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The Influence of Layer Height on the Quality of 3D Print for Selected Construction Materials

KEYWORDS
3D printing, material strength, surface roughness

ABSTRACT

Typical rapid prototyping is based on additive manufacturing techniques. Prototype design is a particular challenge for technologists. The very essence of the concept of prototype suggests that we are dealing with something new, which means that there is usually no prior knowledge or experience. Documentation must be simplified and often provide alternatives. The physical properties of the materials from which a part, device or machine will be manufactured are not always clearly defined. Of course, the cost of producing a prototype also plays an important role. However, this is difficult to estimate at the prototype design stage. This manuscript presents the development of 3D additive technologies, machines used in additive manufacturing processes and materials used for printing.

The purpose of this study was to investigate the layer thickness of 3D printed specimens for the strength and stereometric properties of the surface layer. The tests were carried out on a Zwick/Roell Z150 testing machine. The results of selected surface roughness parameters obtained with the use of the T8000 RC120-400 profilometer from Hommel-Etamic were analyzed. The results of the manuscript will not only allow you to better understand the basics of additive manufacturing, but also provide specific data that can facilitate the selection of appropriate machines, materials and printing parameters in order to obtain an element with the right properties.

NOMENCLATURE

Symbols

Ra **–** arithmetical mean height of a line
Rz **–** maximum height of profile
Rq **–** root mean square deviation

Acronyms

SLA **–** Stereolithography
FDM **–** Fused Deposition Modeling
DLP **–** Digital Light Processing
SLS **–** Selective Laser Sintering
CAD **–** Computer Aided Design
PLA **–** PolyLactic Acid
ABS **–** Acrylonitrile-Butadiene-Styrene copolymer
CNC **–** Computer Numerical Control
TPU **–** ThermoPlastic Polyurethane
PP **–** PolyPropylene
PA **–** PolyAmide

1. INTRODUCTION

3D printing is an additive manufacturing method of creating three-dimensional elements. The origins of 3D printing date back to 1980. The first 3D printer was patented by Chuck Hull, who used the SLA technique which consists of hardening successive layers of photosensitive resin, one on top of the other, until the final element is made. In the following years, new 3D printing methods appeared. Some of the most popular methods are [1]: Fused Deposition Modeling (*FDM*), Stereolithography (*SLA*), Digital Light Processing (*DLP*), and Selective Laser Sintering (*SLS*). Fused Deposition Modeling (*FDM*) is one of the oldest and most widely used 3D printing methods. It involves layering subsequent layers of material until a finished element is obtained. Prior to printing, a 3D model needs to be designed in a *CAD* program, (e.g. Inventor, Fusion, Solidworks, etc.). The prepared model is then transformed using a slicer (Cura, Slicer, ideaMaker, etc.) into a G-code, i.e. a set of commands for a *CNC* machine.

The material is deposited onto the print bed through a nozzle. Both the nozzle and the print bed are heated to a temperature depending on the selected material. The target shape is obtained by appropriate movement of the head, the workpiece, or both along the X and Y axes parallel to the table. The application of subsequent layers is made possible by jumping along the Z axis [2].

The factors behind the widespread use of the *FDM* method include relative simplicity of printing, good mechanical properties, availability of materials, and the fact that private individuals can build *FDM* printers by themselves.

Over the years, not only printing methods have changed, but also the materials used for that purpose. In addition to plastics, elements manufactured using the additive method can be made of resin or metal [3]. Material selection depends on the capabilities of the printer and desired properties that the finished object should have. The most popular materials are *PLA* and *ABS*.

PLA (polylactic acid) is biodegradable and perfect for *FDM* printing. *PLA* is widely regarded as the "easiest material to print" due to its properties such as low processing shrinkage, ability to print without a closed chamber and at a relatively high speed, as well as the possibility of printing complex shapes [4, 5]. Thanks to the above, *PLA* is used for printing mock-ups, enclosures, figurines, and structural elements [6, 7]. However, due to its brittleness and sensitivity to temperature and humidity, *PLA* is unsuitable for elements exposed to harsh environmental factors.

Materials such as *PLA* and *PETG* have found their application in biomechanics. These materials, combined with the wide use of 3D printing in the production of elements with complex shapes, are used in the production of various types of prostheses. Depending on the required parameters of the prosthesis, *PLA* or *PETG* material is chosen. *PLA* material has high static strength, which makes it better suited for elements that are supposed to carry a higher load. However, *PLA* is a brittle material, which can cause the risk of breakage if the force is too high. *PETG* is a durable material and is more resistant to environmental conditions compared to *PLA* [15].

ABS (acrylonitrile-butadiene-styrene copolymer) is the second (after *PLA*) most frequently used material in 3D printing. Apart from printing, it is used as a material for producing components through injection molding. *ABS* has very high thermal shrinkage, which may cause difficulties in printing, especially on a printer without a closed chamber. Due to its high thermal shrinkage upon cooling, it is also recommended to use adhesives to increase the adhesion of the first layer to the table. The advantages of this material include greater mechanical strength and greater resistance to higher temperatures than those of PLA. *ABS* is used in the production of less demanding machine parts and elements under load, e.g. 3D printer elements [8, 9].

Another important aspect of 3D printing concerns the type of printers. The finished print greatly depends on the parameters of a printing machine. Each company introduces its own solutions to enhance their printers and thus increase their manufacturing possibilities. Some of the basic parameters of printers are related to the size of the printing volume, the number of print heads, open or closed chamber printing, passive or active chamber heating, kinematics, maximal temperature, and printing speed.

The choice of a printer therefore depends on what we want to achieve. Low-budget printers usually have one print head and no chamber. These types of printers are frequently used for the fabrication of art projects such as mock-ups or simple machine parts that are not subject to high loads. The most common material used with these printers is PLA. Professional printers, on the other hand, may have more print heads, a closed chamber and a table with automatic leveling. Printers of this type are most often used by large companies to produce heavy-duty machine parts or large-sized elements. 3D printers are further developed to improve the quality of printing, and each company introduces its own solutions.

3D printing is a constantly developing industry that is gaining more and more interest every year. However, despite its significant development, 3D printing is not yet widely used [10]. This may result from the relatively recent adoption of this technique compared to other manufacturing methods. Analyzing the global market, one can observe an increase in the number of studies on 3D printing, 3D printers, materials, and printing methods. The reason for the intensive and fast development of the 3D printing technique is its wide application in various industries, including rapid prototyping, industrial electronics, medicine, automotive, and aviation [11].

Today 3D printing is not only one of manufacturing methods employed by large corporations, but it is also increasingly used by private individuals.

With a growing interest in 3D printing, many studies are undertaken to better understand phenomena occurring during printing, as well as to examine the impact of various factors on the properties of finished elements [12]. In addition, many studies are conducted to determine the properties of printed elements depending on initial parameters.

2. RESEARCH

The aim of this study was to investigate the effect of the layer thickness of 3D printed samples on the strength and accuracy of their surface. Static tensile tests were performed and selected surface roughness parameters were examined using a profilometer. The test samples had the following layer thicknesses: 0.12 mm, 0.20 mm, 0.28 mm.

The following computer programs were used to design the models of test samples and to create G-Code: Autodesk Inventor 2024 and Ultimate Cura 5.2.1. The following printers were used to make the samples: Creality Ender-3, DOUBLE P255, 3DGence.

Strength and surface roughness tests were performed with the use of the following tools: a Zwick/Roell Z150 tensile testing machine and a device for measuring contour, roughness and 3D topography T8000 RC120-400 from Hommel-Etamic.

