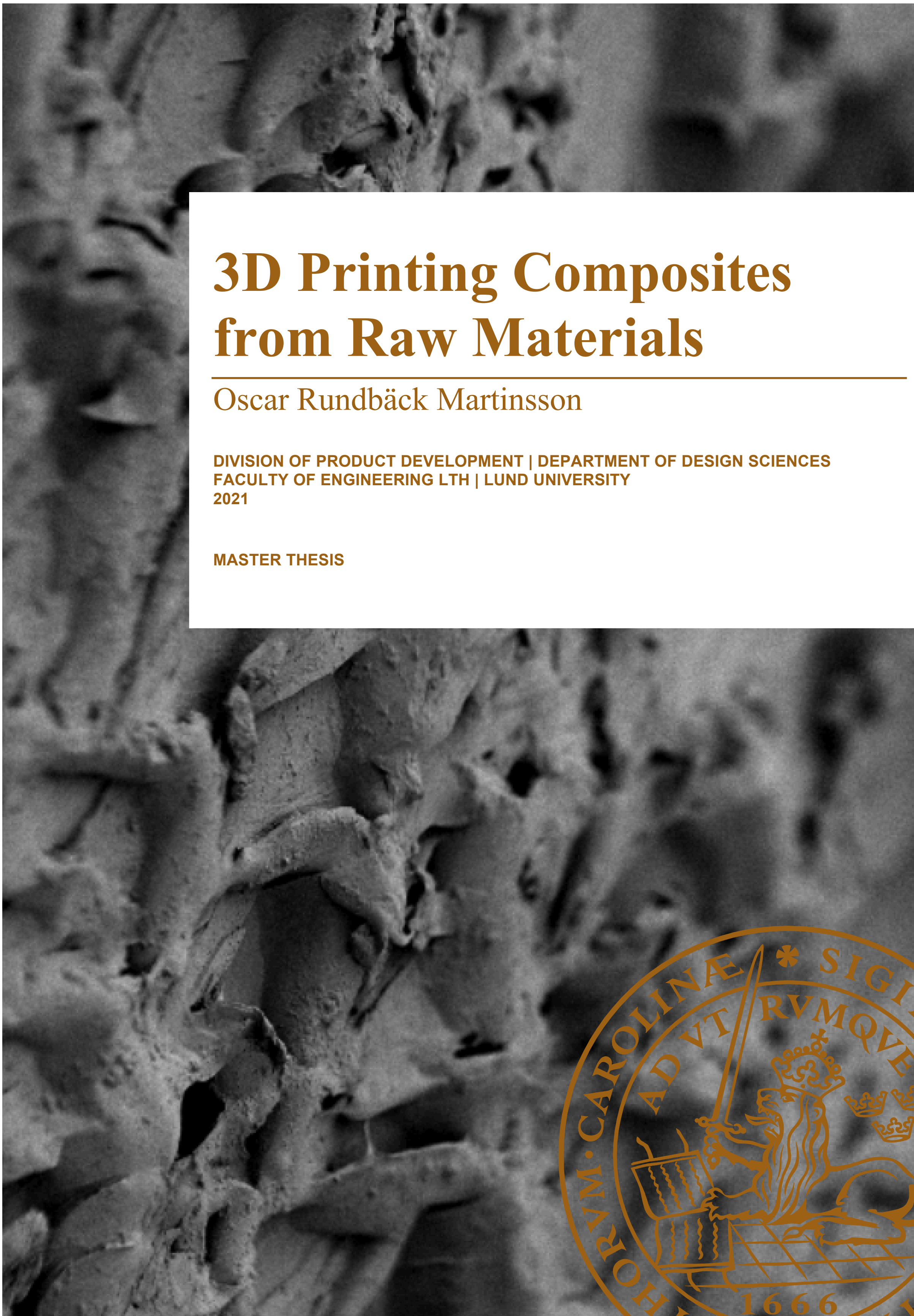

3D Printing Composites from Raw Materials

Oscar Rundbäck Martinsson

DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
2021

MASTER THESIS

3D Printing Composites from Raw Materials

On the compounding of additives in scaled-down extruders

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Cover photo: Scanning electron microscopy of a *PLA/$CaSiO_3$* composite by Oscar Rundbäck Martinsson

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Abstract

For the last decades, the subject of Additive manufacturing, also known as 3D-printing, has been rapidly developing in both the industrial and recreational fields. As new applications are discovered, materials and methods have to be researched and developed at the same pace to not stunt the creativity that 3D-printing brings out. The material most commonly used in 3D-printers are in a filament form, which is created in large industry extruders. This creates a barrier for users who want to create new types of filament with different material compositions or colors who at the moment have to rely on large scale producers, which greatly increases the cost and time of any project. The extrusion process for creating composite materials is at the moment of writing complicated and expensive, requiring a twin-screw extruder or a very complicated extrusion screw design.

For this master thesis, the theoretical ideas and practicalities surrounding extruder limitations are explored, with a focus on the compounding of materials directly in the extrusion process. This is achieved by designing and constructing a 3D-printer which can extrude and print directly from the raw material which filaments are made from. Benchmarking of the compounding for the most common additive types; fibres, metal powders and a ceramic, is performed to confirm the results.

The most important conclusion drawn from this master thesis is that scaling down the size and volumetric output of an extruder positively affects the compounding of a composite. This change is comparable to large scale producers in the ability to create a well homogenized composite which instantly can be used for a large variety of uses. Feasibility was proven using mechanical testing as well as scanning electron microscopy on several composites. This is a very positive result, opening the path to a more accessible research field for both researchers and recreational producers.

Keywords: *Additive manufacturing, Extrusion, Compounding, 3D-printing*

Sammanfattning

Under de senaste decennierna har friformsframställning, även benämt som 3D-utskrift, utvecklats snabbt inom både industri- och hobbyområdet. När nya applikationer upptäcks måste både material och metoder undersökas och utvecklas i samma takt för att inte hämma den kreativitet som 3D-utskrift framkallar. Materialet som vanligast används i 3D-skrivare är i filamentform, vilket produceras i storskaliga extruderare. Detta skapar en barriär för användare som vill skapa nya typer av filament med olika materialkompositioner eller färger. Dessa måste för tillfället lita på storskaliga producenter, vilket avsevärt ökar kostnaden och tiden för alla projekt. Extrusionsprocessen för att skapa kompositmaterial är vid skrivande punkt komplicerad och dyr, och kräver en tvillingskruvextruderare, en mycket komplicerad skruvdesign eller avancerade extrudersingsprocesser.

I detta examensarbete undersöks de teoretiska idéerna och praktiska aspekterna kring extruderingsbegränsningar, med fokus på homogenisering av material direkt i extruderingsprocessen. Detta uppnås genom att formge och konstruera en 3D-skrivare som kan extrudera och skriva ut direkt från den råvara som filamenten är tillverkade av. Mätning av de vanligaste tillsatstyperna; fibrer, metallpulver och keramik, genomförs.

Den viktigaste slutsatsen som dras från detta examensarbete är att genom att skala ner storleken och den volymetriska effekten hos en extruderare skapas det bättre möjligheter att uppnå en homogeniserad komposit. Denna komposit är jämförbar med storskaliga producenter i förmågan att producera en välblandad komposit som direkt kan användas inom flertalet användningsområden. Resultaten bekräftades med hjälp av flertalet mekaniska- samt elektronmikroskoptester på flertalet kompositer. Detta är ett mycket positivt resultat som öppnar vägen för ett mer tillgängligt forskningsfält för både forskare och hobbyproducenter.

Nyckelord: *Friformsframställning, 3D-printing, Homogenisering, Extrudering*

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To my loving parents, who have supported me throughout my studies and always been there for me when I needed them.

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Acronyms & Definitions

ABS	Acrylonitrile Butadiene Styrene.
Additive	A material which is dispersed in a matrix to strengthen it or in other ways change its properties.
AM	Additive Manufacturing.
ANOVA	Analysis of Variance.
DoE	Design of Experiments.
Elemental Mapping	An image showing the spatial distribution of elements in a 2D-section of a sample.
Extrudate	Material that has been extruded through a die.
FEM	Finite Element Method.
Heat-sink	Passive heat exchanger designed to maximize surface area in contact with the cooling medium surrounding it.
L/D	Length/Diameter ratio.
Matrix	A homogeneous and monolithic material in which an additive system of a composite is embedded.
PLA	Polylaktid.
SEM	Scanning Electron Microscope.

Chapter 1

Introduction

The introductory chapter will introduce and explain the inspiration and purpose of this master thesis, as well as describe the general dissertation of the paper.

1.1 Introduction & Purpose

This project was born out of an interest in Additive Manufacturing (AM), also known as 3D-printing, a relatively new production method which manufactures 3-dimensional structures by bonding together thin layers of material. AM can create advanced structures with low cost printers without much of the practical skill or education required in traditional, more costly production methods such as milling or casting. This combined with the large collaborative communities of hobby users which help to develop new ideas and applications make AM one of the most democratic production methods available at the time of writing.

For 3D-printing to be optimally used by the public, knowledge about AM have to be more widespread within its user base and by combining the knowledge of industrial AM and the multitude and creativity of the general public the societal gains can be limitless. The shared knowledge of creating and printing can be greatly increased with much faster pace than traditional production methods which are not as readily available to the public market. Further development of AM should give the larger mass of users, not only researchers and companies, the tools and possibilities to create a framework in which both idea development and testing is readily available to all. One step towards this goal is to construct machines that can help facilitate the small-batch creation of materials such as composites, that can be used in research or testing of new product ideas without having to rely on a large scale producer.

To be able to create well homogenised composites in small batches, scaled-down extruders have to be created. This raises the question; *how well can composites be homogenised through extrusion in a scaled-down extruder?*

1.2 Dissertation

This thesis consists of four main components, listed below:

Background
The background lists the polymer extrusion and other theoretical backgrounds of this thesis along with the body of the literary review done during this project. It will also list the hypothesis of the thesis, which will list the discrete goals and aspirations of the construction and testing process.

Method and construction
These parts explains the methods used during the development process and construction methods which lead to the finished parts. The *DMAIC* process will be described and explained along with a comprehensive flow-chart which illustrate the practical steps taken.

Tests and results
This segment covers the methodology of testing the parts which were machined for this thesis. It also covers the results for the three different extruders used during this project, along with results from both *FEM* simulations, *yield strength tests* and *SEM* testing.

Discussion and conclusion
The culmination of the thesis lists the discussion and following conclusion stemming from the results of the tests conducted. It also covers the sources of error and suggestions for projects which could build on this thesis.

Chapter 2

Background

The chapter will cover the background regarding AM and material extrusion, which will lay as a foundation for the *Purpose* of this thesis. The sections *Designing for AM* and *AM as a democratisation tool* covers the most important points regarding the industry approach for AM, as well as the potential that this has to help laypeople create and design. The section *Direct pellet extrusion* contains a description of the original V0 extruder which this master thesis is built on, to properly understand the system which will then be improved. This chapter will end with a *Hypothesis*, summarising the goals of the thesis.

2.1 Polymer extrusion

Extrusion is a fast paced production method for manufacturing products of constant cross-section and infinite length such as pipes, rods and films. This is done by using a screw, combining rotating and linear push, to force a heated polymer mixture through a die with an opening, shaping the extrudate (similar to pressing toothpaste from a tube). The polymer is fed into the extruder through a hopper and is transported through a heated barrel, gradually melting and compressing it before being extruded [1]. In figure 2.1, an example of a basic extruder design can be seen.

