5-2023

Testing the Effects of Different Designs on the Physical Properties of 3D-Printed Watch Bands

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Testing the Effects of Different Designs on the Physical Properties of 3D-Printed Watch Bands

An undergraduate honors thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Industrial Engineering with Honors

By

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Spring 2023

University of Arkansas

College of Engineering

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Abstract

Technological innovation progresses at an ever-increasing rate, and this is especially true in the field of 3D-printing. 3D-printing has become popular in manufacturing settings and among amateur hobbyists alike, largely because 3D-printers can fabricate an enormous number of designs from an array of materials and allow for fine-tuning through several setting options. Individuals with proficient 3D-printing abilities can produce a nearly infinite number of components for diverse applications in manufacturing, recreation, ergonomics, and many more. Some individuals use their skills to create functional substitutes for name-brand items, including bands to fit and be worn with a smart watch. However, little is known about how various print setting options may affect the quality and durability of printed components. This research seeks to uncover how some design changes can affect these physical properties. We use a full factorial experiment to test the effects of print infill pattern and print infill density on the peak tensile strengths of printed components and conduct a bend test to study the durability of such components.

Acknowledgements

The Department of Industrial Engineering faculty provided tremendous support for my research, and I am very appreciative of their efforts. I would like to thank my research advisor, Dr. Haitao Liao, for supporting, sponsoring, and mentoring me throughout this process. His valuable input and advice made every step of this project work, from inception to final analysis. I would also like to thank Dr. Kelly Sullivan for facilitating the initial conversation of research topics between myself and the industrial engineering faculty. Dr. Sullivan also helped immensely with my research proposal, providing advice and ideas about my topic's direction.

Several individuals supported my 3D-printing and testing efforts for this research. I would like to thank Dr. Chase Rainwater for procuring a 3D-printer and materials for my research and for providing printing support and instruction. Dr. Rainwater also graciously reviewed my thesis for my final defense. I would like to thank Mr. Hieu Bui for teaching me to use 3D-modeling software to design components and fabricate those designs on a printer. I am also grateful to Mr. Mike Kyle for providing access to a tensile testing machine, showing me how to use it, and giving technical advice for part design and testing procedure.

This research was also made possible by several organizations. I would like to thank the Department of Industrial Engineering for teaching me the technical and conceptual knowledge and skills required to design experiments and analyze results. I would like to thank the Honors College for providing support through grant funding. Finally, I would like to thank the University of Arkansas for supporting my education over the past four years.

Sincerely,

Ross Harper

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1. Introduction

1.1 Background

3D-printing is quickly becoming a lucrative industry and hobby. Several hobbyists have started creating printed bands to be worn with smartwatches. Smartwatches are an increasingly valuable technology due to their wide variety of applications in healthcare and entertainment. These applications include measuring heart rate and blood pressure, monitoring sleep, tracking steps, and sending and receiving text messages, emails, and telephone calls. The global smartwatch market was estimated at $57.3 billion in 2021 and is projected to reach $132.9 billion by 2026 [1]. Global smartwatch shipments grew by 35% from Q1 2020 to Q1 2021, with Apple increasing its share of the market from 30.3% to 33.5% over the same period [2].

The Apple watch band accessory, which allows the device to be worn by the user, comes in a variety of designs and materials. Variations in design include length, width, perforations, and the presence of clasps [3]. The watch bands also come in several different materials, such as fluoroelastomer, woven nylon, and silicone [3]. These materials have high tensile strengths, excellent resistance to water, chemicals, and heat, and are relatively inexpensive, making them ideal candidates for use in watch bands [4]. It stands to reason that as the market for smartwatches grows, so too will the market for 3D-printed bands to accompany them.

1.2 Literature Review

Modern 3D-printing software and technology allows for the design and creation of parts without the need for more elaborate manufacturing techniques. Thermoplastic polyurethane (TPU) and polypropylene (PP) are common materials used in 3D printing that are also strong, flexible, and resistant to water, heat, and chemicals [4]. 3D-printed TPU has also been shown to be strong enough for some medical applications [5]. Research has also shown that the addition of

PP fibers to geopolymer (a chain of mineral molecules linked with covalent bonds) mixtures results in increased compressive strength, flexibility, and fracture energy compared to parts that contain no PP fibers [6]. This suggests that a mixture of TPU and PP may have higher strength than either material alone.

Some research has been conducted into certain 3D-printed component parameters, especially physical dimensions and design. A 2020 study found a positive correlation between printed parts' length and tensile strength [7]. Research has also shown that, for parts that have a perforated design, a component's tensile strength improves with a larger perforation diameter and is decreased with a greater number of perforations [8]. Layer thickness also has a significant effect on strength, with decreased thickness resulting in stronger parts [9]. However, it does not appear that ample research has been done into the effects of print settings on component strength and durability. This is the focus of the following research.

2. Methodology

This section explains the methods used for this research, including sample design, sample fabrication, and sample testing.

2.1 Design

Samples used for this research were designed in Autodesk Fusion 360, a 3D modeling and computer-aided design software provided free for educational use through the University of Arkansas. Design specifications were dictated based on fixturing of the tensile testing machine provided for use by the Department of Mechanical Engineering. A drawing supplied by Mr. Mike Kyle, Undergraduate Lab Engineer for the Department of Mechanical Engineering, was used as the basis for sample design (Figure 1).

