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Article

Optimizing 3D printing parameters: Evaluating infill type and layer height effects on tensile fracture force

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SUMMARY

While the concept of 3D printing has existed for decades, only recently has it expanded into our homes, workplaces, and everyday lives. In fact, 3D printing is already being used in a variety of important applications, ranging from prosthetics to automobiles. Nowadays, people can purchase a 3D printer and start 3D printing gadgets from their own homes for under $200. As the concept of 3D printing inevitably continues to develop, it is important that products that are 3D printed are strong and durable, especially if these products are designed to be used frequently or are subject to high loads of stress or pressure. Therefore, this study evaluated the effects of the infill pattern and layer height on the tensile fracture force of tensile testing specimens. To evaluate strength in the XY-directions, we printed tensile testing specimens in the horizontal orientation with different infill patterns and a constant layer height. We hypothesized that the gyroid infill pattern would have the highest tensile strength because it maintains a constant curvature in all directions, therefore having the longest path of least resistance and the maximum tensile strength in a given volume. In order to evaluate strength in the Z-direction, we printed testing specimens in the vertical orientation with varying layer heights and a constant infill pattern. We hypothesized that the lowest layer height of 0.08 mm would yield the highest fracture force because, in the Z-direction, the lowest layer height allows the shapes of extrusions to resemble elongated rectangles instead of ideal circles, which results in larger contact area between the layers. On average, specimens with the gyroid infill pattern exhibited the highest tensile fracture force (mean = 583.14 N) in the XY-directions, and specimens with a layer height of 0.08 mm showed the highest tensile fracture forces in the Z-direction (mean = 526.49 N). Both sets of data supported the hypotheses, showing that the gyroid pattern and 0.08 mm layer height are most practical in terms of strength when 3D printing objects.

INTRODUCTION

The concept of 3D printing as it is known today existed long before the term “3D printing” itself emerged, in a method known as additive manufacturing (1). The American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) define additive manufacturing as “[the] process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” (1). The technologies and processes of 3D printing are classified as forms of additive manufacturing. One prominent type of 3D printing technology is Fused Filament Fabrication, more commonly known as Fused Deposition Modeling (FDM). FDM is currently the most widely used technology in desktop 3D printers. In fact, the number of companies utilizing FDM increased from 12% to 46% between 2017 and 2018, representing an almost fourfold increase (2).

FDM 3D printing is a process by which plastic filament is heated to a temperature above its melting point and extruded through a nozzle layer-by-layer, where each new layer adheres to the previous layer or print bed through heat and pressure, until a completed three-dimensional structure is created (3). From the fundamental understanding of this process, it can be assumed that an object with maximum strength should have a solid interior, which will provide the most amount of supporting material in the XY-directions and the most contact area in the Z-direction. However, on a practical note, a solid interior in a 3D printed object would result in an exponential increase in the weight, amount of filament, and time required to print a comparatively larger object. To address this problem, most parts are printed with infill instead of a solid interior. Infill is a repetitive structure that takes up space inside a 3D printed object with a non-solid interior, making the process of 3D printing objects more practical (4). Different infills, such as the triangle or honeycomb patterns, are designed strategically to speed up the print, save filament, and maintain the strength of the part (4).

Another factor that can affect the print time and strength of a 3D printed part is the layer height. The layer height is the height of the plastic extruded on each layer (5). A lower layer height is optimal for improving the appearance of the printed part as the closer distance between layers means that the layering is less visible. This is ideal if the part is to be displayed or used as a final product. However, to optimize a part for maximum printing speed, it should have the highest layer height, because it allows the printer to be able to reach a certain height faster by printing fewer layers (5). In addition, the layer height can also affect the strength of a 3D printed part in many ways, especially in the Z-direction, so it is important to choose a layer height that is optimized for both print time and strength (5).

Therefore, this experiment evaluates the effect of infill type and layer height on the tensile fracture force of 3D printed specimens. From this experiment, any 3D printer user, from amateurs to professionals, could acquire an understanding of which infill patterns and layer heights work best with the objects they are printing, from basic, ordinary gadgets to complex, sophisticated machinery.

