

How do the layer height and temperature of a 3D-printed plastic object influence its fracture point due to tension?

Eloi Prat's IB Physics Extended Essay

Word Count: 3936/4000

Contents

1	Introduction	1
2	Research question	2
3	Background information	3
4	Variables	9
5	Equipment	11
6	Methodology	14
7	Results	15
8	Conclusion	24
9	Bibliography and appendices	25

1 Introduction

Since its rise in popularity around 2013 (Trends, [n.d.](#)), 3D printing has become a crucial tool across various industries. As Phadnis, [2014](#) explains, 3D printers were first used solely as a prototyping method. Today, they are used to manufacture a final product, offering a better speed and price than injection molding in industries with a demand for very customized parts or a low number of orders. (See figure [1](#)).

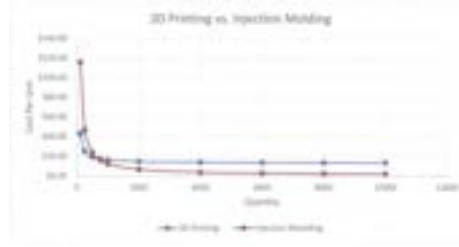


Figure 1: Sourced from (Phadnis, 2014)

3D printing can transform global supply chains by decentralizing production to smaller industrial centers or homes. This shift impacts consumer experiences and addresses climate issues, worker conditions, and product quality. Additionally, 3D printers could create an economy centered around selling design files. All of this is speculation, but 3D printing has already brought many changes. Some of the most impressive advancements in 3D printing have been the progress towards 3D printing organs and living tissue. Currently, 3D printing is even possible to use to deposit cement and build small houses. (Formlabs, n.d.)

2 Research question

This essay investigates: **“How do the layer height and temperature of a 3D-printed plastic object influence its fracture point due to tension?”**. This question was chosen because most 3D printing methods are produced layer by layer, affecting their mechanical properties, as the adhesion between these layers is not as strong as the material it has been printed with, making prints prone to failure between layer lines. Figure 2 illustrates the issue.



Figure 2: A 3D printed boat that broke parallel to the printing lines. Own source.

Although there has been research (Vaezi and Chua, [2010](#)) on the topic, findings are often conflicting, and many others focus only on force applied in parallel to the printing lines. (Fisher et al., [2023](#)) The investigation aims to determine how layer adhesion can be optimized, considering the controlled variables of layer height and printing temperature, a choice explained in the variables section. [1](#)

3 Background information

This investigation will focus on Fused Deposition Modeling (FDM) 3D-printing. As the name states, these printers fuse a material, which they then melt and extrude through a nozzle to deposit to create objects layer by layer. There are infinitely many variations of this, but the following diagram [3](#) shows the most common components of all 3D FDM printers.

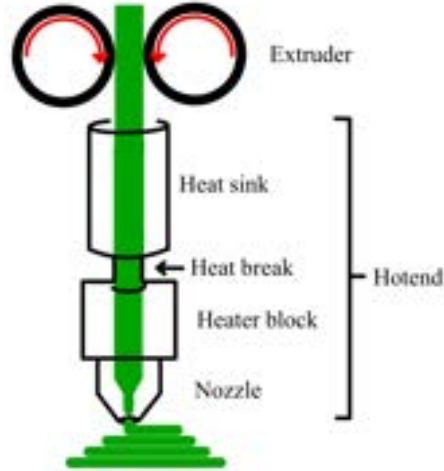


Figure 3: The components of a plastic FDM 3D printer. Own Source.

The printing process begins with an extruder, which pushes the material into the machine, with the red arrows in 3 showing the direction of rotation. The extruder then pushes the material into the hot end. The first part of the hot end is a heat sink that ensures the filament does not heat up too early, causing a clog in the channel. Next, the heat break separates the heat sink and the fusion zone to avoid excessive conductive heat transfer between the two. Then, the heater block has the thermistor to monitor the temperature and the heat cartridge to heat the block through conduction. This is where the fusion happens. The nozzle is a tip at the end of the heater block and changes the shape of the filament to go from its original size, usually 0.75mm, to a smaller one to deposit the plastic line. This line of plastic that leaves the nozzle has two main qualities to describe its size: the line width and the layer height, which refers to the layer height. (Ferretti et al., 2021) The following drawing shows these concepts visually.

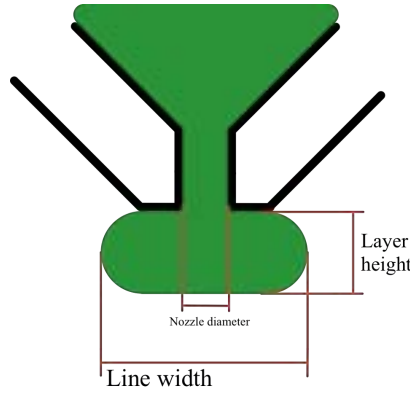


Figure 4: A close-up section of the end of the nozzle with material getting deposited shows the qualities that describe the size of a line. The size differences are exaggerated, as the Nozzle diameter and the Line width are often the same. Own source.

The material from which a piece is made is key to determining its properties, too. Focusing on 3D printed plastics, the thermoplastic material many FDM 3D printers use is called filament. The most common printing material for the consumer level is Polylactic Acid, generally called PLA, at a 0.75mm diameter, which will be our material of choice for the study. However, some other plastics, such as Acrylonitrile Butadiene Styrene (ABS) or polyethylene terephthalate glycol (PETG), are also popular and offer different properties. There are infinitely many filaments, and even within the same kind of plastic, the pigment added to give it color can influence its mechanical properties.

All plastics and FDM 3D printers share features in the nature of a 3D-printed object. To explain this, this small boat was designed and is often used as a benchmark to assess 3D printing quality (Tools, [n.d.](#)). Before looking at the printed part, it is interesting to look at the slicer diagram. The slicer is software that transforms a solid digital 3D object into coordinate instructions for the 3D printer. Once the object is sliced, it displays a preview of it, as in diagram 5, showing some of the many variables that will affect a 3D print. The slicer used for this study was Cura by Ultimaker. (UltiMaker, [2024](#))

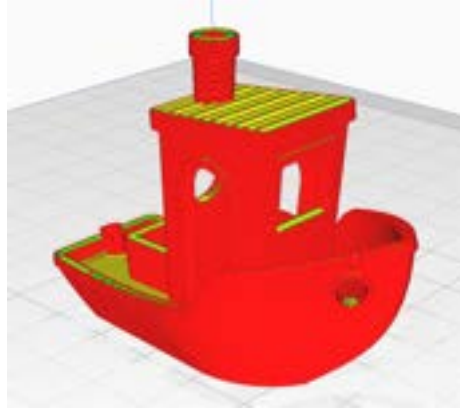


Figure 5: The diagram offered by the slicer before printing shows the object with a 0.2mm layer height and 0.4mm line width.

