Master’s Degree Thesis Mechanical Engineering

Optimizing Fused Filament Fabrication 3D printing for durability

Tensile properties & layer bonding

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Abstract

With the rapid increase in utilization of the cheap and user friendly Fused Filament Fabrication, FFF 3D printer, a deeper knowledge about the technique is needful. The frame restricting the 3D printers for prototyping purposes is fading and a new phase of endless application possibilities is emerging. To bridge the gap in possible applications from prototypes to real products it is key to know and improve the factors affecting durability. With over a hundred settings and parameters to tweak the FFF 3D printing process there are a lot of opportunities, opportunities to optimize for durability.

The tensile properties of some of the most used FFF 3D printing materials together with a few nylon based materials are examined, which are popular in engineering applications. The materials tested are ranging from rigid to flexible, rubber like materials. The most common failure scenario of a FFF 3D printed product is layer bonding failure. The factors affecting layer bonding performance are studied.

The measurements are carried out using tensile testing equipment at Blekinge Institute of Technology. All tested specimens are manufactured at Creative Tools AB Halmstad with the FFF 3D printers Flashforge Dreamer and Makerbot Replicator 2X.

The tensile strength of 3D printed PLA is found to be 51 MPa. PET has a tensile strength of 40 MPa and ABS 34 MPa. Stress-strain behavior of the materials shows that ABS is slightly softer than PLA and PET are slightly softer than ABS. PLA being the hardest material in the test. ISO 527-2 tensile testing standard is used but the tests diverge from the standard in several ways. The measurement data presented in this study can be very useful to guide the design engineer to choose the most durable plastic for the unique application.

Five basic 3D printing settings are evaluated for layer bonding performance, by measuring the load capacity of a specimen loaded transversally relative to the layers. Four of the settings show to possibly affect the layer bond's load capacity by 50 % or more individually.

The results of this study are presented in graphs, diagrams and pictures. These may help the 3D printer user to tweak basic settings to increase layer bonding performance and ultimately the durability of the product significantly.

Keywords: *3D printing, Fused Deposition Modeling, tensile strength, layer bonding*

Sammanfattning

Med den snabbt växande användningen av den billiga och lättanvända Fused Filament Fabrication, FFF 3D skrivaren, behövs djupare förståelse för tekniken. Ramen som begränsar dessa 3D skrivare till prototypändamål suddas ut och en ny fas med ändlösa applikationsmöjligheter träder fram. För att göra det möjligt att tillverka riktiga, användbara produkter är det viktigt att veta vilka faktorer som påverkar den mekaniska hållbarheten och hur man förbättrar denna. Med fler än hundra inställningar och parametrar att justera i FFF 3D utskriftsprocessen finns mängder med möjligheter, möjligheter att optimera för hållfasthet.

Draghållfasthetsegenskaperna för några av de mest använda plasterna och några nylon baserade plaster som är populära i ingenjörssamanhang är studerade. De testade materialen sträcker sig från hårda till mjuka, gummiliknande material. Den svagaste länken i en 3D utskrift är ofta vidhäftningen mellan lagerna av plast som byggs upp i utskriftsprocessen. Faktorerna som påverkar lagervidhäftningsförmågan är undersökta.

Mätningarna är utförda med hjälp av en dragprovsmaskin på Blekinge Tekniska Högskola. Alla dragprovsstavar är tillverkade på Creative Tools AB i Halmstad med FFF 3D skrivarna Flashforge Dreamer och Makerbot Replicator 2X.

Brottgränsen för 3D utskriven PLA är uppmätt till 51 MPa. PET har en brottgräns på 40 MPa och ABS 34 MPa. Spännings och töjningsförhållandet visar att ABS är något mjukare än PLA och PET något mjukare än ABS. PLA är det hårdaste materialet i testet. Hänvisningar från dragprovsstandarder är utnyttjade men testen skiljer sig från standard på flera sätt. Mätdata som är presenterad i studien kan hjälpa designingenjören att välja den starkaste plasten för den unika applikationen.

Fem grundläggande inställningar är undersökta för lagervidhäftningspåverkan genom att mäta den maximala lasten en provstav klarar av när den är belastad tvärs lagerna. Fyra av inställningarna visar sig kunna påverka lagervidhäftningens maximala belastningskapacitet med 50 % eller mer vardera.

Resultaten i studien presenteras i grafer, diagram och bilder. Dessa kan hjälpa FFF 3D skrivaranvändaren att optimera inställningar för att förbättra styrkan i utskriften signifikant.

Nyckelord: *3D skrivare, brottgräns, lagervidhäftning*

Preface

This thesis project is written as a part of the five year programme Master of Science in Engineering, Mechanical Engineering with emphasis on Applied Mechanics at Blekinge Institute of Technology.

Big thanks to Creative Tools AB for providing me with all the means necessary to achieve my goals of this project. Huge thanks to Paulo Kiefe for the feedback and help he has given me. Paulo is a great role model and a good source for inspiration. Thanks to Thomas Palm for support and useful thoughts along this project's road. I would also like to thank Shafiqul Islam for assisting me with tensile testing. Finally I would like to thank my supervisor Mats Walter at Blekinge Institute of Technology.

Frans Johansson 2016-06-11

Nomenclature

Notations

Symbol	Description
σ	Tensile stress (MPa)
σ_M	Tensile Strength (MPa)
ε	Tensile strain (mm)
ε_0	Initial strain (mm)
ε_M	Tensile strain at tensile strength (mm)
ε_t	Nominal strain (mm)
E	Modulus of elasticity (MPa)
T_G	Glass temperature (°C)
T_M	Melting temperature (°C)

Acronyms

CAD	Computer Aided Design
3D	Three dimensional
FFF	Fused Filament Fabrication
FDM	Fused Deposition Modeling (synonym with FFF)
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
PET	Polyethylene Terephthalate
(N/A)	Not available
AM	Additive Manufacturing

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1 INTRODUCTION

1.1 Introduction

3D printing is the new and promising technology now everybody wants to explore. But the 3D printer is not something new, the first 3D printer was invented already 1983 [1], [2], but since then until a couple of years ago the patents have been closed and 3D printing has been a small market mainly for specialized enterprise. John Hornick & Dan Roland writes in 3Dprintingindustry.com. "It was the expiration of some Fused Deposition Modeling patents, such as U.S. Patent No. 5,121,329 to Stratasys's Scott Crump that apparently spawned a boom of growth in the consumer-level 3D printing industry." [3], [4]. In the last five years the interest has exploded and the number of sold consumer-level 3D printers have increased exponentially [5]. The trend seems to continue and many companies are planning to start using 3D printers in the near future [6].

The 3D printing manufacturing technique is interesting for a lot of reasons, a few of them are explained here. Compared to commonly used plastic manufacturing methods like injection molding, 3D printing is cheap and produces little waste, which also gives it an ecological advantage. 3D printing also allows for very complex geometries, which in many cases is an area where no other manufacturing methods can compete. The 3D printing technology is superior in speed when many unique pieces are being produced, when it comes to large quantities of the same product the 3D print is a bad alternative compared to molding techniques. The 3D printer can also be a very pleasant manufacturing tool for the not so skillful craftsman, a quite unique quality for a complex tool with this extensive capability.

This project focuses on FFF 3D printing technology, fused filament fabrication, also known as FDM, Fused Deposition Modeling. Essentially it is a process where plastic is deposited through a heated nozzle layer by layer. This is a relatively easy to handle and affordable type of printer. The FFF 3D printer is the most common 3D printing technique in the lower price market section. Today you can find FFF printers priced at 3000 SEK. Some advantages for this technique compared to other 3D printing techniques is that it offers a wide variety of material choices and is easier when it comes to handling.

For the first couple of years after the FFF patents was released the technology has been available mainly for enthusiasts and you could say it has been in sort of an experimental phase. In this period the development has been focusing on improving the machine for usability and esthetically good quality prints. It is not until now more sophisticated 3D printers has been hitting the market. A printer where you put in your digital model and get out a physical model in decent quality without any extensive maintenance or knowledge. Until now the focus has been on optimizing the software settings to produce clean and precise prototypes. The models being manufactured are often tests of concept, not actual useful and durable products [7].

1.2 Background

A new phase is emerging in the FFF 3D printing technology development where the 3D printed prototype is approaching a practical and lasting product. To be able to achieve this the user needs to know which settings are affecting the durability outcome and how to optimize settings and material choice to get a strong print. B. Wittbrodt and J. M. Pearce at Michigan Technology University writes "With the rapid growth of consumer FFF 3-D printing market and a large focus on providing useful, real-world applications of the technology comes an increasing demand to fully understand the material properties of the final 3-D printed components" [8].

Another aspect that indicates on missing information is seen on the majority of 3D printer plastic vendors here in Sweden. Very sparse or no information about the material properties is provided. For a design engineer it is key to have material properties in hand when choosing materials.

The 3D printing technology is not only promising on the professional and enterprise side, the interest for home 3D printing is growing rapidly. Some researchers say that a 3D printer in an average American household can save thousands of dollars a year in the best case scenario [9], this study can hopefully contribute in favor of this scenario.

In the most advanced type of 3D printing software you can choose between hundreds of parameters to tweak your manufacturing process, as a 3D printer user this will effectively give you infinite combinations, but also a lot of opportunities. Opportunities to optimize for durability.

1.2.1 About Creative Tools AB

"If you can place "3D" as a prefix or suffix to a product or phenomenon it is more than probable that we have it or are involved. Creative Tools is a reseller of market leading brands of software and hardware that relates to 3D technologies. We have been suppliers of solutions for 3D visualization and rapid prototyping since the nineties in one form or another.
Our customers span over very diverse market segments. From mechanical and electronics industries to game development and fashion design. Our motto is 3D – All things 3D." [10]. This is Creative Tools AB's official introduction.

Creative Tools is interested in examining the factors affecting mechanical properties of the 3D printed product. Their goal is to provide information to the community and customers to help them improve their 3D printing experience. Favorably the information should be easy to access and understand as well as there should be a possibility for contribution by the community.

1.3 Objectives

In this study the settings and material choice affecting the durability of a FFF manufactured part are examined. The intention is to learn how to use the FFF machine and software. Focus will be on optimize for durability with the basic and easily accessible tools available for all FFF 3D printer users. This data and information should be valuable for the whole range of users, from beginners to professionals. The goal is to produce valuable data to educate people to easier accomplish their goals of making useful and durable 3D printed parts.

1.3.1 Open source

This projects data and results will be free and open for everyone to use and be presented in the fairest possible manner. Johan Kristensson, area manager at the Swedish engineering consulting company Semcon writes “Open development is the way forward. By being open for impressions and interact with your surroundings you will be a part of a dynamic environment. You give and take.” [11]. The 3D printing community have achieved a great deal by having this open source philosophy. Having the data and measurements free is the natural way to go.

1.4 Delimitations

This project covers a few of the available settings and materials of FFF 3D printing. The most interesting settings and materials on a durability perspective are chosen based on investigation and prior experience. The possible factors affecting the 3D printed models durability are very many and only a small segment is covered in this study.

1.5 Thesis question

How do you optimize FFF 3D printing settings and materials choices for durability?

1.6 Process overview

An overview of the project process is shown in figure 1 below.

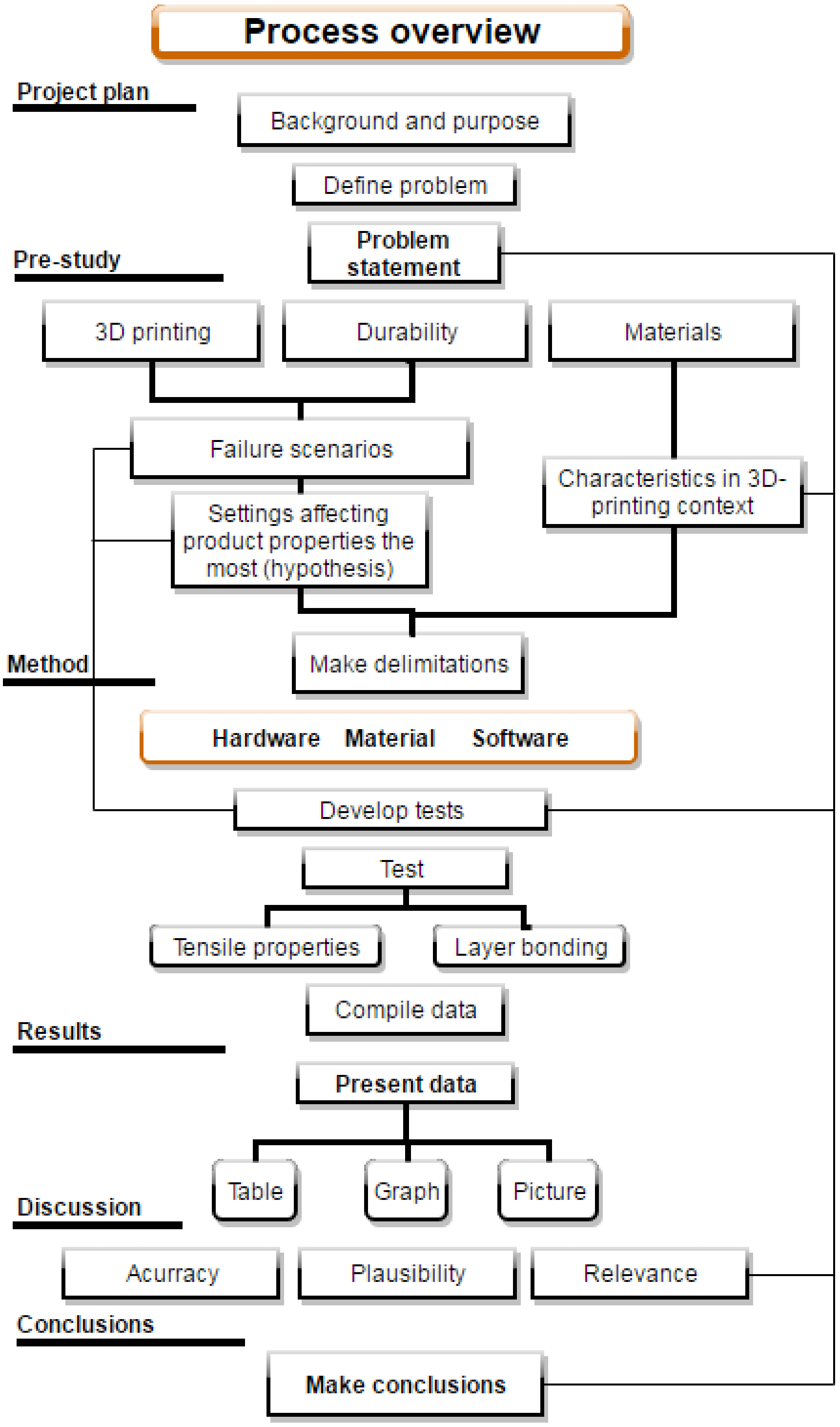


Figure 1: Project process overview

2 THEORETICAL FRAMEWORK

2.1 FFF hardware

The most commonly used 3D printing technique for the lower price segment is the FFF, fused filament fabrication. The FFF process is essentially a process where molten plastic is deposited in very precise strings on a building plate. Layer by layer your desired model is built up from a flat plane. An illustration of the basic FFF technique is displayed in figure 2.

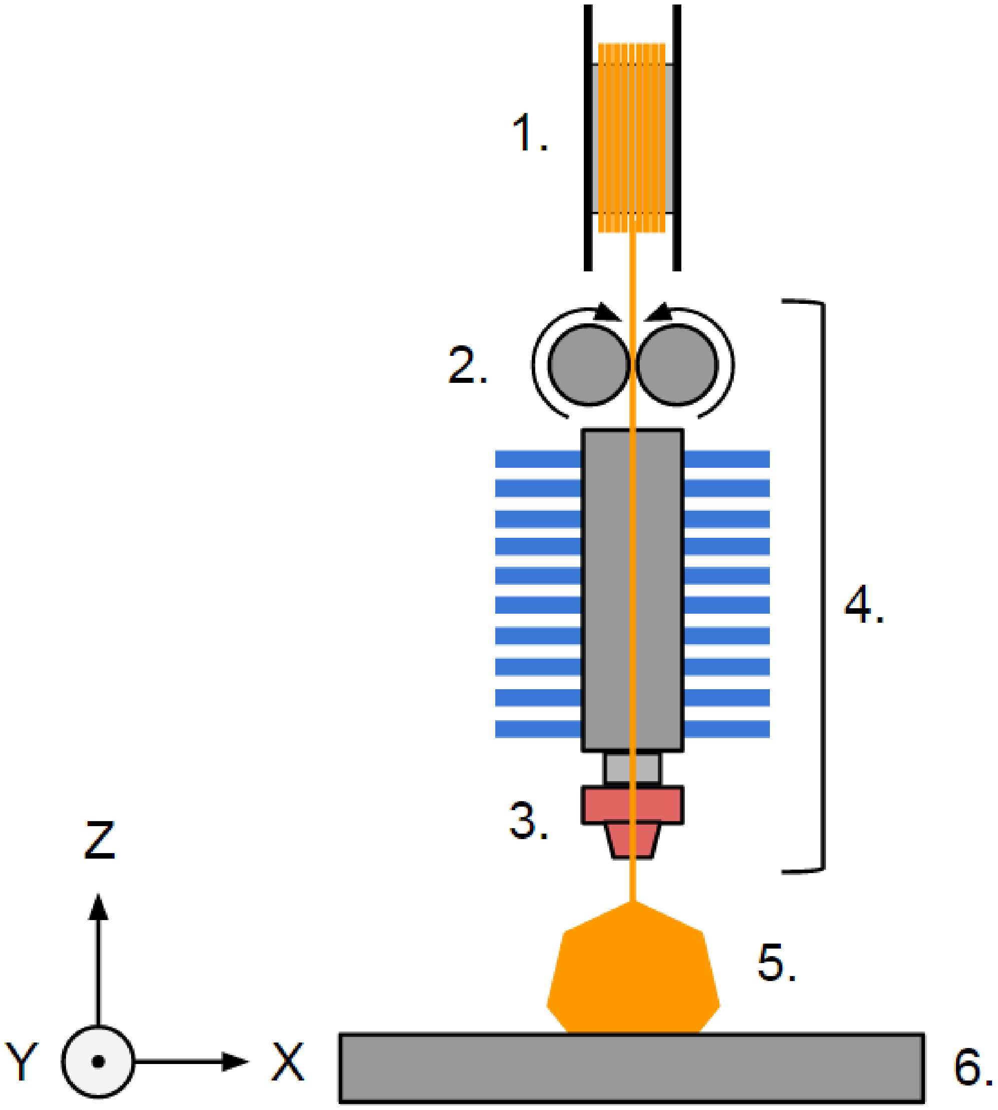


Figure 2: Fused filament fabrication illustration, not to scale

1. Plastic thread also called filament in 1.75 mm or 3 mm diameter on a spool is the primal material.
2. The filament thread is fed down with high precision.
3. A heated nozzle is melting the plastic and reducing the diameter of the thread to about 0.4 diameter.

4. The printer head or also known as extruder is moving in 3D space relative to the bed. Motion is often translated into x, y and z axis. Each axis controlled by one or more stepper motors.
5. The model stuck to the bed.
6. The bed or also called building plate.

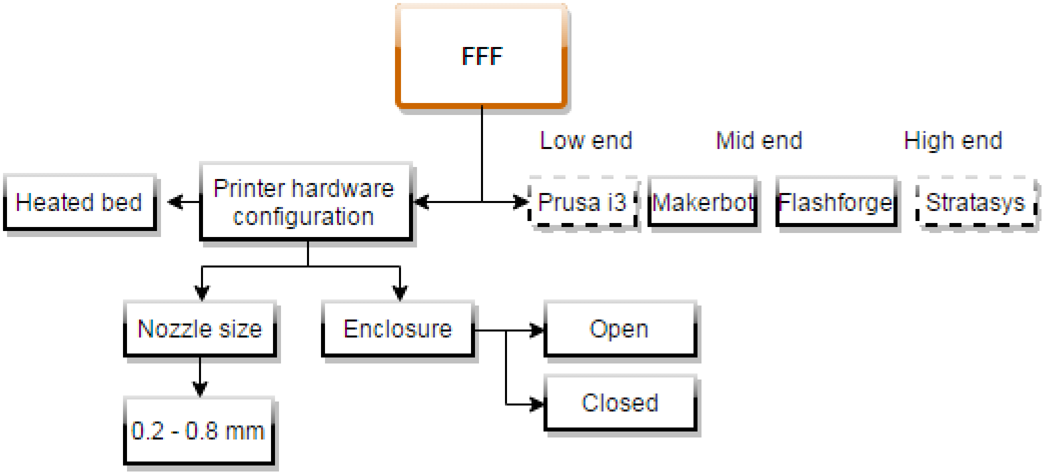


Figure 3: Hardware options overview of FFF

The essential hardware configurations available of Fused Filament Fabrication is presented in figure 3.

2.1.1 Printer construction

The 3D printer frame is providing motion for the extruder or the bed in a three dimensional space. Most printer frames are made from plastic, metal or wood. Extruder or bed is often translated along polished metal rods with linear bearings. Force is provided with stepper motors with attached drive belts or threaded rods.

2.1.2 Enclosure design

Some 3D printers has a shielding enclosure covering the building plate. The enclosure can be actively cooled or heated so that the printed part has a constant ambient temperature. This feature is often provided on more expensive printers.

2.1.3 Nozzle size

The nozzle can be of various diameters, 0.4 mm is typical. With a wider nozzle it is possible to extrude more plastic at a time. A smaller nozzle size enables for printing with higher resolution.

2.1.4 Heated bed

Some printers comes with the option of heating up the building plate. This helps the model to adhere to the bed but also to reduce uneven shrinkage during the printing process. For materials like ABS a heated bed is very useful.

2.1.5 Room & ambient temperature

The present room temperature is also a factor that can affect the printing process. The room temperature will have a slight effect on the true temperature of the nozzle and heated bed. It will also affect the speed of which the plastic cools down. If the printer has an open design. The room temperature and ambient temperature will be the same. Some printers features an enclosure design. This creates a more controlled atmosphere around the printing process.

2.2 FFF Software & settings

Every line and layer in the manufacturing process is generated in the so called slicing procedure. The following settings are conventionally used to adjust and compromise between printing time and visual quality. They are also tweaked for the particular plastic used. The slicing programs are made with that in mind. This report will not cover how settings are affecting the visual quality of the 3D printed part in depth. There are very many parameters to tweak in the slicing program. The most basic software options are shown in figure 4.

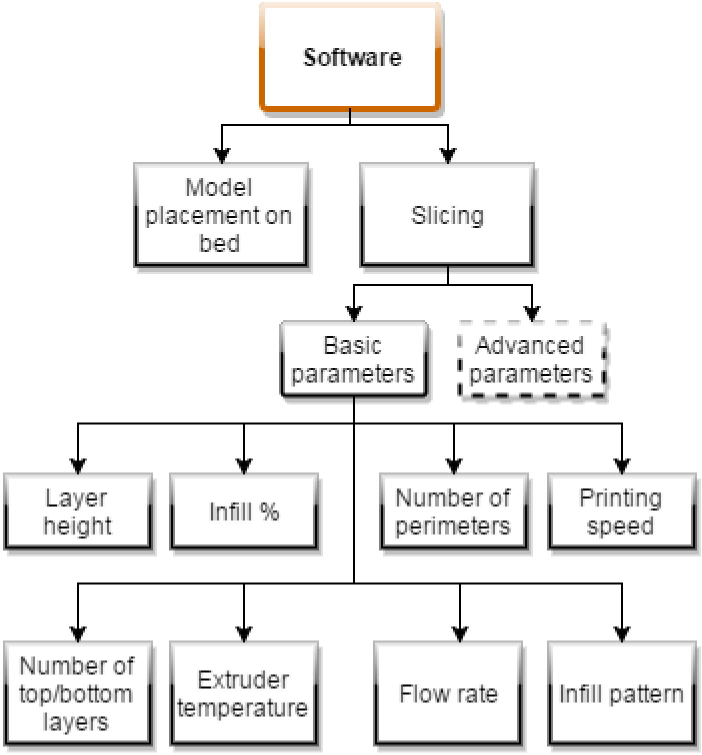
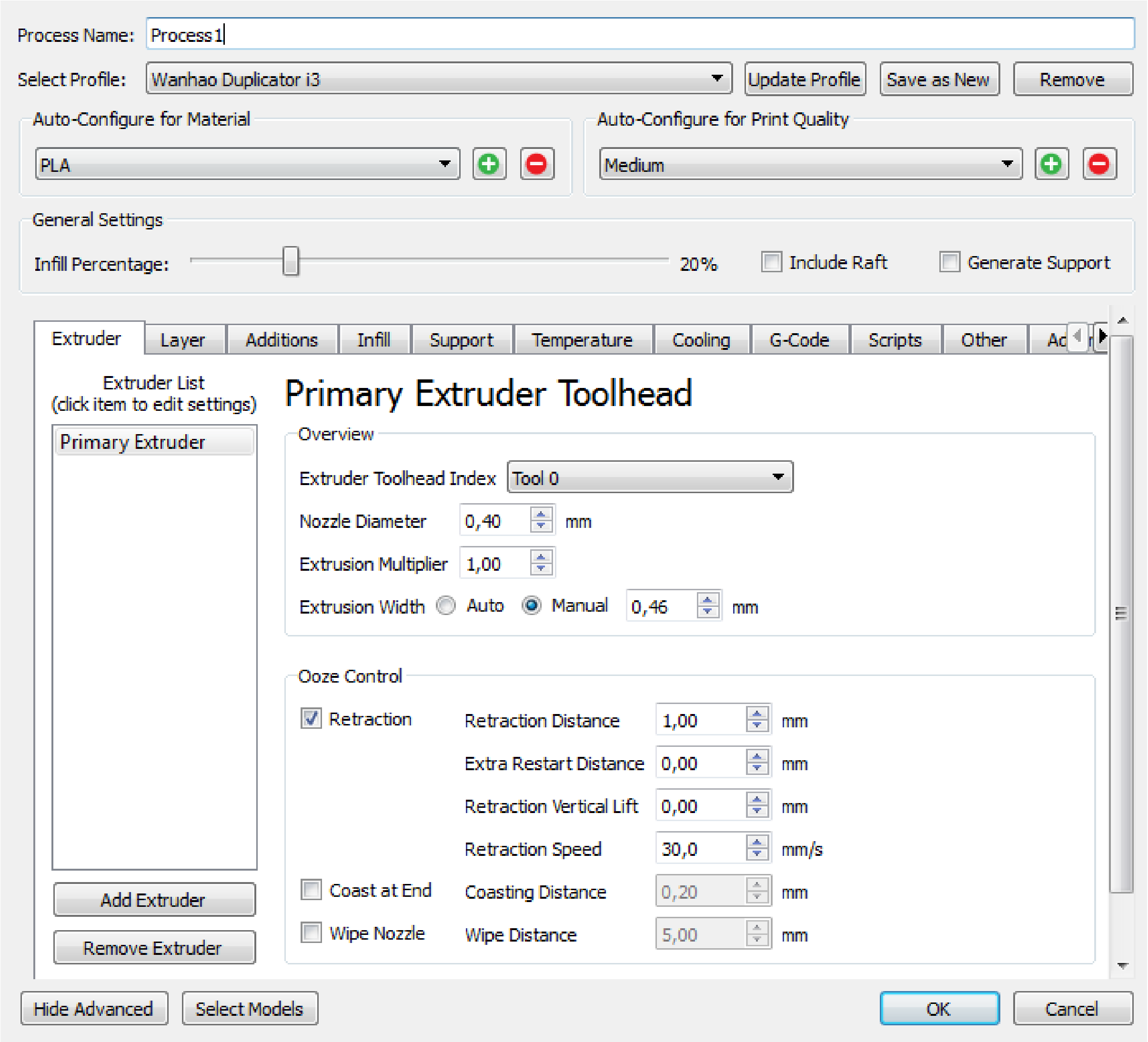


Figure 4: Software options overview of FFF

2.2.1 Slicing software

The commonly used CAD file format used in 3D printing is .STL, this is a format where the CAD file is only represented in surface geometries consisting of polygons [12].
When you have prepared your .STL file it is time to convert the model to an X, Y and Z based code that the printer can read, this code is called a g-code. As the 3D printer is using X, Y and Z coordinates to navigate this code is needed.

The process where a .GCODE is generated in 3D printing context is called slicing. Figure 5 is showing the interface of the slicing software Simplify3D.



Process Name: Process1

Select Profile: Wanhao Duplicator i3

Auto-Configure for Material: PLA

Auto-Configure for Print Quality: Medium

General Settings

Infill Percentage: 20%

☐ Include Raft

☐ Generate Support

Primary Extruder Toolhead

Overview

Extruder Toolhead Index: Tool 0

Nozzle Diameter: 0,40 mm

Extrusion Multiplier: 1,00

Extrusion Width: ○ Auto ● Manual 0,46 mm

Ooze Control

☑ Retraction

Retraction Distance: 1,00 mm

Extra Restart Distance: 0,00 mm

Retraction Vertical Lift: 0,00 mm

Retraction Speed: 30,0 mm/s

☐ Coast at End

Coasting Distance: 0,20 mm

☐ Wipe Nozzle

Wipe Distance: 5,00 mm

Figure 5: Simplify3D slicer software interface

There are a wide variety of available slicing software. Some that are very simple to use and have few settings to very advanced slicing programs that have hundreds of settings. Usually the 3D printer brand has its own dedicated slicing software, these software are often very basic.

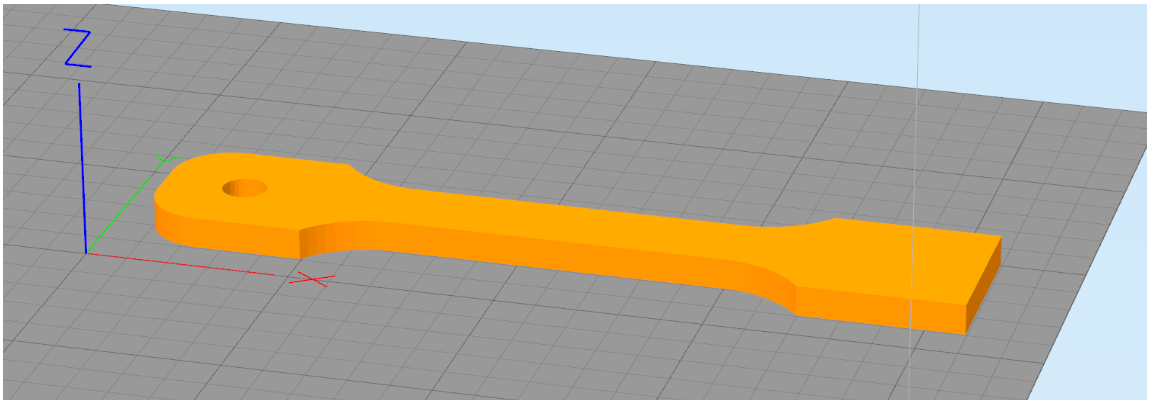


Figure 6: 3D .STL Model placed on the virtual bed in Simplify3D

Figure 6 shows the specimen placed flat on the building plate virtually in the slicing software. X, Y and Z axis directions are shown.

2.2.2 Layer height

Layer height decides on how high each layer will be, in other words how much the extruder is translated in Z direction for each layer shift. Figure 7 shows a layer height of 0.3 mm.

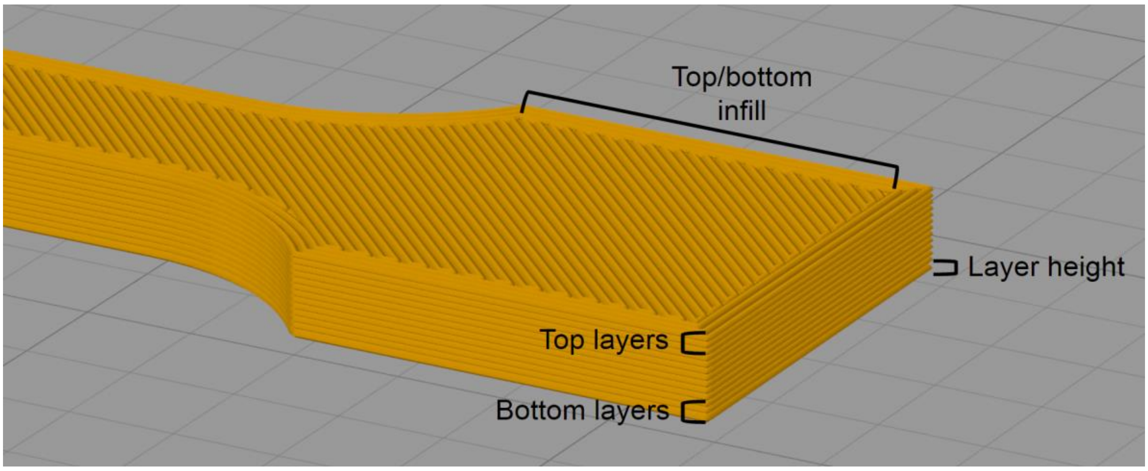


Figure 7: Slicing preview of the specimen showing layer height, top/bottom layers and top/bottom infill

2.2.3 Top & bottom layers

In the slicing software you can choose a number of solid top and bottom layers your model should have. Figure 7 shows a solid rectilinear pattern for top and bottom layers. In figure 7 there are 3 top layers and 3 bottom layers.