3. RESEARCH METHODOLOGY

Two 3D printers were selected for this study: Creality Ender-3 and DOUBLE P255 – 3DGence. These machines differ with respect to many parameters, such as the number of print heads, the size of the work table and the possibility of printing with a closed chamber. A key difference between the printers is their price. Creality Ender-3 is a low-budget printer, which makes it the most popular initial choice for private individuals. The 3Dgence printer is more intended for industrial applications. Results of this study will allow a comparison between the quality of elements created by printers for professional and amateur tasks.

Tensile strength tests were conducted on a ZWICK/ROELL Z150 testing machine. The key parameter determining the choice of this machine was its maximum breaking force of 150 kN. In addition to the above-mentioned testing machine, a ZWICK/ROELL Z2.5 testing machine with a maximum breaking force of 2.5 kN was also used for the tests. The first two measurements were made on the ZWICK/ROELL Z2.5 tensile testing machine; however, the measuring range was found to be insufficient during testing, which led changing the machine.

The surface roughness of manufactured elements was examined using a device for measuring contour, roughness and 3D topography, T8000 RC120-400 from Hommel-Etamic.

Table 1 lists the parameters of the printers used in this research.

Table 1. Parameters of DOUBLE P255 – 3DGence and Creality Ender 3 [13, 14]

Parameter	Creality Ender 3	DOUBLE P255 – 3DGence
Printing technique	*FDM*	*FDM*
Work volume	220x220x250mm	190 × 255 × 195 mm
Filament	PLA, TPU, ABS	PLA, PP, PA, ABS, TPU
Layer thickness	0.1-0.4mm	Minimum 20 μm
Nozzle diameter	0.4mm	0.4/0.4 mm
Nozzle temperature	255℃	270°C
Bed temperature	110℃	160°C
Filament diameter	1.75 mm	1.75 mm

The course and parameters of the tests were applied in compliance with the PN-EN ISO 527-1:2012 standard. The test samples had the form of dumbbells with the dimensions shown in Figure 1. In order to eliminate measurement errors, 4 samples were made for each layer thickness, and the final result was the average of four measurements. In this way, a total of 36 samples were obtained. Figure 1 shows the dimensions of the samples according to the PN-EN ISO 527-1:2012 standard.

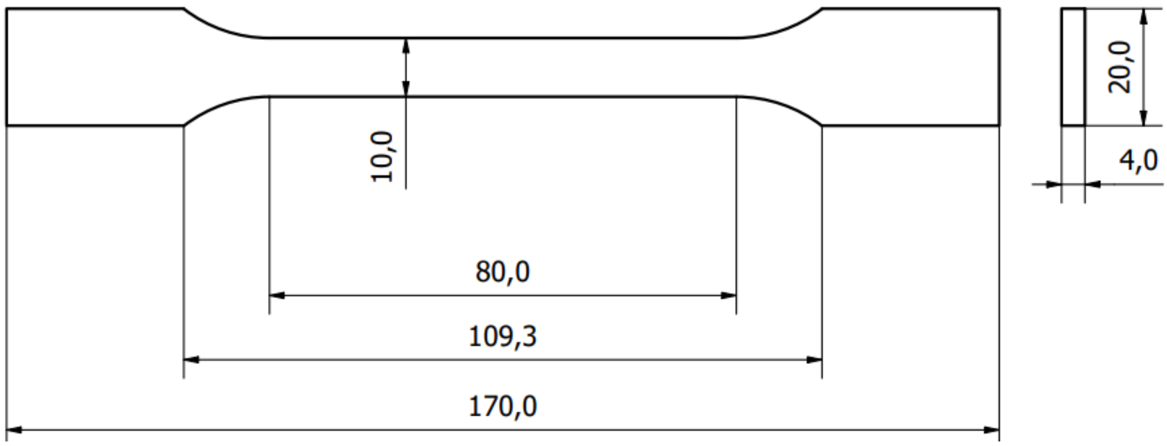


Figure 1. Dimensions of a test sample in compliance with the PN-EN ISO 527-1:2012 standard jaws

Figure 2 shows a sample mounted in a holder of the ZWICK/ROELL Z 150 testing machine.

Figure 2. Sample mounted in the testing machine's

Table 2 lists the parameters of tensile strength tests.

Table 2. Parameters of tensile strength tests

Preload	0.1 [MPa]
/*Tension module speed*/	1 [mm/min.]
Speed of test	50 [mm/min.]
Initial jaw distance	120 [mm]

The roughness of the samples and their surface texture were measured with Hommel-Etamic's device for measuring contour, roughness and 3D topography, T8000 RC120-400. The test samples had the layer thickness of 0.12 mm, 0.20 mm, 0.28 mm and the dimensions of 30 mm x 30 mm (Fig. 3). They were scanned over an area of 3 x 3 mm. Figure 4 shows a device for measuring surface contour, roughness and topography.

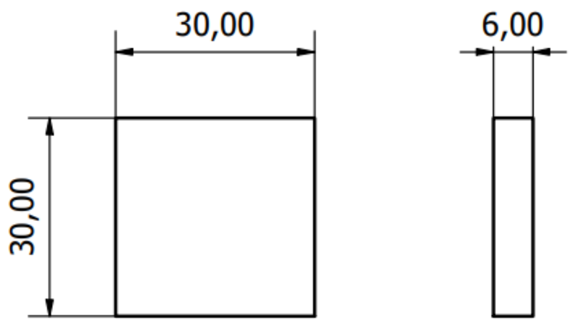


Figure 3. Dimensions of a sample used for roughness testing

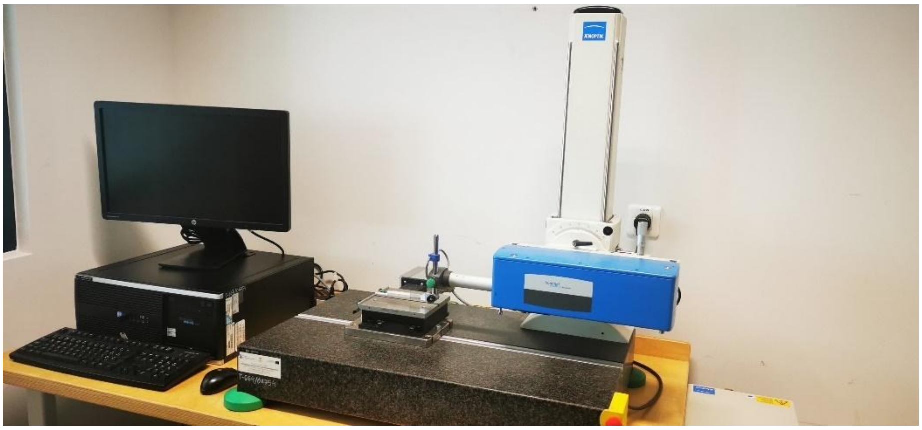
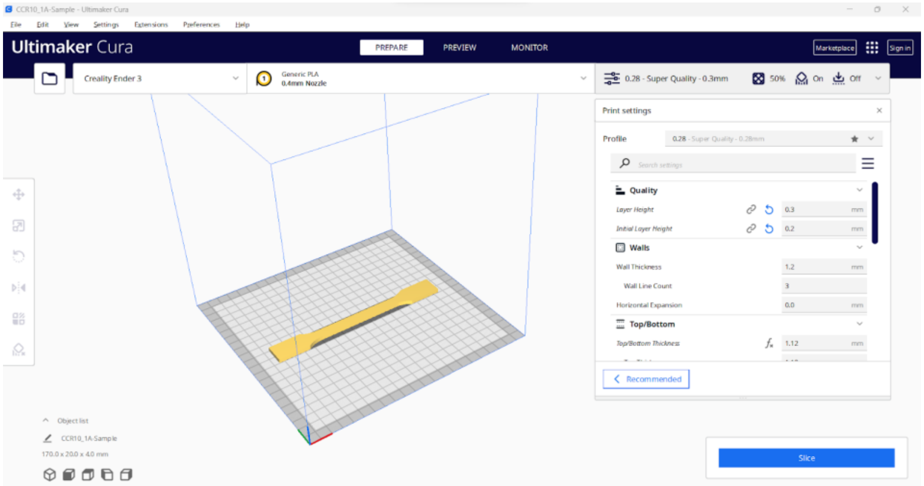


