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Enhancing Dimensional Accuracy in Fused Filament Fabrication: A DOE Approach

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ABSTRACT

3D printing is widely used in various fields and industries and is one of the most popular methods. Most popular advantage of this method is its flexibility in printing complex shapes and sizes. Quality is one of the important aspects when using this kind of technology which has a high advantage of printing complex shapes as this includes many factors like temperature, speed, material, infill types etc. In this paper one such analysis has been done by 3D printing parts under different factors. Analysis is done on how scaling factors affect the dimensions like height and diameter of a 3D printed part and check factors affecting these variations using Design of Experiments (DOE) analysis.

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Introduction

Using the technique of three-dimensional (3D) printing, a computer design can be transformed into a tangible object. At the start of the process, it is necessary to apply thin layers of various materials, such as liquid or powdered plastic, metal, or cement [1]. Once that step is complete, the layers must be fused together. Smaller 'work area' 3D printers have become more accessible and affordable over time, making the technology more widely available. Function of 3D printing, As previously discussed, the 3D printing process involves creating a continuous stream of liquid plastic to manufacture an object. With each layer that solidifies, the subsequent layer is carefully imprinted on top, gradually bringing the item to life. To create a 3D print, a computerized file is necessary to provide instructions to the 3D printer regarding the printing location. The G-code documents are widely recognized as the most popular record design for this. This document essentially includes instructions to control the printer's movements, both horizontally and vertically - also known as the X, Y, and Z axes. 3D printers are capable of printing these layers at different thicknesses, which is referred to as the layer level. Just like pixels on a screen, adding more layers to a print will help achieve a higher 'goal'. This will result in a more polished appearance, but it will require a longer printing time.

Various types of 3D printers, such as SLS and FDM, are capable of printing a wide range of materials including polymers, metals, glass, and wood. These are referred to as composites and involve a subset of the characteristics of the combined material. This is because the organic material is found on spools of thin fiber. Combined testimony demonstrating, or FDM for short, is a technique used in additive manufacturing where materials are extruded through a nozzle and fused together to create 3D objects. Specifically, the "standard" FDM process separates itself from other material expulsion methods, like cement and food 3D printing, by involving thermoplastics as feedstock materials, normally in the types of fibers or pellets. While actually warm, these layers meld with one another to make a three-layered part at last. In this process the Need for quality control is high to get a perfect product with less deviations, and quality depends on several factors such as temperature, infill rate, scaling, feed speed, surface roughness, types of materials, types of infills etc. Analysis must be done in one such process to identify the cause of issues and reduce the deviations.

Literature Review

3D printing is a widespread technology used in various fields. Products of different sizes and types can be printed using this technology. It is a process where material is melted and placed in the form of layers one up on each other to form a final product. There are various factors affecting the quality of the product. This technology works based on different parameters like layer thickness, nozzle temperature, printing speed, infill rate etc. As this process is based on multiple parameters the chances of deviation will be high where these deviations ultimately result in final product quality. There is a need to analyze and control these deviations to get a final product of good quality. Several research studies have been done in this aspect and some papers are referred to in this section.

3-D printing

The process of printing a physical object from a three-dimensional model by using layers of melted material is known as 3D printing. The other name for this is Additive manufacturing. In present situations the usage of this technology is high because of its flexibility and design benefits [2]. The STL file is widely recognized as the most commonly used file format in the 3D printing process. First, the 3D model needs to be converted into a series of thin layers and a G-code file is generated. There are various software options available for this conversion, with "slicer" being the most used [3]. After conversion this STL file is used to 3D the designed product. This process requires less postproduction machining process when compared to traditional production process where there is a requirement of custom molds which is not the case of 3D printing. 3D printing can be done in 3 important stages: Modeling, Printing and Finishing. In the initial stage modeling of the desired part is done using CAD software with all the geometric data which we have regarding the product. Later in the second stage slicer is used to convert the model into thin layers and the product is printed using the STL file. In the final stage some products are printed oversized and then the excess material is removed to get high resolution output of the product [3].

