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PRELIMINARY STUDY OF THE AREAL ROUGHNESS PARAMETERS IN 3D PRINTING OF WORKPIECES OF PLA MATERIAL

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Abstract. *The field of production engineering is constantly expanding, as novel manufacturing procedures are being introduced and spread in the industrial environment. The creation of complex parts by the application of some kind of printing process is a relatively new method compared to the other traditional chip-removal processes. It can be applied in various fields, where the greatest advantage can be utilized, which is the lower restrictions on the geometry of finished parts. In this paper, the surfaces on 3D printed parts are being studied. The effect of the printing speed, layer height and nozzle temperature are analysed on the surface roughness of the experimental workpieces. The experimental setup plan is designed according to the full factorial design method. The results of this preliminary study are the general determination of the affecting factors on the surface roughness.*

Keywords: *3D printing; full factorial design; PLA; roughness height.*

1. Introduction

Additive Manufacturing (AM), also known as 3D printing (rapid prototyping) is mainly preferable technology in last decades because of it allowing the production of complex geometries with easier ways. The technology build parts by using layer-by-layer method that gets data from digital designs (stereolithography files), offering flexibility, customization, and cost-effectiveness in comparation with traditional methods [1–3]. In analysing materials used in 3D printing, Polylactic Acid (PLA) has high demand especially in desktop and hobbyist settings, as well as in industrial applications. PLA is a renewable, biodegradable thermoplastic made from natural resources such as corn starch or sugarcane. Its environmentally friendly properties combined with its low cost and ease of use, have made it a popular choice for AM. Because of its strong mechanical properties, PLA can be used for many types of purposes, such as tooling, end-use parts, and prototyping. On another side, PLA is a popular choice based on its compatibility with different 3D printing technologies, including Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). Its relatively low melting temperature minimal distortion during printing process, makes it an attractive option for both beginner and expert users [4–7]. In this situation, understanding and controlling the surface quality of printed parts is an important factor. Surface roughness plays an important role in determining the practical and aesthetic properties of printed polymer materials. To achieve a better surface finish is critical for applications where smoothness, precision, and visual appeal are required. The optimized surface roughness in polymer printing is essential factor to ensure the success of printed parts in different applications such as rapid prototyping, product development, medical devices and consumer goods. By optimizing printing parameters and applying different post-processing techniques, manufacturers and designers can improve surface quality, and reduce defects, which unlock new possibilities for additive manufacturing [8–11].