To determine the tensile fracture forces with varying infill patterns and layer heights, we 3D printed specimens with different infill patterns in the XY-directions and different layer heights in the Z-direction. We performed a tensile test for each specimen using a tensile testing machine to find the tensile fracture force of specimens printed with varying infills and layer heights. Overall, we found that the gyroid infill pattern withstood the highest tensile forces in the XY-direction, at a mean of 583.14 N, while the 0.08 mm layer height exhibited the highest mean tensile fracture forces in the Z-direction, at 526.49 N. Therefore, the 0.08 mm layer height and gyroid infill pattern would be strongest in a real-life scenario.

Infill

Different patterns of infill used to 3D print an object can have a considerable effect on the strength of the part in the XY-directions. The fracture line (the path where the material separates into two or more pieces) during a tensile test will always occur at the path of least resistance, which is the most efficient way to travel from one point to another (normally a straight line) (6). With this information, triangle and star infills should be the weakest because they contain lines that are almost perfectly perpendicular to the direction of the tensile forces; therefore, the path of least resistance is the shortest and these infill patterns are prone to fracture more easily (6). Rectilinear and grid infills contain perpendicular lines at a 45° angle to the tensile forces, so the path of least resistance is increased; therefore, they should have higher tensile fracture forces compared to the triangle and star shapes (6). However, the most ideal 2D infill shape is the honeycomb structure. The honeycomb structure contains a distinct lack of long, straight lines, so the path of least resistance is not completely straight, thus increasing its tensile strength (6).

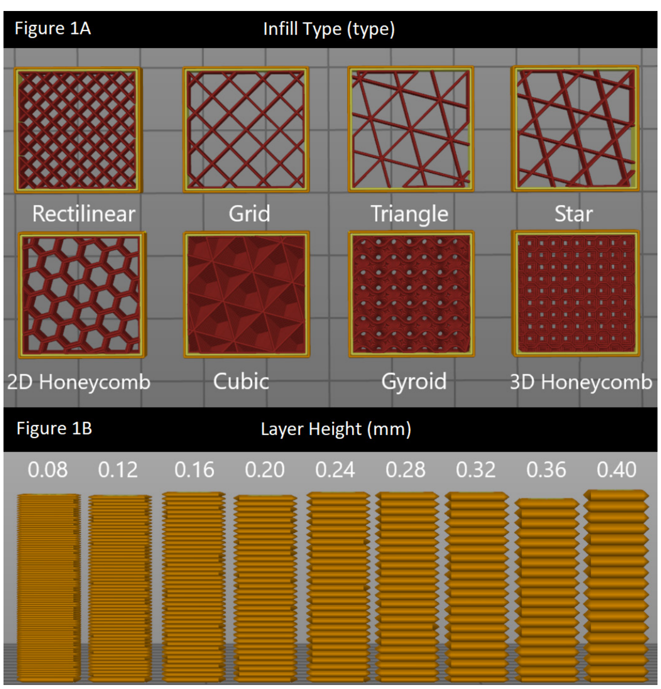

Figure 1: Infill patterns and layer heights. (A) Different infill patterns printed in the XY-direction and (B) different layer heights printed in the Z-direction used in this experiment to determine tensile fracture force.

3D infills are able to distribute forces to all directions, allowing for better strength no matter where the force is applied. They also lack straight lines in all axes, which further improves their strength from 2D infill patterns. The gyroid shape, a 3D infill, is the strongest infill shape because it maintains a constant curvature and therefore has no planes of symmetry (7). This causes an absence of straight lines where the maximum stress is usually exerted, and results in the object having the maximum strength in a given volume (7). Although other 3D shapes such as 3D honeycomb and cubic infill may not have a constant curvature like that of the gyroid shape, they still lack straight lines in a 3D scale and should have a higher tensile strength than the 2D infill patterns (7).

Given this current scientific understanding, here we hypothesized that if the infill type is related to the tensile fracture force and the tensile fracture force is tested with a tensile testing machine and testing specimens printed with different infill patterns, then gyroid infill would withstand the highest tensile forces, followed by 3D honeycomb, cubic, 2D honeycomb, rectilinear, grid, triangle, and star. This outcome is expected because the gyroid pattern maintains a constant curvature and therefore has a longer path of least resistance, allowing it to have the maximum tensile strength in a given volume (3).

