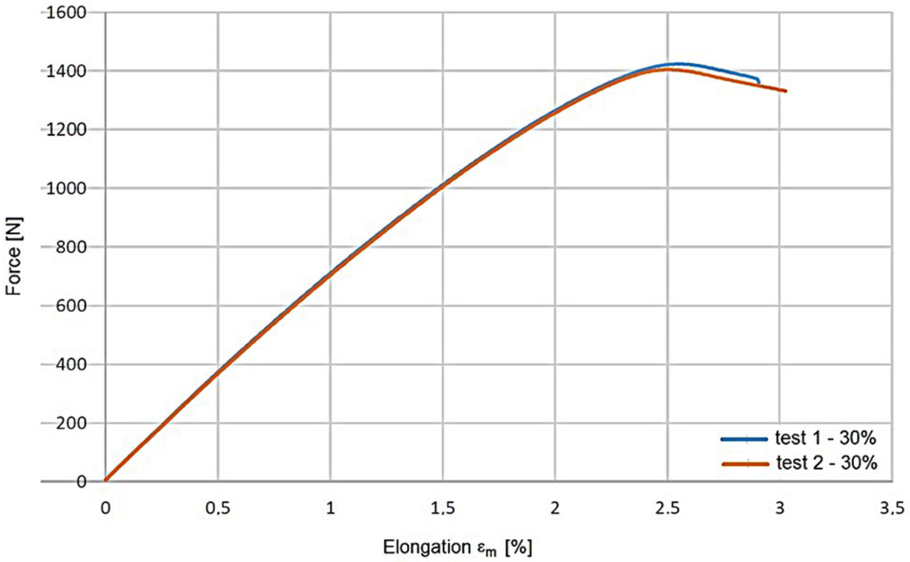

Figure 3. Dependence of elongation on tensile force for PLA, filling method – honeycomb

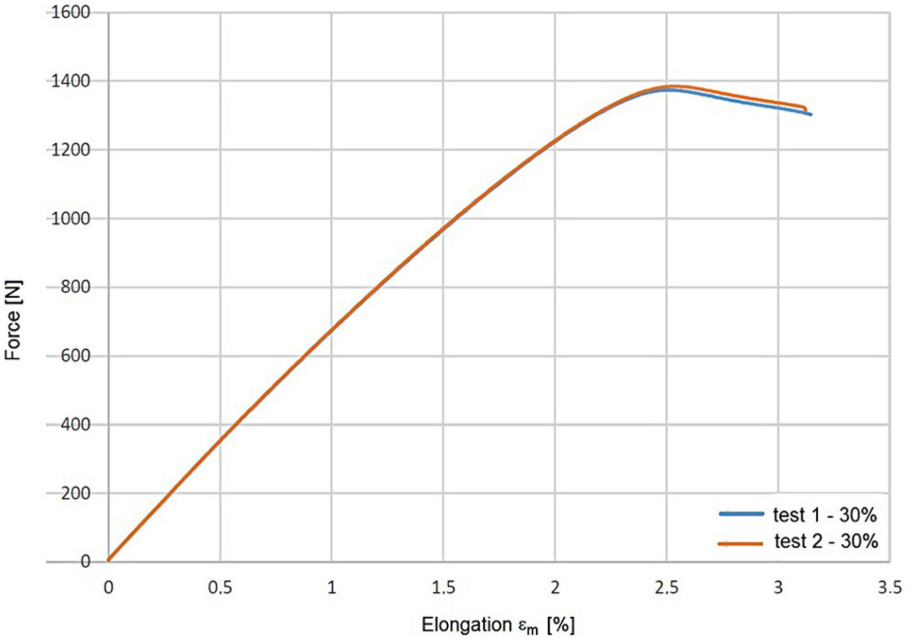

Figure 4. Dependence of elongation on tensile force for PLA, filling method – line

1514.9 MPa, with the elongation of the specimen being about 2.5%. However, the tensile strength reached an average value of 29 MPa [1, 15].

