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The Effect of Layer Thickness and Orientation of the Workpiece on the Micro- and Macrogeometric Properties and the Machining Time of the Part during 3D Printing

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Abstract

3D printing technologies have developed significantly over the last 30 years, with a major impact on all segments of today's industry. With the introduction of additive manufacturing, product development time can be greatly reduced and printing functional parts directly is also a viable option. Another advantage of additive manufacturing is that it allows greater design freedom than traditional manufacturing technologies. This makes it possible to print products with complex geometries and even different material qualities. In this paper, the authors investigated the effects of printing time, the layer thickness and the orientation on the surface roughness and cylindricity of the printed parts. The aim is to find the combination of layer thickness and part orientation which causes the best results in terms of surface roughness and cylindricity as a function of printing time.

Keywords

3D printing, FDM, surface roughness, cylindricity, PLA, printing costs

1 Introduction

The development of 3D printing processes has changed every segment of the automotive industry today. Additive Manufacturing (AM) also offers the possibility to produce test and finished parts, reducing product development time and costs [1] while producing higher quality parts. This technology is used in concurrent engineering, where different tasks are tackled at the same time, and not necessarily in the usual order [2, 3]. This allows the product to be tested in both real and in simulation environments. This process leads to significant competition between companies [4, 5].

Additive Manufacturing also known as 3D printing, is the process of producing the required parts layer by layer based on models produced by Computer Aided Design (CAD) [6, 7]. These technologies allow greater design freedom than traditional manufacturing. One such design freedom is generative design, which allows conventional parts to be replaced by lighter parts with matching or identical strength characteristics. In addition, 3D printing processes offer the possibility to print complex parts without assembly [8, 9], even from multiple materials (e.g. composites) [10]. This allows car manufacturers to achieve significant weight reductions to comply with increasingly stringent emissions regulations, and to save on substantial assembly costs [11]. In other words, Additive Manufacturing made it possible to build lighter, safer and environmentally friendly cars [12].

There are many studies comparing 3D printing processes, but the most comprehensive study was carried out by Hanon et al. [8]. The most common 3D printing processes in the industry were compared in terms of accuracy, printable size, post-processing, number of raw materials, machine size and price of the machine. It was found that, based on these factors, the FDM 3D printing process is the most favorable overall. Based on this research work, FDM 3D printing technology was selected for the experiments in this paper, because it is a relatively cheap process compared to other processes and has a wide range of available materials, therefore it is widely used in the industry. Its accuracy falls short compared to some processes, but if the functional surfaces are not printed ready-to-use, but

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are post-machined (such as threads), and a precise and aesthetically outstanding finish on the rest of the part is not a requirement, it can be an excellent choice.

In FDM 3D printing, the thermoplastic polymer filament is extruded while the extruder head moves along the "*x*-*y*" axes on a given cross-sectional layer of the model to be printed. Once a layer is created, the whole platform is lowered by the layer thickness in the "*z*" direction and the process is repeated until the whole model is created [13–16].

This paper presents a preliminary study to investigate the effect of layer thickness and object orientation on the surface roughness, cylindricity and machining time of a printed workpiece. The aim is to determine the combination of layer thickness and part orientation which causes the best results in terms of surface roughness and the smallest form error as a function of printing time. For cylindricity, each point on the real cylindrical surface must be located between two coaxial cylindrical surfaces with a radius difference of the specified tolerance [17], as shown in Fig. 1.

2 Methodology

2.1 3D printer and printing methods

The test pieces were printed on a Prusa I3 3D printer. The parts were printed from thermoplastic Polylactic Acid (PLA) [18], the property ranges of which are shown in Table 1 [13, 19].

A total of 8 cylindrical test pieces of Ø 20 × 50 mm were printed. 4 of these were in vertical orientation and 4 in horizontal orientation, as shown in Fig. 2.