These diagrams allow us to see the inside structure of a 3D-printed object through cut sections. The orange lines are what is known as infill, which is a structure inside of the print designed to give it more mechanical strength. Not only this but as visible in figure 6, it can be used to sustain print elements that would have otherwise been printed mid-air.

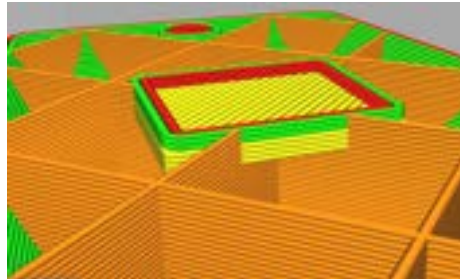


Figure 6: A close-up of a part that would've been printed mid-air without the presence of infill.

The infill is also useful to increase the area of each layer of the print, something that helps with layer adhesion. With this general understanding of the basics of 3D printing and some of the effects its layered production has on it, it can be a good time to define what exactly will be studied.



Figure 7: 3D Printed object with the same settings as in the diagram, using a 0.2mm layer height at 220°C and a 0.4 .

One of the most significant aspects identifiable in FDM 3D-printed objects, such as the one in figure 7, is the layers we have mentioned repeatedly. They are also visible in the diagram of figure 5 or closely in 8.



Figure 8: A closer look at the layers in the 3D print.

This essay aims to quantify these layers' binding or layer adhesion and, hence, resistance to tension stress. To do this, the nature of mechanical stress and deformation is important. Tensile stress is the force per unit area experienced by a material when it is subjected to stretching forces. The process of undergoing tension can be broadly described through two phases. The first is elastic deformation, going from more than zero stress to yield strength. This phase is "A temporary shape change that is self-reversing after the force is removed so that the object returns to its original shape." (University, [n.d.](#)). If additional stress is applied, it can exceed the yield strength, resulting in a plastic deformation phase. During this phase, the stress becomes sufficient to deform the material as several atomic bonds break permanently. If too many of these bonds break, the stress will reach its fracture point, leading to a break. (University, [n.d.](#)) How this occurs depends on various factors, but this study will

only see brittle fractures.

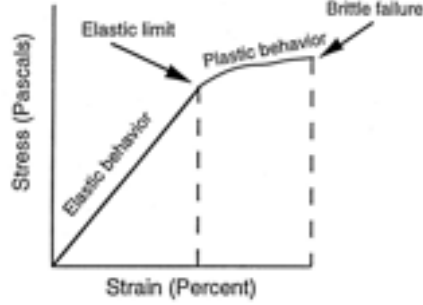


Figure 9: Sourced from (for Dummies, [n.d.](#))

For the rest of this essay, stress will be referred to as σ and strain as ϵ . The advantage of focusing on stress instead of force is that it makes the experiment more generalizable. It considers the area of the object being tested under tensile force, allowing it to describe the force structures of other areas that can also resist, also explaining the usefulness of infill. In the following equation, F represents the applied force, while A indicates the area resisting that force.

$$\sigma = \frac{F}{A}$$

The strain is a dimensionless ratio representing the deformation relative to the initial length since an object's absolute change in length has varying impacts based on its size. Here, ΔL denotes the absolute change in length, while L_0 refers to the original length.

$$\epsilon = \frac{\Delta L}{L_0}$$

The graph 9 shows a directly proportional Stress/Strain relationship for the period of elastic deformation. During that period, the test behaves like a spring, meaning a version of Hooke's law ($F = kx$) can be used to model it.

$$\sigma = E\epsilon$$

Where E is Young's modulus, a rise over run for stress over strain that represents the material's stiffness.

$$E = \frac{\sigma}{\epsilon} = \frac{\frac{F}{A}}{\frac{\Delta L}{L_0}}$$

By knowing Young's modulus, one can model a material's elastic deformation. In this study, after failing at trying to measure ΔL during the stress test, both due to safety concerns and because the force was not applied at a constant rate, this theory is considered important due to its relevance to the topic but will not be deepened further in the study.

4 Variables

To decide the research question, different types of mechanical stress had to be considered as options for the dependent variable under study.

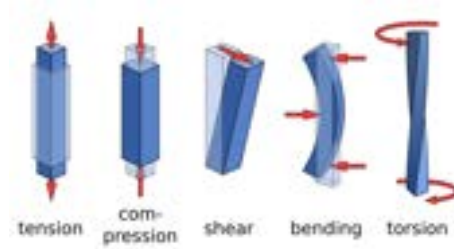


Figure 10: The five types of mechanical stress. Source: (MikeRun, [2021](#))

Tension was chosen for mechanical stress investigation due to its direct measurement of adhesion between layers with tensile force applied perpendicular to them. Tensile tests are also easy to set up, making the experiment accessible and repeatable. Additionally, established standards like ASTM and ISO enhance their reliability, although I initially overlooked this benefit. Nozzle temperature and layer height are crucial independent variables affecting layer adhesion. Lower layer heights create fewer weak spots, impacting visual quality, print time, and nozzle flow rate, which will impact the heating time for the plastic.

Variable	Variable Type	How Was It Controlled?
Layer height	Independent	Set by slicer software
Nozzle temperature	Independent	Set by slicer software
Stress at fracture	Dependent	Measured with the experiment
Printing bed temperature	Control	Set by slicer at 50°C
Printing speed	Control	Set by slicer at 50 mm/s
Line width	Control	Set by slicer at 0.4 mm
Nozzle diameter	Control	Kept constant at 0.4 mm
Wall/ceiling thickness	Control	Set by slicer at 0.8 mm
Infill percentage	Control	Set by slicer at 0%
PLA filament type	Control	Used the same PLA filament of 0.75mm diameter
Ambient temperature when breaking	Control	Room temperature
Filament properties	Extraneous	Variations exist between PLA filament brands

Table 1: Categorization of variables used in the study.

Choosing temperature as a variable is based on the idea that layer adhesion and stress resistance are influenced by material temperature. This is related to PLA's molecular and thermal properties, affecting layer adhesion. PLA consists of long polymer chains connected by intermolecular forces. (ScienceDirect, [n.d.](#)) These chains soften when heated and solidify when cooled without permanent chemical changes. When PLA is heated above its glass transition temperature, the chains gain kinetic energy, changing from brittle to viscous and rubbery at higher temperatures. During 3D printing, the increased kinetic energy allows the chains to diffuse into the previous layer, creating molecular entanglement supported by Van der Waals forces. Although no new chemical bonds form, this entanglement is crucial. For PLA, significant intermolecular forces include dispersion and dipole-dipole interactions from electromagnetic charge and dipole interactions. Excessive heat can also harm PLA's mechanical properties, leading to thermal degradation that breaks down polymer chains and causes oxidation. This makes the material brittle with reduced tensile strength and increased porosity from voids or air bubbles that expand, weakening the print. This theory provides a basis for understanding how temperature affects layer adhesion and identifying patterns, even with limited data. (Esakkimuthu et al., [2024](#)) (Mileo

et al., 2023)

The tests were conducted using temperatures ranging from 190 to 240 degrees with 10-degree increments and layer heights from 0.05 to 0.30, in 0.05 increments. PLA in 3D printing is typically used at temperatures between 200 and 220 degrees, and for this specific filament, the recommended temperature is 220 degrees. As a result, the chosen values spanned from 190 to 240 degrees to gather data on performance outside the typical temperature range for PLA plastic. When selecting the layer height range, it is advised not to exceed 80% of the nozzle diameter. The height of 0.35 was excluded because it represents a minimal proportional difference from 0.30.

