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Investigation of Printing Speed Impact on the Printing Accuracy of Fused Filament Fabrication (FFF) ABS Artefacts

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This paper introduces a customized Fused Filament Fabrication (FFF) printer, featuring an advanced electromechanical system that achieves a substantial 500% increase in printing speed compared to conventional FFF printers. This research scrutinizes the printer's capabilities, emphasizing the dimensional accuracy. Specifically, this study focuses on the investigation of the effect of high printing speeds on the dimensional accuracy of linear artifacts. The material selected is Acrylonitrile Butadiene Styrene (ABS) and the FFF-fabricated parts are designed and measured based on the ISO ASTM 52902-2021 standard. Last but not least, statistical analysis and comments are following, showing remarkable results on such high-speeds.

Keywords: High-Speed Fused Filament Fabrication, Printing Speed, Dimensional Accuracy, ABS

1 Introduction

Fused Filament Fabrication (FFF) is a 3D printing method, in which the fabricated object is built layer-by-layer. Specifically, thermoplastic filament is melted and then extruded through a nozzle on the building bed over the previously previously solidified layer [1], [2]. The most important advantage of this method is its ability to fabricate highly customized and lightweight objects with very complex geometries [3].

The above advantages make FFF a very promising method for the fabrication of products in aerospace, electronics, biomedical, construction and automotive industries [4]. Nevertheless, FFF has not been adopted yet by the industry due to its high printing times required [5]. For this reason, researchers try to develop high-speed 3D printers. Czyżewski et al. [6] used a larger diameter nozzle of 0.8 [mm] and 1.2 [mm] instead of the standard 0.4 [mm] nozzle in FFF printing and doubled the printing speed, by achieving faster extrusion rates. Chauvette et al. [7] used of four-nozzle system in FFF and achieved printing speeds up to 250 [mm/s], with a flow rate of approximately 320 [mm^3/s]. Allen et al. [8] introduced a parallel robot in the FFF system and achieved printing speeds of up to 300 [mm/s].

Such a high-speed FFF printer has also been developed by the researchers of the Laboratory of Manufacturing Technology of the School of Mechanical Engineering of National Technical University of Athens (NTUA). The novelty of this FFF printer is its advanced electromechanical system that allows excellent controllability of the nozzle movement and the filament deposition, which allows it to achieve speeds up to 350 [mm/s] with minimum losses regarding the quality and mechanical strength of the fabricated object. This high-speed FFF printer has already been optimized regarding its construction and the optimization methodology has already in published in [9]. Now, a second phase regarding the development of this printer has started which include the testing of the dimensional accuracy at such high-speeds.

Dimensional accuracy has already been studies for traditional low-speed (up to 80 [mm/s]) FFF systems. Agarwal et al. [10] studied the dimensional accuracy of ABS specimens manufactured with FFF with different printing speeds and layer heights. They showed that for relatively simple models, the highest dimensional accuracy is specifically achieved by using high printing speeds and low layer heights. Alexopoulou et al. [11] fabricated resolution holes with different printing speeds and they showed that low-cost FFF printers can achieve high repeatability, but not so good accuracy. However, these studies were limited to low printing speeds and thus there is no kwowledge regarding the achievable dimensional accuracy when printing with very high speeds and how much does this diverge compared to the accuracy achieved by low-speed printers.

The target of this paper is to test the performance of the FFF printer, developed by the authors of this study, regarding its dimensional accuracy under very high speeds. Specifically, linear ABS artefacts are printed according to the ISO ASTM 52902-2021 standard with different printing speeds (50, 100, 150, 200, 250, 300 and 350 [mm/s]). The novelty of the current paper is that it correlates high printing speeds with the achieved dimensional accuracy and it compares it with the results of conventional printing speeds (50 [mm/s]).

2 Experimental Methods

According to the ISO ASTM 52902-2021, the FDM-printed linear artifacts (Fig. 1) consist of two different protrusion thicknesses (5 [mm] and 2.5 [mm]) and four different protrusion spacings (5 [mm], 7.5 [mm], 10 [mm] and 12.5 [mm]) which have been printed on the in-house built high-speed additive manufacturing machine of the laboratory. The linear artifacts were chosen from the ISO for their design, print and measurement simplicity. Printing speed is the investigated process parameter and was chosen so that it would cover a wide range of the abilities of the current 3D printer. Extruding Nozzle Temperature and Build Platform Temperature were chosen regarding the authors' previous experience with ABS. Below, in Table 1, more information on the printing settings can be found.