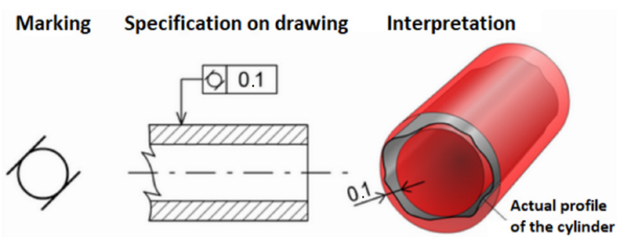
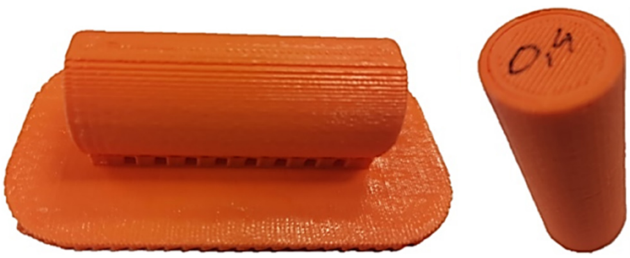


Fig. 1 Interpretation of cylindricity, adapted from [17]

Table 1 Property ranges for PLA materials [13, 19]

Properties	PLA
Tensile strength (MPa)	15.5–72.2
Tensile modulus (GPa)	2.020–3.550
Elongation at break (%)	0.5–9.2
Flexural strength (MPa)	52–115.1
Flexural modulus (GPa)	2.392–4.930
Printing temperature (°C)	190–220
Printing speed (mm/s)	40–90



(a) (b)

Fig. 2 Printed workpieces: (a) horizontal, (b) vertical

The cylinder was modelled and the STL file was exported in the CAD software Solid Edge. During the exporting the angle subtended by the planes was 3° and the tolerance was 0.05 mm. Printing was done with 30% density gyroid type infill, which gives the highest strength of all with minimal material consumption [20].

For the horizontally oriented workpieces, it was also necessary to design the support material for manufacturability, which was designed in places with up to 40° inclination. This is shown with the gyroid infill in Fig. 3.

Due to manufacturing characteristics, the number of top and bottom layers has been increased, otherwise the filling part would start earlier and the workpiece would not conform during machining. Therefore, the lathe knife will certainly not encounter the printed infill of the model during the turning experiment. This can also cause errors, as the concentricity of the walls during printing can only be ensured layer by layer. For the unsupported parts, where the wall is supposed to be steep enough, it was necessary to use active cooling because without it the layers became misaligned, as shown in Fig. 4.

The printing parameters are shown in Table 2.

2.2 Surface roughness measurement

The surface roughness of the printed parts was measured by Mitutoyo Formtracer SV-C3100 tactile roughness tester according to MSZ EN ISO 4287:2002 [21] and the results were evaluated in Microsoft Excel.

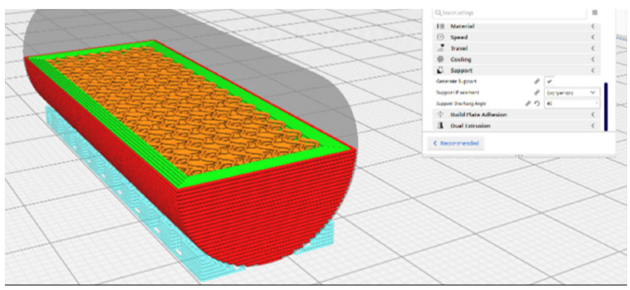


Fig. 3 Production planning for the horizontally oriented workpieces
Note: horizontal orientation, 0.4 mm layer thickness