5 Equipment

To conduct the experiment, we must print samples to test their resistance to tensile stress. For this, we need a 3D printer. Fortunately, my school had a relatively simple Cartesian Ender 3 V1. To ensure a thorough study, a new spool of 3D printing filament was used, as PLA loses some of its properties over time. (Rasselet et al., 2013) The spool is grey PLA produced by LiON. (lion3d, n.d.) To measure the bars' resistance to tension stress, I designed and 3D printed a tensile strength test. The pieces are printed using PLA at 100% infill and designed to work on a HIWIN HGR15C rail with a HIWIN H15C block (HIWIN, n.d.) that I obtained from the scraps of a local workshop. In addition to the 3D printed parts and the HIWIN components, the setup also uses a hanging digital scale to measure force, a 5mm diameter screw bar, 6 matching M8 nuts, a washer, and a couple of optional zip ties to reinforce strength. The following diagrams illustrate the designs of the pieces for the stress test, along with some of their most important measurements for experiment replication.

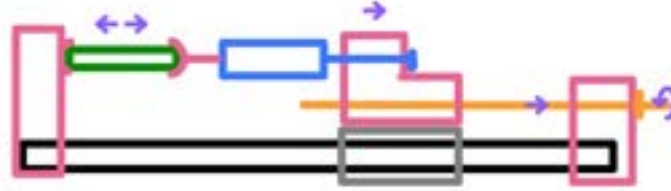


Figure 11: Sketch of the stress test's workings. Black represents the rail. Grey is the moving block. Pink is 3D-printed structural parts. Green is the 3D-printed part under the stress test. Blue is the scale. Orange is the screw bar and the nuts. Purple arrows are a rough sketch of the movements and forces drawn for conceptual understanding.

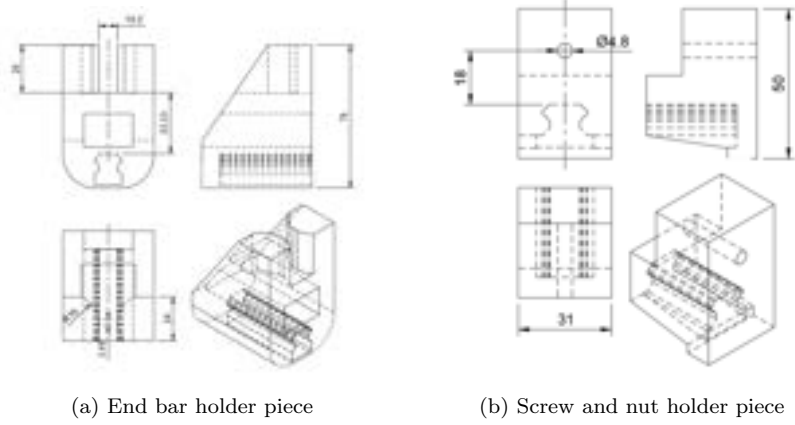


Figure 12: Pieces at the extremes of the rail

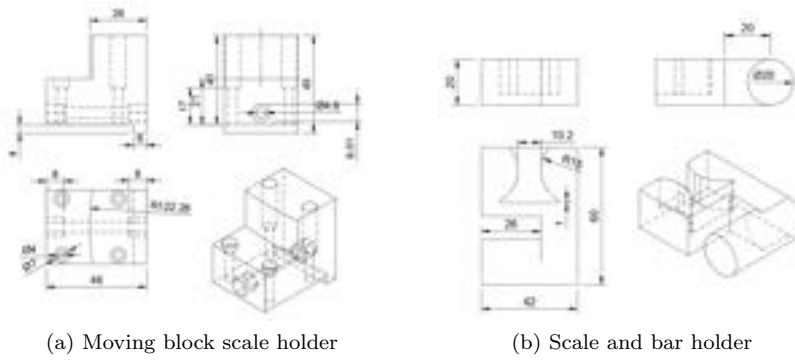


Figure 13: The two pieces in contact with the scale.

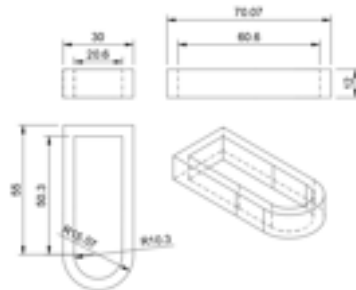


Figure 14: Strength aid for the scale and bar holder

Once printed and assembled, this is how it looks:



Figure 15: Zenith's view of the stress test



Figure 16: Side view of the stress test

A luggage scale is used to measure force (Etekcity, [n.d.](#)). It gives the values in kilograms and specifies the uncertainty in its measurement. The tool has a low random measurement uncertainty and will serve the purpose very adequately. It works by having a load cell with a strain gauge applied that measures the change in conductivity as the load cell bends the strain gauge due to the force applied to it.



(a) Disassembled scale.



(b) Load cell with a protected strain gauge.

Figure 17: Scale pictures, own source.

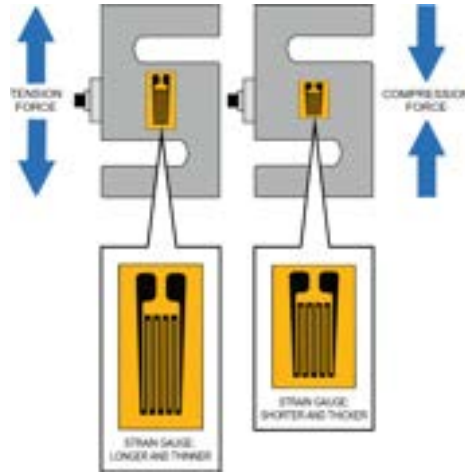


Figure 18: (Techniques, [n.d.](#))

In the assembly process of the tension test, four nuts were inserted into the moving block to ensure that the screw bar did not slip.



(a) Washer and double nuts that are tightened to apply force



(b) Heat-inserted nuts

Figure 19: The added components to the setup.

With the current setup, measurements of up to 490 Newtons (50 Kilograms) can be made as the scale's manufacturer-specified maximum.