2.2.4 Perimeters

The perimeters or shells, often set to be a 1-4, are the number of outlines of the geometry. Figure 8 is showing 3 perimeters.

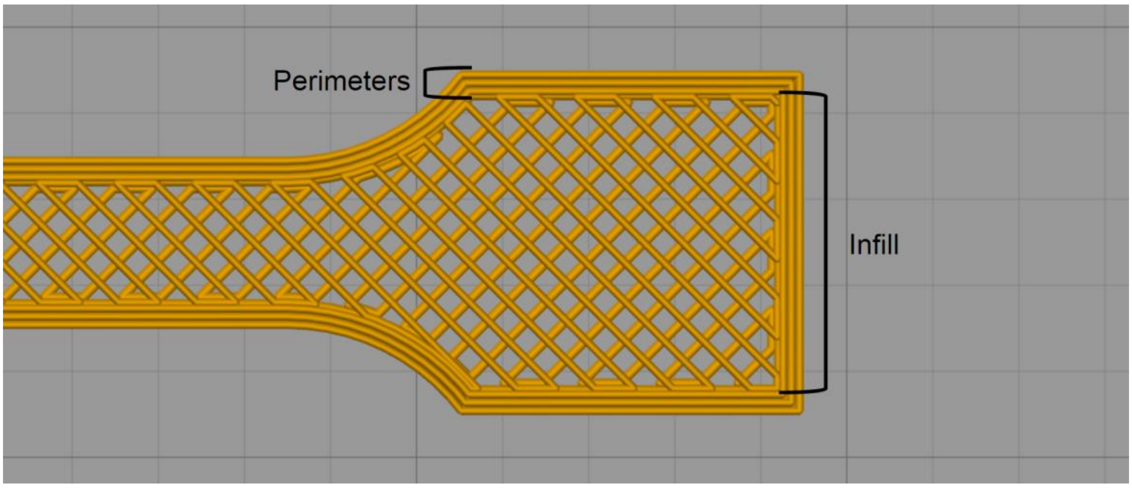


Figure 8: Slicing preview of cross section of the specimen, revealing perimeter and infill pattern

2.2.5 Infill

This setting is deciding the density of plastic filling the model inside of its perimeters, bottom and top layers. The infill has a specific pattern and is specified in percentage altering the density of the pattern. Figure 8 is showing the sliced model without top and bottom layers to reveal the infill of the model. In this particular case it is set to 30 % with a rectilinear patterned infill.

2.2.6 Extruding temperature

The temperature of the heated nozzle. In theory the temperature of the plastic has when it is extruded. For the most commonly used FFF 3D printing materials this is between 190°C and 300°C. When 3D printing the extruder temperature is one of the most important parameters to consider. It is necessary to adjust the temperature depending on many factors. One of them is material. Generally a plastic with lower glass transition temperature needs a lower extrusion temperature. The difference on how the plastic behave under the printing process may vary between some polymers.

A phenomenon that is of great importance when 3D printing is how the plastic behaves the seconds after it has been extruded to the model. This naturally depend on what the plastic string hits when it comes out of the nozzle but also the plastics' temperature and the ambient temperature. If the plastic is extruded on a narrow area on the preprinted layer, for example on models with overhang relative to the printing bed. The plastic may due to gravitational be deformed causing the model to diverge from the intentional geometry. This is something that can be partly avoided by adjusting the extruding temperature and use of a cooling fan blowing cool air where the plastic is extruded, this is called a nozzle fan. This phenomenon is very influenced by the particular material used.

2.2.7 Printing speed

The printing speed is the speed which the extruder moves in X and Y direction. This is usually set between 20 mm/sec and 150 mm/sec.

2.2.8 Added plastic to the part

The amount of plastic added in the 3D printing process is determined and affected by a lot of factors. The actual plastic added is therefore very hard to know. How much plastic that is extruded from the nozzle is controlled by how much the extruder motor is turning. How much the motor will turn is depending on very many factors. It is automatically altered with the change of for example layer height or the setting for filament diameter. If you have a higher layer height of course more plastic needs to be extruded or if you use a thicker filament it needs to be less. To accurately alter and measure the amount of plastic extruded to the model is very hard.

2.2.9 Model placement on bed

In the slicing software you can decide how the model should be oriented on the building plate. Naturally this affects how the layers are arranged in the final part. This will be explain in depth in the following chapters.

2.3 Polymers

Plastic is defined as the technically useful product of one or more polymers [13]. A plastic does not usually only contain the polymer but also a variety of other substances, such as stabilizers or fillers. A polymer is a substance which has an exceptionally long molecular chain length. The chemical reaction which the polymer is made in is called polymerization. This is a process where substances with a short molecular chain length is combined to create a larger one. Like other organic compounds the polymer is softening at relatively low temperatures, their hardness or stiffness will be substantially lower than materials like ceramics or metals.

It is useful to know the molecular structure of polymers to understand the material's properties. Because the chain structure of the polymer greatly influences it mechanical properties. The fact that the chemical binding force between the chains are much lower than between the molecules of the chains themselves means in practice that no material is stronger than the weakest binding force. This is important to take into account when evaluating softening temperatures and stiffness properties.

Polymers can be categorized into three types:

Native polymer or biopolymer. For example cellulose or starch based polymers like PLA.
Semi-synthetic polymer. Chemically modified biopolymers. For example cellulose diacetate or vulcanized rubber.
Synthetic polymer. For example ABS and PET.

As explained before the molecular structure of a polymer is of great importance. Some basic structures are:

1. Linear, the simplest form of a chain. It has no branches
2. Branched, a molecular structure which has attached chains from its length.
3. Network, a three dimensional network of cross linked chains.

The three structures has the basic look as seen in figure 9.

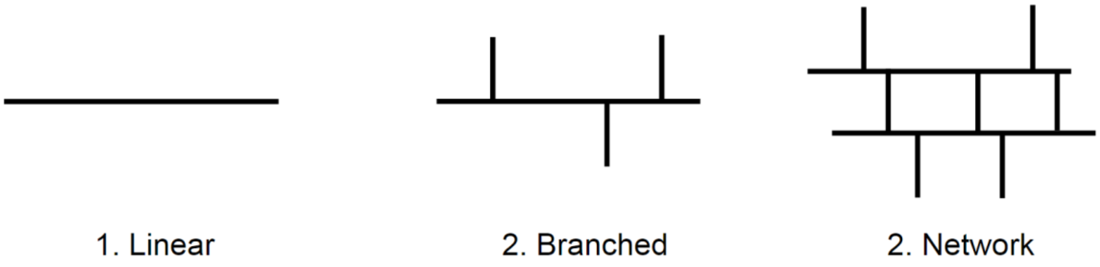


Figure 9: Illustrations of three basic polymer structures

Plastics of linear or branched kind are called thermoplastics. The forces between the molecules are weak so called van der Waals attractive forces. If the material is heated these forces will loosen up, making the material soft. If heated up further the material will transform into a plastically formable melt. Theoretically the thermoplastic can be melted and solidified an infinite number of times, but chemical degradation is setting a limit.

Polymers with molecule chains in a network are called a thermosetting polymer. In this case the polymerization and hardening process are the same and this is when the molecule chains are crosslinked. The hardening process of thermosetting plastics is irreversible unlike thermoplastics.

2.3.1 Polymer morphology

The term morphology generally describes the arrangement of the molecular chains in the polymer. If the polymer's chains are simple and symmetrically arranged it is called a crystalline polymer. The chains are never perfectly symmetrical and therefore not perfectly crystalline. However a partly crystalline polymer is often called just crystalline.

If the polymer's chains does not arrange in a symmetrical pattern they are called amorph. The amorphous polymers has randomly arranged molecular chains. Plastics with this structure has a glass-transition temperature, T_G, on which they get soft but do not melt. The principal chain structure for amorphous, semi-crystalline and crystalline is show in figure 10.

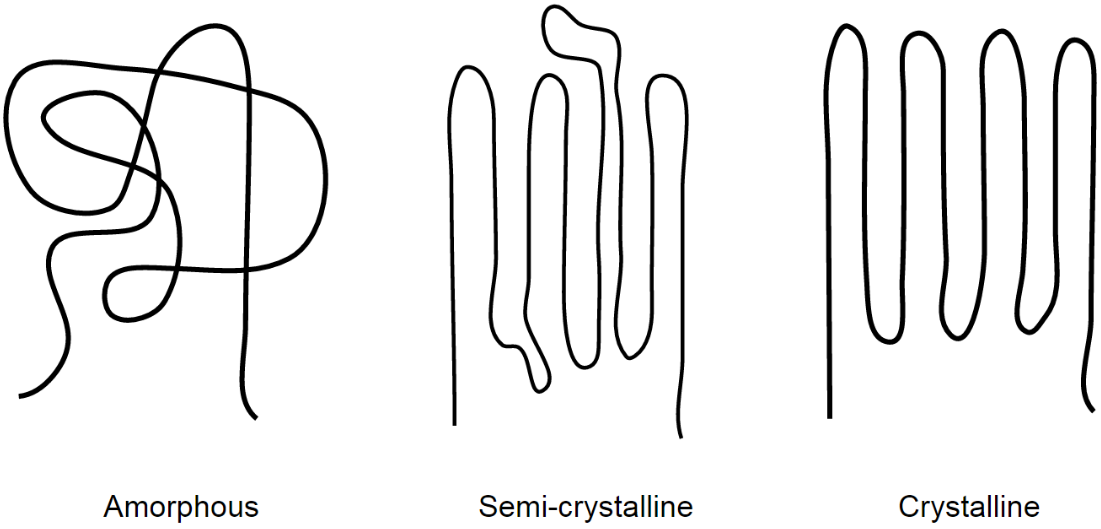


Figure 10: Illustrations of basic polymer morphology pattern

When a crystalline polymer reaches its melting temperature, T_M, the symmetrical pattern loosen up. As no polymer can be perfectly crystalline all thermoplastics have a T_G and a T_M. When a semicrystalline polymer reaches its melting temperature the symmetrical chain structure loosens up. At T_G only the amorphous part of the crystalline polymer gets loose. In practice this means that T_G only has a slight effect to the mechanical properties of a crystalline polymer.

For amorphous plastics T_G is very important. The value is often set in the middle of the range in which the material softens. The interval is relatively wide, normally $T_G \pm 10°C$. At this interval and above the E-modulus of the polymer drastically decreases.

2.3.2 Molecular weight

Another property of molecular level that is of importance is the molecular weight. This principally measures the length of the molecular chains. The molecular weight is very important when it comes to forming the material. The viscosity of the polymer in its molten form is greatly dependent on its molecular weight. When manufacturing products with injection molding the plastic need to be fluid when heated. A polymer with low molecular weight is preferable. This is to make it possible for the plastic to run through small mold channels. For extrusion methods it is possible to use more viscid polymers, in other words higher molecular weight. A high molecular weight are generally more difficult when it comes to orientation related deformations as well as residual stresses.

2.4 Mechanical properties for plastics

Compared to metals or ceramics the polymer’s material behavior under load significantly depends on temperature and time. Mechanical calculations for plastics are often much more complicated compared to metals. When making structural components in plastic materials they are often designed to withstand maximum 25 % of their tensile strength under continuous conditions. This is a good guideline that will compensate for effects like creep [14]. Some of the polymers considerable properties are briefly covered below.

2.4.1 Shrinkage

All thermoplastics will shrink when cooled down. Some may shrink several times more than other polymers. If the plastic is cooled down too fast in the printing process the model can deform and come loose from the printing bed. This is especially a problem when printing materials like ABS that has a high shrinkage factor. The ABS also has higher T_G as PLA. When cooled from T_G to room temperature the ABS will shrink more.

2.4.2 Residual stresses

The polymer's chain pattern and orientation may be changed from its natural state if it is cooled fast. A melt that is cooled too rapidly may cause the chains to get stuck in a non-relaxed form causing internal residual stress in the material. These stresses will introduce an increased risk of several problems, for example cracks and warping. The residual stresses may decrease the expected mechanical strength of the product. The cooling process is therefore very important to consider. When heating the plastic a significant phenomenon to know is that cooling speed is exponential relative to temperature. If the plastic have a higher temperature when injected to a mold it will cause it to cool of more rapidly.

2.4.3 Crystallinity

The crystallinity of the polymer is dependent on temperature change. Crystallinity can also be affected by additives in the polymer, like color additive. The degree of crystallinity of the polymer will have effect on the mechanical properties.

2.4.4 Creep

Under relatively low loads a plastic will slowly start to deform, a phenomenon called creep. The elastic part of the plastics elongation during load is short compared to metals.

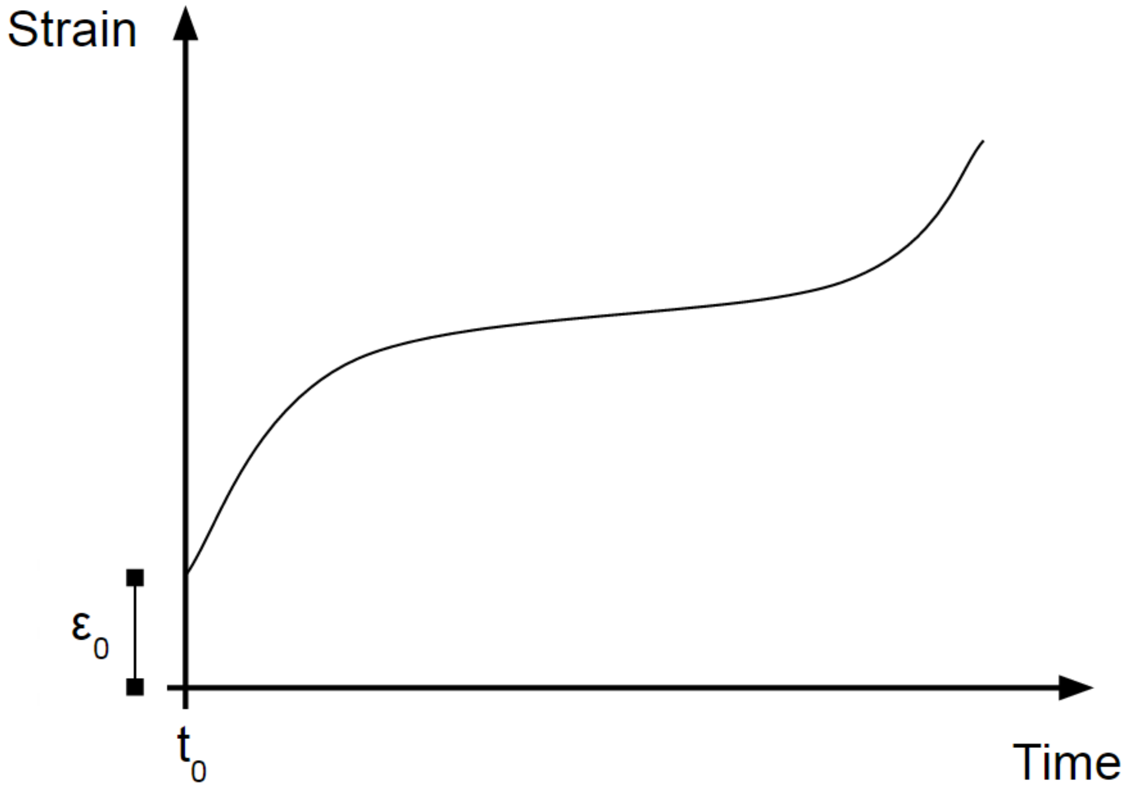


Figure 11: Strain by time of a polymer under static stress

Figure 11 shows a typical creep behavior of a polymer under static stress. Time scale several hours or more [14].

2.5 Tensile testing

To test and compare materials mechanical properties there are a variety of conventional methods. Many has good standardization background. These standardization documents will provide methodology enable one to make accurate and comparable tests.

A conventional way to test plastic is tensile testing. This is done under specific conditions. A specimen is mounted in two grips. The grips will slowly start to move away from another, putting the specimen under load. The displacement and force is measured during the pulling action. It is carried out under a set strain rate. For plastics the strain rate is about 1 mm/min [15], [16]. The described tensile testing is not considering the decreasing section area when the specimen is extended, this is called engineering stress-strain. A tensile test is illustrated in figure 12.

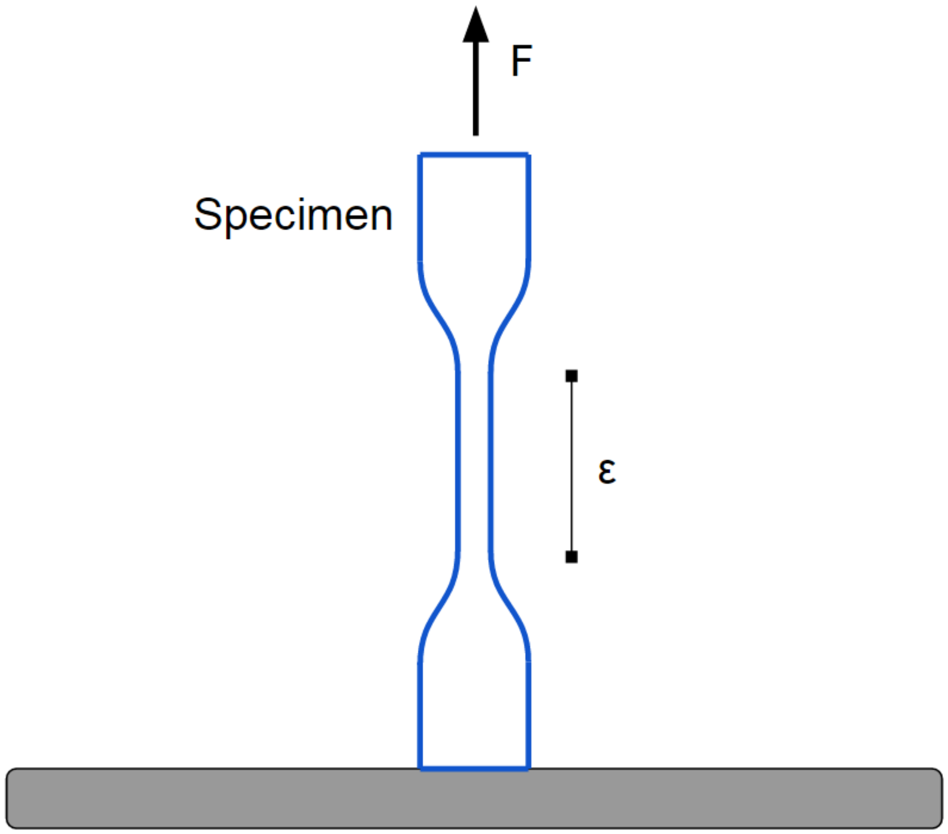


Figure 12: Illustration shows how specimen is loaded and how strain is measured

Some basic definitions of tensile testing are:
Tensile stress σ**,** is the force per unit area in the specimen.
Tensile strength, maximum tensile stress, ultimate tensile strength σ_M**,** is the maximum stress under the tensile test.
Tensile strain ε, the increase in gauge length relative to the initial gauge length.
Tensile strain at tensile strength ε_M**,** is the strain point at which the material reaches its maximum stress.
Yield stress σ_Y, the stress at which necking occurs.
Nominal strain ε_T, increase in length between specimen grips.
E-modulus E, inclination of the initial linear part of the stress-strain curve.
[15], [16].

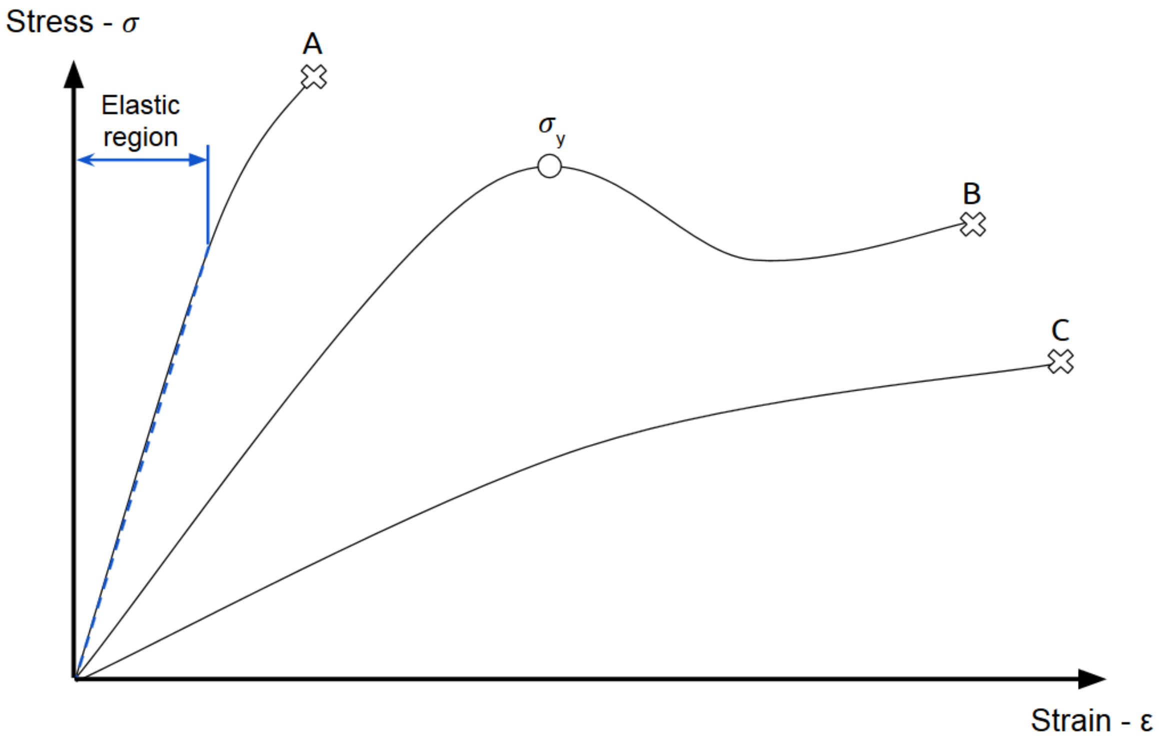


Figure 13: Three types of materials typical stress-strain behavior

A. Brittle fracture
B. Tough fracture
C. Elastic fracture

Figure 13 shows typical behavior of three different categories of materials. Graph with end A has a stress strain correlation typical for a brittle material. B shows a tensile graph for a tough material with a yield stress, σ_Y, at which necking occurs. Graph C has typical behaviour for a very elastic material. Within the elastic region the material will regain its original shape when unloaded.

2.5 Material properties

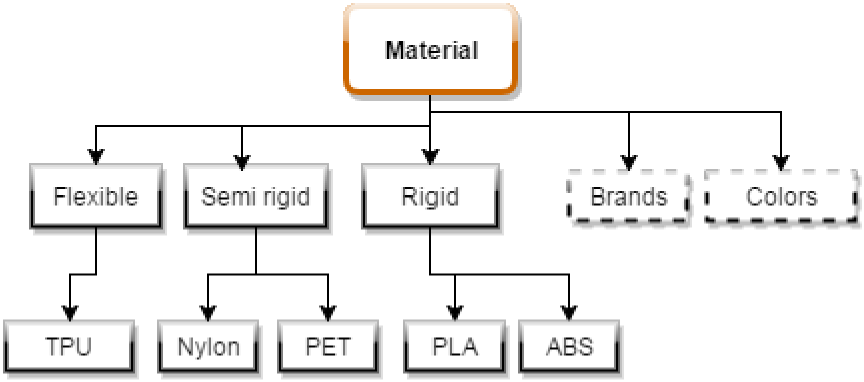


Figure 14: Material options of FFF

There are many types of plastics to choose from when printing with FFF. Some are well known basic polymers like ABS and PET. Some filaments are especially made for 3D printing and are therefore not so well known. Some of the most common filaments are presented in figure 14. For 3D printing purpose a polymer with relatively low glass transition or melting temperature is suitable. Most FFF 3D printers have a maximum extrusion temperature of about 300°C. Data about a few of the most used polymers in 3D printing is provided in table 1 below.

Table 1: Properties of some common polymers, approximate values from various sources, /Standard used/ [17]-[21].

	T_M (°C)	T_G (°C)	**Tensile strength (MPa)**	**E (MPa)**
ABS	N/A	110	40-48 /ISO 527-2/	1730-2760 /ISO 527-2/
PLA	160	50	48-70 /ASTM D638/	310-5600 /ISO 527-2/
PET	250	75	55-75 /N/A/	2700-3100 /N/A/

2.5.1 ABS

Acrylonitrile butadiene styrene is an amorphous and non-translucent plastic derived from petroleum resources. ABS is a very commonly used polymer and is popular for a lot of reasons. It has good properties for injection molding and machining is easy. The polymer is inexpensive to manufacture and has good resistance to corrosive chemicals. The ABS has also good mechanical properties like stiffness and impact strength. Common applications are keyboards and LEGO [19].

2.5.2 PLA

Polylactic acid is a biopolymer based on renewable raw materials as sugar or corn. It is cost efficient to produce and biodegradable. Commonly the PLA is used for plastic films and bottles. The PLA has good mechanical properties like tensile strength and hardness. This polymer softens at relatively low temperatures and is therefore not suitable for working temperatures over 40°C [22].

2.5.3 PET

Polyethylene terephthalate is the fourth most produced plastic. PET can be semi crystalline or amorphous depending on processing and thermal history. The polymer is lightweight and has very good impact strength. Uses are bottles and other food packaging [20].

2.6 Sustainability

From a sustainability perspective the FFF 3D printing technique offers some very interesting features. This manufacturing method will generate an extremely small amount of waste product. 3D printing is known as an Additive Manufacturing method, AM, and needless to say that is using only the material you need for the produced part. In contemporary to machining where the material is successively removed from the object.

The most popular plastic for FFF 3D printing is the biopolymer PLA. Creative Tools AB, one of Sweden's biggest reseller of 3D software and hardware says that 90 % of their filaments sold is PLA. This plastic is made from starch. The raw product is corn, potatoes, wheat or beets. This means that the majority of PLA compound is made from renewable resources. The resources are also flexible, not limiting the manufacturers to only one resource.

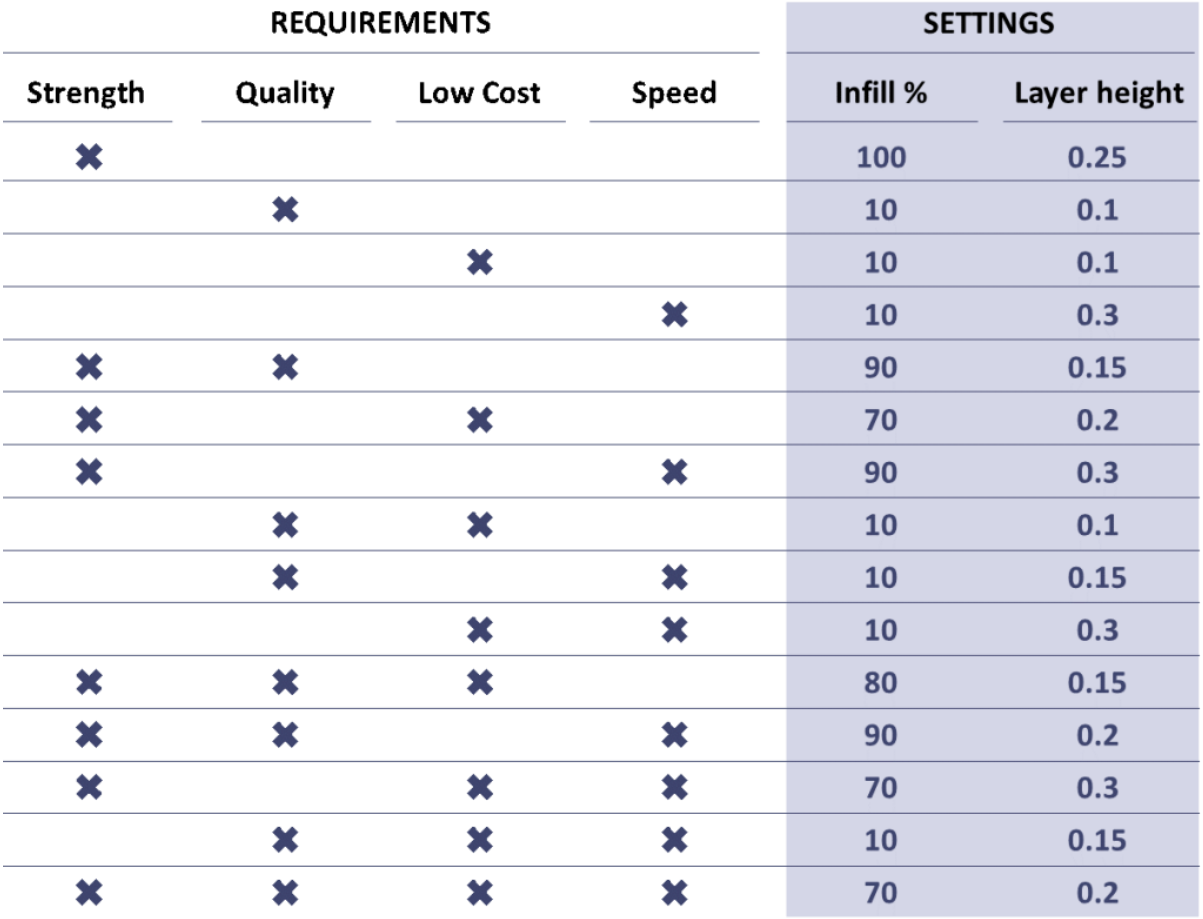
PLA consumes less energy and emits less greenhouse gases when produced compared to commercial plastic in for example soft drink bottles. The plastic is also recyclable at some facilities and biodegradable in commercial composts [23]. From a sustainability perspective PLA comes with a lot of benefits.

Another ecological aspect is that the 3D printer can provide a locally based manufacturing for a wide variety of products. Many products manufactured far away from the consumer may be produced locally and transportation is unnecessary. If 3D printers are wisely implemented there are a lot of potential for reduction of fossil fuel consumed by shipping vehicles.

In the future it is possible that every household can have a 3D printer to be used for manufacturing products. Digital files for all possible things can be downloaded from the internet then produced in your own home. A few raw materials stored at home can be used to make a vast variety of products.

2.7 Earlier studies

An extensive study made by 3D Matter shows how infill, layer height and infill patterns affecting the strength, print speed and visual quality. 3D Matter did tensile test on specimen similar to the ASTM D638 standard but did not follow the standardized tensile test procedure. The key findings of 3D Matter’s study are beautifully presented in two tables, see figure 15 and 16. These tables allow you to pick out the best combination of strength, print speed, cost and visual quality by your own preferences by adjusting infill and layer height. The study also includes a test of 5 infill patterns. The test shows that the infill pattern may significantly affect the strength of the 3D printed part [24].



REQUIREMENTS				SETTINGS	
Strength	Quality	Low Cost	Speed	Infill %	Layer height
✖				100	0.25
	✖			10	0.1
		✖		10	0.1
			✖	10	0.3
✖	✖			90	0.15
✖		✖		70	0.2
✖			✖	90	0.3
	✖	✖		10	0.1
	✖		✖	10	0.15
		✖	✖	10	0.3
✖	✖	✖		80	0.15
✖	✖		✖	90	0.2
✖		✖	✖	70	0.3
	✖	✖	✖	10	0.15
✖	✖	✖	✖	70	0.2

Figure 15: Preferred settings to use for the specific application based on four major requirements [24]

Strength [MPa]		Infill %						
		10	30	50	70	80	90	100
Layer Height [mm]	0.1	8	12	17	25	29	33	39
	0.15	9	14	20	28	33	38	44
	0.2	10	15	21	30	35	40	46
	0.25	10	15	22	31	37	42	49
	0.3	10	15	22	31	36	42	48

Speed [mins]		Infill %						
		10	30	50	70	80	90	100
Layer Height [mm]	0.1	21	35	47	61	68	74	80
	0.15	14	23	32	41	46	50	54
	0.2	10	18	24	31	35	38	41
	0.25	8	14	20	25	28	31	33
	0.3	7	12	16	21	24	26	28

Cost [cents]		Infill %						
		10	30	50	70	80	90	100
Layer Height [mm]	0.1	6	9	13	17	18	21	22
	0.15	6	10	14	18	19	21	23
	0.2	6	10	14	18	20	22	23
	0.25	6	10	14	18	20	22	23
	0.3	6	10	14	18	20	22	23

Quality		Infill %						
		10	30	50	70	80	90	100
Layer Height [mm]	0.1	very high						low
	0.15	high						
	0.2	medium						
	0.25	low						
	0.3	very low						

BEST 🟩 ⟷ 🟥 **WORST**

Figure 16: Trade-offs when choosing infill and layer height [24]

3D Matter also makes some conclusions about the anisotropy nature of the FFF technique. Tensile strength under some specific conditions are found to be 20 % to 30 % weaker if the specimen is printed with the layer direction across the load direction, in other words the specimen is printed vertically on the building plate. Maximum elongation were found to be about half in this case.

