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EFFECT OF INFILL PATTERN, INFILL DENSITY, AND INFILL ANGLE ON THE PRINTING TIME AND FILAMENT LENGTH OF 3D PRINTING

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To optimize the 3D printing process, the influence of its parameters on the performance of the printing process needs to be investigated. This research investigates the effect of infill pattern, infill density, and infill angle on the printing time and the filament material length. First, this research collected the printing time and the filament length data for each combination of infill pattern, infill density, and infill angle. The data collection was conducted by implementing Repetier-Host v.2.1.6 software as a data acquisition tool. Then, the General Linear Model was applied to analyze the effect of infill pattern, infill density, and infill angle on the printing time and filament length. Based on the analysis, higher infill density increases the printing time for each infill pattern and each infill angle. Also, higher infill density increases the filament length for each infill pattern and each infill angle. The implementation of the Gyroid type of infill pattern reduces the required printing time for each density. Meanwhile, the implementation of the 3D honeycomb type of infill pattern increases the filament length for each infill angle. The use of the 45° infill angle increases the filament length and printing time. To reduce the filament length and printing time, the 90° infill angle should be implemented.

Keywords: *: Infill Pattern; Infill Density; Infill Angle; Printing Time; Filament Length; 3D Printing.*

1. INTRODUCTION

3D printing or Fused Filament Fabrication (FFF) is a manufacturing process of a physical object based on a digital model input by printing the object layer by layer. The performance of the 3D printing process, especially for engineered structural applications, is affected by the printed material and the process parameters [1]. Therefore, the influence of 3D printing process parameters on the process performance needs to be investigated to optimize the process. Suteja and Soesanti [2] identify several important 3D printing process parameters in building a printed part. The parameters are build orientation, layer thickness or layer height, feed rate or infill deposition rate, infill density, deposition angle or raster angle or infill angle, extrusion temperature, infill pattern, number of outer shell layers, shell thickness, material type, printer type, strain rate, coloring agent, and nozzle diameter or infill width. This research concerns only to investigate the influence of three process parameters, which are infill pattern, infill density, and infill angle. Infill pattern is the pattern of the material used to build the volume of the printed part. Infill density shows the volume ratio between the cellular printed part to the solid printed part. The infill angle is the angle between the pattern line to the X/Y/Z-axis. For example, Figure 1 below shows a rectilinear infill pattern with different infill densities and a certain infill angle.

Various infill patterns have been introduced and implemented. Perimeter or concentric infill pattern is used by Chacón et al. [3] to characterize the effect of build orientation, layer thickness and feed rate on the mechanical performance of PLA. Sukindar et al. [4] and Ouhsti, et al. [5] implemented a rectilinear infill pattern to investigate the influence of process parameters for tensile strength using polylactic acid (PLA) material. Tao et al. [6] implemented a circle, square/grid, and voronoi infill pattern to investigate their compression performance. Nazir et al. [7] reviewed octahedron, 2D honeycomb, 3D honeycomb, square,