6 Methodology

To measure the resistance to tension stress in 3D printed objects, the study will utilize the bars shown in [20](#) as samples for which the tension setup has been designed. The design was based on previous tension stress tests I observed, but

I didn't think of adhering to a standard until it was too late, a big mistake on my side. Although this limits the comparison with external studies, the data in this study can still be compared and offer valuable insights. As discussed in the variables section, the bars will be printed with varying layer heights and temperatures as independent variables. The infill will be set at 0%, and the walls and top layers will measure $0.8mm$.

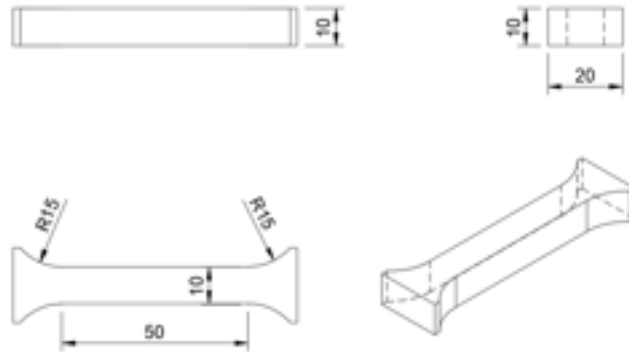


Figure 20: The bars that will be put under tension stress as samples.

To measure the fracture point, I placed the experiment under a stool with a hole for a camera to record the test. I reviewed the video to find the fracture time. Screenshot 21 shows the frame used to determine the fracture point in one test.



Figure 21: The breaking of a random measurement, in this case at 16,98 kg for a 200° , 0.25 mm bar.

7 Results

Even before the measurements, some 3D-printed bars' structures struggled due to high heat while printing. Those with low layer heights and high temperatures showed stringing and rough surfaces. This happens because the plastic is too hot, as explained in the theory of variables. Since the plastic is too liquid, it leaks even when not being pushed, causing those strings.



Figure 22: The 0.25mm, 240 degrees bar.

After breaking 180 3D-printed bars, the experiment produced the following results.

	190 $\pm$ 1°C	200 $\pm$ 1°C	210 $\pm$ 1°C	220 $\pm$ 1°C	230 $\pm$ 1°C	240 $\pm$ 1°C
0.05 test 1	20.270 $\pm$ 0.01	10.420 $\pm$ 0.01	12.620 $\pm$ 0.01	13.080 $\pm$ 0.01	11.420 $\pm$ 0.01	9.810 $\pm$ 0.01
0.05 test 2	18.010 $\pm$ 0.01	9.830 $\pm$ 0.01	10.420 $\pm$ 0.01	9.890 $\pm$ 0.01	9.610 $\pm$ 0.01	9.860 $\pm$ 0.01
0.05 test 3	22.030 $\pm$ 0.01	12.990 $\pm$ 0.01	9.410 $\pm$ 0.01	12.200 $\pm$ 0.01	10.740 $\pm$ 0.01	10.330 $\pm$ 0.01
0.05 test 4	19.600 $\pm$ 0.01	10.900 $\pm$ 0.01	10.700 $\pm$ 0.01	10.780 $\pm$ 0.01	12.330 $\pm$ 0.01	8.090 $\pm$ 0.01
0.05 test 5	23.170 $\pm$ 0.01	13.620 $\pm$ 0.01	11.940 $\pm$ 0.01	11.820 $\pm$ 0.01	12.700 $\pm$ 0.01	10.490 $\pm$ 0.01
0.1 test 1	15.590 $\pm$ 0.01	26.810 $\pm$ 0.01	13.838 $\pm$ 0.01	13.710 $\pm$ 0.01	11.500 $\pm$ 0.01	10.150 $\pm$ 0.01
0.1 test 2	23.530 $\pm$ 0.01	23.440 $\pm$ 0.01	12.865 $\pm$ 0.01	9.440 $\pm$ 0.01	17.740 $\pm$ 0.01	12.380 $\pm$ 0.01
0.1 test 3	20.160 $\pm$ 0.01	21.090 $\pm$ 0.01	15.125 $\pm$ 0.01	13.390 $\pm$ 0.01	11.540 $\pm$ 0.01	15.870 $\pm$ 0.01
0.1 test 4	19.630 $\pm$ 0.01	30.320 $\pm$ 0.01	12.152 $\pm$ 0.01	16.960 $\pm$ 0.01	16.480 $\pm$ 0.01	16.230 $\pm$ 0.01
0.1 test 5	22.080 $\pm$ 0.01	28.890 $\pm$ 0.01	13.284 $\pm$ 0.01	16.600 $\pm$ 0.01	16.370 $\pm$ 0.01	12.100 $\pm$ 0.01
0.15 test 1	19.410 $\pm$ 0.01	20.760 $\pm$ 0.01	22.890 $\pm$ 0.01	15.890 $\pm$ 0.01	18.070 $\pm$ 0.01	11.000 $\pm$ 0.01
0.15 test 2	15.050 $\pm$ 0.01	25.390 $\pm$ 0.01	19.030 $\pm$ 0.01	13.480 $\pm$ 0.01	16.580 $\pm$ 0.01	15.040 $\pm$ 0.01
0.15 test 3	18.950 $\pm$ 0.01	23.190 $\pm$ 0.01	17.700 $\pm$ 0.01	14.250 $\pm$ 0.01	13.580 $\pm$ 0.01	13.600 $\pm$ 0.01
0.15 test 4	20.040 $\pm$ 0.01	22.150 $\pm$ 0.01	18.600 $\pm$ 0.01	14.080 $\pm$ 0.01	15.430 $\pm$ 0.01	10.390 $\pm$ 0.01
0.15 test 5	22.340 $\pm$ 0.01	23.580 $\pm$ 0.01	16.410 $\pm$ 0.01	16.840 $\pm$ 0.01	13.040 $\pm$ 0.01	12.120 $\pm$ 0.01
0.2 test 1	13.350 $\pm$ 0.01	10.290 $\pm$ 0.01	25.700 $\pm$ 0.01	22.030 $\pm$ 0.01	14.250 $\pm$ 0.01	11.390 $\pm$ 0.01
0.2 test 2	12.770 $\pm$ 0.01	15.310 $\pm$ 0.01	21.970 $\pm$ 0.01	21.760 $\pm$ 0.01	12.280 $\pm$ 0.01	13.450 $\pm$ 0.01
0.2 test 3	14.890 $\pm$ 0.01	10.320 $\pm$ 0.01	27.260 $\pm$ 0.01	23.580 $\pm$ 0.01	14.630 $\pm$ 0.01	11.360 $\pm$ 0.01
0.2 test 4	11.110 $\pm$ 0.01	13.010 $\pm$ 0.01	21.940 $\pm$ 0.01	21.450 $\pm$ 0.01	13.780 $\pm$ 0.01	13.660 $\pm$ 0.01
0.2 test 5	13.820 $\pm$ 0.01	12.410 $\pm$ 0.01	23.650 $\pm$ 0.01	20.840 $\pm$ 0.01	14.160 $\pm$ 0.01	15.250 $\pm$ 0.01
0.25 test 1	14.110 $\pm$ 0.01	11.480 $\pm$ 0.01	21.680 $\pm$ 0.01	25.930 $\pm$ 0.01	18.310 $\pm$ 0.01	20.580 $\pm$ 0.01
0.25 test 2	12.490 $\pm$ 0.01	13.760 $\pm$ 0.01	22.880 $\pm$ 0.01	28.570 $\pm$ 0.01	20.200 $\pm$ 0.01	18.700 $\pm$ 0.01
0.25 test 3	11.050 $\pm$ 0.01	17.760 $\pm$ 0.01	24.170 $\pm$ 0.01	30.190 $\pm$ 0.01	22.120 $\pm$ 0.01	21.830 $\pm$ 0.01
0.25 test 4	12.970 $\pm$ 0.01	16.980 $\pm$ 0.01	26.740 $\pm$ 0.01	31.770 $\pm$ 0.01	24.050 $\pm$ 0.01	17.850 $\pm$ 0.01
0.25 test 5	10.470 $\pm$ 0.01	11.620 $\pm$ 0.01	24.590 $\pm$ 0.01	29.880 $\pm$ 0.01	21.750 $\pm$ 0.01	18.400 $\pm$ 0.01
0.3 test 1	13.670 $\pm$ 0.01	11.790 $\pm$ 0.01	20.280 $\pm$ 0.01	31.080 $\pm$ 0.01	37.580 $\pm$ 0.01	41.430 $\pm$ 0.01
0.3 test 2	15.860 $\pm$ 0.01	13.780 $\pm$ 0.01	17.610 $\pm$ 0.01	37.880 $\pm$ 0.01	36.880 $\pm$ 0.01	35.110 $\pm$ 0.01
0.3 test 3	11.270 $\pm$ 0.01	14.330 $\pm$ 0.01	15.520 $\pm$ 0.01	40.290 $\pm$ 0.01	34.980 $\pm$ 0.01	34.830 $\pm$ 0.01
0.3 test 4	12.620 $\pm$ 0.01	13.020 $\pm$ 0.01	18.880 $\pm$ 0.01	35.470 $\pm$ 0.01	42.940 $\pm$ 0.01	32.930 $\pm$ 0.01
0.3 test 5	11.040 $\pm$ 0.01	15.980 $\pm$ 0.01	17.130 $\pm$ 0.01	35.080 $\pm$ 0.01	34.780 $\pm$ 0.01	36.330 $\pm$ 0.01