There are numerous studies in the literature that explored the factors influencing surface roughness in 3D-printed polymers [12]. The performed research works help to shed light on the limitations and complexities of this critical aspect of AM. For instance, the research work [13] investigated that how different layer thickness values in 3D printing affect the surface qualities of wood flour/PLA filament. This research work investigated that how different layer thickness values in 3D printing affect the surface qualities of wood flour/PLA filament. Reducing layer thickness value improved surface roughness, while increasing it improves wettability. The results suggested that a layer thickness – 0.2mm is ideal for balancing surface quality and production time in 3D printed wood/PLA examples. In the next article [14], the impact of layer thickness parameter on the surface properties of 3D printed materials was analysed specifically for wood flour/PLA filament composites. In realized investigations, three circular textures were printed and tested under dry and lubricated conditions. The findings showed that texture size has a substantial impact on the coefficient of friction which texture T2 (texture diameter 1.5 mm) had the lowest friction under dry conditions, while T3 (texture diameter 2 mm) performed best under lubricated conditions at low speeds. Similar to the previous one, the paper [15] explored the influence of layer thickness on the surface properties of printed materials which were produced from wood flour/PLA filament. It highlighted the importance of surface coatings in improving mechanical properties and also discussed the applications of coated 3D printed parts in several industries. The study also shows the importance of understanding surface characterization, especially in the case of printed polymeric parts. The next work [11] analysed how the layer thickness parameter affects the surface qualities of printed parts. The study seeks to optimize printing conditions by modifying process parameters such as layer thickness, nozzle temperature, and infill density in order to improve surface quality, tensile strength, and hardness of printed specimens. The final results demonstrated the need for parameter adjustment to get the necessary mechanical and surface properties in mass production. With the similar purpose – the article [16] investigated the impact of layer thickness parameter on the surface quality of polymer materials. In this research study, samples were printed with different layer height values (from 0.05 to 0.25) by using the "Creality Ender 3" printer. The obtained results showed that optimal parameters found at 0.15 mm and 0.20 mm for surface roughness and printing time. In addition, the paper [17] analysed the influence of different printing parameters on the surface properties of 3D printed denture base resins. And the study found that although printing orientation and post-curing time have little effect on the surface roughness, they have considerable effect on the hardness. 3D-printed denture base resins have reduced hardness than conventional heat-polymerized resins, however post-curing increases their hardness values. The placement of the parts to be printed also has an important factor in the result [18]. The geometry of the product significantly affects the resulting efficiency of the joint solution of the considered problems of technological process planning for additive manufacturing [19]. The following study [20] focused into the surface treatment of printed polymers using different coatings, focusing on visual aesthetics as well as environmental protection. Results showed that the characteristics of the substrate and the properties of the coatings have highly effect on the surface properties such as hydrophobicity, colour, gloss, and adhesion. In addition, understanding the relationship between substrate chemistry and coating composition is critical to achieve good surface finishes in additive manufacturing. The article [21] researched the influence of different fused filament fabrication 3D printing parameters on the printed surface of PLA polymers. The investigations were specifically focused on curved surfaces resembling hip prosthesis components. Performed ANFIS modelling demonstrated that layer height and nozzle diameter had a major impact on roughness, where smaller layer heights resulted in smoother surfaces. This study offered knowledge on optimizing 3D printing parameters to reduce surface roughness in complex, curved structures. The following study [22] compared the surface qualities of interim indirect resin restorations produced using CAD-CAM, 3D printing, and traditional methods. The observed results showed that 3D-printed resin restorations had similar flexural strength and micro-hardness to CAD-CAM-fabricated specimens, but much higher surface roughness. Studies suggested that 3D rapid prototyping technology is an appropriate option for the clinical production of provisional resin restorations. Additionally, the surface properties of ABS material printed by using fused deposition modelling were analysed in research work [23]. According to the gathered results, increased infill density and lower layer height parameters led to better surface roughness while increasing layer height results in rougher surface. Furthermore, a 0.06mm layer height and 100% infill density result in an optimum surface finish.

The main purpose of this study is to investigate the effect of different printing parameters, on the topography of FDM printed PLA parts. With analysing the results on the roughness, this research aims to provide a better understanding to optimize printing parameters to realize better surface quality for PLA parts.

2. Experimental conditions and methods

For the current research, all experiments were printed by using the "Qidi Tech X-CF Pro" 3D printer which is known for its high temperature and precise printing capabilities. The Qidi Tech X-CF Pro has a build volume of 300x250x300mm, which provides wide space for printing several complex geometries. With a heated build plate and a dual extrusion mechanism, this printer has the capability to print a wide range of filament types while providing optimal layer adhesion.

The printing material used in the production of all samples was PLA (biodegradable thermoplastic) which is known for its environmental friendliness and ease of use. This included nozzle temperature, printing speed, layer height, infill density, and etc which were set to get uniform printing results. Furthermore, the slicing software of the printer was used carefully to ensure that digital designs (in stereolithography file format) were accurately converted into physical items.

The experimental setup for this research work involved systematically changing printing parameters to investigate their impact on the surface roughness of printed PLA parts. Additionally, it should be also noted that the same PLA filament was used for all prints to eliminate material-related factors.

Table 1 illustrates the eight different experimental setups, where each of them is characterized by unique combinations of layer height (h_l), nozzle temperature (T_n), and printing speed (v_p).

The parameter combinations were selected based on their common use in 3D printing applications and their ability to affect surface roughness. By systematically changing the mentioned parameters and keeping other printing conditions constant, the main purpose was to analyse their individual effects on surface quality. The printed workpiece was designed to have a 6 mm x 6 mm flat surface. Each experimental setup was carried out two times, where the orientation of this flat surface changed: the to be studied surface was parallel to the base plate of the machine in the first case (hence this will be called “Horizontal” position) and it was perpendicular to the base plate in the second case (thus this will be called “Vertical” position). This resulted in 16 experimental setups overall.

After completing all the printing processes, all the samples were tested using a profilometry surface roughness test to evaluate their surface roughness. The necessary measurements were carried out after the experiments with an AltiSurf 520 three-dimensional topography measuring instrument using a triangulated laser probe.