Figure 4. Hommel-Etamic's T8000 RC120-400 for measuring contour, roughness and 3D topography

The conditions for measuring surface roughness (length of the measuring section 3 mm, elementary section 0.8 mm, needle rounding radius 2 µm).

After determining required parameters the samples were modeled using CAD software. Models of the tested samples were created using Autodesk Inventor 2024. After that a G-Code was created for 3D printers. For this purpose, Ultimate Cura 5.2.1 and Slicer 4.0 from 3D-Gence were used. Figure 5 shows test samples modelled with Ultimate Cura 5.2.1 for: a) tensile strength tests, b) roughness tests.

a)



b)

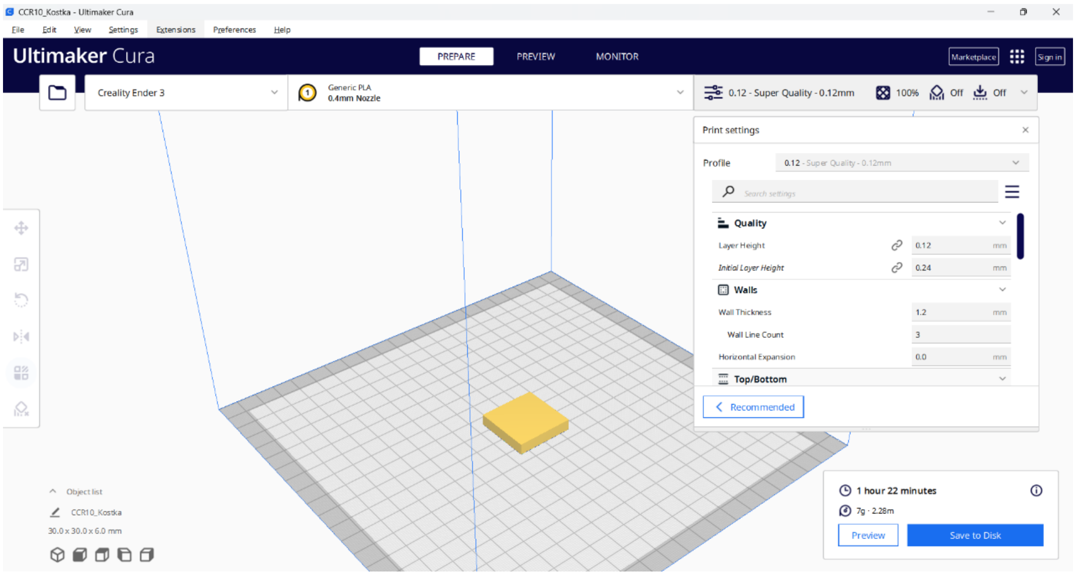


Figure 5. Creating a G-code in Ultimate Cura 5.2.1 a) for strength tests b) for roughness tests

The program visualizes the nozzle movement path for a given layer and estimates print duration.

4. RESEARCH RESULTS

The following parameters were analyzed in the tests: maximum allowable stresses, Young's modulus, and selected surface roughness parameters of the samples. Obtained results are presented in tables and as diagrams to facilitate a comparison of the samples fabricated with the use of two printers: Creality Ender-3 and DOUBLE P255 – 3DGence. Two materials were analyzed: PLA and ABS. ABS samples were printed with DOUBLE P255 – 3DGence. Figure 6 shows the samples after static tensile testing.

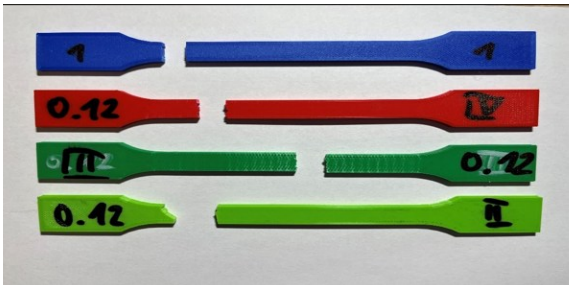


Figure 6. Samples after static tensile testing

The static tensile test results are presented in this section.

Figures 7 to 9 show the stress curves of the samples with layer thicknesses of 0.12, 0.20 and 0.28 in order to illustrate the differences in tearing process. Figure 8 shows the stress curves of PLA samples printed with Ender 3. Figure 9 shows the stress curves of the PLA samples printed with 3D Gence. Figure 10 shows the tensile test results obtained for ABS samples. From each series of 4 samples, the sample with the maximum stress closest to the average value was selected.