Samples with 30% packing density showed slightly higher parameter values compared to samples with 10% packing density. The tensile modulus value is 5% (1588 MPa) greater than the value of the same parameter for samples with 10% fill density. On the other hand, the tensile strength of samples with a 30% filling exceeds the same parameter of samples with a 10% filling by slightly more than 1%. All fittings with grid filling were characterized by sample elongation in relation to the initial length by approx. 2.5%.

Taking into account the filling of the hexagonal and linear type with the same degree of compaction (30%), the samples with honeycomb filling showed greater strength. The tensile strength, tensile modulus and elongation values with tensile strength were respectively: 35.3 MPa; 1823.4 MPa; 2.5% for hexagonal fill and 34.5 MPa; 1728.5 MPa; 2.5% for linear fill. The line-filled samples showed slightly lower parameter values than their honeycomb counterparts [2, 19]. These values are lower,

Table 5. The average tests results for static tensile test for PLA

Probe	E_t	σ_m	ε_m	SD $\sigma_{\varepsilon m}$	σ_b	ε_b	*b*	*h*
	[MPa]	[MPa]	[%]	[-]	[MPa]	[%]	[mm]	[mm]
Grid 10%	915	22.69	4.41	0.025	22.69	4.41	10	4
Grid 30%	959	23.54	4.01	0.046	23.54	4.01	10	4
Grid 60%	1224	24.82	2.42	0.016	24.82	2.42	10	4
Line 10%	1012	24.15	4.10	0.141	24.15	4.10	10	4
Line 30%	1058	25.27	3.66	0.029	25.27	3.66	10	4
Line 60%	1310	26.55	3.15	0.054	26.55	3.15	10	4
Honeycomb 10%	975	25.01	3.97	0.022	25.01	3.97	10	4
Honeycomb 30%	1070	26.52	3.72	0.032	26.52	3.72	10	4
Honeycomb 60%	1518	26.12	3.14	0.043	26.12	3.14	10	4

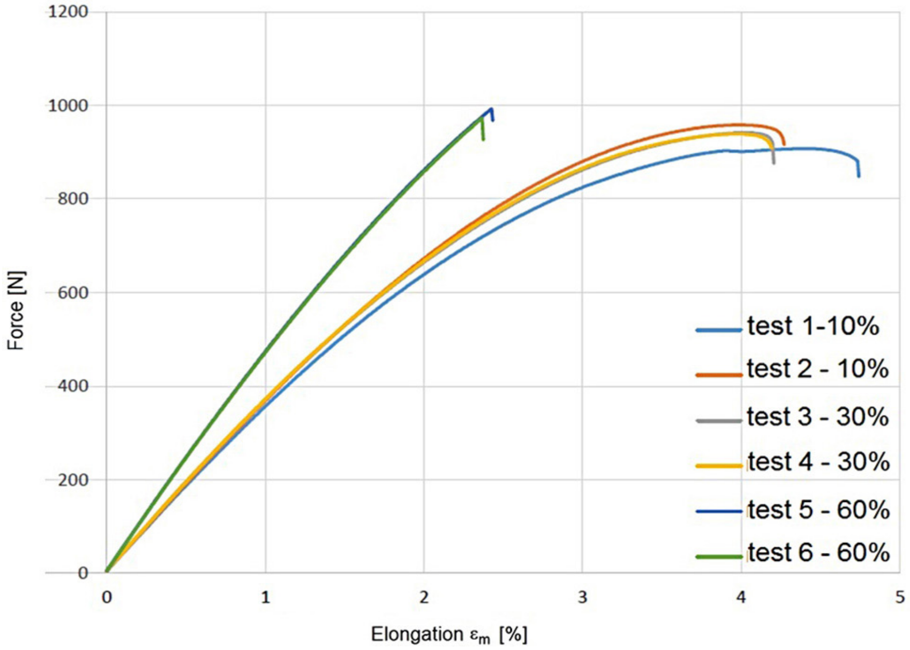

Figure 5. Dependence of elongation on tensile force for PETG, filling method – grid

