

19WS02 INDIVIDUAL PROJECT
BEng Product Design Engineering

FDM 3D PRINTING WITH HIGH TEMPERATURE MATERIALS

FINAL REPORT
2019/2020

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Chapter 1: Introduction and Project Planning

1.1 Introduction

Polyether-ether-ketone (PEEK) is a popular high-performance polymer used in engineering and medical fields due to its combination of exceptional mechanical properties, chemical stability and biocompatibility.

Recently, due to the advancements in high-temperature 3D-printing, PEEK have been able to replace many metal parts and create even more sophisticated innovations while minimizing weight and costs for systems.

PEEK is generally used for creating robust items in demanding applications such as bearings, piston parts, or compressor plate valves. More recently, due to the rise in additive manufacturing, PEEK has also been used for creating customisable patient implants that replaces the need for coated titanium implants.

As PEEK is an expensive polymer, subtractive manufacturing is seen as an unideal process for manufacturing PEEK components due to the costly waste material generated. Similarly, injection moulding is also costly and does not provide the opportunity to create customable 'one-off' parts, a feature in which the medical industry is highly interested in. Therefore, when patent protection for various material extrusion techniques started to expire in 2009, fused filament fabrication (FFF) desktop printers became a competitive option to manufacture PEEK components.

Last year, two project students at Loughborough University built an early prototype 3D printing machine capable of printing PEEK by upgrading an existing low-cost desktop 3D printer manufactured by Velleman. This was exciting, as high temperature printers in the market are not very affordable, costing an upwards of £6000. Their upgrades enabled the printer to reach the thermal requirements necessary to print PEEK, however, much more

development was needed for the system to print reliably and produce samples of a higher quality. Figure 1 depicts the final PEEK sample delivered by the project students last year.

Lastly, the difficulty surrounding printing PEEK on an FFF printer is the high glass transition temperature of 144°C and a melting temperature of around 344°C. Previous project students chose to print this sample at a nozzle temperature of 400°C and a bed temperature of 100°C. Discussions with the previous students disclosed an ambient temperature of 130°C was used for the final sample. Previous students also used paper to help the part adhere to the base plate. The final results from last year study, as seen in Figure 1, manifests noticeable discolouration, warping and the formation of black specks.

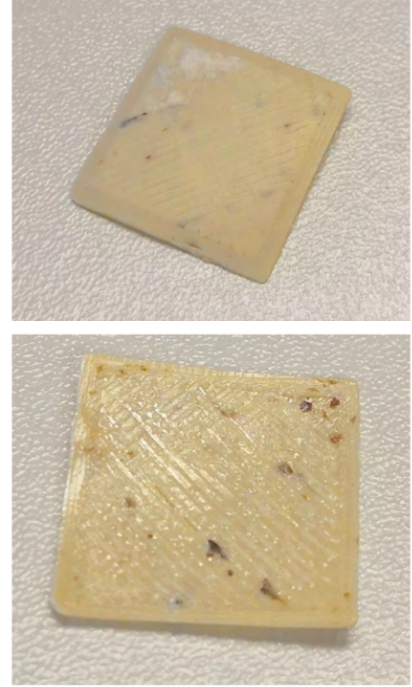


Figure 1 – Final PEEK sample produced by a project student last year printed on paper (1).

1.2 Project Aim

The project aim was to produce high-quality¹ PEEK prints using a modified desktop FFF printer (Velleman K8200) with the provided KetaSpire® PEEK material filament. This also included making any modifications that will aid the quality of the print.

1.3 Project Objectives

Several project objectives were set at the start of the project to ensure that the project aims were met to a high standard. To achieve the project aims, several features of the printer were also upgraded to improve the safety, performance and reliability of the printer.

¹ The term *quality*, in this paper, is defined in terms of following categories: accuracy of printed parts against the original specifications, surface finish, and tensile strength.

The project objectives included:

- Conducting a literature review to identify and collate print parameters that may affect the quality of the PEEK print.
- Conducting a thorough assessment of the printer at handover to identify faults and limitations to enable repairs and modifications.
- Assessing available options and justify chosen upgrades decisions
- Upgrading components to help achieve thermal requirements
- Manufacturing modifications to improve reliability and safety of the printer.
- Verifying design specifications provided by previous project students and calibrate printer if necessary
- Updating and recording the cost of the entire 3D-printing system
- Documenting changes made to the hardware and software of the printer
- Performing tensile tests on printed samples following the recognised ASTM standards
- Evaluating the final printer design compared to design at handover and providing future recommendations for further work.
- Exercising effective time management throughout the duration of the project.

1.4 Project Deliverables

- Construction of a Gantt chart to support effective time management
- Production of an extensive literature review that covers properties of PEEK, selected machine component upgrades, printing variables to optimise the quality of PEEK prints and other background knowledge.
- Collection of quantitative data in regards to heating and cooling rates of the enclosure, temperature fluctuations, as well as data from tensile testing of samples.
- Tensile test samples and results.
- Functional prototype with increased safety features

1.5 Project Planning

Initially, a detailed Microsoft Project Gantt chart was created to aid project planning. However, due to the inaccessibility of the software programme on Apple devices, an alternative Gantt chart was created using the provided template on Microsoft Excel. Figure 2 manifests the Gantt chart created on Excel. Highlighted in orange are the milestones or University deadlines, while the individual tasks are broken down under each section highlighted in light blue.

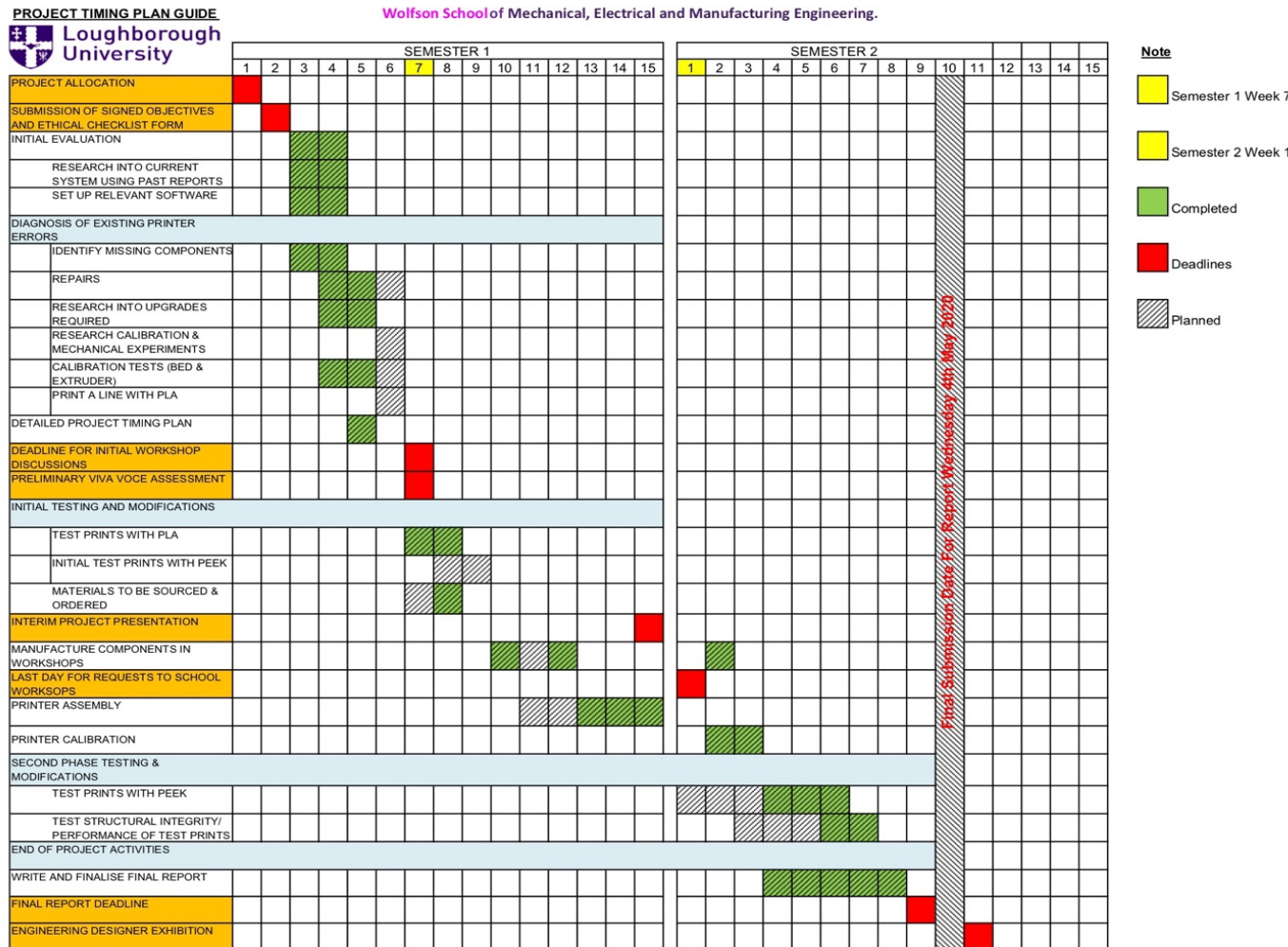


Figure 2- Gantt chart depicting the time allocated to each key phase of the project, broken down tasks and project deadlines

The timing plan helped the author with keeping track of upcoming deadlines as well as with evaluating her progress in relation to what she should have completed at a certain point in time.

However, what occurred in real life was much less straight-forward. The plan essentially follows a waterfall model, but due to changing requirements (such as the need to modify the printer to achieve prints of satisfactory quality) and technical uncertainty, an agile approach was applied much more frequently throughout the project. Details and reflections regarding the execution of the project plan will be further discussed in Chapter 7 of the report.

Chapter 2 Literature Review

2.1 A Background into PEEK and its Industrial Applications

PEEK is a thermoplastic within the polyketone family (1). While the polyketone family also includes other semi-crystalline polymers such as polyaryletherketones (PAEK) and polyetherketones (PEK), PEEK is still the most widely used polymer within the family due to its exceptional and unique combination of performance characteristics.

PEEK has an excellent combination of strength, stiffness, toughness and environmental resistance. Additionally, it possesses outstanding chemical resistance, flame resistance characteristics and excellent surface wear properties (2). These properties are highly desirable in the medical and engineering fields. Moreover, due to its relatively stiff aromatic polymer backbone, PEEK is fatigue and creep resistant in high operating temperatures of up to 260°C (3). As presented in Table 1, PEEK has a glass transition temperature (T_g) of 144°C and a melting temperature (T_m) of 344°C.

With an inherently low specific gravity of 1.3 g/cm³, PEEK appeals especially to the aerospace and automotive industries. A low specific gravity enables PEEK components to possess strength and modulus properties similar to aluminium or steel while occupying a much lower weight. According to Rahman et al. (4), a 70% weight reduction with similar mechanical properties to aluminium or steel is achievable with PEEK.

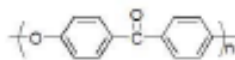
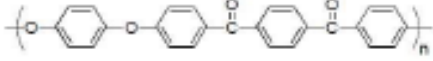
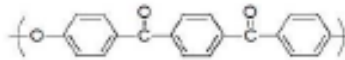
Polymer	Chemical Name	Chemical Structure	$T_g^{\circ}\text{C}$	$T_m^{\circ}\text{C}$
PEK	Polyetherketone		163	361
PEEK	Polyetheretherketone		144	344
PEEKK	Polytheretherketoneketone		154	358
PEKK	Polyetherketoneketone		165	384-391

Table 1 - Glass transition and melting temperatures of polymers within the polyaryletherketone family (1).

PEEK is also increasingly used as an effective biomaterial for implantable medical devices such as orthopaedic, spinal and cranial implants (5). This is because, compared to stainless steel and titanium, an implant made of PEEK has clear benefits relating to temperature sensitivity and weight reduction without sacrificing structural integrity and radiology advantage (2,6).

In summary, PEEK is a versatile material with various application opportunities in industries ranging from automotive to medical. With its unique combination of properties, PEEK continues to inspire numerous research topics relating to the alteration of PEEK properties to fit specialised applications.

2.2 FFF 3D Printers & Their Relative Advantages Over Other Processing Methods

Before additive manufacturing (AM) techniques became accessible, only traditional processes such as injection moulding, extrusion or hot pressing were used to produce PEEK components. However, these processes limit the level of complexity of the component produced and incur high set-up costs.

While the selective laser sintering (SLS) technique was the first AM technology to adopt PEEK printing, FFF is now the most widely used and recognized AM technique for producing functional PEEK structures (7).

Unlike SLS, extrusion-based 3D printers, such as FFF printers, present a way for the operator to create PEEK parts with fewer concerns over the safety, contamination and degradation aspects of handling powdered PEEK (4). Moreover, material extrusion is a low-cost process compared with the SLS process, while providing greater control of pore size, an essential factor to control when producing patient implants. According to Vaezi et al. (8), the smallest achievable pore size in SLS is currently limited to around 400-500µm; this is because as the pore size gets smaller, the difficulty removing excess unsintered powders trapped inside the pores increases. While the smallest achievable pore size produced using SLS can still meet the requirements recommended in literatures

for bone in-growth and vascularisation, Vaezi et al. (8) explained that it might not be optimal for bone cell attachment where pore size ranging from 200 to 350 μ m is usually suggested. FFF printing, therefore, has an advantage as a wide range of pore sizes can be achieved.

Another advantage of using extrusion-based technology such as FFF printing over SLS is that much less waste material, gas or pollution gets generated with this method. Moreover, as powerful laser modules are not employed to form the material, the energy consumption involved in producing the parts significantly reduces (9).

2.3 Principles Behind FFF 3D Printers

FFF, more commonly known under Stratasys' trademarked term fused deposition modelling (FDM), is the most common type of extrusion-based 3D printing method.

As demonstrated in Figure 3 and as explained by Gibson et al. (10), a typical FFF printing process involves the following steps and principles:

- Feeding a strand of filament through the extruder until it reaches the heater block.
- Liquification of the material by heating the hot-end to the material's melting point.
- Application of pressure to push the material through the nozzle.
- Extrusion of the thermoplastic onto the build platform.
- Plotting according to a predefined path and in a controlled manner.
- Bonding of the material to itself to form a coherent solid structure

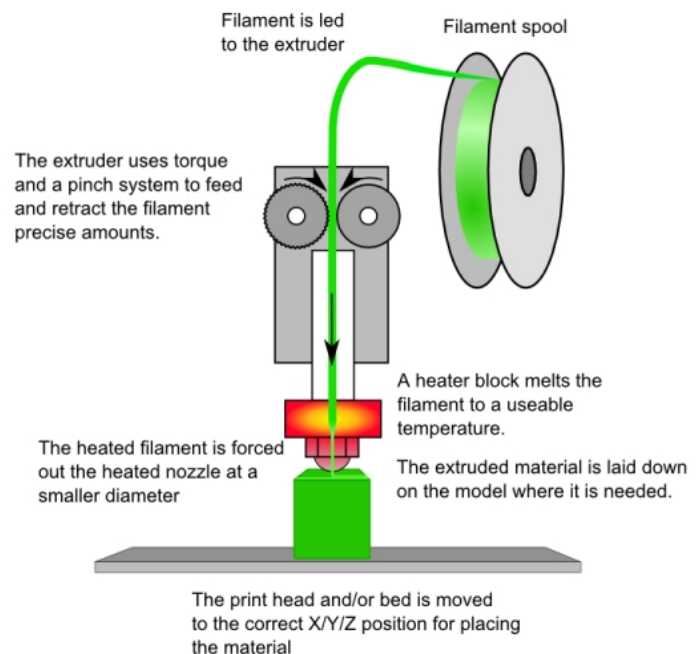


Figure 3 - Schematic diagram of a typical FFF process. Image source: (48).

- Inclusion of support structures to enable advanced geometrical features when necessary.

2.4 Processing Parameters That Affect the Mechanical Properties & Surface Finish of 3D-Printed PEEK Components

Various processing parameters and their significance have been explored and discussed extensively by researchers working on producing (PEEK) components using the FFF printing process. This section aims to compile some of the discussions from published articles to help form a general guideline for optimising processing parameters that can help improve the quality of the printed components.

2.41 Nozzle Diameter and Layer Thickness

A publication by Wu et al. (9) noted that as the layer thickness of PEEK increased and especially exceeds half of the nozzle diameter, the surface quality deteriorated in the vertical direction. The study reported that the nozzle diameter should be at least 1.5 times the value of layer thickness to assure strong cohesion between printed polymer's filament. A strong adhesion between layers is important as it makes it possible to internally transfer the stress imposed during tensile testing, conversely, voids create punctual defects that weaken the part's properties.

Similarly, the authors explained that a decrease in accuracy of the sample geometry was also observed and outlines more readily displayed the staircase phenomenon when the layer thickness increased (9).

However, while printing parts with a small layer thickness can yield many structural benefits, the authors acknowledged that using a smaller nozzle size will inevitably lead to longer printing times and an increased chance of the nozzle getting clogged.

In a similar study conducted by Wang et al. (11), samples built with a 0.3 mm layer thickness had the greatest strengths in all the mechanical tests performed (Table 2).

Meanwhile, the strength of samples with 0.4 mm layer thickness decreased significantly. It was also found in the study that although the layer thickness had a great influence on tensile strength, it had little influence on bending and compressive strengths.

Factors		Tensile strength (MPa)	Bending strength (MPa)	Compressive strength (MPa)
Layer Thickness (μm)	200	40.1	52.1	53.6
	300	56.6	56.1	60.9
	400	32.4	48.7	54.1
Raster Angle ($^{\circ}$)	0°/90°	56.6	56.1	-
	30°/	41.8	48.5	-
	-60°			
	45°/	43.3	43.2	-
	-45°			

Table 2 – Impact of layer thickness and raster angle on mechanical properties of FDM 3D printed samples (11).

2.42 Raster Angle (Deposition Orientation)

A lesser known, but surprisingly widely discussed topic among scholars in this area of research, is the effect raster angles have on the mechanical performance of FFF printed components. Raster angle is defined as the direction of the beads of material relative to the loading direction of the part (12), as demonstrated in Figure 4.

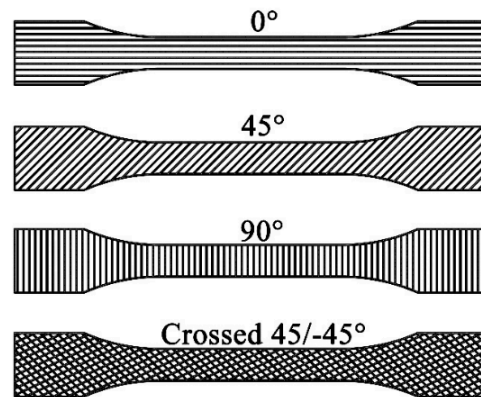


Figure 4– Raster direction angles. Image source: (49)

Table 2 aims to provide a broad overview of the general trends attained between the different studies focusing on the impact of raster angles on mechanical properties for FFF 3D printing.

Authors	Material	Raster Angle	Ultimate Tensile Strength (MPa)	Flexural Strength (MPa)	Compressive Strength (MPa)
Rahman et al. (4)	Proprietary PEEK from Arevo Labs	0	73.01	-	80.87
		0/90	66.52	-	72.78
		90	54.04	-	
Arif et al. (13)	Vitrex PEEK 450G	0	82.58	142	80.87
		90	72.88	124.3	
Wu et al. (14)	Unfilled PEEK from Jilin University	0/90	56.6	56.1	no correlation*
		30/-60	41.8	48.5	
		45/-45	43.3	45.2	
Cicala et al. (7)	Industrial grade PEEK (Luvocomm)	0/90	51.03	78.95	-
		30/-60	51.35	78.35	-
		45/-45	51.37	78.17	-
Magri et al. (15)	VESTAKEEP 3300G	45/-45	74.24	-	-
		0/15/-15	78.31	-	-

* due to cylindrical shape of compressive test samples, authors concluded that raster angle had no correlation with compressive strength

Table 3 – The impact of raster angles on the mechanical properties of FFF 3D printed samples.

As different authors tested different combinations of raster angles, it is hard to pinpoint the optimal set of raster angle. However, from the table, there is a general consensus between Rahman et al. and Arif et al. that parts printed with a raster angle of 0° yielded superior tensile test results to those printed with a 90° raster angle. On the other hand, the 0°/90° alternating angles also seem to be favourable to parts requiring high flexural strength according to the studies by Cicala et al. and Wu et al.

2.43 Printing Speed

The effect of FFF printing speed on the extruded PEEK microstructure was studied by Geng et al. (16). Using Vitrex PEEK, the authors created a roll of filament with the diameter of 1.75 ± 0.16 mm. By testing all three nozzle diameters (0.4mm, 0.5mm and 0.6mm), the authors concluded that the optimal extrusion speed for enhanced extruded PEEK microstructure is below 109.8 mm/min. Under this situation, the authors explained that the extrusion characteristic is in a relatively stable state, and the PEEK filament could provide the extrusion force to maintain the melt flows stably and continuously.

Magri et al. (15) also investigated the effect of printing speed on tensile strength. It was found that with the nozzle deposition temperature of 400°C, extrusion rate of 30mm/s produced the highest average tensile strength in comparison to 20mm/s and 40mm/s. However, the authors concluded that printing speed and retraction speed should be considerably tested by the operator, as the outcome may vary with the PEEK types and manufacturer.

2.44 Chamber Temperature & Rate of Cooling

The chamber temperature and the rate of cooling play a significant role when it comes to preventing part warpage in PEEK samples. Schwitalla et al. (11) noticed that as the chamber temperature increased from 90°C to 130°C, the warping deformation of the samples reduced from 1.93 mm to 0.65 mm, as demonstrated in Figure 5. Moreover, the authors discovered that the chamber temperature has more influence on the warping deformation than the nozzle temperature. Hu et al. (17) also reported that the warpage of their PEEK samples decreased from 20.4% to 5% when they applied a higher chamber temperature.

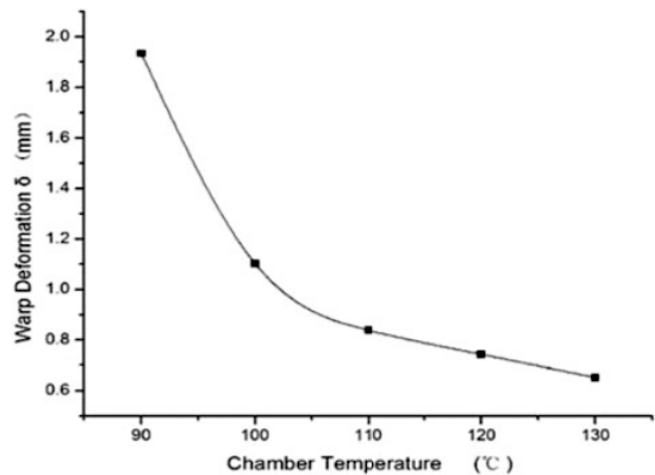


Figure 5 - Influence of chamber temperature on warpage deformation (11).

The reduced warpage is most likely a result of the minimised temperature difference between the processing/nozzle temperature and the chamber temperature. As the material exits the nozzle, the higher the chamber temperature, the slower the rate of cooling of the newly extruded PEEK filament.