More complex variants of extruders can include decompression areas and cooling to exactly control temperature and gas release inside the polymer. When trying to create more complex materials such as composites or coloured materials, double screw extruders are preferred as they are far superior when compounding materials. Polymer extrusion can also be utilised in injection moulding, where molten plastic under high pressure is injected into a mould, creating fairly complex structures in a matter of seconds. Products created by injection moulding, such as Lego pieces or plastic chairs, have good tolerances and a very high production rate, compared to other manufacturing methods which can create similar parts.

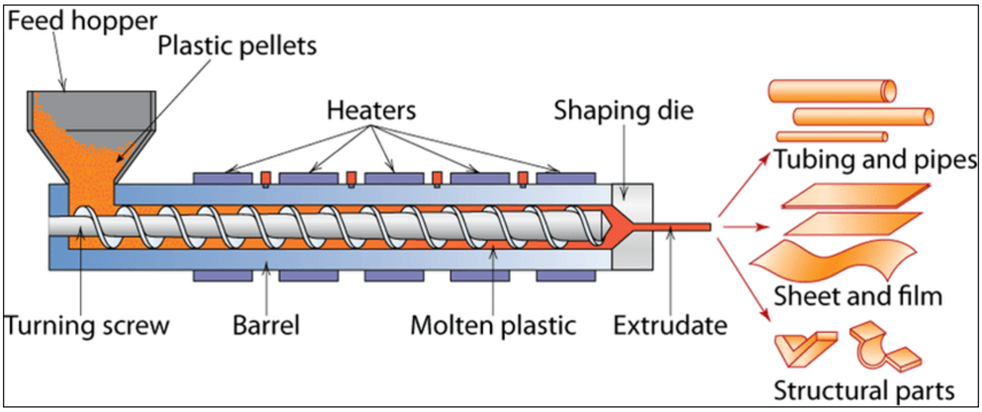
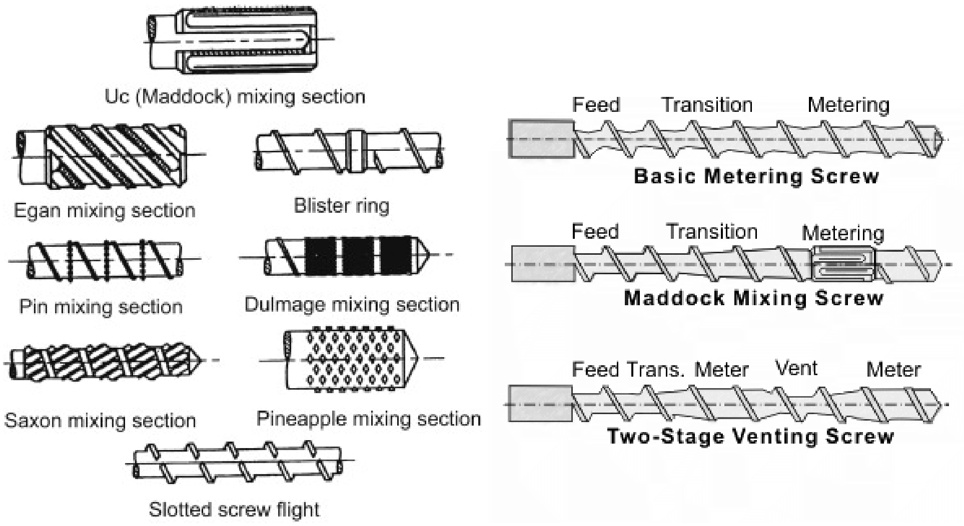


Figure 2.1: Overview of polymer extruder [1]

2.1.1 Extrusion screw design

The screw design has a great impact on the dispersion of the additive throughout the matrix. Altering the screw from a standard conveying screw to a screw which allows for material to be mixed rather than only moved through the barrel can be done to increase the mixing of the extrudate. Extruder screw mixing variations include *mixing pins*, *Dulmage section*, *Dray Mixer*, and *Maddock Mixer*. These can be combined in many ways to achieve desired mixing outcomes. Several screw variations and a few complete screws where different designs are used can be seen in figure 2.2.



(a) Common variations of feed screw mixing designs, courtesy of John R. Wagner, Eldridge M. Mount, Harold F. Giles

(b) Example extrusion screw designs, courtesy of K. T. O'Brien (Ed.), Carl Hanser Verlag, Munich.

Figure 2.2: Screw mixer designs

The dulmage section is commonly used and gives a great improvement in dispersion in single-screw extrusion which is explored in *The Evaluation of Mixing Characteristics of Dulmage Screw* [2]. A comparison between a standard conveying screw and a dulmage section can be seen in figure 2.3, showing that the dispersion of a red coloring agent is greatly improved in plastics when using a mixing section such as a dulmage section. This can be considered equally true for any mixer design, as any disruption will cause distributive mixing [3].

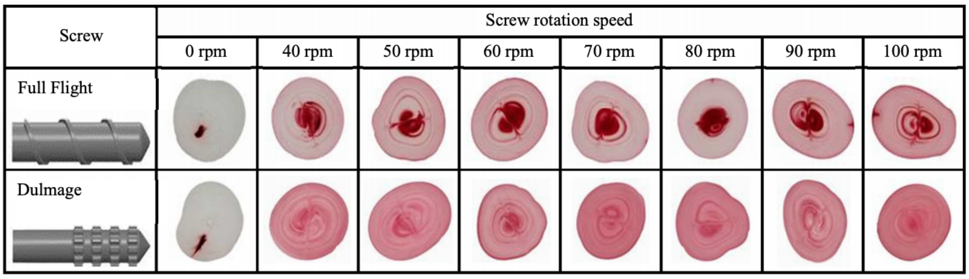


Figure 2.3: Cross sections of sample with and without dulmage section [2]

Standard Length/Diameter ratio (L/D) of an extrusion screw is 24:1 to allow for the extrudate to properly melt and homogenise before being extruded, but can vary from 18:1 - 40:1 depending on the specific extruder [4].

A simplified formula for calculating the throughput of material through a single screw extruder is provided by Tim Womer [5].

$$Q = 0.063 \cdot D^2 \cdot h_m \cdot MD \cdot N \tag{2.1}$$

where:

Q = Throughput (g/h)
D = Screw diameter (mm)
h = Metering depth (mm)
MD = Melt density of the resin (gm/cc)
N = Screw speed (rpm)

2.2 Additive Manufacturing

> *People often say that, for entrepreneurship and innovation, it is important to fail fast and fail often. With additive manufacturing, we now have the ability to fail extra fast and extra often. And that's a good thing!*
>
> –Olaf Diegel, 2020

Additive Manufacturing, or 3D printing as it is more commonly called, is a relatively new production method which is based on the principle of creating a product by adding thin layers on top of each other. It is, compared to traditional production methods, a very material efficient technique as it only uses exactly the material which is needed for the product, apart from some structural supports needed to support the part during construction. Traditional production methods such as lathing or milling uses a larger block of material which is then carved away to create a finished end-product. Traditional processes takes a lot of time, skill and excess material which could be saved through instead designing for, and utilising AM methods. As the AM process is highly accurate, it is very suitable for high precision products as well as highly complicated and specialised parts. The sophisticated methods can allow for moving parts to be printed whole, instead of separately manufacturing and assembling parts. There can also be an advantage in creating parts which could not be made traditionally such as high performance car parts or heat exchangers with very complicated internal structures.

AM was first conceptualised by Otto John Munz in his 1951 patent *Photo-glyph recording* [6] which was later refined into several different fields [7]. In this report, focus will be on material extrusion, also known as *Fused deposit modelling*, where an object is created by layering plasticised material which hardens instantly to form layers. The most common materials for this application is polymers but other materials such as concrete, glass and different food items have been used to create products. Shown in figure 2.4 is an experimental 3D printer which can build horizontally, i.e. without regard for gravitational that limits conventional 3D printers.

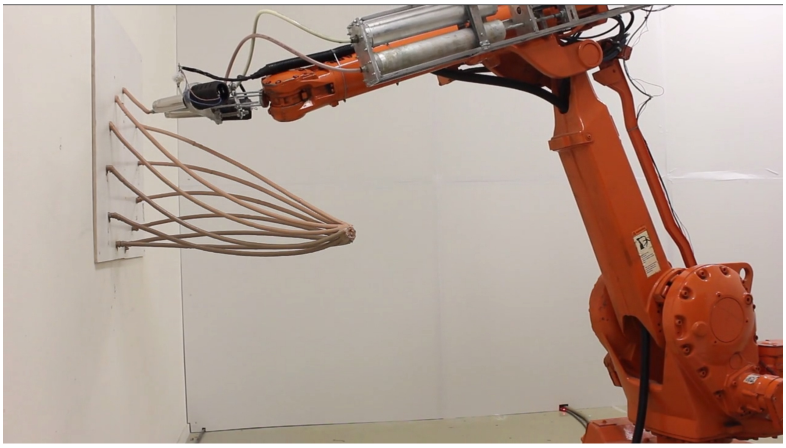


Figure 2.4: Mataerial additive printer, courtesy of the IAAC [8]

2.2.1 AM as a democratisation tool

AM technology has greatly democratised the world of making and creating, allowing people who do not have access to machining facilities or a workshop, to build and specialise products for their everyday life and their households. As this is a very new technology and the general public does not have education in creating and designing products, the parts produced by the public are often of varying degrees of finesse and often without any deeper thought about how a product designed for additive material processing should be built. This entails products which often waste material and printing time by either not utilising the free complexity provided by the production method, or by printing parts which easily can be replaced by standard parts available in any build store, such as simple nuts and bolts.

2.2.2 Designing for AM

AM is not a fix-all for every problem in production. It shifts the problems to new constraints and restrictions which must be considered [9] such as manufacturing times and the costs that this can result in. In figure 2.5, a comparison between costs for traditional manufacturing and AM is shown for a product with increasing complexity. As the per unit cost for increasing complexity is low compared to traditional manufacturing methods, it is important to take advantage of the free complexity that AM provides.

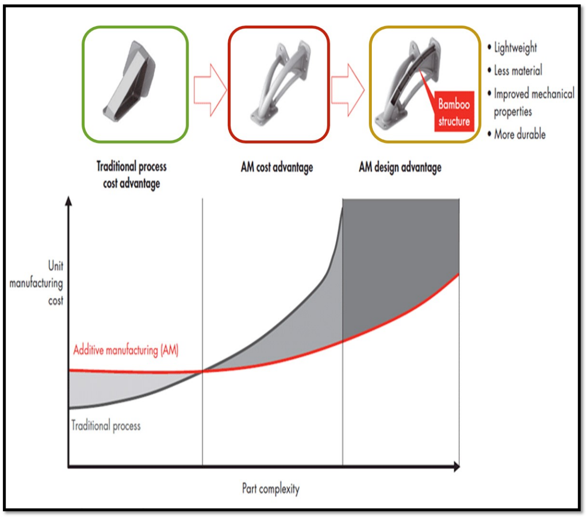


Figure 2.5: Comparison between traditional and additive manufacturing [10]

As many 3D printed parts often are designed to minimise post processing, extra time spent on removing support removal is a large extra expense for the producer. It can also provide better solutions to the function of the manufactured part. Another important part of design for AM is topology optimisation, a process in which a 3D model is gradually altered to optimise its design to fulfil one or more conditions, such as minimising volume or deformation in a certain area. To calculate tensions and deformations in a body, finite element calculations are used by creating a mesh of triangles over the body and calculate current forces [11]. The placement and size of the mesh is important, as a mesh with too large triangles will result in an inaccurate result. A trade-off between processing time and simulation accuracy is made, as a mesh that is too detailed will result in more time consuming simulations, without improving results noticeably.