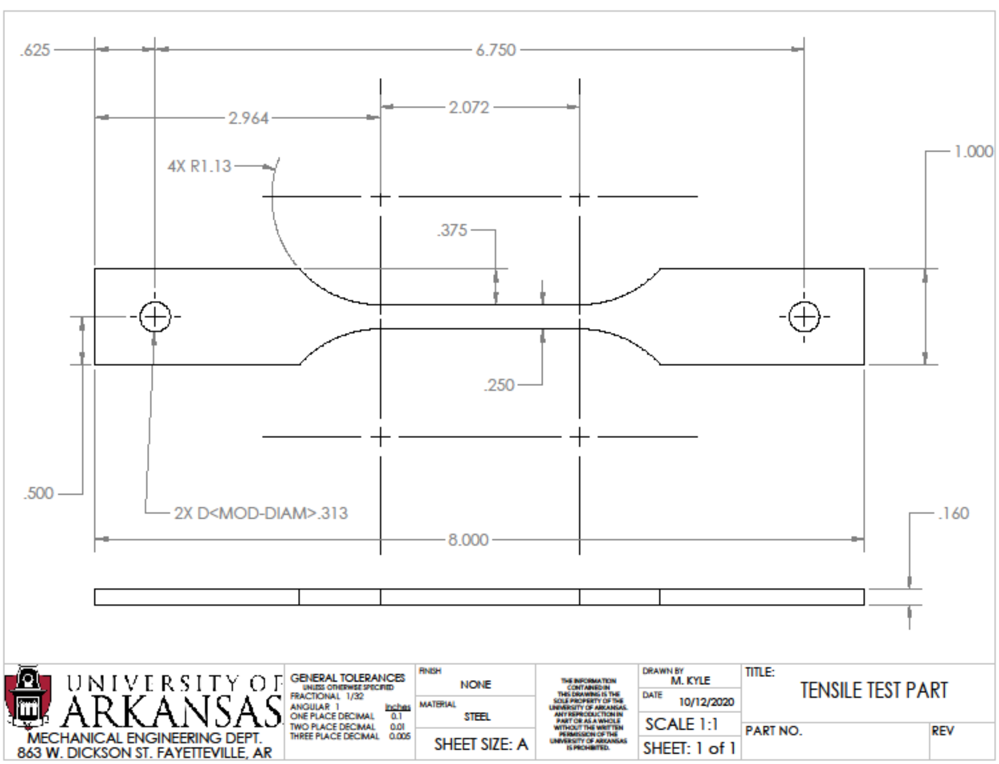

Figure 1. Drawing of tensile test part used for sample design, provided by Mr. Mike Kyle

To save material, reduce printing time, and increase printing multiplicity, samples were shortened to a length of five inches in Autodesk Fusion 360 (Figure 2). All other dimensions, including width, thickness, and hole diameter, remained consistent with the original drawing.