Layer Height

Different layer heights can affect the strength of the printed object in the Z-direction. Recent work has shown that as the layer height increases with the same nozzle diameter, the individual threads of plastic more strongly resemble an ideal circle as opposed to the elongated rectangle shape seen in lower layer heights. This causes the interlayer contact area to reduce as the layer height increases; thus, less material will be bonded between layers with a higher layer height, decreasing the strength in the Z-direction (8). This is further suggested by research conducted by Rankouhi, *et al.*, who measured air gaps in the layer extrusions at 0.2 mm and 0.4 mm layer heights. Their work showed that the 0.2 mm layer height had a 0.3% air gap to material ratio while the 0.4 mm layer height had a 5.26% air gap to material ratio, an increase of over 17-fold (9).

Based on the information measured in the air gap sizes and interlayer contact area at different layer heights, we hypothesized that if the layer height is related to the tensile fracture force and the tensile fracture force of specimens printed with different layer heights are tested with a tensile testing machine, then the specimens with a 0.08 mm layer height will have the highest tensile fracture force, followed by 0.12 mm, 0.16 mm, 0.20 mm, 0.24 mm, 0.28 mm, 0.32 mm, 0.36 mm, and 0.40 mm. This outcome is expected because the strength of the specimen is dependent on the air gap or contact surface area between each of the layers, and a higher layer height results in an increased air gap and less contact surface area (8).

RESULTS

Infill Type (XY-directions)

To determine the effect of the infill pattern on the tensile

Table 1: Effect of the infill type on the tensile fracture force. At an average of 583.14 N, the gyroid infill pattern had the highest mean tensile fracture force. The variation among trials was relatively low and mostly similar for each infill type. We performed five trials for each infill pattern.

Infill Type (shape)	Tensile Fracture Force (N)							
	Rectilinear	Grid	Triangle	2D Honeycomb	Star	Gyroid	Cubic	3D Honeycomb
Trial 1	508.25	425.46	453.99	392.30	517.68	486.02	601.94	575.38
Trial 2	516.55	446.08	433.62	421.36	530.81	509.65	571.37	567.85
Trial 3	480.37	474.29	427.75	416.01	498.40	513.08	564.31	557.88
Trial 4	486.00	448.83	437.48	421.81	492.32	509.65	609.03	555.78
Trial 5	505.46	458.38	447.12	408.54	502.87	500.55	569.07	598.59
Mean	499.33	450.61	439.99	508.42	412.00	583.14	499.79	571.10
Standard Deviation	13.79	15.98	9.42	13.98	10.95	18.52	9.81	15.45
Range	36.18	48.83	26.24	38.49	29.51	44.72	27.06	42.81
Maximum	516.55	474.29	453.99	530.81	421.81	609.03	513.08	598.59
Minimum	480.37	425.46	427.75	492.32	392.30	564.31	486.02	555.78

fracture force, we 3D printed ISO 527-2 Model 1A tensile testing specimens in the horizontal orientation with the different infill patterns shown in **Figure 1A**. Specimens printed with different infill patterns used a constant layer height of 0.20 mm since 0.20 mm is half the nozzle diameter of 0.40 mm and the standard layer height used in most applications. We subsequently loaded each specimen into a tensile testing machine where we performed a tensile test to determine the tensile strength of the specimen. **Table 1** shows the individual trials, means, and variations between tensile fracture forces for each infill pattern. **Figure 2** shows the mean tensile fracture forces for each infill pattern with the minimum and maximum tensile fracture forces represented by the error bars. Gyroid infill exhibited the highest mean tensile strength at 583.14 N, followed by 3D honeycomb (571.10 N), 2D honeycomb (508.42 N), cubic (503.79 N), rectilinear (499.33 N), grid (450.61 N), triangle (439.99 N), and star (412.00 N). The 3D infill patterns (gyroid, cubic, and 3D honeycomb) generally performed better than the 2D infill patterns, with the exception of the 2D honeycomb pattern (**Figure 2**). Within each infill type, the ranges and standard deviations were relatively small (**Table 1**). An ANOVA test performed for the yielded a *p*-value of 3.3405E-18, showing that the tensile fracture forces among the infill patterns was significantly different. Additionally, we estimated the print times of the different infill patterns using the slicer software and we measured the weights of the specimens after printing. Both variables had a difference between patterns of less than 10%. In general, 3D infills (gyroid, cubic, and 3D honeycomb) had the highest