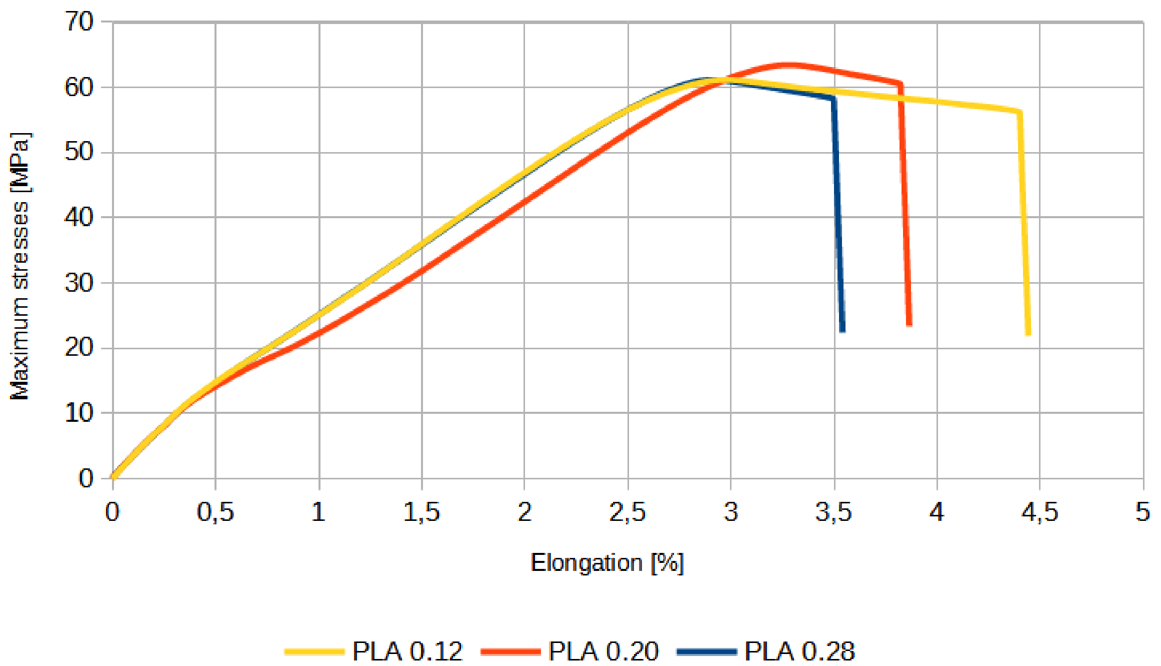


Figure 7. Stress curves of *PLA* samples printed with Ender 3

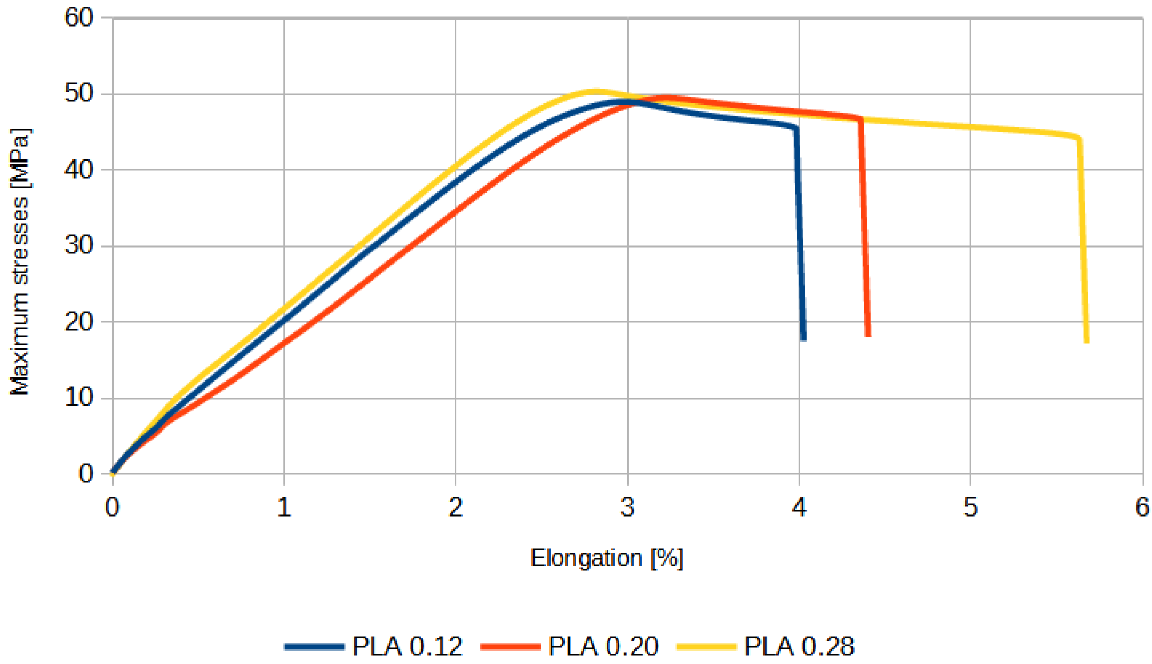


Figure 8. Stress curves of *PLA* samples printed with Gence 3D

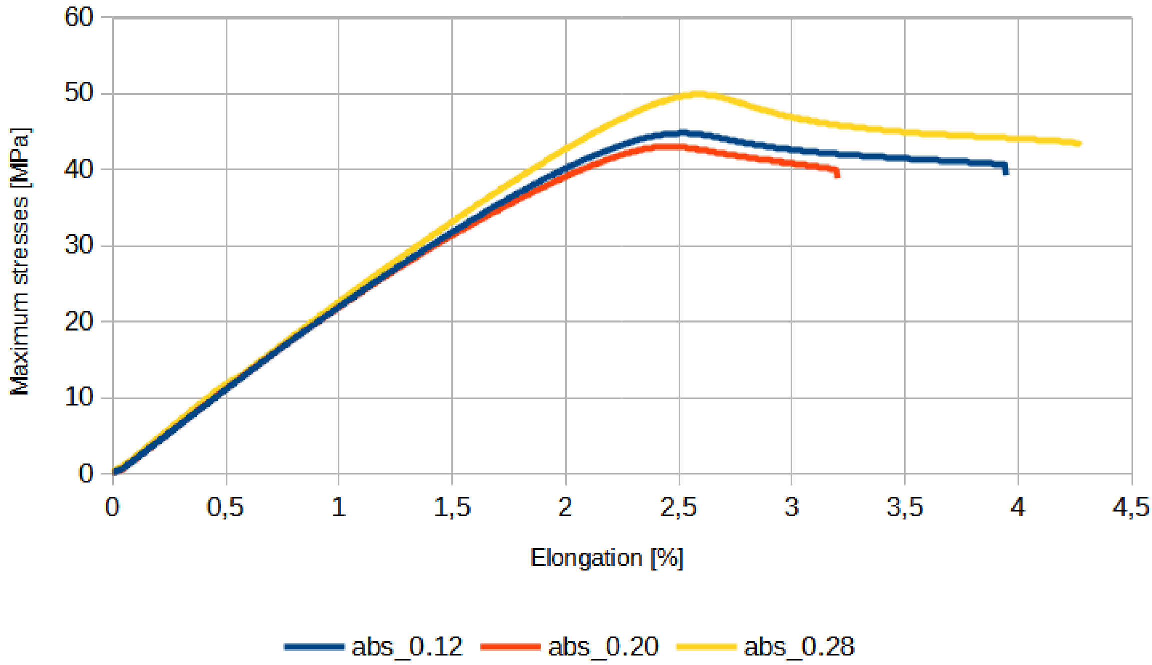


Figure 9. Stress curves of *ABS* samples printed with 3D Gence

An analysis of the results given in Figures 10–11 demonstrates that for the *PLA* material, a change in the layer height has little effect on the strength of the samples. Taking into account the standard deviation, it can be observed that the actual maximum stresses may be very close. The diagram in Figure 10 shows that the Ender 3 printer produced stronger samples than the 3D Gence printer. A comparison of the *PLA* and *ABS* samples showed that in two cases (layer thicknesses 0.12 mm and 0.20 mm) the PLA material is stronger. In Table 3 are listed the maximum stresses of PLA and ABS samples printed with Ender 3 and 3D Gence.

Table 3. Average stresses and standard deviations (in MPa) of *PLA* and *ABS* samples printed with Ender 3 and 3D Gence

Layer thick-ness [mm]	*PLA* – Ender 3 [MPa]	Standard deviation [MPa]	*PLA* – 3D Gence [MPa]	Standard deviation [MPa]	*ABS* – 3D Gence [MPa]	Standard deviation [MPa]
0.12	61.3	3.9	48.8	0.36	45.2	0.96
0.20	60.3	7.5	49.2	1.55	42.8	1.27
0.28	61	0.38	50.5	0.64	50.2	0.4

Figure 10 shows a comparison of the maximum stress values of *PLA* samples printed with Ender 3 and 3D Gence.