2.2.3 AM material choices

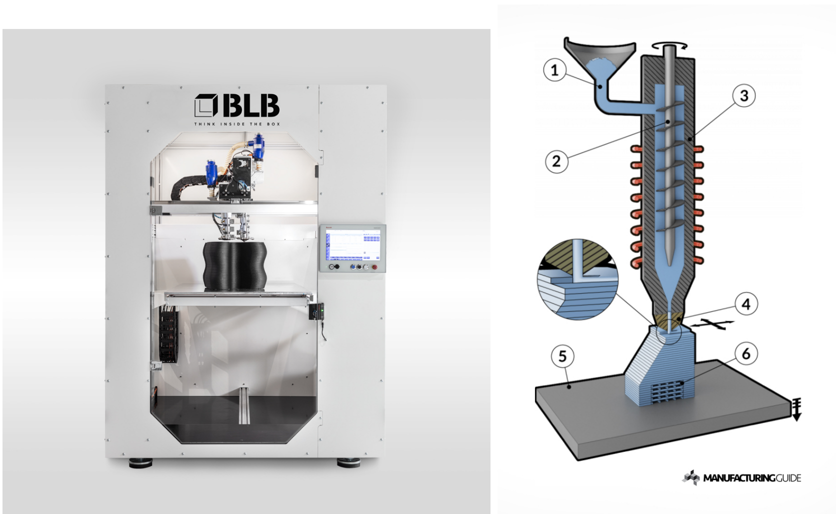
There is a multitude of materials available to those who want to 3D print, everything from pure polymer filament to composites and wooden filaments. The most common filaments are based on a pure thermoplastic such as Acrylonitrile Butadiene Styrene (ABS) or Polylaktid (PLA) where an additive can be used to change colour of the filament. An additive can also be used to modify the mechanical properties or make the filament magnetic, fluorescent or conductive. There are also a large amount of bio-degradable filaments which have a better affect on the environment. Several of the polymers used also theoretically allow for infinite reuseability.

(a) Different coloured filaments [12] **(b)** Wooden filament [13]

Figure 2.6: Examples of available filament

2.3 Direct pellet extrusion

Apart from filament, there are 3D printers which can print directly from the raw material which the filament is made from, such as the BLB 3D printer seen in figure 2.7, which uses a scaled-down extruder. This printer extrudes up to 35 kg/h from a pellet material which can be made from different polymers or pre-fabricated composites [14]. At the moment of writing, there are no available solutions which can create a polymer composite in the extrusion process itself.



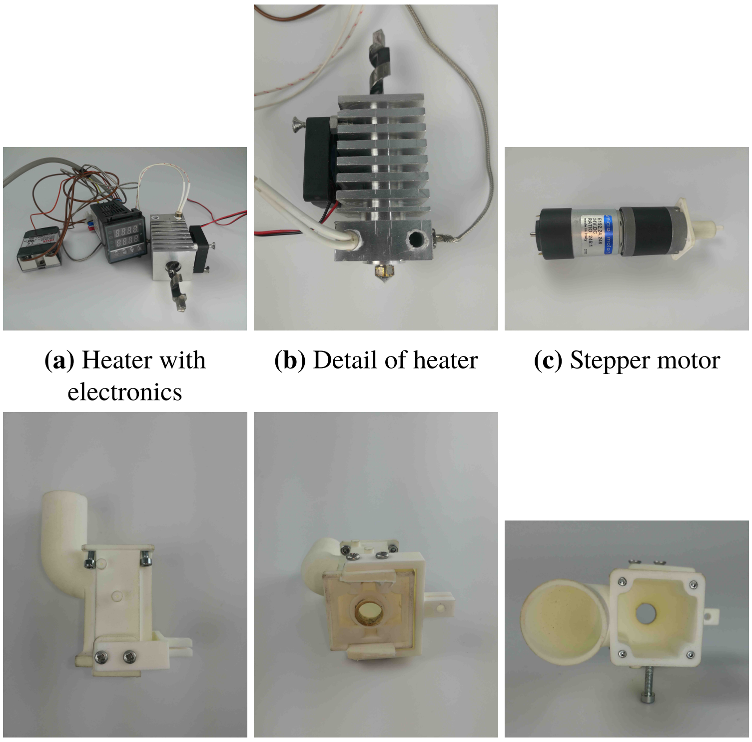
(a) Model overview **(b)** Extrusion screw

Figure 2.7: Box 1500 pellet extruder [14]

The 3D printer which this master thesis is based on is a design created by Paolo von Krogh [15], as a master thesis where the goal was to design and build a single screw extruder which could be mounted on a 3D printer and print directly from polymer pellets, as opposed to polymer filament. This design will be referred to as *V0* in this report.

The stepper motor, which can be seen in figure 2.8c, is a micro motors brand stepper motor, with a nominal voltage of 24 V and maximum torque of 2 Nm [16].

The heater can be seen in figure 2.8a and has a 400 W thermostat which can achieve temperatures of up to 400 °C as well as a modified drill, which is used as the screw in the extruder system. The heater design also incorporates a heat-sink system, with a mounted 5 V fan which cools the upper parts. As the heater can reach very high temperatures, it is very important to effectively cool the printer head, as it will lead to melting and warping of the 3D-printed extruder parts if not properly cooled.



(a) Heater with electronics **(b)** Detail of heater **(c)** Stepper motor

(d) Feeder side view **(e)** Feeder bottom view **(f)** Feeder top view

Figure 2.8: Components of V0

The feeder, which can be seen in figure 2.8d is the largest 3D printed part in the design and has the main function of connecting the heater to the stepper motor, as well as allowing material to enter the printer head. It is composed of a funnel and connections for the heater and stepper motor.

This design creates a good basis which can be improved upon, to increase output and reliability.

2.3.1 Krakatoa extruder casing

The improved printer head was built to fit a Hyrel brand 30M printer due to the high modularity and adaptability of this particular printer. It is also equipped with code which already combines a stepper motor with heating, allowing for easier installation of the new printer head.

Instead of building an entirely new printer head, the decision was made to build a module for the already existing printer head, the Krakatoa head which can be seen in figure 2.9. This decision was made to minimise material usage as well as build time.

The Krakatoa printer head consists of a heated aluminium casing, which holds a delivery tube that can be filled with clays, pastes, waxes etc. This material is then extruded by rotating the threaded rod, pushing a plunger down the delivery tube. It is also equipped with a *11HS20-0674S-PG27* stepper motor and has a torque output of 4 Nm. A complete data sheet can be seen in appendix A. The aluminium casing head has two heating elements which are installed on either side of the delivery tube.

(a) Side View **(b)** Front View **(c)** Delivery tube

Figure 2.9: Original printer head fitted for Hyrel 30M printer.

2.4 Hypothesis

As this thesis will attempt to construct an extruder which can combine and extrude composites in the printing process, it will have to reach certain standards. Some of these standards are present in current extruders, and some will have to be adopted from industrial solutions. These standards are listed below:

Temperature
The temperature has to be high enough for the printer to properly melt the polymer extrudate. For most polymers used in AM, this process happens at temperatures around 170 – 260 °**C**.

Volumetric flow
The construction should, ideally, match or improve on the current standard volumetric output found in standard 3D-printers, which is about 15 $\mathrm{mm/s}^3$ [17]. This to ensure that it does not negatively impact the extrusion duration, causing the user to abstain from using this method of AM.

Weight
As the construction has to be suspended in air and moved around during the extrusion process, the total weight should be low enough to make these movements possible. Higher mass will lead to more inertia in the printer head, which can cause inconsistencies in the printing process or, as a worst case, cause the entire 3D-printer to fall over. The weight of a comparable 3D printer head was weighed to 1.3 kg.

Durability
The chemical and mechanical wear on a polymer extruder is significantly higher than in a filament 3D-printer, which will have to be accounted for in this project. This increase in wear is due to the forces which occur during the compression and compounding of the polymer and additive, which are considerably larger than the forces which occur during the plasticization of pre-made filament.

Chapter 3

Method

This chapter will describe the theories and methods used to improve the V0 extruder, and will then describe the improvement process of this extruder into the V1 and V2 modules.

3.1 DMAIC Method

When designing a new product as well as improving an already existing product, many different methods and approaches can be used. Some of these methods are *Lean product development*, *Six sigma* and *User-centred design*. These are all competent methods for product development based on different views and criteria and for this project the DMAIC method of the six sigma method will be used. The DMAIC method is considered the best suited for the goals and limitations of this project, as it is focused on improving a single product without needing to go into larger production without a larger development team and the need for production steps which needs checking.

The traditional *DMAIC* method of product development, where emphasis is on optimising and improving already existing designs, is used in this thesis. The reasoning for this is that there is already an existing product which this project is built on.

If used properly, the six sigma process can be a very dependable tool to develop or improve a product and achieve satisfactory results. A limitation to the process is that it does not help with developing new products or ideas as it is focused on minimising already existing problems. During the development of new products, the *Design for six sigma* [18] method should be used as it has the objective of determining and solving the needs of the customer and product during the product development process.

Improvements are done by using a set structure of steps or techniques to ensure good quality improvement of the product in question. The steps or techniques are well defined in the publication *Six Sigma Breakthrough and Beyond - Quality Performance Breakthrough Methods* [19] and are as follows:

3.1.1 Define

Create a definition system, with the project goals and requirements. Find the important variables, resources and timeline which affect the end process.

In this project, after testing of the original printer head along with a review of standard 3D-printer [17], a list of factors which need to be considered when improving the design was created and can be seen in table 3.1.

3.1.2 Measure and analyse

The current system specifications and goals and must be measured and analysed to verify the cause-effect relationship for the system, as well as the data output. Relationships have to be determined. Ensure all factors are considered. Identify

Factor	Desired Value	Unit
Temperature	300	°C
Feed rate	13.5	mm^3/s
Weight	1.5	kg
Max current	10	A

Table 3.1 Considered parameters

factors, a root cause, which need to be improved. Collect data and calculate the system process capability in its current state, a baseline capability. This is a very important step as good and suitable measurement systems are crucial for the project results.

Consideration was taken to the experiences and results from the operation of the V0 printer head, which was fully tested with the goal of creating a consistent extrudate. These results are reviewed in section 5.1.

3.1.3 Improve

Identify needed improvements, testing and implementing a solution to the stated problem. The solution can be a partial or complete solution, depending on the situation. In this step, it could be suitable to utilise a Design of Experiments (DoE) based approach, if quantifiable data is needed. The details of this method are covered in section 3.1.4.

This step can be seen in chapter 4.

3.1.4 Control

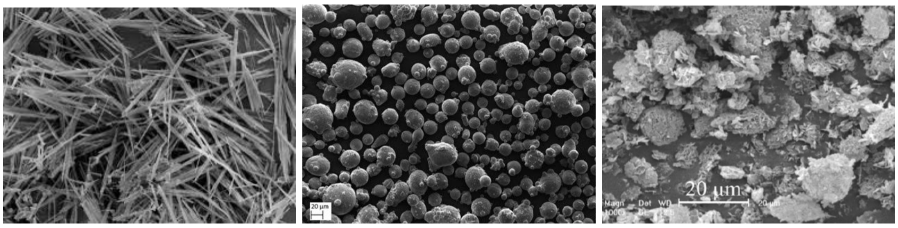
Understand and check the results, to make sure that they are as desired. This can be done with different testing methods, such as measuring or evaluating the results, based on the nature of the project.