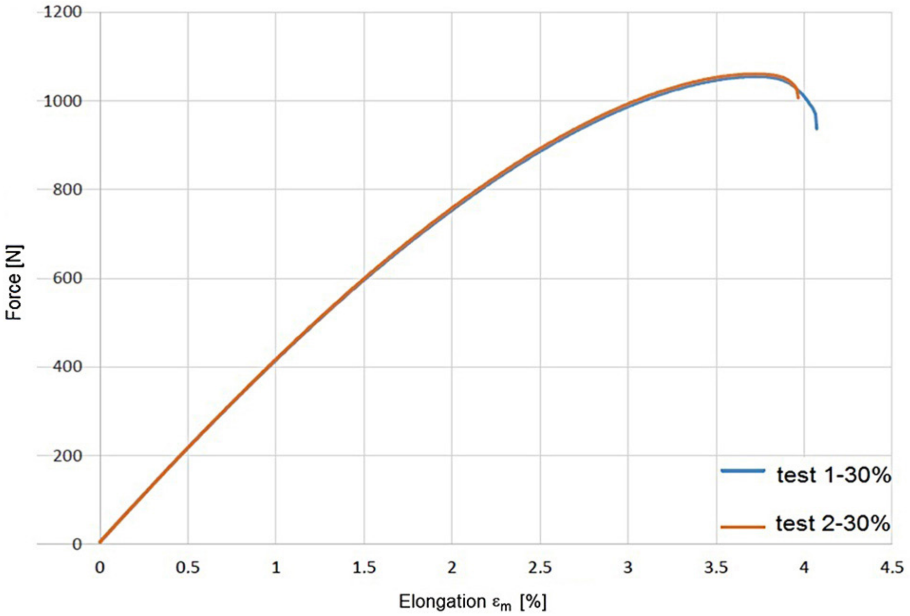

Figure 6. Dependence of elongation on tensile force for PETG, filling method – honeycomb

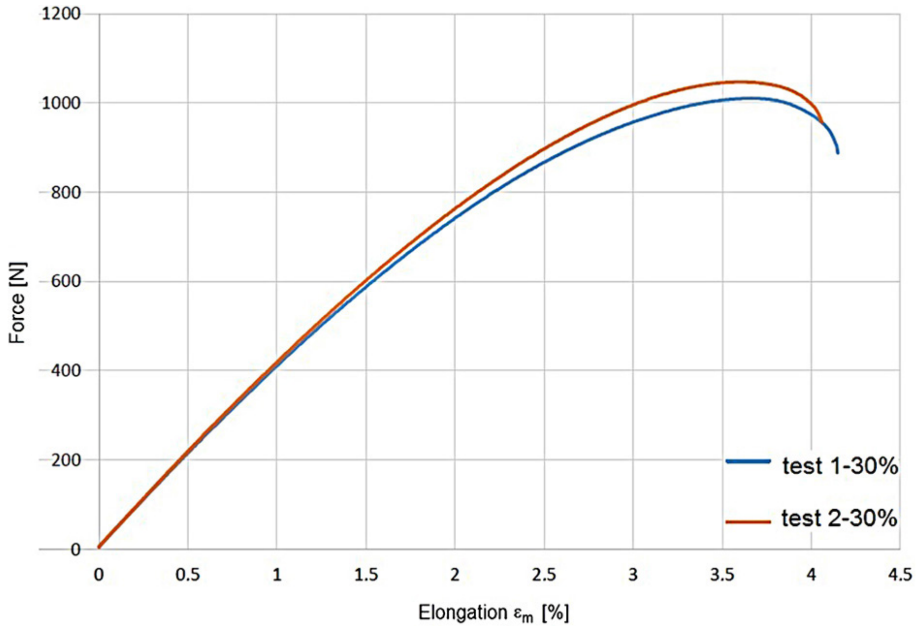

Figure 7. Dependence of elongation on tensile force for PETG, filling method – line