Table 1 – Experimental setups

Setup	1	2	3	4	5	6	7	8
h_l [mm]	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3

T_n [°C]	210	210	230	230	210	210	230	230
v_p [mm/s]	60	60	60	60	90	90	90	90

In this study, the following roughness parameters are measured and studied (ISO25178-2:2012):

- S_{10z} – Ten-point height [μm], the average value of the heights of the five peaks with the largest global peak height added to the average value of the heights of the five pits with the largest global pit height.
- S_{5p} – Five-point peak height [μm], the average value of the heights of the five peaks with the largest global peak height.
- S_{5v} – Five-point pit height [μm], the average value of the heights of the five pits with the largest global pit height.

Equations were worked out for the analysis using the form in Equation 1 according to the 2^3 full factorial design method. The y is the dependent value and k_i are the coefficients describing the effect of the different factors on the dependent value. O represents the orientation of the specimen. The independent variables are the layer height (h_l), nozzle temperature (T_n) and printing speed (v_p).

$$y(h_l, T_n, v_p)^O = \mathrm{k}_0 + \mathrm{k}_1 h_l + \mathrm{k}_2 T_n + \mathrm{k}_3 v_p + \mathrm{k}_{12} h_l T_n + \mathrm{k}_{13} h_l v_p + \mathrm{k}_{23} T_n v_p + \mathrm{k}_{123} h_l T_n v_p \quad (1)$$

3. Experimental results

The workpieces were printed out and the surface topography are measured for each setup. The resulted profiles were evaluated, and the studied parameters were recorded. These values are shown in Table 2 and 3.

Table 2 – Measurement results of horizontally printed specimens

Setup	1	2	3	4	5	6	7	8
S_{10z} [μm]	39.5	95.6	55.8	165.9	62.5	133.1	45.0	159.9
S_{5p} [μm]	24.2	37.9	30.8	54.6	24.2	52.6	22.9	37.4
S_{5v} [μm]	15.3	57.8	25.1	111.3	38.3	80.4	22.1	122.5

Table 3 – Measurement results of vertically printed specimens

Setup	1	2	3	4	5	6	7	8
S_{10z} [μm]	102.5	225.6	107.6	400.0	53.7	160.1	70.9	240.3

S_{5p} [μm]	42.8	82.5	50.2	163.6	27.5	79.5	28.9	126.6
S_{5v} [μm]	59.7	143.0	57.4	236.4	26.2	80.6	41.9	113.7

The formulas in the form of Equation 1 are determined for the calculation of the ten-point height of the roughness. Equation 2 shows the result for horizontally printed specimens and Equation 3 presents the formula, which determines the vertically printed parts.

During the study of the surface roughness, the peak height and pit height parameters are analysed by the application of their ratios with the total height of the roughness profile. In this way the structure of the produced surface can be characterized in 3D printing as well.

$$S_{10z}(h_l, T_n, v_p)^H = 595.5 - 7422h_l - 3.132T_n + 4.879v_p + 36.64h_lT_n + 38.57h_lv_p - 0.02417T_nv_p - 0.1608h_lT_nv_p \quad (2)$$

$$S_{10z}(h_l, T_n, v_p)^V = 8102 - 38530h_l - 39.13T_n - 79.11v_p + 190.9h_lT_n + 366.2h_lv_p + 0.3742T_nv_p - 1.77h_lT_nv_p \quad (3)$$

Table 4 – Calculated ratios of the roughness parameters (horizontally printed specimens)

Setup	1	2	3	4	5	6	7	8
S_{5p}/S_{10z} [-]	0.61	0.40	0.55	0.33	0.39	0.40	0.51	0.23
S_{5v}/S_{10z} [-]	0.39	0.60	0.45	0.67	0.61	0.60	0.49	0.77

Table 5 – Calculated ratios of the roughness parameters (vertically printed specimens)

Setup	1	2	3	4	5	6	7	8
S_{5p}/S_{10z} [-]	0.42	0.37	0.47	0.41	0.51	0.50	0.41	0.53
S_{5v}/S_{10z} [-]	0.58	0.63	0.53	0.59	0.49	0.50	0.59	0.47

$$S_{5p} / S_{10z} (h_l, T_n, v_p)^H = 18.54 - 64.82h_l - 0.07686T_n - 0.2821v_p + 0.2768h_lT_n + 1.051h_lv_p + 0.001236T_nv_p - 0.004647h_lT_nv_p \quad (4)$$

$$S_{5v} / S_{10z} (h_l, T_n, v_p)^H = - 17.54 + 64.82h_l + 0.07686T_n + 0.2821v_p - 0.276h_lT_n - 1.051h_lv_p - 0.001236T_nv_p + 0.004647h_lT_nv_p \quad (5)$$