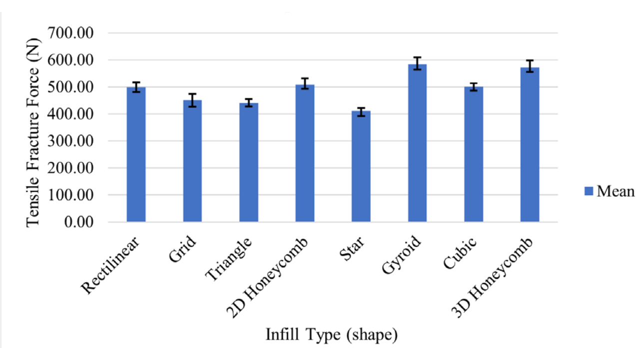

Figure 2: Means for each infill type. Gyroid infill had the highest mean tensile fracture force while the star shape had the lowest. Error bars indicate the range of tensile forces for each infill pattern. An ANOVA analysis showed a *p*-value of 3.3405E-18.

Table 2: Effect of the layer height on the tensile fracture force. A layer height of 0.08 mm produced the highest mean tensile fracture force, at 526.49 N while the 0.40 mm layer height produced the lowest mean. As the layer height increased, the tensile fracture force decreased. There was higher variation among trials within each layer height compared to that of the infill patterns. We performed five trials for each layer height.

Layer Height (mm)	Tensile Fracture Force (N)								
	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40
Trial 1	545.53	414.60	435.54	388.68	377.75	351.98	317.79	243.87	219.28
Trial 2	546.29	394.43	399.48	419.06	392.71	366.49	321.59	215.96	185.79
Trial 3	504.06	483.76	411.82	384.27	387.80	355.60	369.57	342.98	187.40
Trial 4	491.87	456.96	389.21	343.69	319.68	396.54	347.56	246.93	162.34
Trial 5	544.71	445.30	351.60	396.99	366.31	332.38	321.40	261.80	194.10
Mean	526.49	439.01	397.53	386.54	368.85	360.60	339.13	262.31	189.78
Standard Deviation	23.61	31.46	27.68	24.55	26.20	21.08	20.06	42.97	18.24
Range	54.42	89.33	83.94	75.37	73.03	64.16	51.78	127.02	56.94
Maximum	546.29	483.76	435.54	419.06	392.71	396.54	369.57	342.98	219.28
Minimum	491.87	394.43	351.60	343.69	319.68	332.38	317.79	215.96	162.34

mean tensile fracture forces (the notable exception being 2D honeycomb), followed by the square-shaped infills (rectilinear and grid), and the triangle-shaped infills (triangle and star), supporting the findings in the background research and the hypothesis.

Layer Height (Z-direction)

We printed the same tensile testing specimens using the rectilinear infill pattern (the default and most commonly used pattern) but with different layer heights (shown in **Figure 1B**) to determine the correlation between the layer height and tensile fracture force. However, we printed these specimens in the vertical orientation rather than in the horizontal direction. The layer heights tested ranged from 0.08mm to 0.40mm in 0.04mm intervals. We repeated the same process of testing the infill patterns with the varying layer heights. **Table 2** shows the individual trials, means, and variations in tensile fracture forces for each layer height, and **Figure 3** includes the mean tensile fracture forces for each layer height with minimums and maximums represented by error bars. The 0.08 mm layer height showed the highest mean tensile fracture force of 526.49 N, followed by 0.12 mm (439.01 N), 0.16 mm (397.53 N), 0.20mm (386.54N), 0.24 mm (368.85 N), 0.28 mm (360.60 N), 0.32 mm (339.13 N), 0.36 mm (262.31 N), and 0.40mm (189.78N). The ranges and standard deviations in the layer height data are notably larger than those shown in data for the different infill patterns. An ANOVA test showed a P-value of 2.3660E-17, showing significant differences in tensile fracture forces between groups for the layer height data. Additionally, a polynomial regression with a degree of 3 yields an R-value of 0.9972 (**Figure 3**), showing a strong correlation between the layer height and the tensile fracture force. There is a clear trend that, in general when layer height increases, the tensile fracture force decreases, which supports our hypothesis and is consistent with previous research. Meanwhile, the print times for the different layer heights were 4 hours 52 minutes (0.08 mm), 3 hours 15 minutes (0.12 mm), 2 hours 27 minutes (0.16 mm), 1 hour 58 minutes (0.20 mm), 1 hour 41 minutes (0.24 mm), 1 hour 27 minutes (0.28 mm), 1 hour 16 minutes (0.32 mm), 1 hour 8 minutes (0.36 mm), and 1 hour 2 minutes (0.40 mm), so as the layer height increased, the print time decreased.