Table 6. The average tests results for static tensile test for Smart ABS

Probe	E_t	σ_m	ε_m	SD $\sigma_{\varepsilon m}$	σ_b	ε_b	*b*	*h*
	[MPa]	[MPa]	[%]	[-]	[MPa]	[%]	[mm]	[mm]
Grid 10%	903	17.20	2.66	0.048	17.20	2.66	10	4
Grid 30%	1003	19.24	2.53	0.026	17.51	2.53	10	4
Grid 60%	1326	24.81	2.42	0.012	23.29	2.42	10	4
Line 10%	1154	21.15	2.58	0.079	21.15	2.58	10	4
Line 30%	1278	23.65	2.43	0.041	20.59	2.43	10	4
Line 60%	1554	25.01	2.31	0.007	25.01	2.31	10	4
Honeycomb 10%	1197	22.60	2.63	0.024	22.60	2.63	10	4
Honeycomb 30%	1330	25.49	2.41	0.044	25.49	2.41	10	4
Honeycomb 60%	1590	27.15	2.38	0.022	27.15	2.38	10	4

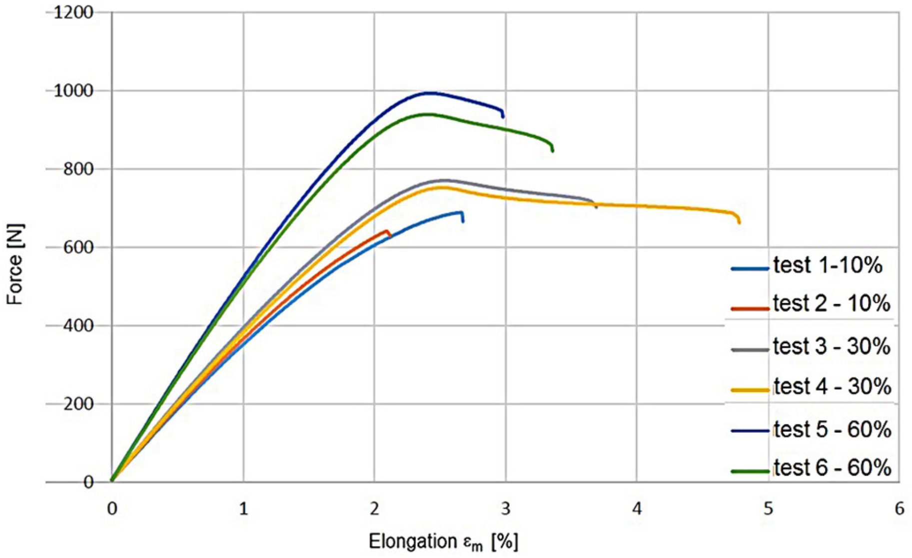

Figure 8. Dependence of elongation on tensile force for Smart ABS, filling method – grid