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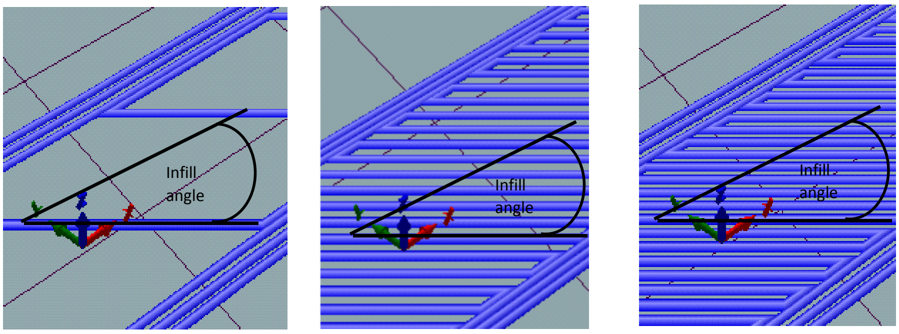
diamond, P-type, gyroid, D-type, and WP type infill pattern to identify the areas that need to be investigated and future research. Ćwikła et al. [8] investigated the influence of rectangular, grid, lines, concentric, hilbert curve, honeycomb, 3D honeycomb patterns on several selected mechanical properties. Wu et al. [9] developed a machine learning and image classification system to detect the defect of the 3D printing process that uses honeycomb, 3D honeycomb, concentric, line, rectilinear, hilbert curve, archimedean chords, and octagram spiral infill patterns. Chen et al. [10] optimized the 3D printing process parameters when manufacturing polylactic acid filament-based Army-Navy retractors by implementing eleven different infill patterns, which are rectilinear, grid, triangles, stars, cubic, line, honeycomb, 3D honeycomb, hilbert curve, archimedean chords, and octagram spiral. Based on the literature study above, various infill patterns are available. However, some infill patterns have slight variation compared to other patterns. Therefore, this research limits the investigation only for hilbert curve, gyroid, archimedean chords, line, 3D honeycomb, octagram spirals, rectilinear, stars, cubic, triangle, concentric, grid, and honeycomb patterns as shown in Figure 2.



10% infill density | 75% infill density | 90% infill density

Figure 1: Infill density and infill angle.

Dave et al. [11] explored the effect of infill density and infill pattern on tensile properties and modes of failure. Quanjin et al. [12] compared five infill pattern structures, which are normal, triangle, square, hexagonal, and tetrahedral patterns, of single polylactic acid tubes and hybrid tubes on their energy-absorbing characteristics. They claim that the infill pattern structure had a significant influence on energy absorbing characteristics. Cho, et al. [13] studied the influence of infill pattern, infill density, and layer thickness on the mechanical strength of PLA material in a 3D printing machine. Vosynek et al. [14] show the influence of filling angle, the shape of the filling, the orientation of the parts during printing, the material and pigment manufacturer to the mechanical properties of the 3D printed part. Iyibilgin, et al. [15] investigated the influence of several infill patterns on the printing time. Khan et al. [16] evaluated the effect of infill pattern on the printing time of the specimen. Baich, et al. [17] investigated the influence of infill patterns on printing costs. According to this research, both filament material length and printing time have an impact on the 3D printing cost.

Based on the literature above, it is obvious that the infill pattern, infill density, and infill angle have an effect on certain mechanical properties of the 3D printed part. However, the research found in the literature does not investigate the influence of the combination of infill pattern, infill density, infill angle to the printing time. In addition, the earlier research does not consider the influence of the infill pattern, infill density, and infill angle on the filament length. According to Medina-Sanchez et al. [18], the simplest printing time estimation can be calculated as the total motion path length divided by the programmed printing speed. As this estimation results in an error of more than 30% from the actual printing time, it is assumed that there is no relation between printing time and filament length. Therefore, the infill pattern, infill density, and infill angle are expected to have an impact on both the printing time and filament length. The filament length influences the material cost and the printing time determines the production cost. As they are both crucial factors to optimize the 3D printing process, it is important to investigate the influence of infill pattern, infill density, and infill angle not only to the printing time but also to the filament length.

The goal of this research is to understand the effect of infill pattern, infill density, and infill angle on the printing time and filament length. Two steps are conducted in this research. First, this research collects the printing time and the filament length data for each combination of infill pattern, infill density, and infill angle. Then, this research analyses the data to understand the influence of these parameters on the required printing time and filament length. By understanding the influence of these parameters, the minimum production cot can be achieved in building a 3D printed part.

The remaining paper is organized as follows. Section 2 discusses the research methodology. In this section, the experiment and the data collection are explained. Then, the result obtained in the experiment and its interpretation are described in Section 3. Finally, section 4 shows the main conclusions of the research.