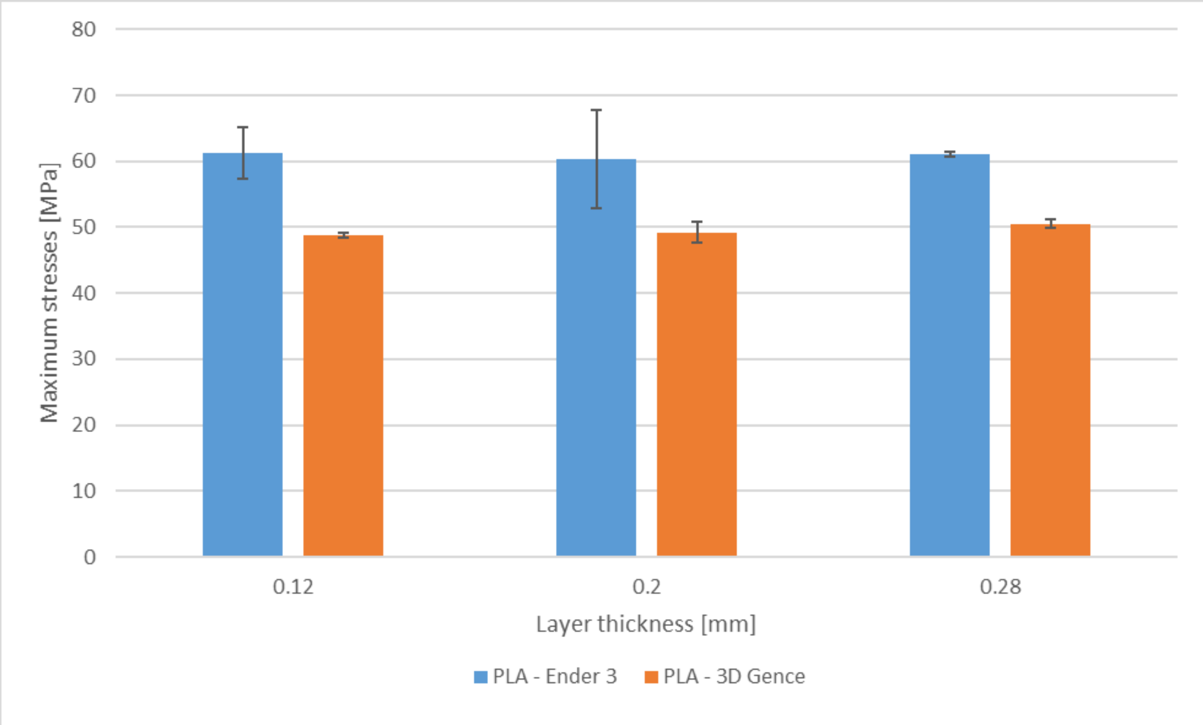


Figure 10. Average maximum stresses of *PLA* samples printed with: a) Ender 3 (blue) b) 3D Gence (orange), for different layer thicknesses

Figure 11 shows a comparison of the maximum stresses of PLA and ABS samples printed with Gence 3D.

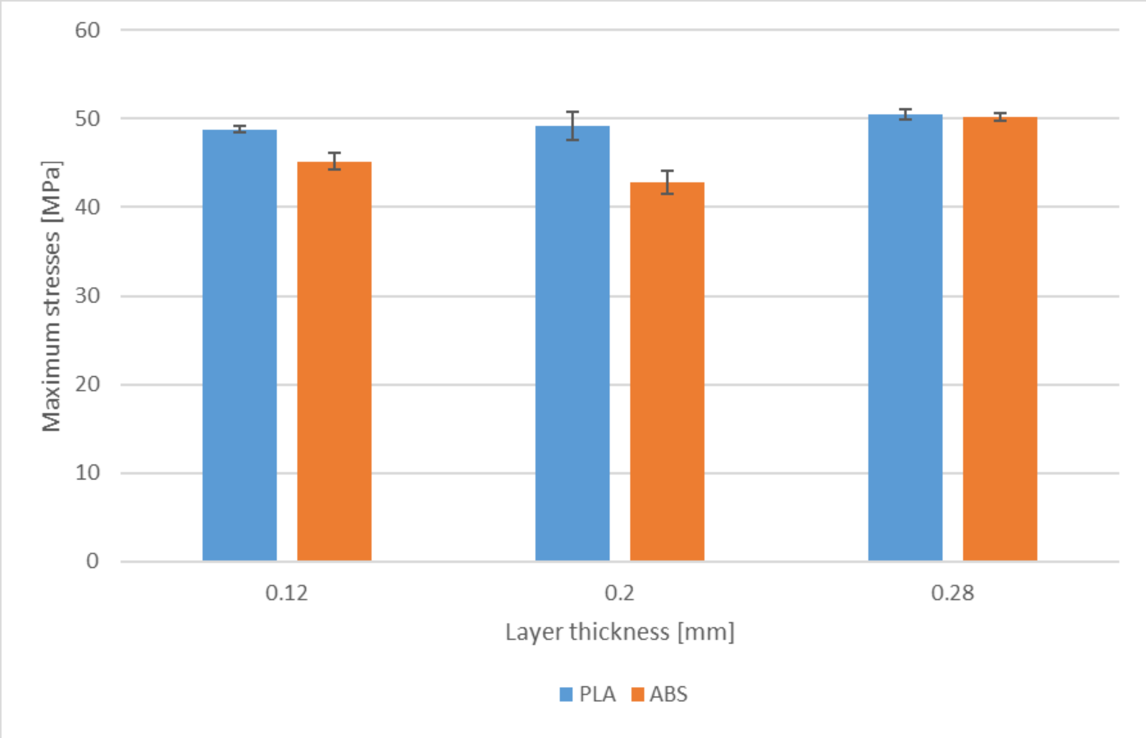


Figure 11. Average maximum stresses of *PLA* (blue) and *ABS* (orange) samples printed with Gence 3D, for different layer thicknesses

An analysis of the results from Table 4 and the diagrams in Figures 12–13 shows that layer height affects Young's modulus. Moreover, the PLA samples printed with DOUBLE P255 show a tendency for the modulus to increase with the layer thickness. A comparison of Ender 3 and DOUBLE P255 demonstrates that the Young's modulus is higher for the Ender 3 printer than for the Gence 3D printer, as shown in Figure 12. In Figure 13, one can observe that *ABS* is characterized by a higher average Young's modulus compared to the *PLA* samples; however, as the layer thickness increases, this difference is reduced.

Table 4 lists the results of Young's modulus along with the standard deviation.

Table 4. Young's moduli of *PLA* and *ABS* samples and their standard deviations (given in MPa), for Ender 3 and 3D Gence

Layer thickness [mm]	*PLA*-Ender 3 [MPa]	Deviation standard [MPa]	*PLA* 3D Gence [MPa]	Deviation standard [MPa]	*ABS* 3D Gence [MPa]	Deviation standard [MPa]
0.12	3235	65.6	1920	549	2290	89
0.20	3040	147	2130	385	2210	64.5
0.28	3150	67.6	2490	379	2480	44.4