Tab. 1 *Printing Settings and their values used in the current study*

Printing Settings	Values of printing settings
Printing Speed (mm/s)	Variable
Extruding Nozzle Temperature [ºC]	245
Build Platform Temperature [ºC]	100
Layer Height (mm)	0.1
Infill Pattern	Lines
Infill Density	100%
Wall Number of Lines	3

Each specimen was printed five times, for each speed setting, so in total there have been printed 35 specimens. The measurements for each protrusion thickness and protrusion spacing were in total 315. The measurements were carried out with a digital handheld caliper as the ISO ASTM 52902-2021 suggests for protrusion thickness and spacing measurements. Each area was measured in three different points, in order to eliminate the human error.

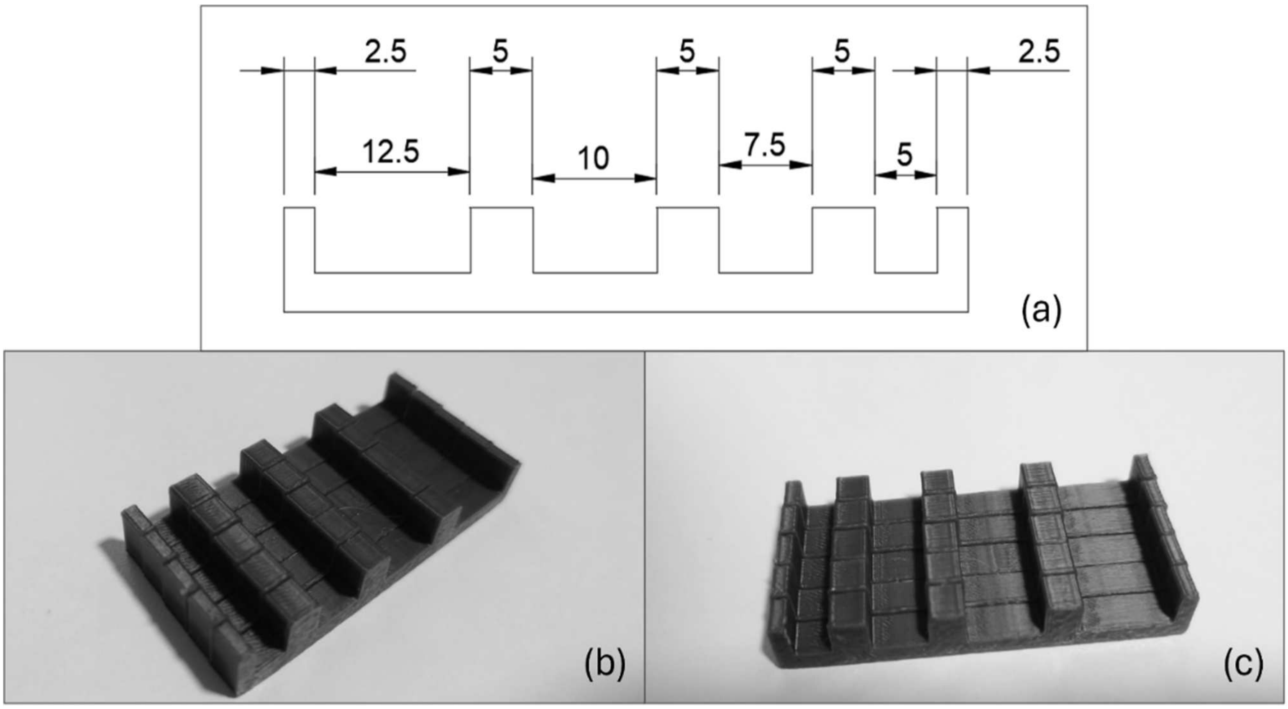

Fig. 1 *FDM-printed linear artifacts; (a) Dimensions of the linear artifact can be seen (all dimensions in [mm]); (b) Perspective view of five printed specimens; (c) Perspective view of five printed specimens under different lighting conditions*

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3 Results and Discussion

The experimental results for the different printing speeds, protrusion thicknesses and protrusion spacings are given, respectively, in Tab. 1 and Tab. 2 below.

As it is observed in Tab. 1 and Tab. 2, the dimensional accuracy achieved with the high-speed printer is very high, as all the errors from the nominal values are below 6%, which are in the same range of errors achieved and by conventional printers [9]. So, the current FFF high-speed printer is valid to be used for the manufacturing of linear artefacts with very high accuracy.

However, for optimization reasons, a correlation of the printing speed, protrusion thickness and protrusion spacing with the dimensional accuracy achieved, is analyzed below (Fig. 2 and Fig. 3).