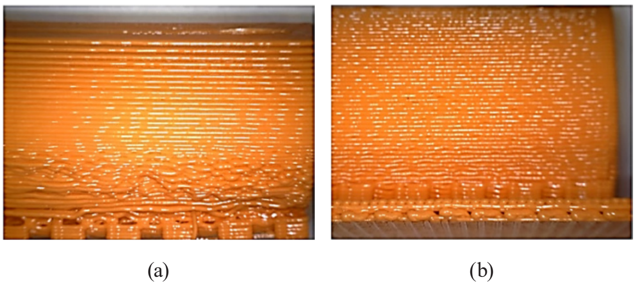


Fig. 4 Printed part (a) without active cooling, (b) with active cooling

Table 2 Printing parameters

Properties	Values
Layer thickness (mm)	0.05; 0.1; 0.2; 0.4
Wall thickness (mm)	2.5
Filling density (%)	30
Printing temperature (°C)	215
Printing speed (mm/s)	40
Fill printing speed (mm/s)	190–220
Active cooling	–

2.3 Cylindricity measurement

Deformation was measured in a prism using a Mitutoyo 543-270B dial indicator with an accuracy of 0.01 mm, measuring the dimensional deviation from the nominal size. The measurement was taken from the end of the workpiece in three planes at 5, 10 and 15 mm. Four measurements were taken in each plane at 0°, 90°, 180° and 270°, as illustrated in Fig. 5 and the results were evaluated in Microsoft Excel.

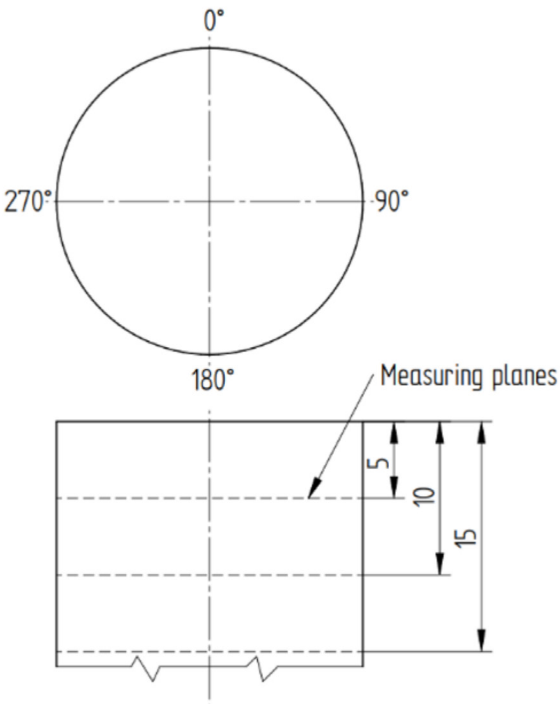


Fig. 5 Principle of measurement

3 Results

3.1 Result of printing time and surface roughness measurement

Printing times as a function of layer thickness and average surface roughness in case of vertical orientation are shown in Table 3.

The average surface roughness as a function of layer thickness and printing time in case of vertical orientation are shown in Fig. 6 and Fig. 7.

Printing errors can be observed when the object is printed with a layer thickness of 0.4 mm, as shown in Fig. 8. This is the reason why the upper limit of the thickness is 0.4 mm.

Table 3 Printing times and surface roughness as a function of layer thickness for vertical orientation

Printing time t (h)	Layer thickness s (mm)	Average surface roughness Ra (μm)
4.58	0.05	7.981
2.28	0.1	11.064
1.15	0.2	12.803
0.58	0.4	24.552

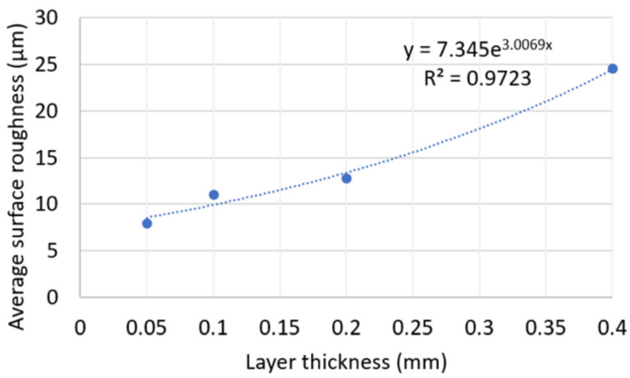


Fig. 6 Average surface roughness as a function of the layer thickness in case of vertical orientation