In addition to a high chamber temperature, Schwitalla et al. (11) maintained the chamber temperature for 20–30 minutes after printing before gradually cooling their samples to room temperature at a rate of 5°C/min. A slower cooling rate gives the polymer more time to relax toward an equilibrium glass state, which, in turn, reduces the residual stress.

2.45 Printing Routine: Slicing Software

In a publication by Wang et al. (11) on the parameters influencing the outcome of 3D-printed tiny medical devices based on PEEK, the authors discussed the importance of printing routine/toolpath in the production of parts via extrusion-based additive processes.

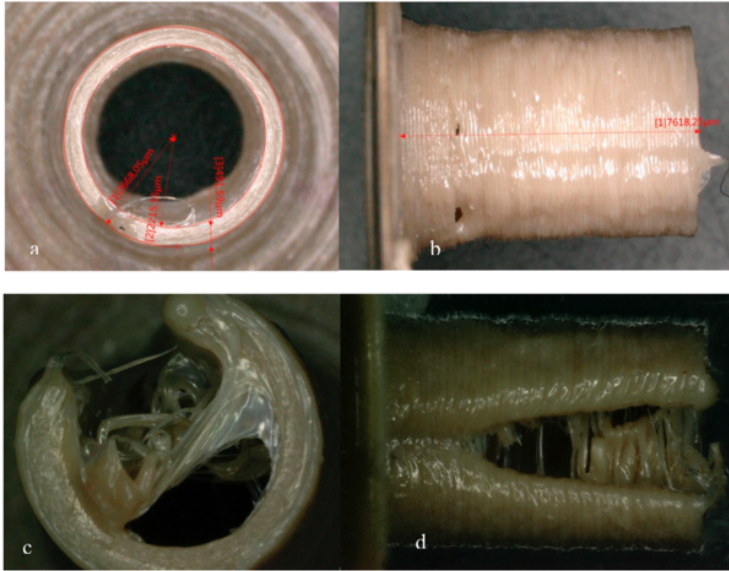


Figure 6 – (a,b) shows barrel printed by Apium HPP155 built-in software, and (c,d) shows the sample printed by Simplify 3D. (11)

They also highlighted that in all the literature concerning PEEK printing, this parameter has not been mentioned as one of the key parameters affecting the quality of samples. However, evidently, in their study, the toolpaths created by two different slicing softwares made significant differences in the outcome of the printed components (Fig 6).

Their study involved printing a cylinder geometry coded by two separate slicing softwares: Simplify 3D and the Apium HPP155 printer's built-in software.

When printing a cylinder coded by Simplify 3D software, the nozzle reportedly moved clockwise and anticlockwise to complete the same layer. The built-in software, on the other hand, had a different routine: the nozzle moved in one direction all the time, with the platform adjusting its Z-axis position almost in the same X and Y coordinates.

The authors summarised that components with a radius of 3mm or less is more susceptible to defects caused by the reciprocating printing pattern (clockwise and anticlockwise) generated by the Simplify 3D or similar slicing softwares. While printing a barrel with a radius of 3 mm, the routine used reciprocating lines around one layer had a "V" split line along the starting point (Figure 6). This result may indicate that the back and forth routine has higher requirements for calibration than the mono-directional routine.

2.46 Nozzle Temperature

The deposition temperature is a crucial parameter as it determines the flow of the material through the nozzle as well as the quality of the extruded material. If the nozzle temperature is too low, the PEEK filament will not melt completely, leading to a plugged nozzle because of the high viscosity. If the nozzle temperature is too high, crosslinking reactions will occur (9), and PEEK may even burn. This will result in material degradation.

The optimal nozzle temperature depend highly on the manufacturer of the PEEK filament and PEEK type, therefore, the author decided that it would be more useful to determine whether there is a relationship between the filament melting temperatures and the optimal printing temperatures reported by the authors.

The experimental results from Wu et al. (9) help conclude that the warping deformation of their PEEK sample is minimal when the nozzle temperature is at 350°C and the chamber temperature is at 130°C (although 130°C is the highest temperature tested within this study). In this study, the PEEK material obtained from the Jilin University Special Plastic Engineering Research Co. Ltd had a melting point of 334°C. Thus, it can be observed that the authors only increased the nozzle temperature to 16°C above the specified melting temperature.

On the other hand, Magri et al. (15) found that the optimum nozzle temperature for printing using their filament is 60°C above the original specified melting temperature. , Magri et al. (15) printed their samples with VESTAKEEP 3300G PEEK, a material with a melting temperature of 340°C, yet found that 400°C was the optimum processing temperature for their material.

While no solid conclusion can be drawn from this section regarding the optimal temperature, Magri et al. (4) advised that a constancy of nozzle temperature should be controlled within +/- 1 degree in order to produce a print with good tensile qualities.

2.47 Post-Processing of PEEK Prints

In many of the publications, PEEK samples were annealed after printing to enhance their overall quality. Heat treatment has shown to improve bonding between layers, enhancing overall material properties while decreasing porosity in printed parts (15). This is because a low heating/cooling rate significantly improves the degree of crystallinity, which in turn reduces the residual stresses, increases dimensional stability, eliminates defects, and improves mechanical properties.

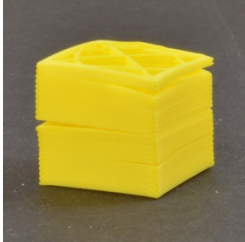
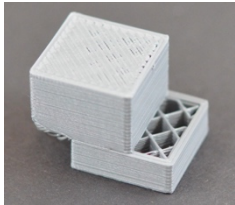
A detailed guide of the annealing process can be found in Magri et al. (15)'s paper.

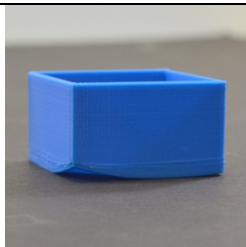
2.48 Key findings applicable to this study

Printing speed and retraction speed should be considerably tested considering PEEK types and manufacturers. The nozzle temperature also depends on manufacturer and type of PEEK as well. Therefore, there is no optimal set of parameters that is universal, however, the reviewed literatures revealed numerous key findings that may be helpful for enhancing the test prints later on.

- Nozzle diameter should be at least 1.5 times the value of layer thickness in order to create parts with better surface quality
- Slicing software and tool path becomes increasingly important when printing PEEK parts with radius of 3mm or less
- Tensile properties were enhanced with unidirectional raster angles, but reduced when the raster angles were increased from 0 to 90°
- The chamber temperature should be increased to as close to the glass transition temperature as possible to reduce part deformation due to shrinkage or warpage
- The slower the cooling rate, the better as a slow cooling rate allows the polymer to relax towards its equilibrium glass state
- The optimal extrusion speed for enhanced extruded PEEK microstructure is below 109.8 mm/min

2.5 Common FFF 3D-Printing Defects and Prevention Techniques

Defect	Description	Image	Potential Causes & Solutions
Layer Separation	When layers do not adhere to previously printed layers, causing a split or separation in the print in the printed object.	 Figure 7 -Source: (18)	• Layer height is too large • Print temperature is too low (18)
Black-Specks Formation	Black-specks formation is a visible defect commonly observed in 3D-printed PEEK components.	 Figure 8 – PEEK with black specks (50)	• impurities within the material • lack of thermal processing control (i.e. temperature fluctuations) • material degradation within the nozzle assembly due to blockages or when temperature is too high. • Maintain a clean nozzle
Discoloration	When improper crystallization occurs, causing the part to show brown discoloration as opposed to a beige colour.	 Figure 9- Discoloured PEEK specimens (19)	• Annealing to solve brown discoloration • print at higher temperatures (20)
Layer Shifting	Sudden shift in print, causing consecutive layers to be misaligned.	 Figure 10 – Source: (18)	• The printer is printing too fast • Loose timing belts on the x and/or y-axes

Warping (Particularly common when printing high-temperature materials)	Warping occurs when an object is cooled unevenly after printing. Cooling causes contraction and increased internal stress. And the quicker the cooling occurs, the greater the stress on the object.		<i>Figure 11 – Edges warping as stress is greatest at corners where two sides meet. Source: Rigid Ink (51).</i>	• Increase the ambient temperature to minimise the difference between the hot-end and chamber temperature. • Improve bed adhesion (e.g. by using rafts, brims or adhesives). • Slow down the rate of cooling and maintaining the temperature close to the material's T_g (21).
Print Not Adhering to Bed	Printed component lifted off the bed during printing, causing subsequent layers not to be printed properly.		<i>Figure 12 – Result of print not adhering to bed (52).</i>	• The platform is not level or the surface is warped • Nozzle too close or too far • Printing first layer too fast • Change build surface material.
Skipped Layers	The print has not shifted, but it appears that an entire layer is missing within the print.		<i>Figure 13 – Source: (53)</i>	• Reduce the Z-axis movement speed • Make sure the Z-axis can travel freely. • Set layer heights to use full steps.
Material Shrinkage	When the printed volume contracts while cooling. This is partly due to the change in density of the polymers from the melt state to the rigid state. For unfilled PEEK, the shrinkage rate (for injection moulding) is 1.2-1.5% (22).		<i>Figure 14 - Shrinkage may cause layer lines to become more visible (54).</i>	• Maintain chamber temperatures near to PEEK's glass transition temperature. • Slow down material cooling rate and maintain even surrounding temperature around the print to avoid further uneven shrinkage. • Account for shrinkage rate in CAD.

2.6 ASTM D638: Standard Test Method for Tensile Properties of Plastics

Tensile testing is a fundamental engineering test in finding out the mechanical characteristics of different materials as well as how the different process parameters can affect the tensile properties of the product. Its purpose is to enable designers and engineers to select a material suitable for the specific application while understanding the limits of its performance.

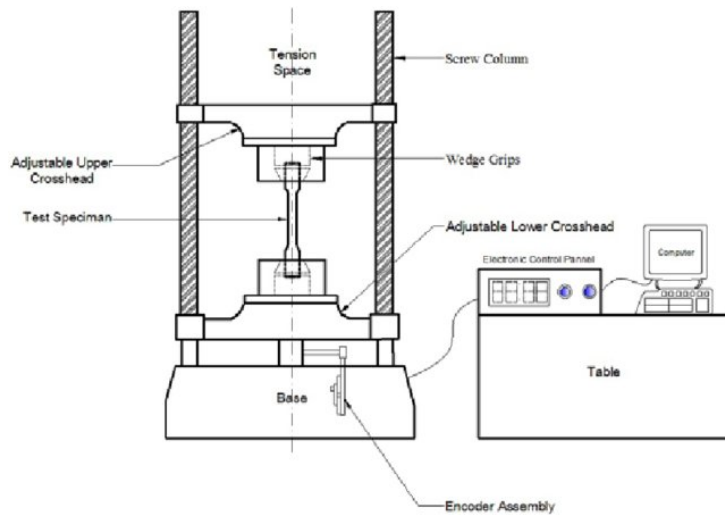


Figure 15 – Schematic diagram of a tensile testing machine

To obtain tensile test properties such as ultimate tensile strength, breaking strength, and maximum elongation, “dog-bone” shaped specimens are produced and tested individually on a universal testing machine. Once the specimen is clamped down by the grips, see Figure 15, the testing machine slowly extends the sample until the point of fracture.

ASTM D638 specifies the methods for determining the tensile properties of unreinforced and reinforced plastics, as well as the accuracy requirements needed for the test frames and accessories employed (23).

For ASTM D638, there is a selection of five types of test specimens. According to (23), Type I is the preferred specimen geometry, especially for material 7mm thick or less. Type II specimen is used if the Type I specimen does not break in the gauge section. Type III specimen must be used when the material thickness is greater than 7mm, however, does not exceed 14mm. Type IV is used when direction comparison is required between materials in different rigidity cases. Lastly, according to (24,25), Type V is used for special circumstances, such as when the specimens need to be tested in a controlled environment (e.g. in a thermostatic chamber) or when the material is limited so specimens can have a thickness of 4mm or less. The detailed dimensions for each type of test specimen can be accessed on the ASTM D638-14 website (23)

The ASTM standard also specifies the minimum number of specimens needed per sample. At least five specimens are needed for each sample in the case of isotropic materials. For anisotropic materials, when applicable, ten specimens should be tested: five specimens normal to and five parallel with the principal axis of anisotropy. In his article, Lambert (26) discusses that FFF printed parts exhibit anisotropic mechanical properties, meaning that the mechanical properties of FDM parts are directionally dependent. This makes sense as the break behaviour for specimens built in the z-direction would only require the separation of the interface between the two stacked layers, whereas when pulling apart a specimen in the X and Y direction would require fracturing many individual extruded plastic fibres, see figure 16.

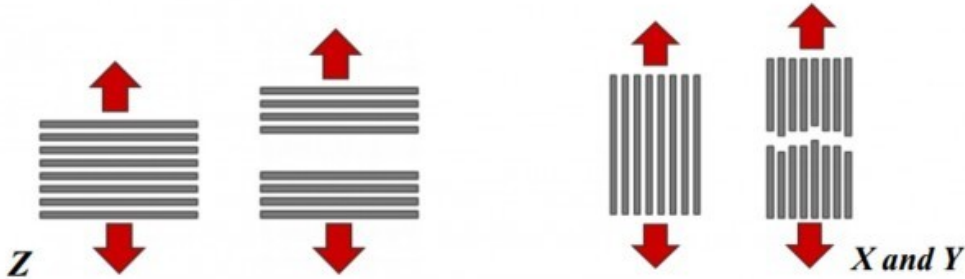


Figure 16 - Separation behaviour of FFF printed specimens

Classification ^B	Specimen Type	Speed of Testing, mm/min (in./min)	Nominal Strain ^C Rate at Start of Test, mm/mm· min (in./in.·min)
Rigid and Semirigid	I, II, III rods and tubes	5 (0.2) ± 25 %	0.1
		50 (2) ± 10 %	1
		500 (20) ± 10 %	10
	IV	5 (0.2) ± 25 %	0.15
		50 (2) ± 10 %	1.5
		500 (20) ± 10 %	15
	V	1 (0.05) ± 25 %	0.1
		10 (0.5) ± 25 %	1
		100 (5)± 25 %	10
	Nonrigid	III	50 (2) ± 10 %
500 (20) ± 10 %			10
IV		50 (2) ± 10 %	1.5
		500 (20) ± 10 %	15

Table 4 - Speed of Testing from ASTM D638-14

Prior to testing, the speed of testing also needs to be selected. According to ASTM D638-14, if the speed is not specified, the lowest speed for the specimen geometry shown in Table 4 can be used as a reference. For testing PEEK samples, Deng et al. (27) chose a loading rate of 2 mm/min.

Regarding the testing procedure, Section 10.1.1 in the ASTM D638 standard states that the width and thickness of the specimens should be measured at the centre of each specimen, within 5mm of each end of the gauge length.

To identify the ideal apparatus and appropriate load cells to use for testing PEEK, related literatures were consulted. In a study carried out by Magri et al. (15), rigid PEEK specimens were tested for tensile strength on an INSTRON 4206 universal testing machine with a 10kN load cell of 0.5% precision in the measured force range. Similarly, an Instron 5985 UTM equipped with a load cell of 10kN and Instron's Blue Hill data control software was employed to test PEEK specimens in a study by Cicala et al. (7).

2.7 Materials and Components Selection

This section aims to briefly review and provide a background understanding into some of the materials and components that have been used or may be considered for making new design decisions later on in the study.

2.7.1 Upgrades to Help Reach Temperature Requirements

PT100 Sensor (for Hot-end Temperature Measurements)

A PT100 sensor was installed by previous project students to replace the thermistor cartridge that came with the original Velleman printer. Although more expensive than a thermistor, this resistance temperature detector (RTD) can monitor a wider range of temperatures, and it is generally applied in applications involving temperatures above 130°C. According to E3D (7), PT100s can measure temperatures up to 500°C, while thermistor cartridges can only reach a maximum temperature of 300°C (28).

PT100 is also known for its accuracy, excellent stability, repeatability, and relatively immune to electrical noise, allowing it to work well around motors, generators and other high voltage equipment (6). It works by measuring the temperature based on the resistance changes in a metal resistor. For a Class A PT100 operating at 40°C, the tolerance is $\pm 0.95^{\circ}\text{C}$ (8). It is important to note that, while similar in the way it operates, the PT100 cannot just be plugged into the normal thermistor inputs on the RAMPS 1.4 board.

E3D Thermistor Cartridge (for Heated Bed Temperature Measurements)

A thermistor works like an RTD but contains a ceramic or polymer resistor instead of metal (10). While operating within a smaller temperature range, thermistors have superior response times to RTDs, detecting changes in temperature much faster.

Thermocouple and Amplifier (for Chamber Temperature Measurements)

Thermocouples are the easiest temperature sensor to identify. A thermocouple probe has two wires identified by a colour code. According to previous reports, the Type K thermocouple has been implemented to monitor the chamber temperature fluctuations. Typically, Type K thermocouples have a temperature range of -200°C to 1250°C (29).

To implement a thermocouple, a thermocouple amplifier must also be installed to amplify the small signal level produced by the thermocouple. In this study, the Adafruit Thermocouple Amplifier for Type K Wire was used. This has a range of -200°C to 1350°C .

Ceramic Fibre Blankets

Superwool® Plus ceramic fibre blanket is used as the main insulation material for the heated chamber in this study. According to the supplier (30), the 25mm thick ceramic fibre insulation can withstand temperatures of up to 1260°C , and possess a thermal conductivity of $0.04\text{W/m}\cdot\text{K}$ at a mean temperature of 200°C .

PTFE Liner

Polytetrafluorethylene (PTFE) coated fibreglass is a wide availability, low cost material with a high operating temperature range up to 260°C . PTFE also has a low friction coefficient of 0.05-0.10.

PIR Insulation Panels

Polyisocyanurate (PIR) is typically produced as a foam and used as a rigid thermal insulation. PIR insulation panels have extremely low thermal conductivity ($\sim 0.023\text{W/m}\cdot\text{K}$) and a high strength to weight ratio (31). It is generally laminated with pure embossed aluminium foil and incorporated into buildings due to its excellent fire performance.

Generally PIR rigid insulation materials can withstand temperatures of up to 250°C for short periods of time with no adverse effects (32)

Bang-Bang Approach

While the Bang Bang Arduino code is not a physical component, it is an integral part of the chamber heating system. The Bang Bang controller is commonly used to turn a device on or off when the set target parameter is reached, in this case, the target temperature.

2.7.2 Bed Levelling & Types of Z-Probes

Maintaining a uniform distance between the nozzle and the bed throughout the build area is crucial for avoiding a plethora of common 3D printing problems such as poor first layer adhesion issues, clogged nozzles or even scratch marks on the build surface. Typically, the operator would manually adjust the screws beneath the bed to level the platform, however, this can be time consuming and ineffective. Hence, many commercial desktop printers have now introduced automatic bed levelling features into their systems to ensure a level bed every time.

Table 5 on the following page exhibits the five most common types of automatic bed levelling sensors used in FFF printing and their relative size, weight, precision and details.

Table 5: Automatic Bed Levelling Z-Axis Probes

Type	Description	Category	Details
Mechanical Sensor (BLTouch)	Uses a servo motor and arm to physically trigger a microswitch sensor	Size and Weight	Medium, Medium
		Compatible Surfaces	Any
		Precision	Medium
		Remarks	Cost: £35.95. If not installed perpendicular to the ground, the output signal will be wrong
Capacitive Sensor	Reacts to objects acting as a dielectric material	Size and Weight	Very large and heavy
		Compatible Surfaces	Any
		Precision	Low
		Remarks	Moisture in air, as well as heat, may influence reading
Inductive Sensor	Uses a magnetic field to detect objects	Size and Weight	Large and Heavy
		Compatible Surfaces	Steel or aluminium
		Precision	Medium
		Remarks	Most types need 12V or 24V power (voltage-level translation may be necessary). Heat may influence precision
Piezoelectric Sensor (E.g. hot-end mounted)	Using a piezoelectric disc to convert pressure generated by the hot end pressing up against the surface into electrical signal	Size and Weight	Medium and light
		Compatible Surfaces	Any
		Precision	Very high
		Remarks	
Reflective/ IR	Emits infra-red light onto the print surface and measuring the intensity of the returned light.	Size and Weight	Small and light
		Compatible Surfaces	Most
		Precision	High when used with opaque (medium or low transparency) surfaces
		Remarks	Power: 5V or 3.3V. Mounted near hot end generally as exposed PCB.

2.7.3 Z-Axis Movement

Trapezoidal Lead screw

Trapezoidal screws, also commonly referred to as lead screws, are mechanical linear actuators that has a contact angle of 30 degrees, as demonstrated in Figure 17. Like many other mechanical linear actuators, lead screws work by converting rotary motion into linear motion. Trapezoidal screws are suitable for vertical applications such as driving the z-axis movement because they are self-locking; therefore, there is no need to apply additional breaks. Moreover, lead screws are generally cheaper than other mechanical linear actuators and easier to maintain.

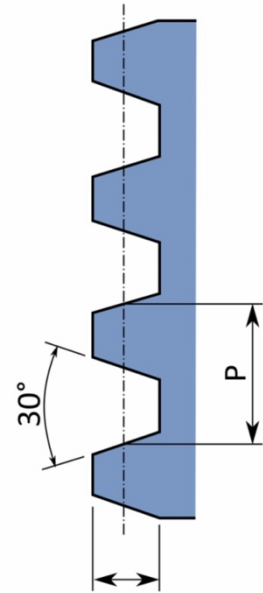


Figure 17 - Trapezoidal lead screw angle to reduce wear and tear when converting rotating motion to linear motion (16).

Before implementing a lead screw, a project engineer should consider the back drive, backlash, thrust, speed, lead accuracy and efficiency required for the mechanism.

To determine whether the screw will back drive, the back-driving torque can be calculated and compared to the friction in the screw assembly. However, according to (33), as a rule of thumb, if the lead is less than 1/3 of the diameter of the screw, back driving is unlikely to occur.

Ball Screws

Ball screw is an alternative power transmission screw that also converts rotary motion into linear motion. While ball screws can carry heavier loads than lead screws and enable motors to use less power due to the reduced friction, ball screws are not self-locking. This means that if power is no longer supplied to the motor, the screw will allow the load, which includes the hot end and extruder, to drop. Hence, ball screws are generally not recommended for vertical applications since additional brakes would need to be added.

Timing belts

While timing belts cannot directly drive the z-axis movement, they are used by some in the replicating rapid prototype (RepRap) community as an addition to stabilise and synchronize z-axis movements across all sides of the printer. This system is especially useful when resources such as stepper motors are lacking, and when the printer is wide so stabilisation is needed. Figure 18 illustrates a modified version of a K8200 printer with a belt drive system successfully implemented.



Figure 18 - Using a timing belt to synchronize z-axis movements for the other end of the K8200 printer. (55).

Linear Guide Rails

Linear guide rails (Figure 19), like timing belts, are used for supporting the motion of an application. They are increasingly implemented into the designs of desktop 3D printers due to their high accuracy, rigidity and precision capabilities. However, just like ball screws, they are not self-locking. Therefore, these linear guides are generally only implemented in the x and y axes.



Figure 19 - Linear guide rail and block (56)

NEMA 17

NEMA 17, as shown in Figure 20, is a stepper motor with a 1.8° step angle (200 steps/revolution) and a shaft size of 5 mm. While a NEMA 17 motor is larger and heavier than, for example, a NEMA 14, it provides much more room for torque. As each phase draws 1.2A at 4V, a NEMA 17 stepper motor can hold a torque of 3.2 kg-cm. Moreover, according to its datasheet (34), the operating temperature of a NEMA17 ranges from -10°C to 40°C .