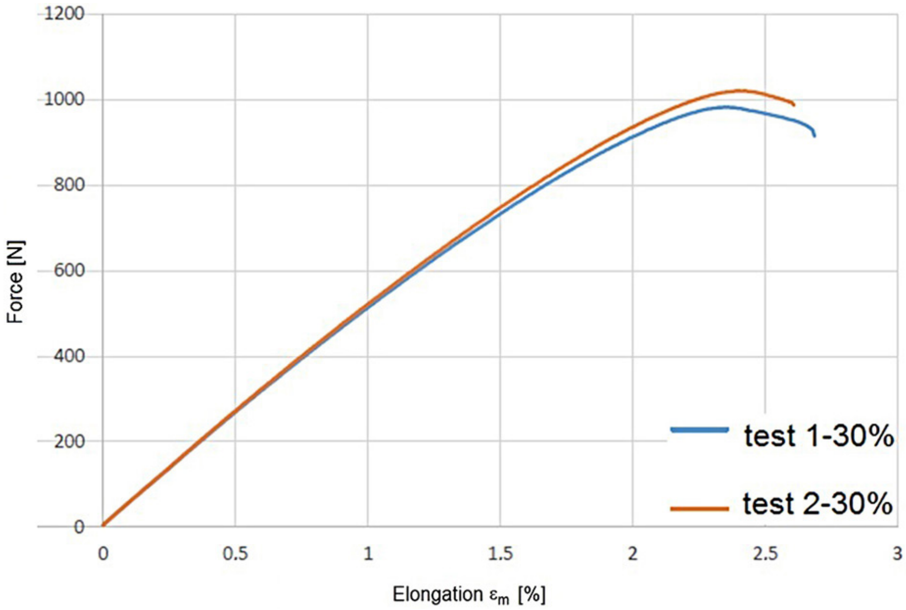

Figure 9. Dependence of elongation on tensile force for Smart ABS, filling method – honeycomb

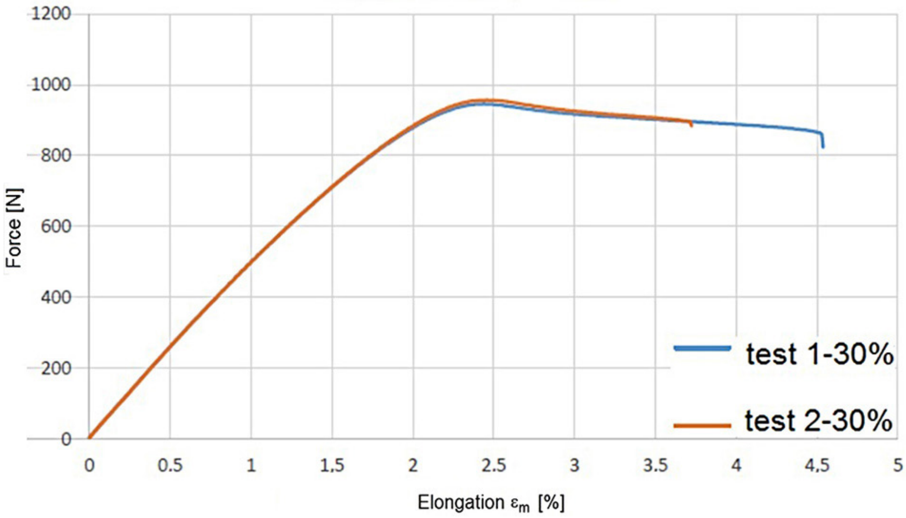

Figure 10. Dependence of elongation on tensile force for Smart ABS, filling method – line

respectively, by 5.1% for the tensile modulus and less than 2.3% for the tensile strength. On the other hand, the difference between the most durable samples (60% filling, grid) and the least durable (10% filling, grid) was 22% in terms of the tensile modulus and 21.2% in the case of the tensile strength.

In the case of samples made of PETG, the samples with a filling density of 60% demonstrate the highest strength and the smallest shapes with a filling density of 10% (Fig. 12). The tensile strength of samples with a 60% fill density is on average 24.6 MPa, showing the value of the tensile modulus of 1220.5 MPa and the elongation at tensile strength of 2.4%. In the case of samples with a filling density of 10%, the values of tensile strength, tensile modulus and elongation at tensile strength reach average values, successively: 23.3 MPa; 927.3 MPa and 4.2%. Samples with 30% filling density show slightly higher tensile strength and tensile modulus values compared to the samples with 10% filling (23.5 MPa and 957 MPa).

In the case of smart ABS samples for a grid-filled sample, a tendency to damage all samples near the ends of the fittings' narrowing can be noticed (Fig. 13).