DISCUSSION

The purpose of this experiment was to evaluate the effect of the infill type and layer height on the tensile fracture force

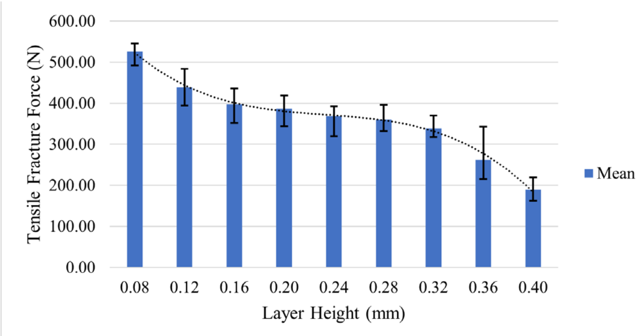

Figure 3: Means for each layer height. The 0.08 mm layer height had the highest mean tensile fracture force, while 0.40 mm had the lowest mean. As the layer height increased, the mean tensile fracture force decreased. Error bars indicate the maximum and minimum tensile forces for each layer height. The dotted line shows a cubic regression curve with an *R*-value of 0.9972. An ANOVA analysis showed a *p*-value of 2.3660E-17.

of 3D printed specimens. The results from the experiment showed that gyroid infill had the highest mean tensile fracture force in the XY-direction, while a layer height of 0.08mm was the strongest in the Z-direction. Overall, lower layer heights and infill patterns with a higher path of least resistance exhibited higher tensile fracture forces.

For the XY-direction, the gyroid infill pattern had the highest tensile fracture force, supporting the hypothesis and background research, because the constant curvature of the gyroid shape allowed it to have the maximum strength in a given volume. 3D infills are constructed to distribute force equally in all directions; however, the cubic infill was mostly comprised of short and straight lines that suppressed the effectiveness of the 3D pattern, which may explain why the 2D honeycomb structure performed better than the cubic infill. The other 2D infills had lower tensile strengths because the paths of least resistance were short and straight, causing the specimen to fracture easily. There was a clear association between the infill pattern and the tensile fracture forces. In addition, since the different infill patterns did not have a notable affect on either the print time or the weight of the specimens, the amount of printed material and subsequently the cost of the 3D printed part were not impacted by the infill pattern. Overall, the gyroid infill pattern had the highest mean tensile fracture force in this experiment and would likely be the strongest in a real-life application.

A closer analysis of the mean values in the Z-directions shows that the layer heights can be separated into groups based on the rate of decline at higher layer heights (**Figure 3**). The first group is the layer height of 0.08 mm, which had the highest tensile fracture force out of all the test specimens. Users who print parts that require the maximum strength possible are recommended to use this layer height; however, it should be noted that the print time, estimated at 4 hours and 52 minutes by the slicer software, was notably longer than the other layer heights since more layers had to be printed. The second group includes all the specimens with layer heights ranging from 0.16 mm to 0.32 mm. This is a region where the tensile fracture force decline rate in higher layer heights lowers and becomes almost linear. This linear region should be recommended for objects that do not require the maximum strength in the Z-direction. Users may decide which layer height to use in this linear region based on other factors such as print time or cosmetic needs. The third and last group include layer heights 0.36 mm and 0.40 mm. Using layer heights within the third group is not recommended as the tensile fracture forces decline rapidly in this group. However, specimens in the third group had lower print times, with a 0.40 mm layer height only requiring an estimated 1 hour and 2 minutes to print. This was because only 426 layers were printed for the 0.40 mm specimen compared to 2,125 for the specimens with a 0.08 mm layer height. Overall, larger layer heights should only be used when lowering the print time is an absolute necessity, while smaller layer heights are ideal for a strong printed part.