Figure 20 - NEMA 17 Stepper Motor

RAMPS 1.4

Every 3D printer has a small control circuitry that amplifies and direct signals to perform specific functions. **RepRap Arduino Mega Pololu Shield (RAMPS)** is an open-source and inexpensive board that serves as the interface between the Arduino Mega and the electronics devices on the RepRap 3D printer.

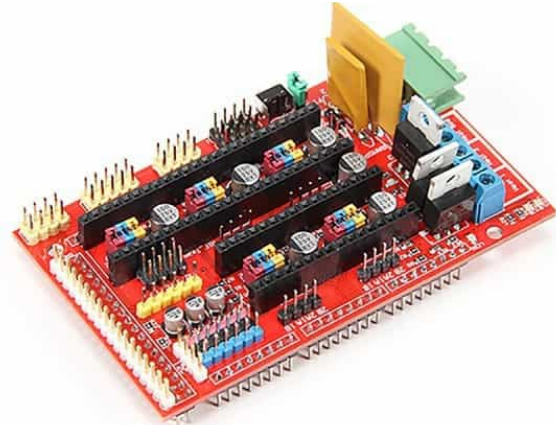


Figure 21 - RAMPS 1.4 board (57)

RAMPS 1.4, as shown in Figure 21, can accommodate all the necessary components needed to run most 3D printers. These include, but are not limit to:

- Socket for 5 stepper drivers. The z-axis connector allows two stepper motors to be driven synchronously.
- Sockets for 3 thermistors.
- Sockets for 6 end stops (for top and bottom limits of the X, Y, Z-axes)
- Screw terminals for 3 heaters.

2.7.4 Filament Extrusion Materials

Filaments are thermoplastic feedstocks for FFF printers. There is a multitude of filaments available, each with different properties and thermal requirements. Filaments typically come in the standard diameters of either 1.75mm or 2.85mm (often referred to as 3mm).

ABS

A nozzle temperature between 210 and 250 °C, and a heated bed around 80 to 110 °C is necessary for printing ABS. Additionally, according to (6), ABS needs to be printed in an enclosed 3D printer so that it cools very slowly to prevent shrinkage or unwanted part warpage.

PLA

Due to its versatility, PLA can print well anywhere from 180 to 230°C. However, according to All3DP (6), PLA prints best at around 210 °C. While it does not require a heated bed, a heated bed of temperatures somewhere between 20 and 60 °C will promote a good first layer adhesion, a crucial factor that affects the successful printing of subsequent layers.

KetaSpire® AM Filament NT1 HC Polyetheretherketone (PEEK)

The PEEK filament used in this study was acquired from KetaSpire®. It is important to document the manufacturer of the filament in this study, as different manufacturers provide filaments that will print optimally at different temperatures. Hence, this study will focus on finding out what the optimal printing parameters for KetaSpire® filament are.

The KetaSpire® comes at a hefty price, costing \$920.21 (~£712.06) per roll of 1kg. The filament comes with a metal spool, hence enabling the hygroscopic material to be put directly into specified drying conditions of 150°C for at least 4 hours. According to the manufacturer (6), this particular material can operate in temperatures up to 240°C in the long run and is ideal for use in high-performance healthcare applications. This is due to its "exceptional chemical resistance, outstanding wear, and abrasion resistance".

Additional KetaSpire® PEEK Specifications	
• Filament Diameter: 1.75mm • Filament Color: Beige • Density: 1.29 g/cm³* • Tensile Strength at Yield: 85 MPa* • Tensile Elongation at Break: 26%* • Notched Izod Impact: 81 J/m*	• Processing Temperature Range: 390-420°C • Recommended Bed Temperature: >200°C • Drying Conditions: 150°C for at least 4 hours • Melt Temperature: 343°C*

Chapter 3: Familiarisation and Initial Investigation

3.1 Introduction of The Early Prototype

The first iteration prototype is a modification of Velleman's K8200 printer. The upgrades were implemented by two project students last year, and Table 6 depicts some of the changes to the specifications after an enclosure was added.

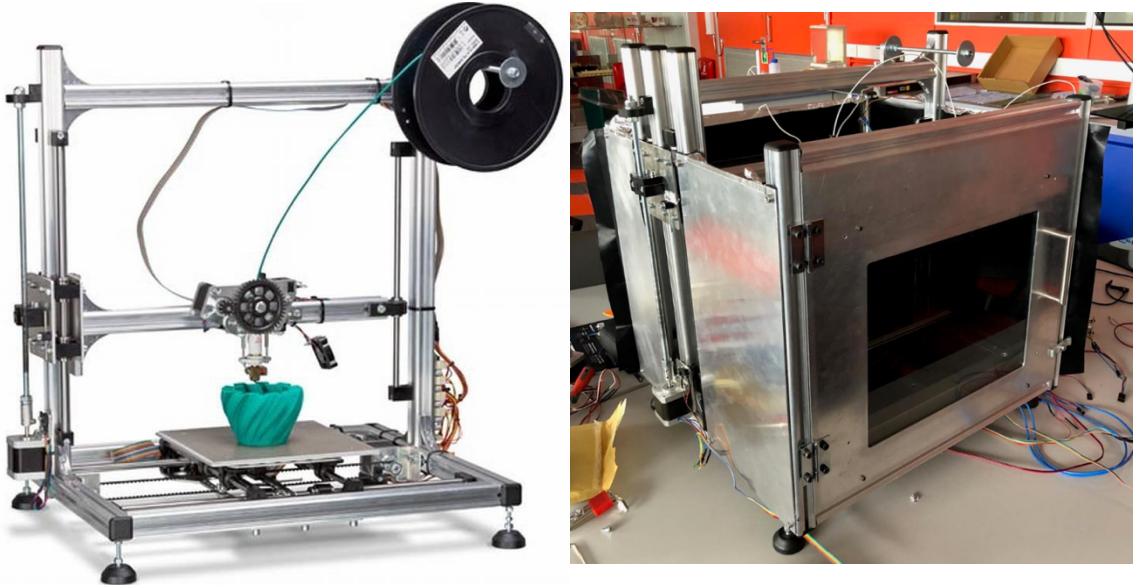


Figure 22 - Left: Original Velleman K8200 Design. Right: Early prototype of modified design with heated chamber.

Table 6: Specifications of the Original Velleman K8200 vs The First Iteration Prototype

	Original Velleman K8200 (35)	First Iteration Prototype
Model	K8200	Custom Prototype
Price	£300.00	£711.80
Build volume (mm ³)	200 x 200 x 200	190x150x180
Max. extruder temp.	345 °C	450 °C
Max bed temp	60 °C	100 °C
Heated Chamber	No	Yes

The early prototype (Fig 22) consisted of various notable features, including a 2mm thick aluminium enclosure lined with a layer of 25mm thick ceramic fibre blanket, a viewing window, and a consumer-grade heat gun to heat up the ambient temperature (Figure 23).

On top of that, a top aluminium panel in which the extruder assembly is mounted on was also added to complete the enclosure, see Figure 23. This design decision meant that chamber volume changed according to the z-axis movements.

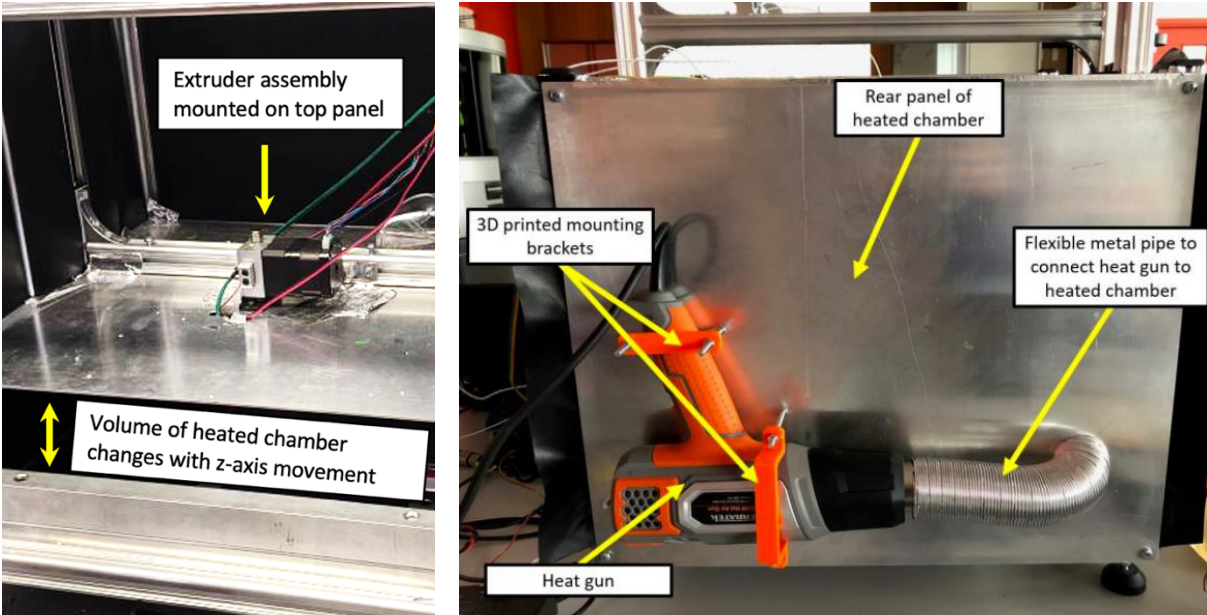


Figure 23 – Left: Top aluminium panel with extruder assembly. Right: Consumer-grade heat gun for heating up the chamber temperature.

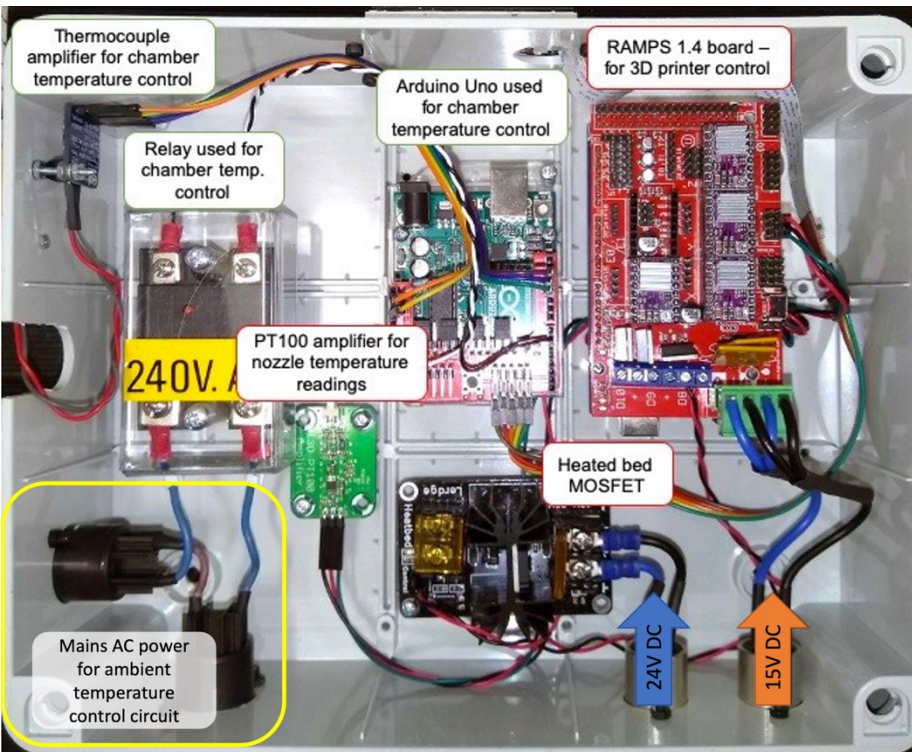


Figure 24 - Labelled electronic box showing electronics used for chamber temperature control system and 3D printer control system.

It is also interesting to note that the prototype's chamber heating system is an entirely separate system from the extrusion movement and control system run by the RAMPS controller, see Figure 24.

3.2 Identified Problems and Solutions

3.2.1 PAT Test Failure

Prior to starting the experimental stage of the project, the lab technician from the additive research lab requested for the machine to be PAT tested for safety reasons. Previous project students were also advised to complete the PAT test, however, due to the time constraints, the machine was never PAT tested. Unsurprisingly, the machine failed the PAT test mainly due to the unsecured circuit boards and exposed live terminals.

As a result, the project was put on pause and the external power supplies were confiscated until the following tasks were completed.

- *Untangle all wires into separate runs possibly with cable ties.*
- *Secure all circuit boards and relays to the base of the enclosure*
- *Fit insulated cover over solid state relay to prevent accidental touching of live terminals.*
- *Ensure all 20 amp wiring terminations are securely tightened.*
- *Make slots in enclosure so that the low voltage wires can fit in with the lid attached.*
- *Separate low voltage wires from mains wiring.*
- *Find the lid to the enclosure and fit it in place.*

To secure the circuit boards into the box, the wires had to be disconnected.

However, as no wiring diagrams were provided, the wires were labelled and a new diagram (Figure 26) was created and updated

throughout the project. After the adjustments, see Figure 25, the machine successfully passed the PAT test.

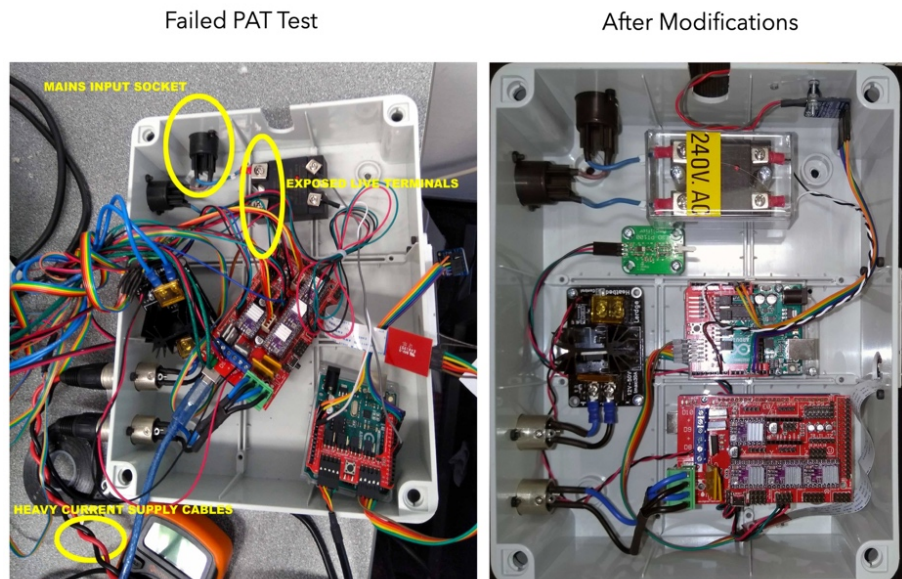


Figure 25 - Before and after the PAT test adjustments.

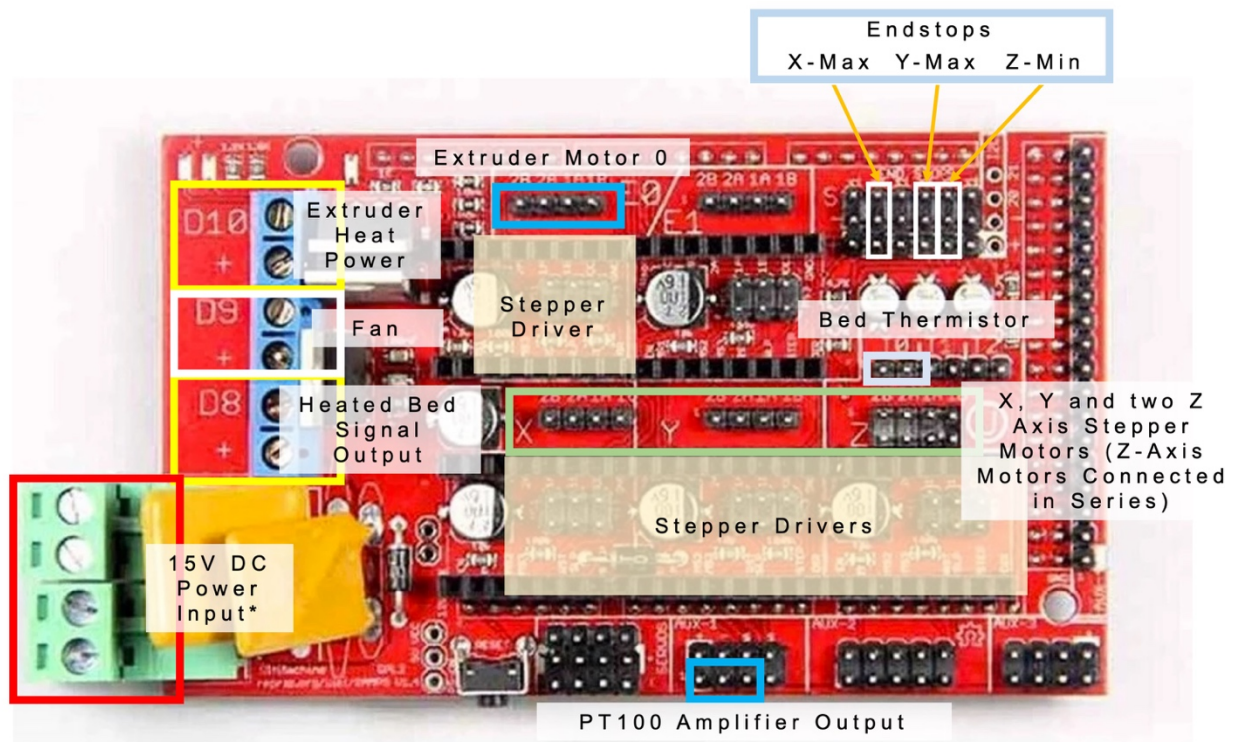


Figure 26 – Updated RAMPS 1.4 Wiring Diagram for the Loughborough University's Custom PEEK 3D Printer

3.2.2 Malfunctioning build plate

The build plate was malfunctioning as it did not heat up. This was a big problem as the heated bed is crucial in enabling for bed adhesion and preventing the components from warping, especially for high temperature materials.

The source of the problem was narrowed down after the multimeter identified that no voltage was coming out of the D8 port, therefore suggesting that it is most likely not the PCB board's fault (see Figure 27). Then, by examining the circuit it was found that the thermistor used for the bed was not connected properly. This disabled the build plate from heating up, as the firmware prevents signals from being sent if a temperature is not detected or if the temperature is out of the predefined range.

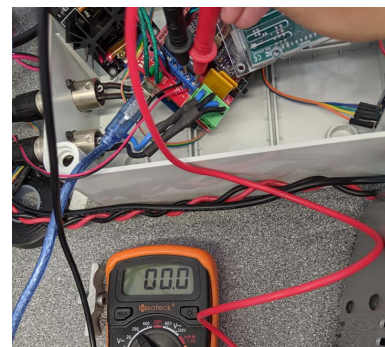


Figure 27 - Using a multimeter to inspect voltage output from RAMPS D8 Port

3.2.3 Wire detached from the PT100 temperature sensor cartridge

Another problem that prevented the machine from working was the damaged PT100 sensor. Due to the frail wiring and weak connection, one of the wires got disconnected from the cartridge as seen in Figure 28. As there was no way to fix the PT100, a replacement part was purchased from the E3D website at a cost of £15.

The new PT100 sensor, see Figure 28, also came with a detachable connector towards the cartridge end to allow the sensor to be easily disconnected for hot end disassembly.

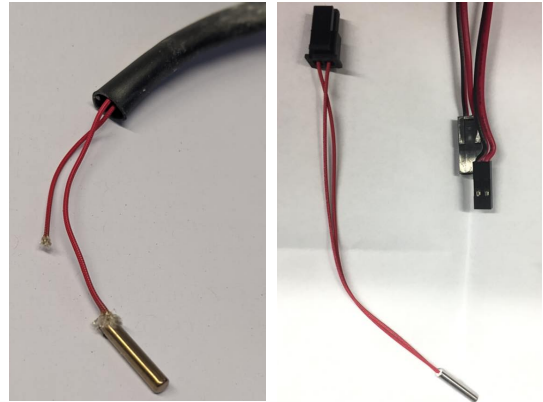


Figure 28- Left: The old PT100 sensor detached. Right: The new PT100 replacement.

3.2.4 Miscommunication between the stepper motors and microswitches

Large vibrations were produced as the stepper motors continued to attempt to move the bed beyond the physical boundaries of the 3D printer. The identified problem was that the X and Y microswitches were not triggered even when the bed was at its limit, pressing down the arms of the microswitches. The status of the endstops were checked using the M119 g-code command (Figure 29). At first, both x_min and y_min returned 'open' even when the microswitches were pressed; this indicated that the signals from the microswitches were not sent/received.

```
>>> M119  
SENDING:M119  
Reporting endstop  
status  
x_min:  
TRIGGERED  
y_min: TRIGGERED  
z_min: open
```

Figure 29 - Results after the microswitches were reconnected.

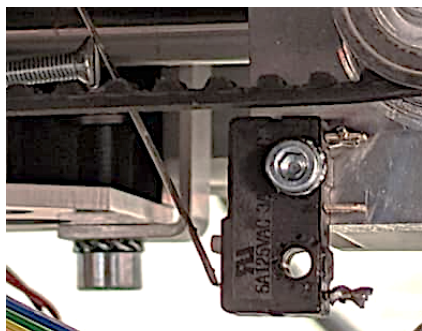


Figure 30 - No wires attached to the x-axis microswitch.

By removing the bellow for a closer inspection, it was discovered that the x-axis microswitch had no wires attached to it, as shown in Figure 30. One wire from the y-axis microswitch was also disconnected. Once the wires were reattached and soldered to the endstops, the system was able to register the signal and stop the bed before it hits the edge of the printer, hence stopping the unwanted vibrations.

3.2.5 The bed going in the opposite direction to the controller commands

As the microswitches are fixed to the maximum ends of the x and y-axes, see Figure 31, but are programmed as x_min and y_min, the coordinate system is flipped (e.g. commanding the bed to move right moves the bed left when observing from the viewing window).

To resolve this issue, x_min and y_min were reprogrammed to x_max and y_max, respectively. This was done by commenting/uncommenting relevant lines of code in the Configuration.h file, as seen in Table 7.

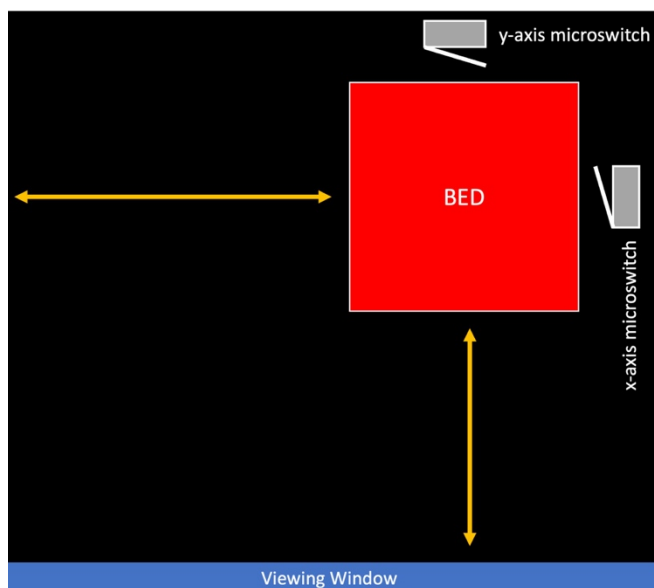


Figure 31 – Schematic diagram depicting the microswitch setup for the custom 3D printer (top view).