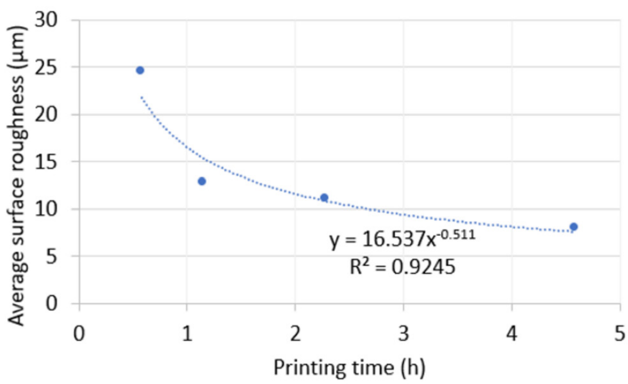


Fig. 7 Average surface roughness as a function of the printing time in case of vertical orientation

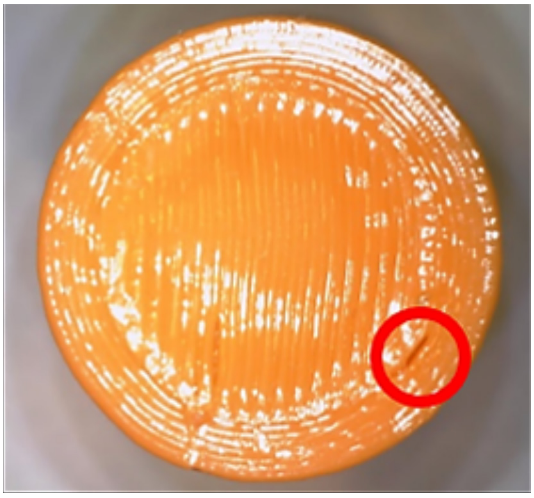


Fig. 8 Printing failure, Note: 0.4 mm layer thickness, vertical orientation

Printing times as a function of layer thickness and average surface roughness in case of horizontal orientation are shown in Table 4.

The average surface roughness as a function of layer thickness and printing time in case of horizontal orientation are shown in Fig. 9 and Fig. 10.

3.2 Results of cylindricity measurement

The deviation from nominal dimensions and calculated tolerance as a function of layer thicknesses and printing times for objects in case of the vertical orientation are shown in Table 5 and Figs. 11, 12.

Table 4 Printing times and surface roughness as a function of layer thickness for horizontal orientation

Layer thickness *s* (mm)	Printing time *t* (h)	Average surface roughness *Ra* (µm)
0.05	4.9	1.895
0.1	2.47	0.651
0.2	1.27	1.785
0.4	0.63	1.721

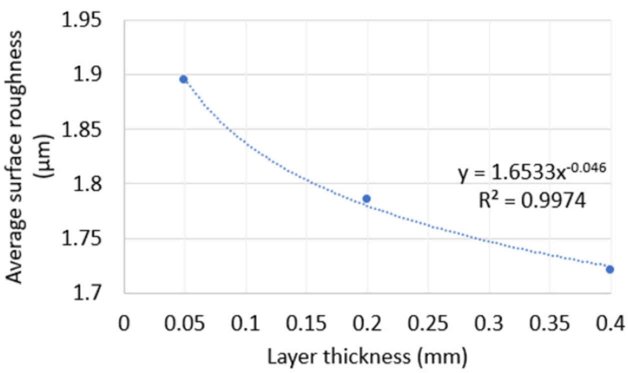


Fig. 9 Average surface roughness as a function of the layer thickness in case of horizontal orientation