Only in the case of samples with a filling degree of 10%, the weight loss of the tested sample was observed (Fig. 13a). Samples

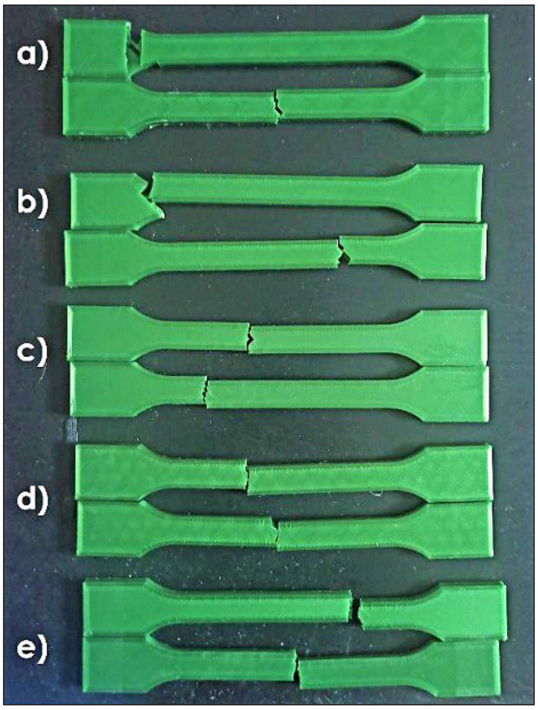

Figure 11. PLA samples after static tensile test: a) 10% grid filling; b) 30% grid filling; c) 60% grid filling; d) 30% honeycomb filling; e) line filling 30%

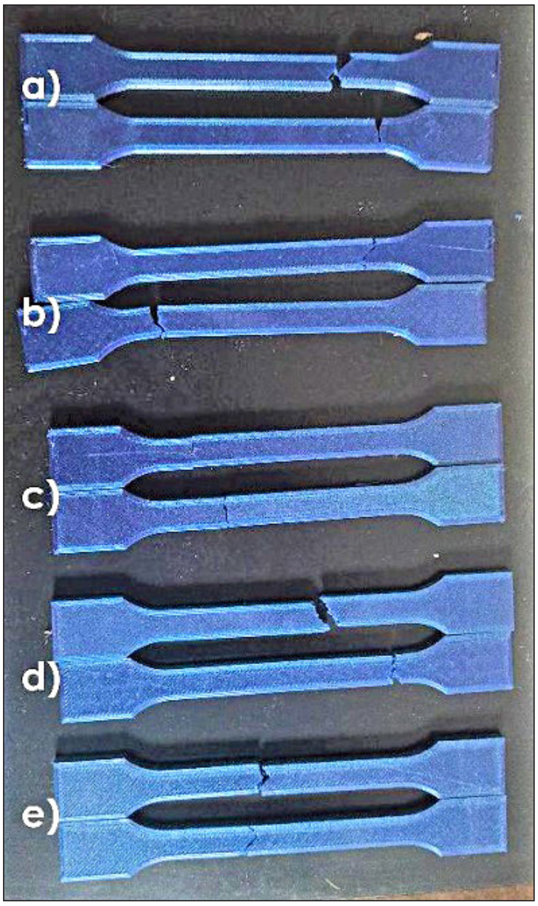

Figure 12. PETG samples after static tensile test: a) 10% grid filling; b) 30% grid filling; c) 60% grid filling; d) 30% honeycomb filling; e) line filling 30%