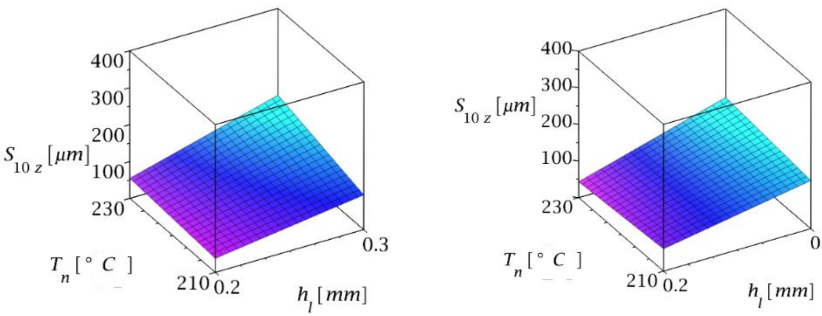
$$S_{5p} / S_{10z} (h_l, T_n, v_p)^V = - 9.212 + 28.65h_l + 0.04614T_n + 0.1518v_p - 0.142h_lT_n - 0.4761h_lv_p - 0.000719T_nv_p + 0.002325h_lT_nv_p \quad (6)$$

$$S_{5v} / S_{10z} (h_l, T_n, v_p)^V = 10.21 - 28.65h_l - 0.04614T_n - 0.1518v_p + 0.1423h_lT_n + 0.4761h_lv_p + 0.000719T_nv_p - 0.002325h_lT_nv_p \quad (7)$$

The ratios of the peak and total heights and the ratios of the pit and total heights are shown in Table 4 for horizontally printed specimens by the application of the data in Table 2. Equation 4 and 5 show the worked-out formulas for the calculation of these. Table 5 contain the beforementioned ratios for vertically printed parts based on the values of Table 3. Equation 6-7 presents the deducted equations in form of Equation 1, which will be further used in the analysis.

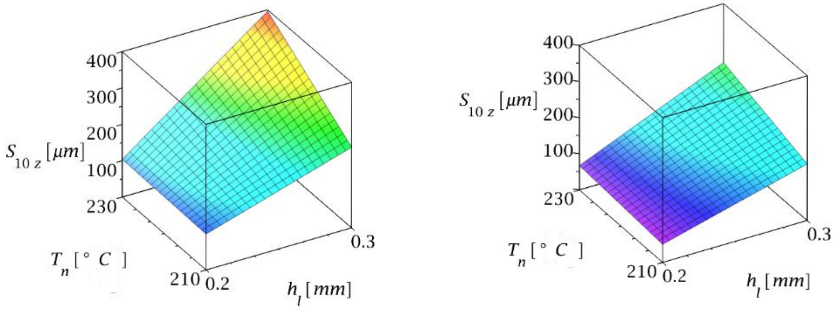
4. Discussion

The analysis of the effect of the setup parameters on the studied roughness parameters started with the evaluation of the total height (S_{10z}). Figure 1 shows the results of the parts which were printed horizontally, while Figure 2 presents the outcomes on vertically printed parts. The first observation, which can be confirmed, is the high impact on the printing direction. The roughness values of the horizontally printed parts are almost half of the result of vertically printed parts at 60 mm/s printing speed, and also lower (but with a lesser extent) at 90 mm/s.



v_p = 60 mm/s v_p = 90 mm/s

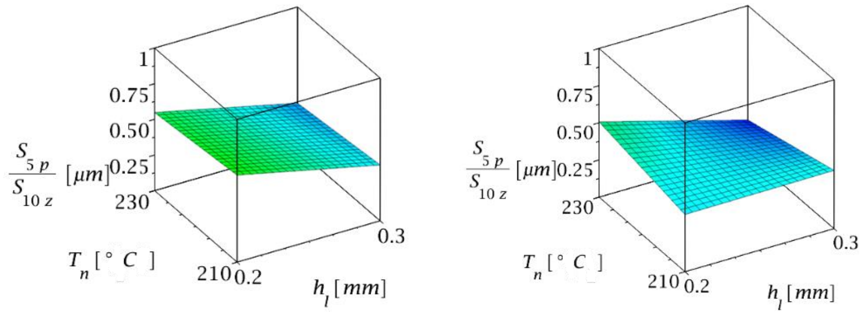
Figure 1 – Alteration of the S_{10z} on horizontally printed surfaces