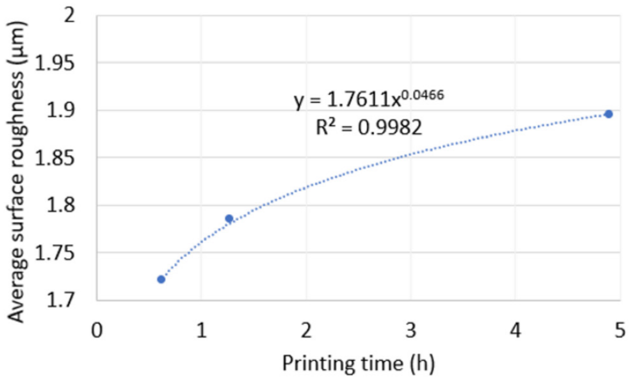


Fig. 10 Average surface roughness as a function of the printing time in case of horizontal orientation

Table 5 Deviation from nominal size and calculated tolerance as a function of layer thickness for vertical orientation

Layer thickness (mm)	Lower limit size (mm)	Upper limit size (mm)	Tolerance field width (mm)
0.05	−0.155	0.002	0.157
0.1	−0.091	0.06	0.151
0.2	−0.035	0.111	0.146
0.4	−0.3	−0.178	0.122

The deviation from nominal dimensions and calculated tolerance as a function of layer thicknesses and printing times for specimens in case of the horizontal orientation are shown in Table 6 and Figs. 13, 14.

4 Analysis

4.1 Results of printing time and surface roughness measurement

As illustrated in Table 3 and Table 4, the printing time decreases with increasing layer thickness for both part orientations. For all layer thicknesses, it can be said that a longer printing time was required for the objects in the horizontal orientation. This was due to the printing of the support material.

For the test objects printed in vertical orientation, Fig. 6 shows that surface roughness degradation increases exponentially with increasing layer thickness. As these parts will be finished by turning, it follows that printing with a layer thickness of 0.4 mm would be the most efficient way to minimize printing time (Fig. 7) and therefore cost, but as shown in Fig. 8, it results in printing errors. In the case of 0.1 mm and 0.2 mm layer thickness, a negligible increase in roughness occurred, but the printing time has been halved, so a 0.2 mm layer thickness should be chosen for vertically oriented workpieces.

For the objects in the horizontal orientation, the above-mentioned trend is not applicable, since essentially

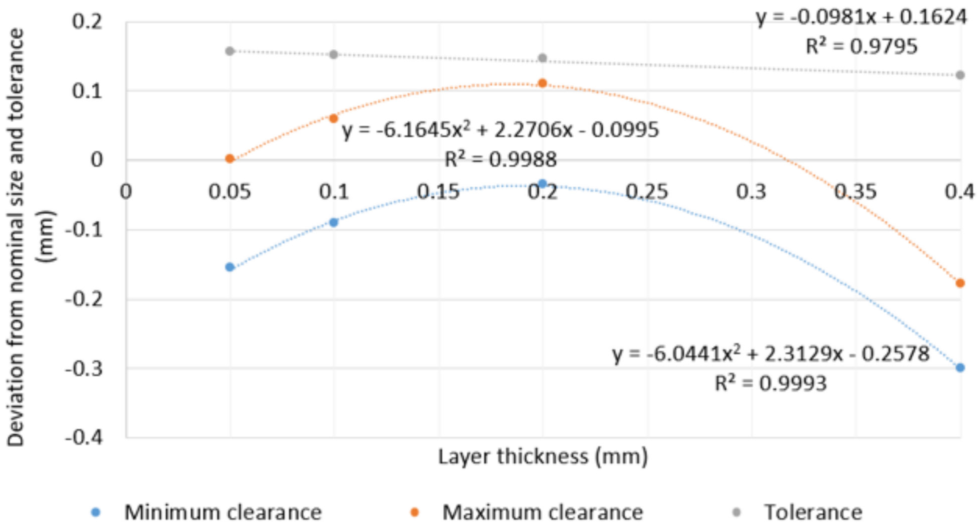


Fig. 11 Deviation from nominal size and calculated tolerance as a function of layer thickness in case of vertical orientation