There are numerous techniques available for 3D printing, but FDM stands out as a popular choice due to its simplicity, cost-effectiveness, and ability to produce intricate parts. In Fused Deposition modeling (FDM), the melted material is carefully directed through a heated nozzle onto the beds. Figure 1 displays the schematic and process parameters of an FDM 3D printer, as presented by Kumar et al. in 2019 [4]. Parts fabricated using FDM have lower dimensional accuracy compared to parts made with other additive manufacturing processes such as SLA, SLS, and Polyjet. This is due to the influence of different process parameters, either individually or in combination with other parameters, on dimensional accuracy [5].

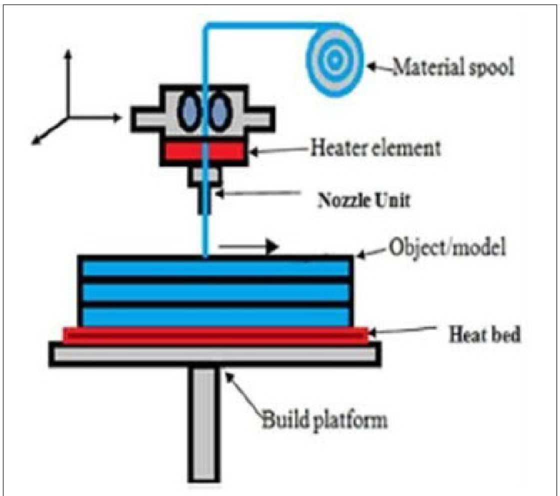

Figure 1: FDM 3D Printer Schematic

There are many materials which can be used for 3D printing Nylon, polyethylene terephthalate, laywooD3, lay brick, polylactic acid etc. but among these PLA (Polylactic acid) is the most used filament material in 3D printers. PLA is used when producing small amounts of products with reduced production cost and cycle [6]. This material is widely used because of its good printability as it is compostable, biodegradable plastic with high mechanical strength and reduced toxicity [7]. PLA is used when producing small amounts of products with reduced production cost and cycle. Though the material is having good properties there are many chances for deviations to occur as it depends on different parameters under which the printing procedure is performed.

Analysis of Printing Layers

The primary limitation of prototypes created through 3D printing using the FDM method is the unevenness in structure that arises from the fundamental principle of this technique. The material distribution throughout the scanned specimens is not uniform, with a noticeable increase in density at the layer building start point. The empty spaces can be found throughout each layer and between certain layers [8]. When the infill percentage is set to 100 percent, it becomes apparent that the filaments exhibit voids, geometric distortions, and winding trajectories, indicating a disruption in the deposition process. There were some observations of voids and unusual filament paths and geometries, indicating potential issues with the quality of the filament deposition during the fabrication of the PLA parts. There is a noticeable lack of consistency in the production of 3D printed parts, with significant variations observed among specimens created using identical process parameters. Deposition failure resulting from filament slippage in the extruder head hobbed pulley was the primary cause of this effect [7].

Quality of the Part

The quality of a product is evident in its mechanical properties and the smoothness of its surface. Surface roughness in 3D printing of polylactic acid material is primarily influenced by the printing temperature. Other factors that also play a role include the printing pattern, infill rate, and the number of shells [9]. Choosing the right orientation can also enhance the surface finish of a 3D object. The choice of printhead and the slicing program used can have a significant impact on the final surface finish of a 3D-printed object. Furthermore, additional post processing treatments are necessary to refine the surface [10].

Certain techniques, such as design of experiments, have not been utilized with precision and thoroughness, resulting in suboptimal quality optimization. According to Wu et al., the use of Taguchi's method and control charts can improve the quality of 3D-printed objects [10]. However, it is important to note that these techniques involve repetitive experimentation, which may not align with the workflow of 3D printing. An experimental method called Taguchi design of experiment is used to minimize the number of experiments and determine the best parameters for achieving maximum mechanical properties, minimum weight, and minimum printing time [2]. The proposed methodology follows a Design of Experiment (DOE) approach, which provides engineers with a framework for conducting experimental studies.

Design of Experiment

DOE techniques zeroed in on producing greatest information with least exertion isn't completely used. The plan of examination strategy can be defined as a genuinely thorough methodology created to survey the influence of certain boundaries (called factors) which have some values inside a reach (called level) affecting the result of a certain interaction. DOE helps the comprehension of an interaction and, what more, proposes the way that the variables may affect it. The DOE measurable examination depends on the correlation of some plan input of an examination, expecting to further develop the cycle information by as few as potential runs, in this way decreasing the requirement for various tests which might be costly both regarding time and cost [11].