I will present some 3D printing related conclusions of research made by a couple of researchers at Michigan Technological University. They examined for example if RepRap 3D printers can compete with more expensive commercial machines. RepRap 3D printers are a family of 3D printers that are based on open source. RepRaps are often cheap to build and many posterity commercial 3D printers have large influence from the RepRap family. Some of the most popular budget printers on the market, like the Wanhao Prusa i3 and Makerbot Replicator have their roots in RepRap community developed designs.

Specimen fabricated in PLA and ABS with various RepRap printers were tested under standardized tensile tests to determine their mechanical properties. Standard ASTM D638 were used but the test diverged from the standard because of variability of specimen geometry and uncontrollable specimen conditioning. The average tensile strength of PLA were found to be 56.6 MPa and E modulus 3368 MPa. For ABS the tensile strength was 28.5 MPa and E modulus 1807 MPa. This test shows that components printed with cheap, open source FFF 3D printers are comparable to parts printed with commercial FFF 3D printers. The results vary significantly from machine to machine as well as with different slicer settings and model bed orientation [25].

They conclude that the FFF technology can fabricate parts with consistent material properties. It is also possible to estimate the part’s properties using the presented data. The material properties will be filament color and printing temperature dependent. Another conclusion they make is that there seems to be a critical printing temperature for the individual color to optimize strength. The printing temperature and color will affect the plastics crystallinity and ultimately its strength [8].

2.8 3D printing & durability

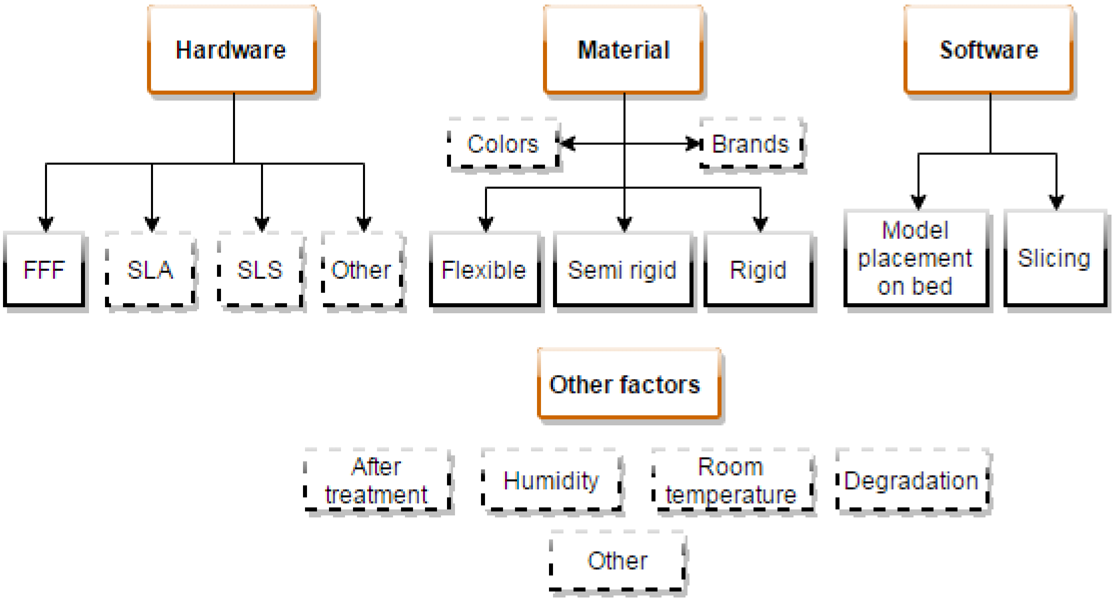


Figure 17: Overview of available options of FFF

3D printing offers a wide variety of hardware, materials and software. Some of the most essential is shown in figure 17. There are more than 100 parameters to choose from in the more advanced slicing software. The range of available hardware and materials are huge. All these factors will affect the final product in one way or another. Ultimately affecting the durability of the product as well. The combinations of temperatures, plastic flow, speed and etcetera are endless. A massive delimitation of parameters to test is necessary.

2.8.1 Visual quality

Sometimes a single parameter or a combination of parameters will result in gaps, holes or other unwanted features in the printed model. Slicing parameters have a potential of affecting the durability of the 3D printed product.

Conventionally when choosing settings for your print it is based on visual quality, print time and strength. Strength is normally assumed to be equivalent to the amount of plastic added to the part, that is number of perimeters, infill and so on. The compromises made are illustrated in figure 18. The compromise between strength and visual quality is not so well know.

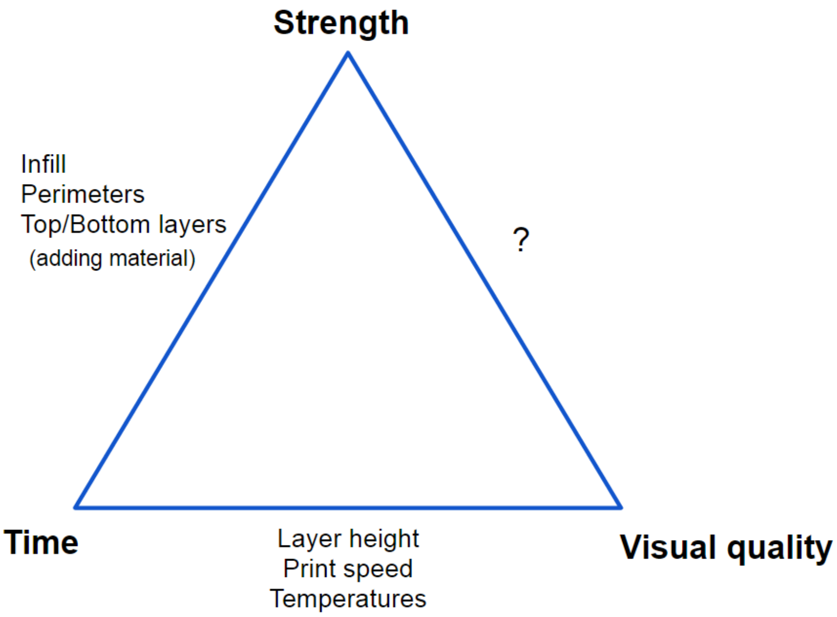


Figure 18: Conventional compromising triangle of 3D printing

Slicing parameters are often tweaked for esthetical and printing speed optimization. It is not possible to print all kinds of combinations therefore the parameters must always be chosen so it is even possible to print the product.

A lot of times if a product looks visibly good it will perform well mechanically. For example, if it is easy to spot holes and gaps in the product the product will most likely perform bad in for instance a tensile test.

2.8.2 Anisotropy & layer bonding

The layer arrangement is determined by the placement of the model on the bed. Normally the strings of plastic are added in parallel strings for each layer. If these strings do not melt together perfectly it is reasonable to assume that the part will have an anisotropic nature. The maximum load the part can withstand can differ depending on the load direction relative to the layer arrangement, figure 19 show three examples of load directions relative to layer direction. The elongation may be different as well. This can be explained by the analogy with rubber bands. Many thin rubber bands will elongate more than one with the combined thickness as solid.

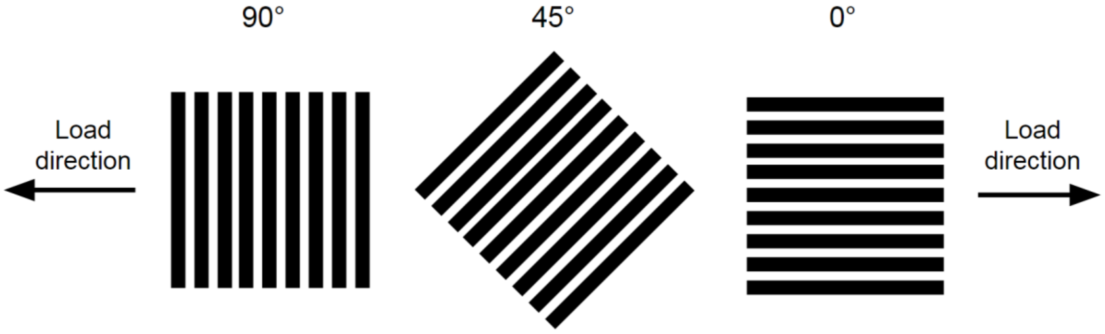


Figure 19: Load direction relative layers

In conventional plastic manufacturing methods like injection molded the plastic product can be said to be close to isotropic, which means the material have the same properties in all directions. For 3D printing this may not be true. The plastic is extruded in complex patterns and the final properties of the part may differ significantly from the equivalent part manufactured with for example injection molding.

The layer on which the extruder puts another layer of plastic is already cooled down to a significantly lower temperature compared to the extruded plastic. Figure 20 shows how the temperature decreases for each layer.

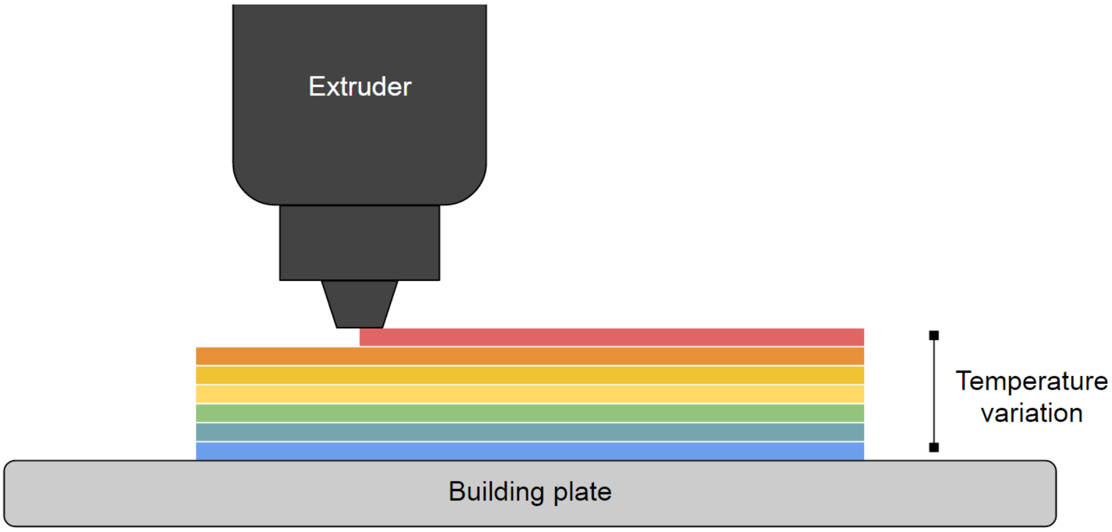


Figure 20: Temp variation by each layer

The difference in temperatures for each layer will cause the plastic to not melt perfectly together. There may also be trapped air pockets between the strings, see figure 21.

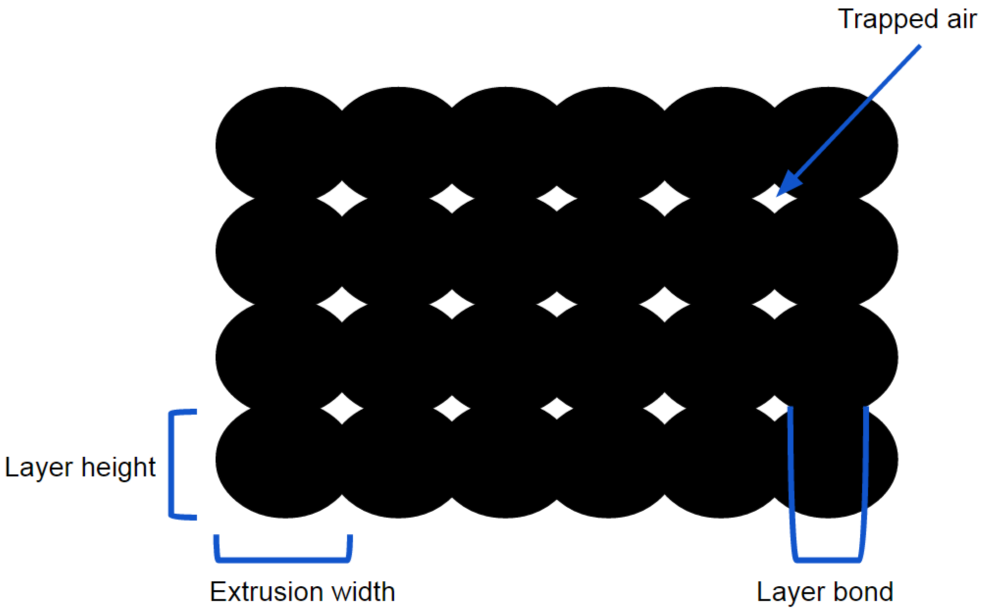


Figure 21: Section view illustration of a 3D printed slab

It is possible that the layer bond, see figure 22, will be weaker than the material in the strings in themselves.

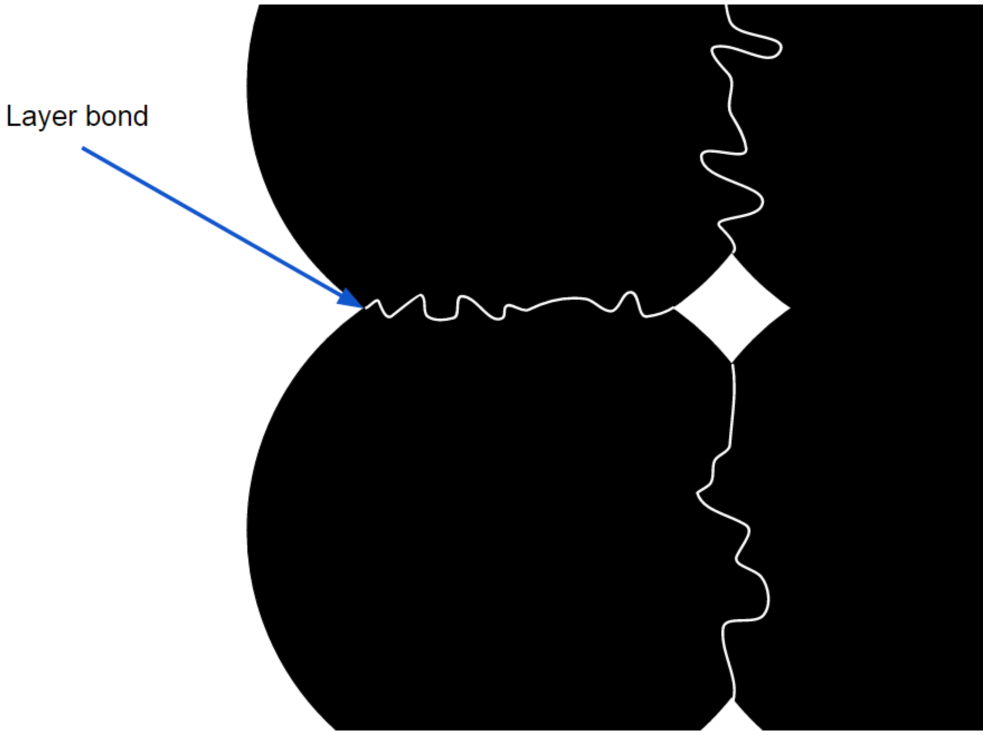


Figure 22: Zoomed section view illustration of a 3D printed slab

2.8.3 Failure scenarios

To get an insight what is most important to know form a durability perspective of a 3D printed product we can study the most common failure scenario. By previous experience of 3D printing the most common failure or fracture in a 3D printed part is cause by layer bonding failure. FFF 3D printer users are often not aware of the anisotropic nature of the product.

Paulo Kiefe, CEO of Creative Tools AB, shares the author’s view on the difficulties with layer bonding. He thinks it would be interesting to examine the parameters affecting the layer bonding. Magnus Nyberg, expert 3D printer user and service technician and at Creative Tools AB agrees with this and thinks a deeper investigation would be interesting. Thomas Palm, founder of Palmiga Innovation and developer of PI-ETPU filament gave some advice by e-mail conversation. He thinks that it is a good idea to find what is affecting the layer bonding. Because it is often between the layers the model has its weakest point. There is also an interests of the subject in the 3D printing forums [26].

Another failure scenario is when 3D printing with insufficient model density. Too low infill can cause the part to crack under load. Printing 100 % solid is rarely advantageously because the gained strength is not worth the increased printing time and cost. See figure 16.

A common mistake when making 3D printed product for certain applications is not being aware of the materials toughness or hardness. For example using a brittle material in a product exposed to short time high intensity loads such as impacts. A brittle material usually breaks from this kind of exposure. The tensile properties are essential to know to make the product durable in its specific application.

2.8.4 Standards

When performing test on plastics it is important to know that the results will only be comparable if the test is performed within the exact same circumstances. This is why strict standardized test conditions often need to be followed. The ISO 527-2 is a standard used for determination of tensile properties of molded and extruded plastic parts [15], [16]. In basic close to a 3D printed plastic part. The standard specifies very specifically the testing conditions, tolerances and settings.

The ISO 527-2 standard has tolerances and specifications that cannot be met with 3D printing. For example it is difficult to manufacture specimen with very narrow tolerances in a 3D printer. The ISO 527-2 documents will therefore only be used as a guideline. My intention is to follow the standard as much as possible to get accurate results. It is very important to notice that the results from my test may not be comparable to other plastic tests. In other words the testing data should only be used for comparison inside the study.

2.8.5 Summary 3D printing & durability

We can see that the durability of a 3D printed product is affected by three main factors. These factors are printing density, layer bonding and the plastics properties itself. All three conditions needs to be taken into account to make a durable product.

3 METHOD

In this study focus is on examining material tensile properties and which factors that are affecting layer bonding performance. The testing will be divided into two parts. One is trying to follow a standard for tensile testing and is for comparing the material properties. This properties are tensile strength and modulus of elasticity. The other test is for examining layer bonding. The materials tested for tensile properties are Creative Tools own filament brand Eco. Three of the most used 3D printing filaments are tested plus a flexible filament called TPU. The tensile properties of three types of nylon based filaments from Taulman 3D are also tested. Nylon based plastics are suited for many engineering applications.

We want to know what is affecting the layer bonding in the manufacturing process of 3D printing. To test this we can measure the maximum load the layer bond can withstand. In this test the load is acting transversally relative to the layers. The layer bonding properties for five different materials were evaluated to see if there are any differences of performance between materials. Five of the most basic 3D printing settings were examined to see if they affect the layer bonding, for this case only one material is evaluated.

3.1 Printing of specimen

When doing this type of comparing tests it is of course important to keep every setting and condition the same except for the specific setting or condition you want to test. My specimen was printed with identical or as close as possible conditions for each case. For some cases adjustments had to be made, because of example print failure or large geometrical divergence. It was very difficult to find settings to that was compatible with the wide range of materials and combinations of parameters desired to test. The printing conditions were carefully chosen to be suitable for the test chosen.

3.1.1 Default settings setup

For the specimens a default setup of slicing parameters and settings were used. The table 2 below shows the most essential slicing settings. All other settings are presented in appendix, figure 69-79. This setup is from now on called Standard 3, S3.

Table 2: Default settings setup S3

Printer:	Flashforge Dreamer
Nozzle size(mm):	0.4
Layer height (mm)	0.3
Layer width(mm):	0.48
Infill (%)	ISO: 100 Matkey:30
Perimeters (nr)	3
Top/bottom layers	3
Printing speed (mm/sec)	40
Extruder temperature (°C)	230
Bed temperature (°C)	50
Nozzle fan (on/off)	On

S3 is a representative and realistic setting setup to use based on experience and commonly used values. S3 is generally a good combination of parameters to print a strong and visually good looking model. Some settings had to be adjusted if the material behavior in the specific case did not allow for the particular setting. This is explained more thoroughly in the next chapter. If other settings are used they are presented in the specific test.

3.2 Printer equipment

The main 3D printer used was a Flashforge Dreamer. The Dreamer has an enclosure and two fans blowing air out of the box when the nozzle fan is activated. A heated bed is featured as well as a double extruder configuration. Figure 23 and 24 show the outside respectively inside of the Flashforge Dreamer.

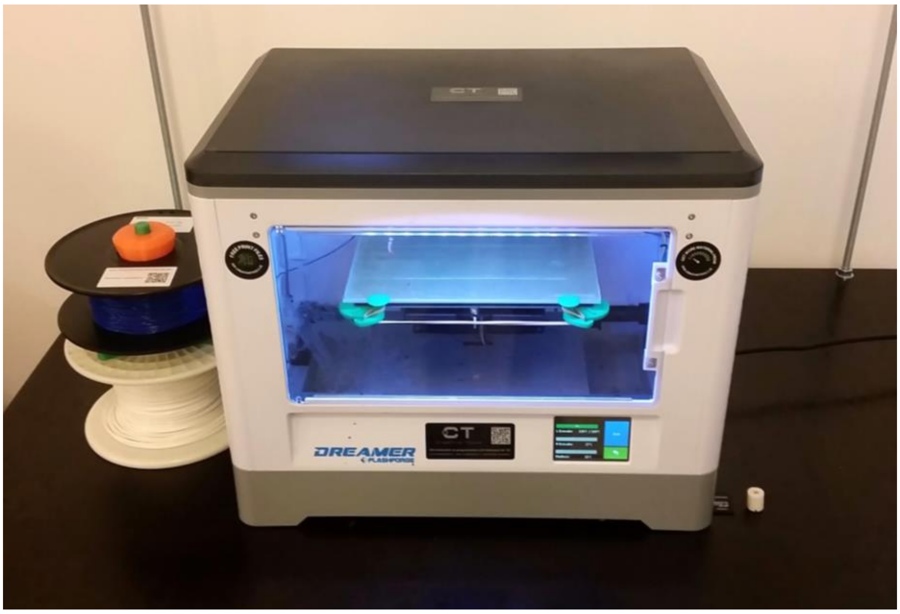


Figure 23: Flashforge Dreamer external view

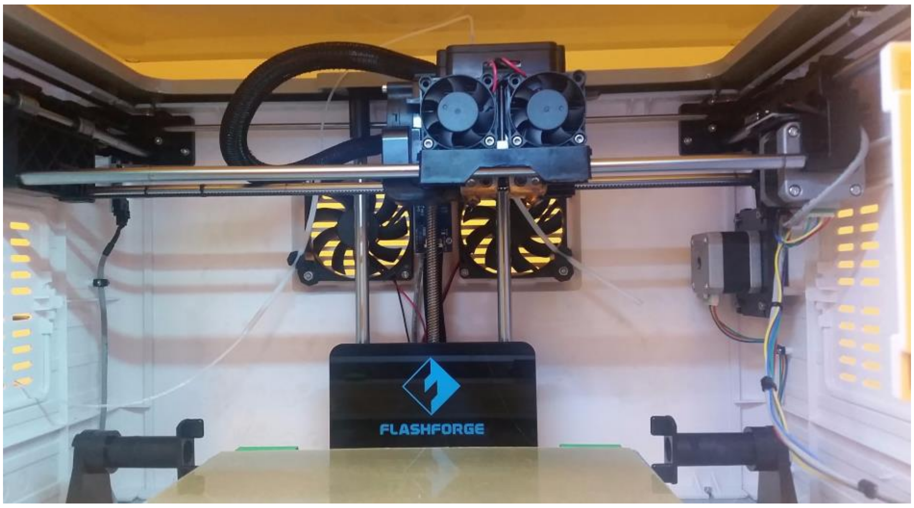


Figure 24: Flashforge *Dreamer internal view*

The Makerbot Replicator 2X is very similar to the Dreamer but has no enclosure fans. The 3D printers inside respectively outside is shown in figure 25 and 26. The Replicator 2X has a closed enclosure design. The Replicator was used for printing nylon as this printer features a bakelite building plate that is suitable for printing nylon based filaments.

Figure 25: Makerbot Replicator 2X external view

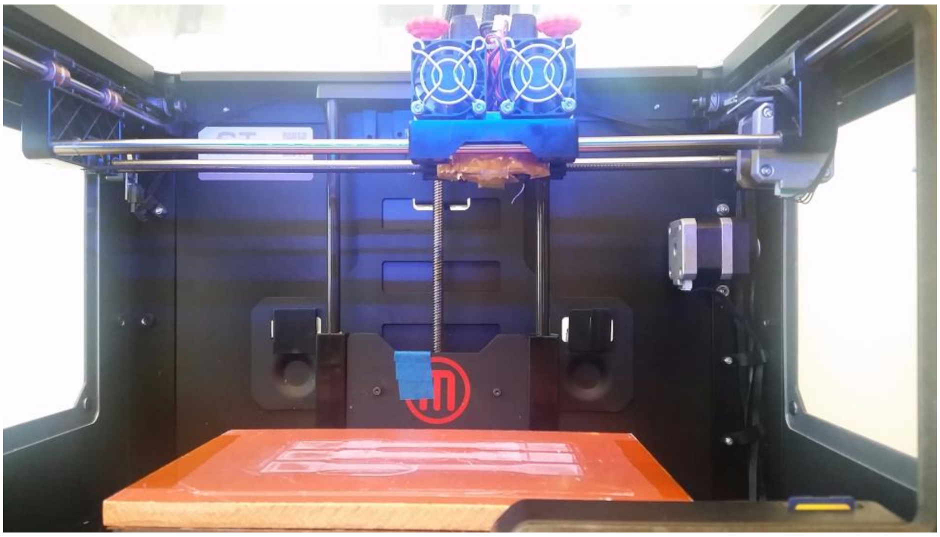


Figure 26: Makerbot Replicator 2X internal view

3.3 Specimen geometry, printing conditions & printing difficulties

I used two types of specimen designs. An ISO 527-2/1A standard specimen design was used for determination of tensile properties. This is the conventional specimen design used for this kind of plastics. For layer bonding tests a similar but shorter design to save printing time was used. This is called the Matkey specimen geometry. The design has features, a hole and rounded edges that allow for visual determination of printing quality. Because no elongation determination was performed on this kind of specimen it did not have to be as long as the ISO type specimen. Figure 27 show the two specimen in comparison with dimensions.

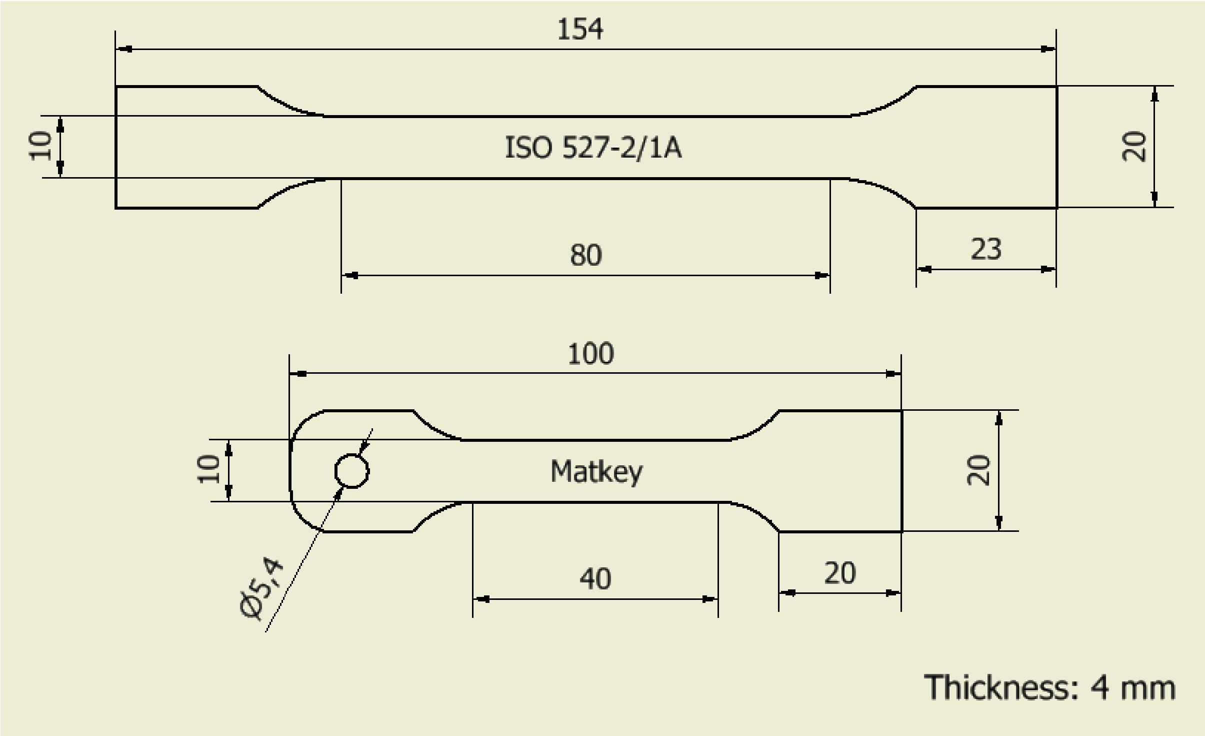


Figure 27: The two specimen geometries used, dimensions in mm

All filaments were checked for diameter consistency of 1.75 mm diameter. The filaments were of various age and stored in room atmosphere. Whenever it was possible all specimen was made in a continuous printing process, see figure 28 and 29. For example when printing specimen with various layer height it was possible to print all at the same time. From 0.1 mm to 0.4 mm, left to right in figure 28. For some cases where this was not possible, three specimen with the specific setting was printed in the same process, see figure 30. For example when printing with various extruder temperature three specimen were printed with a constant extruder temperature. The extruder temperature takes time to cool down or heat up so it would not be possible to print all specimen in a single process.

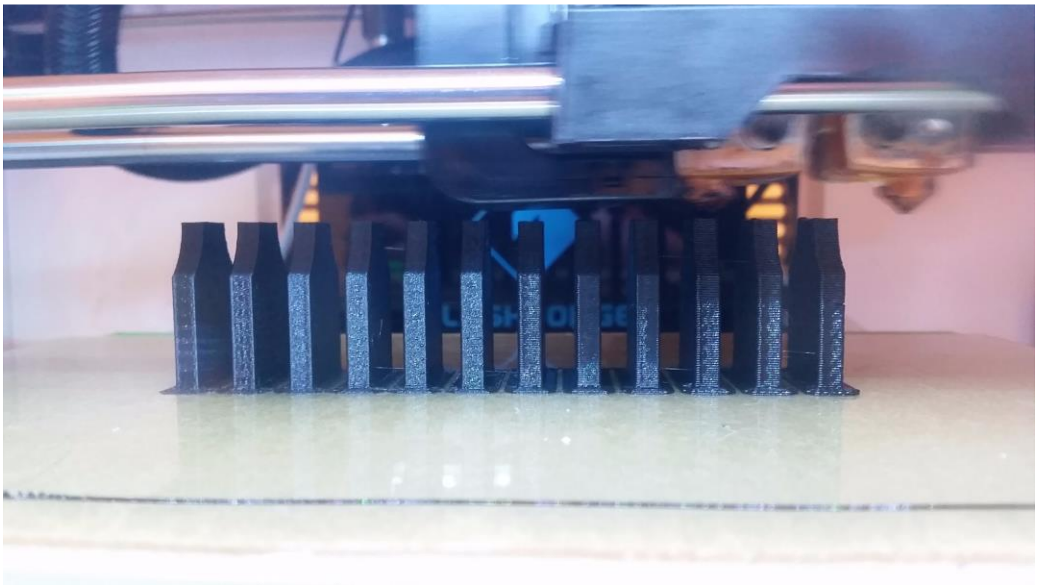


Figure 28: Set of specimen printed in a single process. In this case layer heights 0.1, 0.2, 0.3 and 0.4 mm. Three specimens of each layer height

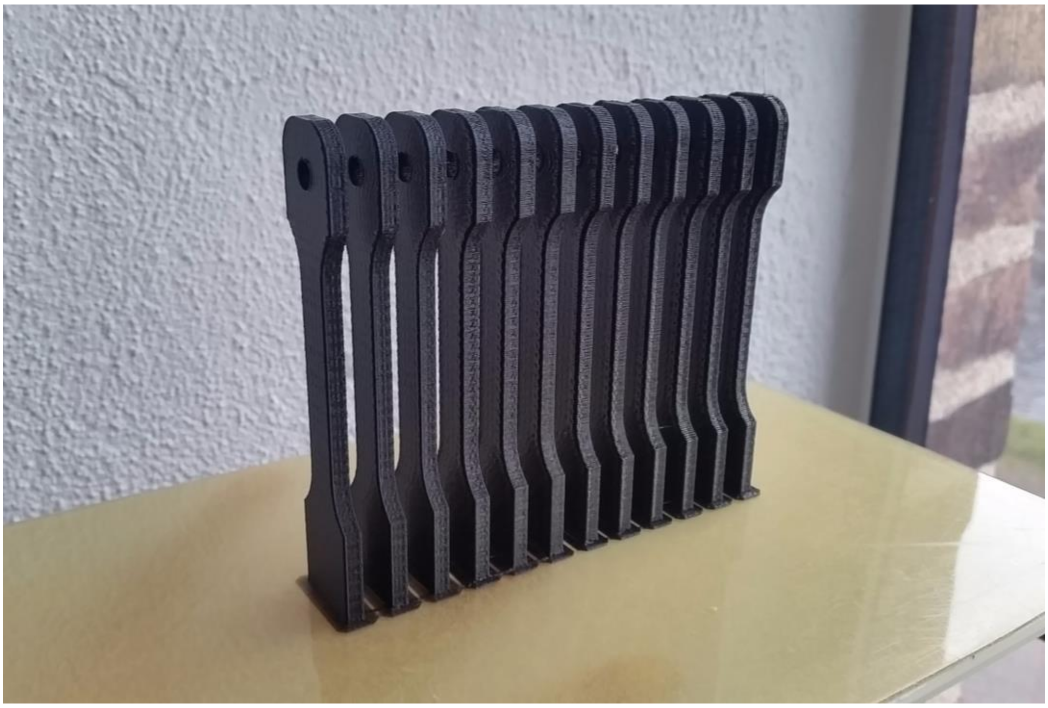


Figure 29: Finished set of Matkey specimens in PLA printed on height on the building plate

Figure 30: Three ISO 527-2/1A specimens in TPU filament printed flat on the building plate

A few of the difficulties encountered in the 3D printing process are explained in this chapter. The PLA has a lower T_g than for example ABS. PLA will be more viscous at 230°C. When printing this has the effect that the plastic will not harden fast enough to make a steady and consistent geometry. For PLA it is preferred to use a nozzle cooling fan to compensate for this issue. If a nozzle fan is used for ABS, remember ABS has a larger shrinking factor compared to PLA, this will cause warping and ultimately making the part lift from the building plate and the print fails. Because of this it is almost impossible to use the same printing conditions for ABS and PLA.