Table 7: Change made to the Marlin Configuration.h file.

Line #	Original Default Settings	Changed
510	#define USE_XMIN_PLUG	//#define USE_XMIN_PLUG
511	#define USE_YMIN_PLUG	//#define USE_YMIN_PLUG
512	#define USE_ZMIN_PLUG	#define USE_ZMIN_PLUG
513	//#define USE_XMAX_PLUG	#define USE_XMAX_PLUG
514	//#define USE_YMAX_PLUG	#define USE_YMAX_PLUG
515	//#define USE_ZMAX_PLUG	//#define USE_ZMAX_PLUG

After the new configuration files were flashed onto the Arduino board, the X & Y endstop wires also had to be reconnected on the RAMPs 1.4 board to the positions as shown in the wiring diagram in Figure 26.

3.2.6 Cooling fan not switching on

Custom buttons (Figure 32) were created on Pronterface to switch the fan at the hot-end on and off, as the g-code commands produced by Cura did not seem to trigger the fan for cooling. G-code command used for the 'on' button: M106 S255. G-code command used for the 'off' button: M107.

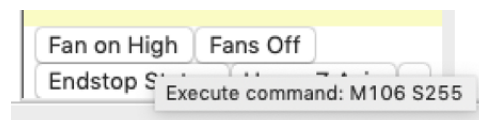


Figure 32 - Custom buttons created on Pronterface to manually switch the fan on/off.

3.2.7 Extruder not extruding

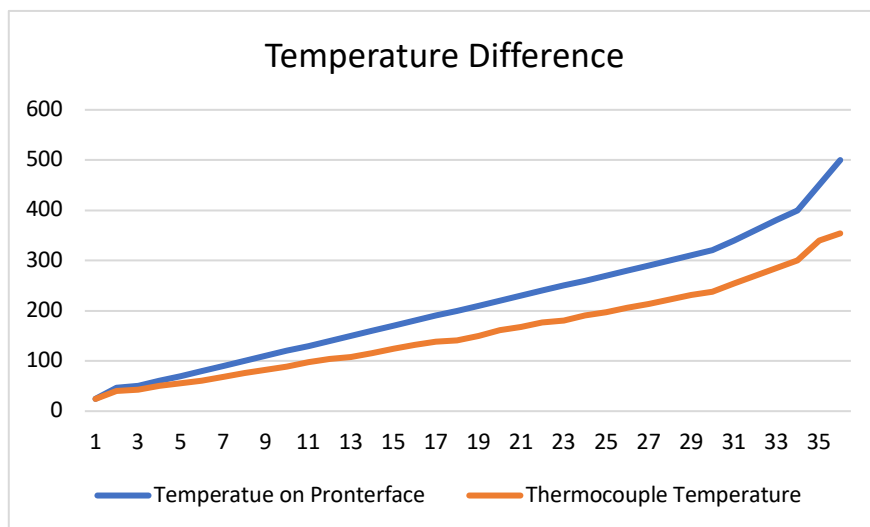


Figure 33 - Difference between the displayed temperature and the actual temperature

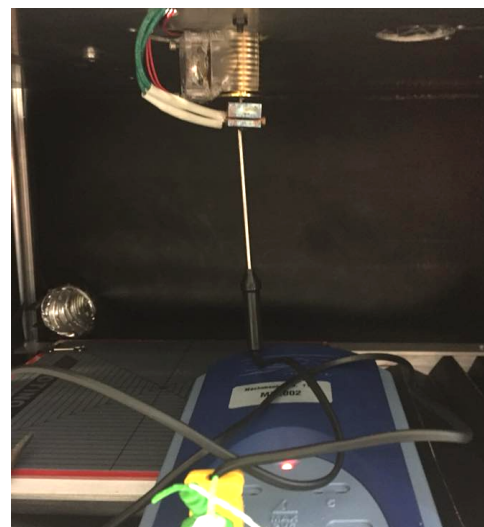


Figure 34 - Using Type K Thermocouple and PicoLog to attain actual hot-end temperatures.

By taking a methodical approach and eliminating possibilities through testing, the cause of this problem was narrowed down to the possibility that Pronterface was not showing accurate readings. To test this hypothesis, a type K thermocouple was used to attain the actual hot-end temperatures (Figure 34). The results were compared to the values shown on Pronterface. Figure 33 shows the drastic difference in temperatures especially as the temperatures increased. To solve this problem, PID auto tune was carried out and the results were verified again with the k-type thermocouple.

3.2.8 Lack of documentation/Wrong information provided in previous project reports

Previous students have already made changes to the original Marlin files. However, through their reports, the documentation of the changes to the code seemed incomplete. To solve this problem, the author contacted both previous project students to obtain the updated Marlin configuration files and the BangBang Arduino code used for activating the chamber heating system. The previous project students also shared with the author about the things that weren't documented in their reports.

3.2.9 Layer shifting

Figure 35 depicts one of the first test prints produced on the custom 3D printer. While there are other problems that need to be addressed based on the quality of this test print, the most urgent concern lies with the drastic layer shifting in the x-axis.

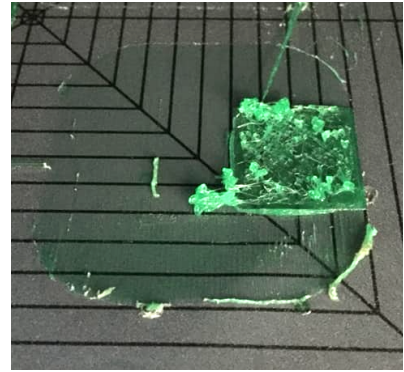


Figure 35 - Layer shifting of the first layer after the raft was built.

According to the troubleshooting section of the literature review, layer shifting can be caused by excessively fast print speeds and/or loose timing belts on the x and/or y-axes. Therefore, to tackle this problem, the speed in the X and Y directions was decreased to 3000mm/min on Pronterface. As that did not fully solve the problem, the timing belts were inspected and the x-axis timing belt was tensioned accordingly. Moreover, the shafts that support the bed in the x and y-axes were also loosened to realign the bearings to reduce unwanted friction.

3.2.10 Difficulty removing the part from the build surface

A second test print was printed successfully without any layer shifting issues, however, the YONITO build surface made the PLA part really challenging to remove. Hence, it was decided the YONITO surface should be replaced with a glass bed, at least temporarily, to solve the problem. The borosilicate glass bed came with the original K8200 kit.

3.2.11 Bed not levelled as there were different sized gaps between nuts (Fig 36)

To solve this problem, everything was tightened until there are no gaps in between the nuts. In addition to printing bed levelling square patches to identify unlevel corners, a DTI dial indicator (Figure 37) was also used to check for the levelness/flatness of the surface. With the glass surface, the build platform is relatively level.

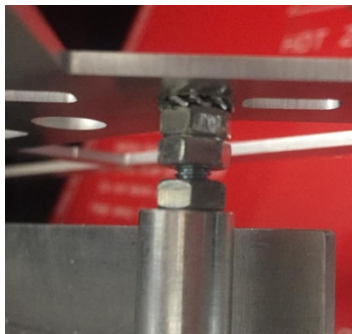


Figure 36 - One of the four corners of the bed mount.



Figure 37 - DTI indicator checking for unlevel surfaces

3.3 General Observations

3.3.1 Lack of Precision

Overall, the system lacks precision and accuracy, especially in the z-axis. Firstly, due to the loose tolerance of the screw holders, the M3 screws often tilt and miss the arms of the microswitches, as seen in Figure 39. This may damage components if the stepper motors continue to operate when the hot-end or bed are at their limits.

Secondly, because the z-axis screw often comes in contact with the z-axis microswitch at different angles, it is difficult to keep to gap between the bed and the nozzle constant. The current system is also very time-consuming and isn't very accurate and repeatable. As seen in Figure 40, the gap between the nozzle and the bed is determined using the popular paper manual bed-levelling technique. Therefore, it is recommended that the modifications should include a more reliable bed-levelling technique.

It has also been observed that the current z-axis threaded rod is stamped, therefore, the precision is unknown. However, typically, threaded rods have much less precision than rolled or machined lead screws.

3.3.2 Lack of Points of Contact for Microswitch and Motors

A new motor bracket was suggested by the supervisor as a potential source of improvement, as currently, the motor is only mounted to the printer at two points (see Figure 41). Moreover, it was observed that all the microswitches are currently mounted with one point of contact. This makes them susceptible to rotational movements. Hence, this may affect the reliability of endstops.

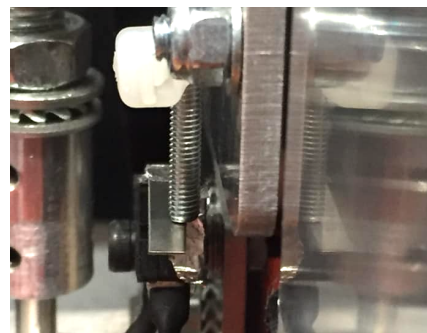


Figure 39 – Top: z-axis levelling screw when coming in contact with the z-axis endstop. Bottom: x-axis microswitch trigger.

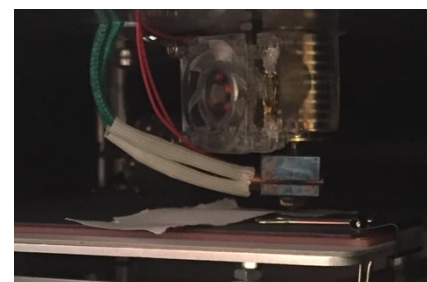


Figure 40 - Manually levelling the bed with a piece of 0.1mm thick paper and by adjusting the z-axis levelling screw.

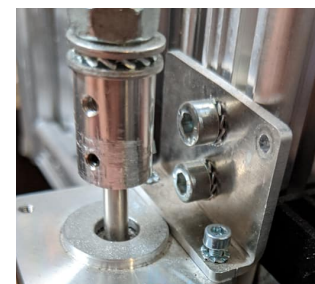


Figure 41 - Motor bracket with only 2 point of contact.

3.3.3 Missing Door Lock

Without the door securing mechanism, the door is constantly half-open, potentially exposing hot air to the surrounding environment. This not only is a health and safety issue for the operator, it also affects the temperature and temperature fluctuations within the chamber.

3.3.4 Poor-Quality Prints Produced

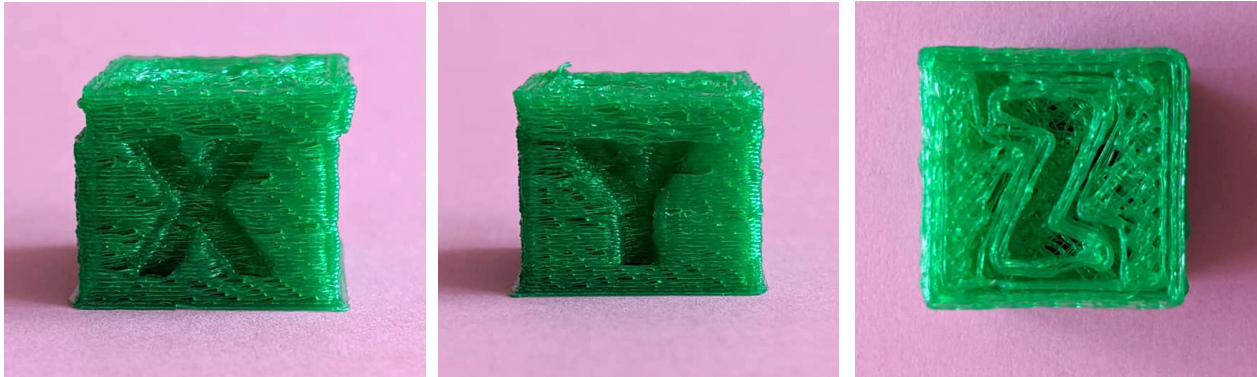


Figure 42 - First complete print produced with PLA (before tensioning of the x-axis belt).

For testing, PLA was used due to the high cost and limited amount of PEEK available. Figure 42 depicts the one of the first completed samples before any modifications were made to the prototype. Layer shifting can be observed in the x-axis, and the print showed signs of under extrusion. The 20x20x20 cube also measured 17x17.3x18 (X, Y, Z). Hence it is highly advised that all the axes, as well as the extruder, should be recalibrated.

3.3.5 Deformation of PETG Corner Mounts

The enclosure was fitted with a viewing window. However, it was observed that the mounts supporting the four corners of the glass window were printed out of PETG, and hence have showed signs of deformation (see Figure 43) under the influence of the high chamber temperatures.

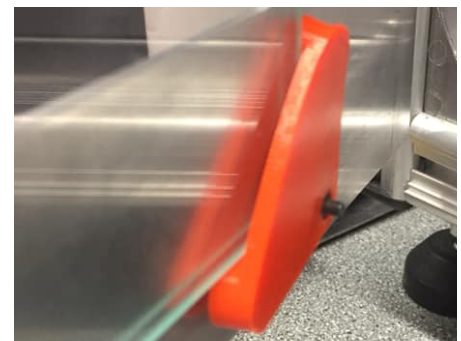


Figure 43 -PETG corner mounts started to deform caused by the heat of the enclosure temperature.

3.3.6 PTFE liner used in the bellow system easily ripped/torn

The bellow system, Figure 44, was developed by one of the project students last year and acts as a clever adaptable insulation solution for the base of the chamber. However, as the previous project student used a steel ruler to go over the folds to create the desired geometry, the top and bottom edges of the bellow are weak and can be easily torn. This resulted in some noticeable gaps within this insulation feature.



Figure 44 - Bellow system as an adaptable insulation solution.

3.3.7 No SD card or WIFI system

Currently, the machine requires plugging in the laptop to connect to Pronterface. While connecting the laptop to the printer physically is not a big issue, the issue arises when the laptop starts running out of battery. As the printer already takes up three separate sockets, the operator may find it hard to find an additional socket to power the laptop or desktop.

3.3.8 The filament contains a high moisture content

Before concluding this section of the project, PEEK was extruded as a final assessment. The extruded filament, as seen in Figure 45, exhibited common signs of a wet filament spool. These included popping and cracking sounds when extruding, uneven extrusion lines and severe blobbing on the surface of the extruded line. The moisture most likely have seeped into the filament during the time it was being stored in a plastic zip-lock bag without any silica gel packs.



Figure 45 - First time extruding PEEK filament. The surface of the extruded line showed severe signs of blobbing and the extruded filament is abnormally wavy.

Chapter 4: Design Decisions and Manufacturing Upgrades

4.1 Introduction

After the initial investigations and assessments were carried out, it was decided that modifications have to be made in order to bring the print quality to a satisfactory level. To aid planning, a house of quality was created to prioritise engineering parameters to focus on. However, the house of quality was soon deemed insufficient and unhelpful as many tasks must happen simultaneously due to time constraints and most importantly, the house of quality does not list out the options for a specific problem such as bed levelling. Hence, it was decided that a morphological chart (Table 8) should be implemented to organise the available options to aid design decisions.

4.2 Safety Improvements

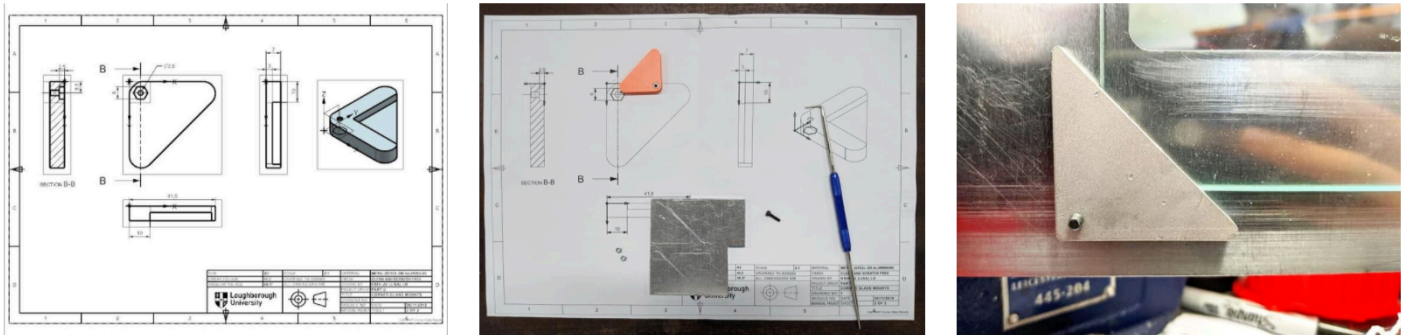


Figure 46 – Remanufacturing the corner mounts in aluminium. Corners rounded for safety considerations.

Issues related to the safety of the machine were prioritised. Therefore, before starting any other modifications, the corner mounts were recreated and remanufactured used aluminium, see Figure 46. This will ensure that the corner mounts will not further deform and drop the glass window during further testing. Another feature that was added on was a door securing mechanism. The door securing mechanism uses a ball catch and required the entire front frame to be disassembled for installation.

Table 8: Morphological Chart for Design Changes. (Chosen options are highlighted in orange).

Ref #	Category	Original Setup	Option 2	Option 3	Option 4	Option 5	Option 6
M1	Bed levelling	Manual levelling (via limit switches by adjusting screw height)	(Removable) mechanical sensor	Piezoelectric sensor	Inductive sensor (only detect metal)	Optical sensor: e.g. infrared probe	Capacitor sensors
M2	Heated Chamber insulation (panels)	Ceramic fibre blanket in between PTFE and 2mm aluminium sheet. No insulation for door.	PIR insulation panel for door and top surface of the printer.	PTFE lining and PIR insulation board for the top surface of the printer.			
M3	Build surface material	Yonito surface	Aluminium/ metal plate	Borosilicate glass lined with Kapton tape	Carbon fibre buildplate		
M4	Z-axis movement	8mm Thread rod	Two parallel trapezoidal lead screws connected with pulleys	Linear rails	Two trapezoidal lead screws driven by two separate motors	Ball screws	Rack and spur gears
M5	To keep PEEK dry	Plastic zip-lock bag	Dry box with Bowden tube that connects directly to direct drive extruder with silica gel	Additional built-in enclosure (like Funmat HT) to dry PEEK while printing			
M6	Prevention from PEEK clogging up nozzle	N/A	Programme in reverse extrude after print and before cooling of hot end	Using nozzle cleaning kit after each printing session			
M7	Bellow system	One layer of PTFE	2 layers of PTFE liners	2 layers of PTFE lined with ceramic fiber			
M8	(Z-axis) End stop designs to trigger microswitch	Screws attached loosely to brackets. Screws with lots of backlash	Machined/bent aluminium bracket that attaches to bearing housing on the side.	3D printed bracket for the screw with tighter clearance (less backlash)	Adjustable 3D printed bracket to replace screws entirely		
M9	GUI for Host	Repetier	Pronterface	Octoprint	LCD screen		
M10	Slicing Software	Slic3r	Simplify 3D	Ultimaker Cura			
M11	Rod Coupler	Rigid coupler specifically for M8 threaded rod	Helix couplers	Spider couplers	3D printed couplers	Aluminium alloy rigid couplers	
M12	Heat break	Stainless steel	Grade 5 titanium				

4.3 Justifications for Modification Decisions

The most significant design modification decisions are discussed thoroughly in this section. Justifications for smaller design decisions will be discussed in later sections.

4.3.1 Bed Levelling

While auto-bed levelling yields many benefits, manual bed levelling was still chosen. This decision was based on several considerations. Firstly, most readings of auto-bed levelling sensors are influenced by heat, so placing it in the heated chamber would be unsuitable. Moreover, mechanical sensors such as BLTouch have exposed printed circuit boards; as circuit boards are generally made of the standard FR4 glass-epoxy laminate, a material with the maximum operating temperature of 110°C, the BLtouch would need to be removable. This option was explored and a removable holder design prototype was also manufactured. However, in the end, it was decided that since the bed size is relatively small (due to the physical boundaries of the printer), and the bed is relatively flat according to the DTI dial in the assessment phase, manual levelling will still be used in conjunction with a new z-axis screw holder.

4.3.2 Heated Chamber Insulation

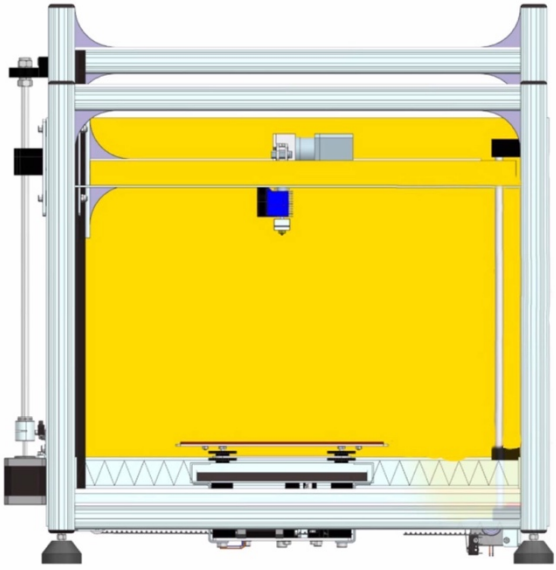
Currently, the enclosure is lined with 25mm thick ceramic fibre on the left, right and back sides. However, the top and front panels are oddly left without any insulation. Luckily, pieces of PIR insulation panels were found in the lab. As the literature review suggested that rigid PIR panels can withstand temperatures of up to 260°C, it was decided that this material would be added as insulation to the top panel as well as the door. The layer of PIR panel would sit above the aluminium panel and help prevent the rising heat from dissipating. Similarly, to prevent the door and door handle from getting too hot, a PIR insulation panel will also be secured to the door.

4.3.3 Build Surface Material

The borosilicate glass and Kapton tape combination was chosen as the build surface for 3D printing PEEK. The decision was as made as other options such as carbon fibre build plates were out of the budget range. Moreover, Kapton tape can accommodate temperatures of up to 260°C, which is much higher than the maximum achievable bed

temperature. While the author was unsure of whether the Kapton tape will help adhere the extruded PEEK onto the build plate, as previous project students disclosed that it was notoriously difficult to get the material to stick to the build surface, the author thought it was worth a try as Wang et al. (36) demonstrated that it was possible to get their PEEK samples to adhere to the Kapton tape surface.

4.3.4 Z-Axis Configuration

Table 9: The Top Three Z-Axis Configuration Options Considered	
Option 1: New Lead Screw <i>Description:</i> New lead screw with original cantilevered-like design. + Much easier to implement than other options. Only the coupler and anti-backlash nut holder need to be replaced. - Does not provide as much stability as other options.	
Option 2: Double Motor <i>Description:</i> New lead screws and stepper motors on each side + simpler to design and implement than pulley system + cheaper to implement than closed loop belt system + reduced wear on mechanical components + more stable than option 1. - Could potentially face problems with stepper motors out of sync and skipping steps.	