Tolerances

Understanding tolerances is crucial for ensuring proper functionality of an object. Precision is crucial when considering the required accuracy for a specific 3D print. The tolerance can be determined by the user and will vary based on the specific application. In most additive technologies, the dimensional tolerance is typically around 0.1 mm. It is evident that the variations in 3D printing surpass those found in alternative technologies like injection molding.

Many papers were reviewed to study about the basic understandings, printing process etc. of 3D printing. Several studies have shown that there is a need for quality improvement in printed parts and also different factors which are affecting the part, it is seen that analysis has been done on factors like surface roughness, infill types, infill rates and temperatures there is also one such factor which is needed to be taken care of which is Dimensions. In this project we analyze how scaling factors affect the dimensional accuracy of a 3D printed part.

Methodology

Design and Printing Process

The methodology involved in this study consists of three major parts. They are design, printing and measurement. A 3D model is built in DS SolidWorks which is a cylindrical body with radius of 25mm and height of 50mm. The file is saved in STL format and further used as input for Slicer software.

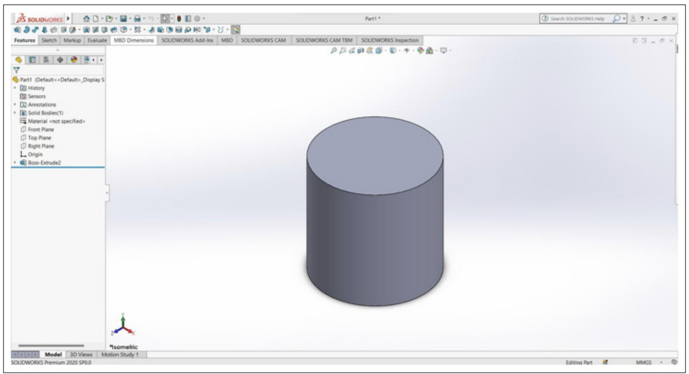

Figure 2: Isometric View of the Model

A slicing software, commonly referred to as a slicer, processes 3D model files such as STL and OBJ. It generates G-code files according to the user's preferences and settings. Understanding the importance of slicers in the 3D printing workflow is essential, as they greatly influence the final quality and resolution of the printed object. The G-code file contains multiple lines of code, with each line serving a distinct purpose in controlling the movement of the nozzle and bed in the X, Y, and Z directions to construct the complete model. They also include instructions for heaters and other connected devices, such as servos or leveling sensors. To generate a G-code file, the most common open-source slicer called Ultimaker CURA 5.2.1 is used. CURA is a beginner friendly software and provides all basic information for the user. Before beginning the slicing, the printer should be added to the slicer. Go to Add printer and search by the name of printer and click Add. The printer used for the study is Flash Forge Finder in one of our laboratories. The printer specifications are mentioned in Table 1.

Table 1: 3D Printer Specifications

Volume of construction	6.0 x 6.0 x 6.6" / 13.0 x 12.97 x 12.0 cm
Quantity of Extruders	2
Extruder Nozzle Diameter Support	00 micron / 0.4 mm
Supported 3D File Types	.obj, .stl
Wired Connections	1 x USB-A 2.0
Resolution of the layer	XY Axis: 150 to 600 micron / 0.1 to 0.5 mm (Setting)
Filament Compatibility	1.75 mm Diameter: PLA

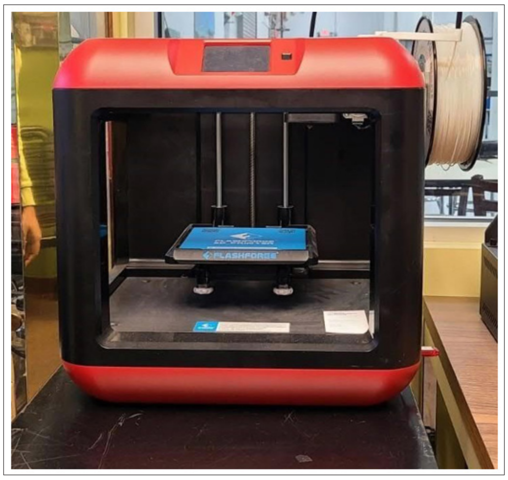

Figure 3: Flash Forge Finder 3D Printer

The next step is to provide the material information to the slicer. The material used is Generic PLA with filament diameter of 1.75 mm. Open the STL file and the model appears on the platform. Figure 4 shows the print settings and model.