Table 2: Raw Data in kg.

To analyze the measurements, the first interest is to change the data from mass to force/area as the independent variable under study is the strain. Scales use g as the net acceleration due to gravitation to transform their deformation from deformation by force measurements into mass ones. We have to undo this and then convert that tension into stress, considering the uncertainties this

implies. To calculate the force, $F = mg$ is used. To quantify the variability of the tensile force measurements, the Google Sheets function STDEV (Google, [n.d.](#)) was used, which uses the sample standard deviation formula. This choice of formula is appropriate because the dataset represents a sample (five trials) of all possible outcomes for each combination of layer height and temperature. Using $n - 1$ in the denominator (Bessel's correction) adjusts for the small sample size and ensures an unbiased estimate of the true variability. The formula for the sample standard deviation is:

$$u_{std} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

Where:

- u_{std} is the sample standard deviation,
- x_i represents the i -th measurement in the sample,
- $\bar{x}$ is the mean of the sample,
- n is the number of measurements.

The standard deviation accounts for the dispersion of the individual measurements around the mean tensile force and has to be combined with the fixed uncertainty given by the machine of ± 0.01 kg or ± 0.098 N to obtain the total uncertainty for each condition. The fixed systematic uncertainty $\Delta_{systematic}$ applies to each measurement. When calculating the average of $n = 5$ measurements, its contribution is reduced by $\sqrt{n}$, resulting in:

$$\Delta_{random} = \frac{\Delta_{systematic}}{\sqrt{n}} = \frac{0.098}{\sqrt{5}} \approx 0.0438 \text{ N}.$$

Then, the total uncertainty is calculated using:

$$u_{total} = \sqrt{u_{measured}^2 + \Delta_{random}^2}$$

Where:

- $u_{measured}$ is the standard deviation of the sample,
- Δ_{random} is the reduced fixed uncertainty of ± 0.0438 N.

F is divided by the area to obtain σ as the stress. A represents the area.

$$\sigma = \frac{F}{A}$$

The area is the same for all bars, as the square of $10 \cdot 10 \text{ mm}^2$ has walls of 0.8 mm of thickness, as represented on [23](#) and measured with a digital caliper. This means:

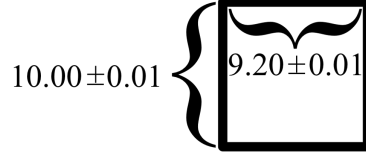


Figure 23: A section drawing of a test, as in a broken layer, empty inside, and with the walls and measurements.

Giving the equation:

$$A = (10 \pm 0.01)^2 - (9.2 \pm 0.01)^2$$

For which, to solve, we will have to take care of both the multiplication and the subtraction rule, finally giving $A = 15.36 \pm 0.27 \text{ mm}^2$, which can be divided by each F taking into account the rule of division of uncertainty, giving us a processed data table.

	$190 \pm 1^\circ\text{C}$	$200 \pm 1^\circ\text{C}$	$210 \pm 1^\circ\text{C}$	$220 \pm 1^\circ\text{C}$	$230 \pm 1^\circ\text{C}$	$240 \pm 1^\circ\text{C}$
0.05mm	13.15 ± 1.53	7.37 ± 1.19	7.03 ± 0.93	7.37 ± 0.92	7.25 ± 0.92	6.20 ± 0.72
0.10mm	12.89 ± 2.15	16.66 ± 2.73	8.58 ± 0.87	8.95 ± 2.09	9.40 ± 2.06	8.52 ± 1.82
0.15mm	12.22 ± 1.90	14.68 ± 1.36	12.07 ± 1.76	9.51 ± 1.06	9.79 ± 1.50	7.93 ± 1.35
0.20mm	8.41 ± 1.04	7.83 ± 1.47	15.38 ± 1.77	13.99 ± 0.90	8.82 ± 0.74	8.31 ± 1.20
0.25mm	7.80 ± 1.07	9.14 ± 2.04	15.32 ± 1.48	18.67 ± 1.72	13.58 ± 1.61	12.42 ± 1.28
0.30mm	8.23 ± 1.40	8.79 ± 1.15	11.41 ± 1.35	22.94 ± 2.60	23.88 ± 2.53	23.05 ± 2.45

Table 3: Processed data table showing the tensile stress (in N/mm^2) and total uncertainty for various layer heights (in mm) and temperatures (in $^\circ\text{C}$).