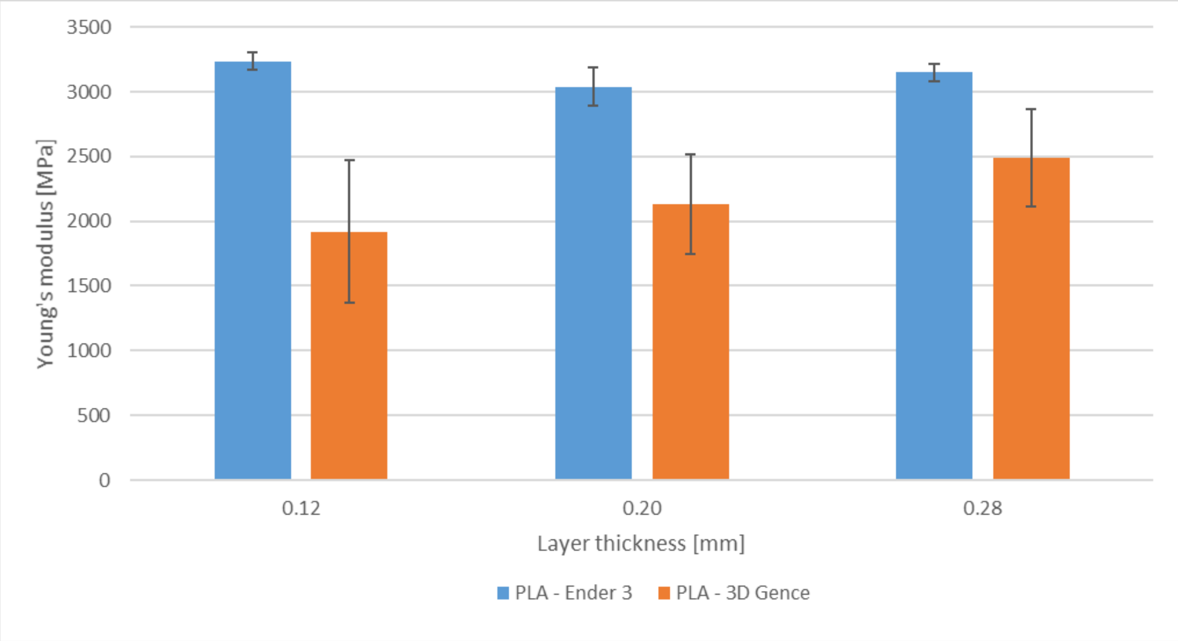


Figure 12. Average values of Young's modulus of *PLA* samples printed with: a) Ender 3 (blue) b) 3D Gence (orange), depending on layer thickness

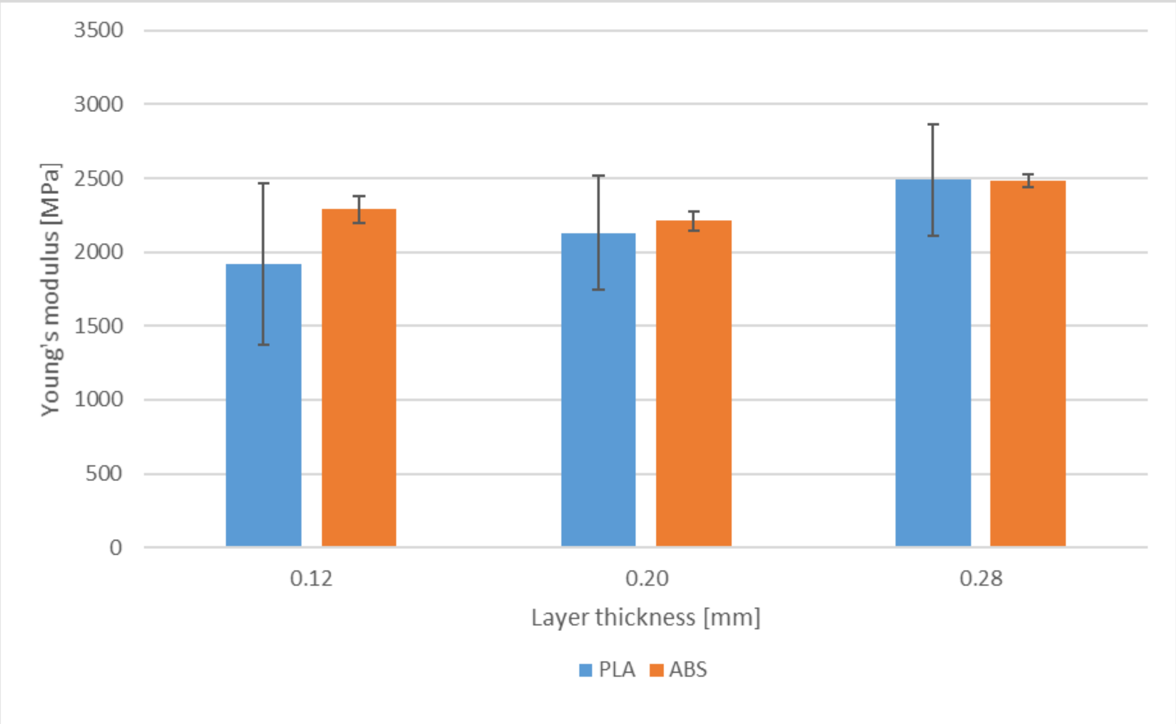


Figure 13. Average values of Young's modulus of PLA samples (blue) and ABS samples (orange) printed with 3D Gence, depending on layer thickness

Another parameter examined in this study was the influence of layer height on surface texture. Images of surface texture were captured and three selected surface roughness parameters: *Ra*, *Rz* and *Rq* were measured. The measurement was made on a square with the dimensions of 30 x 30 mm. Measurement parameters were collected from 5 selected points, the mean and standard deviations were determined.

Below are given the surface texture results of *PLA* samples printed with Ender 3. Figure 14 shows the end face and lateral surface of the samples. Tables 5 and 6 show 2D and 3D images of the two analyzed surfaces. The images show how the layers are arranged. Additionally, one can observe printing inaccuracies in the image of the lateral surface. The images captured with the T8000 RC120-400 device show that the layers are arranged in a barrel-like manner. This effect is best visible for the 0.12 mm layer

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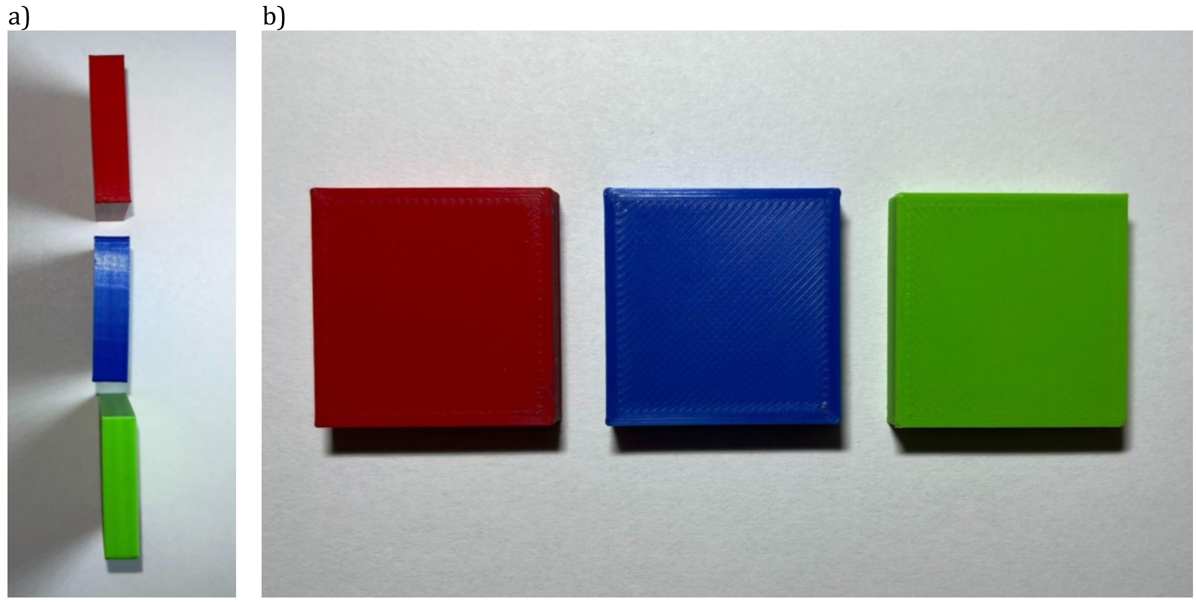