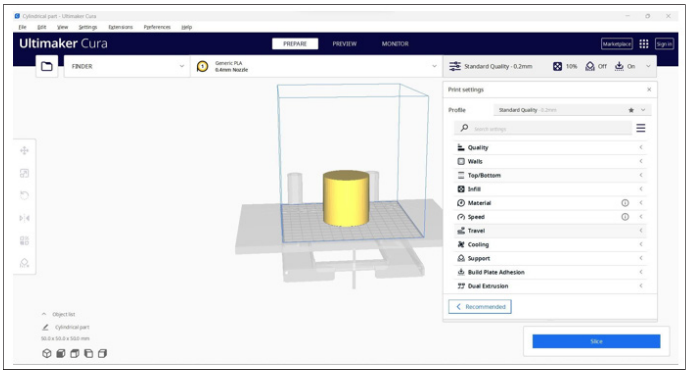

Figure 4: Print Settings and the Model

The generated G-codes are used to print the samples in a 3D printer. Total 16 samples were printed depending on four factors which are temperature, infill rate, infill speed and scaling. Each sample is printed by changing one factor, Table 2 shows the factors and respective values using which the samples have been printed. PLA material is used along with layer thickness of 0.2 mm, infill pattern – Honeycomb /(Tri-hexagonal) and travel speed of 150mm/s. Table 3 shows the specifications of each sample under which they are printed and labeled with numbers from 1 to 16. One after the other each sample is printed, figure 5 shows 16 printed parts in which 8 samples were printed at scaling level 2 and 8 were printed under scaling level 1. The next step in this process is to measure the samples.

Table 2: Varying Factors Used to Print the Samples

Temperature	210 - 220 ^{0}C
Infill Percentage	10 - 20
Speed	60 - 80
Scaling size	1 - 2

Figure 5: 3D Printed Samples

In this measurement phase by using vernier calipers the diameter of each sample is measured at 3 different locations of the sample which includes one at the top, bottom and at the center of the sample and average value has been taken for all the samples and also measured height of the samples at 3 different locations. Along with these measurements weight of the samples is taken 3 times for each sample and average is calculated. Printed parts with sample numbers along with their respective average height, diameter and weight are shown in Table 3.

Table 3: Sample Specifications and Average Values

Sample	Temperature	Infill	speed	scaling	Height(mm)	Diameter(mm)	Weight(gms)
1	220	20	60	2	50.14	49.92	34.00
2	220	20	60	1	25.15	24.93	5.00
3	210	20	60	2	50.17	49.80	32.00
4	210	20	60	1	25.15	24.86	5.00
5	220	20	80	2	50.18	49.94	32.00
6	220	20	80	1	25.14	24.85	5.00
7	210	20	80	2	50.12	49.85	32.00
8	210	20	80	1	25.15	24.89	5.00
9	220	10	60	2	50.08	49.86	22.00
10	220	10	60	1	25.07	24.87	4.00
11	210	10	60	2	50.14	49.92	22.00
12	210	10	60	1	25.13	24.87	3.67
13	220	10	80	2	50.12	49.97	22.00
14	220	10	80	1	25.13	24.82	3.67
15	210	10	80	2	50.09	49.89	21.00
16	210	10	80	1	25.13	24.88	4.00

Analysis

The 24 full factorial design is performed using Minitab. The three responses considered are tolerance in height, diameter and weight difference. Table 4 shows the tolerances observed in height, diameter, and weight for 16 samples.