To analyze this data quantitatively, we will use regression models implemented in Python(Python, [n.d.](#))(GeeksforGeeks, [2023](#)). Regression models are mathematical tools that employ algorithms to create equations that minimize residuals, which are the differences between the observed data points and the model's predictions. This process aims to find an equation that represents the trends in the data and identifies relationships among the variables, specifically layer height, temperature, and stress. Since we are using two independent variables and one dependent variable, 3D and 2D polynomial regression will be applied for the analysis. The algorithms in the regression apply the least squares method, based on the Gauss-Markov theorem, to determine the optimal fit of a mathematical surface for the given data.

To produce a quality 3D fit, it's interesting to first look at its "slices" as 2D fits, choosing one of the values in temperature T or layer height L_h and then

plotting the other independent variable's values in that chosen value against the strain, making σ vs L_h and σ vs T graphs. Given the already-mentioned theory, we expect to see peaks in certain temperatures or layer heights.

Hence, these graphs show some possible polynomial fits in different L_h .

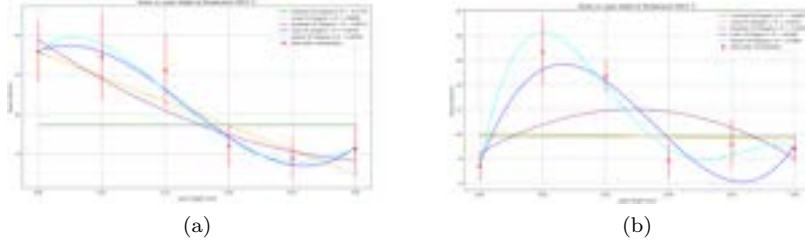


Figure 24: The σ over L_h graph for 190°C and 200°C

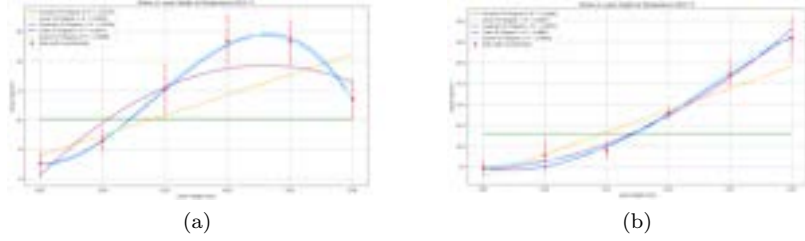


Figure 25: The σ over L_h graph for 210°C and 220°C

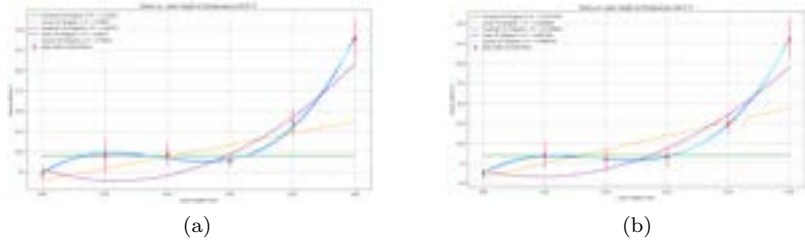


Figure 26: The σ over L_h graph for 230°C and 240°C

Analyzing these fits, it is arguable that the nature of the measurements taken is cubic concerning the L_h to σ relationship, as it offers a high R^2 compared to a quadratic. At the same time, a 4th-degree polynomial seems overfitting given the limited data points, so it's better to disregard it. It also supports the theory behind the study; as we discussed, there should be a peak but also a

strong drop if the temperature is too high or too low. However, the cubic fitting appears adequate only because of our range of values allowing us to see only one peak and one of the drops. Taking the theory into account, if more layer heights were studied, the current data suggests we might see one peak, then two flat sections on both sides that, in very extreme hot or cold temperatures and in an unknown rate, descend to zero as very high or very low temperatures drop its resistance to σ . The following diagram illustrates this concept.

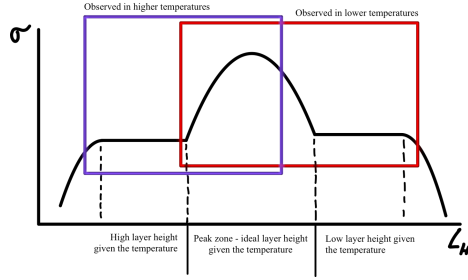


Figure 27: A hand-drawn relationship that could explain some of the data.

The peak in this relationship shifts to other layer heights as the temperature changes, potentially becoming larger or smaller. This shift explains why it has been observed in various locations at different layer heights. This qualitative model interprets the data using critical values of L_h , where the data transitions from one trend to another, illustrating the high peaks and the flat lines surrounding them. The decreases in σ at the extremes qualitatively indicate that it must decline at a certain point due to extreme overheating or underheating, although this study does not provide empirical evidence of such occurrences. Since the qualitative model resembles a Gaussian one, an attempt was made to fit it, but the scarcity of data points led to bad results. The shape is a conjecture based on theory and the behavior of other adhesive materials [28](#), but the data do not substantiate it due to the insufficient number of points to establish a clear profile. Although the data collected for this experiment is thorough, it will not adequately describe the shape of the fit or the bump. Therefore, it is intriguing to examine the broader features of the experiment and attempt to explain how the peak in resistance to u shifts. For this purpose, considering the other dimension may be beneficial.

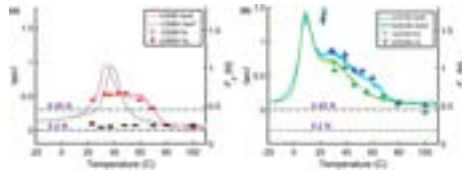


Figure 28: (Farre-Kaga et al., [2021](#))

When plotting T against σ the analysis gets more complicated. The following figures show the efforts made to find a good fit.