Figure 31: Specimen printed in PLA with, at the top, and without nozzle cooling below

Figure 31 shows PLA printed with, top specimen in figure, and without nozzle fan, bottom specimen. The specimen printed without nozzle cooling showed big flaws in geometrical consistency. In this case the specimen was not flat enough to be attached to the tensile testing machine and therefore it was rejected.

TPU is a soft 3D printing material. When printing this filament with normal speed it tends to deform slightly in the extruder and the feeding gear starts to slide. This caused insufficient amount of plastic being extruded and resulting in bad quality models. Figure 32 shows TPU printed in 20 mm/sec and figure 30 printed at 30 mm/sec.

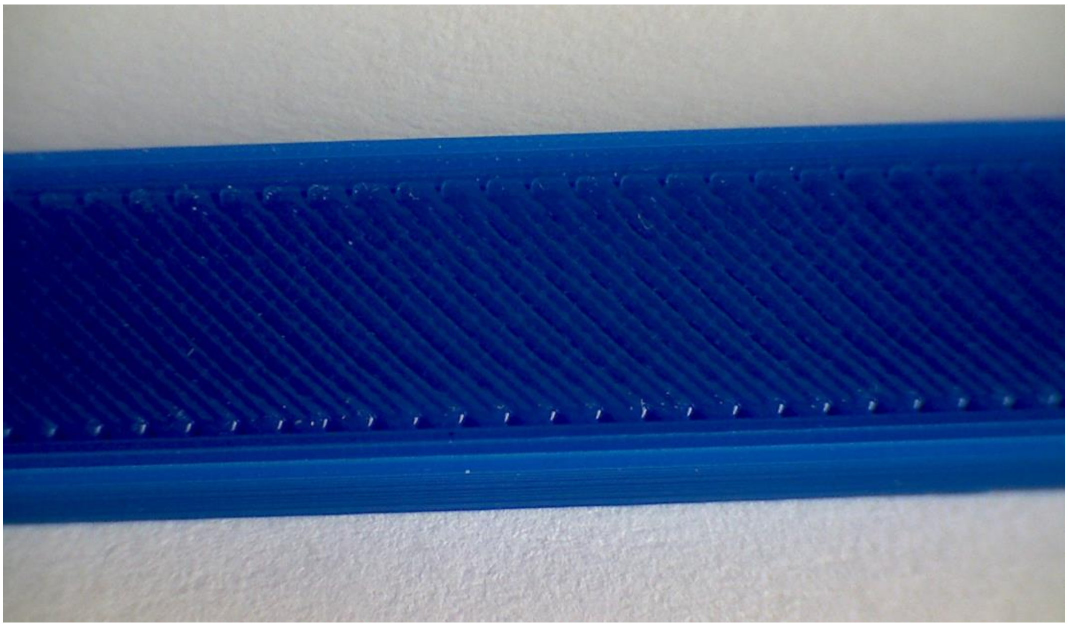


Figure 32: TPU filament printed at 20 mm/sec

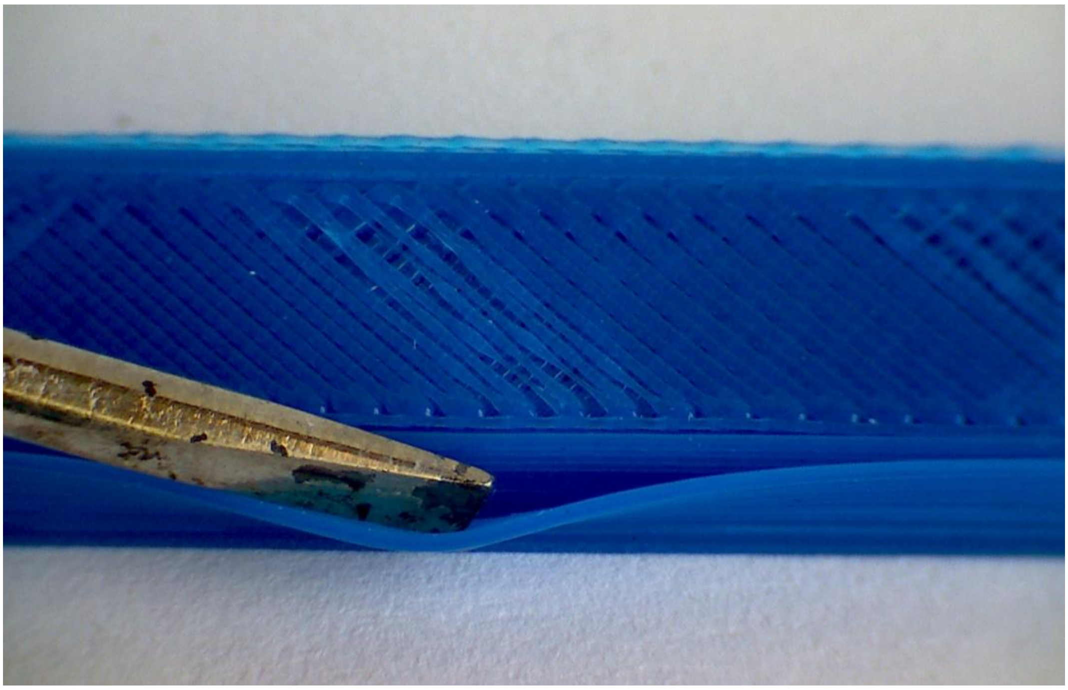


Figure 33: TPU printed at 30 mm/sec

There are a lot of gaps and holes in the model. If the perimeters is printed with insufficient amount of plastic they do not bond to each other properly, see figure 33. The specimen in figure 32 has solid layers with good layer bonding.

The specimens was always checked for this kind of flaws before put into test. If some minor flaw was found and it was obvious that it was introduced by the specific setting that was intentional to test the specimen was of course not rejected.

3.4 Test equipment & procedure

The tensile test machine used was a MTS QTest 100 Elite and the software was Testworks 4. The load cell used for ISO specimens are specified for maximum load of 100 kN and resolution of 20 N. Maintenance and calibration of the machine was performed 2015-03-30. The equipment is shown in figure 34.

Figure 34: QTest 100 Elite tensile test machine

3.4.1 General testing procedure

If the test requires the specimen to be measured, the width and thickness of each specimen were measured. A caliper with 0.02 mm resolution was used and four significant figures read. One measurement for each dimension was taken.

The regular tensile testing procedure consisted of first checking if the sensors seemed ok. The grips were moved to approximate positions. The force and extension meters were zeroed. The specimen was mounted in the grips with the use of the carefully adjusted centering pins, making sure the specimen was aligned accurately. Figure 35 is showing how the specimen was attached. The grips were then firmly tightened to prevent slipping. But not tightened too hard causing damage to the specimen.

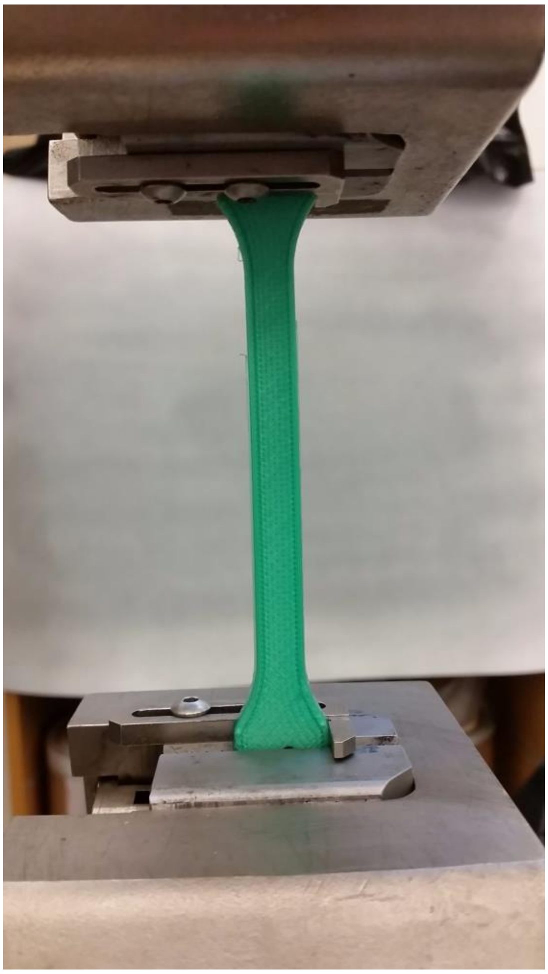


Figure 35: ISO specimen mounted in the grips.

The load was checked to still be close to zero, if not, the grip's distance were carefully adjusted so the load was $0 \pm 15\ N$. As the load cells accuracy is 20 N this is as close to zero initial load as we can get.

Width and thickness of the individual specimen was saved in the software. The test was initiated at the specified test speed. After the specimen snapped off the translation and force data was exported.

Table 3: Used testing speeds

Test speed (mm/min)	**Material/Test**
1	PET, PLA, ABS
5	Layer bonding
20	Nylons, TPU

The test speed for ABS, PET and PLA were 1 mm/min like it is recommended in the ISO 527-2 standard [15], [16]. For the flexible materials like nylons and TPU a higher test speed had to be used. The reason for this was because it would take more than an hour to perform a test for a single specimen and the computer could not handle the amount of data gathered. Used testing speeds are presented in table 3.

Some problems were encountered with attachment of specimens in the tensile machine. Some specimen were a little rough in the ends making them hard to fasten in the grips. Some specimen started to slip slightly in the start of the test causing the test to fail. The standard procedure were repeated if the test failed.

The tensile testing machine used does not have an extensometer measuring the gauge length. The machine is only measuring distance between the grips. Because of this flaw only measurements of the nominal strain could be made. The E-modulus is therefore not accurate. Initial gauge length was set to 113mm, same as the distance between the grips.

3.4.2 Specimen data management

For each material three identically printed specimen were tested. A simple Matlab code was used to calculate and plot stress-strain curves. The code is available in appendix, code 1. The stress-strain curves were plotted and the weakest specimen out of three was picked out for further comparisons. For example, figure 36 shows the stress-strain graphs of three specimen in ABS. The curve in yellow, specimen 3, shows the weakest tensile strength and strain at break. Specimen 3 was used for further comparisons. The maximum stress and E-modulus for each specimen were also exported. Testworks 4 is calculating the E-modulus by using linear regression.

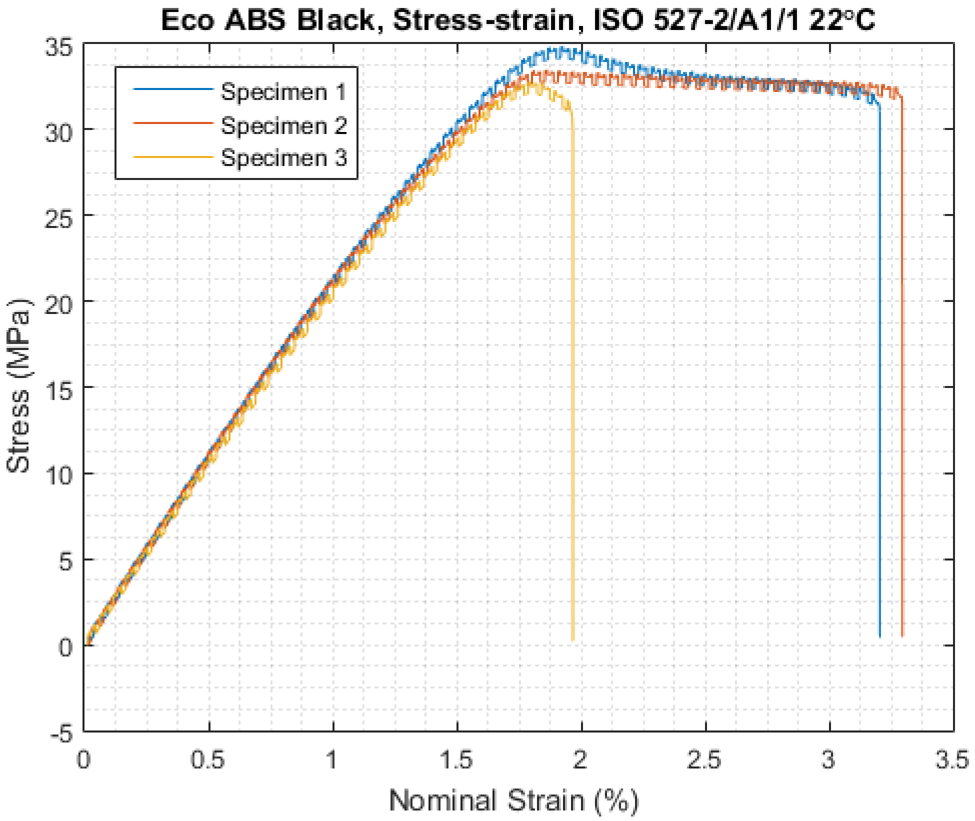


Figure 36: Example of ABS stress-strain for three specimen

For layer bonding tests three specimen for each condition were tested. Only max load data was exported for layer bonding tests.

3.5 Performed tests

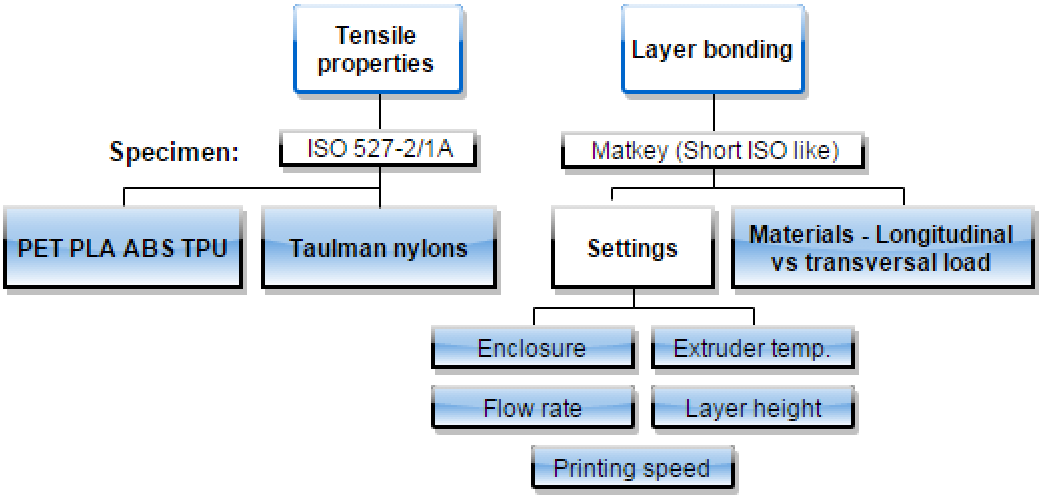


Figure 37: Performed tests categories overview

The test results are only comparable within each of these test categories, blue gradient squares shown in figure 37.

3.5.1 Tensile properties

Tensile properties tests were performed with guidelines from the ISO 527-2 standard. The testing conditions were diverging from the standard in many ways due to for example geometrical variance and uncontrollable conditioning. The specimens were printed with 100 % infill. In theory they are solid and the cross section area can be measured and stress calculated.

The tested materials and their corresponding exceptions from the default printer settings, S3, see table 2, are shown in table 4 and 5 below. Figure 38 shows filament spools of Taulman plastics.

Table 4: Tested basic materials and used settings

Material	Exceptions from default settings S3
Black Eco PET	None
Black Eco PLA	None
Black Eco ABS	Heated bed: 100°C Nozzle fan: OFF*
Blue Eco TPU 95	Printing speed: 20 mm/sec

*When nozzle fan is inactive the case fans automatically turns off.

Figure 38: Filament spools of Taulman nylon based plastics

Table 5: Tested nylon materials and used settings

Material	Exceptions from default settings S3
Taulman Nylon 910, 645, 618	Makerbot Replicator 2X Extruder temperature: 245°C Heated bed 100°C Printing speed: 20 mm/sec Nozzle fan: OFF

3.5.2 Layer bonding

To test the layer bonding performance the specimen were printed on height, arranging the layer orientation transversally along the specimen's length. In this way the layer bond in the material is exposed. Because the specimens were intentionally printed with 30 % infill, they were not solid. The cross section area could therefore not be measured. This test was very simplified and only maximum load capacity for each specimen was measured, not stress-strain behavior. The Matkey specimen geometry was used. Layer orientation relative load is illustrated in figure 39.

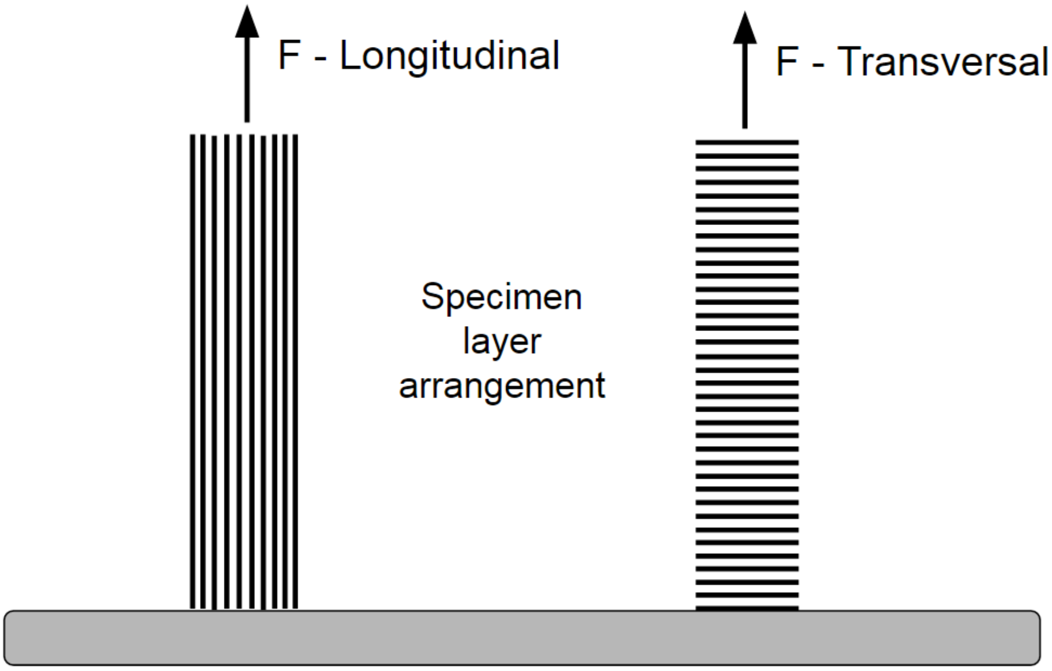


Figure 39: Testing load direction relative to layer orientation

A test to see if there are any differences between materials in layer bonding performance was made. The tested materials and their respective printing settings used are presented in table 6.

Table 6: Materials tested for longitudinal versus transversal maximum load and used settings

Material	Exceptions from default settings S3
Black Eco PET	None
Black Eco PLA	None
Black Eco ABS	Heated bed: 100°C Nozzle fan: OFF*
Taulman Blue T-glase	Filament diameter: 1.65 mm*
Flashforge Natural PLA	None

*When nozzle fan is inactive the case fans automatically turns off.

**The filament was measured to be 1.65 mm not 1.75 mm like all other filaments.

Five basic settings were tested to see if they affect layer bonding performance. For this test the specimen layers are oriented transversely relative to the load, see figure 39. The choice of settings and parameters that were evaluated was based on experience and knowledge of 3D printing and materials. The settings tested were the ones believed to have the largest impact on layer bonding. Settings are show in table 7.

Table 7: Tested settings and parameters range

	From	**Increment**	**To**	**All specimen printed in the same process or printed 3 at a time**
Enclosure	Open	Normal	Closed	3 per mode
Extruder temp (°C)	190	30	250	3 per temperature
Flow rate	0,9	0,1	1,1	All on same
Layer height (mm)	0,1	0,1	0,4	All on same
Printing speed (mm/sec)	10	40	130	All on same

Three types of enclosure designs were tested. The ambient temperature inside the printer was measured under printing progress for each enclosure design. Temperature sensor placement is show in figure 40. Measured temperatures are presented in table 8.

Table 8: Ambient temperatures for tested enclosure designs

Enclosure design	Ambient temperature (°C)
Open	25
Normal	26
Closed	48

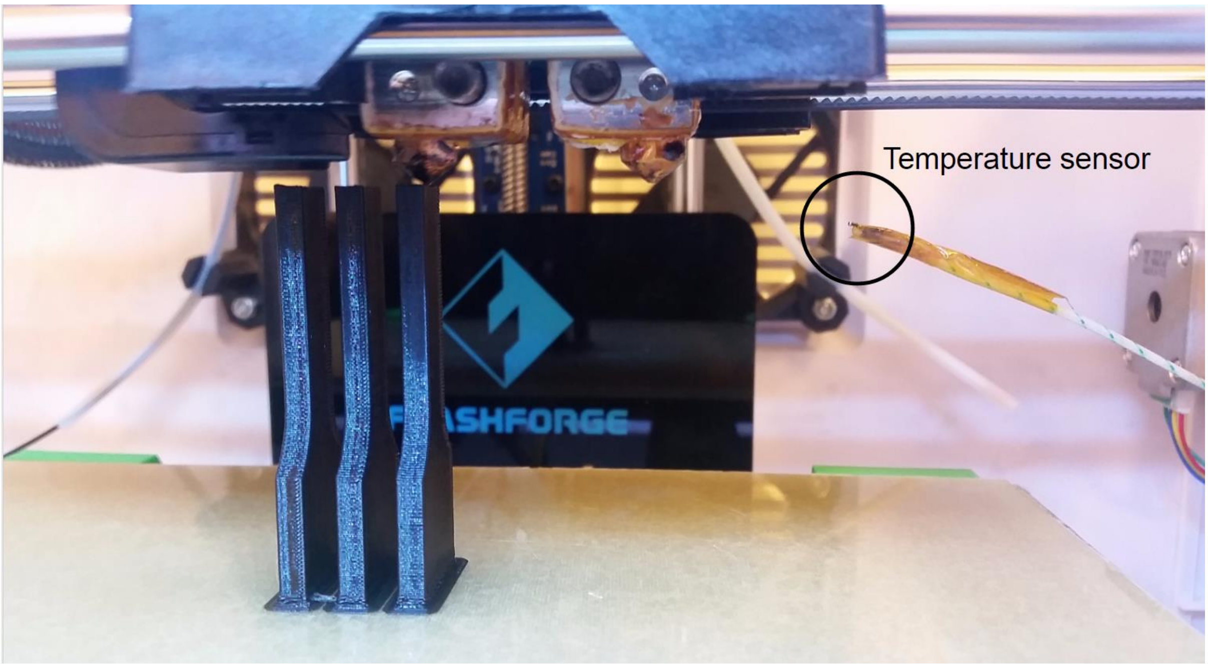


Figure 40: Temperature sensor measurement point

The open design is simulated by opening all doors on the Flashforge Dreamer, shown in figure 41. Normal enclosure design is when all doors a closed and case fans active. Case fans are two 80 mm standard computer fans blowing air out of the enclosure, seen in the back of figure 40. Closed design is with case fans turned off.

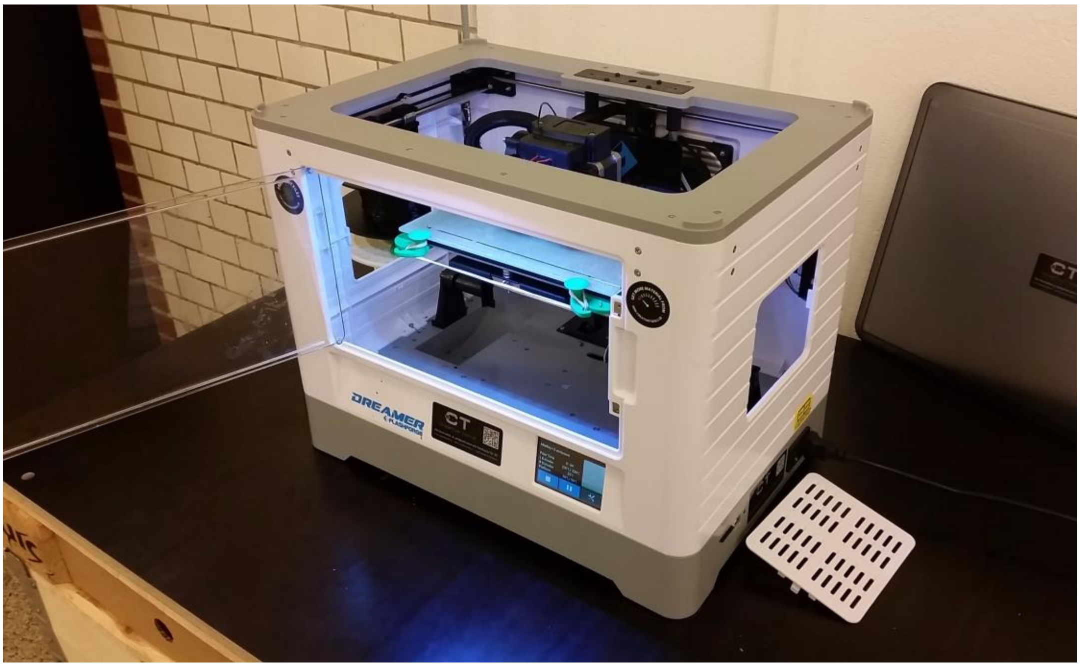


Figure 41: Open design mode of the Dreamer

The flow rate specifies the amount of plastic extruded. Rate 1 is default. Rate 0.9 is 90 % of the default rate. 1.1 is 110 % and so on.

3.5.3 Visual inspection

One specimen from each test was inspected with microscope. The fracture picture was saved and examined.

4 RESULTS

Keep in mind that the conditions of specimens and tests are varying. Results from different tests may not be comparable. See figure 37 in chapter 3.5.

4.1 Tensile properties

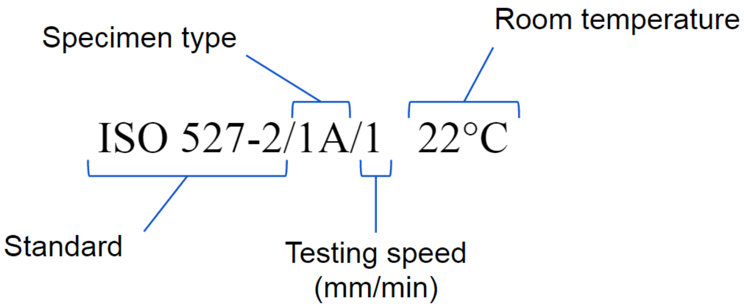


Figure 42: Diagram titles explanation

Diagram titles are described in figure 42. For all stress-strain diagrams the measurement data from the weakest specimen out of three is used. Stress-strain curves for all specimen are available in appendix, figure 80-85.

4.1.1 Tensile Properties of basic materials

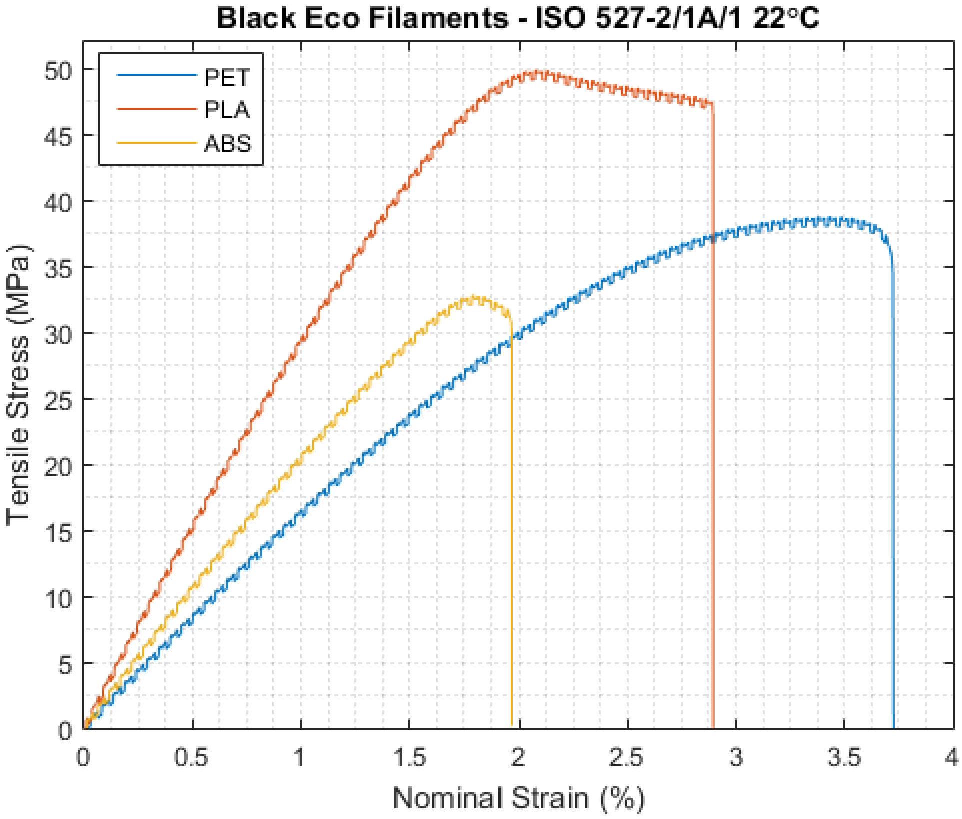


Figure 43: Stress-strain curves of three basic plastics. Weakest specimen out of three. Printing settings used see table 2 and 4

A clear difference in stress-strain behavior for the three materials are shown in figure 43. PLA has the highest inclination in the elastic part and PET the lowest, ABS places somewhere just in between the PLA and PET. This indicates that PLA is a harder material than ABS and PET, ABS is slightly harder than PET. Some apparent difference in tensile strength is also shown. Strain at break differs significantly for ABS specimens but shows small difference for PET and PLA specimens.