Table 4: Minitab Data with Tolerance

Temperature	Print speed	Infill	Scale	Height Tolerance	Diameter Tolerance	Weight Difference
210	60	10	1	0.13	-0.13	0.33
220	60	10	1	0.07	-0.13	0
210	80	10	1	0.13	-0.12	0
220	80	10	1	0.13	-0.18	0.33
210	60	20	1	0.15	-0.14	0
220	60	20	1	0.15	-0.07	0
210	80	20	1	0.15	-0.11	0
220	80	20	1	0.14	-0.15	0
210	60	10	2	0.14	-0.08	0
220	60	10	2	0.08	-0.14	0
210	80	10	2	0.09	-0.11	1
220	80	10	2	0.12	-0.03	0
210	60	20	2	0.17	-0.20	2
220	60	20	2	0.14	-0.08	0
210	80	20	2	0.12	-0.15	2
220	80	20	2	0.18	-0.06	2

Doe Analysis - Height Tolerance

With the response as tolerance in height, a regression equation is found and the normal plot of the effects is shown in Figure 6. The normal plot shows the factor C, which is infill density, has a significant effect on the response. As the points that are not close to the line implies that it is an important effect. The infill density has a major influence on the response. The pareto chart of the effect gives the magnitude of the effect by showing the absolute value [12-16].

Regression Equation

Height Tolerance = 13.82 - 0.06600 Temperature - 0.1760 Print speed - 1.070 Infil- 3.000 Scale + 0.000850 Temperature*Print speed+ 0.005100 Temperature*Infil + 0.01500 Temperature*Scale+ 0.01470 Print speed*Infil + 0.03950 Print speed*Scale+ 0.5050 Infil*Scale - 0.000070 Temperature*Print speed*Infil- 0.000200 Temperature*Print speed*Scale - 0.002400 Temperature*Infil*Scale - 0.007350 Print speed*Infil*Scale + 0.000035 Temperature*Print speed*Infil*Scal