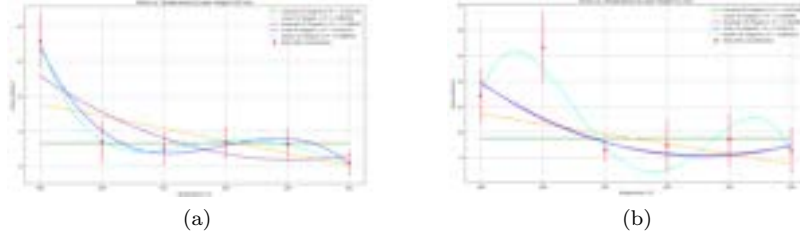


Figure 29: The σ over T graph for 0.05mm and 0.10mm

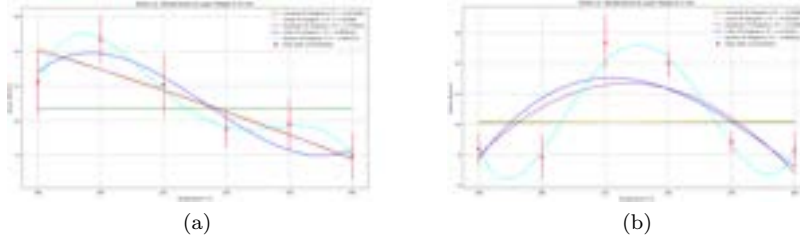


Figure 30: The σ over T graph for 0.15mm and 0.20mm

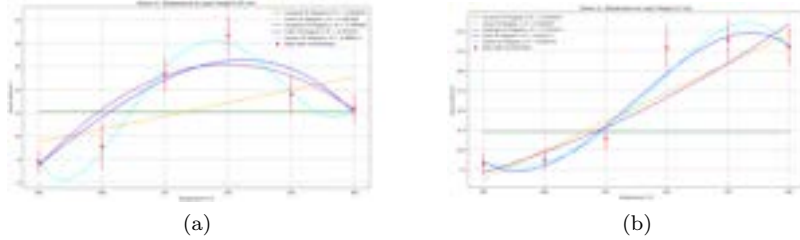


Figure 31: The σ over T graph for 0.25mm and 0.30mm

Considering these results, there remain peaks similar to those described in the previous section that support the theory of an ideal temperature. Additionally, dismissing the 4th degree as overfitting, the 3rd degree presents an even poorer fit than before. While most fits hover around $R^2 \approx 0.8$ or higher, some fall significantly short, particularly the 0.1mm layer height, which has $R^2 = 0.36$, and the 0.2mm layer height, with $R^2 = 0.51$. This severely undermines the notion of a cubic fit, and due to the scarcity of proof, this 3rd-degree model will

now only illustrate the relationships within the current dataset rather than serve as a basis for conclusions beyond the experiment's parameters. Referring back to the highly qualitative 27, the data can be utilized to focus on a broader yet still innovative idea: instead of attempting to model all values of σ for each L_h to T combination, the objective is to identify the regression fit demonstrating the highest resistance to σ within the L_h to T relationship. To achieve this, the apex of each 2D slice was selected. The error attributed to layer height accounts for the distance between the L_h measurements, as the highest point may also be located there. The machine provided temperature readings within $\pm 1^\circ\text{C}$.

Highest Points for L_h		Highest Points for T	
L_h (mm)	T ($^\circ\text{C}$)	T ($^\circ\text{C}$)	L_h (mm)
$\Delta L_h = 0.025$	$\Delta T = 1^\circ\text{C}$	$\Delta T = 1^\circ\text{C}$	$\Delta L_h = 0.025$
0.05	190	190	0.05
0.10	200	200	0.10
0.15	200	210	0.20
0.20	210	220	0.30
0.25	220	230	0.30
0.30	230	240	0.30

Table 4: Highest tensile resistance points for each layer height and temperature.

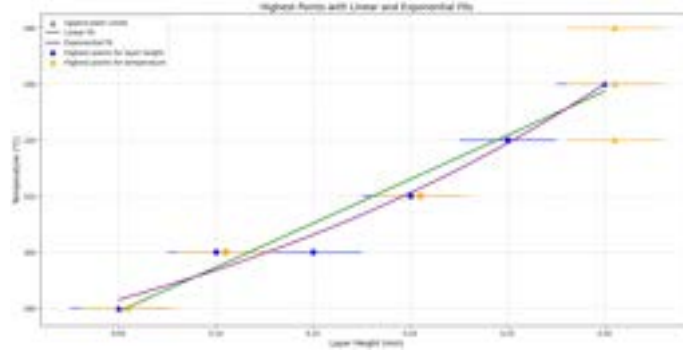


Figure 32

This graph provides a clear understanding of the conclusion this study can convey. While the 230°C peak does not align closely with the regression fit, this may be attributed to statistical variations. The peak of 240°C represents an upper limit and can extend beyond the boundaries of the graph, a possibility also applicable to the peaks of 190°C , 220°C , and 230°C , which is why they are indicated as limits by the triangle. There is a noticeable relationship indicating that a greater layer height needs a higher temperature to endure larger σ values, and this appears to be well-characterized by a linear fit within this range of values. To make a broader comparison with the overall data, rather than solely

focusing on the selected σ peaks, the linear fit will be overlaid with a hypercubic fit. Despite the limitations associated with the cubic fit and its general inability to represent the true relationship accurately, it has proven to be the closest fit given the limited data without overfitting.

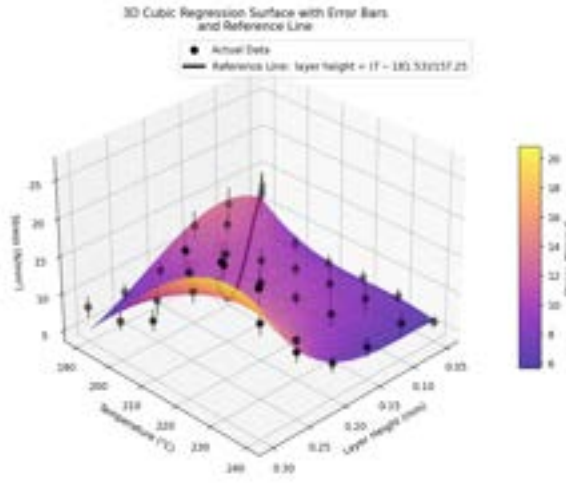
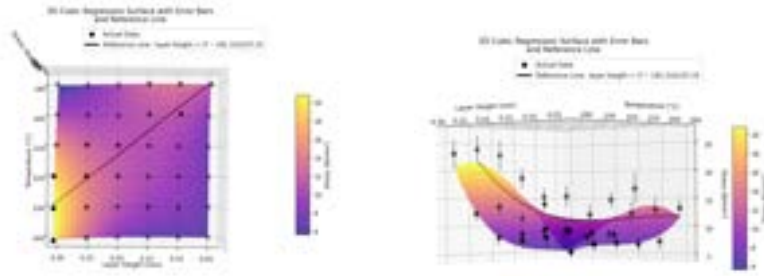


Figure 33

This hypercubic fit follows the form

$$\begin{aligned} \sigma = & (1.60 \pm 0.60) \times 10^3 L_h^3 + (-1.40 \pm 0.69) \times 10^{-4} T^3 + (12.4 \pm 2.2) L_h^2 T \\ & + (-3.40 \pm 0.62) \times 10^3 L_h^2 + (-4.20 \pm 1.00) \times 10^{-2} L_h T^2 + (0.095 \pm 0.045) T^2 \\ & + (15.5 \pm 4.7) L_h T + (-1.24 \pm 0.54) \times 10^3 L_h + (-21.4 \pm 9.7) T \\ & + (1.60 \pm 0.70) \times 10^3. \end{aligned}$$

Offering an R^2 of 0.77.