Tab. 2 *Protrusion Thicknesses for different Printing Speeds*

Printing Speed [mm/s]	Protrusion Thickness (nominal: 2.5 [mm])/Error (%)	Protrusion Thickness (nominal: 5 [mm])/Error (%)
50	2.43/2.8	4.88/2.4
100	2.44/2.4	4.88/2.4
150	2.42/3.2	4.86/2.8
200	2.43/2.8	4.84/3.2
250	2.36/5.6	4.79/4.2
300	2.36/5.6	4.8/4.0
350	2.4/4	4.8/4.0

Tab. 3 *Protrusion Spacings for different Printing Speeds*

Printing Speed [mm/s]	Protrusion Spacing (nominal: 5 [mm])/Error (%)	Protrusion Spacing (nominal: 7.5 [mm])/Error (%)	Protrusion Spacing (nominal: 10 [mm])/Error (%)	Protrusion Spacing (nominal: 12.5 [mm])/Error (%)
50	5.06/1.2	7.56/0.8	10.02/0.2	12.51/0.1
100	5.07/1.4	7.57/0.9	10.23/2.3	12.56/0.5
150	5.06/1.2	7.58/1.1	10.07/0.7	12.56/0.5
200	5.13/2.6	7.65/2.0	10.18/1.8	12.66/1.3
250	5.13/2.6	7.71/2.8	10.18/1.8	12.66/1.3
300	5.11/2.2	7.68/2.4	10.17/1.7	12.66/1.3
350	5.15/3	7.71/2.8	10.17/1.7	12.66/1.3

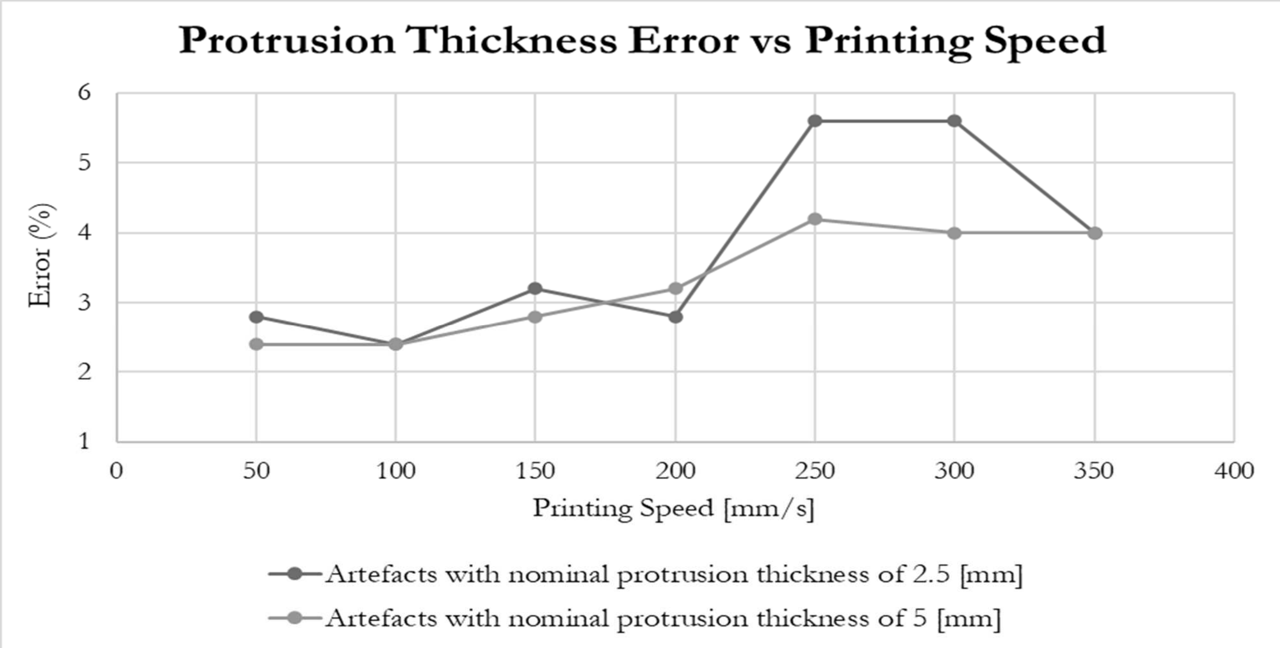

Fig. 2 *Protrusion Thickness Error vs Printing Speed*

Protrusion thickness error is differentiating in higher printing speed settings. The observed findings of the measurements were expected, given that high speeds amplify oscillation phenomena and elasticity phenomena, such as the elasticity of the belt-driven system in the printer. For speeds up to 200 [mm/s], researchers observe a consistent and minor error. However, the error abruptly rises between 200 and 250 [mm/s], and then remains constant once again. This is due to the fact that the oscillation effects become significantly more noticeable beyond these rates, as the printer's motion control system strives to match these speeds over very limited print distances, such as 2.5 [mm] and 5 [mm]. Moreover, the investigation and explanation of the data clearly indicate that there is a negligible difference in error rates between using a speed of 200 [mm/s] and using a speed of 50 [mm/s]. Considering the fact that the specimens are printed at a speed of 200 [mm/s], the printing time is reduced by over fifty percent. Error of 2.5 [mm] protrusion thickness gets relatively bigger than 5 [mm], over speed changes. That is because, given the oscillation phenomena have a distinct amplitude corresponding to each varying speed. Hence, as the measurement length increases, the impact of oscillation amplitude on the overall length diminishes.