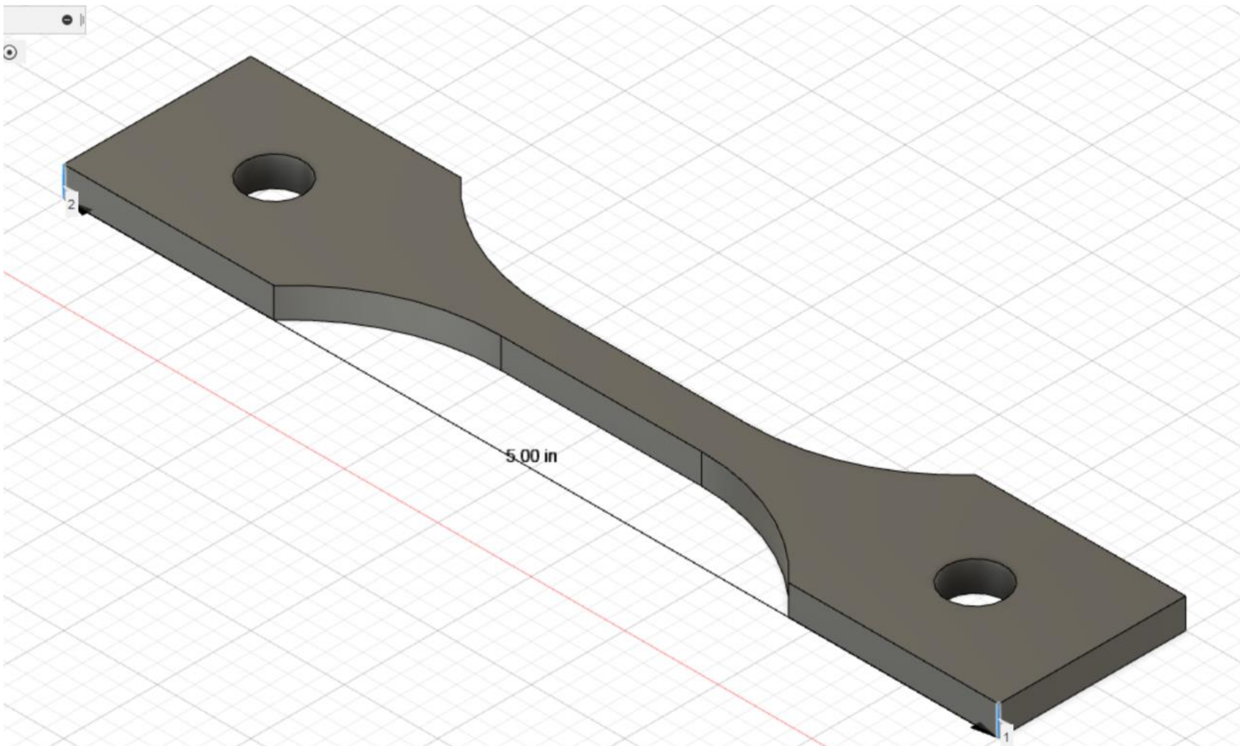

Figure 2. Final sample design 3D model, as viewed in Autodesk Fusion 360

2.1 Fabrication

Part samples were printed using a MakerBot Method X 3D-printer provided by the Department of Industrial Engineering. This was the only machine used to fabricate parts to reduce sample variability. Samples were printed with Jabil TPE SEBS 1300 95A, a thermoplastic elastomer designed for 3D-printing with similar properties to TPU, PP, and other synthetic rubbers (Figure 3).

Figure 3. Printed sample before bending or testing

MakerBot's printing preparation webpage was used to define print settings. MakerBot's default print settings for PETG, a popular plastic for printing, were used as a basis for these setting definitions. Through trial and error and recommendations from Jabil, it was determined that several settings be changed to produce viable samples for testing. These settings were kept constant across all samples (Table 1).

Table 1. Print setting changes for all fabricated samples

Printer Settings:	**Value**	**Unit**
Chamber Temp	0	Degrees Celsius
Platform Temp	60	Degrees Celsius
Filament Cooling Fan Speed	0%	
Extruder Settings:		
Extruder Temp	260	Degrees Celsius
Fan Power	0%	
Roofs:		
Fan Speed	0%	
Print Speed: Roof Surface	25	millimeters per second
Sparse Roof Surface Fill	25	millimeters per second
Shells:		
Print Speed: Insets	20	millimeters per second
Print Speed: Outlines	20	millimeters per second
Infill:		
Print Speed: Solid	20	millimeters per second
Print Speed: Sparse	25	millimeters per second
Print Speed: Spurs	25	millimeters per second
Floors:		
Print Speed: Floor Surface	15	millimeters per second

MakerBot's printing preparation webpage allows for customization of several print settings at several levels. For this research, two levels of infill pattern and two levels of infill density percentage were used as factors for experimentation. Infill patterns chosen were a linear design and a hexagonal design. Each of these patterns were physically designed and fabricated using the webpage's default slicing software. Infill density percentages chosen were 20% and 40%. These were also designed and fabricated using the default software. Over the course of this research, seven samples of each factor combination were fabricated and tested, or twenty-eight samples in total (Table 2).

Table 2. Replicate count for factor levels from print settings

	Infill Density Percentage	
Infill Pattern	Twenty	Forty
Linear	7	7
Hexagonal	7	7

To test the durability of samples across print settings, a fatiguing operation was performed on some samples. This operation consisted of bending a sample in half lengthwise a certain number of times. One "bend" is defined as bending the sample in half in one direction, then bending in half in the opposite direction. The goal of the operation was to deform the band and partially compromise its physical integrity (Figures 4-9).

Figure 4. Linear infill pattern with 20% infill density sample after 25 bends, top view

Figure 5. Linear infill pattern with 20% infill density sample after 25 bends, bottom view

Figure 6. Linear infill pattern with 20% infill density sample after 25 bends, side view

Figure 7. Linear infill pattern with 20% infill density sample after 50 bends, top view

Figure 8. Linear infill pattern with 20% infill density sample after 50 bends, bottom view

Figure 9. Linear infill pattern with 20% infill density sample after 50 bends, side view

Fatiguing levels used for testing were twenty-five bends and fifty bends. Two samples of each print setting level combination were used for fatiguing for each level of bending (Table 3).

Table 3. Final replicate count across all factors and levels

	Infill Density Percentage					
	Twenty			Forty		
	Number of Bends			Number of Bends		
Infill Pattern	Zero	Twenty-Five	Fifty	Zero	Twenty-Five	Fifty
Linear	3	2	2	3	2	2
Hexagonal	3	2	2	3	2	2

2.3 Testing

After fabrication and any required fatiguing, samples were tested using a tensile testing machine. Traditionally, these machines are used to measure the tensile strength at break for plastic or metal samples. Due to the highly elastic properties of TPE, preliminary samples were observed to stretch considerably without sharply breaking. Thus, this research recorded the maximum force withstood by each sample before decline. A decline in force withstood is analogous to a sharp break for more brittle materials as the sample is permanently deformed and its integrity compromised. All samples were tested using the same elongation rate (five millimeters per second) and maximum force (in Newtons) was recorded (Table 4, Figure 10).