(a) Zenital view of the two fits

(b) Horizontal view of the rise in σ resistance toward high temperature and high layer height.

Figure 34

8 Conclusion

This Extended Essay investigated how **layer height and temperature** influence the resistance to tensile stress of 3D-printed layers. The experiment revealed a **linear relationship** between peak stress, temperature, and layer height. **Higher layer heights (0.20-0.30 mm) performed better at elevated temperatures (220-240°C)**, whereas **lower layer heights (0.05-0.15 mm) exhibited greater strength at lower temperatures (190-210°C)**. This trend suggests temperature and layer height must be carefully balanced to optimize mechanical strength in fused deposition modeling (FDM) 3D printing.

A key observation was that prints at **0.30 mm and high temperatures (230-240°C) were the strongest overall**, even outperforming prints at other heights within their optimal temperature ranges. This may be due to **fewer layers, reducing fracture points, and increasing interlayer adhesion**. Conversely, when the temperature was too high, polymer degradation weakened the structure. At lower temperatures, insufficient heating led to poor bonding, particularly in thicker layers where material extrusion was faster.

While these findings provide valuable insights, several aspects remain unresolved. The study could not develop a complete **3D mathematical model** to describe the full relationship between layer height, temperature, and resistance to tensile stress. The use of a **third-degree polynomial fit** provided a reasonable correlation, but it does not capture the underlying physics of layer adhesion. Furthermore, the identified **“bump” pattern** in the data suggests a potential peak in tensile strength at specific parameter combinations, though further testing is required to confirm its exact shape and cause. In terms of precision and accuracy, the design of experiments has been done to avoid systematic errors, and has significantly succeeded. However, due to many aspects such as the printer being old or the printing environment being a classroom, the range of random errors and lack of precision has been surprisingly big.

To improve the reliability of future studies, researchers should consider **standardized ASTM/ISO tensile test bars** for greater comparability. Additionally, other factors such as **printing speed, extrusion rate, and cooling conditions** should be investigated, as they could further influence inter-layer bonding. A future study could also examine whether **print speed interacts with layer height**, affecting the exposure time of extruded material to heat and its ability to form strong bonds.

Overall, this investigation **reinforces the importance of optimizing both temperature and layer height** in 3D printing to enhance mechanical performance. While limitations exist, the findings provide a foundation for refining printing parameters and guiding future research on the mechanical properties of FDM 3D-printed objects.

9 Bibliography and appendices

References

- Esakkimuthu, E. S., Ponnuchamy, V., Sipponen, M. H., & DeVallance, D. (2024). Elucidating intermolecular forces to improve compatibility of kraft lignin in poly(lactic acid). *Frontiers in Chemistry*, 12. <https://doi.org/10.3389/fchem.2024.1347147>
- Etekcit. (n.d.). Etekcit digital luggage scale - portable handheld suitcase scale with lcd display. https://www.amazon.es/dp/B0C4XZR7W9?ref=ppx_yo2ov_dt_b_fed_asin_title
- Farre-Kaga, H. J., Saed, M. O., & Terentjev, E. M. (2021). Dynamic pressure sensitive adhesion in nematic phase of liquid crystal elastomers. *Advanced Functional Materials*, 32(12). <https://doi.org/10.1002/adfm.202110190>
- Ferretti, P., Leon-Cardenas, C., Ciotti, E., Santi, G. M., Donnici, G., & Frizziero, L. (2021). Fdm 3d printing parameters optimization: The key role of line width. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 921–922. <https://www.ieomsociety.org/proceedings/2021india/257.pdf>
- Fisher, T., Almeida, J. H. S., Falzon, B. G., & Kazancı, Z. (2023). Tension and compression properties of 3d-printed composites: Print orientation and strain rate effects. *Polymers*, 15(7), 1708. <https://doi.org/10.3390/polym15071708>
- for Dummies, M. (n.d.). The phenomenon of brittle failure — metallurgy for dummies. <https://www.metallurgyfordummies.com/the-phenomenon-of-brittle-failure.html>
- Formlabs. (n.d.). 25 (unexpected) 3d printing use cases. <https://formlabs.com/asia/blog/25-unexpected-3d-printing-use-cases/>
- GeeksforGeeks. (2023, June). 3d curve fitting with python. <https://www.geeksforgeeks.org/3d-curve-fitting-with-python/>
- Google. (n.d.). Stdev - google docs editors help. <https://support.google.com/docs/answer/3094054?hl=en>
- HIWIN. (n.d.). Linear guideways — hiwin. <https://www.hiwin.de/en/Products/Linear-guideways/c/4354>
- lion3d. (n.d.). Lion 3d pla printing filament 1.75mm for 3d printers. https://www.amazon.in/dp/B0CHW99BNF?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1
- MikeRun. (2021, July). Different types of mechanical stress. https://commons.wikimedia.org/wiki/File:Different-types-of-mechanical-stress_EN.svg
- Mileo, P. G. M., Krauter, C. M., Sanders, J. M., Browning, A. R., & Halls, M. D. (2023). Molecular-scale exploration of mechanical properties and interactions of poly(lactic acid) with cellulose and chitin. *ACS Omega*, 8(45), 42417–42428. <https://doi.org/10.1021/acsomega.3c04880>

- Phadnis, S. (2014). Impact of 3d printing on global supply chains by 2020. <https://dspace.mit.edu/handle/1721.1/92106>
- Python. (n.d.). Python releases for windows. <https://www.python.org/downloads/windows/>
- Rasselet, D., Ruellan, A., Guinault, A., Miquelard-Garnier, G., Sollogoub, C., & Fayolle, B. (2013). Oxidative degradation of polylactide (pla) and its effects on physical and mechanical properties. *European Polymer Journal*, 50, 109–116. <https://doi.org/10.1016/j.eurpolymj.2013.10.011>
- ScienceDirect. (n.d.). Poly lactic acid polymer. <https://www.sciencedirect.com/topics/chemistry/poly-lactic-acid-polymer>
- Techniques, T. (n.d.). What is a load cell? <https://www.transducertechniques.com/what-is-a-load-cell.aspx>
- Tools, C. (n.d.). 3dbenchy. <https://www.3dbenchy.com/>
- Trends, G. (n.d.). Google trends. <https://trends.google.com/trends/explore?date=all&q=%2Fm%2F04rk8g&hl=en>
- UltiMaker. (2024, December). Ultimaker cura - ultimaker. <https://ultimaker.com/software/ultimaker-cura/>
- University, I. S. (n.d.). Nondestructive evaluation physics: Materials - structure and deformation. <https://www.nde-ed.org/Physics/Materials/Structure/deformation.xhtml>
- Vaezi, M., & Chua, C. K. (2010). Effects of layer thickness and binder saturation level parameters on 3d printing process. *The International Journal of Advanced Manufacturing Technology*, 53(1–4), 275–284. <https://doi.org/10.1007/s00170-010-2821-1>