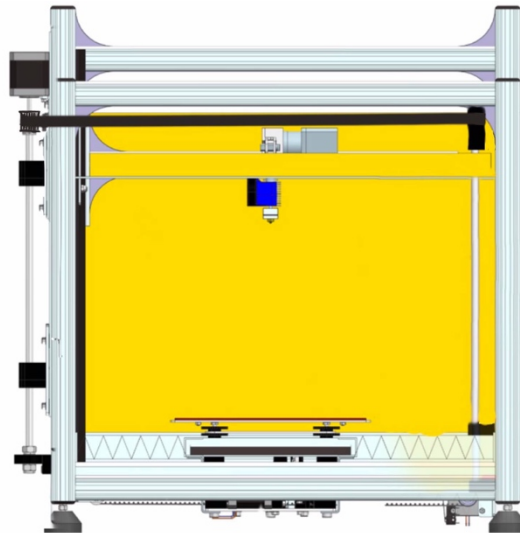
Option 3: Timing Belt Synchronisation

Description:

New lead screws with pulleys and timing belt to drive the screw on the other side (i.e. only one z-axis motor is used for both sides).

+ both sides are always in sync when installed correctly.

- more engineering & components required (e.g. pulleys, timing belt, tensioner, support bearings.)
- more power required by stepper motor to drive timing belt system.



The early prototype used an 8mm threaded rod that was in a slightly bent and had an unknown precision. Hence, it was decided that a lead screw should replace the threaded rod as an upgrade to the printer.

However, apart from replacing the threaded rod with a lead screw, new z-axis configuration options, see Table 9, were also considered in order to further improve the accuracy and reliability of the z-axis.

Option 2 from the three considered options was chosen as most of the parts required for the upgrade, such as the NEMA17 motor and z-axis bearing housing, were already available. Moreover, while option 3 may provide the most reliability due to the perfect synchronisation, it was the most time-consuming to implement.

Lastly, a TR8 2mm lead screw was chosen, as it was calculated that the single start lead screw with an 8mm diameter and 2mm pitch, along with the Nema17 motor, would be able to achieve 0.01mm movement per step. This is satisfactory for creating accurate PEEK prints. It should be noted that the chosen lead screws have a 0.1mm per 300mm lead accuracy.

4.3.5 Z-Axis Endstop Triggers

The loose z-axis screw holder was an issue that was addressed earlier in the assessment section. To solve this problem, it was decided that a new screw holder should be printed. This solution was chosen as opposed to machining an entire bracket with adjustable features simply because it is the fastest and most effective solution.

Following this decision, a compatible screw holder design on Thingiverse (37), see Figure 47, was found.

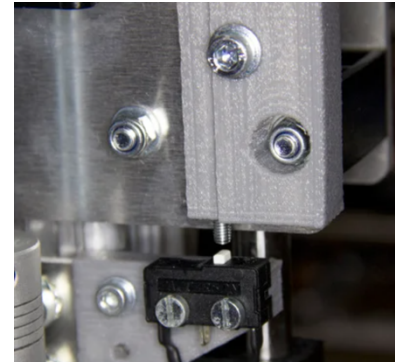


Figure 47 - Screw holder with a much tighter tolerance.

4.3.6 Heat Break

The stainless-steel heat break received at the start of the project was observed to be bent and on the brink of snapping. As another heat break needed to be purchased, a titanium heat break was selected. According to E3D (38), the improved internal surface finish will help to reduce extrusion force and improve reliability on retractions, and more importantly, the new heat break would have a better performance and reliability in high temperatures. This is because the material is exceptionally strong and has a lower thermal conductivity than stainless steel, allowing the cold side of the hot end to keep cool. This creates a more sharply-defined melt zone within the hot side, creating greater extrusion control.

4.4 Manufacture, Installation & Assembly

4.4.1 Background

Before the new upgrades can be installed, the enclosure, square aluminium extrusions, motor mounts, bellows, door and guiding rods all had to be disassembled (Figure 48). To accommodate for a new z-axis configuration, the original chamber wall, top panel and structural arrangements were modified.

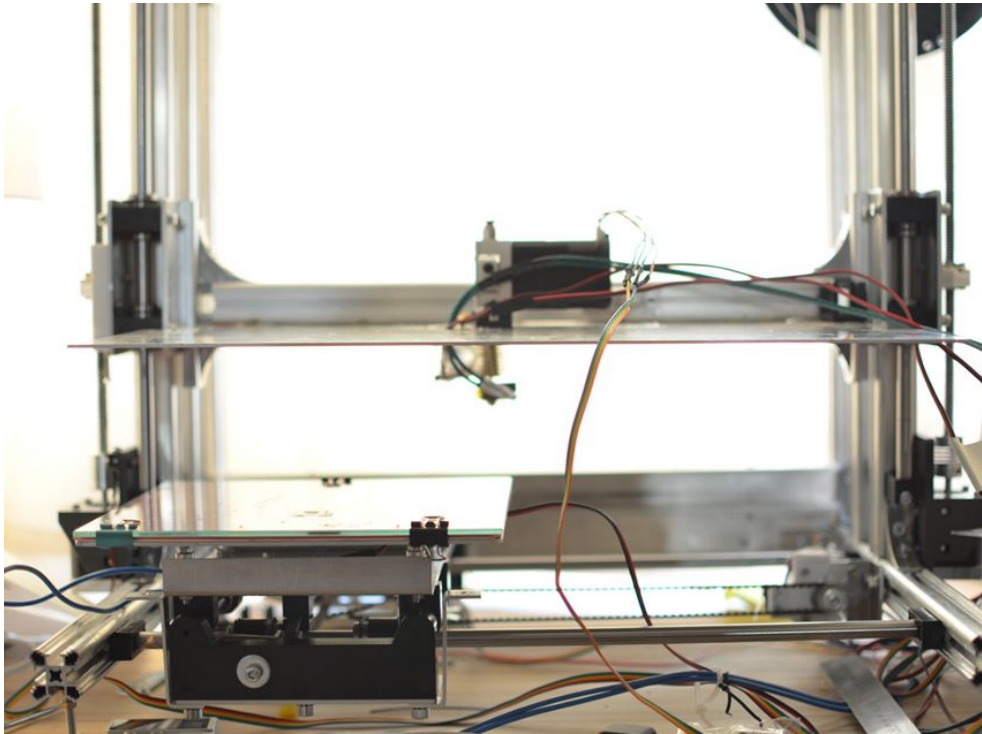


Figure 48 - Printer disassembled in order to install the new upgrades.

4.4.2 Upgrades for Accuracy Improvement

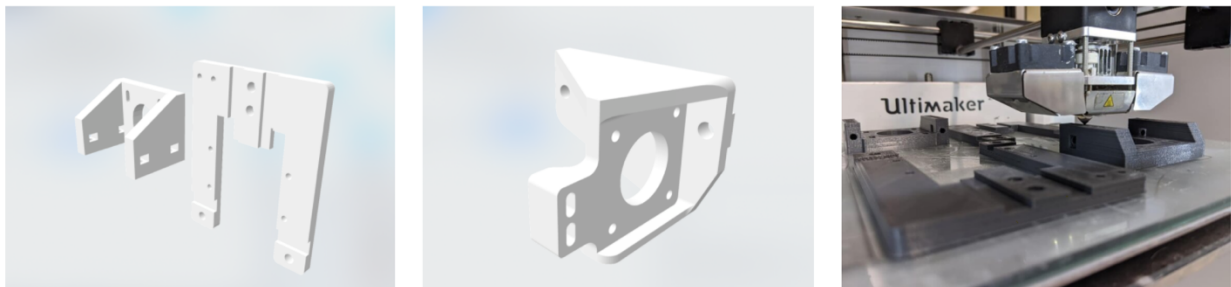


Figure 49 - Motor brackets with 4 points of contact. Left: z-axis bracket. Middle: X-axis bracket. Right: 3D printing the brackets.

Two motor bracket designs were carefully chosen. The z-axis motor bracket (Fig 49), sourced from (39), features four mounting points for the motors, as well as two mounting points per microswitch. The x-axis motor mount, sourced from (40), also

features two mounting points for the microswitch. These designs were printed on the Ultimakers in Wolfson School in PLA with 80% infill ratio. The prints were surprising strong, and most importantly, the brackets gripped onto the motors tightly without any showing problems.



Figure 50 - Replacing the original M8 nut with an anti-backlash nut.

To translate the rotary motion to a linear motion, the anti-backlash nut also had to be implemented. To do so, a z-axis anti-backlash nut holder was designed in CAD and printed in PLA as shown in Figure 50.

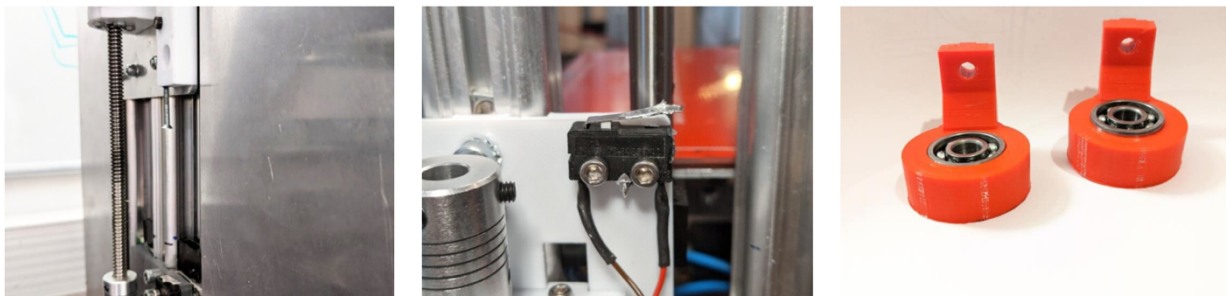


Figure 51 - Left: Assembled z-axis configuration. Middle: microswitch with snapped arm. Right: M8 bearing holder for lead screw alignment.

To complete the z-axis upgrade, the helix rod couplers were installed with the lead screws onto the stepper motors. Helix rod couplers were chosen as they are easier to install than rigid couplers (since the alignment on this printer isn't great) and were more readily available than spider couplers. Bearing holders from (41) were also printed to help with the alignment of the lead screws. Last but not least, the arm of the z-axis microswitch was trimmed down as the long arm was no longer needed, see Figure 51.

4.43 Final Components List and Total Cost

The final cost of the newly modified system is £873.

Subsystem	Component	Cost (£)
Base	Velleman K8200 Kit	300
Printhead Modules	E3D V6 Gold Edition Hot end	104.4
	E3D V6 Plated Copper Heat block	23.4
	E3D PT100 sensor and amplifier	30.6
	E3D V6 Titanium Heat Break (1.75mm)	17.04
3D Printer controller	RAMPS 1.4 and Arduino 2560	60
Heated Bed	MK2B PCB Heat bed	15
	Heat bed power circuit	6
	24V 15A DC power supply	17
	E3D Thermistor cartridge	5.4
Electronics Enclosure	Temperature controlled enclosure	150
Temperature controller	Heat gun	17.99
	Metal flexi-hose	3.35
	Elegoo - Arduino Uno R3 Starter Kit	7.99
	Solid-state relay	12.17
	MAX31855 thermocouple amplifier	12.76
	Type-K thermocouple	N/A
Heated chamber	2mm aluminium panel enclosure	16.62
	Ceramic fibre insulation blanket	9.79
	Glass panel	15.99
	PTFE liner	4.32
Bellow System	U-profile extrusion	8.04
	PTFE liner	3.12
Positioning System	3ps of NC microswitches	4.56
	T8 2mm Pitch 30mm Lead Screw with Copper Nuts	9.78
	Additional NEMA 17 Motor for z-axis	7.86
	2 x 8mm Aluminum Alloy Helix Shaft Couplers	5.49
	Additional Velleman spare parts (lead screw guide/slider, aluminium tubes)	N/A
Filament Storage (for PEEK filament)	Instant Read Hygrometer	4.85
	Filament storage box	N/A
	Total Approximate Cost of System	873.52

4.4.2 Upgrades for Insulation Improvement

Two main upgrades were implemented in terms of insulation. The first was adding on the PIR insulation panels and the second was upgrading the bellow system by doubling the PTFE layers and adding a layer of ceramic fibre in between.

Figure 52 displays the additional PIR panels added to the printer. Two additional pieces of PIR material were added to the sides to shield the PLA from the chamber temperatures. The top and door panels were cut to size and sealed with aluminium foil tape to prevent the heat from warping the material from the inside.

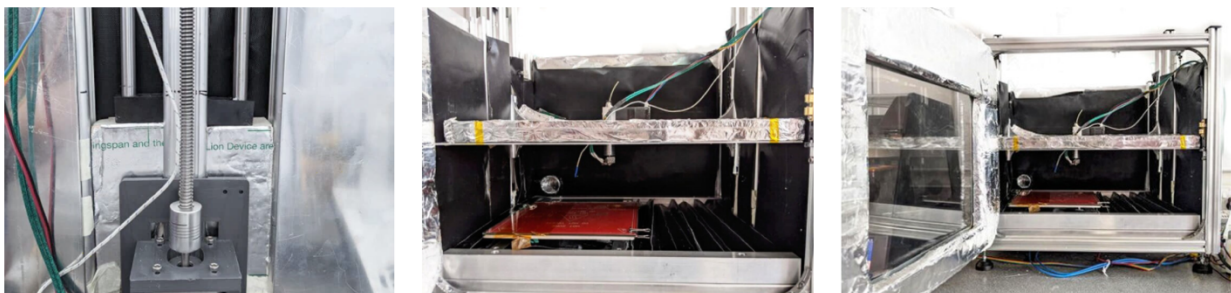


Figure 52 - Left: Guide rod moved upwards to accommodate the PIR insulation. Middle: PIR panel resting on top of the z-axis panel. Right - PIR panel cut to fit the door and its features.

The bellow upgrade was a little more complicated and time-consuming. Firstly, the left-over PTFE liner from last year was folded and combined with the original bellows. Since no additional purchase was made for PTFE liners, original bellows needed to be reused despite of some wear and tear. Secondly, a layer of ceramic fibre blanket was sandwiched in between the bellows. Finally, using a sewing machine, the edges are sewn together. Additionally, the bellows are also sewn in between the peaks, as seen in Figure 53, to still enable the natural fold.



Figure 53 – Left: Sewing the bellows together with a layer of ceramic fibre in between. Middle: Folding and doubling the PTFE layers. Right: original bellows with some gaps in between.

Chapter 5: Calibration, Testing & Printing PEEK

5.1 Preparation

In section 3.3.8, an early experiment showed that the PEEK filament was wet, causing quality problems such as severe blobbing. Hence, before attempting to print PEEK again, the roll of filament was placed into a laboratory hot-air oven at



Figure 54 - Left: PEEK filament in the oven with silica gel packs. Right: PEEK in an air-tight box with packs of silica gel and a hygrometer.

150°C for 6 hours (as specified by the manufacturer of the KetaSpire® PEEK filament).

After drying, the roll of PEEK filament was placed into a repurposed air-tight box with a hygrometer (to keep track of the level of humidity in the box) and a Bowden tube, see Figure 54. The initial idea was to suspend the PEEK filament within the box using two bearings and a shaft, then feed the filament from the Bowden tube directly to the extruder. However, due to several considerations such as where the box would be mounted and the limited project budget, it was decided that the Bowden tube system will not be implemented. Instead, the box will act solely as a storage unit.

5.2 Calibration

Calibration was needed as the original threaded rods were replaced with the new trapezoidal screws. Moreover, the assessment stage of the project indicated that calibration is needed for all the axes, as well as for the extruder to achieve a higher-quality print in terms of surface finish and accuracy.

Calibration of the Z-Axis

Using PrusaPrinters' RepRap calculator (42), the steps per millimetre for the new lead screw was attained. Then, the new steps_per_mm figure for the z-axis was inputted into the Configuration.h file, and re-uploaded to the Arduino Mega. One unexpected issue that the author faced while calibrating the z-axis was that the steps per millimetre did not seem to change even after the new configuration file was uploaded. Later, it was discovered that as EEPROM was enabled, the EEPROM had to be updated with the new configurations using the following g-code commands:

M502; read values from configuration files

M500; store values into EEPROM

Extruder Calibration

Calibrating the extruder was relatively straight-forward. The filament was loaded into the extruder and 120 mm of filament was measured and marked using a permanent marker as shown in Figure 55. After creating the reference mark, the following g-code command was sent on Pronterface to extrude 100 mm of filament through the hot end: G1 E100 F100. Once the extrusion was over, the filament was measured again from the original measuring point. If calibrated correctly there should be exactly 20 mm of filament left. It should be noted that PLA filament was used for this occasion as it was the cheapest and most accessible option. The following equation was used to calculate the new rate of extrusion:

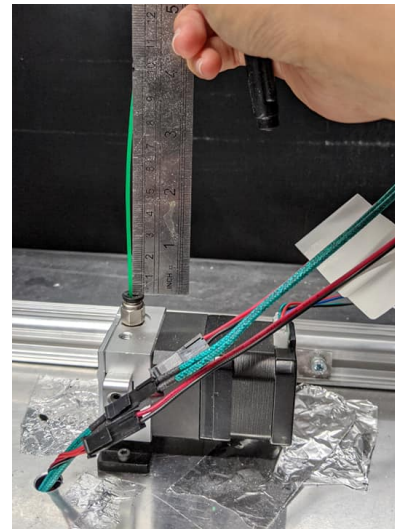


Figure 55 - Marking out the intended filament amount for extrusion.

Equation 1- Steps per millimetre calculation

$$\text{Accurate steps/mm value} = \frac{\text{Desired filament length}}{\text{Attained filament length}} * \text{Old steps/mm value}$$

The value was then updated on Marlin and uploaded. This calibration process was repeated until the extruder achieved to extrude exactly 100mm when instructed.

Calibration for X, Y & Z-Axes Using Calibration Cubes

The calibration cubes were employed to calibrate the x, y and z-axes. A 20 mm calibration cube file from (43) was downloaded from Thingiverse before the start of the test, and relevant parameters were inputted into Cura to generate a g-code file. For the calibration cube, both the travel and print speed were kept at 20mm/s to prevent layer shifting. The calibration cube in Figure 56, was printed with 99 layers without raft, at a layer height of 0.2mm and a 10% infill ratio. PLA was used due to the low shrinkage rate of 2.0-2.5%.



Figure 56 – First calibration cube

Cube 1	x	y	z
Measurement 1	19.96	20.23	N/A
Measurement 2	20.03	20.17	N/A
Measurement 3	19.96	20.2	N/A
Average	19.98	20.2	N/A

Table 10 – First calibration cube measurements

As shown in Table 10, each axis was measured three times using a calliper, and the average was taken to recalculate the new steps per millimetre value. The z-axis measurements were not taken since the cube clearly showed some z-axis defects such as skipped layer lines. Hence, only the x and y values were calibrated in the first round. The following changes were inputted into the configuration file:

ORIGINAL: #define DEFAULT_AXIS_STEPS_PER_UNIT { 128.5, 128.5, 3200, 1000}

ALTERATION: #define DEFAULT_AXIS_STEPS_PER_UNIT { 128.6, 127.2, 3200, 1000}

Before printing a second calibration cube, an investigation into the cause of the skipped layer line was conducted. It was found that the z-axis always seemed to be caught in the same position as the misalignment between the z-axis anti-backlash nut and the helix coupler were exemplified in that position. By adjusting the alignment of the z-axis and by applying more lubrication on the lead screws, the skipped layer line was eliminated and the results, as shown in Table 11, were attained. The new steps per millimetre figures were, again, calculated for all three axes, and inputted into the configuration file. After updating the firmware, the calibration section of the project was completed.

Cube 2	x	y	z
Measurement 1	19.94	20.16	19.80
Measurement 2	19.88	20.01	19.84
Measurement 3	19.98	20.27	19.78
Average	19.93	20.15	19.80

Table 11 – First calibration cube measurements



Figure 57 - Measuring the second calibration cube using a digital calliper.

5.3 Thermal Testing

Table 12: Summary of the Thermal Testing Experiments		
SYSTEM	TEST #	GOAL
Heated chamber temperature controller	Test 1	To understand of the relationship between the different heat gun settings and the temperature attainable within the maximum chamber volume of 43886.25cm ³ , as well as the rate of heating to specified chamber temperatures.
	Test 2	To examine the extent of the chamber temperature fluctuations.
	Test 3	To document the rate of cooling for chamber volume of 43886.25cm ³
Insulation	Test 4	To identify and document inadequacies in chamber insulation using the FLIR TGG167 thermal imaging camera

5.3.1 Test 1: Understanding Heat Gun Settings & Rate of Heating

Background & Methodology

As demonstrated in Figure 58, the heat gun has a dial with a total of 9 settings and a switch for alternating between the two fan speeds and power off settings. This test was conducted to understand how these settings translate to the different chamber temperatures.

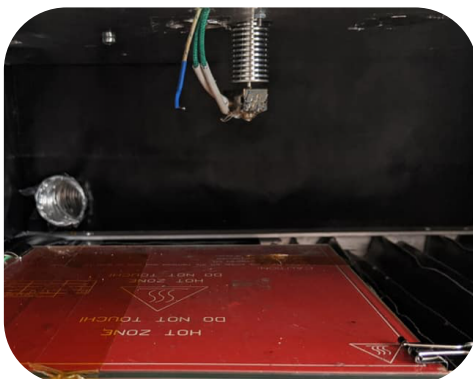


Figure 59 - Thermocouple placement

The Type K thermocouple was placed next to nozzle (Figure 59) to take in the temperature readings.



Figure 58 - Heat gun dial and fan settings switch

To control the chamber temperature, the Bang-Bang Arduino code, as seen in Appendix B, produced by Thomas Cullen (44) last year for this project was uploaded to the Arduino Uno. The

maximum temperature for this test was set to 150°C.

Moreover, the serial monitor on Arduino IDE was used to monitor the temperature readings. As the serial monitor did not have an option to export the data, the author found a way to save and separate the data columns by manually copying and pasting the temperature measurements into Text Edit, then changing the file to the csv format.

The Experiment

The experiment started with the dial setting on 4 to reduce the time needed for conducting the experiment. The author increased the dial setting incrementally whenever the temperature started to plateau. This was repeated until 150°C is reached. While two fan settings were available, only the highest fan setting was used tested as the author is interested in the fastest possible heating rate.