Table 4. Maximum force withstood for all replicates across all factors and levels

	Infill Density Percentage					
	Twenty			Forty		
	Number of Bends			Number of Bends		
	Zero	Twenty-Five	Fifty	Zero	Twenty-Five	Fifty
Infill Pattern	Maximum Force Withstood (N)					
Linear	130	118	120	128	134	120
	122	127	119	125	122	124
	125			130		
Hexagonal	137	128	123	143	137	130
	132	131	122.5	147	135	132.5
	125			152		

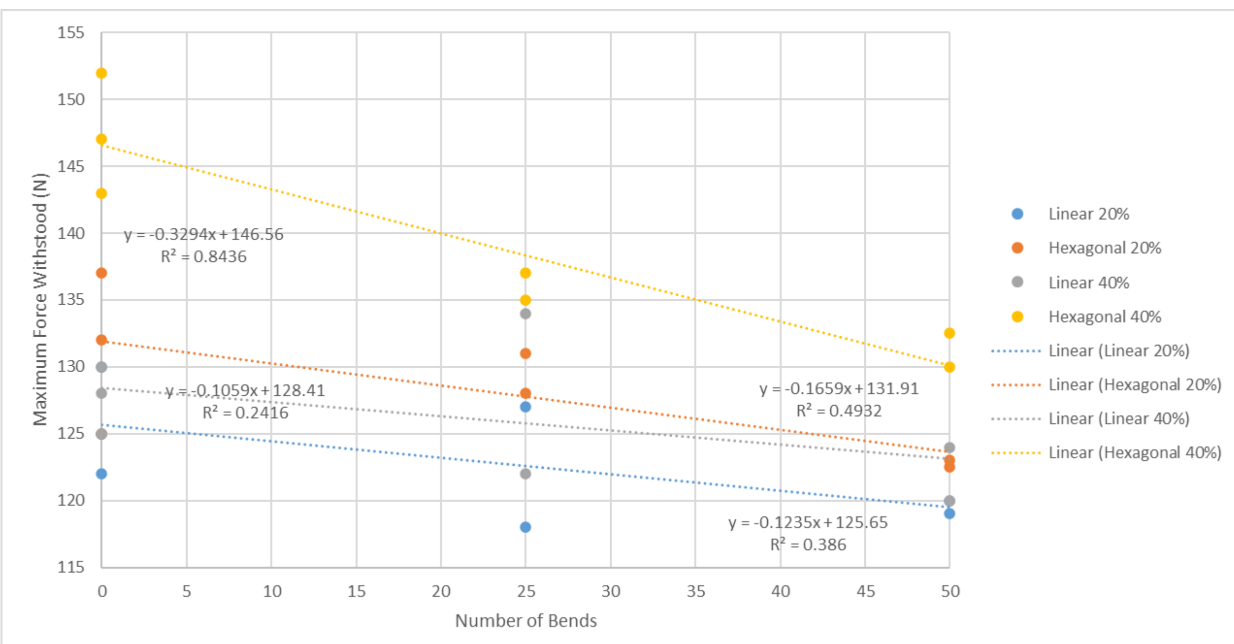

Figure 10. Plot of maximum force withstood versus number of bends, grouped by infill pattern and density percentage treatment level

3. Results

Tensile strength testing was performed in two stages. In the first stage, testing was limited to infill pattern and infill density percentage using samples with no fatiguing. This stage served as an initial idea of how these factors affect strength. In the second stage, fatigued samples were tested to study the durability of each combination of infill pattern and infill density percentage.

3.1 Stage One

Analysis of experimental results began with analysis of variance for infill pattern and infill density percentage effects and interaction. Only samples with no bends were used for analysis, meaning three samples at each combination of infill pattern and density percentage were used for a total of twelve data points. Based on the results of ANOVA, all main effects and interaction effects are significant [for $\alpha = 0.05$] (Figures 11-14).

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Infill Percentage	1	184.1	17.82%	184.1	184.08	5.84
Infill Pattern	1	396.7	38.41%	396.7	396.75	12.60
Infill Percentage*Infill Pattern	1	200.1	19.37%	200.1	200.08	6.35
Error	8	252.0	24.40%	252.0	31.50	
Total	11	1032.9	100.00%			

Source	P-Value
Infill Percentage	0.042
Infill Pattern	0.008
Infill Percentage*Infill Pattern	0.036
Error	
Total	

Figure 11. ANOVA results for infill pattern and infill density percentage with zero bends