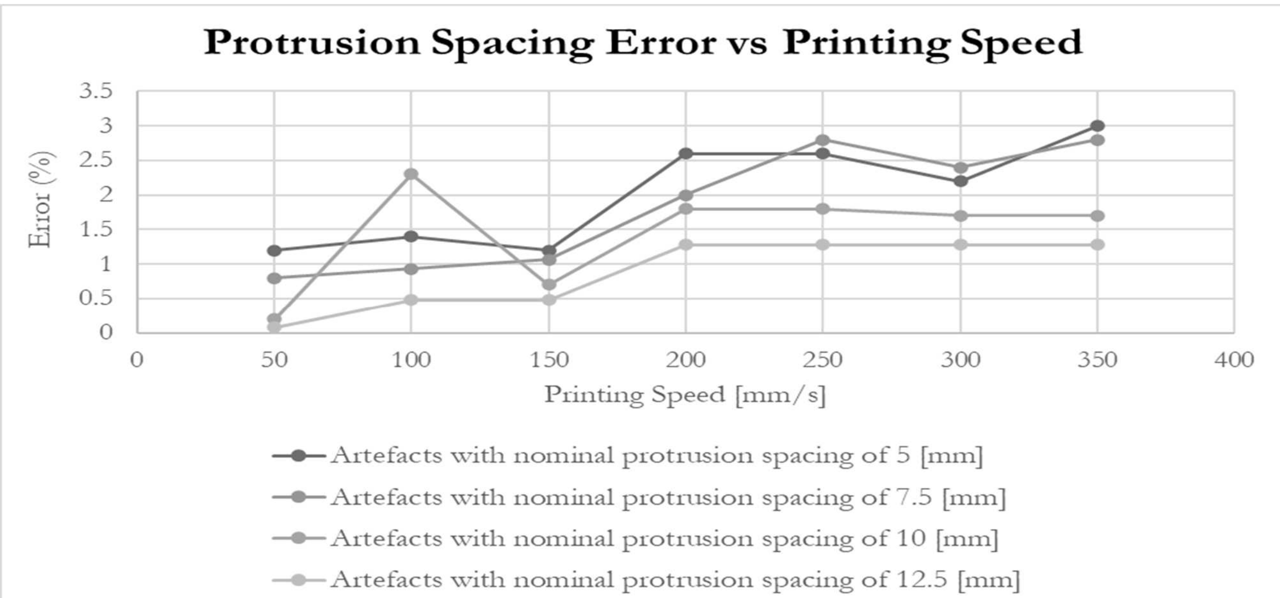

Fig. 3 *Protrusion Spacing Error vs Printing Speed*

Protrusion spacing is impacted from all the range of different speed settings. It can be observed that the larger the protrusion spacing, the smaller the error. This is expected, given the oscillation phenomena have a distinct amplitude corresponding to each varying speed. Hence, as the measurement length increases, the impact of oscillation amplitude on the overall length diminishes. Furthermore, error rises sharply above 150 [mm/s] of printing speed, and after that becomes constant again. The main cause of this phenomenon is that oscillations are being amplified during 150 [mm/s] and 200 [mm/s]. This amplification is directly linked to the inherent frequency of the system and its harmonics. Last but not least, the investigation and explanation of the data clearly indicate that there is a negligible difference in error rates between using a speed of 150 [mm/s] and using a speed of 50 [mm/s]. Considering the fact that the specimens are printed at a speed of 150 [mm/s], the printing time is reduced by over 40 percent.

4 Conclusions

The study has revealed significant findings on the correlation between printing speed and dimensional accuracy in high-speed Fused Filament Fabrication (FFF). The tests, carried out using ABS material and following the ISO ASTM 52902-2021 standard, have shown that the sophisticated electromechanical system of our customized FFF printer can uphold precise dimensional accuracy even while operating at higher speeds. Speeds of up to 200 [mm/s] were found to provide the best accuracy while also greatly reducing printing time. Once the threshold is exceeded, namely at speeds up to 350 [mm/s], there is a discernible trade-off in precision. However, it still falls within acceptable boundaries for situations where speed takes precedence over absolute accuracy.
In general, given the measurements of protrusion thicknesses and protrusion spacings, if precision is prioritized, it is advisable to print at a speed of 200 [mm/s]. However, if print time is prioritized over achieving optimal accuracy, printing speed can be increased to 350 [mm/s].

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