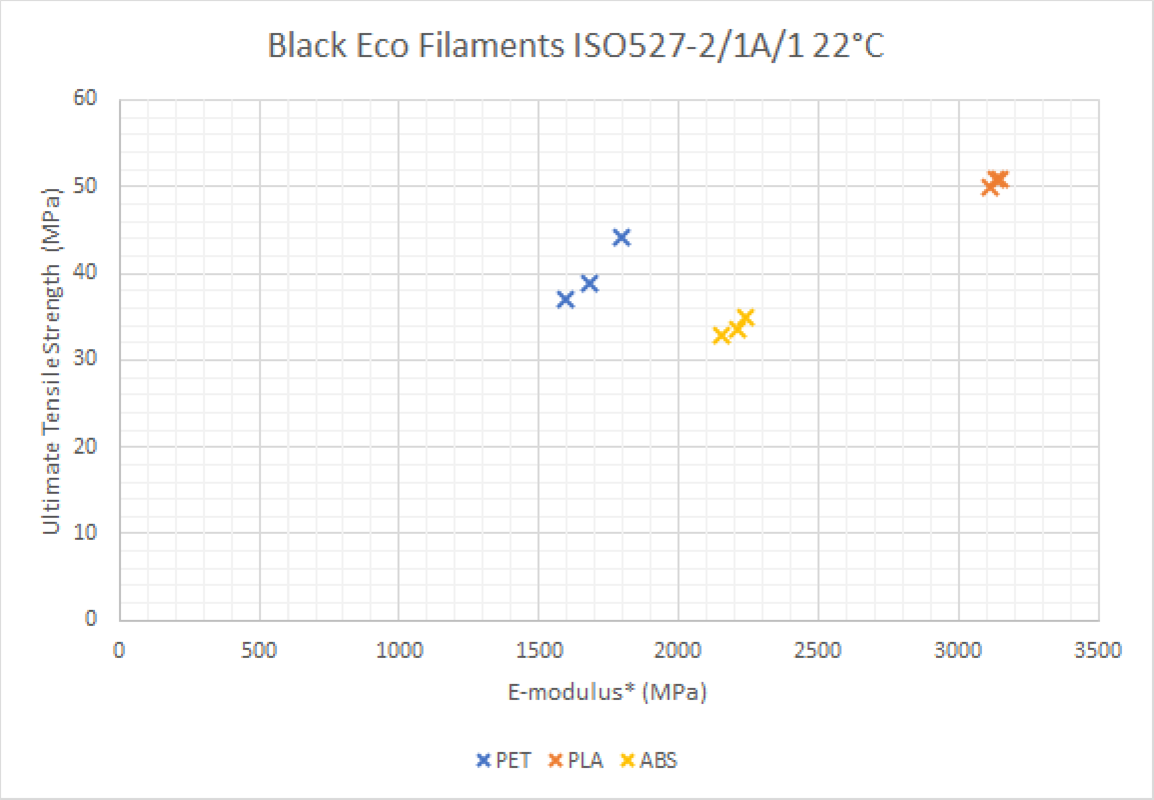


Figure 44: Tensile Strength vs E-modulus measurement data for all tested specimen of the basic plastics. Printing settings used see table 2 and 4

In figure 44 we can see how much the specimen's measurements are varying. We can also compare the tensile properties of the materials. The specimens for PLA and ABS seems to give very consistent results in terms of tensile strength and E-modulus. The PET measurements have some variation.

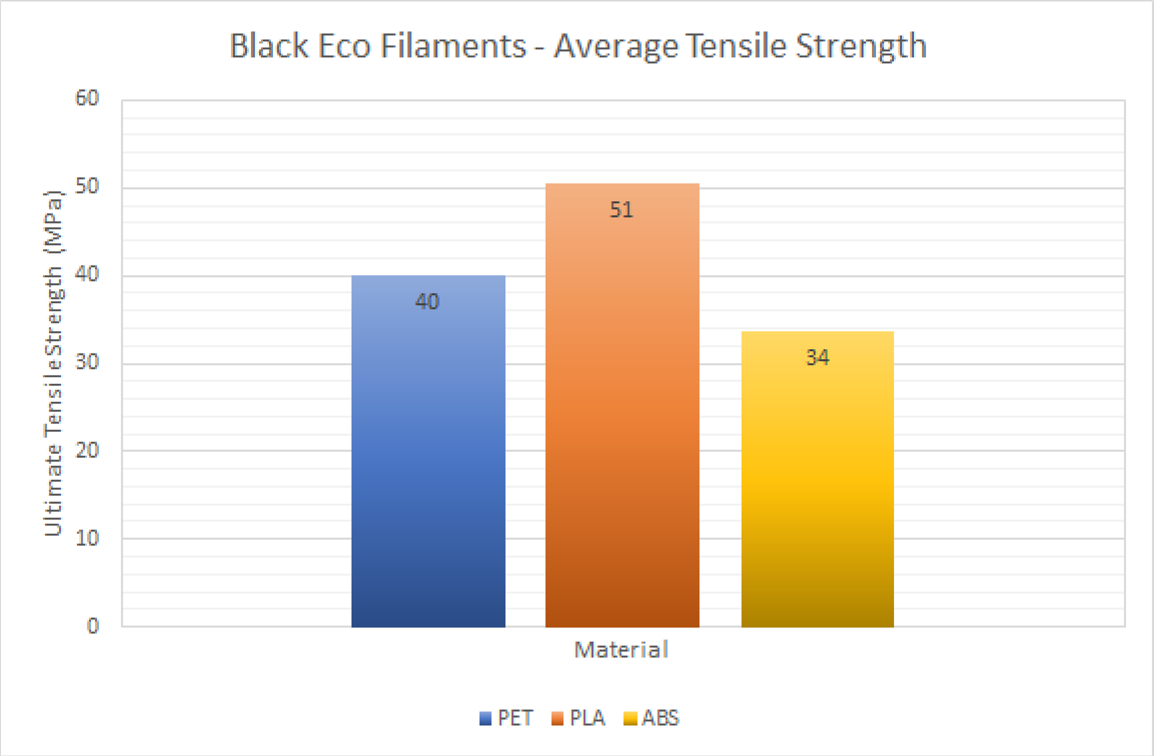


Figure 45: Average Tensile Strength of three basic plastics. Printing settings used see table 2 and 4

In figure 45 a comparison of average tensile strength is presented. PLA has an average tensile strength of 51 MPa which is the highest, ABS measures 34 MPa which is the lowest. PET has an average tensile strength of 40 MPa, somewhere midway between the other two.

The TPU filament tensile test failed because the machine reached its maximum position. At that point it had an elongation of about 340 % and a tensile stress of about 20 MPa. E-modulus for TPU could not be calculated.

Below the fractures for the materials are shown, figure 46 and 47.

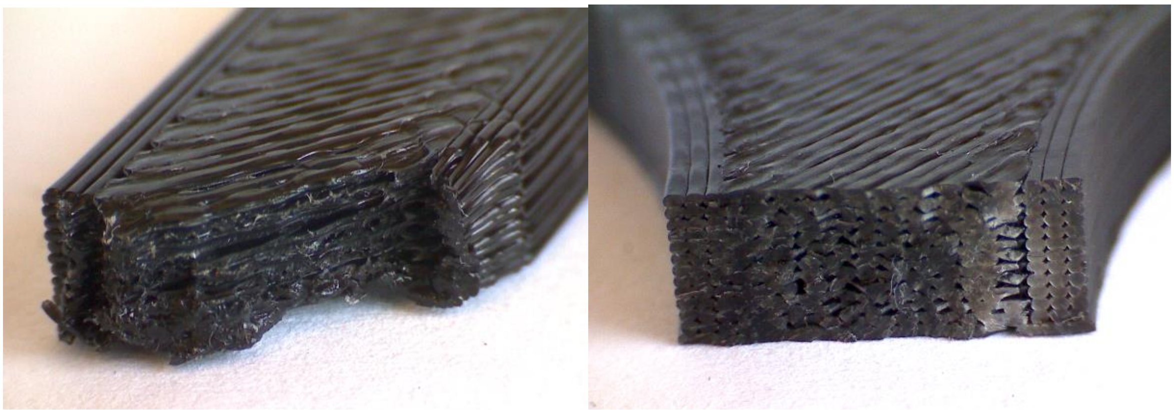


Figure 46: Fractures of PET, left, and PLA to the right. Printing settings used see table 2 and 4

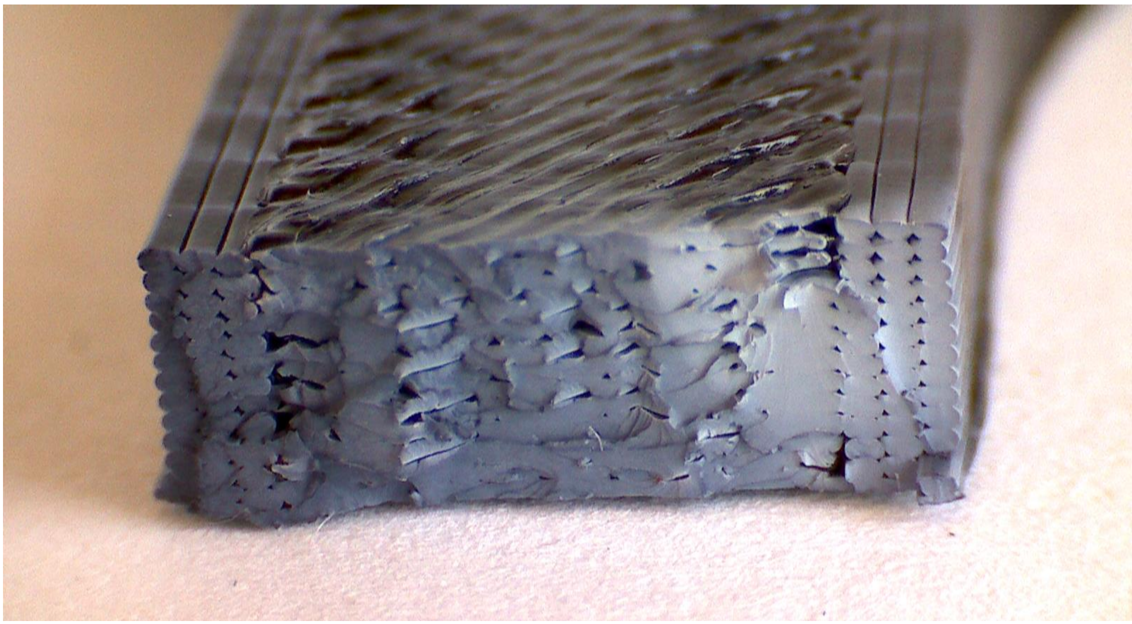


Figure 47: Fracture of ABS. Printing settings used see table 2 and 4

Figure PET shows some necking tendency and has more of an elastic fracture compared to PLA and ABS. PLA and ABS shows a straight clean brittle fracture. In the PLA and ABS fractures we can clearly see small air pockets between the layers.

4.1.2 Tensile Properties of Nylons

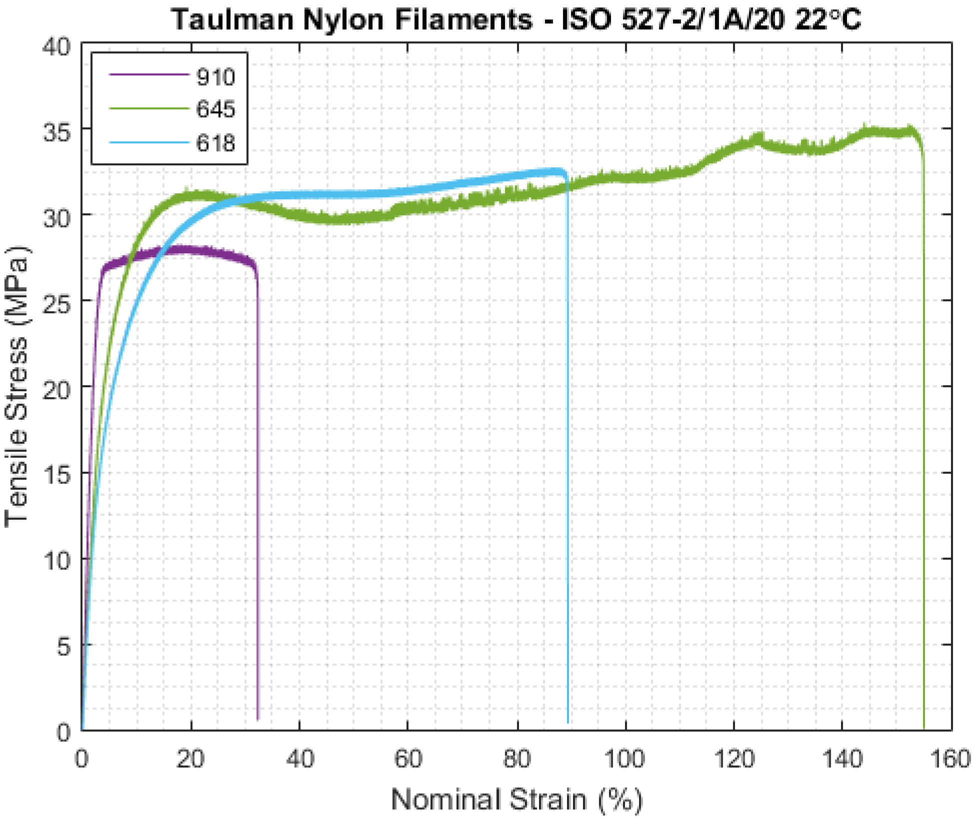


Figure 48: Stress-strain measurements of three Taulman nylon based plastics. Weakest specimen out of three. Printing settings used see table 2 and 5

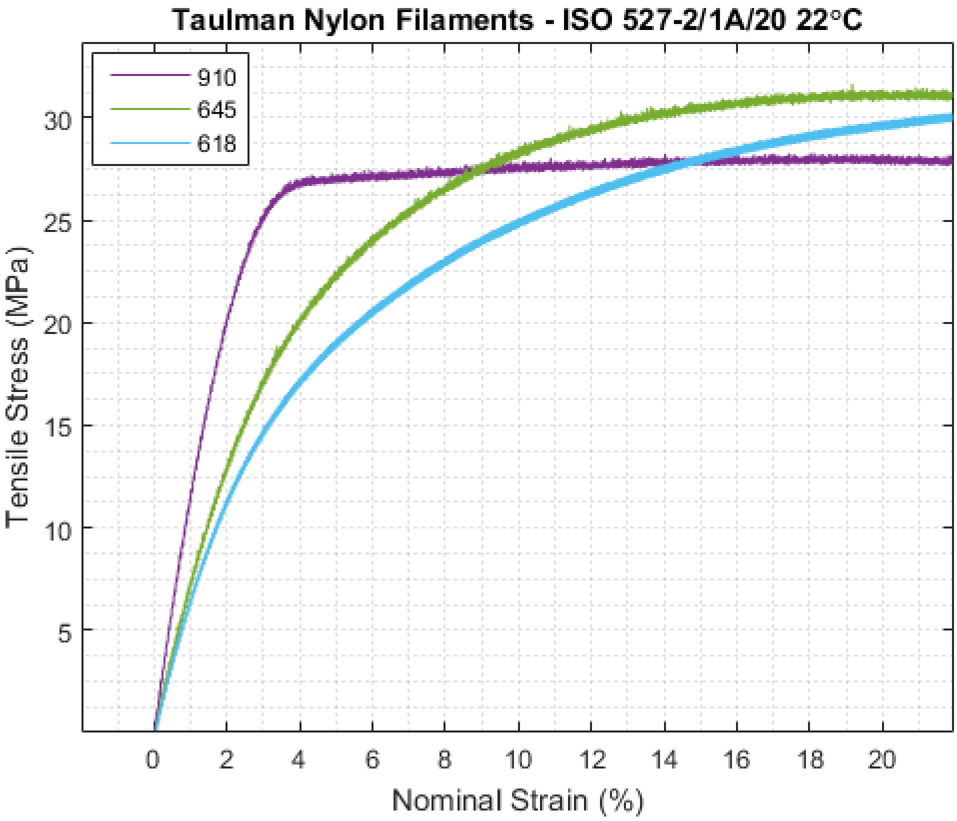


Figure 49: Zoomed stress-strain measurements of three Taulman nylons. Weakest specimen out of three. Printing settings used see table 2 and 5

The stress-strain behavior for nylons 645 and 618 are quite similar, a typical behavior for an elastic material, seen in figure 48 and 49. One specimen of 645 had an elongation of 240 %. The 910 nylon shows to have a significantly higher inclination in the elastic region. This means it is a much stiffer material. The stress strain behavior of 910 shows a relative wide elastic region, this will have the effect that the material will regain its original shape after bending better than the other two nylon materials. One of three 910 specimen shows significantly weaker behavior than the other two 910 specimen.

The individual specimen stress-strain curves for all of the nylons shows great variety in strain at break. See curves in appendix, figure 82-84.

We are observing some quite big difference in yield point and maximum tensile stress for all nylon materials.

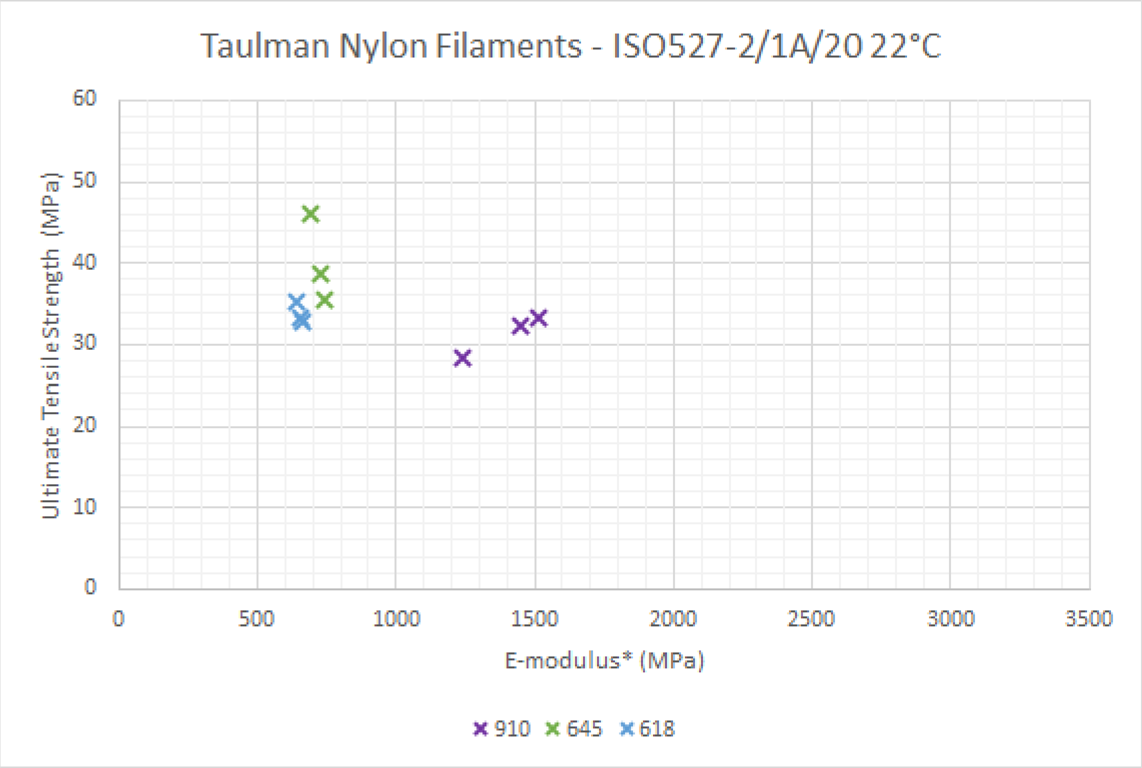


Figure 50: Tensile Strength vs E-modulus measurement data for all tested specimen of the nylon plastics. Printing settings used see table 2 and 5

*Using E-modulus based on Nominal Tensile Strain not normal Tensile Strain.

We can see some discrepancies of the 645 and 910 specimen measurements in terms of tensile strength and E-modulus, figure 50. A significant difference in E-modulus for 910 specimens are observed. 645 and 618 have almost the same E-modulus. 910 has significantly higher E-modulus than the other two nylons.

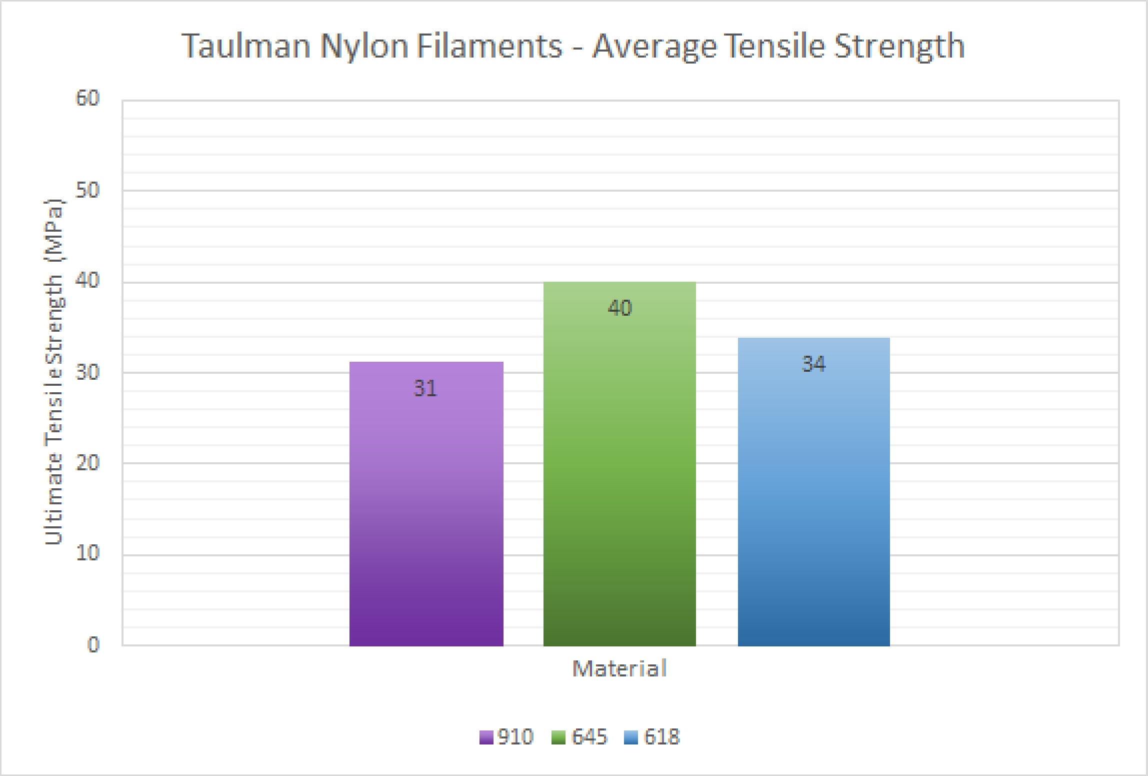


Figure 51: Average tensile strength of three nylon based plastics. Printing settings used see table 2 and 5

Nylon 645 has the highest average tensile strength, 40 MPa, figure 51. The measured tensile strength of 618 is 34 MPa and 31 MPa for 910.

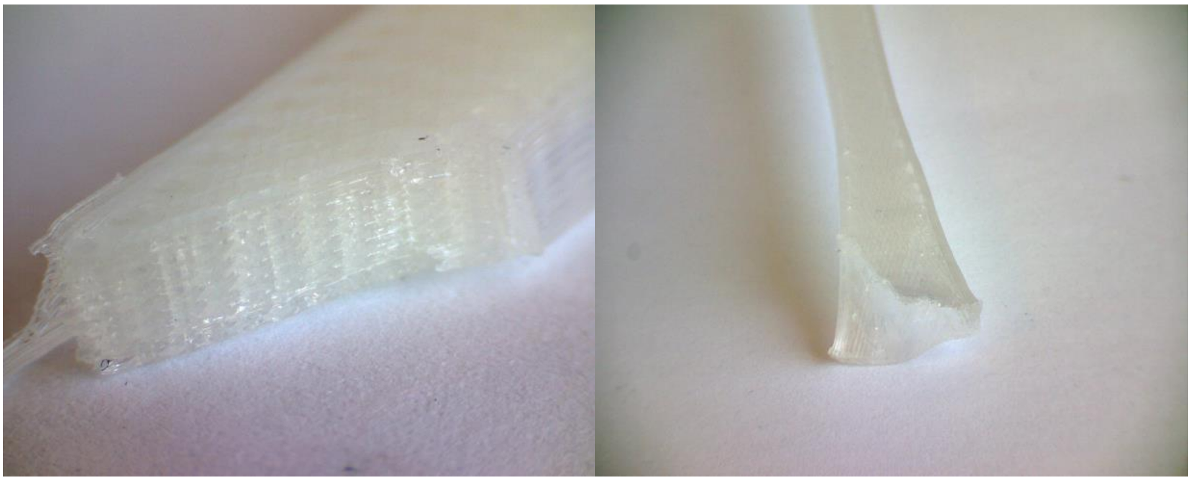


Figure 52: Fracture of 910 to the left and 645 to the right. Printing settings used see table 2 and 5

Figure 53: Fracture of 618. Printing settings used see table 2 and 5

The fractures are quite different for the three materials as we can see in figure 52 and 53. 910 has an angled fracture. The 645 specimens broke close to the grips. 645 and 618 specimen had necking starting somewhere along the gauge length and then spreading across the whole gauge length before breaking.

4.2 Layer bonding

4.2.1 Layer bonding of materials

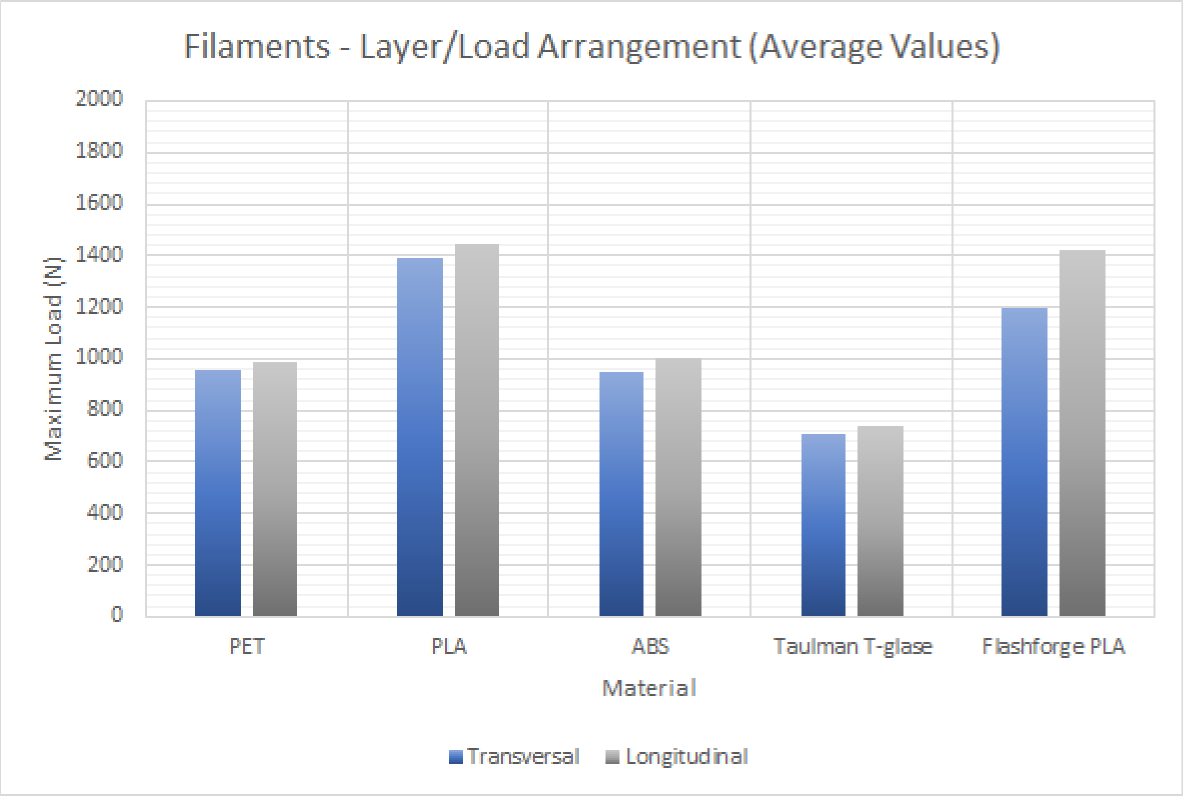


Figure 54: Comparison of average load capacity of specimen loaded transversally and longitudinally relative layers. Five different materials. Printing settings used see table 2 and 6

Almost all materials seem to have the same magnitude of difference in load capacity when loaded transversally and longitudinally relative layers, see figure 54. The only material that stands out is the Flashforge branded PLA. When this material is loaded transversally relative to layers it is about 20 % weaker.

The TPU filament tensile test failed because of slippage in the grips.

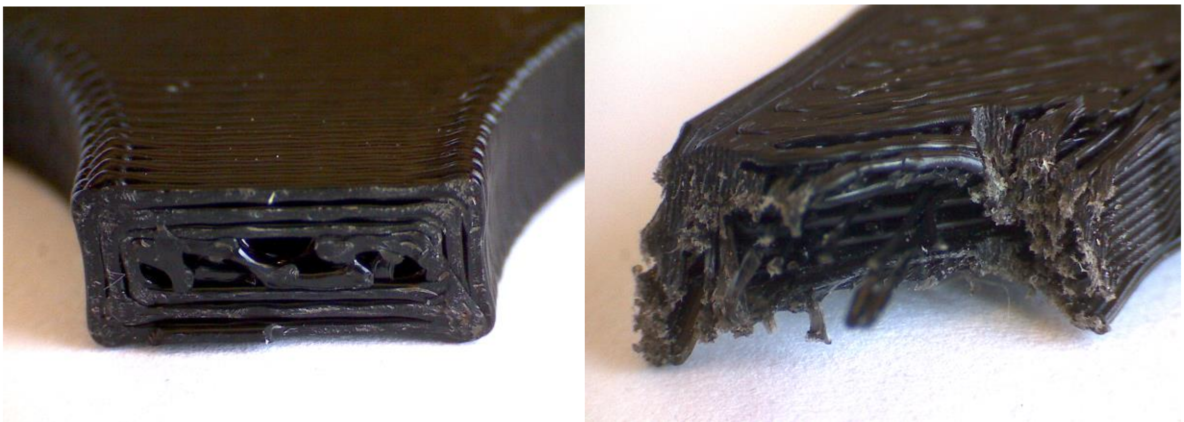


Figure 55: Fractures of PET. Printed standing to the left and flat to the right

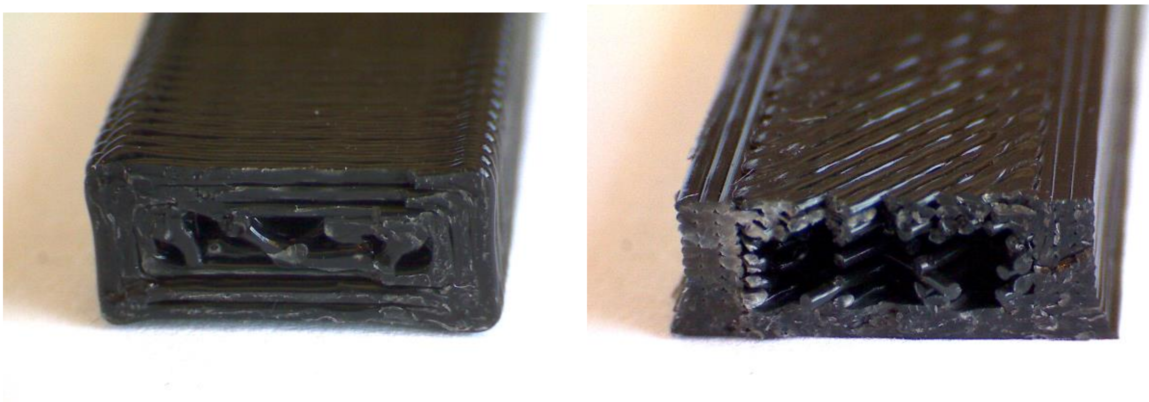


Figure 56: Fractures of PLA. Printed standing to the left and flat to the right

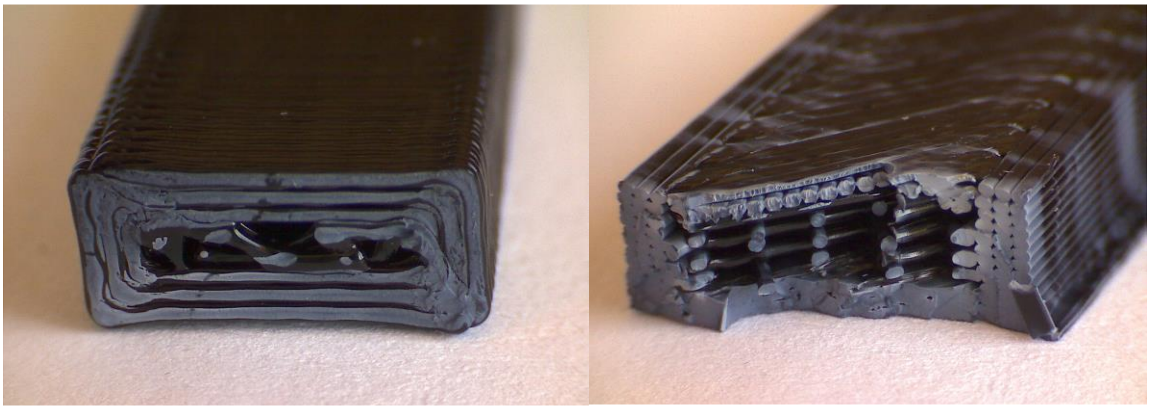


Figure 57: Fractures of ABS. Printed standing to the left and flat to the right

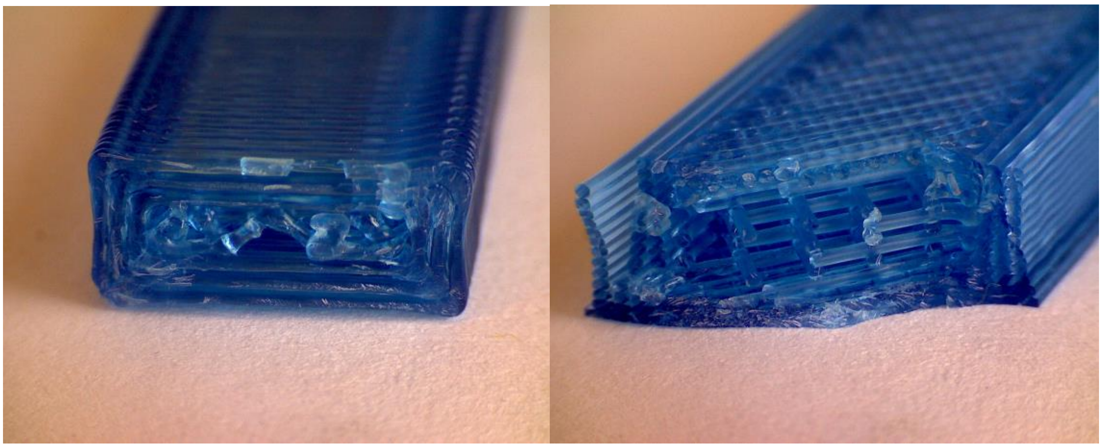


Figure 58: Fractures of Taulman T-glase. Printed standing to the left and flat to the right

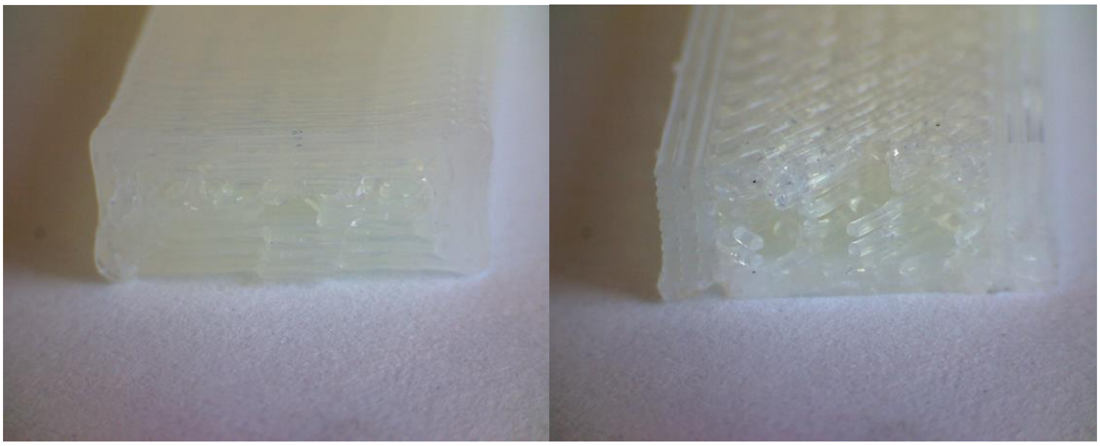


Figure 59: Fractures of Flashforge Natural PLA. Printed standing to the left and flat to the right

The fractures of specimen loaded transversally relative layers shows to look very similar, figure 55-59. All of the tested materials broke straight over the layer bond. The specimen with longitudinal layers the fractures of PET, ABS and T-glase shows an angled fracture. Eco PLA as well as Flashforge PLA shows a straight fracture.