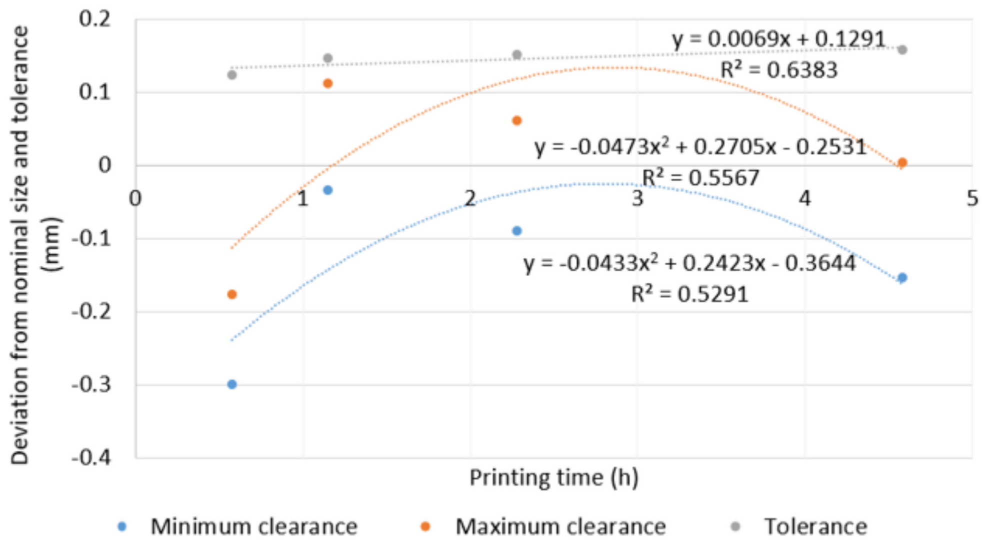


Fig. 12 Deviation from nominal size and calculated tolerance as a function of printing time in case of vertical orientation

Table 6 Deviation from nominal size and calculated tolerance as a function of layer thickness for horizontal orientation

Layer thickness (mm)	Lower limit size (mm)	Upper limit size (mm)	Tolerance field width (mm)
0.05	−0.097	0.296	0.393
0.1	0.012	0.352	0.34
0.2	0.095	0.36	0.265
0.4	0.343	0.688	0.345

the surface roughness decreases only minimally with increasing layer thickness, as illustrated in Fig. 9. For a layer thickness of 0.1 mm, a large reduction in roughness is observed, however, the printing time was quite high as shown in Fig. 10. Since the intersection of the printing time and the average surface roughness curve is closer to the 0.2 mm layer thickness value, this value can be considered the optimum for printing in horizontal orientation.

In the end, the results of the 2 orientations cannot be compared, because while in the vertical orientation the measurements were taken perpendicular to the printed layers, in the horizontal orientation the measurements were taken parallel to the layer orientation. This is due to the large difference in roughness between the two orientations.

4.2 Results of cylindricity measurement

For objects with a vertical orientation, it can be generally stated from Figs. 11, 12 and Table 5 that the deviation from the nominal size increased in the negative direction with increasing layer thickness and printing time. Also observed that as the layer thickness increased, the width of the tolerance decreased, so if we can compensate for this dimensional difference in the design, we can produce items faster and more accurately with a narrower tolerance field.