This section covers the preparation of materials and additives, and calibration of the extruder settings for the tests performed in the project.

Materials

As the material choice for the composite matrix and additive are imperative to the outcome of the experiments as well as the accuracy of the measurements taken, great consideration is taken to make sure that the material chosen is representative of standard materials used within AM. In this project, the material chosen for the matrix is 4043D grade PLA plastic, which has a working temperature of 180 – 230 °C [20] and is well suited for AM along with being biodegradable. Three different materials will be used as additives to give a broad reference view of the results. The materials used are a fibre, a small particle metal and a large particle ceramic and are:

> $CaSiO_3$ *Wollastonite*, a calcium inosilicate mineral which may contain small amounts of iron, magnesium and manganese. It has great potential in replacing more expensive materials such as glass fibre due to low costs as well as its small, needle-like structure which aligns in a similar way to fibres and increases tensile strength by up to 30 % [21].
>
> $AlSi10Mg$ *Aluminium alloy powder*, produced for additive manufacturing and consists of a 90/10 Aluminium/Silicone mixture with small amounts of magnesium, iron and titanium. It is manufactured by inert gas atomization, based on composition specifications of casting alloys are particularly suited for automotive, with thin walls, complex geometries and light-weight aerospace applications. Used in a polymer matrix, it can also be treated in an oven after extrusion to melt away the polymer and leave a solid aluminium part.
>
> $MgCO_3$ *Magnesium Carbonate*, an inorganic salt commonly used in mountain climbing, and is also often used as a filler material to make cheaper polymers while keeping the mechanical properties, such as elastic modulus and tensile strength, stay very near to the original material. It also improves elongation and impact strength of the polymer matrices [22] when added with a liquid modifier to improve compounding.



(a) $CaSiO_3$ Wollastonite [23] **(b)** $AlSi10Mg$ Aluminium [24] **(c)** $MgCO_3$ Magnesium [25]

Figure 3.1: Electron microscopies of used additives

Additive	Particle size (µm)	Density (g/mm^3)
Wollastonite	21 ± 19	2.84
AlSi10Mg	63 ± 20	1.54
Magnesium	3 ± 1	2.96

Table 3.2 Material properties for used additives

These are three very different materials which act differently during the compounding process and which give widely different mechanical properties to the finished material. The PLA is delivered in pellet form with a radius of approximately 4 mm and is mixed thoroughly with the additive before it is poured into the feeder for extrusion.

Calibration and extruding

To properly calibrate the printer, testing on pure PLA pellets are performed with two different parameters, screw rotational speed and printer temperature. The screw rotational speed is varied between $9 - 12$ rpm and the temperature is varied between $180 - 205$ °C in conformity with a 2 factor DoE, see table 3.3.

Tests	Temperature	Speed
1	200 °C	9 rpm
2	200 °C	12 rpm
3	180 °C	9 rpm
4	180 °C	12 rpm

Table 3.3 Parameters and levels for DoE testing the extruder

After being thoroughly blended with the PLA, the additives described in 3.4 are put through the extruder. Between each additive test the extruder is cleaned with pure PLA, to ensure that cross-contaminations are kept as low as possible. The extruder is allowed to run for enough time to properly homogenise the extruded composite which is cut into samples to be analysed, creating 4 different samples, pure PLA included. The extrudate is extruded directly into a water bath, shown in figure 3.2 to increase cooling and retain a constant material thickness, increasing reliability during testing.

Sample	Additive	Test A	Test B
1:	None	–	–
2:	Wollastonite	0%	40%*wt*
3:	AlSi10Mg	0%	40%*wt*
4:	Magnesium	0%	40%*wt*

Table 3.4 Extruded sample specifications

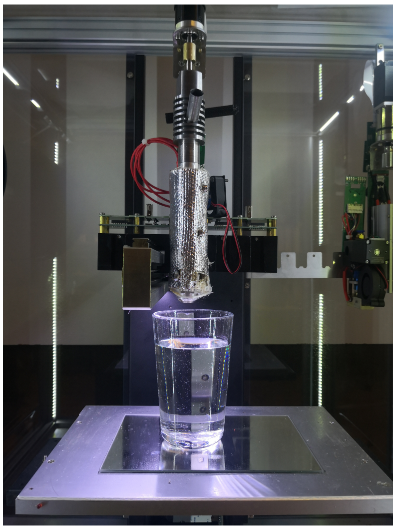


Figure 3.2: Extrusion setup with water bath

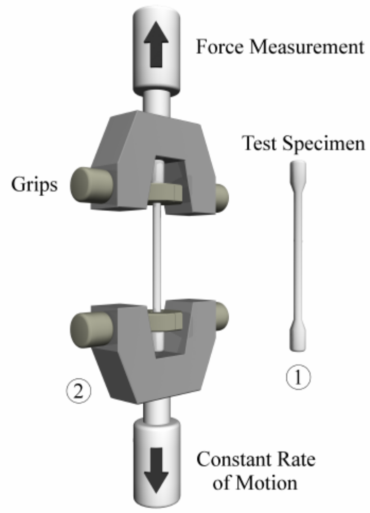
Quantification

Extrusion samples are tested in two different ways, to evaluate and quantify possible differences between additives used:

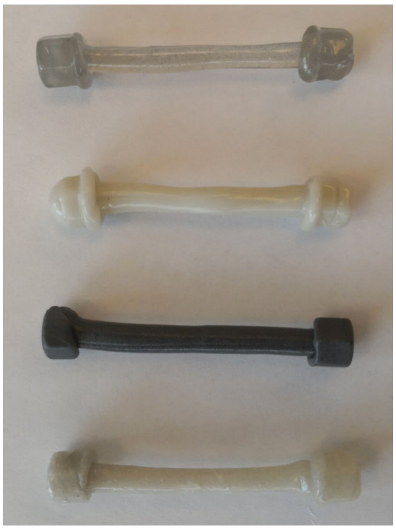
1. **Electron microscopy** is used to help evaluate the compounding of the materials as well as finding any inconsistencies such as air bubbles. The sample is put through a Scanning Electron Microscope (SEM), which can give precise imagery of very small samples. This can be used to retrieve reliable results on how well a compound is homogenised by counting the amount of particles in the matrix per area unit. It also clearly shows faults in the extrudate, such as air bubbles, non molten material and large non-homogeneous parts. The electron microscope used is a *JSM6700F*, which takes photos at $10 - 15$ kV at a high magnification of $20 - 100$ kX with a working distance of 15 mm, and can be seen in figure 3.3a. An elemental mapping is then performed on a cut cross-section of the sample to measure which elements it contains. The non conductive materials are coated in a conducting layer before being processed.

2. **Tensile testing** is used to evaluate tensile yield strength in the materials and help give a clear overview of the difference that an additive can make to a matrix material. The results from tensile testing are very applicable while considering materials for AM, and a standard tensile test is performed by taking a sample and fastening it into a vice which pulls the sample from both ends while measuring the force required to break the specimen apart and how much the sample deforms before breaking [26]. The setup and process along with samples prepared for testing can be seen in figure 3.3b and 3.3c. The samples were made by extruding a 5 mm cylinder, heating the ends with a heat-gun and deforming them manually, creating ends that the yield stress machine can grab and pull, without crushing the sample.

(a) JSM6700 electron microscope



(b) Ultimate tensile test process



(c) Prepared samples

Figure 3.3: Quantification methods

These quantification methods give a broader sample analysis, helping to give a more complete figure of the material properties of the produced samples.

Design of Experiments

> *"Design of Experiments* (DOE) *is a powerful technique used for both exploring new processes and gaining increased knowledge of existing processes, followed by optimising these processes for achieving world-class performance."*
>
> –Jiju Antony, 2014

The DoE method was proposed by Ronald Fisher in his 1935 book *The Design of Experiments* [27], to compare different variables' impact on a specific outcome by performing concurrent analyses of several factors by determine their relationships. This was more efficient than the classical approach of testing each parameter individually which was an expensive and time consuming method. The mathematical method was then refined and generalised by Genichi Taguchi [28] to make it more suited for industrial purposes. When developing or improving products, the DoE is a crucial tool for minimising testing without compromising on results, as it can discover relationships between variables which are not apparent at first. When using DoE, a *fractional factorial* can be made to determine the factor effect without having to do full factorial analysis, but risk missing some interactions. A fractional factorial can usually omit at least half of all possible combination, saving large amounts of time and money. The results are then calculated to achieve a cross reference of the relevant factor interactions, a process seen in table 3.5. If possible, an Analysis of Variance (ANOVA) can then be performed to verify the results.

Factor Assignment

		Main Effects			Interactions			
		A	**B**	**C**	**D (A-B)**	**E(A-C)**	**F(B-C)**	**G(A-B-C)**
Tests	1	–	–	–	+	+	+	+
	2	+	–	–	–	–	+	+
	3	–	+	–	–	+	–	+
	4	+	+	–	+	–	–	–
	5	–	–	+	+	–	–	+
	6	+	–	+	–	+	–	–
	7	–	+	+	–	–	+	–
	8	+	+	+	+	+	+	+

Table 3.5 DoE for 3 parameters

3.2 Process flow chart

Following is a process flow-chart containing the actions performed in the different steps of the *DMAIC* method.