4.2.2 Layer bonding of settings

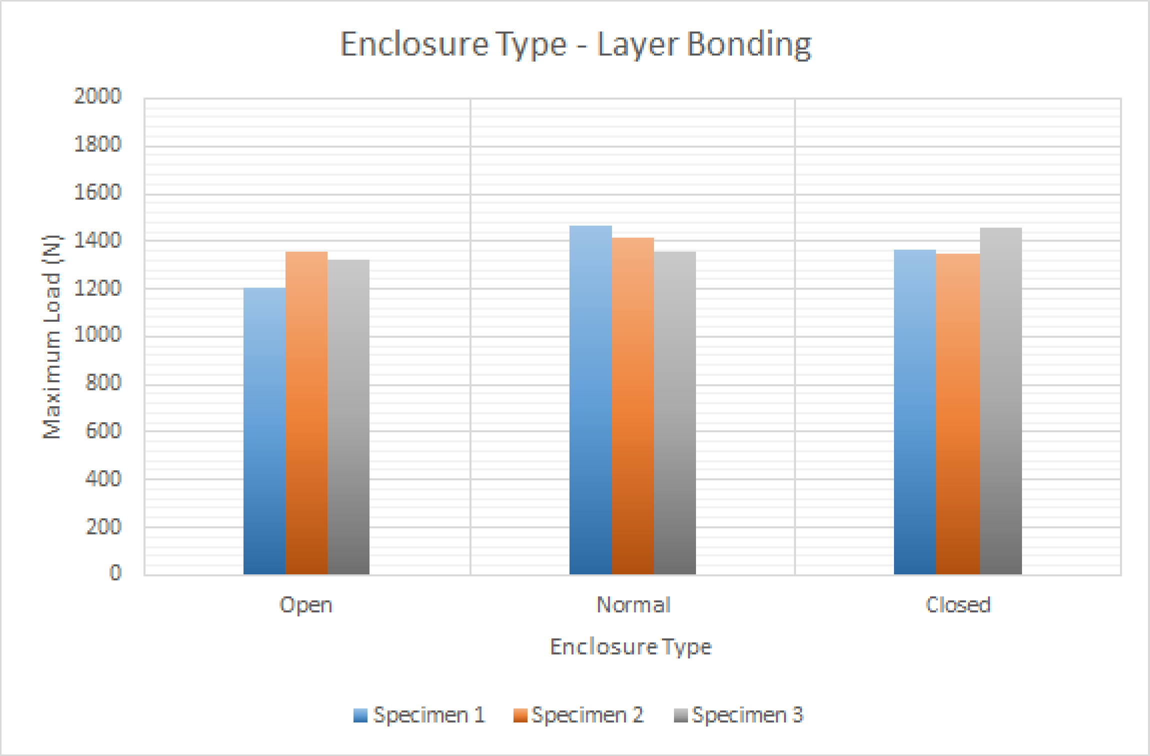


Figure 60: Maximum load measurements of specimen printed with various enclosure designs. Printing settings used see table 2 and 7

We can see a slight improvement in layer bonding when using a normal or closed enclosure design compared to an open, see measurements in figure 60. Difference in average between open and normal is 9 %. Measurements show very small difference between normal and closed enclosure. No apparent difference is seen in the microscope pictures. See appendix figure 86.

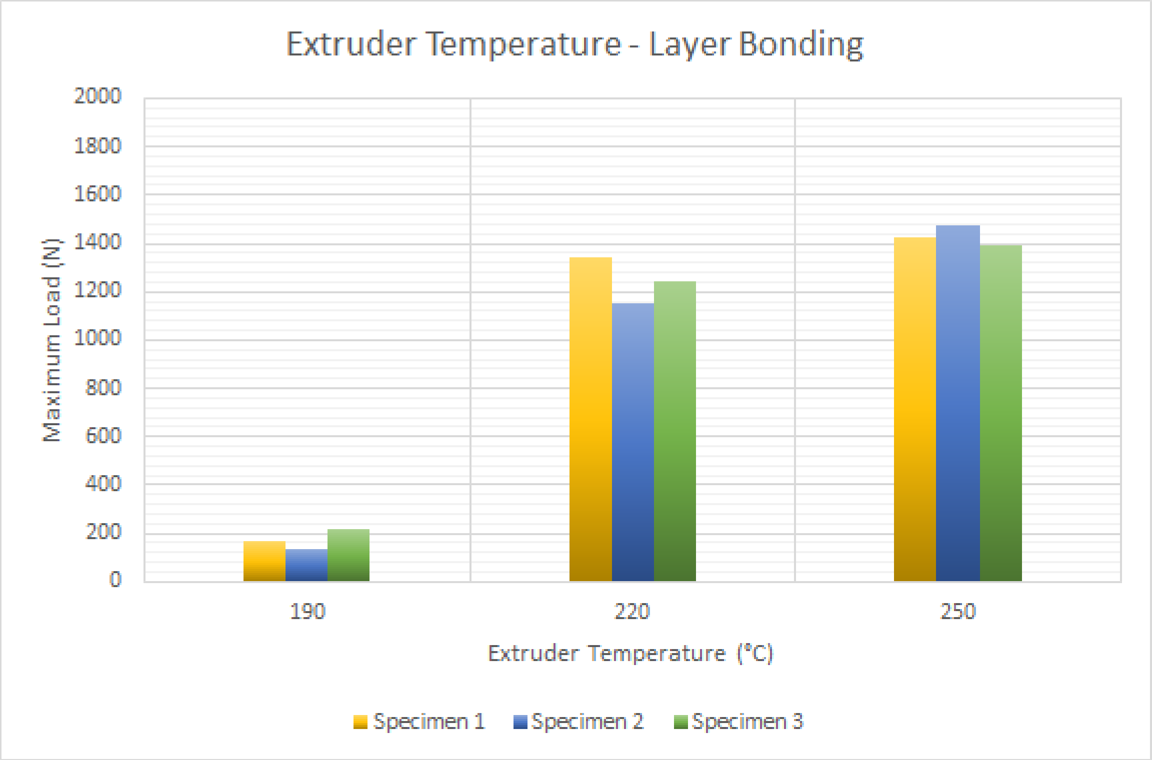


Figure 61: Maximum load measurements of specimens printed with various extruder temperature. Printing settings used see table 2 and 7

At 190°C extruder temperature we can see that the layer bond is very weak. 250°C measures on average to have 721 % better load capacity compared to 190°C, shown in figure 61. The actual extruder temperature is slightly lower than the target temperature. This is due to the case and nozzle fans is cooling the extruder and the heater cannot keep up. The monitored extruder temperature was 216°C when the target temperature was set to 220°C.

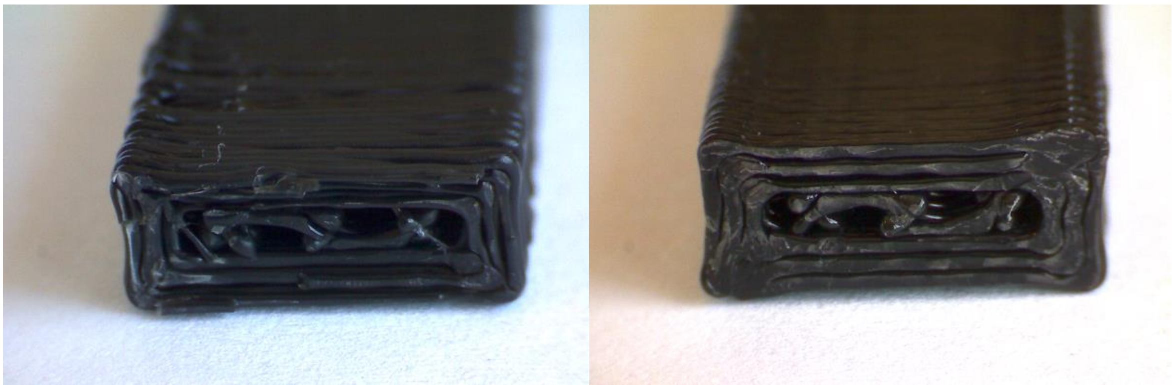


Figure 62: Fractures of specimen printed with extruder temperature 190°C to the left and 250°C to the right

We can see some apparent difference in the fracture for 190°C and 250°C, figure 62. For 190°C extruder temperature the fracture shows very inadequate layer bonding.

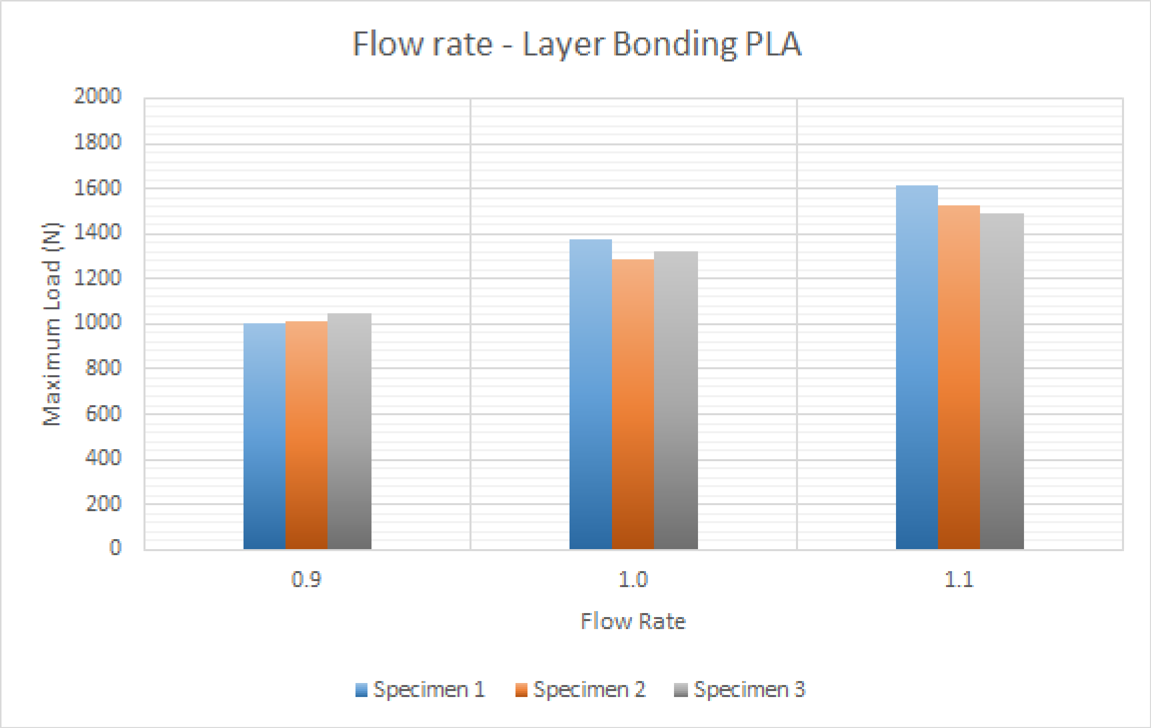


Figure 63: Maximum load measurements of specimen printed with various flow rates. Printing settings used see table 2 and 7

We can see a steady increase in layer bonding performance by flow rate. Load capacity is 51 % higher for flow rate 1.1 compared to 0.9.

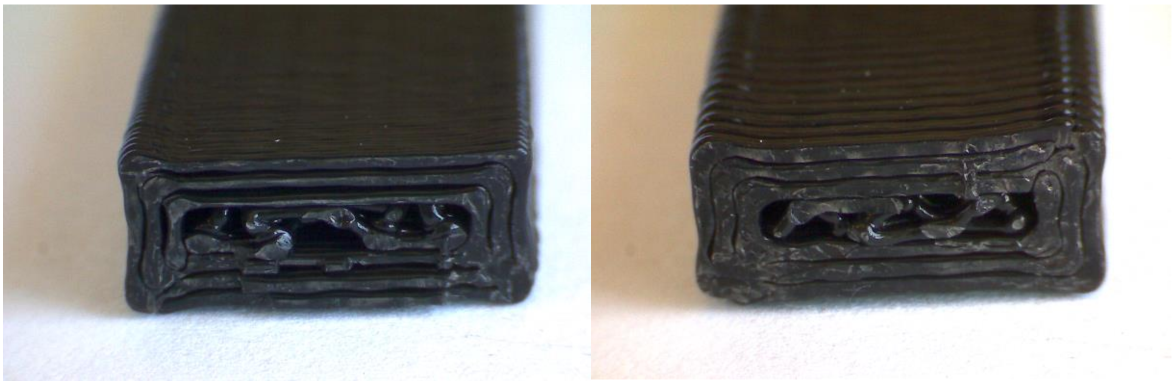


Figure 64: Fractures of PLA specimens printed with 0.9 flow rate to the left and 1.1 to the right

An apparent difference is seen in the fracture inspections for flow rate, see figure 64. A higher flow rate seem to make the layers get increased layer contact and therefore increasing layer bonding performance.

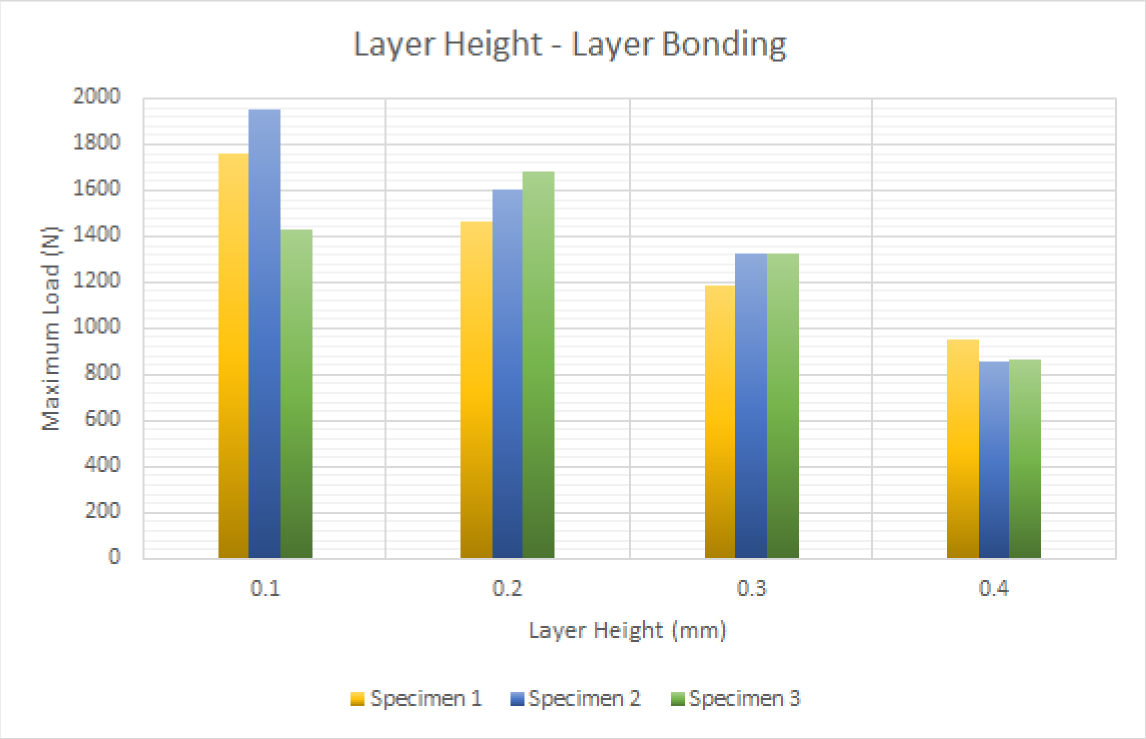


Figure 65: Maximum load measurements of specimen printed with various layer heights. Printing settings used see table 2 and 7

When decreasing layer height from 0.4 mm to 0.1 mm the load capacity increases with 91 %, measured average of three tested specimen, see figure 65. The results show a linear relation between layer height and load capacity.

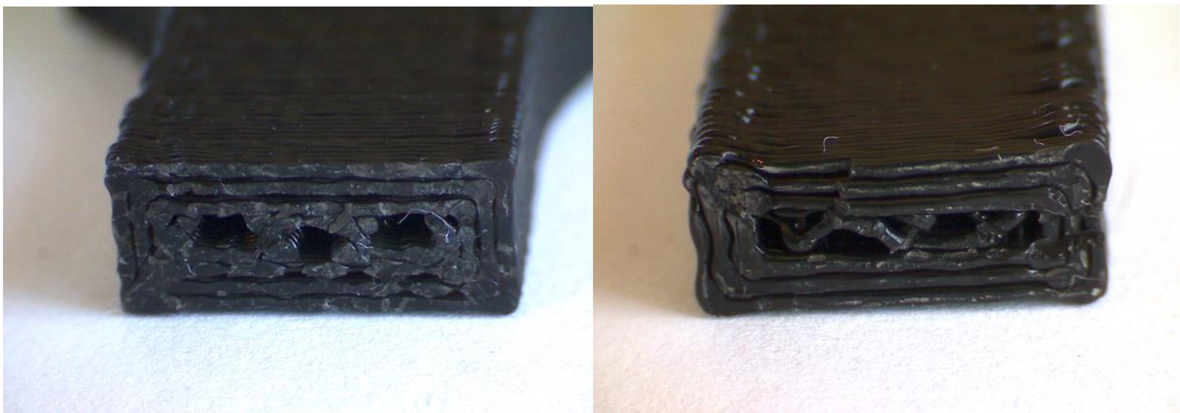


Figure 67: Fractures of specimen with layer height 0.1 to the left and 0.4 to the right

In the microscope pictures the difference between 0.1 mm and 0.4 mm layer height is clear. The geometry is better shaped at 0.1 mm layer height. It looks like the layers are slightly better pushed down on each other in the 0.1 mm case. The layers of 0.1 mm seem to have been extruded more evenly compared to the 0.4 mm.

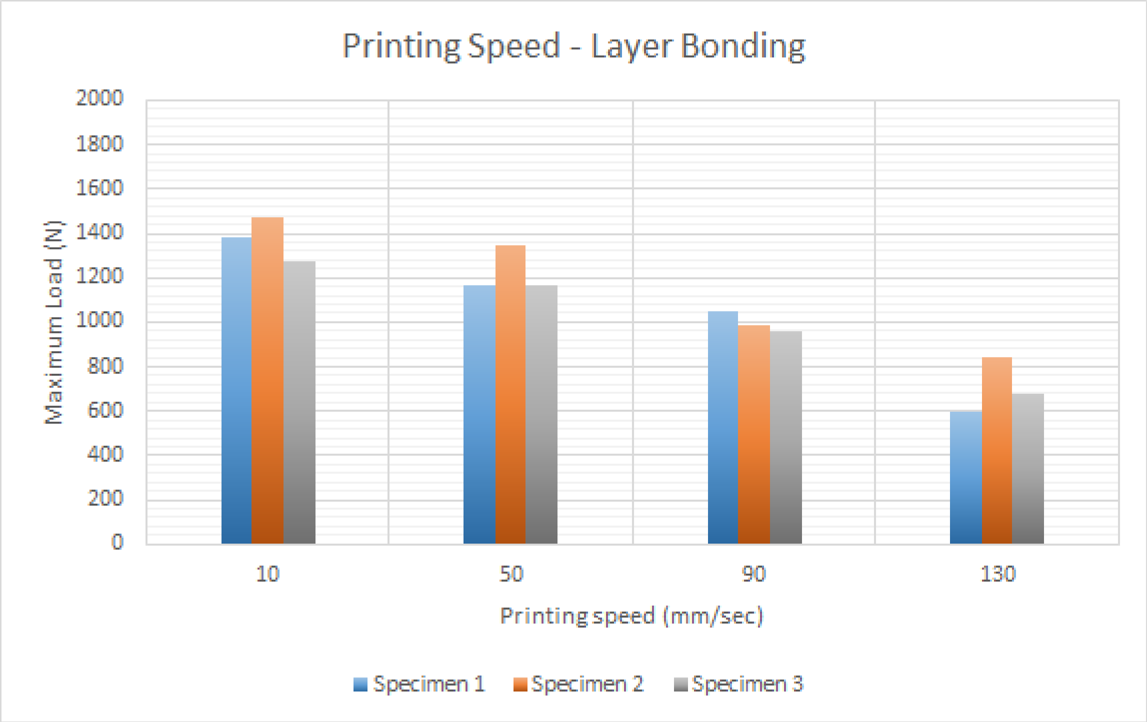


Figure 68: Maximum load measurements of specimen printed with various printing speed. Printing settings used see table 2 and 7

A very clear tendency of decrease in layer bonding performance with increasing printing speed is seen in figure 68. From 10 mm/sec to 130 mm/sec the load capacity drops by 95 %.

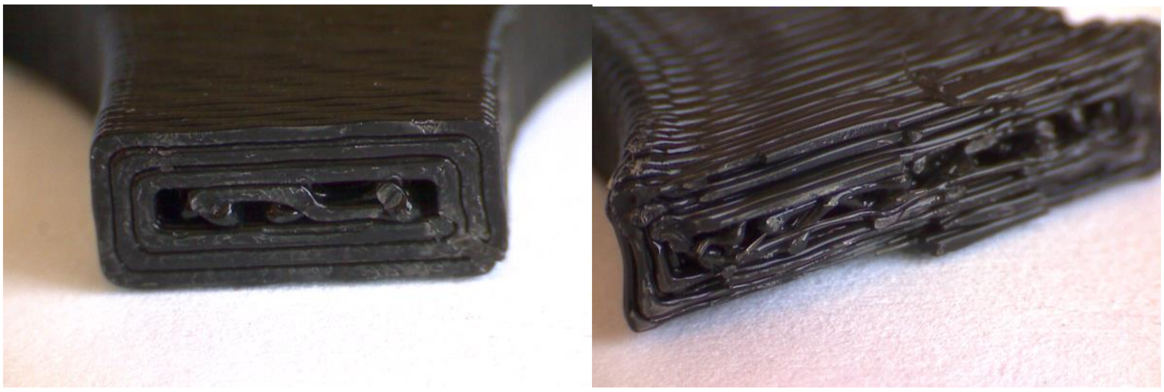


Figure 68: Specimen fractures with printing speed 10 mm/sec to the left and 130 mm/sec to the right

The fractures of the specimen printed at 130 mm/sec shows big flaws in the layer bonds. The layers are disordered and the contact surfaces between the layers are small.

5 DISCUSSION

5.1 Tensile properties

The strain measured is actual nominal strain because it is measuring translation between the grips. The conventional way to measure strain is between the gauge section of the specimen. The E-modulus is based on this nominal strain and may therefore not be comparable to real E-modulus of other plastics.

It is important to notice that all tests performed in this study is not under the same circumstances, the results may therefore not be directly comparable cross test categories. For example PET, PLA and ABS was performed at 1 mm/min testing speed while the nylon based filaments were tested at 20 mm/min. This is a factor that can cause difference in the test results.

5.1.1 Tensile properties of basic materials

We can see some quite big difference between the tensile properties of ABS, PET and PLA, see figure 43. The stress-strain behavior is expected. The PLA is known as a hard and brittle material. PET is a somewhat more flexible material in comparison, just like the tensile test shows. The stress-strain curve of ABS shows that it is a little softer material than PLA, which is expected. ABS places somewhere in between the PLA and PET in stress-strain behavior.

If we compare the measured tensile strengths of PET, PLA and ABS they are quite similar to what Pearce's and the other researchers study of 3D printed materials shows. They measured tensile strength of PLA to 56.6 MPa were 51 MPa is measured in this study. They measured 28.5 MPa for ABS while 34 MPa in this study. The E-modulus measured in their study for PLA was 3368 MPa were this study measures 3150 MPa. For ABS they measured 1807 MPa and in this study's case it was 2300 MPa. So the E-modulus are rather similar as well. This tests are made under different circumstances and therefore they will naturally vary to some extent. But it confirms that my measurements are adequate.

Strain at breaks appear to diverge between the specimens of each material, figure 80-85. This seems to apply for all tested materials. For example we would expect the ABS to break at strain levels like two of three of the specimens tested. One ABS specimen shows a behavior of a brittle material after maximum stress. The measured material behavior after yield or maximum tensile strength is questionable. The specimen may not have been printed and conditioned exactly identical and therefore there may be some variation.

A polymer's molecular structure is manipulated by temperature and time. The crystallinity of the plastic in the final product may have been affected by the processing. For instance the extruder temperature and ambient conditions can have an effect on the mechanical properties of the material itself. And this effect will most likely vary for the specific material used.

The TPU 90 showed some great elasticity. The measurement failed because of equipment limitations so no results could be extracted.

5.1.2 Tensile properties of nylons

The elongation is of magnitude approximately 10 times or more than of the basic plastics tested, see figure 44 and 50. It is expected that these nylon based polymers has a more flexible behavior than PET, PLA and AB.

We can see variation in strain at break for the different specimen used for all nylons, see figure 83-85 in appendix. Tensile strength seems to have some variation as well for all three nylons. This may be to uneven conditioning or mounting of the test specimen, see figure 50. E-modulus and yield stress is consistent for 645 and 618. Before yield stress all specimen of 645 and 618 produce similar stress-strain results which indicates on good testing consistency. Two of three 910 specimen shows equal stress-strain behavior but one measurement shows large divergence. This odd specimen may have had some flaw in the conditioning or in its test procedure.

The nylon materials by Taulman have many other features that should be considered for the specific application, for example chemical resistance and suitability for contact with food.

5.2 Layer bonding of materials

As explained in chapter 2.3 and 2.7 the crystallinity is affected by the temperature-time relationship. This phenomenon may influence the mechanical properties and ultimately the results of this study. This factor is not studied in depth in this project.

Important to notice is that the cross section area seems to be significantly bigger for the specimen printed on height. This can be seen in figure 87. This is because each layer has a higher width than height. The printed strings are not symmetrical in that sense. They are rather of elliptic shape. This is confirmed by looking at the fractures in figure 88. This results in a greater cross section area for the specimen printed standing. This greater cross section area probably gives the specimen printed standing a so to say undeserved advantage against the specimen printed flat. If model was thicker and wider, like in many realistic cases, this advantage will be negligible because the space for infill will be larger relative to perimeters than in the measured case.

Gaps between layers for ABS seem to get bigger the further away from the building plate it gets, this is apparent in figure 88 in appendix. This may be an effect due to the higher bed temperature for ABS and temperature variation caused by the nozzle getting further away from the bed for each layer. This phenomenon is explained in chapter 2.8.2 and can give the ABS specimens a higher E-modulus than PET and PLA because it will be more solid.

5.2 Layer bonding of settings

5.2.1 Enclosure

It was expected to see a subtle difference between the open, normal and closed enclosure design. With all doors of the Dreamer open the ambient temperature just drops one degree. A truly open design with no walls may have an even lower ambient temperature. This may influence the layer bonding.

By the authors previous experience it is seen that some materials like for example ABS have a greater benefit of enclosure. ABS printed with an open enclosure can result in bad layer bonding. We can see in the previous test of layer bonding performance between materials the ABS performs well with a closed enclosure design. Because the nozzle fan is turned off for ABS the case fans are as well, this may give ABS an advantage. The PLA seem to get good layer bonding in open as well as closed enclosure design. ABS and other materials may not.

5.3.2 Extruder temperature

Printing with PLA at 190°C is resulting in very bad layer bonding. It seems like the plastic is not soft enough to be extruded and therefore insufficient plastic is added to the model. This results in bad printing quality both visually and strength wise. This can be seen in figure 61 and 62.
The melting temperature for this PLA is probably around 190°C because it seems to be a tipping point determining the lowest temperature it is possible to print this particular type of plastic. Another factor that can contribute is that when the extruder temperature is set to 190°C the real temperature will be a few degrees lower because of case fans and nozzle fan is cooling the extruder slightly and the heater cannot keep up.

Printing with 220°C greatly improves the layer bonding performance. Increasing the temperature 30°C further slightly increases layer bonding performance. This may be due to the plastics temperature when it is touching the layer below has a higher temperature and therefore it will get a greater bonding with the other layer.

5.3.3 Flow rate

Increased flow rate improves layer bonding with even inclination. This is expected due to the fact that increased plastic flow should in theory increase the contact surfaces between layers. It is reasonable that the amount of plastic added to the part will influence the strength.

5.3.4 Layer height

The layer height appear to be an important factor by the measurements. This is probably a result of the plastic being pushed in closer to the model for each layer. The nozzle is just 0.1 mm from the layer below making the heat from the nozzle likely helping the two layers bond good together. At layer height of 0.4 more plastic is extruded at a time which should result in the plastic to cool slower and therefore increase the layer bonding performance.

5.3.5 Printing speed

The results show that printing speed is a very important factor to optimize for durability. Printing at high speed results in very bad layer bonding performance. This may have been caused by too fast cooling of the plastic. The extruded layer is not added with sufficient temperature which results in a bad adhesion to the layer below.

5.3.6 Generally valid results

The results may not apply for all FFF 3D printers and software. The author believe the results can be said to apply generally in most cases but it is not sure that other 3D printers or software will get the same results.

6 CONCLUSIONS

PET and PLA shows to be very strong materials. With higher tensile strength compared to the very commonly used polymer ABS. The PET offers some flexibility while the PLA is very hard. PLA has a tensile strength of 51 MPa, PET 40MP and ABS 34 MPa. The measured values shows to be similar to others studies and can therefore be assumed to be adequate. The soft material TPU 95 testing procedure failed and no data could be extracted.