v_p = 60 mm/s v_p = 90 mm/s

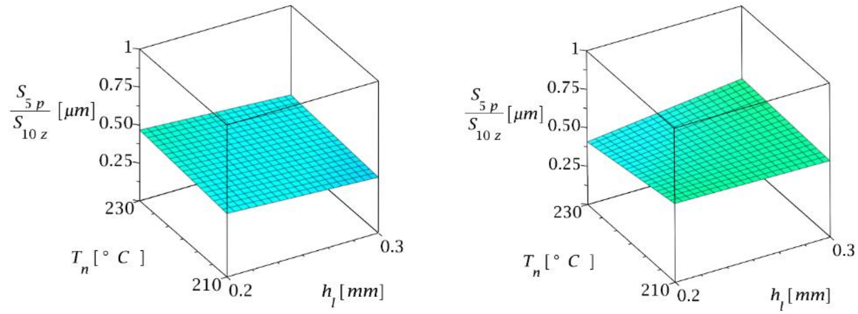
Figure 2 – Alteration of the S_{10z} on vertically printed surfaces

We identify based on the 16 setups, that increasing the layer height has a higher effect in vertical printing, while its have a lower increasing effect in horizontal printing. The previous statement can be easily seen, since the layer height means the periodicity of the profile in vertical printing, thus it has an increasing effect on the roughness. In horizontal printing, the layer hight should not have a direct effect on the roughness height, however its increasing effect can be observed here as well. Higher layer height alters the mechanism of the layering of the different material levels, which leads to a rougher surface. The nozzle temperature has also an increasing effect, because of the secondary plastic deformations, which occur in the before layered materials. Increasing the printing speed has no clear effect in horizontal printing, while it has a noticeable lowering effect in vertical printing. As we saw earlier, the contact characteristics between the previously layered sections and the recently printed material is important factor. If we increase the printing speed, we lower the contact time, which changes the secondary plastic deformations.



v_p = 60 mm/s v_p = 90 mm/s

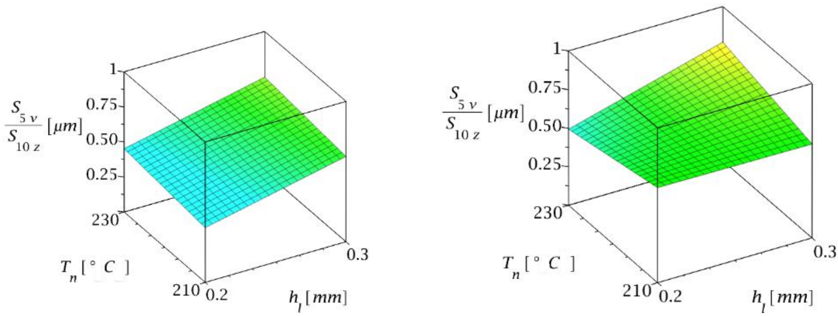
Figure 3 – Change of the peak to total height ratio on horizontally printed surfaces



v_p = 60 mm/s v_p = 90 mm/s

Figure 4 – Change of the peak to total height ratio on vertically printed surfaces

The study continued with the analysis of the beforementioned ratio parameters. Figure 3 and 4 shows the results of the ratios of the peak height and the total height in horizontally and vertically printed parts, while Figure 5 and 6 presents the pit height to total height ratios. Here we can also state that the printing direction has a significant effect on the composition of the total roughness height. The horizontally printed parts has higher pit heights while they have lower peak heights. This observation corresponds with the previously stated fact, that the horizontal printing has a lowering effect on the surface roughness. The characteristic of the surface profile changes as we alter the printing direction, which change leads to lower surface roughness. Among the analysed setup parameters, the layer height had the highest impact, which is followed by the printing speed in the point of view of the studied ratio parameters. It can be determined for a given application, which parameter setting would benefit more, if the task is to modify the surface topography characteristics. Higher peaks or higher pits can be achieved with the choice of the proper parameters.