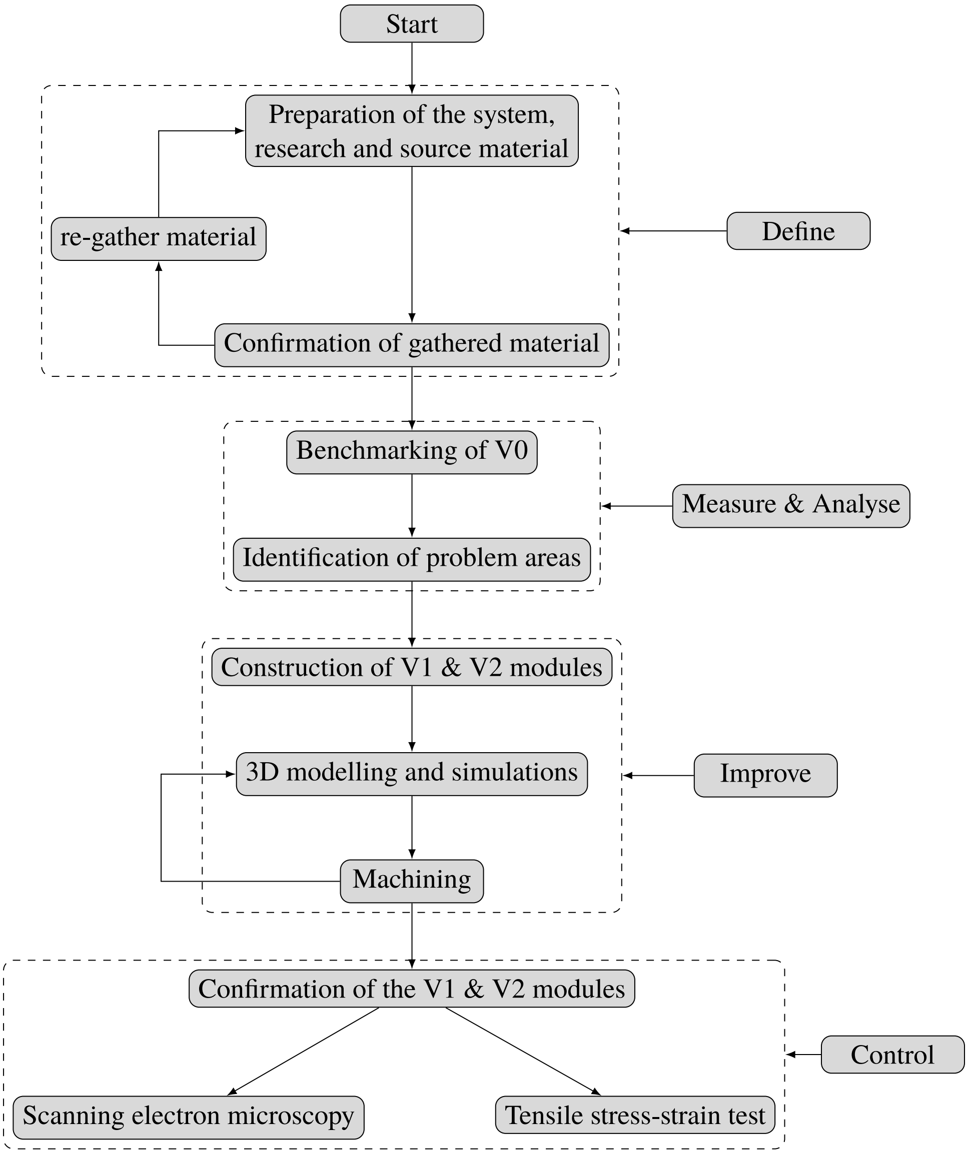


Figure 3.4: Flow chart of performed method

Chapter 4

Polymer extruder development

This chapter will account for the development and construction process of the extruder modules built in this thesis project.

4.1 V1 Module

Improvements from the V0 design are mainly in the problem areas which were identified when testing the first design, heat sensitivity and ineffectiveness. A modular design was chosen, to easily accommodate for the creation of new parts as well as assembly with as few tools as possible. Heat resistant materials are also preferable as they have better mechanical properties under stress. The decision was made to keep the single screw extruder design, due to space constraints and a focus on maintaining a relatively simple design.

As the original heaters of the krakatoa only can achieve a temperature of 80 °C, they are replaced with two 40 W elements, which theoretically will allow the head to reach temperatures in excess off 400 °C. The casing is also equipped with a heating shield, which will limit the heat radiation and help stabilise the temperature of the module.

4.1.1 Design improvements

During the redesign process, care was taken to ensure that each part got redesigned and improved. Below are accounts of the parts of the V0 printer head along with weaknesses identified in section 5.1.

Heating element
The heater has a good basic design, which integrates a heat-sink, but contains a complicated electronic setup, which needs several power sources which lacks a common off switch for the entire system, making it hard to manage.

A good redesign of the heating element would be to insulate it to minimize heat radiation, as well as integrating the electronics with the stepper motor and fan to keep the controls as simple as possible.

Material choices
During operation of the printer head, the feeder would come under immense heat and mechanical forces, which would deform it. This is a large problem as it affects the extruding process. It also displayed problems with moving materials into the heater.

A good solution to these problems is to make an extruder which is as heat resistant as possible and which would not deform due to heat.

Stepper Motor and cooling fan
The motor and fan are independently driven by a separate power source, which could be easily fixed by integrating their electronics with the rest of the printing head.

Redesigning the printer head to fit the *Krakatoa*, integrating all the electronics into one circuit, would facilitate easier handling and simplify the printing process. It would require building a cylinder part, which mirrors the measurements of the feeder tube, which would be 20 mm in diameter. It would also include adding a feeding part which can withstand the heat and mechanical force of the stepper motor.

During the redesign process, the cylindrical part is identified as a fairly basic design, which will need to fit a printer nozzle and a suitable mount for the feeder. The feeder will need to mount to the cylinder and effectively input the extrudate to the screw. It will also need to prevent the screw from moving vertically during the printing process to ensure consistent printing. Ideally it would also need to implement a heat-sink design and a fan to easier regulate the temperature of the system.

4.1.2 Iterations

During the product development process, several iterations of the parts were made. The largest differences in-between the first ideas and the machined part can be seen in the feeder part, as it is the only part which has a possibility to change. This as the cylinder has a set outer perimeter and very limited uses which could be improved.

Some underlying idea sketches and rudimentary calculations can be seen in appendix B. The most prominent ideas generated in a brainstorming session are listed below.

A . **Angle feeder input** compared to a *L*-shaped input, which is used in the V0. This would increase input and make sure that no materials get stuck before the screw. The work-time for this modification would be the same as machining a horizontal input hole.

B . **Implement heat-sink structure** which increases surface area of the printer head, allowing for greater heat dispersion in parts which do not need to be heated. The increased work-time as well as part complexity would be the similar as machining the part to a consistent diameter.

C . **Add internal barriers to cylinder part**, an implementation used in industry scale extruders and helps to randomise the extrudate movement through the process, increasing compounding. This modification would be very complex to create in a single screw design, as it would have to be very precisely machined and fitted for the screw used.

D . **Add vertical stop for screw** to help minimise axial movement of the screw, helping to create a constant flow of extrudate while helping to protect the stepper motor, which is sensitive to axial forces. This could be machined in the same time as a larger hole diameter, but adds some extra machining time to modifying the screw as well.

E . **Modify standard drill-bit** to mimic an industry grade extruder screw by adding differently shaped sections to help randomise the compounding process. This is is a fairly time consuming process, but has great potential to help accommodate compounding in this project.

Table 4.1 evaluates on the suggestions by using the decision matrix developed by Stuart Pugh [29]. The chosen criteria for the decision matrix are:

1. **Time consumption**, which estimates the time needed to perform the suggested feature.

2. **Labour intensity**, which estimates the amount of labour needed to finish the feature.

3. **Function**, which estimates the value added to the part, by adding the feature.

4. **Manufacturability**, which estimates how easy the suggested feature is to manufacture.

5. **Durability**, which estimates how long the suggested feature would last during normal operation.

In the *eliminatory* criterion, a three is ranked as the same performance as a standard feature and a zero is a great improvement. In the *ranking-only* criterion, a three is ranked as the same performance as a standard feature and a five is a great improvement.

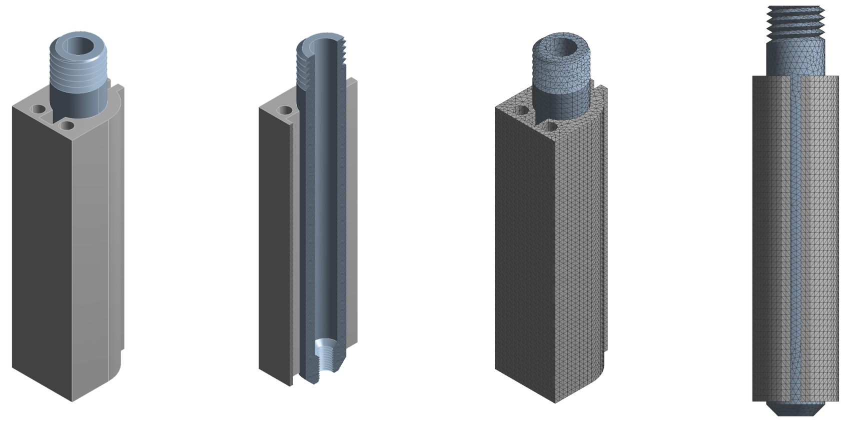
After consideration, the decision was made to implement the angled feeder input, the heat-sink and the vertical stopper for the screw as well as modifying a standard drill, as they were promising ideas would be possible to make during this thesis project.

Criterion Type ("Eliminatory" or"Ranking-only")	Criterion	A.	B.	C.	D.	E.
Eliminatory	Time consumption	3	3	5	3	4
Eliminatory	Labour intensity	3	3	5	3	4
Ranking-only	Function	5	4	2	5	5
Ranking-only	Manufacturability	3	3	1	3	2
Ranking-only	Durability	4	2	1	5	3
		6	3	-6	7	2
		Overall weighted score				

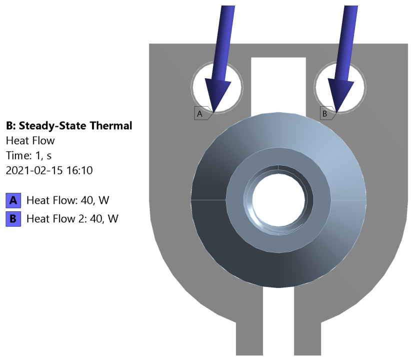
Table 4.1 Decision matrix for suggested modifications

4.2 Simulations

Prior to construction of a second extruder, Finite Element Method (FEM) simulations were made on the planned parts with the goal to approximate the dispersion of heat through the planned module as well as the casing that will connect it to the printer head. The simulations were made in ANSYS on simplified versions of the aluminium casing and delivery tube. The parts for both simulations can be seen in figure 4.1 along with the heat flow setup, which simulate the two heating elements situated along the bottom 40 mm of the casing. In these tests, two heat flow effects are tested, 30 W and 40 W, which are industry standard for the heating elements.



(a) Tested Assembly - full view **(b)** Tested Assembly - section view **(c)** Mesh of simulation **(d)** Front view of mesh



(e) Heat flow settings

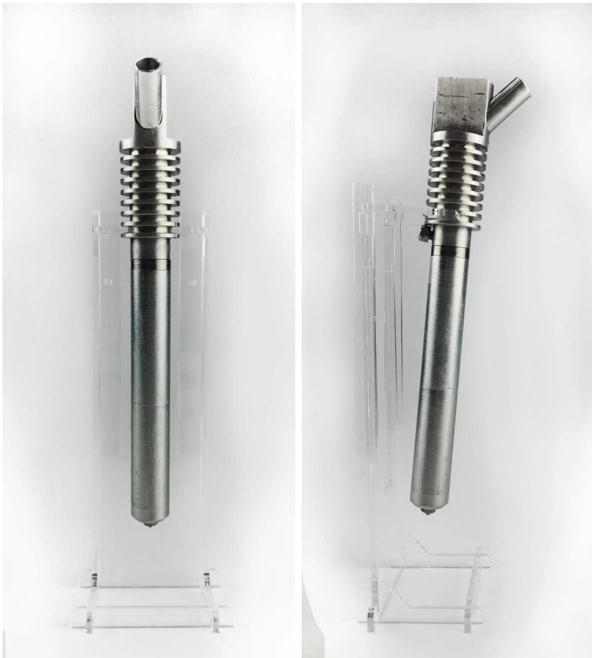
Figure 4.1: Boundary conditions of suggested design

The material chosen for the simulation is standard grade aluminium for the casing as well as the module. When testing for effect was completed, a material comparison was made for the feeder part to find the optimal material. A standard steel was compared with aluminium, to compare heat diffusion throughout the complete module assembly. For both simulations, thermal isolation was assumed to be ideal around the casing. Special consideration was also taken for temperature at the feeder port, where the material will start to plasticize. The results of these tests can be seen in chapter 5.2.

After simulations were made, the feeder was modified to implement a heat-sink structure which allows it to more effectively expel heat, protecting the stepper motor and parts close to the printer module.