All nylons have useful properties when needing a tough material. The nylon 910 have a stiffer behavior than 645 and 618 and is good when needing some flexibility while not being too soft, keeping its original shape at high load. 645 and 618 are good choices in an applications where flexibility is of importance. The following tensile strength of the tested nylon based materials was measured: 645 40 MPa, 618 34 MPa and 910 31 MPa. The variation of stress-strain behavior between specimens of all nylon plastics was relatively large. The inclination of the elastic part of the stress-strain curve shows good consistency between specimens for 645 and 618, but not for 910. Because of this the measured tensile properties is not very accurate.

Knowing the tensile properties as a design engineer is very crucial. The data in this study can aid the 3D printer user to choose a suitable material for the desired application and ultimately make a durable product.

All tested materials except one seem to have good layer bonding performance under the specific conditions used. Eco PLA, ABS, PET and Taulman T-glase shows similar difference when comparing load capacity transversally and longitudinally relative to layers. Flashforge natural PLA has a slightly lower load capability when loaded transversally.

The major factors available to improve layer bonding seems to be extruder temperature, layer height and printing speed. Load capacity of a specimen loaded transversally relative to layers printed with extruder temperature 250°C is seven times higher than specimen printed at 190°C. If printing with layer height 0.1 mm the measurements shows an increased load capacity of 91 % compared to 0.4 mm. A printing speed of 10 mm/sec show 95 % better layer bonding performance than 130 mm/sec. Closed and normal enclosure design appears to give slightly better layer bonding compared to an open design. The printing flow rate increases load capacity with 51 % comparing 0.9 with 1.1, with 1.1 giving the best layer bonding. These factors may not apply to all 3D printers, software or geometrical shapes.

The tested printing settings effect on layer bonding may not stack. However it may be very useful to have several options when optimizing your 3D printing for durability due to other important factors considering visual quality, weight and printing time. The results of this study may help the 3D printer to tweak basic settings to increase layer bonding performance significantly. This study will serve as knowledge in how to optimize Fused Filament Fabrication 3D printers for durability.

7 RECOMMENDATIONS AND FUTURE WORK

The wide range of available filaments on the market call for further tests of tensile properties. There are a lot of other materials, settings and parameters to be tested for layer bonding performance. A wider range in setting parameters and smaller increments would be interesting to test.

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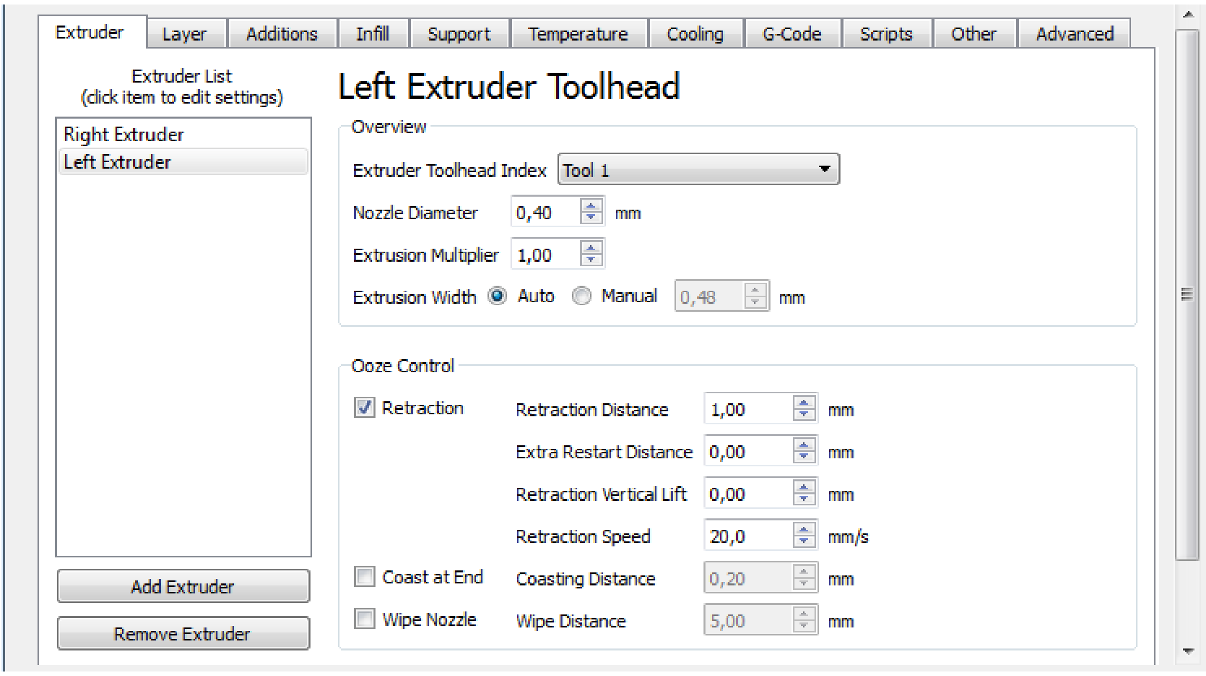
APPENDIX

Default settings setup Simplify3D



Extruder List
(click item to edit settings)

- Right Extruder
- Left Extruder

Left Extruder Toolhead

Overview

Extruder Toolhead Index: Tool 1

Nozzle Diameter: 0,40 mm

Extrusion Multiplier: 1,00

Extrusion Width: ● Auto ○ Manual 0,48 mm

Ooze Control

☑ Retraction — Retraction Distance: 1,00 mm

Extra Restart Distance: 0,00 mm

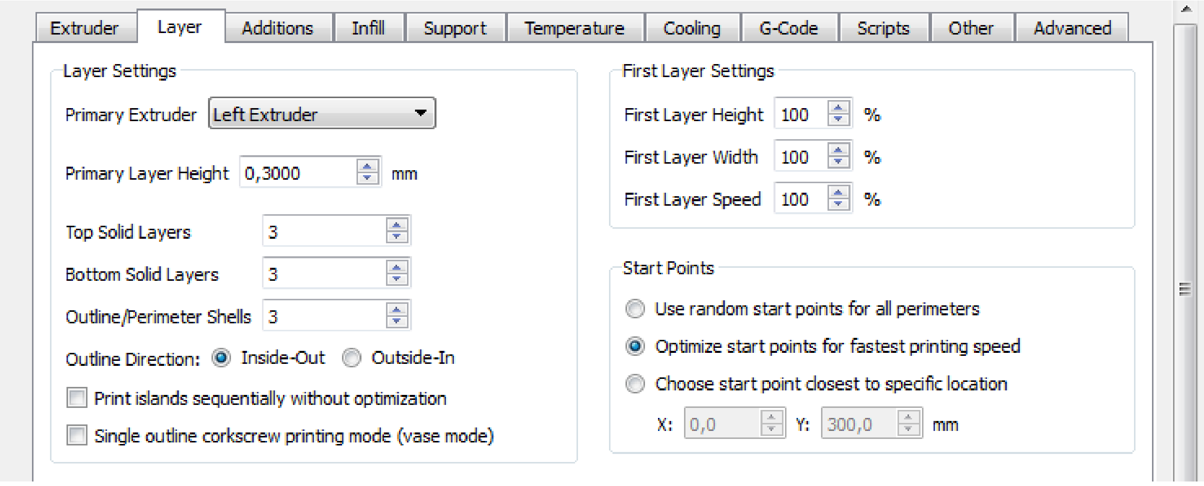
Retraction Vertical Lift: 0,00 mm

Retraction Speed: 20,0 mm/s

☐ Coast at End — Coasting Distance: 0,20 mm

☐ Wipe Nozzle — Wipe Distance: 5,00 mm

Figure 69: Simplify 3D Settings part 1



Layer Settings

Primary Extruder: Left Extruder

Primary Layer Height: 0,3000 mm

Top Solid Layers: 3

Bottom Solid Layers: 3

Outline/Perimeter Shells: 3

Outline Direction: ● Inside-Out ○ Outside-In

☐ Print islands sequentially without optimization

☐ Single outline corkscrew printing mode (vase mode)

First Layer Settings

First Layer Height: 100 %

First Layer Width: 100 %

First Layer Speed: 100 %

Start Points

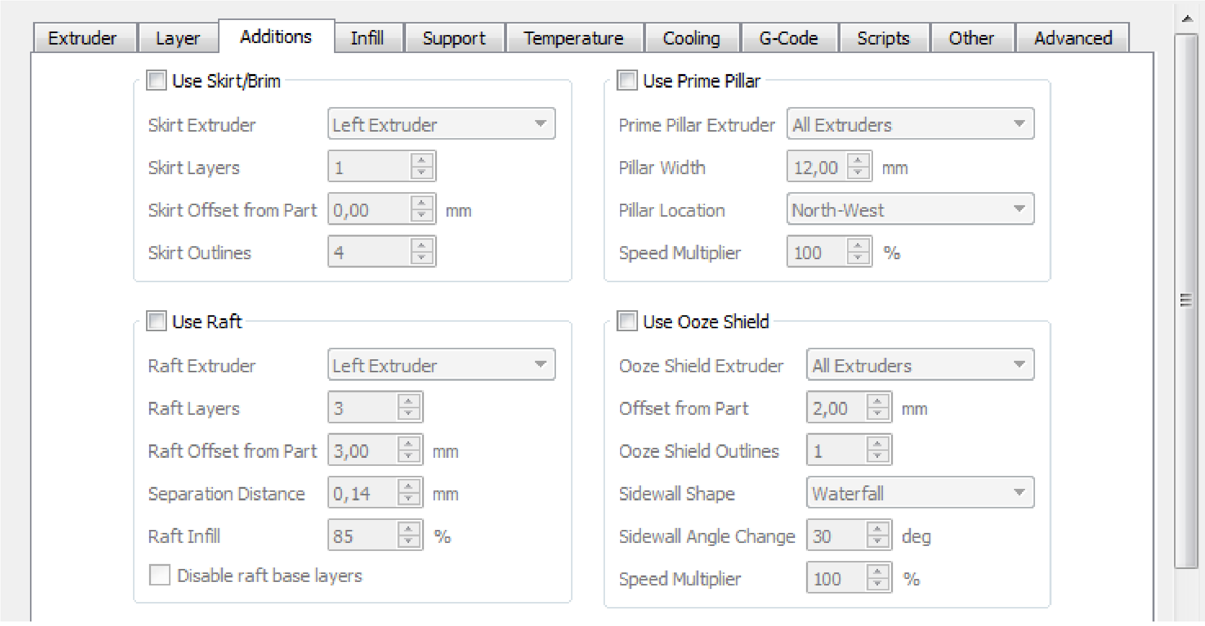
○ Use random start points for all perimeters

● Optimize start points for fastest printing speed

○ Choose start point closest to specific location

X: 0,0 Y: 300,0 mm

Figure 70: Simplify 3D Settings part 2



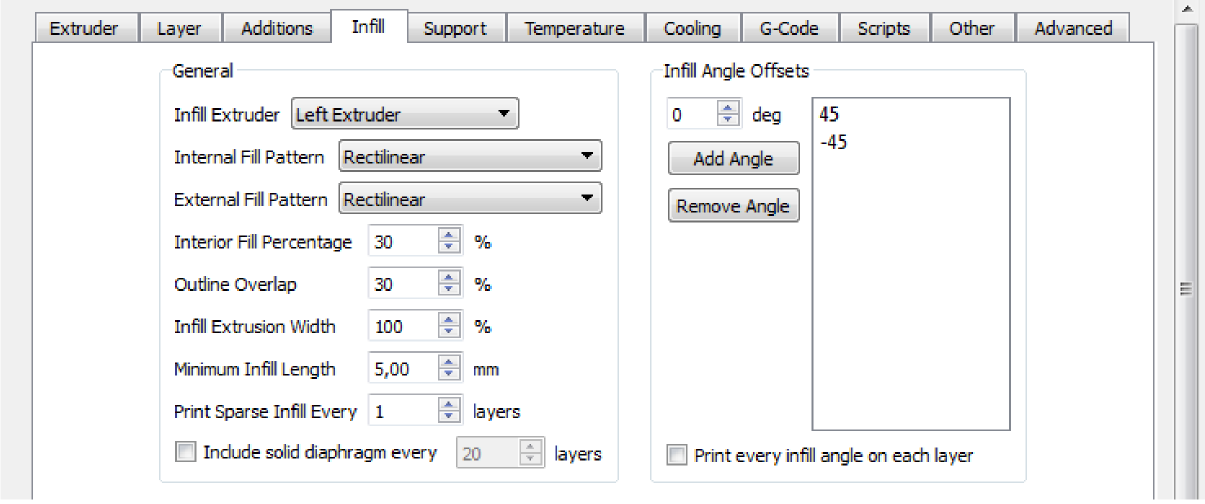
☐ Use Skirt/Brim
Skirt Extruder: Left Extruder
Skirt Layers: 1
Skirt Offset from Part: 0,00 mm
Skirt Outlines: 4

☐ Use Prime Pillar
Prime Pillar Extruder: All Extruders
Pillar Width: 12,00 mm
Pillar Location: North-West
Speed Multiplier: 100 %

☐ Use Raft
Raft Extruder: Left Extruder
Raft Layers: 3
Raft Offset from Part: 3,00 mm
Separation Distance: 0,14 mm
Raft Infill: 85 %
☐ Disable raft base layers

☐ Use Ooze Shield
Ooze Shield Extruder: All Extruders
Offset from Part: 2,00 mm
Ooze Shield Outlines: 1
Sidewall Shape: Waterfall
Sidewall Angle Change: 30 deg
Speed Multiplier: 100 %

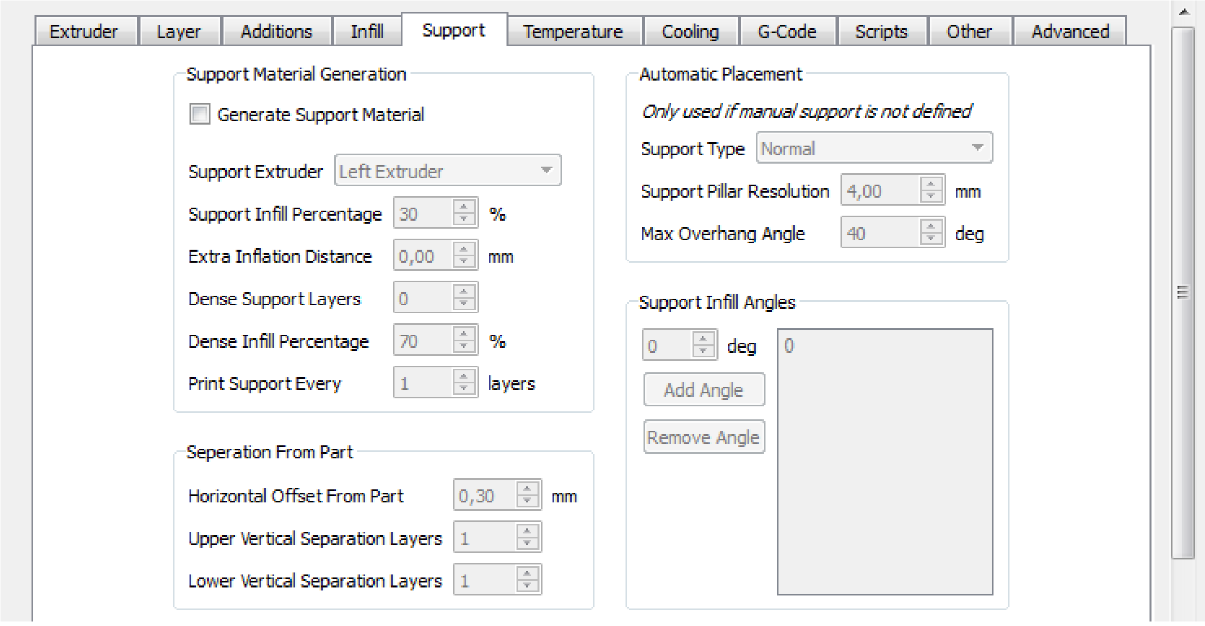
Figure 71: Simplify 3D Settings part 3



General
Infill Extruder: Left Extruder
Internal Fill Pattern: Rectilinear
External Fill Pattern: Rectilinear
Interior Fill Percentage: 30 %
Outline Overlap: 30 %
Infill Extrusion Width: 100 %
Minimum Infill Length: 5,00 mm
Print Sparse Infill Every: 1 layers
☐ Include solid diaphragm every 20 layers

Infill Angle Offsets
0 deg
45
-45
☐ Print every infill angle on each layer

Figure 72: Simplify 3D Settings part 4



Support Material Generation

☐ Generate Support Material

Support Extruder: Left Extruder

Support Infill Percentage: 30 %

Extra Inflation Distance: 0,00 mm

Dense Support Layers: 0

Dense Infill Percentage: 70 %

Print Support Every: 1 layers

Seperation From Part

Horizontal Offset From Part: 0,30 mm

Upper Vertical Separation Layers: 1

Lower Vertical Separation Layers: 1

Automatic Placement

Only used if manual support is not defined

Support Type: Normal

Support Pillar Resolution: 4,00 mm

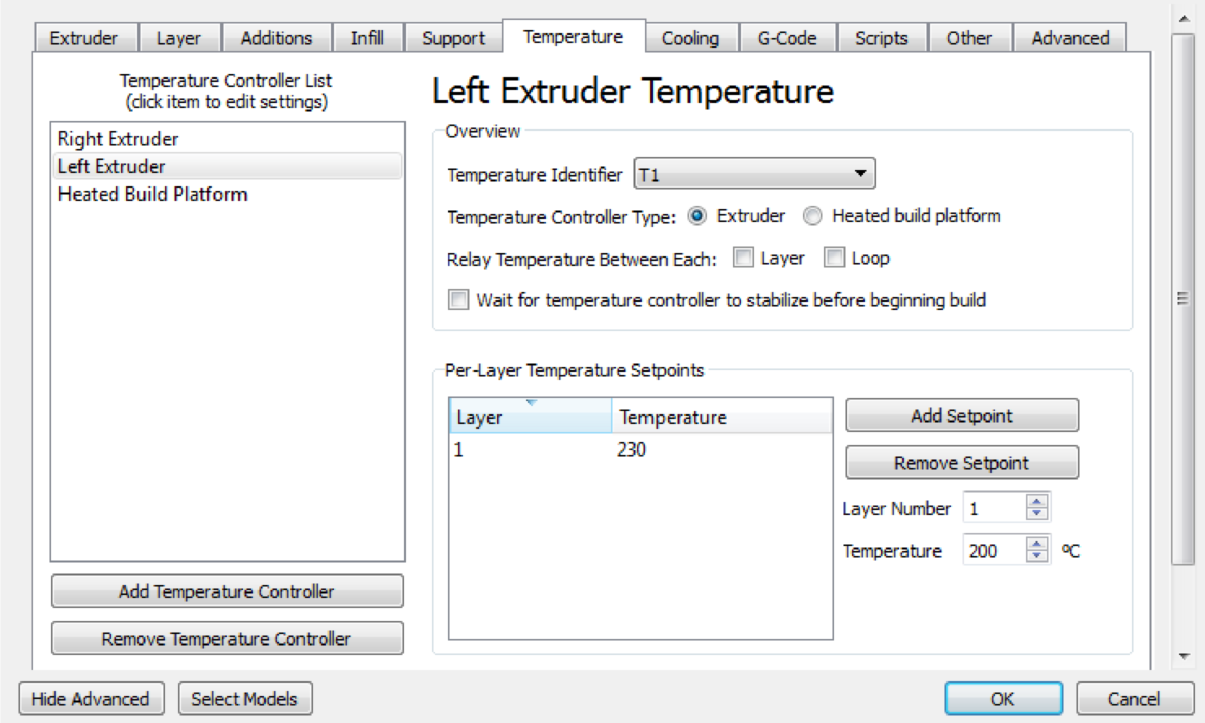
Max Overhang Angle: 40 deg

Support Infill Angles

0 deg

0

Figure 73: Simplify 3D Settings part 5



Temperature Controller List
(click item to edit settings)

Right Extruder
Left Extruder
Heated Build Platform

Left Extruder Temperature

Overview

Temperature Identifier: T1

Temperature Controller Type: ● Extruder ○ Heated build platform

Relay Temperature Between Each: ☐ Layer ☐ Loop

☐ Wait for temperature controller to stabilize before beginning build

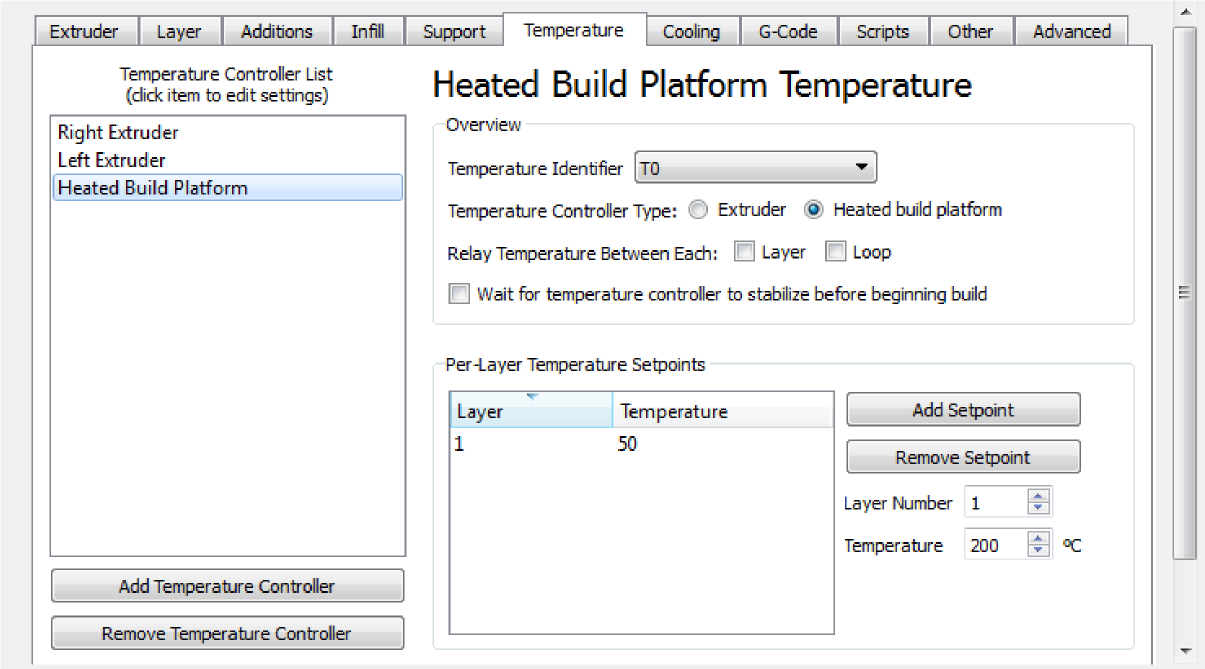
Per-Layer Temperature Setpoints

Layer	Temperature
1	230

Layer Number: 1

Temperature: 200 °C

Figure 74: Simplify 3D Settings part 6



Temperature Controller List
(click item to edit settings)

Right Extruder
Left Extruder
Heated Build Platform

Heated Build Platform Temperature

Overview

Temperature Identifier: T0

Temperature Controller Type: ○ Extruder ● Heated build platform

Relay Temperature Between Each: ☐ Layer ☐ Loop

☐ Wait for temperature controller to stabilize before beginning build

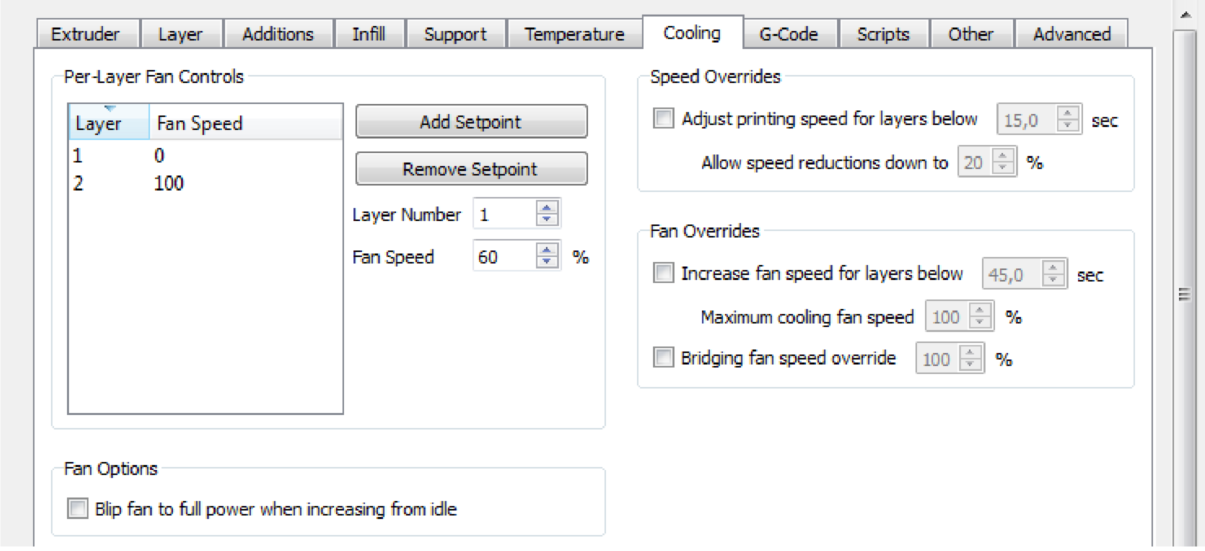
Per-Layer Temperature Setpoints

Layer	Temperature
1	50

Layer Number: 1

Temperature: 200 ºC

Figure 75: *Simplify 3D Settings part 7*



Per-Layer Fan Controls

Layer	Fan Speed
1	0
2	100

Layer Number: 1

Fan Speed: 60 %

Speed Overrides

☐ Adjust printing speed for layers below 15,0 sec

Allow speed reductions down to 20 %

Fan Overrides

☐ Increase fan speed for layers below 45,0 sec

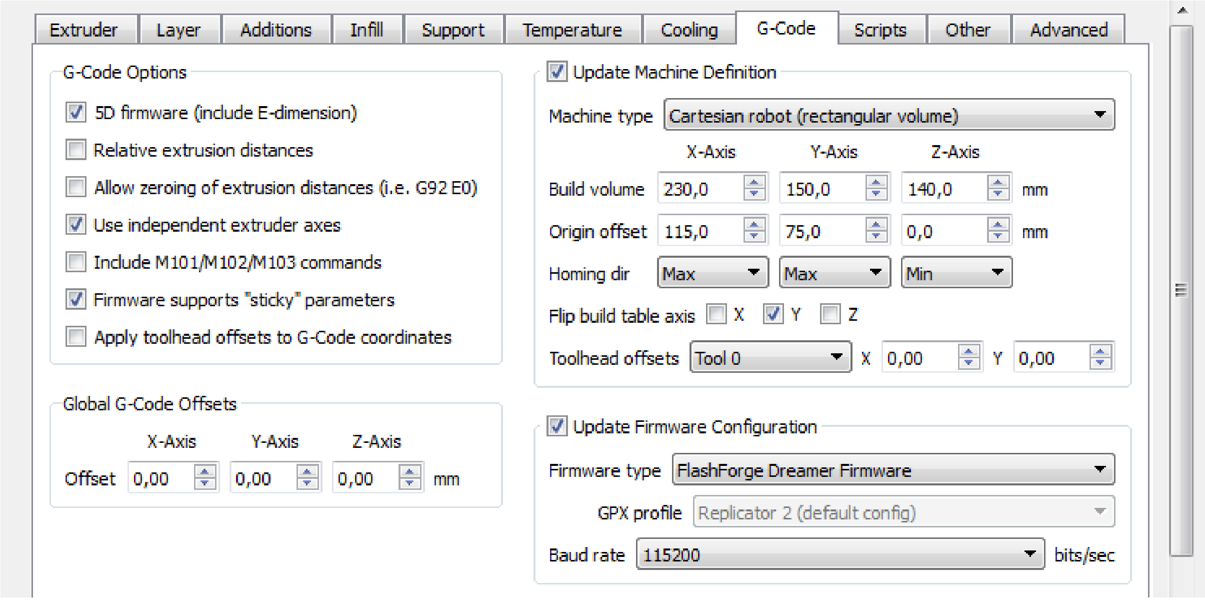
Maximum cooling fan speed 100 %

☐ Bridging fan speed override 100 %

Fan Options

☐ Blip fan to full power when increasing from idle

Figure 76: *Simplify 3D Settings part 8*



G-Code Options

☑ 5D firmware (include E-dimension)
☐ Relative extrusion distances
☐ Allow zeroing of extrusion distances (i.e. G92 E0)
☑ Use independent extruder axes
☐ Include M101/M102/M103 commands
☑ Firmware supports "sticky" parameters
☐ Apply toolhead offsets to G-Code coordinates

Global G-Code Offsets

	X-Axis	Y-Axis	Z-Axis	
Offset	0,00	0,00	0,00	mm

☑ Update Machine Definition

Machine type: Cartesian robot (rectangular volume)

	X-Axis	Y-Axis	Z-Axis	
Build volume	230,0	150,0	140,0	mm
Origin offset	115,0	75,0	0,0	mm
Homing dir	Max	Max	Min	

Flip build table axis ☐ X ☑ Y ☐ Z

Toolhead offsets: Tool 0 X 0,00 Y 0,00

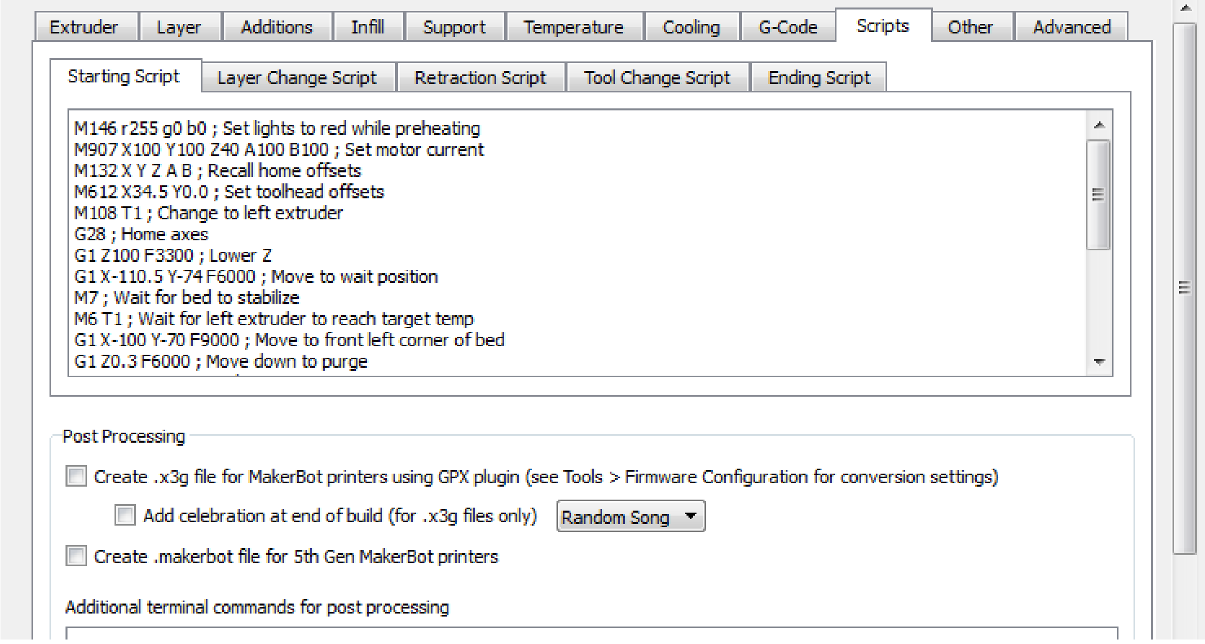
☑ Update Firmware Configuration

Firmware type: FlashForge Dreamer Firmware

GPX profile: Replicator 2 (default config)

Baud rate: 115200 bits/sec

Figure 77: Simplify 3D Settings part 9



```
M146 r255 g0 b0 ; Set lights to red while preheating
M907 X100 Y100 Z40 A100 B100 ; Set motor current
M132 X Y Z A B ; Recall home offsets
M612 X34.5 Y0.0 ; Set toolhead offsets
M108 T1 ; Change to left extruder
G28 ; Home axes
G1 Z100 F3300 ; Lower Z
G1 X-110.5 Y-74 F6000 ; Move to wait position
M7 ; Wait for bed to stabilize
M6 T1 ; Wait for left extruder to reach target temp
G1 X-100 Y-70 F9000 ; Move to front left corner of bed
G1 Z0.3 F6000 ; Move down to purge
```