Inconsistencies exhibited in the data within each type of specimen likely resulted due to minor discrepancies in the quality of the filament and the surroundings when the specimens were being 3D printed. For example, the filament used to 3D print the specimens used in this experiment may have contained additives that negatively affected the consistency of the filament, causing inconsistent extrusion while printing (10). In addition, the 3D printer used in this experiment was a "Cartesian i3" style printer, meaning that the print bed is attached to the Y-axis (11). This can result in the specimens printed for layer height in the Z-direction to offset slightly due to flexing when the Y-axis accelerates, which may explain why the specimens printed vertically had higher ranges and standard deviations than those printed horizontally. Although we tried to keep the consistency of the 3D printed parts to the highest level possible, there may have been inconsistencies that may have affected the readings of the tensile fracture forces.

In the present paper, one factor was a constant (e.g. layer height) while another factor was varied (e.g. infill type) to evaluate the impact on the latter factor on the tensile fracture force, and vice versa. In future studies, experiments could be performed to vary the two factors together (e.g. 0.16 mm layer height and honeycomb infill pattern) to study how they jointly affect the tensile fracture force. With the data collected thus far, we would predict that a 0.08 mm layer height and the gyroid infill pattern would result in the highest tensile fracture force in either direction since they had the highest tensile fracture forces when tested individually in the XY- and Z-directions. More trials could also be performed for each layer height and infill pattern to ensure higher accuracy. In addition, future studies could evaluate how changing other parameters in a 3D printed part, like the infill percentage, infill angle, and number of perimeters, would affect the tensile fracture force. External parameters such as the material or the manufacturer of the filament in relation to tensile fracture force could also be examined. Furthermore, in addition to testing the tensile fracture force of the 3D printed specimens, testing the compressive strengths of 3D printed specimens could be an interesting area of future study. With all of these variables combined, it would be possible to determine the most efficient way to 3D print parts in order to create a strong product.

MATERIALS AND METHODS

Testing Parameters

Most modern FDM 3D printers utilize computerized instructions called G-code generated from a software called a "slicer" (12). The slicer converts the 3D model, commonly in

STL or stereolithography file format, into a G-code file that the 3D printer can read and execute (12). The parameters for the infill pattern and layer height were set and changed for each group of specimens through the PrusaSlicer slicer software while all other parameters were kept the same throughout the testing process. These other unchanged parameters include a 20% infill percentage, 45° infill angle, 4 top and bottom layers, 2 outer perimeters, 210°C first layer temperature, 205°C normal print temperature, and 40mm/s overall print speed, all of which are default slicer settings in PrusaSlicer with the Ender-3 3D printer. Any additional parameters in the slicer were also left as default and were kept unchanged throughout the printing process.

The infill patterns tested in this experiment were the most commonly available patterns in the slicer software and are shown in **Figure 1A**. The rectilinear pattern is composed of parallel lines printed perpendicular to each other at each layer. The grid, triangle, 2D honeycomb, and star patterns are the shapes of a square, triangle, hexagon, and star, respectively. The cubic and 3D honeycomb patterns are composed of cubes and honeycombs stacked on top of each other, respectively. Finally, the gyroid pattern is an infinitely curving pattern in the shape of a wave. All the infill patterns used had roughly the same weight and similar print times. For the specimens printed for infill pattern testing, a layer height of 0.20 mm was used because it is 50% of the nozzle diameter of 0.40 mm and the default setting in the slicer.

On the other hand, for the specimens with different layer heights, layer heights between 0.08 mm and 0.40 mm were chosen, with 0.04 mm increments (**Figure 1B**). 0.08 mm is the lowest practical layer height that one may use while 0.40 mm is the theoretical maximum layer height when the printer is using a 0.40mm nozzle, which is the most common nozzle diameter and the nozzle diameter used to print the specimens in this experiment. Additionally, specimens printed for layer height testing used rectilinear infill because it is the default setting for infill pattern in the slicer software.