4.3 Module part development

The V0 was replaced with a modular part, whose main components are a *delivery barrel*, the *feeder section* and a screw. Instead an interlying part which would connect the barrel to the feeder was built out of stainless steel. This part will act as a heat barrier. As the feeder is made from aluminium, the heat-sink design will be more effective. The finished assembly can be seen in figure 4.2, with machine drawings in appendix C.



(a) V1 - Front View **(b)** V1 - Side View

Figure 4.2: V1 module assembly

The two main parts are connected by a threaded pipe, which more efficiently stops heat travelling between these parts and facilitates easy assembly and disassembly. The feeding tube does not allow the extrudate to rotate around the screw without going into the barrel. Material choices were also made to minimise plastic parts which could melt and cause dangerous disruptions in the printing process. The design of the feeder also stops vertical movement of the screw, protecting the stepper motor from axial forces caused by the extrusion process and ensuring a more consistent extrusion process.

4.3.1 Screw design

The screw design of the extruder is of large importance, as it determines how the material is compounded, and under what pressures it is processed. In this project, a standard concrete drill with a L/D of 20:1 is used in place of an optimised extrusion screw. This decision was made due to budget and time constraints. To approximate the design of a optimal extruding screw, the screw chosen has a shallow thread with a low rise, to allow for maximal compression. Modifications were made to the purchased drill-bit, to optimise the compounding and throughput. This was done by grinding down the screw in order to get a thread depth which would decrease as the material moved through the extruder, increasing pressure and friction along the screw.

4.4 Improved module V2

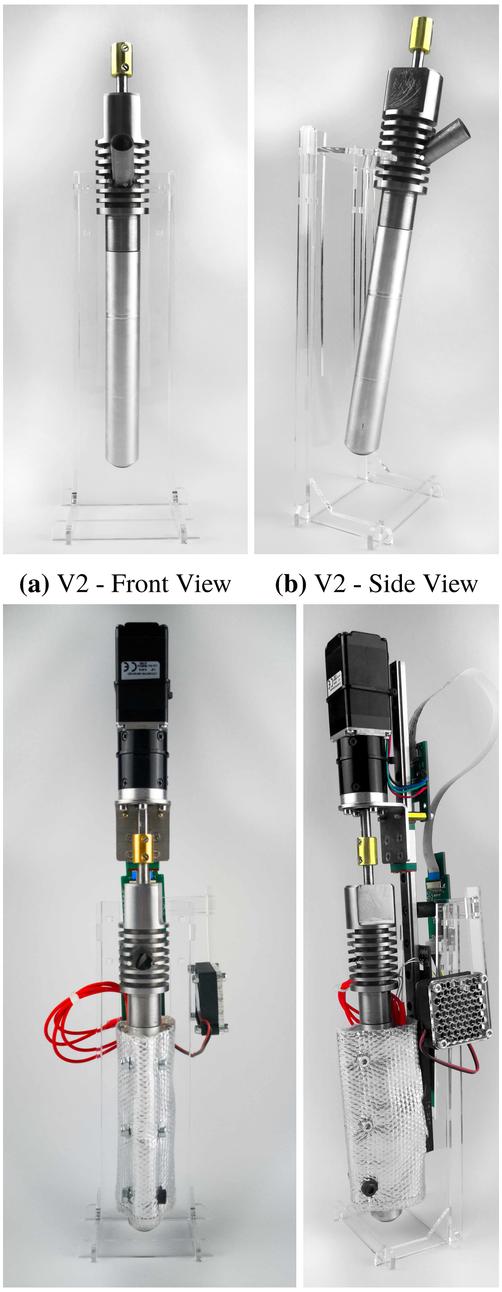
A rebuild of the module in more durable parts was made, to decrease wear on the parts and help increase the lifetime. The differences between the V1 and V2 modules are listed below:

The **feeder** part was remade in stainless steel, which has a higher hardness and lower heat conductivity. This keeps the heat from dispersing into the surrounding air and helps maintain heat in the extruder.

The **barrel** was remodelled to consist of two parts, one continuous stainless steel pipe, threaded on one side to match the feeder, and on the other side to match a standard 3D printer nozzle. This stainless steel part was encapsulated in an aluminium casing which helps disperse the heat from the heating unit evenly throughout the barrel. This redesign helps increase the durability of the part as well as retain heat inside the barrel.

A **waffle spring** was added on top of the screw to help create a counterforce to the extrudate, which pushes the spring up, creating a pool of plastic which stays inside the barrel and creates stoppages when the extrudate is cooled.

Schematics of the V2 module can be seen in appendix D and in figure 4.3, the finished parts are displayed along with a complete assembly. The screw was unchanged between the two iterations.



(a) V2 - Front View **(b)** V2 - Side View

(c) V2 Assembly Front View **(d)** V2 Assembly Side View

Figure 4.3: V2 module assembly

Chapter 5

Results

This chapter will cover the results of the various test made during the course of this master thesis. The main areas are the results of the V0 extruder printing tests, the heat-exchange simulations made in Ansys prior to the construction of the V1 module and improvements with the V2 module. Both mechanical and microscopy results from the testing of the V2 module can also be seen, along with information regarding extrusion testing.

5.1 V0 extruder

The initial printer tests resulted in an extrudate 1 1 mm in diameter and is extruded at a rate of 0 8 mm^3/s, but at no consistency and in no relevant quantities.

The problem areas identified with the V0 extruder were mainly within the extrusion printing process, as it had large issues to maintain structural stability. This due to the stepper motor exerting torque on the rest of the structure, which drove the feeder and heat sink apart, causing gaps. There was also problems noted with the parts connecting the feeder and heat sink, which was subject to the combination overheating and the full torque of the screw.

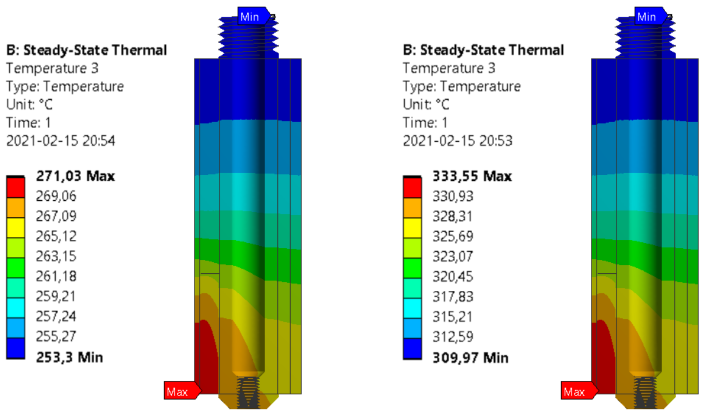
This combination of strains caused these nylon parts to plasticise and break apart. There was also a problem with the feeder design, where a large part of the material was rotated around the chamber without getting moved down with the screw. There were also noted problems with operating the design, as it needed three separate voltage sources to function, one for the heater, one for the stepper motor, and a separate 5 V battery pack to run the fan which keeps the plastic parts from overheating.

All these problems causes issues when attempting to achieve a consistent extrudate, as well as trying to smoothly operate the extruder.

5.2 FEM Simulations

The FEM analysis resulted in two simulations which represent an approximation of using 30 W and 40 W heating elements respectively. The results can be seen in figure 5.1 and temperature range can be seen in table 5.1. The results can be considered more ideal than in real life, with higher temperatures, as the assumption for isolation was ideal. These results are, however, a good reference for continuing the construction.

As the printing temperature for polymers mostly used in AM is in the range of 200 – 260 °C. With consideration to the fact that some extra material will be added to the assembly (Screw, extruded material et), the 40 W heating elements are more suited towards this goal.



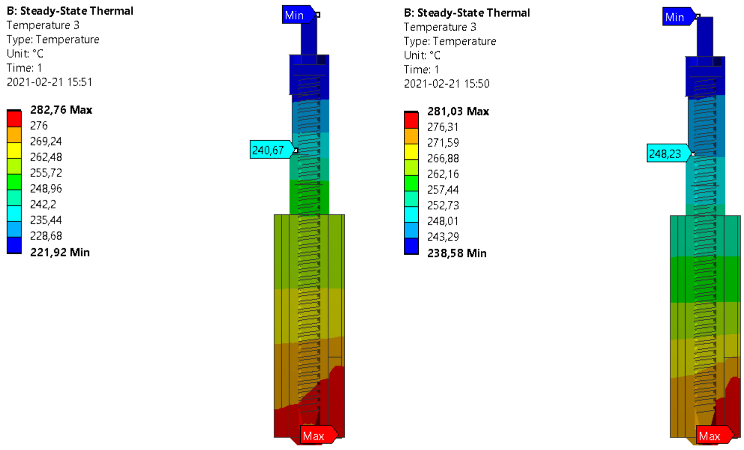
(a) 30W effect **(b)** 40W effect

Figure 5.1: Heat simulation results of figure 4.1

Heater effect	Temperature range (min–max °C)
30 W	253–271
40 W	297–334

Table 5.1 Temperature range of heat exchange simulation

Results for the material tests can be seen in figure 5.2. A heat difference of approximately 20 °C in the top end of the part can be observed between the two simulations, with a negligible temperature difference in the feeder input. The difference in temperature can be explained by the lower heat conductivity in the steel, which slows down the heating. This allows the barrel to better distribute heat internally which leads to a much better heat dispersion in the simulation with a steel feeder. The stainless steel also has a higher mass, which helps retain the heat inside the module as well as distribute it evenly. As the simulations provide a more favourable heat dispersion, stainless steel should be used in the final construction.



(a) Steel feeder part **(b)** Aluminium feeder part

Figure 5.2: Material comparison in the feeder part

5.3 V1 tests

During the testing of the V1 module, the materials chosen for the mechanical parts did not withstand the stresses which the extrusion process achieved, which caused the parts to wear at a much higher rate than anticipated.

The extrudate which was put trough the extruder got to a stopping point about 5 cm from the input and started to rotate with the screw instead of being conveyed. This resulted in higher wear and torque on the machined parts, which caused them to separate and malfunction.

The module was also incapable of retaining heat long enough to melt the extrudate which hindered the conveying of material along the screw.

5.4 V2 calibrations

The results from the calibrations according to table 3.3 can be seen in figure 5.3. They show the relations between temperature and screw rotational speed, and help show any relations between the two on yield strength.