Post Processing

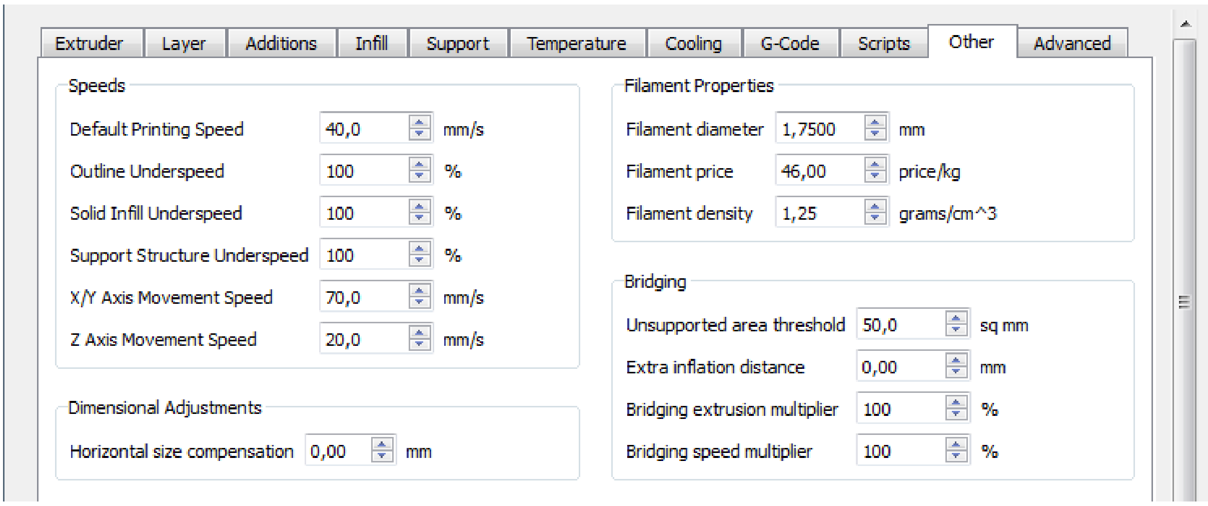
☐ Create .x3g file for MakerBot printers using GPX plugin (see Tools > Firmware Configuration for conversion settings)

☐ Add celebration at end of build (for .x3g files only) Random Song

☐ Create .makerbot file for 5th Gen MakerBot printers

Additional terminal commands for post processing

Figure 78: Simplify 3D Settings part 10



Speeds

Default Printing Speed 40,0 mm/s
Outline Underspeed 100 %
Solid Infill Underspeed 100 %
Support Structure Underspeed 100 %
X/Y Axis Movement Speed 70,0 mm/s
Z Axis Movement Speed 20,0 mm/s

Dimensional Adjustments

Horizontal size compensation 0,00 mm

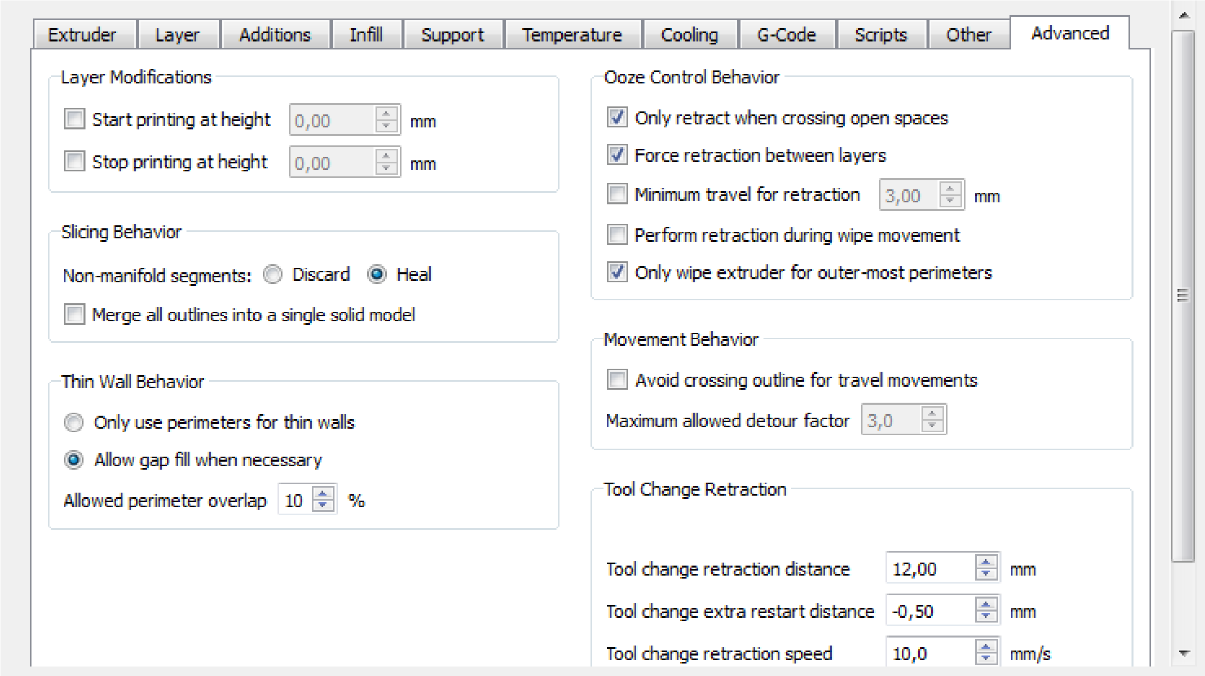
Filament Properties

Filament diameter 1,7500 mm
Filament price 46,00 price/kg
Filament density 1,25 grams/cm^3

Bridging

Unsupported area threshold 50,0 sq mm
Extra inflation distance 0,00 mm
Bridging extrusion multiplier 100 %
Bridging speed multiplier 100 %

Figure 67: Simplify 3D Settings part 11



Layer Modifications

☐ Start printing at height 0,00 mm
☐ Stop printing at height 0,00 mm

Slicing Behavior

Non-manifold segments: ○ Discard ● Heal
☐ Merge all outlines into a single solid model

Thin Wall Behavior

○ Only use perimeters for thin walls
● Allow gap fill when necessary
Allowed perimeter overlap 10 %

Ooze Control Behavior

☑ Only retract when crossing open spaces
☑ Force retraction between layers
☐ Minimum travel for retraction 3,00 mm
☐ Perform retraction during wipe movement
☑ Only wipe extruder for outer-most perimeters

Movement Behavior

☐ Avoid crossing outline for travel movements
Maximum allowed detour factor 3,0

Tool Change Retraction

Tool change retraction distance 12,00 mm
Tool change extra restart distance -0,50 mm
Tool change retraction speed 10,0 mm/s

Figure 79: Simplify 3D Settings part 12

Tensile properties graphs

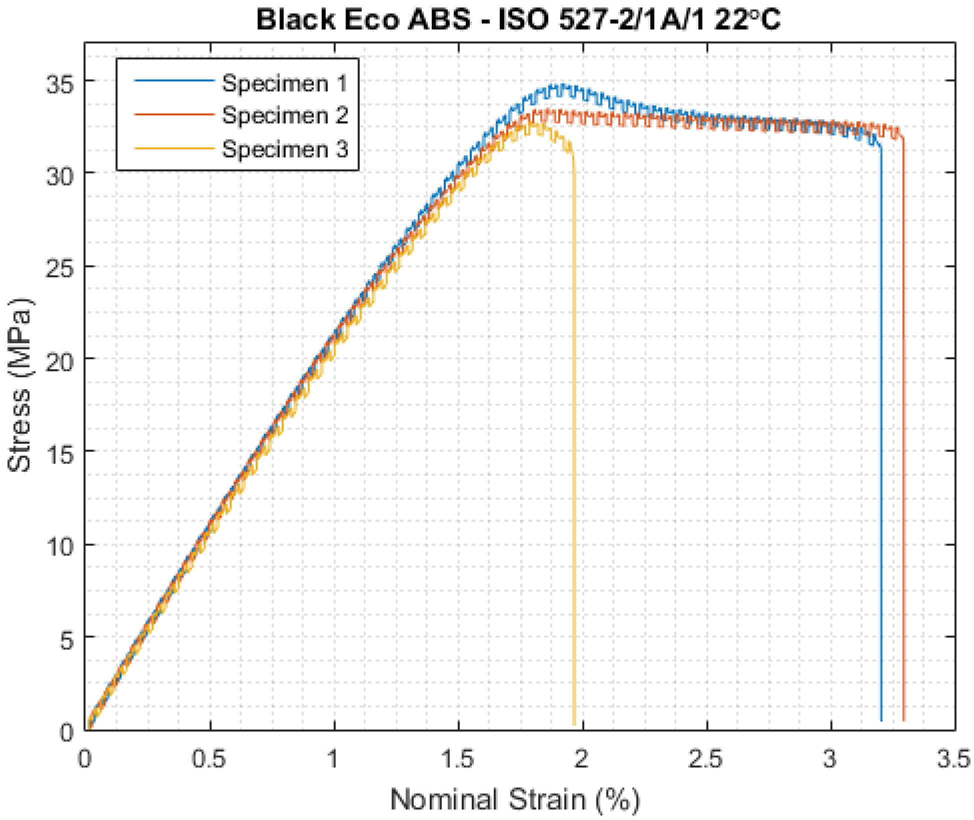


Figure 80: Stress-strain of three ABS specimen

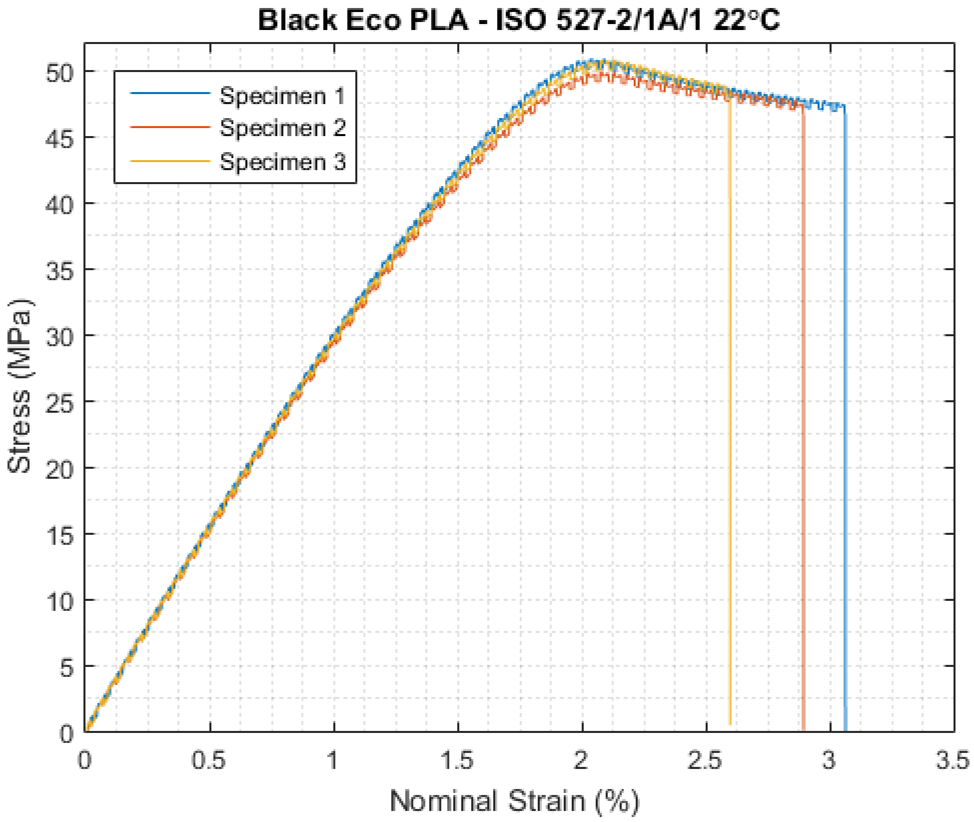


Figure 81: Stress-strain of three PLA specimen

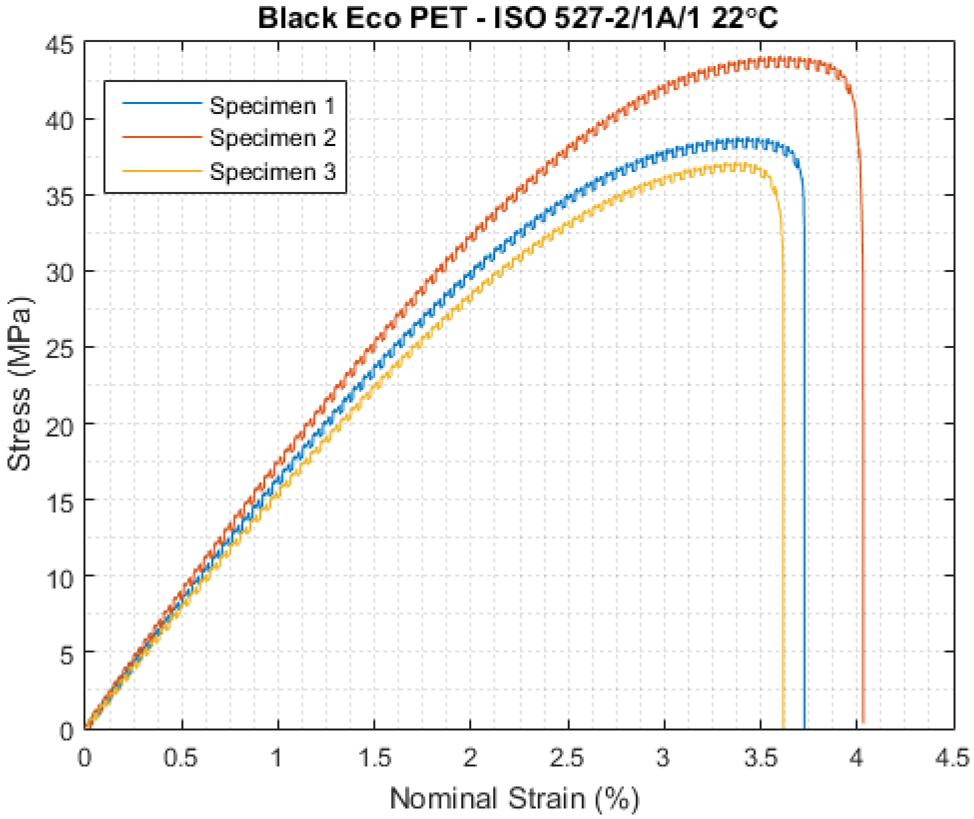


Figure 82: Stress-strain of three PET specimen

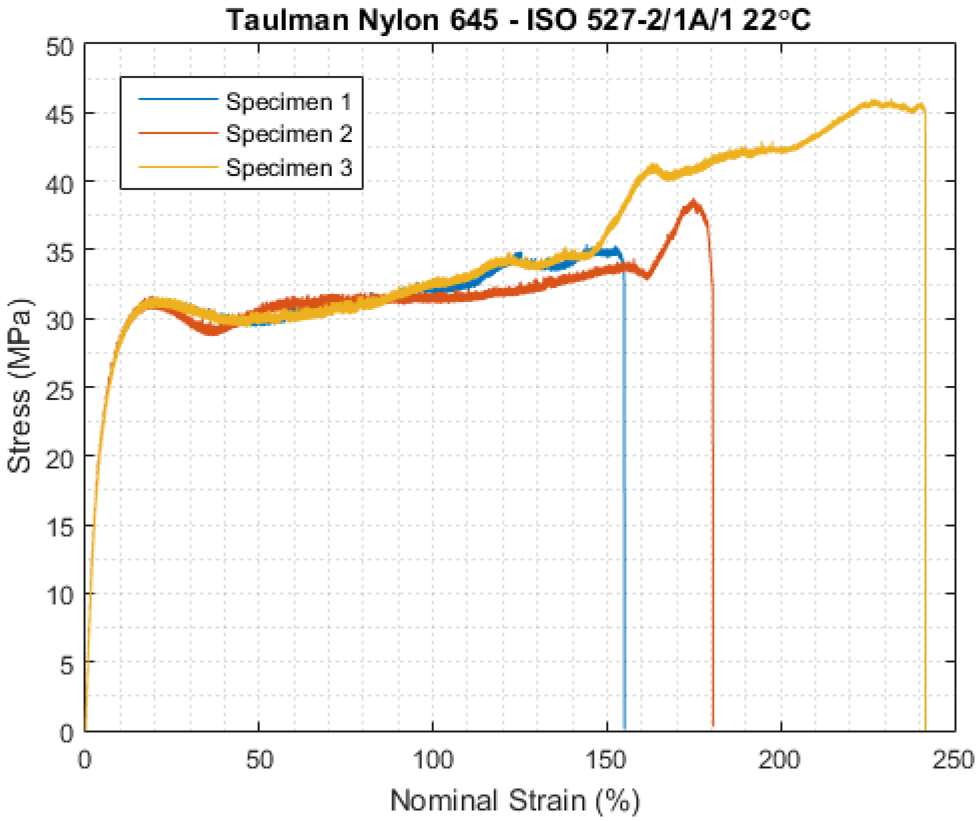


Figure 83: Stress-strain of three 645 specimen

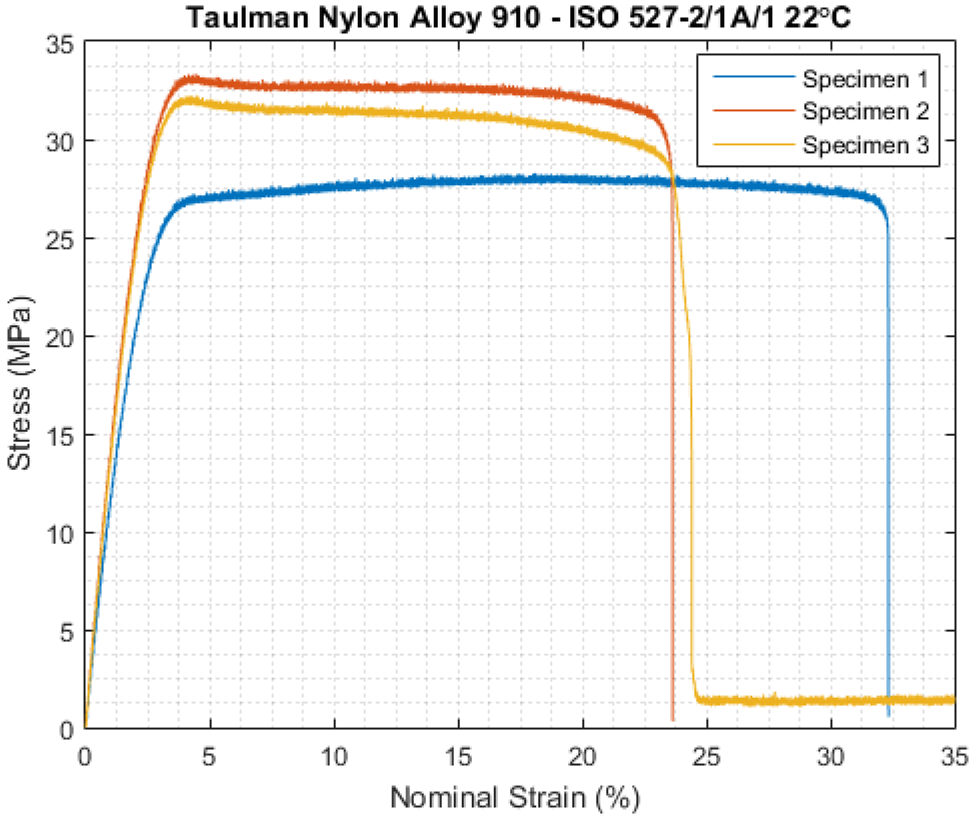


Figure 84: Stress-strain of three 910 specimen

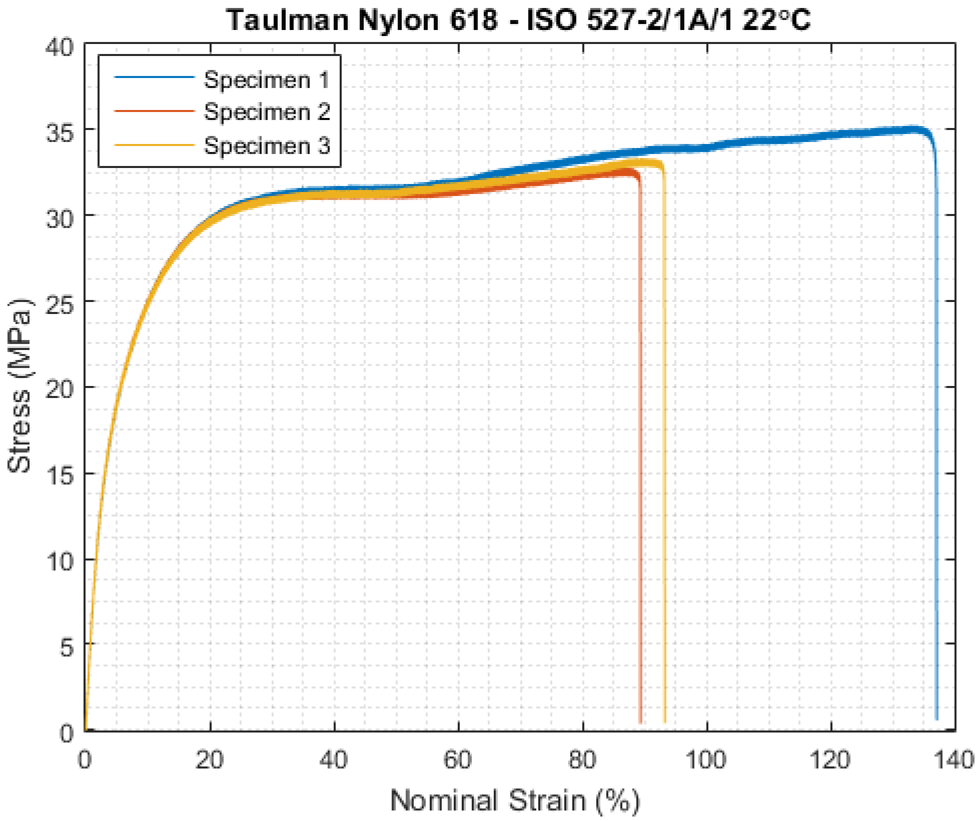


Figure 85: Stress-strain of three 618 specimen

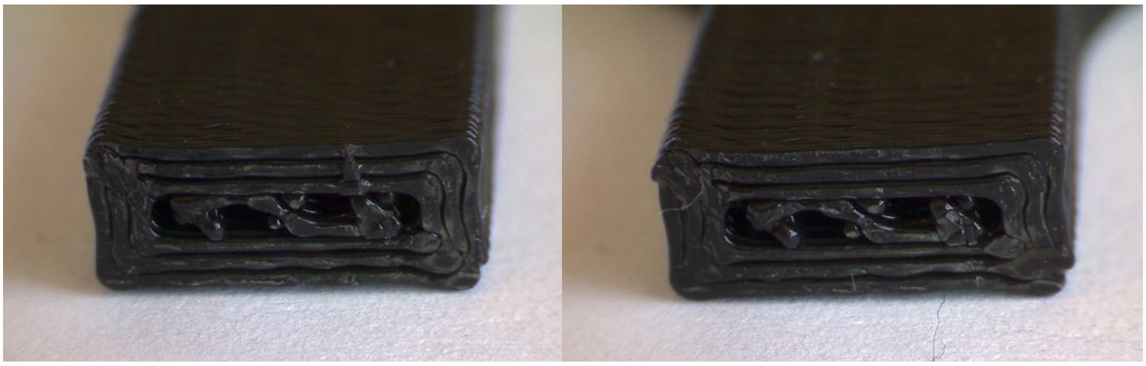


Figure 86: Specimen printed with open enclosure to the left and closed to the right

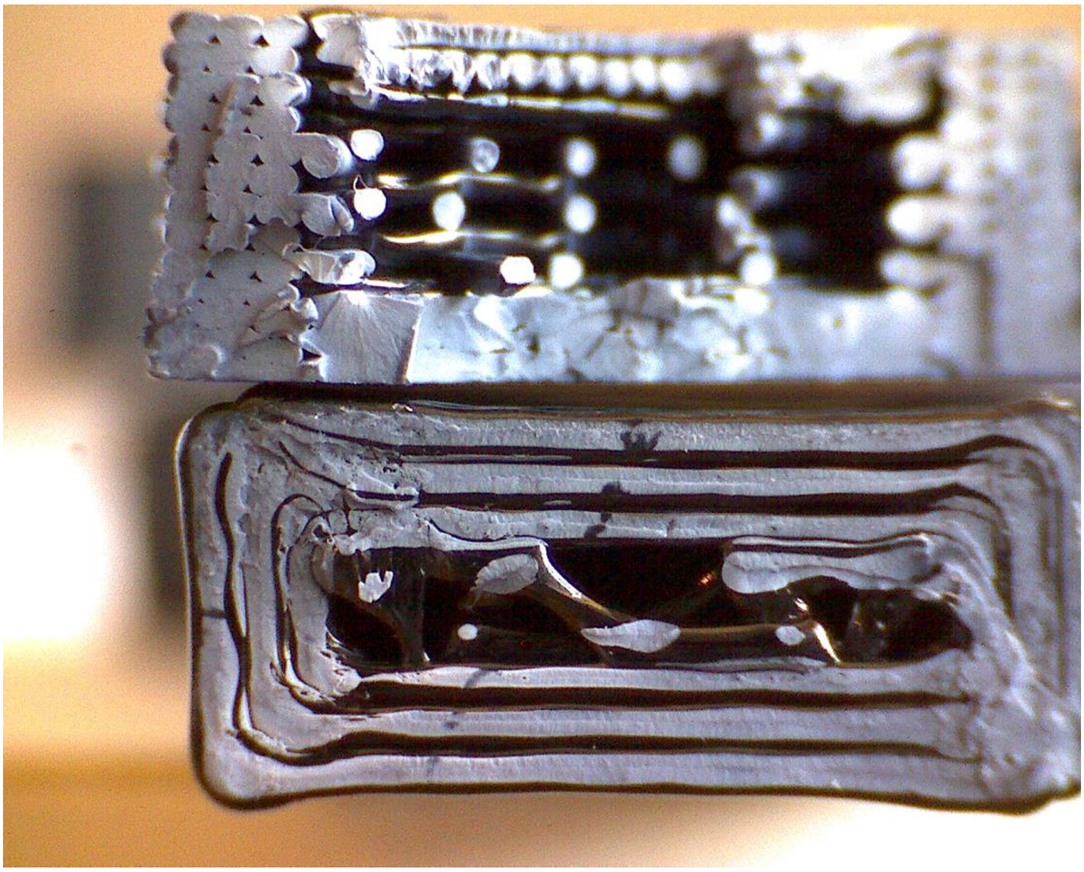


Figure 87: Comparison of specimens in ABS loaded longitudinally at the top and transversally at the bottom

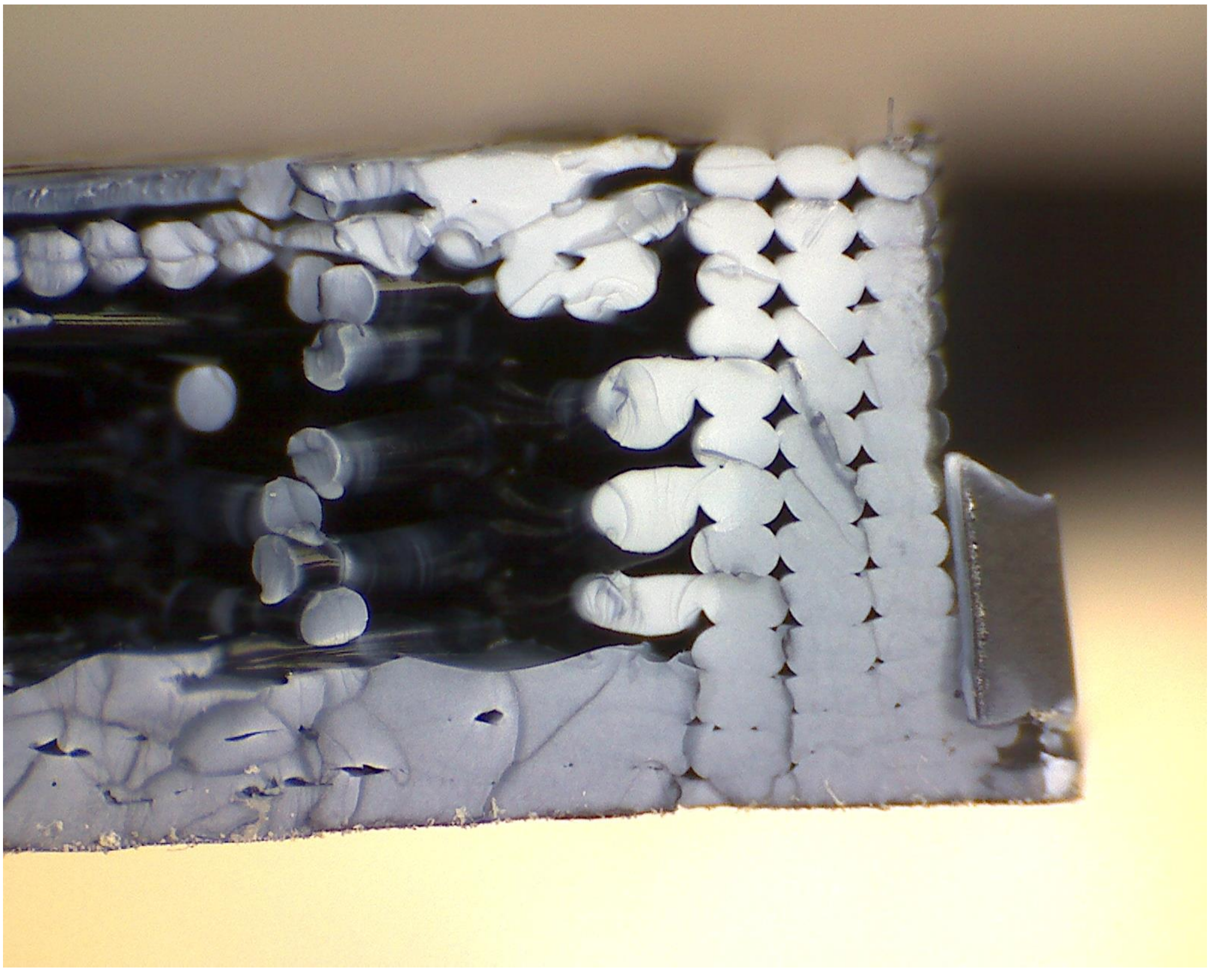


Figure 88: Zoomed fracture view of ABS specimen layers

Matlab code for stress-strain

Code 1:

```
% ISO 527-2/1A/50
L0=113; % 50mm, Gauge length(See ISO 527-2)
%[Sample,Spcmn,Width,Thickness,Specimen_Comment,PeakLoad,PeakStress,StrainAtBreak,Modulus] = importsample('S1.txt');
[Width,Thickness] = importsample2('S1.txt')
[LoadN1,Extensionmm1,Times1] = importspecimen('1.txt',6, inf);
[LoadN2,Extensionmm2,Times2] = importspecimen('2.txt',6, inf);
[LoadN3,Extensionmm3,Times3] = importspecimen('3.txt',6, inf);
%[LoadN4,Extensionmm4,Times4] = importspecimen('4.txt',6, inf);
%% Force vs extension
% figure
% plot(Extensionmm1,LoadN1,'b')
% hold on
% plot(Extensionmm2,LoadN2,'r')
% plot(Extensionmm3,LoadN3,'g')
% grid minor
```

```
% title('Force vs extension, ISO 527-2/A1/5 20% Infill')
% legend('Specimen 1','Specimen 2','Specimen 3')
% xlabel('Extension [mm]')
% ylabel('Force [N]')
%% Stress vs strain
Stress1=LoadN1/(Thickness(1)*10^-3*Width(1)*10^-3); % (MPa) kN/m
Stress2=LoadN2/(Thickness(2)*10^-3*Width(2)*10^-3);
Stress3=LoadN3/(Thickness(3)*10^-3*Width(3)*10^-3);
%Stress4=LoadN4/(Thickness(4)*10^-3*Width(4)*10^-3);
Strain1=(Extensionmm1/L0)*100;
Strain2=(Extensionmm2/L0)*100;
Strain3=(Extensionmm3/L0)*100;
%Strain3=(Extensionmm3/L0)*100;
% Spara ner till (en fil per graph) lägsta grapherna för att slippa omräkna s-s hela tiden??
%Color 1
figure
plot(Strain1,Stress1,'Color',[0,0.4470,0.7410])
hold on
plot(Strain2,Stress2,'Color',[0.8500,0.3250,0.0980])
plot(Strain3,Stress3,'Color',[0.9290,0.6940,0.1250])
% Color 2
% figure
% plot(Strain1,Stress1,'Color',[0.4940,0.1840,0.5560])
% hold on
% plot(Strain2,Stress2,'Color',[0.4660,0.6740,0.1880])
% plot(Strain3,Stress3,'Color',[0.3010,0.7450,0.9330])
title('Black Eco Filaments - ISO 527-2/1A/1 22{\circ}C')
legend('PET','PLA','ABS')
ylim([0 52]);
%xlim([0 35]);
xlabel('Nominal Strain (%)')
ylabel('Tensile Stress (MPa)')
grid minor
```