v_p = 60 mm/s v_p = 90 mm/s

Figure 5 – Change of the pit to total height ratio on horizontally printed surfaces

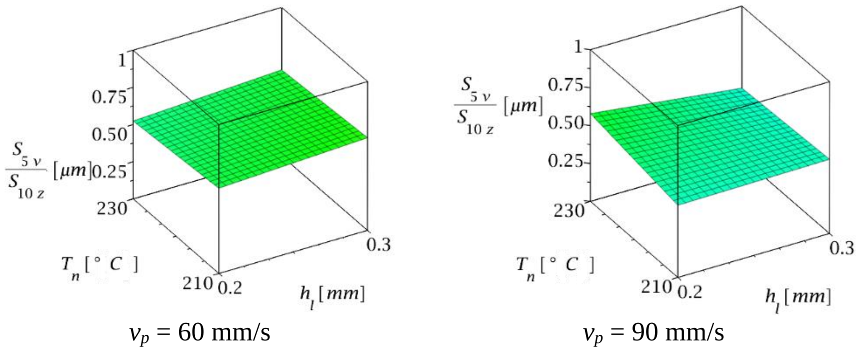


Figure 6 – Change of the pit to total height ratio on vertically printed surfaces

5. Conclusions

In this paper, 3D printing experiments were carried out to study the surface roughness of differently orientated parts, which values play an important role in the quality of the products. The nozzle temperature, the printing speed and the layer height is changed to analyse their effect. In the study of the results the following observations can be highlighted:

- The roughness values of the horizontally printed parts are almost half of the result of vertically printed parts.
- Increasing the layer height has a higher effect in vertical printing, while its have a lower increasing effect in horizontal printing.
- Increasing the printing speed has no clear effect in horizontal printing, while it has a noticeable lowering effect in vertical printing.

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ПОПЕРЕДНЄ ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ШОРСТКОСТІ ПОВЕРХНІ ПРИ 3D-ДРУКУ ЗАГОТОВОК З МАТЕРІАЛУ PLA

Анотація. *Сфера виробничої інженерії постійно розширюється, оскільки нові виробничі процедури впроваджуються і поширюються в промисловому середовищі. Створення складних деталей шляхом застосування певного процесу друку є відносно новим методом у порівнянні з іншими традиційними процесами виготовлення, пов'язаними з видаленням стружки. Він може застосовуватися в різних галузях, де найбільшою перевагою є менші обмеження на геометрію готових деталей. У цій роботі досліджуються поверхні на 3D-друкованих деталях. Проаналізовано вплив швидкості друку, висоти шару і температури сопла на шорсткість поверхні експериментальних заготовок. План експериментальної установки розроблений відповідно до методу повного факторного планування. Результатом цього попереднього дослідження є загальне визначення факторів, що впливають на шорсткість поверхні. У цій статті проведено експерименти з 3D-друку для дослідження шорсткості поверхні різноорієнтованих деталей, значення якої відіграють важливу роль у якості продукції. Тут можно констатувати, що напрямок друку має значний вплив на склад загальної висоти шорсткості. Горизонтально надруковані деталі мають більшу глибину ямок, тоді як вони мають* *меншу висоту піків. Це спостереження узгоджується з раніше встановленим фактом, що горизонтальний друк має знижувальний вплив на шорсткість поверхні. Характеристика профілю поверхні змінюється при зміні напрямку друку, що призводить до зниження шорсткості поверхні. Серед проаналізованих параметрів налаштування найбільший вплив має висота шару, за якою з точки зору досліджуваних параметрів співвідношення слідує швидкість друку. Для конкретного застосування можна визначити, яке налаштування параметрів принесе більше користі, якщо завданням є зміна характеристик рельєфу поверхні. Для аналізу їх впливу змінювали температуру сопла, швидкість друку та висоту шару. При вивченні результатів можна виділити наступні спостереження: значення шорсткості горизонтально надрукованих деталей майже вдвічі менші, ніж у вертикально надрукованих деталей; збільшення висоти шару має більший ефект при вертикальному друці, тоді як при горизонтальному – менший; збільшення швидкості друку не має чіткого ефекту для горизонтального друку, тоді як для вертикального друку має помітний ефект зниження.*

Ключові слова: *3D-друк; повний факторний план; PLA; висота шорсткості.*