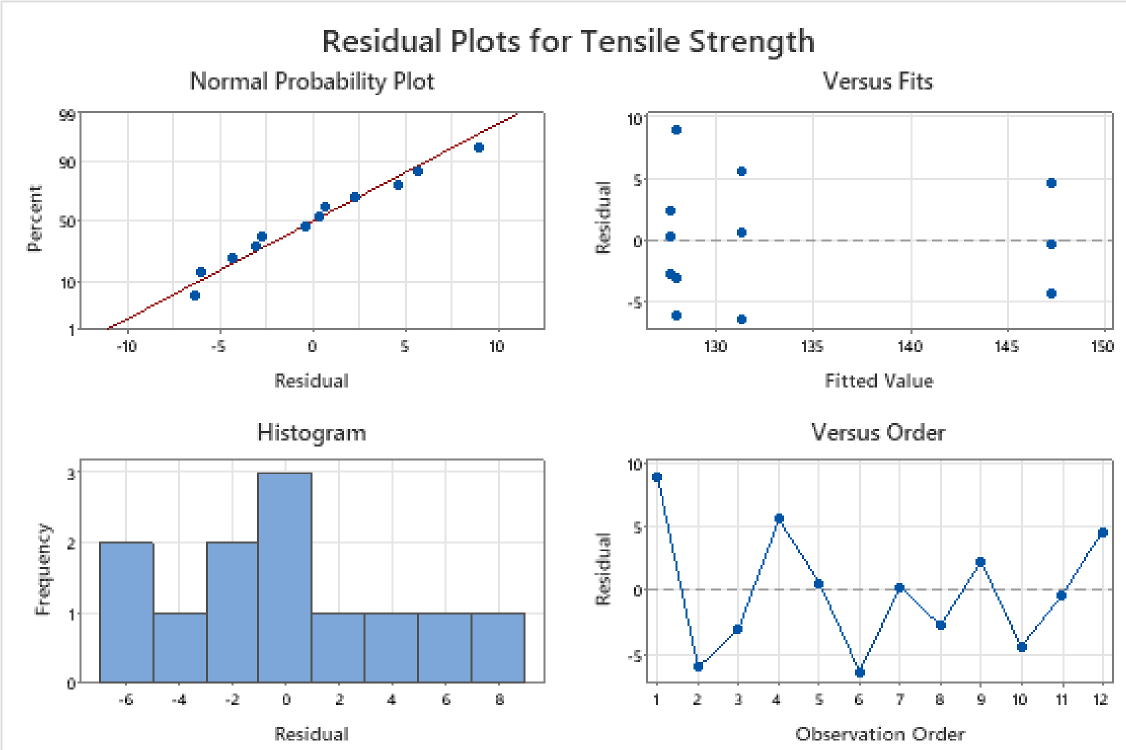

Figure 12. Residual plots for tensile strength for infill pattern and infill density percentage with zero bends

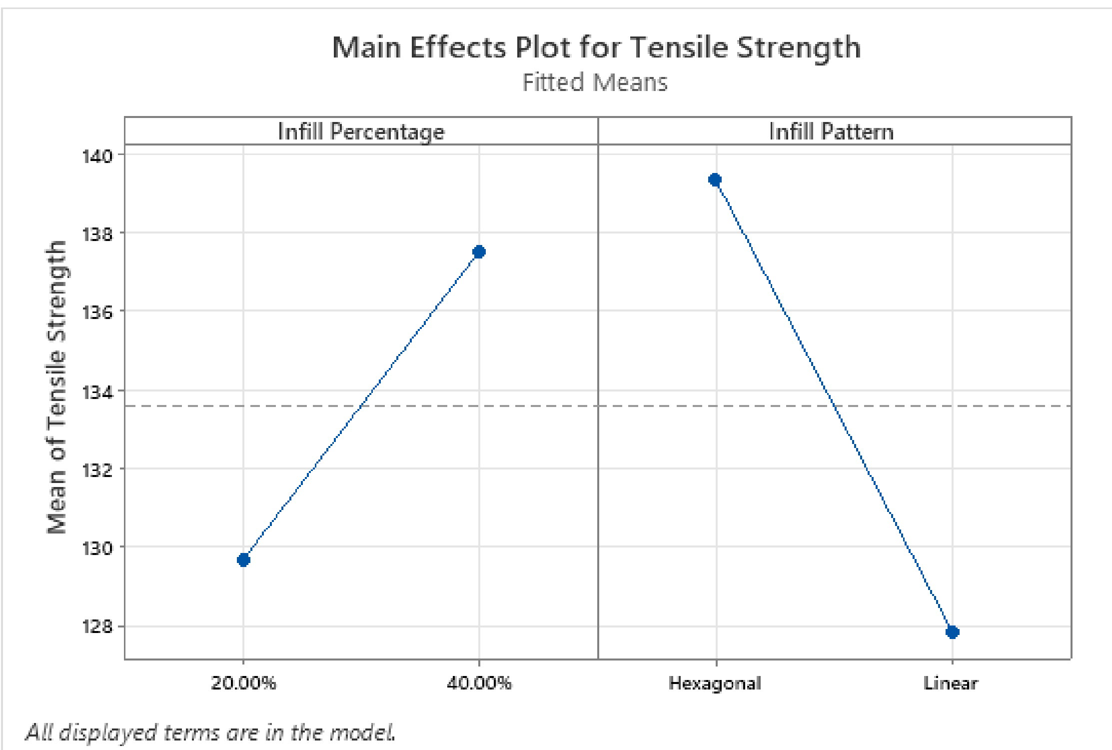

Figure 13. Main effects plot for tensile strength for infill pattern and infill density percentage with zero bends