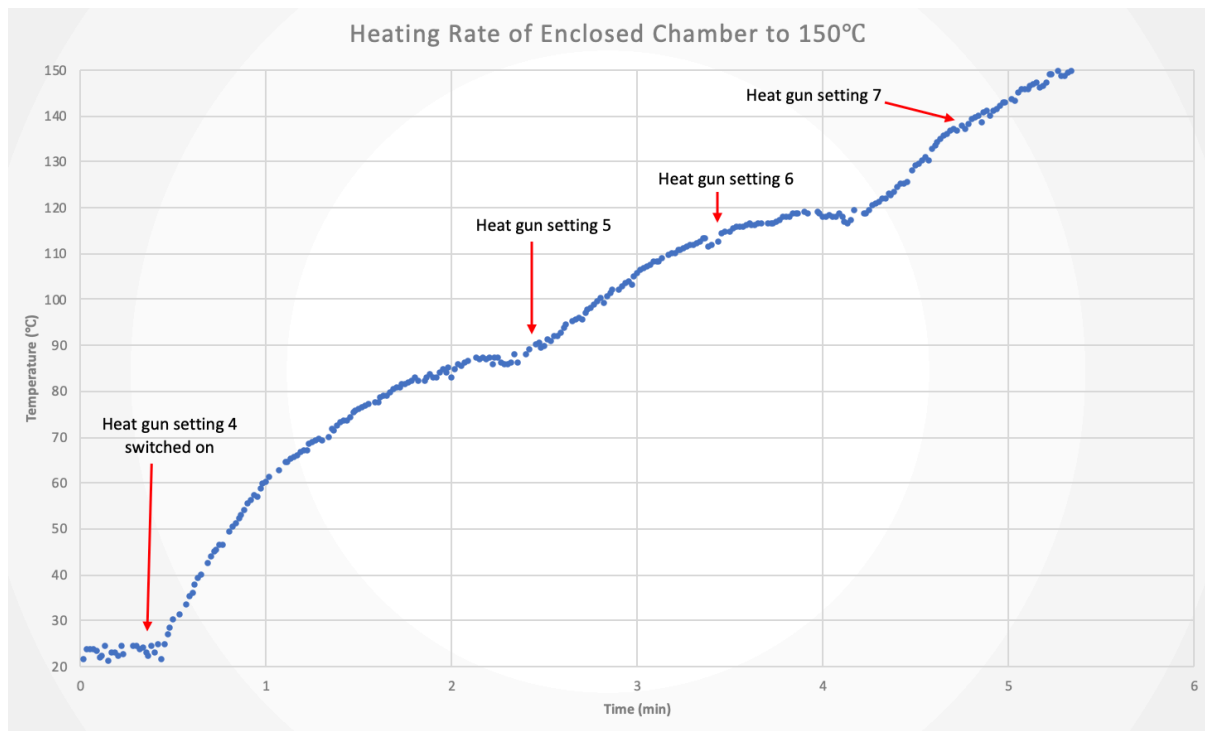


Figure 60 - Rate of heating and corresponding heat gun settings.

Observations

- Setting 4 (from T= 20s) plateau temp – ~87 C
- Setting 5 (from T= 140s) plateau temp – ~118C
- Setting 6 (from T= 207s) plateau temp – ~100 C
- Setting 7 (from T= 250s) plateau temp – ~150 C

150°C was attainable with fan speed 2 setting 7. This maximum temperature was reached within 6 minutes of starting the experiment (Figure 60).

Limitations:

As the Bang Bang approach was used, the SSR switched off the heating whenever the target temperature is reach. This caused temperature drops and fluctuations, which is not ideal for printing PEEK.

5.3.2 Test 2: Temperature Fluctuations

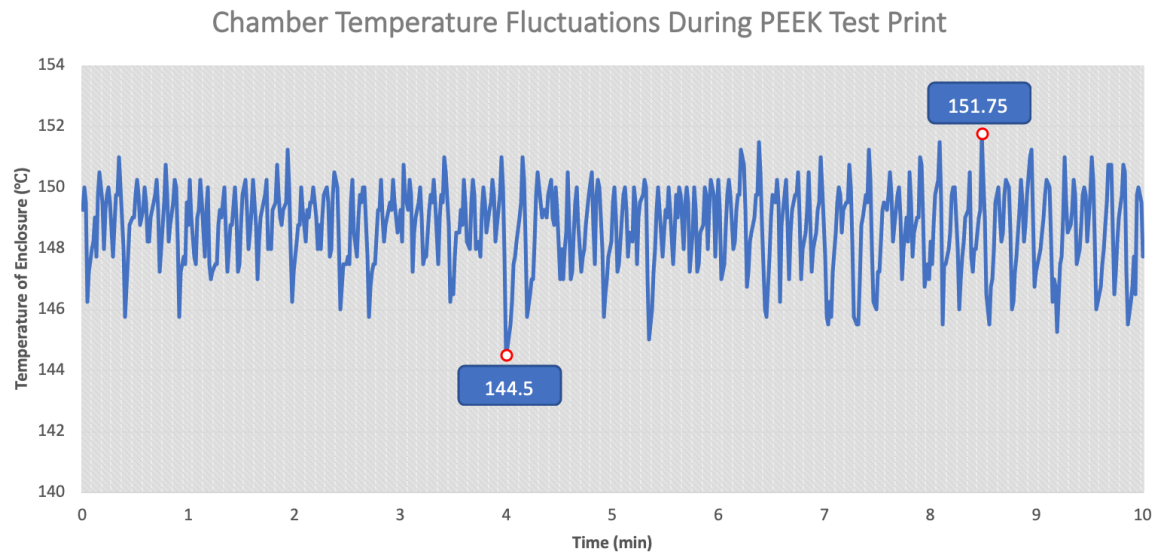


Figure 61 – A 10-minute snippet of the enclosure temperature during a test print.

Following the previous test observations, it was decided the chamber temperature fluctuations need to be examined. A 10-minute snippet of the enclosure temperature was recorded while the printer was also performing a PEEK print. As seen in Figure 61, the temperature fluctuates by 7.25 degrees, which is more than 6 degrees higher than what was recommended in the literature review (Magri et al. (15) recommended that the temperature fluctuation should be kept within +/- 1 degrees Celsius).

5.3.2 Test 3: Documenting the Rate of Cooling

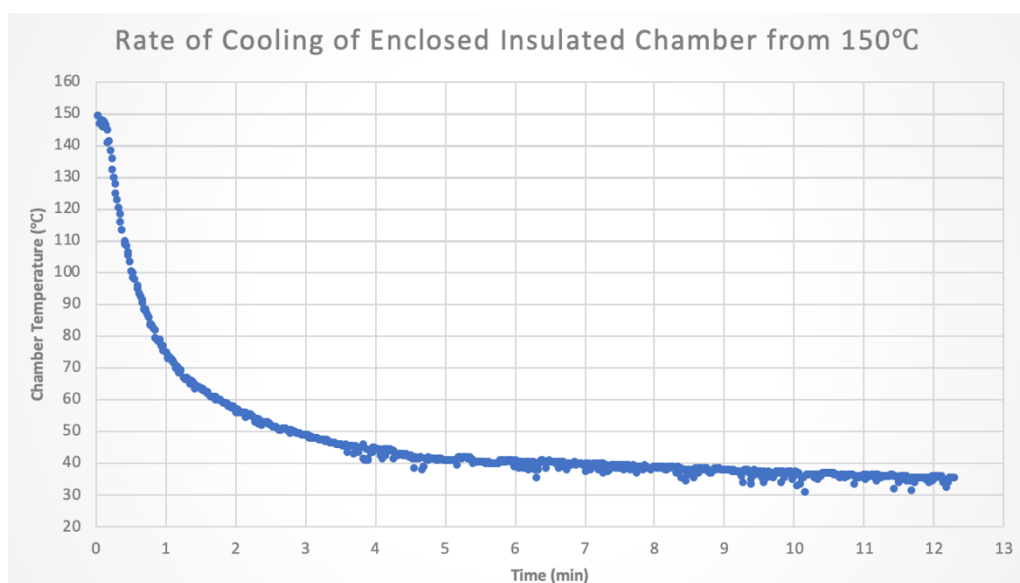


Figure 62 - Natural rate of cooling of chamber from 150°C

For this test the heat gun was switched off and chamber was left to cool on its own from 150°C. This was partly to determine the effectiveness of the insulation. The rate of cooling graph is displayed in Figure 62.

Table 13: Temperature Drop in °C per minute			
min = 1	min=2	min=3	min=4
76.5	18.75	7.25	3.75

As displayed in Table 13, the temperature dropped 76.5°C in the first minute, followed by a further 18.75°C in the second minute. This cooling rate is much higher than the cooling rate of 5-10°C/min suggested by the literature review. Hence, it is noted that cooling must be aided by continuously lowering the settings on the heat gun dial.

5.3.3 Test 4: Insulation Quality Check

To check the effectiveness of the newly incorporated insulation features and to identify any inadequacies in chamber insulation, a TGG167 thermal imaging camera was employed. The heated chamber was maintained at 150°C when the following images were captured.

Figure 63 identified that the holes cut out to accommodate the bearing housings were leaking heat. This solve this problem, additional pieces of PIR insulation panel were added to the seal the sources of heat leakage. Figure 63 also identified that the modified bellow works well as an adjustable insulation feature.

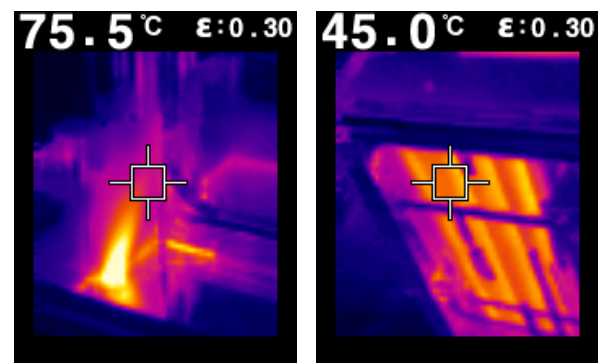


Figure 63 - Left: the left side of the top panel. Right: the bellow from the bottom.

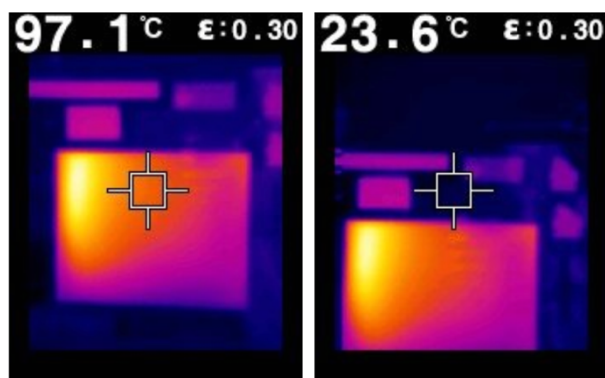


Figure 64- Door with PIR insulation

A PIR insulation panel was also added to the door during the manufacturing stage. Figure 64 confirmed that the PIR insulation for the door works really well, enabling the user now to touch the door handle without worrying about the heat.

5.4 Printing PEEK

5.4.1 Quick Extrusion Test

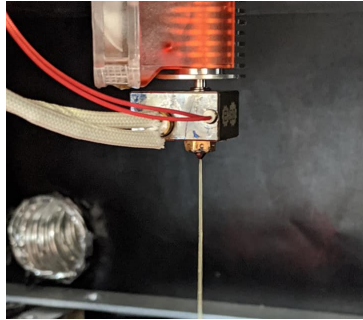


Figure 65 - Extrusion test

A quick extrusion test confirmed that the PEEK filament was sufficiently dry. As seen in Figure 65, the PEEK filament flowed effortlessly through the nozzle, without showing signs of any surface defects, such as blobbing. This showed a great improvement from the initial test during the assessment stage.

5.4.2 Printing PEEK Cubes

Table 14: Summary of the PEEK Print Trials

	Trial 1	Trial 2	Trial 3	Trial 4
Hot-end Temp °C	380			
Bed Temp °C	125	130	140	150
Chamber Temp °C	125	140	150	150
Layer height (mm)	0.2			
Nozzle Dia (mm)	0.35			
Speed (mm/s)	15	15	15	20
Raft or Brim	No	No	8mm Brim	15mm Brim
Bed lining	20mm Kapton tape lined up side by side, parallel to x-axis			

The goal of this section is to find the optimum processing parameters for this printer. Calibration cubes were, once again, chosen as the subject for the test prints. The calibration cube can give a clear indication of whether the printer can print details such as the x and y letters. Moreover, the cube geometry can enable the author to measure the shrinkage rate easily. Prior to starting the PEEK prints, manual bed levelling was performed through trial and error, as the paper technique could not be performed in the heated chamber. At the end of each print, while the nozzle was still hot, the filament was reverse extruded and stored it back in the box with the silica gel packs.

The temperatures and parameters were altered based on an iterative approach. The layer height of 0.2mm and nozzle diameter of 0.35mm was chosen as the literature review suggested that the nozzle diameter should be at least 1.5 times the layer thickness to produce parts with greater surface quality. This nozzle diameter and layer thickness combination adheres to this rule. Table 14 summarises all the relevant print parameters used by each trial.

Trial 1

Observations: Warping of right-hand corner when $Z=1.90\text{mm}$. To counteract that, bed target temperature was increased to 130°C and the heat gun dial increased to 4.5 (half way between 4 and 5), providing temps of $128\text{-}130^{\circ}\text{C}$. When $Z=2.9\text{mm}$, the peek peeled off completely.

Trial 2

Observations: When $Z=0.9\text{mm}$ the left corner started peeling. To counteract that, the bed temperature was increased to 140°C . At $Z=2.1\text{mm}$, the print got removed from bed. The reason why the author attempted to increase the bed temperature was because when printing ABS, increasing the bed temperature to counteract the curling worked. However, this method might not work for PEEK due to its high glass transition temperature.

Trial 3

When $Z=19.7\text{mm}$, the print peeled off and stuck to nozzle (Figure 66). It was observed that, due to the thin first layer, the print peeled off very easily. It was also observed that the z-axis calibration cube seemed much shorter than 19.7mm . This was thought to be due to material shrinkage.

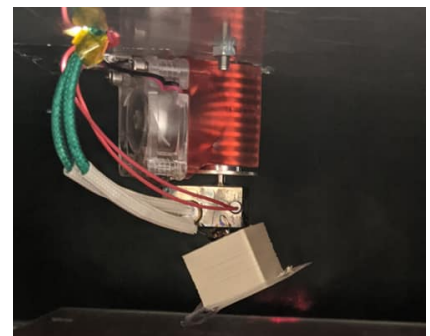


Figure 66 - PEEK cube getting stuck to the nozzle.

Trial 4

For trial 4, the brim width was increased. This resulted in a good initial layer adhesion. Moreover, the print speed was reduced when printing the letters X and Y, as it was observed that nozzle was going too fast with small movements.

The result, as seen in Figure 67, was satisfactory apart from the compressed z-axis. It was found that the squashed z-axis was caused by the motors skipping steps. As the PIR insulation panel for the door expanded in reaction to the chamber temperature, the top panel got caught and pushed the z-axis downwards. This issue was solved after the insulation panel was sanded down.



Figure 67 - First completed PEEK cube.

Chapter 6: Tensile Test Results & Microscopic Imaging

6.1 Introduction

While this section is primarily for assessing the quality of the printed product in terms of its tensile properties using this modified desktop printer, it also aims to investigate the impact of infill patterns on the tensile strength.

ASTM D368 Type V specimen was chosen given the limited timeframe of the project. A Type I specimen printed at 20mm/s would take nearly 2.5 hours to complete, whereas Type V would only take 30 minutes. Moreover, the shorter print time would enable the operator to closely monitor the print, identifying and reacting to faults when they arise.

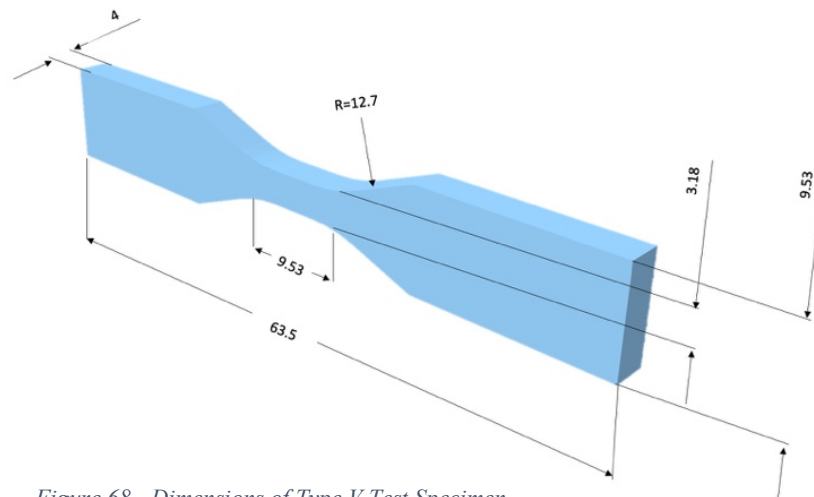


Figure 68 - Dimensions of Type V Test Specimen

Type V specimen, as shown in Figure 68, was modelled according to the dimensions provided by the standard. Furthermore, an Instron 3345 universal testing machine with a 5kN load capacity was employed in this investigation.

Unfortunately, due to the project being cut short by the unexpected COVID-19 outbreak, only the initial three test samples were produced, each with a different infill pattern and thickness. While it is not ideal to have over one independent variable between the samples and less than five test specimens per sample, the initial samples were still tested at the very last minute to collate some insight into the quality of the prints and to provide further insight to aid future work.

6.2 Preparation of Tensile Test Samples

The previous section searched for the optimum printing parameters. As Trial 4 demonstrated that its parameters can help create a successful print, the first tensile test sample was printed based on those parameters.

A couple of parameters were altered between each iteration, see Table 15 for parameters of test samples. Initially, the first sample, printed with a nozzle temperature of 390°C as a test run, produced a sample with some visible black specs along the side of the specimen. The print, as seen in Figure 69, was also paused before the print was completed due to the brim being lifted from the plate. This caused the thickness to be far thinner than anticipated.

Sample I.D.	1	2	3
Thickness (mm)	1.35	2.24	3.017
Infill Pattern, Raster Angle	Concentric	Grid -45°/45°	Line, 0°
Infill Ratio	100%		
Print speed (mm/s)	20		
Hot End Temp (°C)	390	380	
Bed Temp (°C)	140		
Chamber Temp (°C)	140-150		
Layer Height	200µm		
Wall Line Count/ Width	3 / 0.8		
Nozzle Diameter (mm)	0.35		

Table 15 - Parameters of Tensile Test Samples.

For the second test, the hot-end temperature was lowered to 380°C in hopes to eliminate black specks, a sign of material degradation within the nozzle. This worked, however, a researcher in the office recommended that the sample should have a thickness closer to the limit of 4mm. Hence, a third sample was printed with 3.2mm expected thickness. Figures 69, 70 and 71 manifests the process and outcome of each test run.

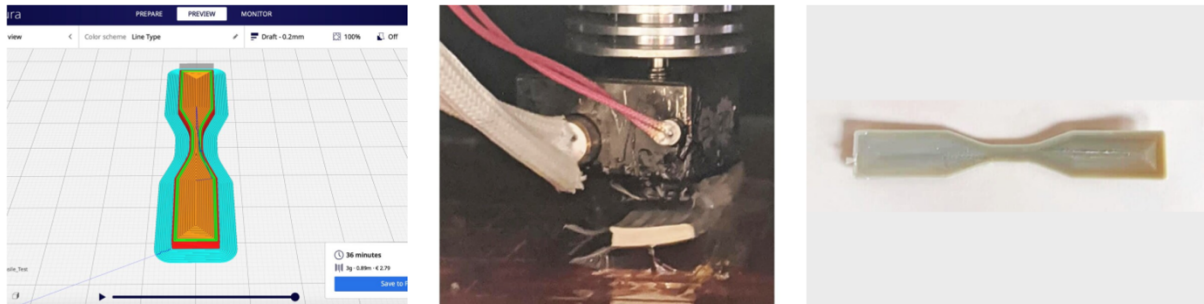


Figure 69 - Tensile test sample 1 with concentric pattern. Left: sample with brim on Cura. Middle: sample being lifted from the bed, causing the print to be halted before completion. Right: printed specimen displaying concentric infill pattern.

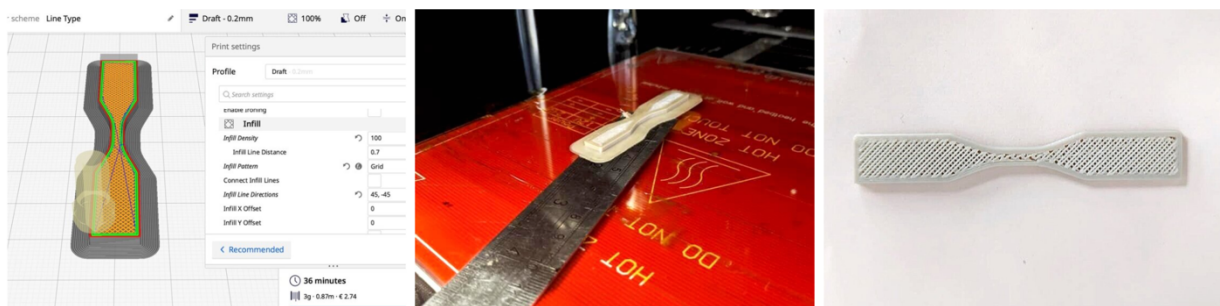


Figure 70 - Tensile Test Sample 2 with grid [-45/45°] infill pattern. Middle: printed sample with brim easily lifted from the bed after the print was completed.

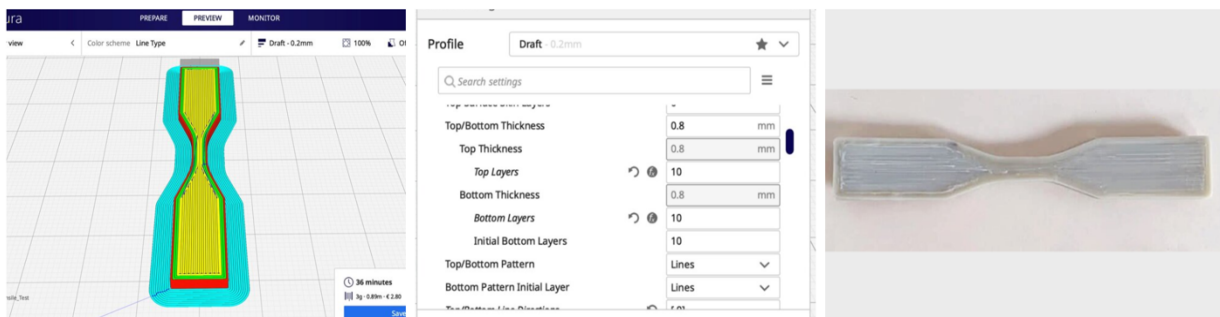


Figure 71- Tensile test sample 3 with 90° lines as infill pattern. Middle: To get a 90°-line infill pattern throughout the specimen, number of top and bottom layers were increased to cover the entire sample as no provided infill pattern matched the requirement

6.3 Tensile Testing

Prior to testing, each sample was measured with a calliper about its centre as per requested by ASTM D638. This was repeated three times per sample, and the recorded thickness for each sample is an average of the three measurements.

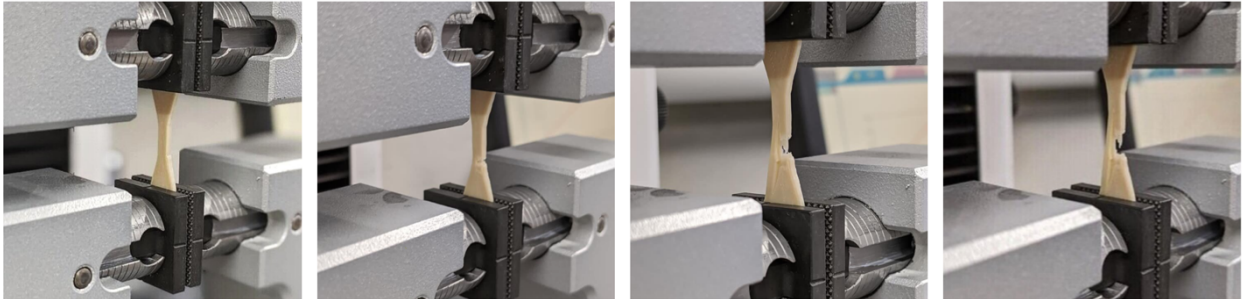


Figure 72 - Tensile test sample 1 under 5kN load at 2mm/min ramp rate.