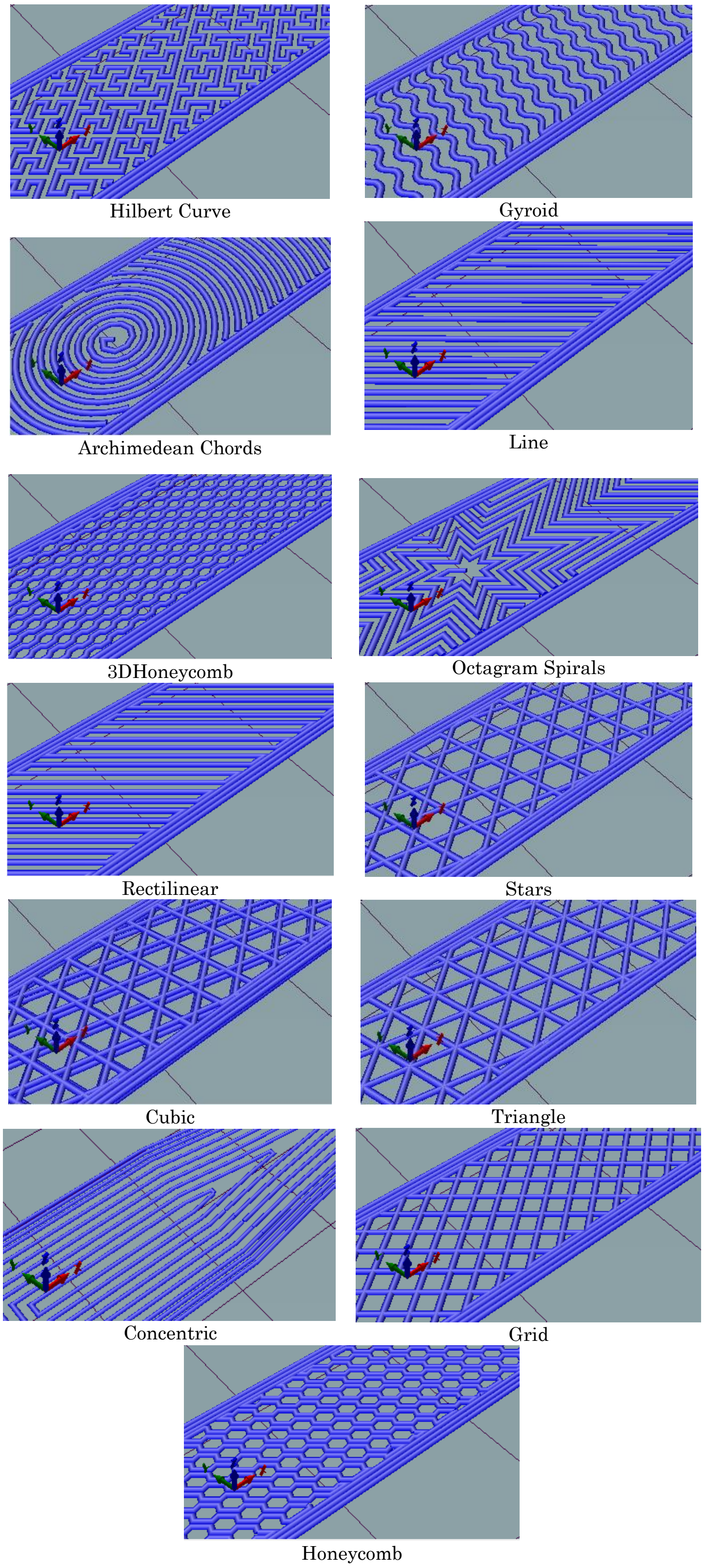


Figure 2: Various infill patterns.

2. RESEARCH METHODOLOGY

A statistical experiment is applied to investigate the influence of infill pattern, infill density, and infill angle of the 3D printing process to the filament length and the printing time. First, this research develops a specimen model as the case study. The specimen is designed based on ASTM D638 standards according to ASTM International for the tensile strength test as shown in Figure 3 [19]. Then, this research collects the required filament length and the printing time to print the specimen as the response parameters. To generate and achieve a consistent filament length and the printing time data, this research implements Repetier-Host v.2.1.6 software as a data acquisition tool.