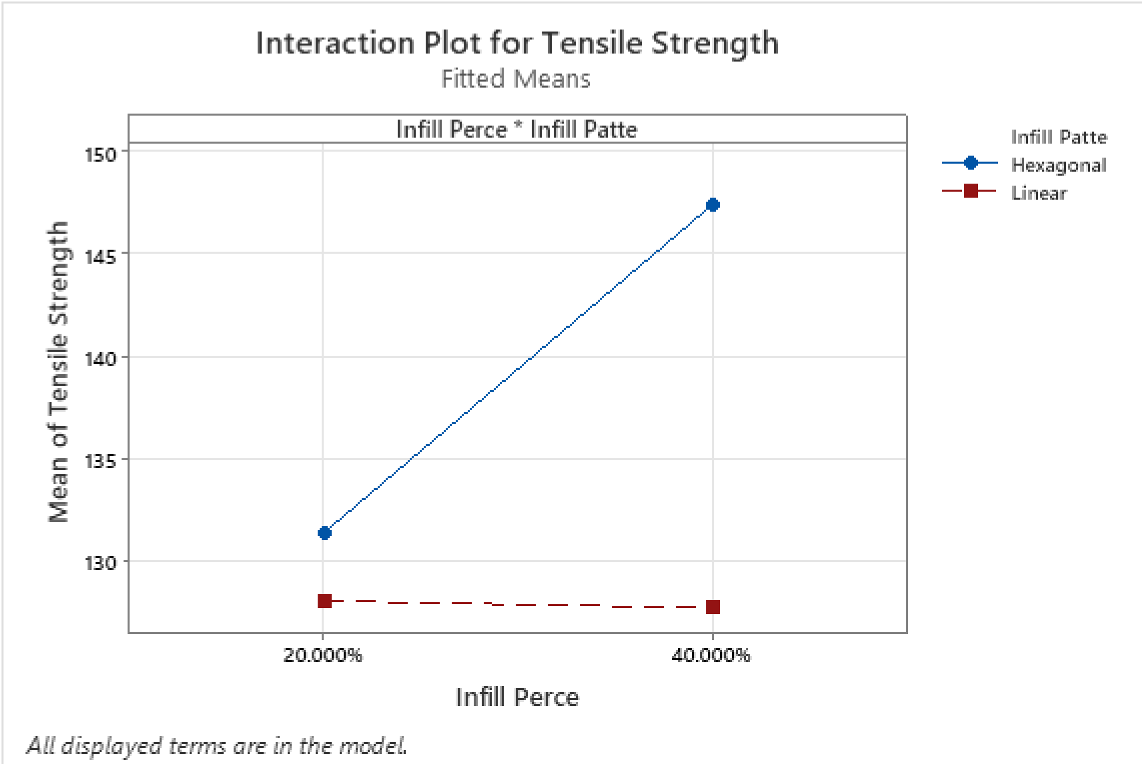

Figure 14. Interaction plot for tensile strength for infill pattern and infill density percentage with zero bends

Tukey pairwise comparisons were performed with 95% confidence for the same set of samples (Figures 15-17). The confidence intervals show significant differences in mean maximum force withstood between linear and hexagonal infill patterns, twenty percent and forty percent infill densities, and hexagonal infill pattern with forty percent infill density and all other treatment combinations.

Tukey Pairwise Comparisons: Infill Percentage

Grouping Information Using the Tukey Method and 95% Confidence

Infill Percentage	N	Mean	Grouping	
40.00%	6	137.500	A	
20.00%	6	129.667		B

Means that do not share a letter are significantly different.

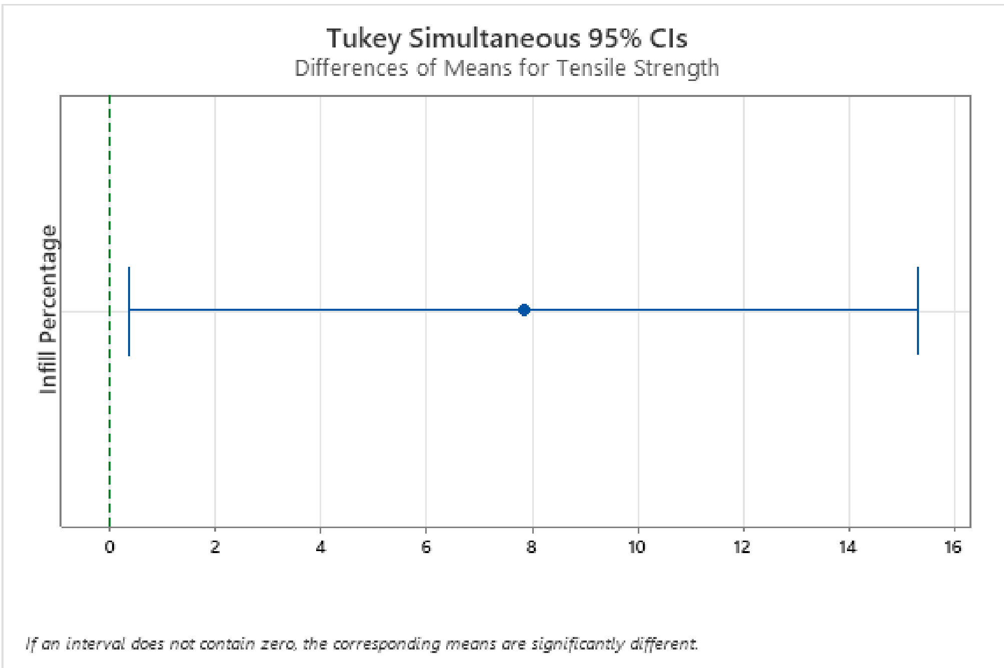

Figure 15. Tukey pairwise comparisons for infill density percentage

Tukey Pairwise Comparisons: Infill Pattern

Grouping Information Using the Tukey Method and 95% Confidence

Infill Pattern	N	Mean	Grouping	
Hexagonal	6	139.333	A	
Linear	6	127.833		B

Means that do not share a letter are significantly different.