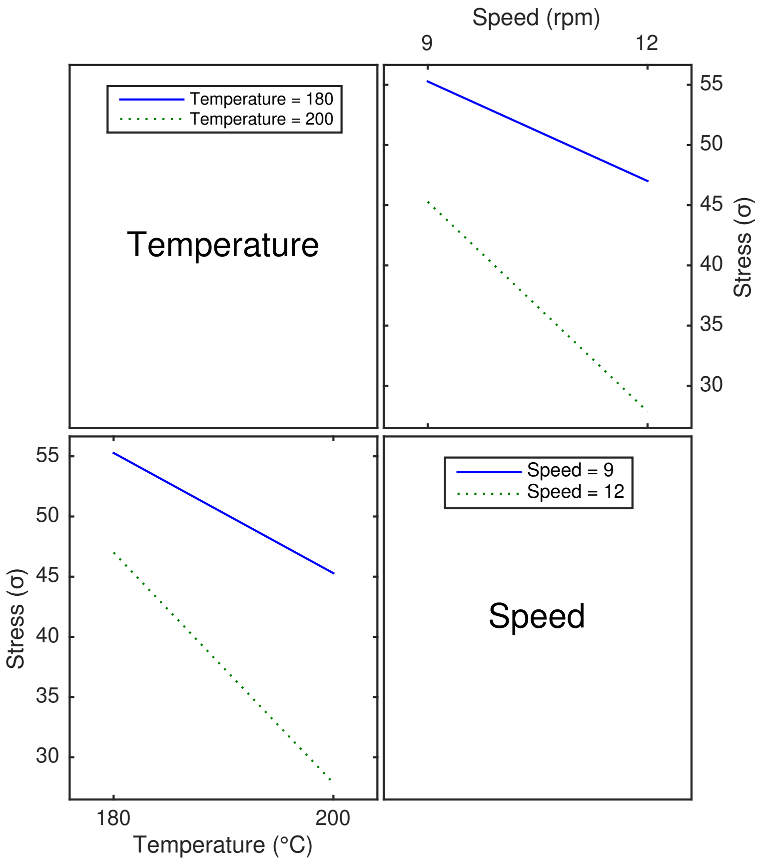


Figure 5.3: DoE plot comparing sample yield strength

As the lines are not parallel, it suggests an interaction between the parameters for the measured results.

From observations made during calibrations, a rotational speed of 9 rpm is required to overcome the friction of the internal walls and convey the extrudate and a temperature above 180 °C is required to achieve a good melt and induce an acceptable melt. If the temperature exceeds 210 °C, the extrudate will seep out through the extruder nozzle and leak.

The highest recorded yield strength in the extrudate is observed in sample 3, with a yield strength of 55.31 MPa, and p-values of 0.1939 and 0.218 for temperature and speed respectively for the DoE. A large difference in volumetric output between the four samples produced in the DoE was noted, depending on the parameters. The highest volumetric output was observed in sample 2 with a estimated difference of 400 %, to the lowest output of sample 3.

This difference, combined with the high p-values suggests that the correlation between temperature, rotational speed and yield strength have to be further evaluated to solidify the results. This motivates that the settings used for sample 2 should be preferred in the project, as real volumetric output is considered more important in this project than the possibility of a higher yield strength.

With the final parameters of the extrusion screw which can be seen in table 5.2, combined with equation 2.1, the V1 printer head has a theoretical throughput of 85.4 g/h equating a volumetric flow of 18.3 mm^3/s compared to the goal volumetric flow stated in table 3.1.

Parameter	Value	
Screw Diameter (D)	10	mm
Metering depth (h)	1	mm
Melt density (MD)	1.13	g/cm^3
Screw speed (N)	12	rpm

Table 5.2 Final parameters of screw

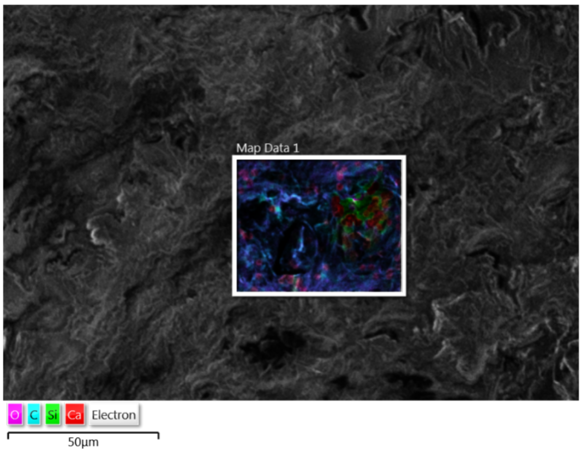
5.5 Quantification

This section will account for the evaluation results of the extruded samples, using SEM and tensile testing to develop a better understanding of the extrudates. This is done in order to establish a broader understanding of the samples produced, and give a better base which future projects can stand on.

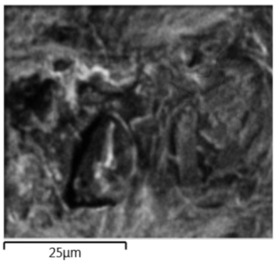
5.5.1 Scanning electron microscopy

The SEM results of the extruded samples are shown below, not including sample 1 as it only contains pure PLA. The figures display an original image that is mapped using elemental mapping to display the presence of elements.

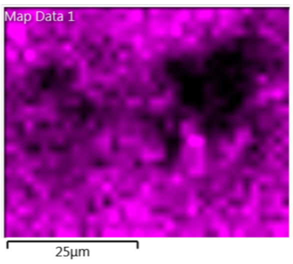
In figure 5.4, an enhanced section is displayed in figure 5.4b along with the mapping for compositional elements in the following figures. When comparing mappings, calcium, silicon and oxygen can be seen inhabiting the same areas where there are black spots of carbon and oxygen.



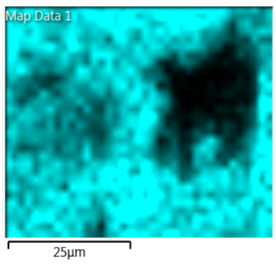
(a) Original image



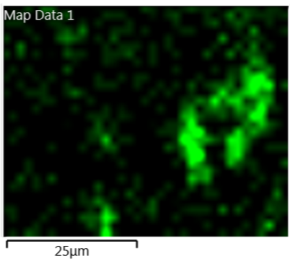
(b) Mapped area



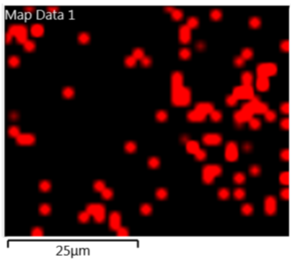
(c) Al-map



(d) Si-map



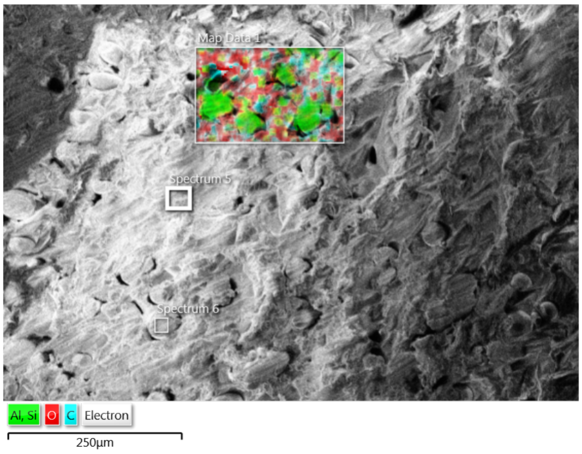
(e) O-map



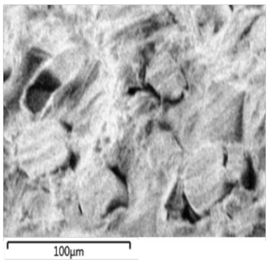
(f) C-map

Figure 5.4: Elemental mapping of $CaSiO_3$

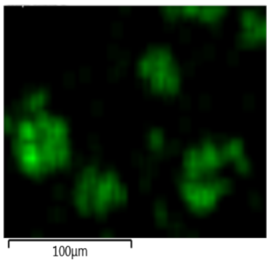
In figure 5.5, an enhanced section is displayed in figure 5.5b along with the mapping for compositional elements in the following figures. When comparing mappings, aluminium and silicon can be seen inhabiting the same areas where there are black spots of carbon and oxygen.



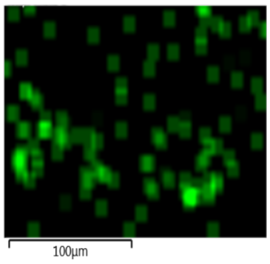
(a) Original image



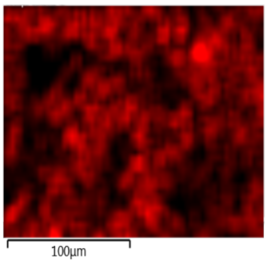
(b) Mapped area



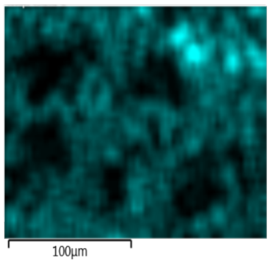
(c) Al-map



(d) Si-map



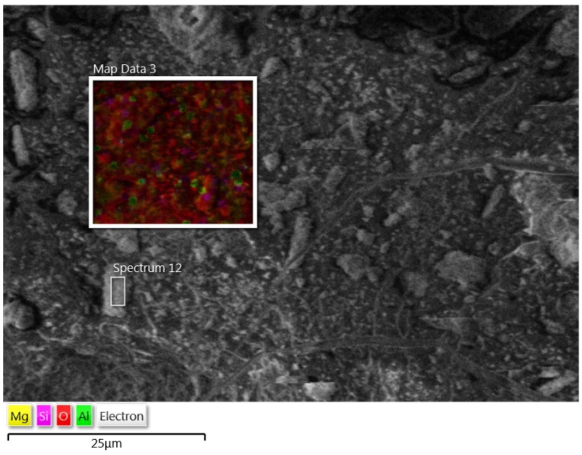
(e) O-map



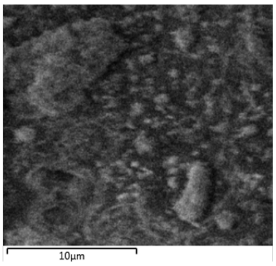
(f) C-map

Figure 5.5: Elemental mapping of AlSi10Mg

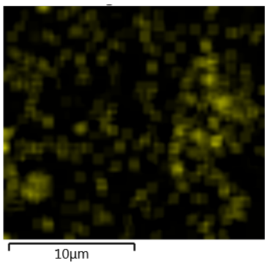
In figure 5.6, an enhanced section is displayed in figure 5.6b which is then mapped for compositional elements in the following figures. When comparing mappings, magnesium can be seen in some areas which coincides with areas in the original image that potentially could be magnesium.



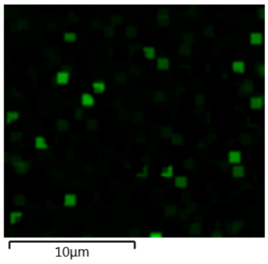
(a) Original image



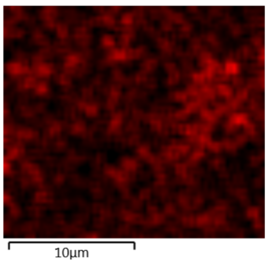
(b) Mapped area



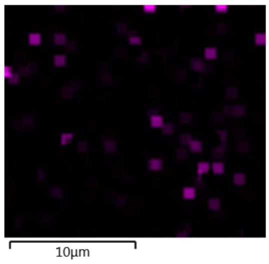
(c) Mg-map



(d) Al-map



(e) O-map



(f) Si-map

Figure 5.6: Elemental mapping of $MgCO_3$

As seen in figure 5.7, a 0.5 mm layer of pure PLA can be observed encasing the sample. This is seen in all the different additive samples.