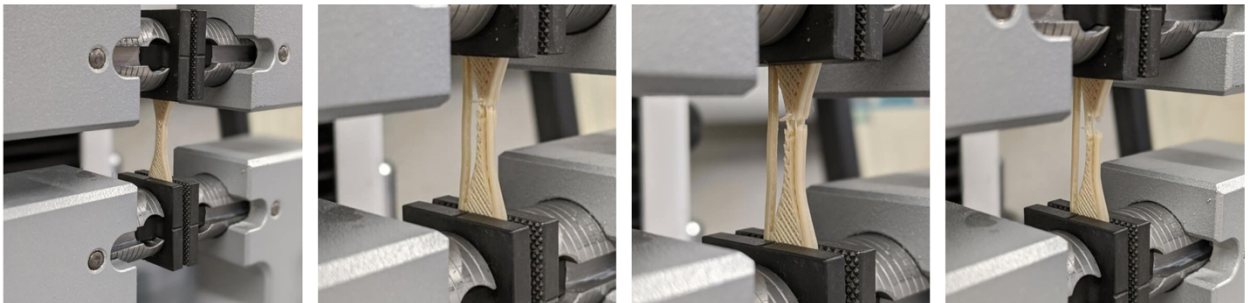


Figure 73 - Tensile test sample 2 during tensile testing.

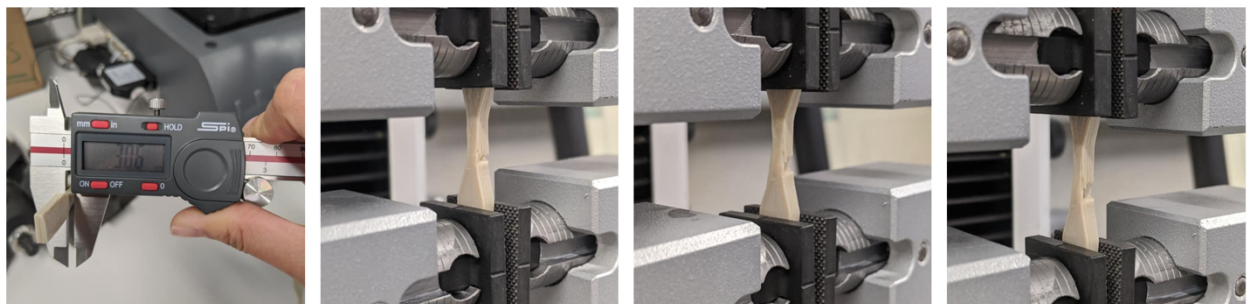


Figure 74 - Tensile test sample 3 measured and tested for tensile properties.

6.3.1 Observations

During the tests of the specimens, it was observed that all the fractures propagated from the same corner. This phenomenon is particularly evident in the first and third sample, as seen in figures 72 and 74. It was also observed that rather than showing signs of necking, all three samples simply started to fracture and showed signs of delamination in certain areas. Moreover, it can be observed from Figure 73 that the outer wall on one side of Sample 2 ruptured away from its infill while the other stuck on and fractured alongside its infill. What was interesting to observe was that Sample

3, as shown in Figure 75, did not achieve to propagate all the way through before 5mm extension was reached and the test subsequently ended.

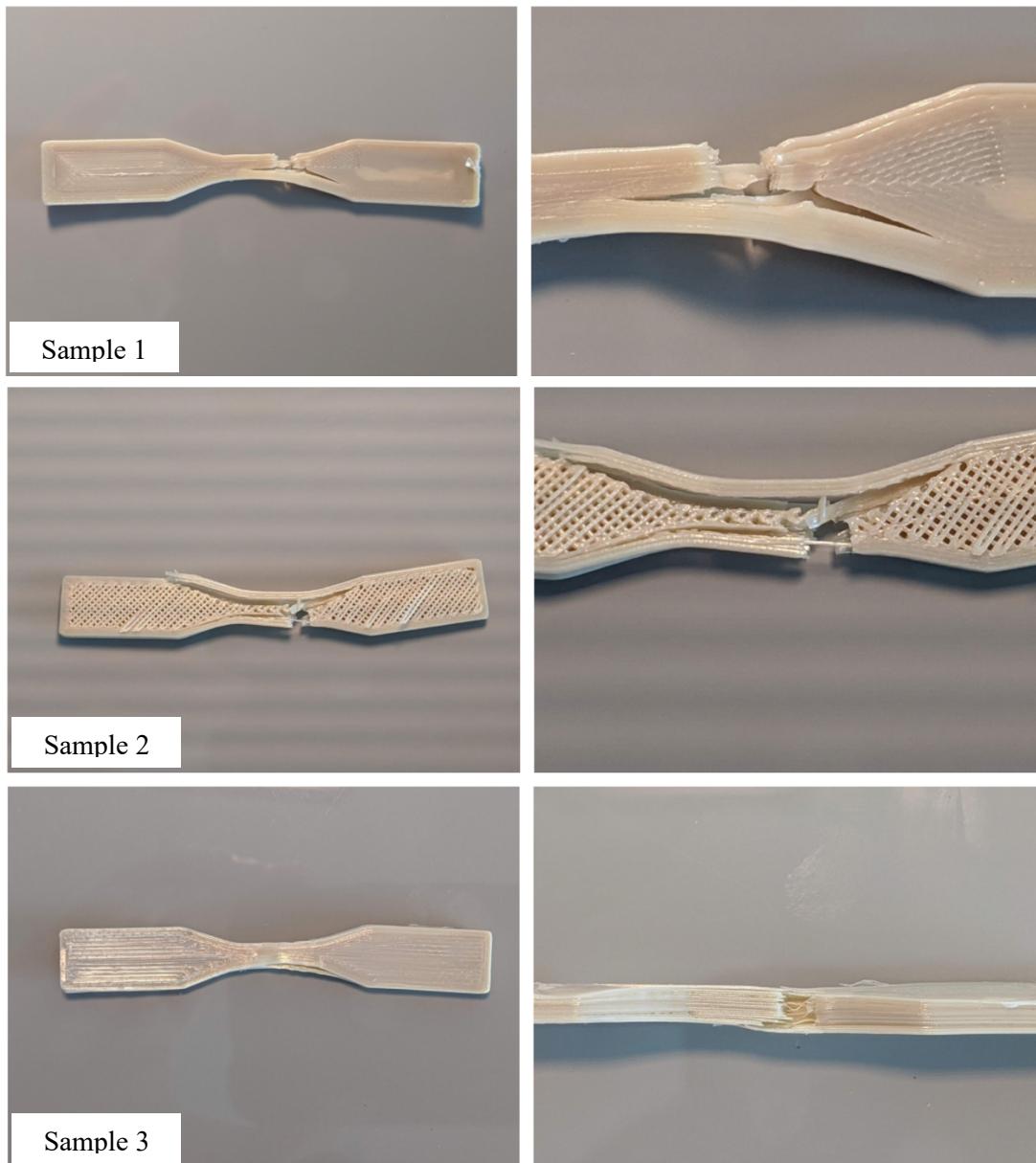


Figure 75 - Test samples after tensile test. Top left picture shows the backside of the sample without any signs of tear or fracture. All samples are still in one piece.

6.3.2 Analysis and Comparison of Tensile Test Results

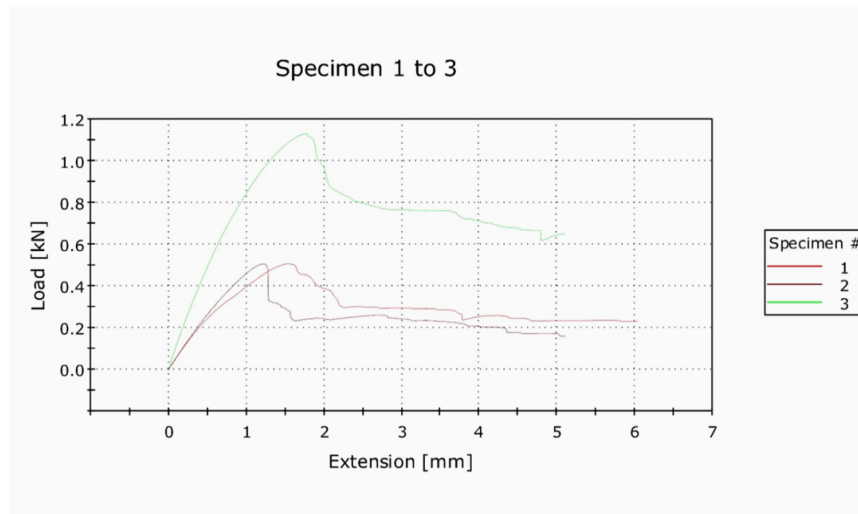


Figure 76 - Load vs Extension chart of the three tested PEEK samples as generated by the UTM software.

Figure 76. However, it is also calculated using the equation below:

Equation 2- Ultimate tensile strength calculation

$$\sigma_f = \frac{P_f}{A_0}$$

where σ_f is the *ultimate tensile strength*, P_f is the load at fracture, and A_0 is the original cross-sectional area. The unit for stress is load per unit area, N/m^2 , also known as Pascals (Pa), in the SI system.

In Figure 76, it can be seen that Sample 1 has the highest maximum tensile strength, followed by Samples 3 and 2. What is striking about this result, however, is that Sample 1, with the concentric infill pattern, is less than half the thickness of Sample 3. This suggests that the concentric pattern, or perhaps but more unlikely the 10°C extrusion temperature difference, produced a sample that is more effective in withstanding a uniaxial pulling force. In other words, Sample 1 can withstand a higher load, as its area, A_0 , is a lot smaller than the one of Sample 3. One other explanation, however, could be that as Sample 3 had more layers in the part, hence implying that it has been exposed to more heating and cooling cycles. Sood et al. (45) explains in their research that with increased number of heat and cooling cycles come increased residual stress; this may result in the part's distortion, interlayer cracking and part delamination or fabrication failure, and hence impact its strength.

Sample 2, on the other hand, exhibited a much lower UTS of 29.73 MPa. This could be attributed to the air gaps between the adjacent rasters, as Sood et al. (45) discovered that the diffusion between the adjacent rasters improves with zero air gap. Similarly, Vaezi et al. (8) also discussed that air gaps influence the strength of the extruded samples through locally decreasing physical cross-sectional area of the material specimens. Their research indicated that the air gaps close to the perimeter contributed to the initiation of micro-cracks, which consequently lead to the rupture of the infill filaments when placed under tension.

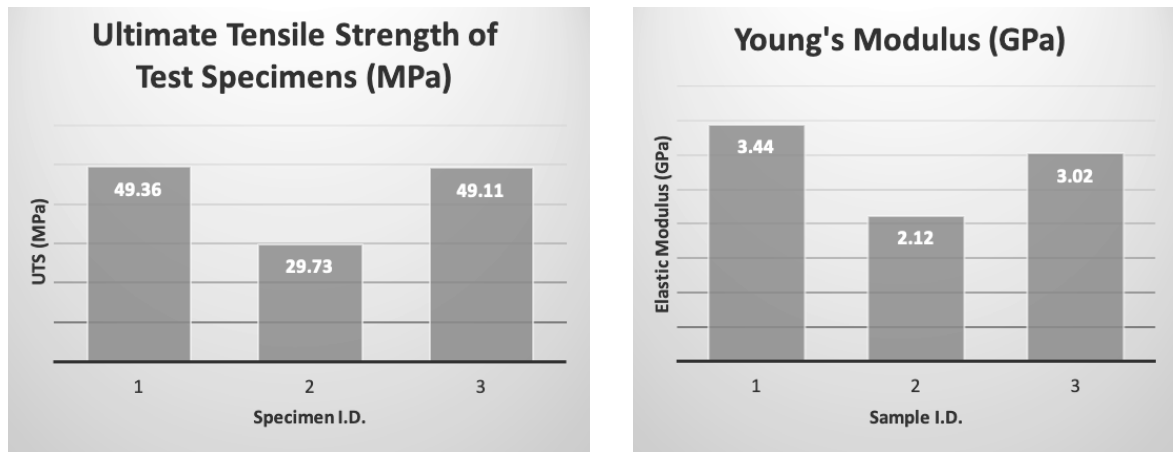


Figure 77 – Ultimate Tensile Strength (Left) and Young's Modulus (Right) of Test Specimens 1-3.

Young's modulus, or modulus of elasticity, on the other hand, is in essence, the stiffness of the material. It measures the load needed to induce a given deformation in the material (46). Like stress, it has the SI unit of Pa.

Equation 3- Young's Modulus Equation

$$E = \frac{L_0 \cdot P}{A_0 \cdot \delta} = \frac{\sigma}{\epsilon}$$

where E denotes the modulus of elasticity, σ denotes *stress*, ϵ is a dimensionless measurement of stretching called *strain*, and δ denotes deformation.

The Young's modulus was attained using a 0.2% offset method on the stress vs strain chart, as demonstrated in Figure 78 with the orange line being the 0.2% offset. From Figure 77, it can be seen that Sample 1 outperformed the other two samples with a Young's modulus of 3.44 GPa. While Sample 1 also had a higher UTS than Sample 3, it outperforms Sample 3 by a larger margin for its modulus of elasticity. Croccolo et al. (47) found in their experiment that the greater the number of contours, the greater

the stiffness; this perhaps explain why the bigger difference exists between Samples 1 and 3 for their modulus of elasticity.

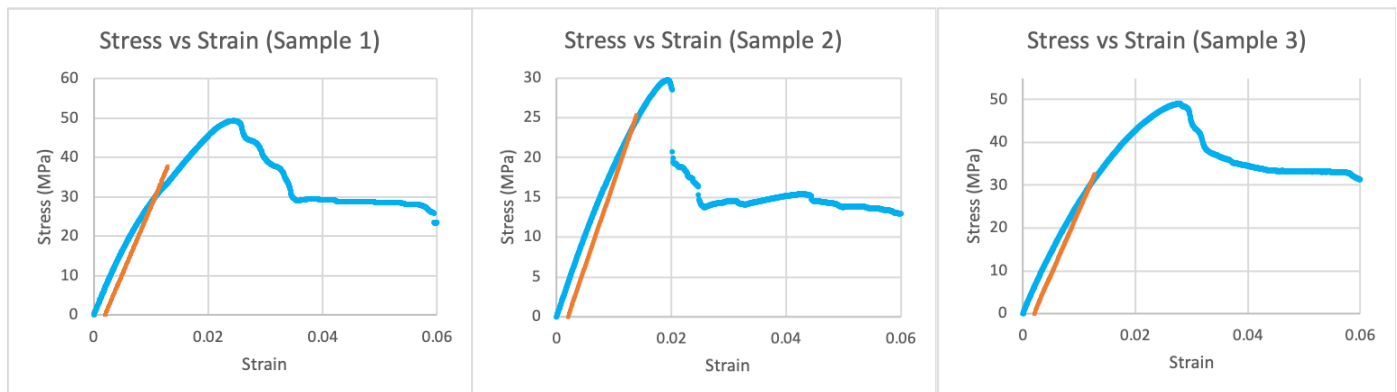


Figure 78 - Stress vs strain charts for Samples 1-3 with 0.2% offset lines in orange.

To truly assess the quality of the printed samples in terms of their tensile properties, a comparison has been carried out between the results attained in this study and the results attained by other researchers who also experimented with producing FFF printed PEEK samples. Figures highlighted in green in Table 16 indicates when the samples of this study outperform the tensile property achieved by other studies, while figures highlighted in red indicate that the study's samples underperformed when measured against results from other research papers.

Table 16: Results Attained in Relevant Studies

	Young's Modulus (MPa)	Tensile Strength (MPa)	Layer thickness (μm)	Infill Ratio	PEEK Manufacturer
Wu et al. (14)	Not included	40.1	200	100%	Jilin University Special Plastic Engineering Research Co. Ltd.
Rahman et al. (4)	2825.66	74.49	250	100%	Proprietary PEEK formulation from Arevo Labs

Vaezi et al (8)	Not included	75.06	200	100%	Victrex® PEEK
Deng et al. (27)	1563.5	40.0 ± 4.4 MPa	200	40%	PEEK-1000 bar (Zhongshan Yousheng Plastic materials Co., Ltd.)
Magri et al. (15)	2,663.07 ± 55.17	68.97 ± 1.67	200	100%	VESTAKEEP 3300G Pellets *extruded into spools by authors
Cicala et al. (7)	3,530 ± 10	69.04 ± 7.01			industrial-grade PEEK by Luvocomm
Wang et al. (11)	2,300 ± 280 GPa.	Not included	50	100%	PEEK from Apium

6.4 Microscopic Imaging

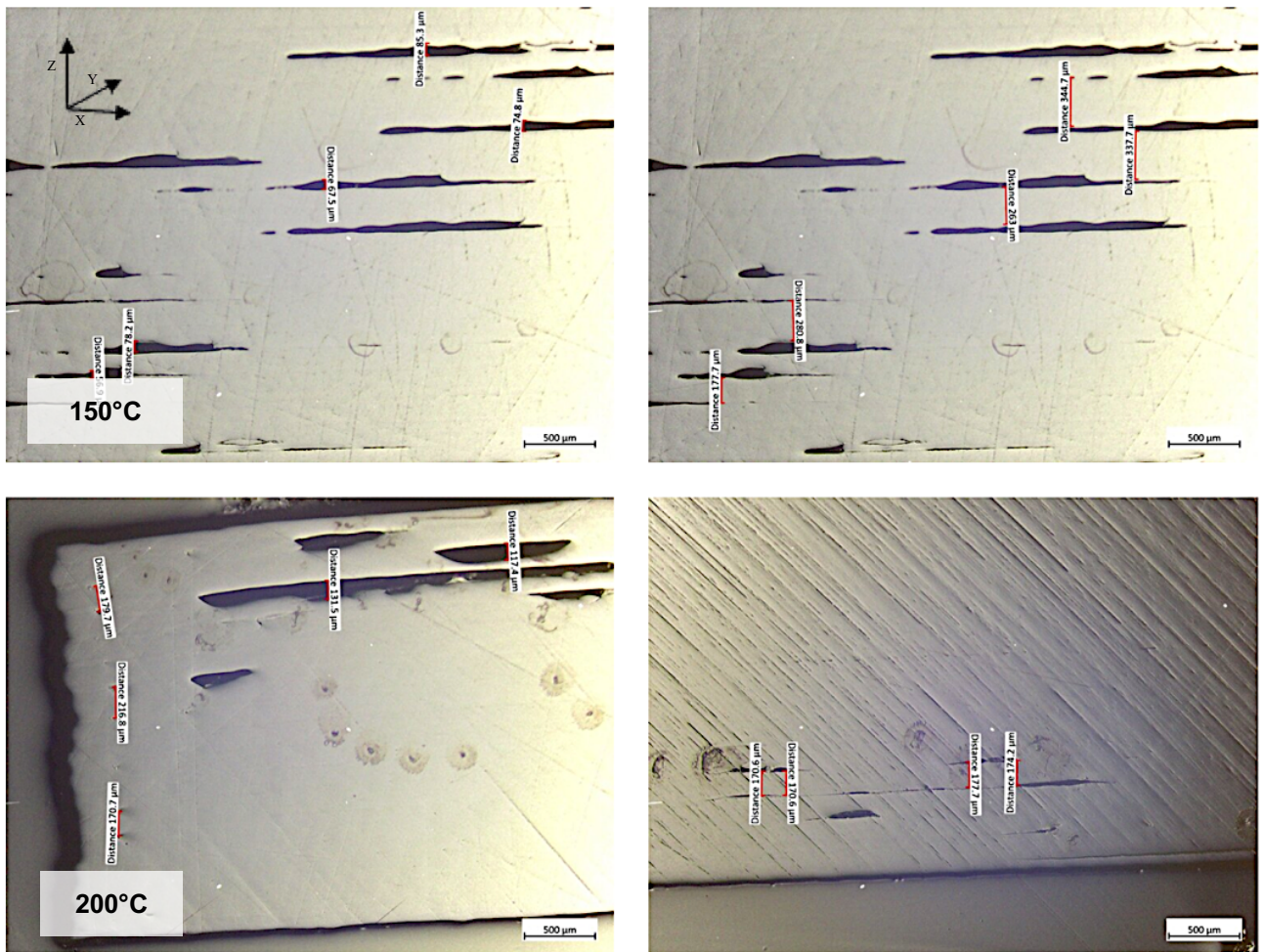
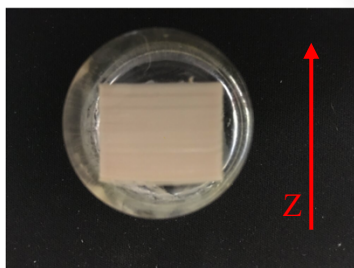


Figure 79 –Top: samples printed in chamber temperature of 150°C Bottom: Samples printed in chamber temperature of 200°C



After the tensile test was performed, microscopic imaging of two samples (see figure 80) was carried out to investigate whether the increase in chamber temperature had an impact on layer fusion and bonding.



Figure 80 - Top: sample printed in 150°C chamber. Bottom: sample print in 200°C chamber.

As the PT100 sensor snapped, potentially due to work hardening while printing the sample with the 200°C chamber temperature, the 200°C sample perimeter size was limited. Nonetheless, it is evident from figure 79 that 150°C sample had more consistent air gaps throughout, while the 200°C sample exhibited less but wider gaps in some cases as shown in the bottom left image of the figure. The second

sample of the 200°C printed object, however, exhibited much smaller air gaps between the layers.

Chapter 7: Evaluations of the Project

7.1 Discussion

The project aim is to produce high-quality PEEK prints using the custom FFF printer with the provided KetaSpire® PEEK filament. To achieve this aim, 11 project objectives were created at the beginning of the project. As seen in Figure 81, most of the project objectives were fully achieved except for objectives 9 and 11.

Due to the COVID-19 situation and the university shutdown, not enough tensile samples were printed in time to enable the test to adhere to the ASTM D638 standard. Moreover, the author faced a change in work environment as she had to fly home before the international borders closed. These circumstances greatly affected the project plan and shortened the results analysis section. Originally, the author also planned on conducting SEM imaging and analysis after the final samples were printed to examine the layer adhesion and surface quality. While microscopic analysis was still conducted at the very last minute with the help and support of Dawn Spencer, Wolfson School's lab technician, this type of analysis was not what the author initially had in mind.

#	Objectives	Achieved?
1	Conducting a literature review to identify and collate print parameters that may affect the quality of the PEEK print.	
2	Conducting a thorough assessment of the printer at handover to identify faults and limitations to enable repairs and modifications.	
3	Assessing available options and justify chosen upgrades decisions	
4	Upgrading components to help achieve thermal requirements	
5	Manufacturing modifications to improve reliability and safety of the printer.	
6	Verifying design specifications provided by previous project students and calibrate printer if necessary	
7	Updating and recording the cost of the entire 3D-printing system	
8	Documenting changes made to the hardware and software of the printer	
9	Performing tensile tests on printed samples following the recognised ASTM standards	
10	Evaluating the final printer design compared to design at handover and providing future recommendations for further work.	
11	Exercising effective time management throughout the duration of the project.	