ISO 527-2 Model 1A testing specimens were used in this experiment. According to ISO, it is a multipurpose testing specimen that is suitable for use with molded plastic (13). Although 3D printing is not directly related to molding, ISO 527-2 is still a widely used standard for tensile testing 3D printed specimens. The dimensions of this testing specimen are shown in **Figure 4**.

All testing specimens were printed using an unmodified Ender-3 3D printer with 1.75 mm Hatchbox Polylactic Acid (PLA) filament. PLA is one of the most popular types of filament used for FDM 3D printing because of its ease of use and its ability to biodegrade (14).

A custom-made tensile testing machine was designed and built specifically for this project, shown in **Figure 4**. First, a design was made in a Computer-Aided Design (CAD) software called Tinkercad that was later improved in Fusion 360. This design can be split into four mechanical parts; these parts are the stationary grip, the moving grip, the moving load cell mount, and the stepper motor mount. The stationary grip holds one end of the specimen in place on one end, while the moving grip holds the other end of the specimen. A 1T (force) rated YZC-516 load cell is attached in between the moving load cell mount and the moving grip, and the moving load cell mount is driven by a lead screw. This lead screw is coupled to the NEMA-17 42HS6015A4 100:1 planetary

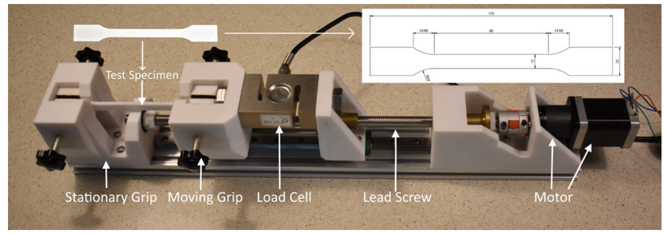

Figure 4: Tensile testing machine. The tensile testing machine used in this experiment is shown with the ISO 527-2 Model 1A testing specimen inserted on the left. The top right photo shows the dimensions of the testing specimen in millimeters.

geared stepper motor shaft, making the drive assembly a so-called linear actuator. Additionally, the stepper motor is driven by an Allegro A4988 stepper motor driver, controlled by an Arduino Nano board, and the load cell readings are measured by an HX711 load cell amplifier/analog-to-digital converter. When the user begins a tensile test, the motion of the lead screw pulls back on the load cell, but the specimen resists the pulling force by exerting an equal and opposite reaction, which is then measured by the load cell at a sample rate of 6.67 Hz or once every 0.15 seconds and recorded through the Serial Monitor. This process continues until the specimen fractures.

For both the infill type and layer height data, a one-way analysis of variance (ANOVA) to determine whether the differences between infill patterns or layer heights was statistically significant. These tests were conducted in Microsoft Excel by clicking on “Data,” “Data Analysis,” and “Anova: Single Factor.” Two separate analyses were performed. The data used in the ANOVA for the infill patterns was taken from **Table 1** and the data used for the layer heights was taken from **Table 2**.

Testing Methods

First, the tensile testing specimens were converted from STL format to G-code with the appropriate parameters using the PrusaSlicer software. Then, the specimens were 3D printed and individually marked.

To start the testing process, a testing specimen was placed on the aligning jigs of the tensile testing machine. Then, the two thumbscrews on either side of the machine were simultaneously rotated clockwise until the knobs were finger tight. The Arduino IDE application was launched on the computer, and the serial monitor was opened by clicking on “Tools,” then “Serial Monitor.” Subsequently, “Fast” was typed in the serial monitor to perform a tensile test. While staying at least 2 meters away from the tensile testing machine to avoid possible injury from the specimen breaking, the specimen was observed until it visibly broke into two or more fragments. Approximately two seconds after the specimen broke, “Stop” was entered into the serial monitor to terminate the tensile testing process. Finally, the tensile fracture force, measured in Newtons (N), was copied into an Excel spreadsheet for analysis. This process was repeated four more times for a total of five trials for each type of specimen. Five trials was reasonable given the consistency of the results. This process was repeated for all of the trials for both the infill pattern and layer height.

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