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Original Article

# Effect of parameters determining production time on the dimensional accuracy of additive manufacturing by material extrusion

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## ABSTRACT

Additive manufacturing via material extrusion has attracted significant attention due to its ability to produce complex geometries with low material consumption. However, in this method, the production time and the dimensional accuracy of the parts produced generally include parameters that have opposite effects on each other. In other words, parameter values that increase dimensional accuracy also increase production time. This study investigated how the most important parameters affecting production time, layer thickness and printing speed, affect dimensional accuracy. An experimental design was created using the Taguchi L9 orthogonal array and the dimensions of the cubes produced according to this design were measured using a CMM in the X, Y and Z directions and their dimensional accuracies were evaluated. In addition, contribution of the parameters on dimensional accuracy was evaluated with ANOVA.

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## INTRODUCTION

Additive manufacturing (AM) is also known as 3D printing technology, was invented by Charles Hull in the mid-1980s [1]. To date, additive manufacturing technology has been rapidly developed and improved using many different methods. Today, it is widely used in many industrial sectors such as automotive, aerospace, and medical. Additive manufacturing is divided into four main categories according to the raw material used: filament, powder, liquid, and solid layer. In the filament category, Material Extrusion (MEX), also known by names such as Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF), is frequently used, a trademark of Stratasys since 1991. FDM technology is one of the most preferred additive manufacturing technologies by users due to its low cost and its ability to be used in many areas[2].

Additive manufacturing through polymer extrusion, particularly using Fused Filament Fabrication (FFF), has emerged as a transformative technology in various industries. However, achieving high dimensional accuracy in printed parts is contingent upon a multitude of process parameters, including layer thickness, printing speed, and infill density. This literature review synthesizes current research on how these parameters influence process time and the resultant dimensional accuracy in additive manufacturing. In this method, where the production speed is relatively low, production time and energy consumption are also very important. Parameters that reduce production time and therefore energy consumption generally reduce dimensional accuracy, and optimization must be made depending on the need in the use of this production method.

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Layer thickness is a pivotal parameter that significantly impacts the dimensional accuracy of AM-processed parts. Research by Kónya indicates that thinner layers generally enhance the adhesion between layers, which can lead to improved dimensional fidelity [3]. This finding is corroborated by the work of Bochmann et al. who emphasize that while thinner layers can improve surface quality, they may also increase the overall print time [4]. Conversely, thicker layers can reduce print time but often result in poorer dimensional accuracy due to the staircase effect, where the surface of the part appears stepped rather than smooth. Furthermore, Bikas et al. highlight that the optimization of layer thickness is essential for balancing print speed and accuracy, suggesting that a systematic approach to parameter selection can yield better results [5].

Infill density and orientation also play crucial roles in determining the mechanical properties and dimensional accuracy of printed parts. Zhang et al. found that higher infill densities contribute to improved tensile strength and dimensional stability, although they also increase the time required for printing [6]. Similarly, the orientation of the printed part can significantly affect the dimensional accuracy, as noted by Dey and Yodo. Their study reveals that certain orientations may necessitate additional support structures, which can complicate the printing process and affect overall accuracy [7]. This is further supported by the findings of Alzyod and Ficzere [8], who conducted a systematic survey on FDM process parameter optimization, indicating that both infill density and orientation are critical for achieving desired dimensional characteristics.

The relationship between process parameters and their cumulative effect on dimensional accuracy is further explored by Alzyod and Ficzere [8], who conducted a comprehensive finite element analysis to assess how various parameters influence residual stress and warpage deformation in 3D printing. Their results underscore the importance of conducting material-specific analyses to optimize printing parameters, particularly focusing on infill patterns and printing temperatures, which are crucial for minimizing warpage and enhancing dimensional accuracy. Additionally, the study by Medellín-Castillo and Zaragoza-Siqueiros [9] emphasizes the need for a holistic approach to parameter optimization, suggesting that integrating multiple parameters can lead to significant improvements in both accuracy and efficiency [10].

Moreover, the impact of printing speed on dimensional accuracy is a critical consideration in industrial applications. As highlighted by Hackney and Wooldridge, the drive for efficiency often necessitates a careful balance between speed and quality [11]. Their research indicates that while faster print speeds can reduce production time, they may compromise the dimensional accuracy of the final product. This is echoed by the findings of Medellín-Castillo and Zaragoza-Siqueiros [9], who advocate for a design-for-manufacturing (DfM) approach that considers both the mechanical properties and the dimensional accuracy of parts during the design phase.