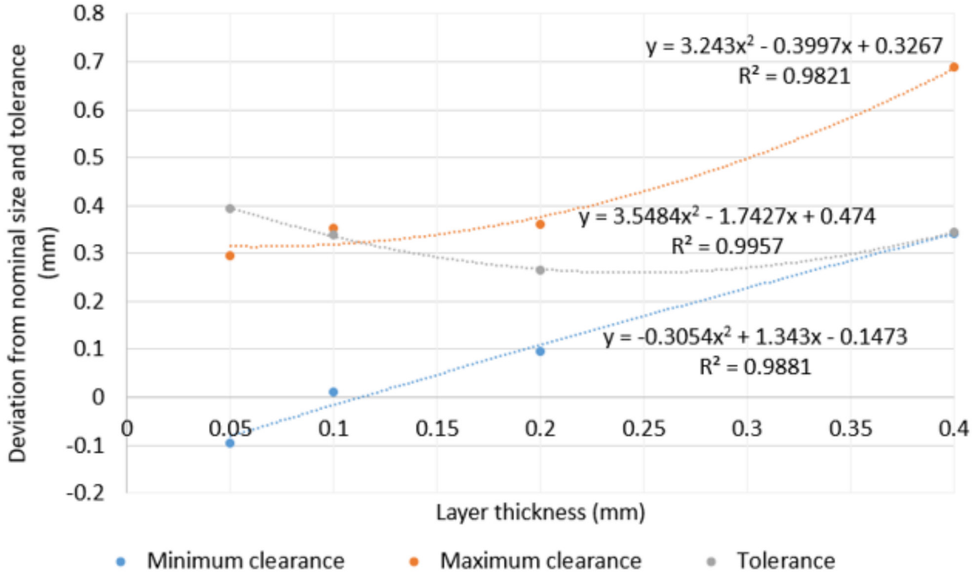


Fig. 13 Deviation from nominal size and calculated tolerance as a function of layer thickness in case of horizontal orientation

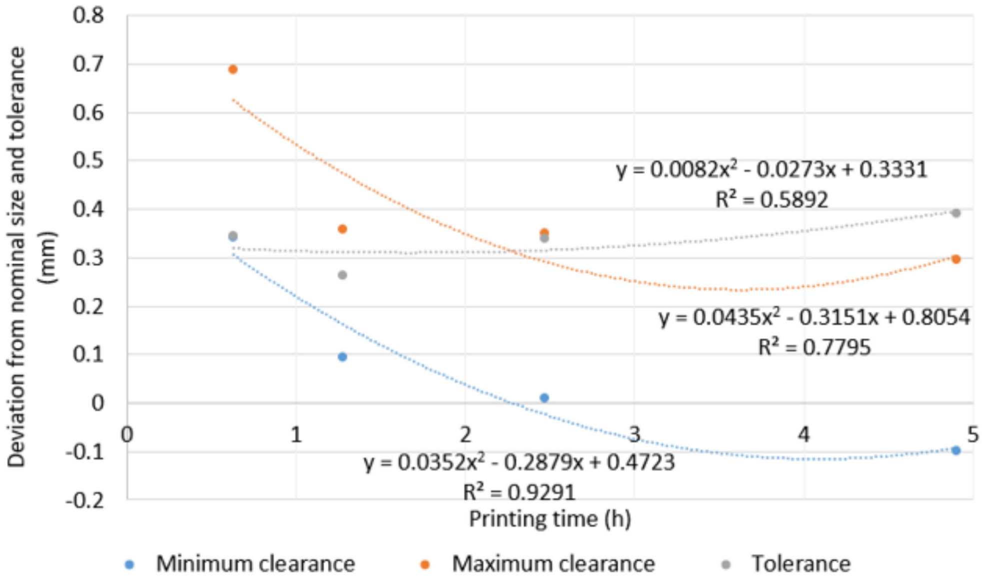


Fig. 14 Deviation from nominal size and calculated tolerance as a function of layer thickness in case of horizontal orientation

For objects in the horizontal orientation, it can be observed on Figs. 13, 14 and Table 6 that the dimensional deviation from the nominal size increased with increasing layer thickness and printing time. At the same time, the tolerance is reduced to a minimum, but an optimum can be seen at a layer thickness of 0.2 mm.

5 Conclusion

Figs. 15 and 16 show comparisons of the deviation from nominal size and tolerance obtained when printing in vertical and horizontal orientation.