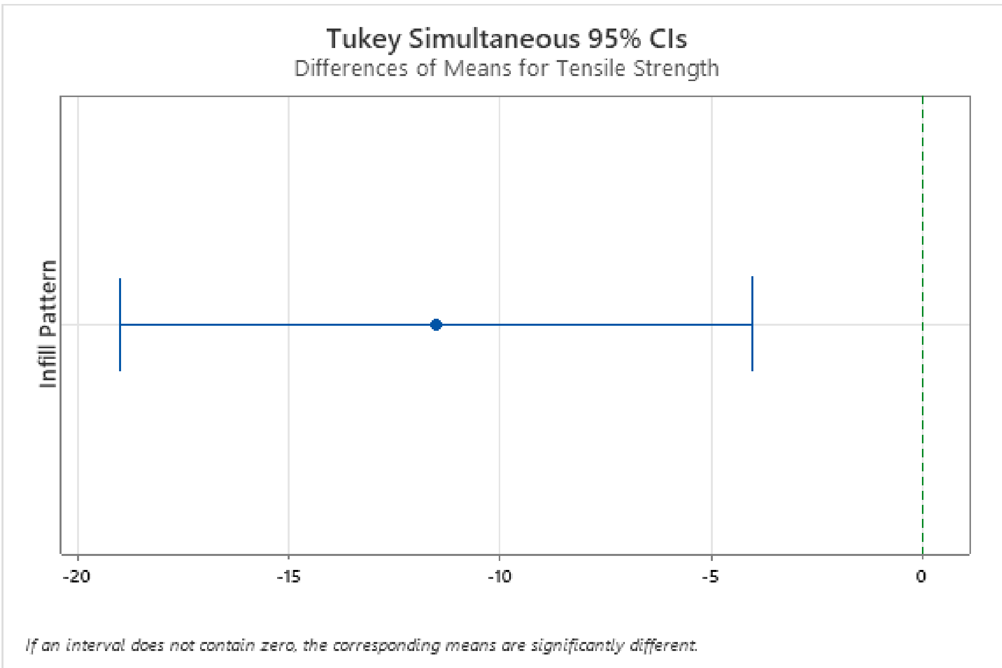

Figure 16. Tukey pairwise comparisons for infill pattern

Tukey Pairwise Comparisons: Infill Percentage*Infill Pattern

Grouping Information Using the Tukey Method and 95% Confidence

Infill Percentage*Infill Pattern	N	Mean	Grouping
40.00% Hexagonal	3	147.333	A
20.00% Hexagonal	3	131.333	B
20.00% Linear	3	128.000	B
40.00% Linear	3	127.667	B

Means that do not share a letter are significantly different.

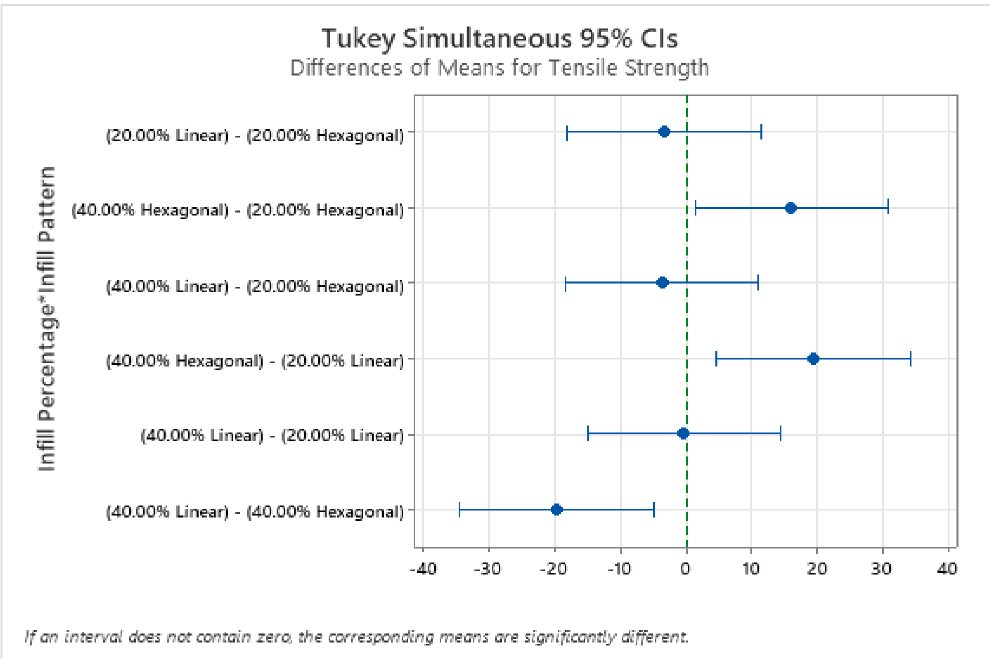

Figure 17. Tukey pairwise comparisons for all combinations of infill pattern and infill density percentage

3.2 Stage Two

Regression analysis was performed on all replicates of all levels of all treatments. The final regression equation includes terms for number of bends, infill pattern, infill density percentage, and interaction between infill pattern and infill density percentage (Table 5, Equation 1).

Table 5. Corresponding values for infill pattern and infill density percentage for the regression equation

Pattern (P)	
Linear	-1
Hexagon	1
Infill Density (I)	
20%	-1
40%	1

$$\textbf{Maximum Force Withstood} = 133.13 - 0.1812\ \text{Bends} + 4.679\ P + 3.571\ I + 2.000\ P{*}I$$

Equation 1. Final regression equation for maximum force withstood as a function of treatment levels.