**Table 1. The parameter values used in production**

| Parameters | Value |
|---|---|
| Nozzle diameter | 0.4 mm |
| Line width | 0.4 mm |
| Shell number | 2 |
| Nozzle temperature | 260 °C |
| Bed temperature | 100 °C |

**Table 2. Manufacturing parameters and levels**

| Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Printing speed (mm/s) | 50 | 150 | 250 |
| Layer height (mm) | 0.1 | 0.2 | 0.3 |

In this study, the dimensional accuracy of parts produced through polymer extrusion in additive manufacturing is investigated. Taguchi L9 experimental design was created using three levels of layer thickness and printing speed parameters, which are considered to be the most important parameters affecting dimensional accuracy. Dimensional accuracy values were determined by measuring X, Y and Z lengths of the produced cubic structures with Coordinate Measuring Machine (CMM). The contribution of the production parameters to dimensional accuracy was evaluated with ANOVA.

## MATERIALS AND METHODS

In this study, high quality and low diameter tolerance 1.75 mm in diameter BASF Ultrafuse Black ABS Fusion+ brand filament was used. To measure dimensional accuracy in 3 directions, cube structures with 10 mm edge length and 100% infill density were produced. The infill pattern was chosen as rectilinear which is ±45-degree direction in each layer. The parameter values used in production were determined as constants to increase dimensional accuracy and these values are given in Table 1 [12].

Samples with dimensions of 10x10x10 were produced with Creality Ender3 Pro 3D printing machine using Simplify3D slicer program. Raft surface was used in all samples so that the curvature of the hot table surface did not affect the measurement results. The image of the sample in the Slicer program and the produced sample are given in Figure 1.

Design of Experiments (DoE) is a statistical and systematic method widely used in the field of research. It investigates the effects of multiple input variables and their interactions and offers effective process optimization. Several DoE methodologies such as Response Surface Methodology (RSM), Box-Behnken Design (BBD), Taguchi design and Central Composite Design (CCD) are used to study the effect of additive manufacturing parameters [13,14]. In this study, the effect of printing speed and layer height, which affect the manufacturing time, on dimensional accuracy was investigated using the Taguchi method. The parameters and levels used in designing the L9 orthogonal array are given in Table 2. In determining the printing speed values