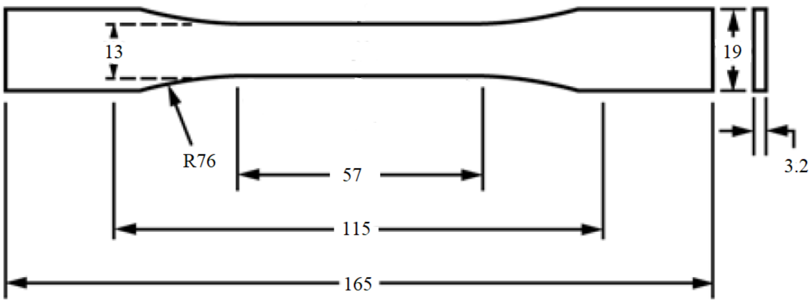


Figure 3: Tensile strength test specimen in millimeter [19].

Two hundred thirty-four experiments are conducted to investigate the influence of thirteen different infill patterns as shown in Table 1. For each infill pattern, two other process parameters, which are infill density and infill angle, are considered at three levels. Three infill density levels are 10%, 50%, and 90%. The value of density level is determined to investigate the least and the densest printed part excluding the hollow and solid printed part. In addition, the angle values of each level of infill pattern are 0°, 45°, and 90°. The value of infill angle level is determined to investigate the longitudinal and the transverse printed part. Meanwhile, the values of other 3D printing process parameters are determined as a constant according to the tools and material catalogs and literature review. Table 2 shows the constant parameter value of the 3D printing process.

Table 1: Value of each factor level.

INFILL PATTERNS	INFILL DENSITIES (%)	INFILL ANGLES (°)
Hilbert Curve, Gyroid, Archimedean Chords, Line, 3D Honeycomb, Octagram Spirals, Rectilinear, Stars, Cubic, Triangle, Concentric, Grid, and Honeycomb	10 50 90	0 45 90

Table 2: Value of each constant parameter.

PARAMETERS	VALUES
Layer Height (mm)	0.3
Number of Outer Shell Layers	3
Shell Thickness (mm)	0.3
Layer Width (mm)	0.4
Bed Temperature (°C)	60
Build Orientation	X-Y
Extrusion Temperature (°C)	205
Printing Speed (mm/s)	80
Diameter Filament (mm)	1.75

3. RESULTS AND DISCUSSION

Table 3 shows the filament length and printing time values for various combinations of infill pattern, infill density, and infill angle. The filament length is measured in millimeter and the printing time is measured in second. The result of the General Linear Model analysis is shown in Table 4 and Figure 4. Table 4 shows which factor that has and does not have a significant effect on the response. The main effect plots for filament length and printing time are shown in Figure 4.

Table 3: Experiment result.

INFILL PATTERNS	INFILL DENSITIES (%)	INFILL ANGLES					
		0°		45°		90°	
		FILAMENT LENGTH (mm)	PRINTING TIME (second)	FILAMENT LENGTH (mm)	PRINTING TIME (second)	FILAMENT LENGTH (mm)	PRINTING TIME (second)
3D Honeycomb	10%	2371	1964	2373	1968	2368	1956
	50%	3019	2135	3020	2140	3015	2128
	90%	3753	2324	3754	2328	3750	2317
Archimedean Chords	10%	2336	1964	2337	1969	2335	1957
	50%	2861	2113	2862	2117	2857	2105
	90%	3384	2259	3385	2263	3381	2253
Concentric	10%	2390	1978	2391	1982	2389	1970
	50%	2889	2118	2890	2122	2885	2111
	90%	3388	2259	3389	2263	3385	2251
Cubic	10%	2375	1975	2421	1989	2413	1977
	50%	2934	2132	2953	2140	2945	2130
	90%	3421	2268	3420	2276	3416	2264
Grid	10%	2431	1979	2423	1981	2428	1972
	50%	2917	2118	2946	2128	2914	2118
	90%	3439	2266	3423	2276	3436	2266
Gyroid	10%	2351	1961	2352	1966	2348	1954
	50%	2802	2079	2803	2083	2798	2071
	90%	3257	2196	3258	2201	3254	2189
Hilbert Curve	10%	2328	1961	2339	1968	2324	1955
	50%	2867	2118	2863	2130	2864	2106
	90%	3379	2269	3385	2282	3375	2260
Honeycomb	10%	2423	1990	2421	1994	2428	1986
	50%	3021	2160	3014	2160	3012	2149
	90%	3462	2283	3468	2288	3462	2275
Line	10%	2354	1964	2377	1975	2347	1955
	50%	2881	2113	2920	2126	2869	2103
	90%	3430	2267	3448	2275	3420	2258
Octagram Spirals	10%	2337	1966	2338	1969	2333	1957
	50%	2859	2113	2860	2117	2856	2105
	90%	3387	2261	3388	2265	3383	2253
Rectilinear	10%	2391	1974	2382	1975	2393	1968
	50%	2887	2113	2905	2122	2877	2103
	90%	3419	2264	3429	2269	3414	2256
Stars	10%	2373	1975	2410	1986	2420	1978
	50%	2969	2143	2954	2141	2949	2130