There appears to be a constant rate of change to maximum force withstood by a component across different combinations of infill pattern and infill density percentage. The regression model is a good fit (P-value = 0.438 for lack-of-fit) given the experimental results and chosen parameters (Tables 6-7, Figure 18).

Table 6. Coefficient significance for final regression model

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	133.13	1.16	114.60	0.000	
Bends	-0.1812	0.0389	-4.66	0.000	1.00
P	4.679	0.810	5.78	0.000	1.00
I	3.571	0.810	4.41	0.000	1.00
P*I	2.000	0.810	2.47	0.021	1.00

Table 7. ANOVA for final regression model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1480.6	370.16	20.17	0.000
Bends	1	398.6	398.59	21.72	0.000
P	1	612.9	612.89	33.39	0.000
I	1	357.1	357.14	19.46	0.000
P*I	1	112.0	112.00	6.10	0.021
Error	23	422.1	18.35		
Lack-of-Fit	7	132.7	18.96	1.05	0.438
Pure Error	16	289.4	18.09		
Total	27	1902.8			

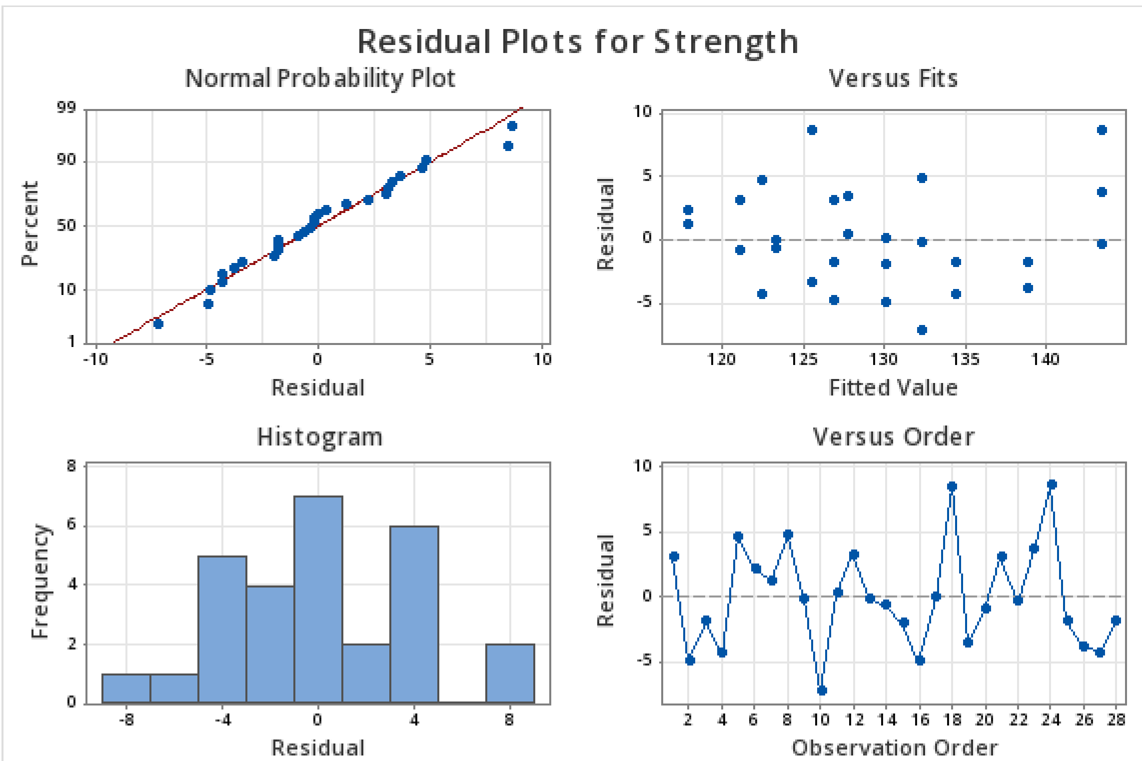

Figure 18. Residual plots for final regression model

4. Conclusion & Further Research

This paper outlines a full factorial design to study the effects of three factors on a 3D-printed components' quality and durability. These factors include infill pattern, infill density percentage, and amount of fatigue at two, two, and three levels, respectively. This research has shown that all factors significantly affect the component's maximum tensile strength. This research also found significant interaction between infill pattern and infill density percentage factors. This research did not find significant effects of infill pattern nor infill density percentage on the rate at which a component's maximum tensile strength decreases as amount of fatigue increases.

Due to time and resource constraints, this research was only able to investigate two factors related to the 3D-printing process. There are several other factors that could affect component quality, including layer thickness, printing speed, printing temperature, material, and many more. Further research into these factors, along with any interaction between them, may yield interesting and valuable results. This research also used a constrained number of replicates for each factor level combination. Further research may simply fabricate and test more samples of the same factors and levels outlined in this research for further clarity of the results.

This research only considered one response in its methodology. There may be other dependent variables worth studying that could be affected by factors relating to 3D-printing, including cost, feasibility, functionality, and comfortability. Further researchers could design experiments to test for these or other responses. These experiments could test factors outlined in this research, factors mentioned in the previous paragraph, or others. Should an experiment test several factors across several responses, researchers may consider a fractional experimental design to reduce the number of samples needed to complete the testing.

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