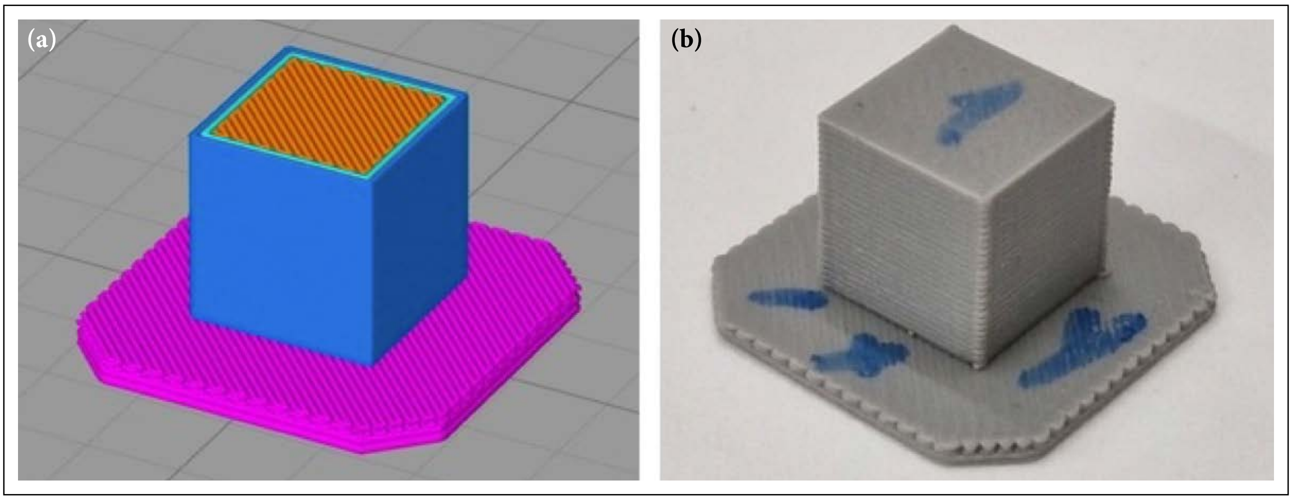


**Figure 1**. **(a)** Image of the sample in the Slicer program, **(b)** Produced sample.

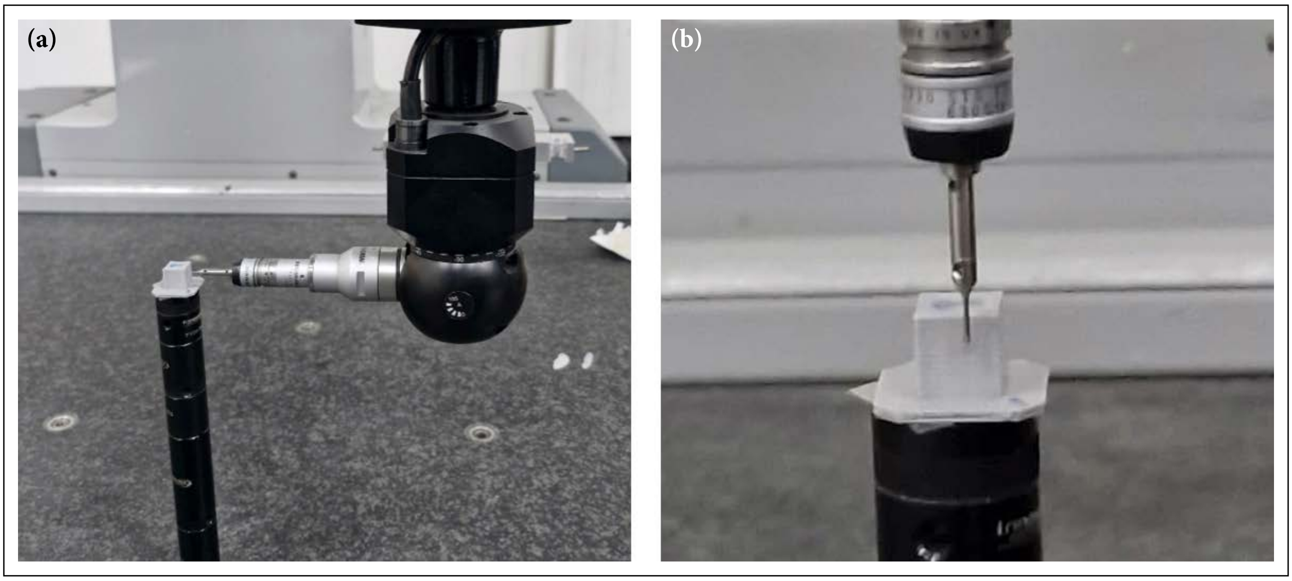


**Figure 2**. Measuring the dimensions of samples **(a)** from side **(b)** from top.

in Table 2, the upper limit of the 3D printer, 250 mm/s, was taken into account and the parameters were determined according to the upper limit at equal intervals. The highest parameter determined for the layer height was determined as 75% of the nozzle diameter [15–17].

A CMM machine with a Renishaw PH10M brand probe was used to measure the dimensions of the samples produced in the X, Y and Z directions. Photographs taken during measurement are shown in Figure 2a and 2b. An example report obtained for the X and Y directions is given in Figure 3a and for the Z direction is given in Figure 3b.

To calculate the average absolute difference from nominal geometry which shows the deviation of dimensional accuracy, the following equation can be used:

$$\Delta L_i = \frac{1}{3}\sum_{i=1}^{n}(|X_i - 10| + |Y_i - 10| + |Z_i - 10|) \quad (1)$$

Where $\Delta L_i$ is average absolute difference for X, Y and Z directions for nth row of experimental design.

## RESULTS AND DISCUSSION

The samples produced using the parameters in the experimental design according to the Taguchi method are given in Figure 4. The results of the dimensional measurements made in the X, Y and Z directions, the dimensional deviation (ΔL) values obtained by using Equation 1 and, S/N ratio values and the printing speed values obtained in the simplify3D slicer program are given in Table 3. The graph of the printing time obtained depending on the printing speed and layer height parameters is given in Figure 5. In the calculation of S/N ratio values, the smaller is better formula was used given in Equation 2 [18, 19].