Figure 14. Samples used for surface roughness testing: a) lateral surface, b) end face surface

Table 5. 2D and 3D image of the final surface texture for different layer thicknesses printed on the Ender 3 printer from PLA material

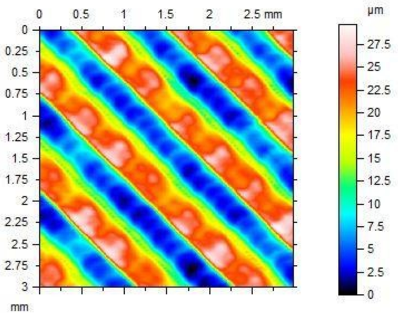
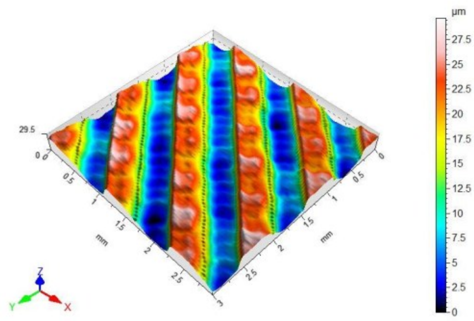
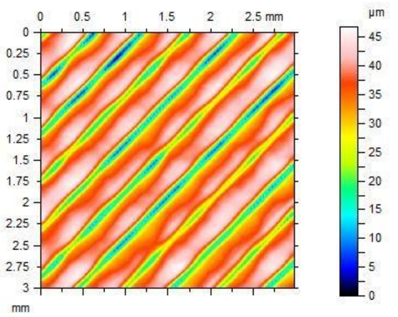
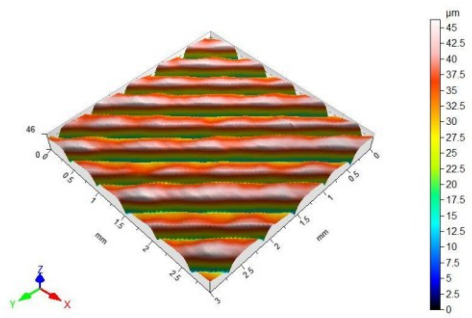
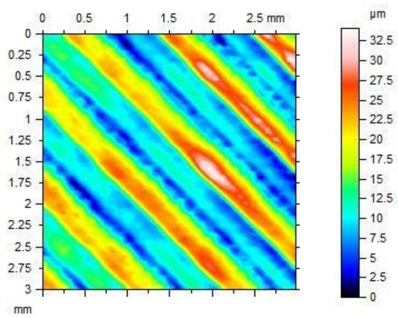
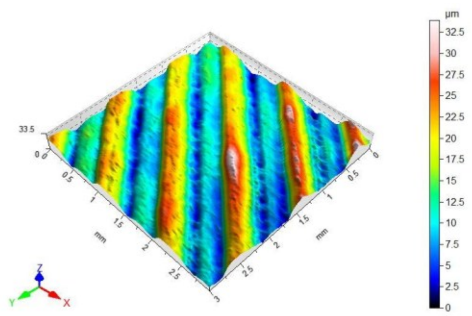
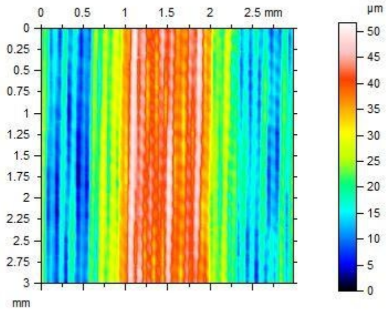
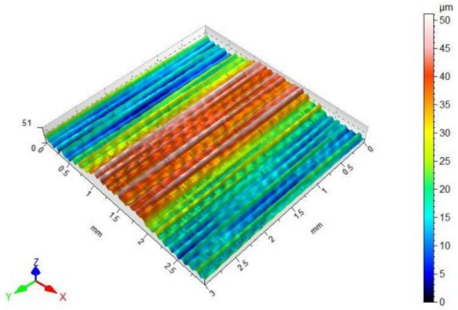
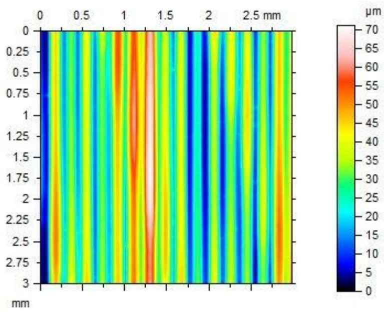
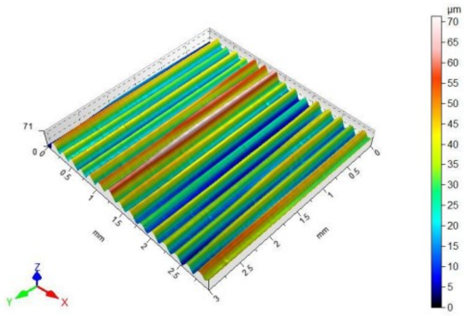
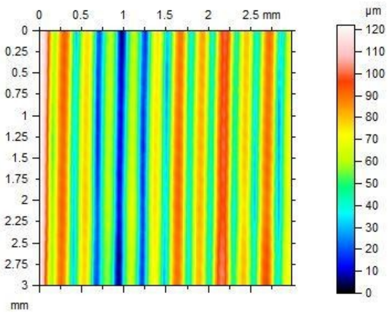
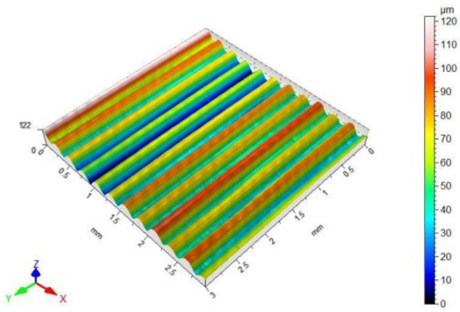
Layer thickness [mm]	2D image	3D image
0.12		
0.20		
0.28		

Table 6. 2D and 3D images of the lateral surface texture for different layer thicknesses printed on the Ender 3 printer from PLA material

Layer thickness [mm]	2D image	3D image
0.12		
0.20		
0.28		

An analysis of the results given in Tables 7–8 and Fig. 15 demonstrates that the lateral surface roughness increases with increasing layer thickness. This trend can easily be observed in the diagram in Figure 15 showing the results and the standard deviation.