Based on the factors examined in the case of this geometry, it can be said that printing in vertical orientation gave a better result. As it can be seen in Fig. 15, the deviation from nominal size is twice as large for the horizontally printed objects than for the vertical printed ones. Fig. 16 shows the evolution of the tolerance as a function of layer thickness for horizontal and vertical orientation. It can be observed that for all layer thicknesses, the tolerance is almost three times higher for the horizontal orientation than for the vertical orientation. Therefore, the process is three times more inaccurate for cylindrical objects in a horizontal orientation.

Moreover, in the case of vertical orientation, with the same layer thickness, shorter printing times were needed, allowing more accurate production. In the case of a

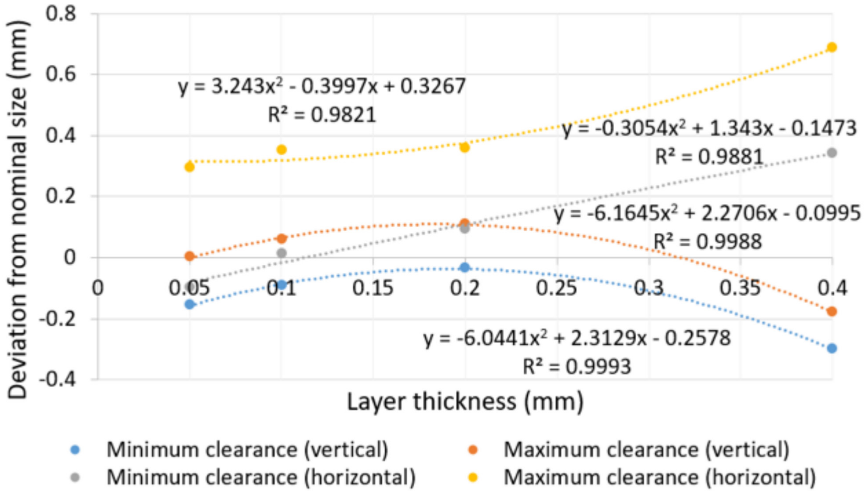


Fig. 15 Comparison of the deviation from nominal size in case of vertical and horizontal orientation

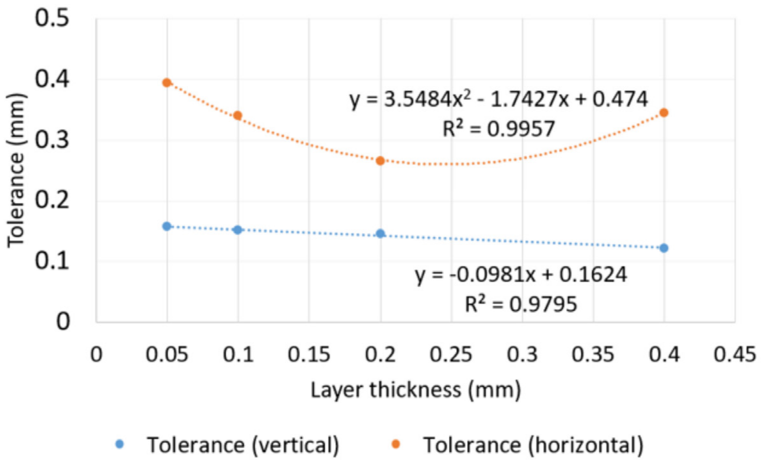


Fig. 16 Comparison of the tolerance in case of vertical and horizontal orientation

workpiece with a horizontal orientation, the support material must be removed, which degrades the surface quality and increases the manufacturing time.

For a vertically oriented object, the optimum print thickness is 0.2 mm as a function of printing time, since the average surface roughness obtained for 0.1 mm layer thickness is only slightly less than that obtained for 0.2 mm layer thickness, but the required printing time is reduced by almost half. Moreover, the accuracy improved between the two layer thicknesses, which generally decreased with increasing layer thickness.

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