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (2)$$

Response tables for mean and S/N ratios of hardness values are given in Table 4 and 5. The main effects plot for

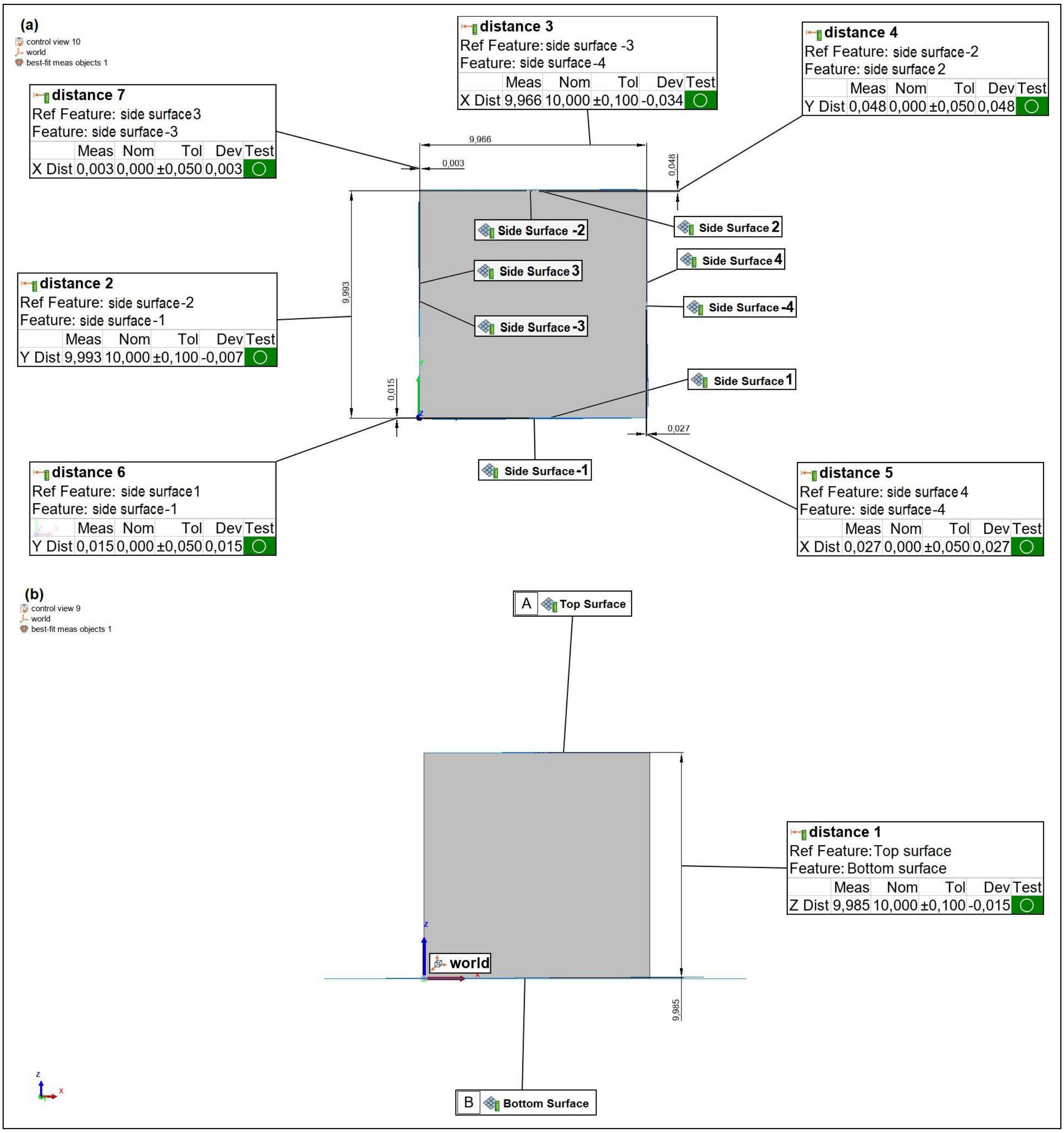


**Figure 3**. An example report obtained **(a)** for the X and Y directions, **(b)** for the Z direction.

means and S/N ratios using the results given in Table 4 and 5 can also be seen in Figure 6 and 7. Main effect plots show how each factor affects the response characteristic. The main effects of the means exhibit a perfect correlation with the S/N ratios. Increasing printing speed and layer height deteriorated the dimensional accuracy. This finding can be attributed to a few phenomenon.

As printing speed increases, the viscosity of the melted material changes, leading to inaccuracies in the extrusion and placement of the filament. This suggests that the control of material flow becomes more challenging at higher speeds, resulting in a less precise deposition of layers [20,21]. In contrast, Nugroho et al. [22] found that there exists an optimal printing speed that minimizes width deviation in printed parts. Their research indicates that while higher speeds can sometimes yield better dimensional accuracy, this is contingent upon other factors such as layer height and material properties.