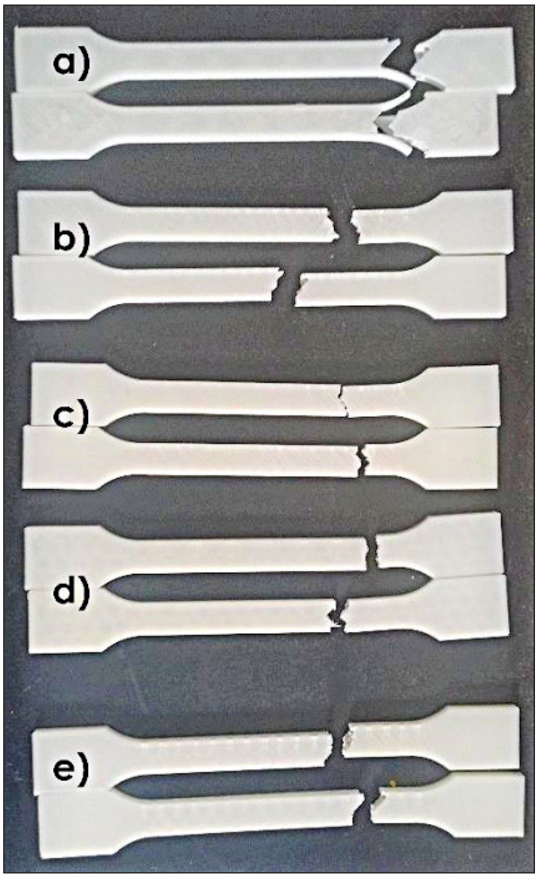

Figure 13. Smart ABS samples after static tensile test: a) 10% grid filling; b) 30% grid filling; c) 60% grid filling; d) 30% honeycomb filling; e) line filling 30%

with 60% filling are characterized by a tensile strength of an average value of 24.1 MPa, with a tensile modulus of an average value of 1310.3 MPa and an elongation of 2.4%. In the case of samples with 10% packing density, the mentioned parameters are, in sequence: 16.6 MPa; 922.7 MPa and 2.4%. Analyzing the results of samples with a 30% filling density, it can be seen (contrary to the samples made of PLA and PETG) that the differences in parameter values between the extreme samples (10 and 30% filling) are more balanced. The tensile strength parameter for fittings made with 30% filling was on average 19 MPa, differing from the same parameter in the case of samples with 10% filling by almost 12.7 and 21.2% in the case of samples by 60% – filling. However, the tensile modulus parameter in the case of samples made with 30% filling was on average 985.9 MPa, differing from the same parameter in the case of samples with 10% filling by 4% and 27% in the case of samples with 60% of filling [2,10,13,19].

CONCLUSIONS

By analyzing the obtained test results, it allows to conclude that the type of material used, the type and degree of filling of the print have a key impact on the durability of the obtained prints. The influence of the type and degree of print filling in individual groups of materials shows that in the case of samples made of PLA, the highest strength was that of the samples with grid filling and filling degree 60%, successively they were honeycomb and filling degree 30%, line 30%, grid 30% and the least durable grid 10%. In the case of samples made of PETG, the samples with honeycomb and line filling and 30% filling degree had the highest strength, then grid 60%, grid 30% and grid 10%. In the case of samples made of Smart ABS, the samples with honeycomb filling and filling degree of 30% had the highest strength, followed by grid 60%, line 30%, grid 30% and grid 30%. Summarizing the test results, it was found that in the case of determining the static tensile strength the most stretchable material is PLA material, the other is ABS, then PETG. When testing the static tensile strength of PLA samples, it was shown that a similar strength of models printed in 3D with a mesh filling with a density of 60% of the total volume can be obtained by using a linear or hexagonal filling with a density of 2 times lower, saving time during the 3D printing process itself. In the case of samples made of Smart ABS and PETG, samples with a honeycomb filling and a line for PETG and a honeycomb filling for Smart ABS showed better strength parameters in relation to the 60% mesh filling.

The research shows that the 3D printing process and the selection of parameters for a specific application are not at all obvious. By using the largest possible filling of the model, we do not necessarily have to obtain a product with the best possible strength parameters. By using a special filling structure of the printed elements, we can reduce material consumption, which results in a reduction in the production time of parts and the costs of the printed element and the production process. Thanks to this, the field of 3D printing is one of the fastest growing sectors of the industry.

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