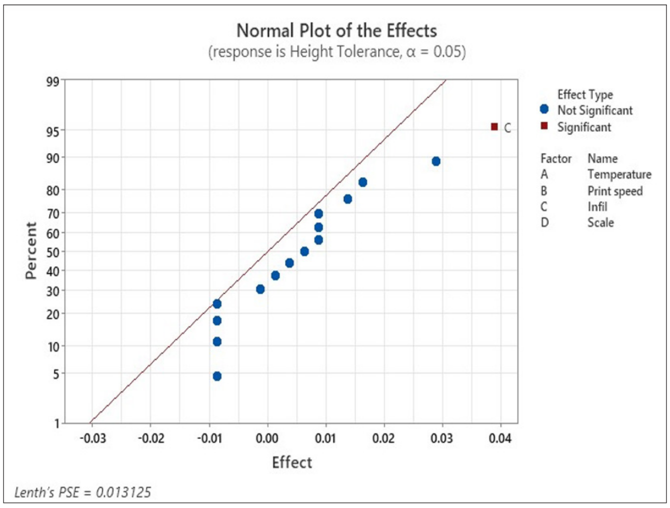

Figure 6: Normal Plot of the Effects

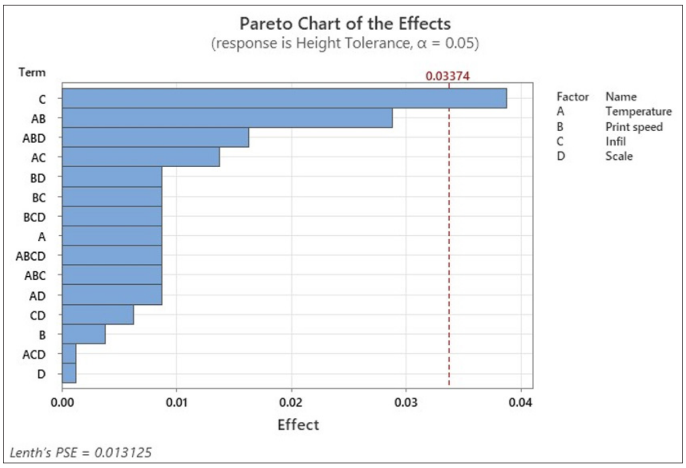

Figure 7: Pareto Chart of Effects

Main Effects

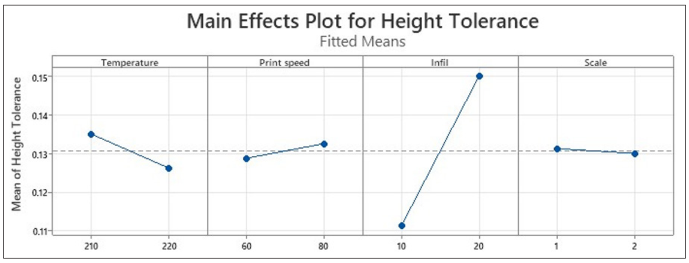

Figure 8: Main Effects Plot for Height Tolerance

Interaction Plots

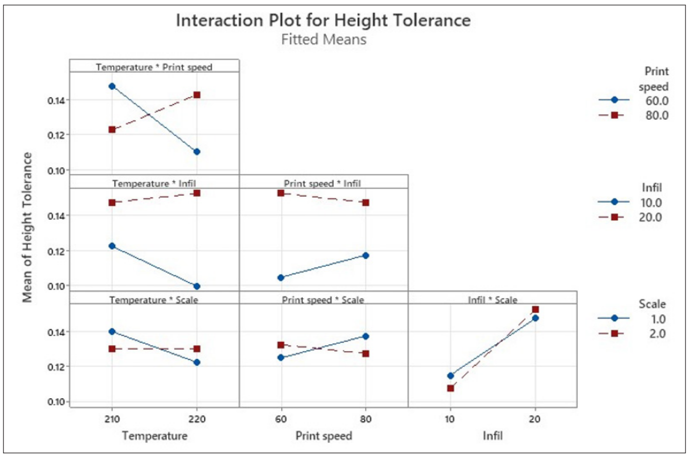

Figure 9: Interaction Plot for Height Tolerance

ANOVA for Height Tolerance

Source	DF	SS	MS	F	P
Temperature	1	0.000306	0.000306	0.47	0.506
Print speed	1	0.000056	0.000056	0.09	0.774
Infil	1	0.006006	0.006006	9.28	0.011
Scale	1	0.000006	0.000006	0.01	0.923
Error	11	0.007119	0.000647		
Total	15	0.013494			

Fisher's Pairwise Comparisons

Infil	N	Mean	Grouping
20	8	0.15000	A
10	8	0.11125	B

Means that do not share a letter are significantly different.

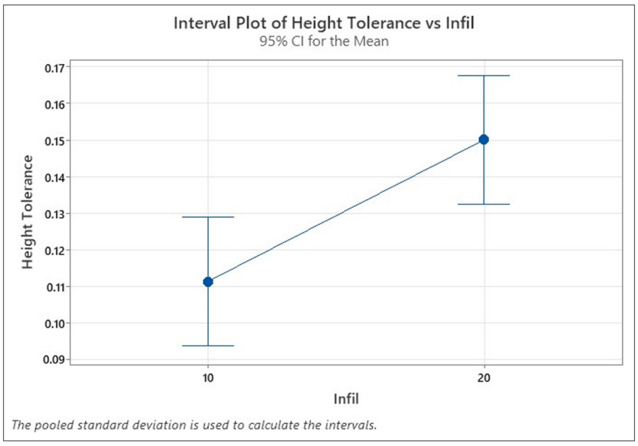

Figure 10: Interaction Plot for Height Tolerance

DOE analysis - Diameter Tolerance

Regression Equation

Diameter Tolerance = -23.44 + 0.1090 Temperature + 0.3510 Print speed + 0.5470 Infil+ 24.19 Scale - 0.001650 Temperature*Print speed- 0.002500 Temperature*Infil - 0.1130 Temperature*Scale- 0.007550 Print speed*Infil - 0.3410 Print speed*Scale- 1.016 Infil*Scale + 0.000035 Temperature*Print speed*Infil+ 0.001600 Temperature*Print speed*Scale+ 0.004700 Temperature*Infil*Scale + 0.01290 Print speed*Infil*Scale - 0.000060 Temperature*Print speed*Infil*Scale