Buj-Corral et al. [23] studied the impact of end-to-end printing parameters on dimensional error and surface roughness. The dimensional accuracy degraded as per the increase in layer thickness on account of the intrinsic stair-stepping phenomenon, which was more elaborative with the increase in layer thickness. Not only does this effect results in poor surface quality but also affect the dimensional accuracy of the final print part. The results of Ah-

**Table 3.** Measured and calculated dimensional deviation values with S/N ratio values

| Experiment No | Printing speed (mm/s) | Layer height (mm) | Printing time (s) | LX (mm) | LY (mm) | LZ (mm) | ΔL (mm) | S/N ratio |
|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 0.1 | 28 | 9.966 | 9.993 | 9.985 | 0.019 | 34.5787 |
| 2 | 50 | 0.2 | 15 | 10.055 | 10.055 | 10.086 | 0.065 | 23.6973 |
| 3 | 50 | 0.3 | 11 | 10.085 | 10.098 | 10.057 | 0.080 | 21.9382 |
| 4 | 150 | 0.1 | 19 | 10.062 | 10.033 | 9.946 | 0.050 | 26.0787 |
| 5 | 150 | 0.2 | 10 | 10.196 | 10.161 | 10.053 | 0.137 | 17.2867 |
| 6 | 150 | 0.3 | 7 | 10.208 | 10.205 | 10.046 | 0.153 | 16.3062 |
| 7 | 250 | 0.1 | 13 | 10.072 | 10.066 | 9.955 | 0.061 | 24.2934 |
| 8 | 250 | 0.2 | 7 | 10.208 | 10.205 | 10.046 | 0.153 | 16.3062 |
| 9 | 250 | 0.3 | 5 | 10.288 | 10.244 | 10.082 | 0.205 | 13.7791 |

**Table 4. Response table for means**

| Level | Printing speed | Layer height |
|---|---|---|
| 1 | 0.05467 | 0.04311 |
| 2 | 0.11311 | 0.11833 |
| 3 | 0.13956 | 0.14589 |
| Delta | 0.08489 | 0.10278 |
| Rank | 2 | 1 |

**Table 5. Response table for signal to noise ratios**

| Level | Printing speed | Layer height |
|---|---|---|
| 1 | 26.74 | 28.32 |
| 2 | 19.89 | 19.10 |
| 3 | 18.13 | 17.34 |
| Delta | 8.61 | 10.98 |
| Rank | 2 | 1 |

**Table 6.** Analysis of variance for means (ANOVA)

| Source | DF | SS | MS | F | Contribution |
|---|---|---|---|---|---|
| Printing speed | 2 | 0.011321 | 0.005661 | 12.35 | 37.57 |
| Layer height | 2 | 0.016981 | 0.008490 | 18.53 | 56.35 |
| Residual error | 4 | 0.001833 | 0.000458 | | 6.08 |
| Total | 8 | 0.030135 | | | 100.00 |

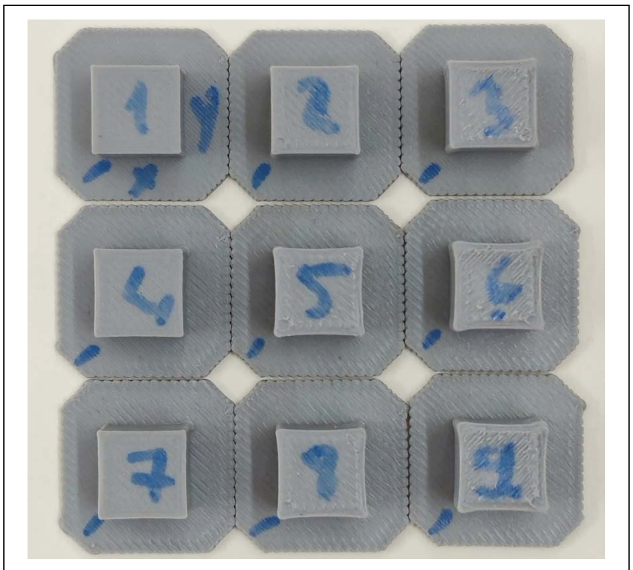

**Figure 4**. Additively manufactured samples.

madifar et al. [24] also add to this conversation, reporting that layer height along with other parameters have significant influence on dimensional accuracy. They highlight the