	90%	3428	2261	3420	2276	3418	2263
Triangle	10%	2375	1976	2415	1987	2421	1980
	50%	2969	2144	2955	2142	2948	2131
	90%	3428	2273	3420	2280	3418	2268

Based on the collected data shown in Table 3, the minimum printing time is achieved by implementing the Gyroid pattern with a 10% density and 90° infill angle. The minimum filament length is achieved by implementing the Hilbert Curve pattern with a 10% density and 90° infill angle. Meanwhile, the implementation of the 3D honeycomb pattern with a 90% density and 45° infill angle requires the maximum filament length and printing time. For 10 % infill density, the implementation of the Grid pattern with 0° infill angle requires the maximum filament length. The maximum printing time is achieved by using the Honeycomb pattern with 45° infill angle. For 50% infill density, the minimum filament length and printing time is achieved by using the Gyroid pattern with 90° infill angle. The implementation of Honeycomb with 0° infill angle requires the maximum filament length and printing time. For 90% infill density, the implementation of the Gyroid pattern with 90° infill angle requires the minimum filament length and printing time.

For each infill angle, the implementation of the Gyroid pattern with 10% infill density requires the minimum printing time. The implementation of the Hilbert curve achieves the minimum filament length for 0° and 90° infill angle. For the 45° infill angle, the minimum filament length is achieved by implementing the Archimedean Chords infill pattern. The maximum filament length and printing time are achieved by using the 3D honeycomb pattern with 90% infill density. Most of the patterns achieve the minimum filament length and printing time by implementing a 10% infill density and 90° infill angle. The maximum filament length and printing time are required by most of the patterns by implementing a 90% density and 45° infill angle.

Table 4: Effect factor to response.

FACTOR	RESPONSE	EFFECT
Infill Density	Filament Length	Yes
Infill Angle	Filament Length	No
Infill Pattern	Filament Length	Yes
Infill Density	Printing Time	Yes
Infill Angle	Printing Time	Yes
Infill Pattern	Printing Time	Yes

Based on the data shown in Table 4 and Figure 4, the infill density is found as the most influenced factor for required filament length and printing time. The implementation of 90% infill density creates the densest printed part. Therefore, it requires the maximum filament length and printing time. On the contrary, the implementation of 10% infill density creates the least printed part. Therefore, the minimum filament length and printing time are achieved by implementing the 10% infill density.

The infill pattern also has a significant effect on filament length and printing time. The gyroid pattern is the simplest geometry compared to other patterns. Therefore, it requires the shortest printing time. Hilbert curve requires the shortest length among other patterns. However, it needs the longer printing time compared to the Gyroid pattern because it implements more rapid nozzle movement with an unfilled path. 3D honeycomb pattern requires the maximum filament length and printing time because it creates a complex and tight path.