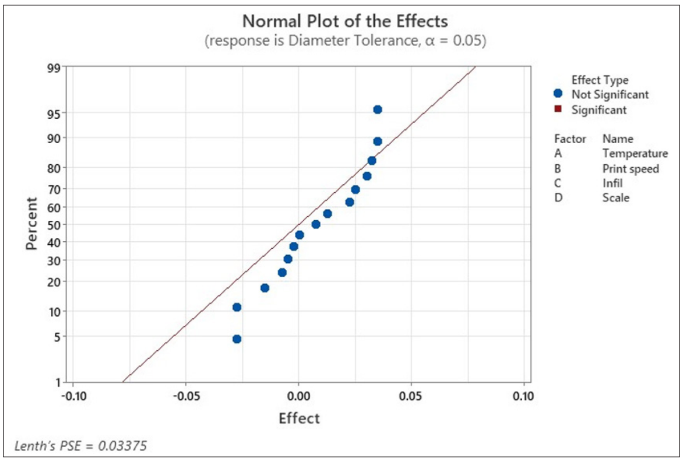

Figure 11: Effects Plot for Diameter Tolerances

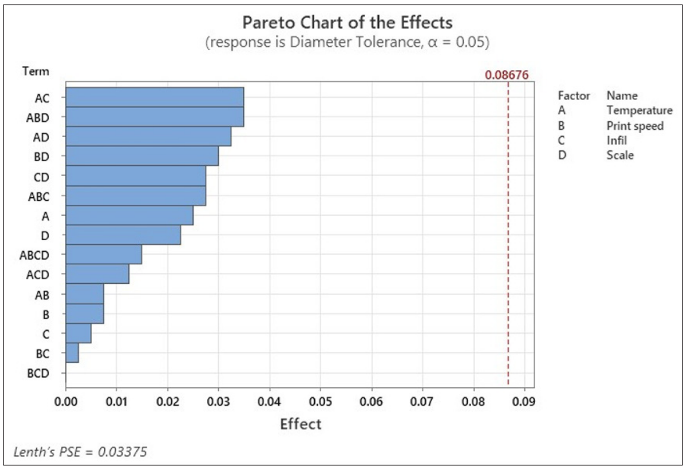

Figure 12: Pareto Chart of the Effects

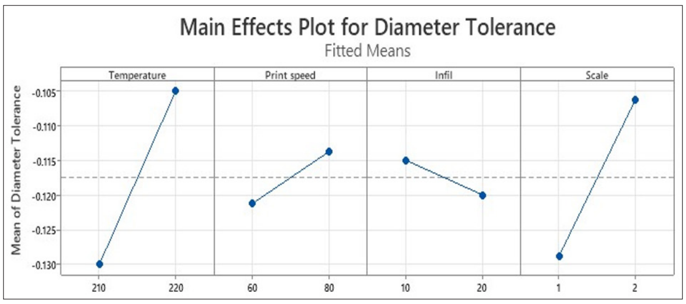

Figure 13: Main Effect Plot for Diameter Tolerances

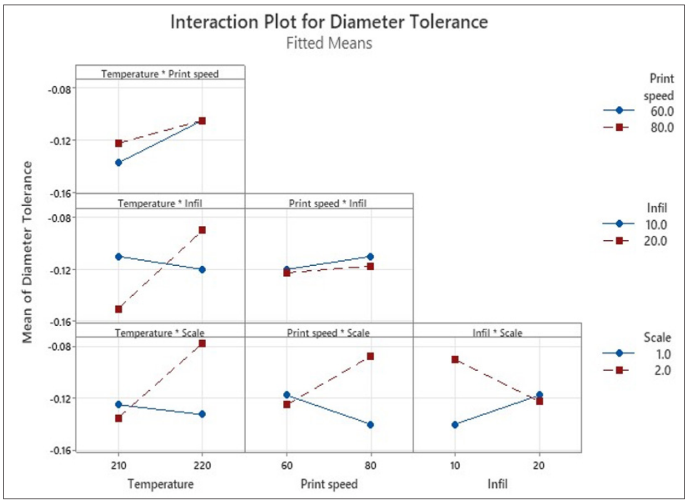

Figure 14: Interaction Plot for Diameter Tolerances

Results and Conclusion

For the two-level factorial design, the data is collected by 3D printing the samples. The values of dimensional tolerances are entered in the Minitab as response and analyzed in the factorial design. The range of tolerance in height and diameter is 0.07mm to 0.18mm and -0.07mm to -0.20mm respectively. From the analysis it shows the temperature and scale played a major role in these deviations. The height of the printed samples is greater than the design dimension. ANOVA for height tolerance shows that infill density affects the height dimension. To obtain the desired infill density the variation in layer thickness probably resulted in height variation. The shrinking in radial direction can also result in internal material pressure in vertical direction. From the general linear model performed in Minitab is able to provide a set of factors which can give dimension closer to the design value. Figure 18 shows that temperature 220, print speed 60, infill density 10 and scale 1 has least dimensional tolerance. It also shows the worst set of factors.

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