Achieved

Partially Achieved

Not Achieved

Figure 81 - Project Objectives Checklist and Achievements

7.2 Conclusion

This study has successfully managed to improve upon the early adaptations of a consumer 3D printer in order to increase its suitability to print PEEK. The physical modifications conducted to the printer improved both the printer's ability to print PEEK, its reliability and its accuracy; for example, the re-design of the z-axis configuration enabled the layer height of 0.01mm to be attained. Tensile test samples were also produced; the tensile test results yielded a maximum Young's Modulus value of 3.44 GPa and an Ultimate Tensile Strength value of 49.36 MPa. These results, while not the best, were competitive amongst the results attained by other academic in this field.

I would like to thank Dave Thompson, David King, Dawn Spencer, the Wolfson Electronics Department and Tony Sutton for their support and guidance throughout this project.

Chapter 8: Further Works

Future work can be carried out to further develop the work conducted from this project. Suggestions include the following:

- **Integrating a Duet3D controller board** to unify the existing two systems. Currently, controlling the printer and the chamber temperature rely on two separate systems and interfaces (Pronterface and Arduino IDE respectively). Not only can a Duet3D board replace all the electronics from both systems, Duet3D also offers a web interface that can enable the chamber temperature to finally be controlled accurately and effortlessly. Alternatively, if the Duet3D board is not implemented, it is suggested that an LCD touchscreen should be still be integrated into the existing system to enable a more accurate chamber temperature control.
- **Improving wire management**, as well as taking more care to **apply strain relief** for wires at the hot end, especially for the PT100 cartridge. In this study, the PT100 sensor was damaged on multiple occasions; this was partly due to work hardening of the frail wires attached to the cartridge. As the hot end, inevitably, must be disassembled to unclog the nozzle at times, it is suggested that boron nitrate thermal paste, which will turn hard when it's dried, can be

applied to the cartridge end of the sensor to lessen the impact. The new wire management system can also use wire loom covered with PET mesh sleeve to further organise and protect the wires.

- **Remanufacturing the x-axis motor mount** with aluminium or polymers with higher operating temperatures. If the chamber temperature of 200°C must be reached in future works, the bellow lined with ceramic fibre may still let out enough heat to distort the current PLA mount.
- **Insulate heated bed** from the metal supporting frame. Currently, the insulation between bed and aluminium frame relies on a piece of 2mm cardboard. This not only may become a health and safety issue as temperature increases (as metal frame may still remain hot once the MK2B is removed), it is also a source of heat loss. Some suggestions include replacing or adding onto the cardboard with ceramic fibre, PTFE or cork boards.
- **Replacing the Bang Bang system.** As seen in section 5.3.2, the temperature fluctuation range is fairly large due to the Bang Bang method of shutting down the SSR once the target temperature was reached. To help reduce temperature fluctuations, a proportional integral derivative (PID) system can potentially be implemented. PID controllers use a control loop feedback with correction based around three constants; proportional, integral and derivative. The PID constants and error between target setpoint and measured variable are used to calculate an appropriate controller output to achieve the target setpoint.
- **Printing a Benchy** to test more complex shapes/geometries to further evaluate the capabilities of the printer.
- **Investigating deeper into the cooling rate/gradient and its impact** on tensile strength and layer bonding.
- **Exploring post-treatment methods** and investigate the effects of annealing, quenching, and tempering.
- **Upgrading the timing belt** for the x and y-axes. By increasing the quality and stiffness of the timing belt, faster travel and print speeds may be attained, and prints of higher accuracy may be achieved.
- **Using orthogonal (experiment method) factor level table** method to analyse, in detail, the effects of different parameters. However, this is a project in itself.

Appendix A

A.1 Project Timing Plan

PROJECT TIMING PLAN GUIDE

Wolfson School of Mechanical, Electrical and Manufacturing Engineering.



Loughborough University

SEMESTER 1															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PROJECT ALLOCATION															
SUBMISSION OF SIGNED OBJECTIVES AND ETHICAL CHECKLIST FORM															
INITIAL EVALUATION															
RESEARCH INTO CURRENT SYSTEM USING PAST REPORTS															
SET UP RELEVANT SOFTWARE															
DIAGNOSIS OF EXISTING PRINTER ERRORS															
IDENTIFY MISSING COMPONENTS															
REPAIRS															
RESEARCH INTO UPGRADES REQUIRED															
RESEARCH CALIBRATION & MECHANICAL EXPERIMENTS															
CALIBRATION TESTS (BED & EXTRUDER)															
PRINT A LINE WITH PLA															
DETAILED PROJECT TIMING PLAN															
DEADLINE FOR INITIAL WORKSHOP DISCUSSIONS															
PRELIMINARY VIVA VOCE ASSESSMENT															
INITIAL TESTING AND MODIFICATIONS															
TEST PRINTS WITH PLA															
INITIAL TEST PRINTS WITH PEEK															
MATERIALS TO BE SOURCED & ORDERED															
INTERIM PROJECT PRESENTATION															
MANUFACTURE COMPONENTS IN WORKSHOPS															
LAST DAY FOR REQUESTS TO SCHOOL WORKSOPS															
PRINTER ASSEMBLY															
PRINTER CALIBRATION															
SECOND PHASE TESTING & MODIFICATIONS															
TEST PRINTS WITH PEEK															
TEST STRUCTURAL INTEGRITY/ PERFORMANCE OF TEST PRINTS															
END OF PROJECT ACTIVITIES															
WRITE AND FINALISE FINAL REPORT															
FINAL REPORT DEADLINE															
ENGINEERING DESIGNER EXHIBITION															

Note

Semester 1 Week 7

Semester 2 Week 1

Completed

Deadlines

Planned

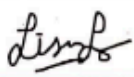
Final Submission Date For Report Wednesday 4th May 2020

A.2 Signed Objectives Form

WOLFSON SCHOOL PART C/D INDIVIDUAL PROJECT OBJECTIVES FORM

ID NUMBER: B714849	SURNAME: LO	FORENAME: HSIN-JU (LISA)
PDE BEng: 400 hours (40-credit module)		
Project Title: FDM 3D printing with high temperature materials		
ETHICALS: Please confirm whether you have considered the ethical issues of the project (by completing the ethical checklist on P. 2). ALL human participant projects require approval from the "Ethics Approvals Sub-Committee"; Please delete as applicable: YES		
Objectives: - PEEK is used extensively in medical and engineering fields. It is an expensive material, therefore manufacturing PEEK parts using additive manufacturing techniques is ideal. PEEK requires a high temperature to print, therefore a new printer was created last year as part of a Part C project. However, the printer can barely print a cube and still needs great improvements. - Test and evaluate existing machine - propose and implement improvements - print and evaluate test samples		
Deliverables: - Literature review - Testing/Evaluation results/writeup - Physical test prints		
Proposed programme of work (not a detailed work plan): - Research - Start evaluating existing system and document results. - Analyse results - Implement improvements and produce test prints. - Evaluate test prints - Write up report.		

I confirm that this project can be completed in the time available:

STUDENT	NAME: Hsin-Ju Lo	Signature: 	Date: 10/10/19
SUPERVISOR	NAME: A. SUTTON	Signature: 	Date: 15/10/19

The Objectives Form (P.1) and Ethical Checklist (P. 2) are requirements of the IMechE and University, respectively. The student is responsible for depositing an electronic copy (a single pdf-format document with both forms) to Learn by 3.30pm, Friday, Week 2.

Appendix B

B.1 Changes in Marlin's Configuration.h File

Original Line #	Original Default Settings	Changed
152	#define DEFAULT_NOMINAL_FILAMENT_DIA 3.0	#define DEFAULT_NOMINAL_FILAMENT_DIA 1.75
313	#define TEMP_SENSOR_0 1	#define TEMP_SENSOR_0 20
318	#define TEMP_SENSOR_BED 0	#define TEMP_SENSOR_BED 1
353	#define HEATER_0_MAXTEMP 275	#define HEATER_0_MAXTEMP 500
510	#define USE_XMIN_PLUG	//#define USE_XMIN_PLUG
511	#define USE_YMIN_PLUG	//#define USE_YMIN_PLUG
512	#define USE_ZMIN_PLUG	#define USE_ZMIN_PLUG
513	//#define USE_XMAX_PLUG	#define USE_XMAX_PLUG
514	//#define USE_YMAX_PLUG	#define USE_YMAX_PLUG
515	//#define USE_ZMAX_PLUG	//#define USE_ZMAX_PLUG
611	#define DEFAULT_AXIS_STEPS_PER_UNIT { 80, 80, 4000, 500 }	#define DEFAULT_AXIS_STEPS_PER_UNIT { 128.6, 127.2, 3200, 1000 }
636	#define DEFAULT_ACCELERATION 3000 // X, Y, Z and E acceleration for printing moves	#define DEFAULT_ACCELERATION 1000 // X, Y, Z and E acceleration for printing moves
637	#define DEFAULT_RETRACT_ACCELERATION 3000 // E acceleration for retracts	#define DEFAULT_RETRACT_ACCELERATION 1000 // E acceleration for retracts
638	#define DEFAULT_TRAVEL_ACCELERATION 3000 // X, Y, Z acceleration for travel (non printing) moves	#define DEFAULT_TRAVEL_ACCELERATION 1000 // X, Y, Z acceleration for travel (non printing) moves
879	#define X_BED_SIZE 200	#define X_BED_SIZE 190
880	#define Y_BED_SIZE 200	#define Y_BED_SIZE 150
888	#define Z_MAX_POS 200	#define Z_MAX_POS 180
1224	//#define EEPROM_SETTINGS // Enable for M500 and M501 commands	#define EEPROM_SETTINGS // Enable for M500 and M501 commands
1246	//#define INCH_MODE_SUPPORT	#define INCH_MODE_SUPPORT
1375	//#define PRINTCOUNTER	#define PRINTCOUNTER

B.2 Changes in Marlin's Pins_RAMPS.h File

Original Line #	Original Default Settings	Changed Settings
194	#define TEMP_0_PIN 13 // Analog Input	#define TEMP_0_PIN 3 // Analog Input
196	#define TEMP_BED_PIN 14 // Analog Input	#define TEMP_BED_PIN 13 // Analog Input
512	#define KILL_PIN 41	#define KILL_PIN 64

B.3 BangBang Arduino Code for Chamber Temperature Control

```
#include <SPI.h>
#include "Adafruit_MAX31855.h"

// define pins for Thermocouple
#define MAXDO  11
#define MAXCS  12
#define MAXCLK 13
#define SSR 6

unsigned long time;

// initialize the Thermocouple
Adafruit_MAX31855 thermocouple(MAXCLK, MAXCS, MAXDO);

void setup() {

  //setup for Thermocouple
  Serial.begin(9600);

  while (!Serial) delay(1); // wait for Serial on Leonardo/Zero, etc

  pinMode(SSR, OUTPUT);

}

void loop() {

  time = millis()/1000;
  Serial.print("Time,");
  Serial.print(time);

  double c = thermocouple.readCelsius();
  Serial.print(",Temp,");
  Serial.print(c);

  if (c < 200) {
    digitalWrite(SSR, HIGH);
    Serial.println(",SSR,ON");}
  else {
    digitalWrite(SSR, LOW);
    Serial.println(",SSR,OFF");}
  delay(1000);

}
```

References

1. May R. Polyetheretherketones. In: Encyclopedia of Polymer Science and Technology [Internet]. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2008 [cited 2020 Mar 27]. Available from: <http://doi.wiley.com/10.1002/0471440264.pst266>
2. Chen F, Ou H, Lu B, Long H. A constitutive model of polyether-ether-ketone (PEEK). *J Mech Behav Biomed Mater*. 2016 Jan 1;53:427–33.
3. Fluorocarbon company Ltd. What is Polyetheretherketone or PEEK? | Fluorocarbon [Internet]. [cited 2020 Mar 27]. Available from: <http://www.fluorocarbon.co.uk/news-and-events/post/13/what-is-polyethererketone-peek>
4. Rahman KM, Letcher T, Reese R. Mechanical properties of additively manufactured peek components using fused filament fabrication. *ASME Int Mech Eng Congr Expo Proc*. 2015;2A-2015(November).
5. Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. Vol. 28, *Biomaterials*. 2007. p. 4845–69.
6. Green DS, Green DS, Schlegel J. A Polyaryletherketone Biomaterial for use in Medical Implant Applications. [cited 2020 Apr 6]; Available from: <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.604.1060>
7. Cicala G, Latteri A, Curto B Del, Russo A Lo, Recca G, Farè S. Engineering thermoplastics for additive manufacturing: A critical perspective with experimental evidence to support functional applications. *J Appl Biomater Funct Mater*. 2017;15(1):e10–8.
8. Vaezi M, Yang S. Extrusion-based additive manufacturing of PEEK for biomedical applications. *Virtual Phys Prototyp*. 2015;10(3):123–35.
9. Wu WZ, Geng P, Zhao J, Zhang Y, Rosen DW, Zhang HB. Manufacture and thermal deformation analysis of semicrystalline polymer polyether ether ketone by 3D printing. *Mater Res Innov*. 2014;18:S5-12-S5-16.
10. Gibson I, Rosen DW, Stucker B. Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Springer US; 2010. 1–459 p.
11. Wang Y, Müller WD, Rumjahn A, Schwitalla A. Parameters influencing the

- outcome of additive manufacturing of tiny medical devices based on PEEK. *Materials* (Basel). 2020;13(2).
12. Ahn SH, Baek C, Lee S, Ahn IS. Anisotropic tensile failure model of rapid prototyping parts - Fused Deposition Modeling (FDM). In: *International Journal of Modern Physics B*. 2003. p. 1510–6.
 13. Arif MF, Kumar S, Varadarajan KM, Cantwell WJ. Performance of biocompatible PEEK processed by fused deposition additive manufacturing. *Mater Des*. 2018 May 15;146:249–59.
 14. Wu W, Geng P, Li G, Zhao D, Zhang H, Zhao J. Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS. *Materials* (Basel). 2015;8(9):5834–46.
 15. El Magri A, El Mabrouk K, Vaudreuil S, Chibane H, Touhami ME. Optimization of printing parameters for improvement of mechanical and thermal performances of 3D printed poly(ether ether ketone) parts. *J Appl Polym Sci*. 2020;(January):1–14.
 16. Geng P, Zhao J, Wu W, Ye W, Wang Y, Wang S, et al. Effects of extrusion speed and printing speed on the 3D printing stability of extruded PEEK filament. *J Manuf Process* [Internet]. 2019;37(December 2018):266–73. Available from: <https://doi.org/10.1016/j.jmapro.2018.11.023>
 17. Hu B, Duan X, Xing Z, Xu Z, Du C, Zhou H, et al. Improved design of fused deposition modeling equipment for 3D printing of high-performance PEEK parts. *Mech Mater*. 2019 Oct 1;137:103139.
 18. Print Quality Guide [Internet]. [cited 2020 Mar 26]. Available from: <https://www.simplify3d.com/support/print-quality-troubleshooting/>
 19. Portfolio » SphèreCo » 3D Printing for the Industry [Internet]. [cited 2020 Apr 14]. Available from: <http://www.sphereco.ca/en/portfolio-en/>
 20. 3D4Makers. Best Practices in 3D Printing PEEK FDM Filament [Internet]. 2017 [cited 2020 Apr 14]. Available from: <https://www.3d4makers.com/blogs/news/best-practices-in-3d-printing-peek-fdm-filament>
 21. PEEK 3D printing: how to prevent warping? - Aniwaa [Internet]. [cited 2020 Apr 14]. Available from: <https://www.aniwaa.com/blog/peek-3d-printing-how-to-prevent-warping/>

22. Omnexus. Shrinkage Value of Plastics Material & Injection Molding - Chart [Internet]. 2019 [cited 2020 Apr 14]. Available from:
<https://omnexus.specialchem.com/polymer-properties/properties/shrinkage>
23. ASTM. AS for T and M. Designation: D638-14 Standard test Method for Tensile Properties of Plastics. ASTM Int. 2014;82(January):1–15.
24. Tensile Test Methods for Plastics: ASTM D638 : SHIMADZU (Shimadzu Corporation) [Internet]. Shimadzu Corporation. 2019 [cited 2020 Mar 27]. Available from:
<https://www.shimadzu.com/an/industry/petrochemicalchemical/n9j25k00000pyu05.html>
25. ASTM. AS for T and M. Designation: D638-14 Standard test Method for Tensile Properties of Plastics. ASTM Int [Internet]. 2014 [cited 2020 Mar 28];82(January):1–15. Available from: <http://www.ansi.org>.
26. Lambert P. FDM vs SLS 3D Printers: Which Tensile Properties? [Internet]. Sculpteo. 2014 [cited 2020 Mar 28]. p. 5. Available from:
<https://www.sculpteo.com/blog/2014/05/14/material-considerations-choose-right-plastic-production-method-part-2/>
27. Deng X, Zeng Z, Peng B, Yan S, Ke W. Mechanical properties optimization of poly-ether-ether-ketone via fused deposition modeling. Materials (Basel). 2018;11(2).
28. Maximum temperature for the V6 - E3D-Online [Internet]. [cited 2020 May 11]. Available from: https://e3d-online.dozuki.com/Wiki/Maximum_temperatures_for_the_V6
29. Corporation RI. Thermocouple Color Codes [Internet]. Thermocoupleinfo.Com. 2011 [cited 2020 May 11]. Available from:
<https://www.thermocoupleinfo.com/thermocouple-color-codes.htm>
30. Superwool 607 HT [Internet]. [cited 2020 May 11]. Available from:
<http://www.goodfellow.com/corporate/news/2011/Superwool-607-HT-Goodfellow-UK-Sept-2011.pdf>
31. What Are PIR And PUR Insulation Products? | Globe Panels [Internet]. [cited 2020 Apr 14]. Available from: <https://globepanels.com/what-is-pir-pur-insulation-products/>
32. Temperature resistance / stability – Excellence in Insulation [Internet]. [cited 2020 May 12]. Available from:

- <http://highperformanceinsulation.eu/home/insulating-with-pu/pu-a-premium-insulant/temperature-resistance-stability/>
33. What is back driving and why is it important? [Internet]. [cited 2020 May 12]. Available from: <https://www.linearmotiontips.com/what-is-back-driving-and-why-is-it-important/>
 34. (No Title) [Internet]. [cited 2020 May 12]. Available from: https://components101.com/sites/default/files/component_datasheet/NEMA17.pdf
 35. Velleman. K8200 3D Printer [Internet]. 2013 [cited 2020 Apr 16]. Available from: <http://www.k8200.eu/manual/building/?c=019>
 36. Wang L, Gardner DJ. Contribution of printing parameters to the interfacial strength of polylactic acid (PLA) in material extrusion additive manufacturing. *Prog Addit Manuf*. 2018 Sep 1;3(3):165–71.
 37. K8200 Precise Z-Axis Home Calibration V1 by mr_cg - Thingiverse [Internet]. [cited 2020 May 13]. Available from: https://www.thingiverse.com/thing:317411/comments?fbclid=IwAR2m4Q27AWu5nQyly_6T13hMLE8sJKn5_Izkxr-J6hCvorsqic1mrCFfgc0
 38. E3D-Online. V6 Titanium Heat Break [Internet]. 2020 [cited 2020 Apr 20]. p. 1. Available from: <https://e3d-online.com/catalog/product/view/id/9284/s/v6-titanium-heat-break/>
 39. New z-Motor-Holder for the Velleman K8200 or 3Drag by mstolt - Thingiverse [Internet]. [cited 2020 May 13]. Available from: https://www.thingiverse.com/thing:144813/comments?fbclid=IwAR3ixHgN_Xnpgf7OrCY6m1UxzQT_LGY9icpxrmO9blhOwZT7nr2KGM_RzTw
 40. K8200 X-Axis holder by Pady - Thingiverse [Internet]. [cited 2020 May 13]. Available from: https://www.thingiverse.com/thing:2967320/comments?fbclid=IwAR1c5oWCZnku_Md46CFUIV6YYCZMk3DA74zfHf4fkselxb-dA0x5eEYIAxo
 41. K8200 Z-Endsupport by 3DFranky - Thingiverse [Internet]. [cited 2020 May 13]. Available from: <https://www.thingiverse.com/thing:175137>
 42. RepRap Calculator - Prusa Printers [Internet]. [cited 2020 May 12]. Available from: <https://blog.prusaprinters.org/calculator/>
 43. XYZ 20mm Calibration Cube by iDig3Dprinting - Thingiverse [Internet]. [cited 2020 May 12]. Available from: <https://www.thingiverse.com/thing:1278865>

44. Project I, Report F, Cullen T. Developing an Insulated Heated Chamber for Consumer Fdm Printer. 2019;
45. Sood AK, Ohdar RK, Mahapatra SS. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater Des. 2010 Jan 1;31(1):287–95.
46. Roylance D. MECHANICAL PROPERTIES OF MATERIALS.
47. Croccolo D, De Agostinis M, Olmi G. Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30. Comput Mater Sci. 2013 Nov 1;79:506–18.
48. 3D printing and Design [Internet]. [cited 2020 Apr 6]. Available from: <https://www.additive.blog/knowledge-base/3d-printers/sla-stereolithography-dlp-cdlp-clip/>
49. Hanon MM, Marczis R, Zsidai L. Anisotropy evaluation of different raster directions, spatial orientations, and fill percentage of 3d printed petg tensile test specimens. Key Eng Mater. 2019;821 KEM:167–73.
50. Radley T. 3D Printing of High-Performance Thermoplastics. 2019;
51. Ultimate 3D Print Quality Troubleshooting Guide 2018 [All 44 Problems] [Internet]. [cited 2020 Apr 14]. Available from: <https://rigid.ink/pages/ultimate-troubleshooting-guide>
52. Avoiding the dramas associated with PLA prints not sticking [Internet]. [cited 2020 Apr 14]. Available from: <https://modfab.com.au/troubleshooting/troubleshooting-3d-prints/my-pla-print-wont-stick/>
53. Original U, Prints GB, Top P. A visual Ultimaker troubleshooting guide - 3DVerkstan Knowledge Base [Internet]. [cited 2020 Apr 14]. p. 1–46. Available from: <http://support.3dverkstan.se/article/23-a-visual-ultimaker-troubleshooting-guide#ringing>
54. shrinkage in clay 3D printing – IAAC Blog [Internet]. [cited 2020 Apr 14]. Available from: <http://www.iaacblog.com/programs/shrinkage-clay-3d-printing/>
55. K8200 (3drag) dual leadscrew z axis upgrade with 2 Velleman K8204 leadscrew Kits by Ichbinsnur - Thingiverse [Internet]. [cited 2020 May 12]. Available from: <https://www.thingiverse.com/thing:1003914>
56. N1H201000LCN-PCZ | NSK N1H Series, N1H201000LCNE01 =N/P KPCZ85,

Linear Guide Rail 20mm width 1000mm Length | RS Components [Internet]. [cited 2020 May 12]. Available from: <https://th.rs-online.com/web/p/linear-guides-rails/8498792/>

57. RAMPS 1.4 3D Printer Controller Board – Review the Specs | All3DP [Internet]. [cited 2020 May 12]. Available from: <https://all3dp.com/2/ramps-1-4-review-the-specs-of-this-controller-board/>