Furthermore, the infill angle has an influence on the printing time. However, it does not influence the filament length. For each density, the 90° and 45° infill angle require the minimum and maximum printing time respectively. The 90° infill angle creates a longitudinal path that requires a shorter unfilled path compared to the 45° infill angle that creates a diagonal path. However, the Triangle, Star, and Cubic infill patterns with 10% density and 0° infill angle require the minimum printing time because they create a longitudinal path in 0° infill angle.

4. CONCLUSIONS

In this research, the influence of infill pattern, infill density, and infill angle to the printing time and the length of the filament material is analyzed. Based on the analysis, higher infill density requires a longer filament length and printing time for each infill pattern and infill angle. On the contrary, the minimum filament length and printing time are achieved by implementing the lowest infill density. The Gyroid infill pattern achieves the minimum printing time for each density. Meanwhile, the 3D honeycomb infill pattern requires the maximum filament length for each infill angle. The implementation of the 45° infill angle requires the maximum filament length and printing time. The minimum filament length and printing time will be achieved by implementing the 90° infill angle.

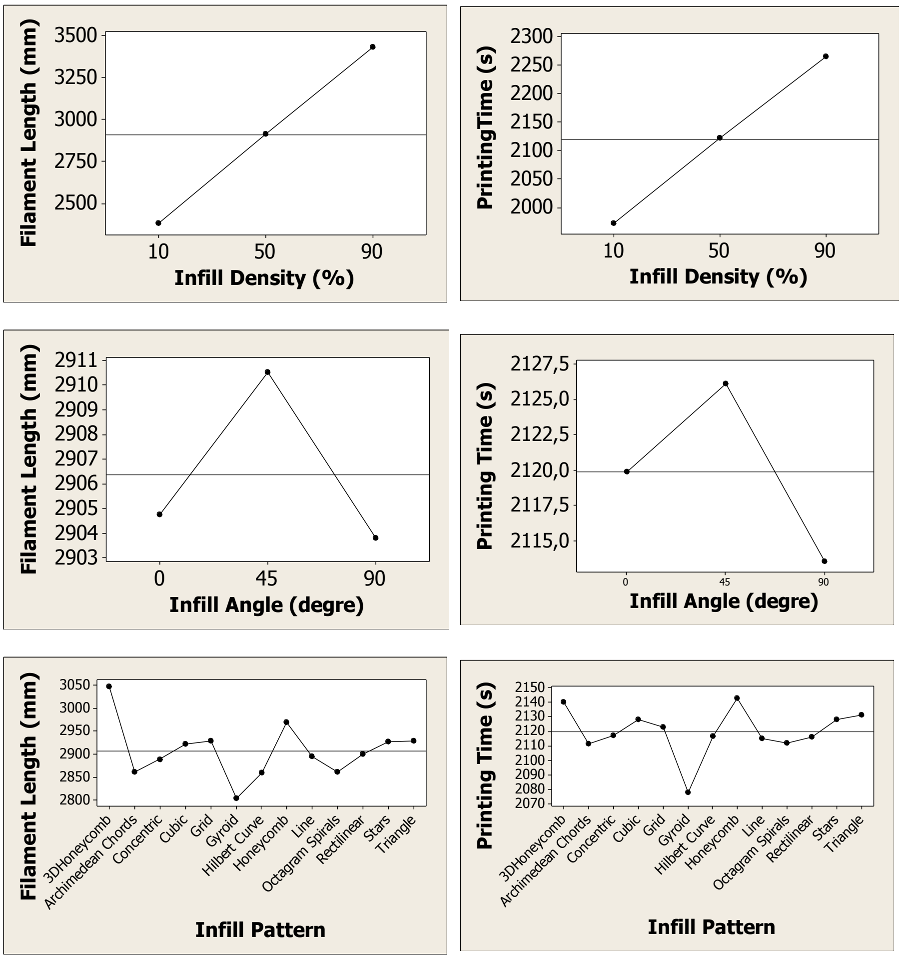


Figure 4: Main effect plot for filament length and printing time.

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