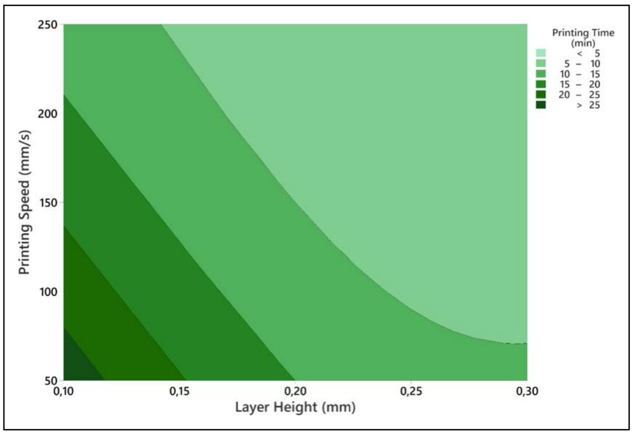


**Figure 5**. Effect of printing parameters on printing time.

importance of low layer height in producing first-quality dimensional fidelity, specifically in industries where precision is key to the printing design.

The statistical method most frequently used to analyze experimental findings and calculate the percentage contribution of each parameter is Analysis of variance (ANOVA). ANOVA was performed to determine the contribution of

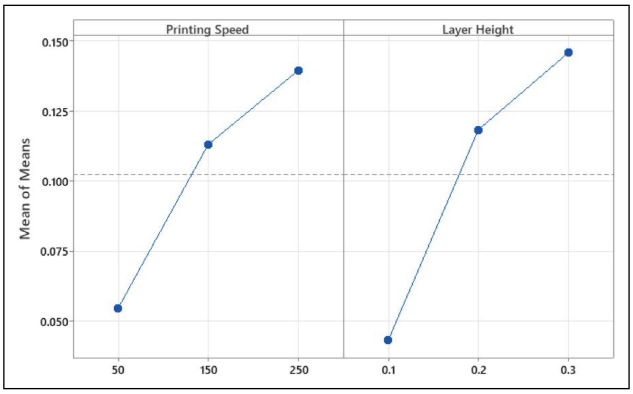


**Figure 6**. Main effects plot for means.

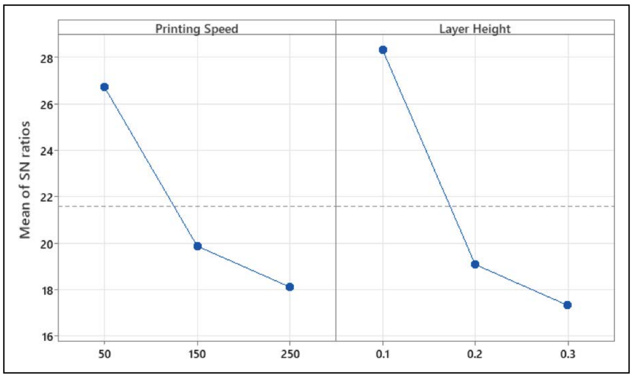


**Figure 7**. Main effects plot for S/N ratios.

the parameters on hardness measurement values. ANOVA table is given in Table 6. According to the table, 93.92% of the total effect on dimensional accuracy can be explained by printing speed and layer height. The most effective parameter was found to be the layer height with a contribution of 56.35% and the contribution of the printing speed was 37.57%.

## CONCLUSION

In this research, the effect of printing speed and layer height parameters, which are the most effective parameters determining production time, on the dimensional accuracy of additively produced ABS samples were investigated using Taguchi method and ANOVA. The main conclusions can be summarized as follows:

- Dimensional accuracy deteriorated with the increase of printing speed and layer height. It means that desired dimensional accuracy and production time should be optimized.
- 93.92% of the total effect on dimensional accuracy can be explained by printing speed and layer height.
- The most effective parameter was found to be the layer height with a contribution of 56.35% and the contribution of the printing speed was 37.57%.
- In the case where the printing speed and layer height were the highest, the printing speed decreased by 82.2%. On the other hand, the situation where dimensional deviations were the highest was observed at these values.

**Data Availability Statement**

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

**Author's Contributions**

Emre Berke Ay: Conception, Design, Supervision, Materials, Data Collection and Processing, Analysis and Interpretation, Literature Review.

Berat Madenci: Conception, Design, Supervision, Materials, Data Collection and Processing, Analysis and Interpretation, Literature Review, Writer, Critical Review.

Mümin Tutar: Conception, Design, Supervision, Data Collection and Processing, Writer, Critical Review.

**Conflict of Interest**

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Use of AI for Writing Assistance**

The authors acknowledge the use of Scite for assistance in drafting parts of the introduction and ensuring language clarity.

**Ethics**

There are no ethical issues with the publication of this manuscript.

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