Table 7. End face surface roughness of samples with different layer thicknesses

	0.12 [mm]			0.20 [mm]			0.28 [mm]		
	Ra [μm]	*Rz* [μm]	*Rq* [μm]	*Ra* [μm]	*Rz* [μm]	*Rq* [μm]	*Ra* [μm]	*Rz* [μm]	*Rq* [μm]
1	2.75	9.40	3.04	5.96	26.2	7.41	2.78	11.7	3.36
2	2.38	9.50	2.70	5.15	24.5	6.45	2.18	8.65	2.62
3	2.95	13.4	3.54	6.16	28.3	7.60	3.09	11.5	3.58
4	2.18	10.3	2.60	4.99	24.1	6.29	2.41	10.2	2.91
5	2.91	13.0	3.55	5.02	23.1	6.22	2.81	10.3	3.21

Average value	2.63	11.12	3.08	5.46	25.24	6.79	2.65	10.47	3.13
Standard Deviation	0.30	1.73	0.40	0.50	1,82	0.58	0.32	1.09	0.33

Table 8. Lateral surface roughness of samples with different layer thicknesses

	0.12 [mm]			0.20 [mm]			0.28 [mm]		
	Ra [µ]	*Rz* [µm]	*Rq* [µm]	*Ra* [µm]	*Rz* [µm]	*Rq* [µm]	*Ra* [µm]	*Rz* [µm]	*Rq* [µm]
1	3.54	18.9	4.36	8.75	36.6	10.2	15.9	59.1	17.9
2	3.40	18.3	4.16	8.60	35.5	9.98	15.9	58.5	17.9
3	3.92	21.6	4.88	8.56	37.0	9.96	15.4	57.9	17.4
4	3.43	18.1	4.34	8.55	36.8	9.92	15.3	57.6	17.2
5	3.32	17.3	4.12	8.34	34.8	9.57	15.5	59.1	17.4
Average value	3.52	18.84	4.37	8.56	36.14	9.92	15.6	58.44	17.56
Standard Deviation	0.21	1.47	0.27	0.13	0.85	0.20	0.25	0.61	0.29

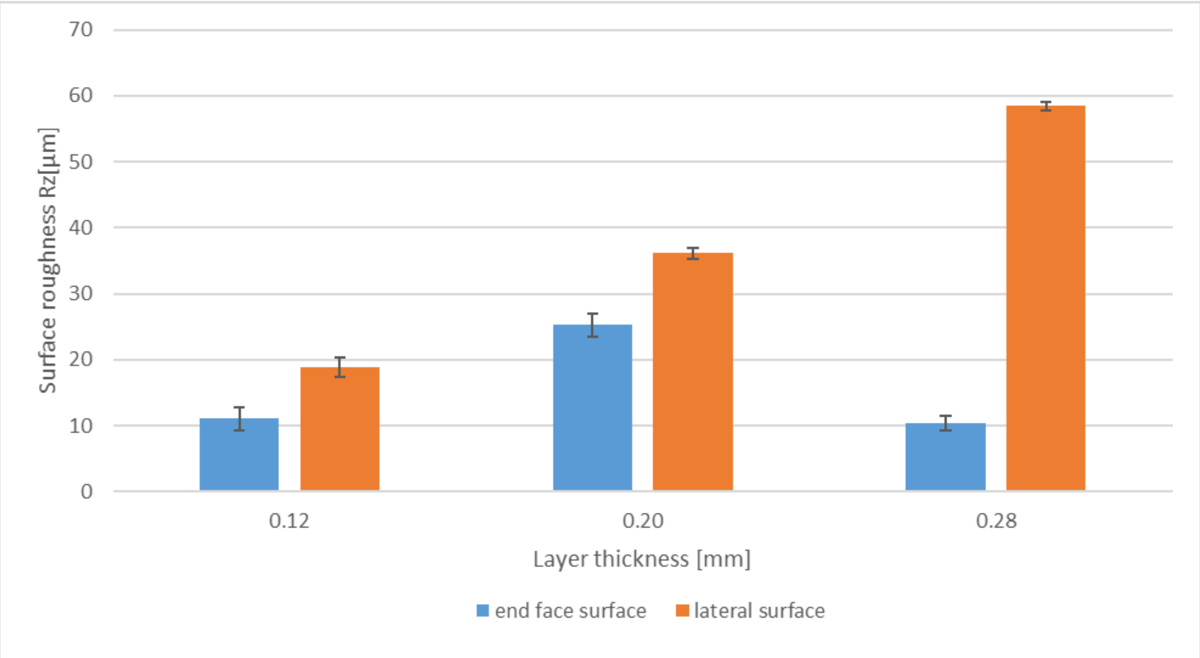


Figure 15. Layer thickness versus surface roughness parameter *Rz*

It is also worth noting that the end face surface of the sample with a layer thickness of 0.20 mm has much higher roughness compared to the samples with a layer thickness of 0.12 mm and 0.28 mm, respectively. Taking into account the standard deviation, it can be stated that the actual surface roughness of the samples changes significantly with increasing layer height.

5. CONCLUSIONS

This study has shown that the layer height of printed elements affects their quality. Considering the test results, it can theoretically be assumed that an increase in the layer thickness of a printed element may increase the tensile strength of the element.

The same situation can be observed with respect to Young's modulus. An increase in layer thickness leads to a higher Young's modulus value.

For the *PLA* material on the Ender 3 printer, the increase in layer height had a minimal effect on the change in the material's strength. The maximum difference was observed by comparing the layer thickness of 0.12 mm and 0.20 mm and it was 1 MPa. The maximum difference in strength for samples made of *PLA* material on the Gence 3D printer was 1.7 MPa. For samples made of *ABS* material, the maximum difference was 7.4 MPa.

For a sample made of PLA material on a Gence 3D printer, the value of Young's modulus increased as the layer height increased. The results showed that the increase in Young's modulus between along with the increase of the layer by 0.08 was around 14%. For samples made of PLA material on the Ender 3 printer, the difference between the smallest and largest measured value was 195 MPa. The maximum difference in the value of Young's modulus for the ABS material was 270 MPa.

The strength tests have also demonstrated that cracking would mostly occur at the end of rounding of the samples. This may result from the accuracy of the rounding itself. To make an arc, printers divide it into small straight sections. In future studies, an attempt should be made to make a more accurate arc because this could lead to higher stresses near the rounding.

The results of surface texture examination have shown that an increase in layer thickness leads to reduced accuracy of a printed element. The results have demonstrated a significant increase in the lateral surface roughness parameters with increasing layer height. The increase in the layer height from 0.12 mm to 0.20 mm increased the Rz parameter by 91%, while the difference in the surface roughness of the side layer with a layer thickness of 0.20 mm compared to 0.28 mm was 61%. In contrast, the same cannot be observed in the case of the end face surface. For this surface, the sample with a layer height of 0.20 mm had the highest roughness. However, given that the end face surface does not depend on layer height, it can be assumed that the layer height has a significant impact on surface roughness. It can be assumed that other external factors may have impact on this surface. This is an interesting observation that may encourage further studies in this field.

A comparison of the Ender 3 and DOUBLE P255 – 3DGence printers reveals an important fact. The produced samples have changed their printing parameters, namely – wall thickness, printing speed, as well as table and nozzle temperatures. These changes may have influenced the final results. An analysis of the maximum stresses and Young's moduli demonstrates that the Ender 3 printer yields their higher values than the 3DGence printer. Importantly, as the layer height increases, the differences between the printers become smaller. It is difficult to assess the impact of the above-mentioned parameters on this observation. In the future tests can be repeated with identical parameters.

The comparison of *PLA* and *ABS* samples, considering the standard deviation, showed the differences in strength and Young's modulus to be insignificant. However, it must be remembered that the printing process for ABS and that for PLA differ, the main differences being the temperature of the table and nozzle, the fact that ABS printing is performed in a closed chamber and requires the use of adhesive to ensure better adherence of the initial layers to the table. Nevertheless, it can be assumed that if a real difference exists, it may be insignificant.

To sum up, 3D printing is a very interesting technique that is widely used in industry, and the potential of this technique is increasingly researched by various institutions. The number of parameters affecting print quality is vast, which offers a wide scope for further research.

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