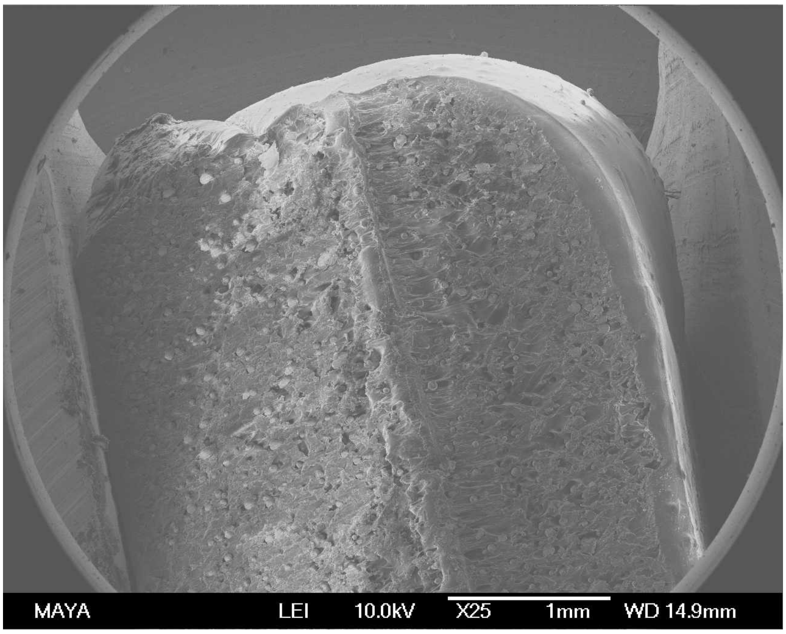


Figure 5.7: Large scale image of AlSi10Mg

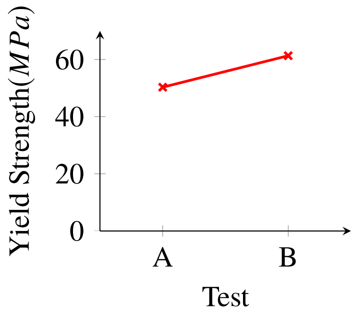
5.5.2 Tensile testing

In table 5.3, the results from the mechanical yield strength tests can be seen. The results are also shown in figure 5.8 where a comparison between the pure PLA and each of the additives can be seen.

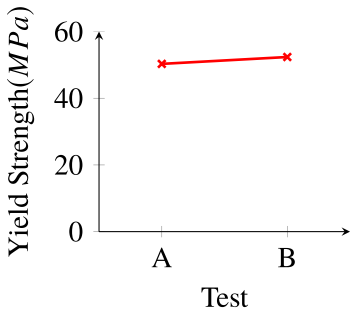
Sample	Additive	Yield Strength (MPa)	Relative change (%)
1	None	50.3	–
2	Wollastonite	61.32	122
3	Aluminium	52.36	104
4	Magnesium	23.77	47

Table 5.3 Tensile test results for the different additives

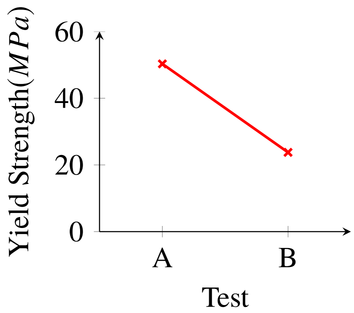
In figure 5.9, a stress-strain plot can be observed. Each curve has been normalised with regard for the initial length and diameter of each sample. Code used as a basis for these calculations can be seen in appendix E.



(a) Wollastonite



(b) Aluminium



(c) Magnesium

Figure 5.8: Tensile test comparing pure PLA (A) to additives (B)

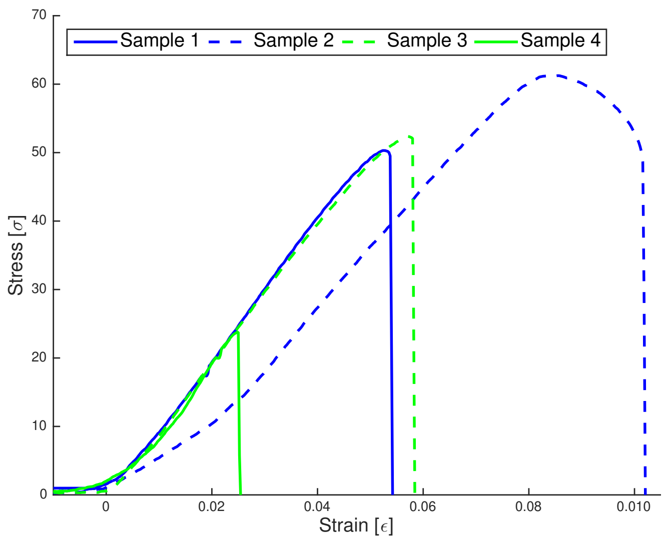


Figure 5.9: Standardised yield strength plot

Chapter 6

Discussion

This chapter will cover the argumentation and examination of both the direct results of the additive extrusion, the SEM and tensile tests performed. Sources of error as well as limitations of this study will also be detailed.

6.1 Simulation and DMAIC

The results of the practical tests differentiated substantially from the simulations performed in section 5.2, with a difference of almost 120 °C lower compared to the simulations. The insulation built onto the *krakatoa* printer head was paramount for the ability to achieve high enough temperature for extrusion. This insulation can be improved by building a better heat-shield or decreasing the volume of the casing. The cooling-ribs helped the heat dissipate into the surrounding air, helping to protect the stepper motor from higher temperatures, they also help to increase cooling when the extrusion process is finished.

6.2 Extrusion and mechanical testing

Wollastonite
During the printing of wollastonite additive, the extrusion process went smoothly and resulted in a well compounded material.

Aluminium alloy powder
The printing process with aluminium additive went without any complications, and extruded with ease. The extruded material displayed a higher heat conductivity than the pure PLA. A consistently coarse surface can be observed on some of the extruded samples, which are not observed in any of the other additives. A longer cooldown time was also noted compared to pure PLA.

Magnesium
The extrusion attempts with magnesium additive were proven difficult as the additive material would create large chunks of magnesium when under pressure, due to its high friction coefficient. This fact, leading to an uneven dispersion of additive throughout the matrix, created a more brittle material than the pure PLA sample. This uneven dispersion can be seen in figure 5.6a

These additives behaved better than expected, considering the small size and rotational speed of the V2 module compared to industrial extruders. The only exception to this is the magnesium, which was very difficult to disperse properly throughout the matrix. In an industrial setting, this is managed by dissolving the material into a ethylene oxide solution [22]. These generally positive dispersion results could possibly be contributed to the small batch size of the V2 extruder compared to an industrial sized extruder or the narrower gap between the screw and the surrounding walls. The results are also indicative of the fact that when the scale of extrusion decreases, the requirements of the screw alters to no longer requiring a double screw design or mixer sections to achieve a consistent composite.

As all the samples showed a thin outer layer of pure PLA, there is a possibility that this is a commonality between all extrusions in this module. This might be due to that the molten PLA expands out after exiting the extruder nozzle, encapsulating the other material. This can be both a positive, seeing it as a layer which protects the additive from corrosion, or negative where the material might lose essential properties such as electric conductivity.

The module designed and constructed in this thesis was made to be adaptable, it can easily be reconstructed into a fairly high volume extruder by mounting it in a horizontal heater and fitting it with a high capacity hopper, as well as exchanging the motor to a high speed and torque variant. This can then be used to create a filament which can be used in a separate filament-based 3D printer. It can also be used to make injection moulding, if the user has the possibility to produce functional moulds. A good future project could be to test a longer fibre, which can greatly increase the toughness of a matrix.

While the DoE results are suggesting that the yield strength is proportional to the extrusion speed and temperature, the high p-value does not corroborate a correlation between these parameters. It is also important to note that these results should be observed with some caution as the tested samples displayed some inconsistent shaping, resulting in variation in results. There is, however, merit in further analysing higher extrusion temperatures resulting in a weaker material by degrading the material at a faster pace, weighting it against the extrusion volumetric speed. An ANOVA was not feasible for this project, as it requires a larger sample size.

The tensile stress test displayed large differences from sample 1 which had an even elongation with a quick break. A large change in ductility can be seen in sample 2, containing wollastonite. This is consistent with the description of the additive, giving a smoother displacement curve and elongates the breaking process of the part. It also increased yield strength by 22 %, compared to pure PLA. Sample 3 displayed no relevant improvement in max yield strength compared to pure PLA, but with the same brittle break displayed in sample 1. Sample 4 showed a large deterioration of ductility, which probably can be accounted to the large chunks of magnesium which were created during the extrusion process. These chunks cause large gaps in the PLA matrix, decreasing the ductility.

6.3 Sources of error

During the simulation, extrusion and measuring processes, the most prominent sources of error identified have been listed below:

Simulations
Simplifications and assumptions have been made to limit computing time and make the simulations feasible. These simplifications include optimising the mesh size to certain areas of interest at a small size. Simplifications have also been made to exclude simulations of the plastic flow through the extruder.

Extrusion
The results from the extrusion process could have been improved by increasing the amount of pure pellets which are put through the extruder to clean it between the different additives, to absolutely make sure that no remnants of previous additives which can alter the tensile strength of the finished material. This is however seen as a small difference in the end product, as no trace elements of additives have been found during the SEM testing.

Measuring
The measuring using tensile testing is impacted by the shape of the parts tested, which are slightly differently shaped with small inconsistencies in thickness. The parts are also affected by the electron beam in the SEM process which moves and deforms the PLA by a small amount, leading to a small shift in the original images taken and the located elemental materials in the scan. The mapping is also based on a 2D image of the area and thus, all of the sample material might not display the same distribution as the mapped area. This is, however, assumed as the area mapped is a cut cross-section of the samples.

Although that the results from the tensile testing have been standardised to account for the varying thickness among the samples, there is still a certain difference between the samples, which has to be considered. Increasing the sample size is preferable as this increases the certainty of the results and the efficiency of the extruder.

6.4 Limitations

The scope of this project had to be limited to make sure that it could be followed through in a timely manner. This project has been limited to not include the ability to 3D print a complete structure as this is seen as trivial when the ability to extrude material has been benchmarked and fulfilled. The consistency of parts used in tensile testing by using a injection mould to create identically shaped parts to test. This would probably require much improved throughput capacity of the extrudate to inject the required volume before the material cools below the melting point. More tests could also have been performed on more samples to verify the results further, but as the costs connected to SEM-testing are very high, this thesis limited the testing to one sample of each additive. As there were not enough samples produced and tested to give a reliable basis for DoE, one was not performed. This is, however, recommended for further projects to give a broader understanding of the compounding of different materials in this extruder.

Chapter 7

Conclusion & Recommendations

This chapter will cover the conclusions drawn from this project, its results and methods. It will also bring up relevant recommendations for projects which are suitable to consider to build on this thesis.

7.1 Conclusion

How well can composites be homogenised through extrusion in a minimal extruder?

This thesis aimed to benchmark the composite compounding capabilities of a scaled-down extruder, to help lay the ground for further research into this area and the results of this thesis are predominantly positive towards this goal. This thesis has shown that a relatively cheap and manageable single screw extruder can produce a usable extrudate fairly quickly, and there are no real limitations to the public constructing these themselves to help increase the development of knowledge surrounding AM and material sciences in these areas. The quality of this extrudate is high enough to be used to effectively benchmark new material ideas or create parts which do not require an exceptionally high quality standard.

The raw materials used to produce filaments are cheap standardised materials, this could be an effective way of minimising costs for a small scale manufacturer or large scale hobbyist. It can also be used to effectively recycle plastics such as PET-bottles, which is a positive environmental achievement.

Not all materials extrude easily and this set-up is not suitable for every additive or composite. It is, however, very well suited for a large amount of popular additives such as metals and different colours which improve or change material properties greatly. As these materials now theoretically could be made at home, the possibilities to create and invent new areas of application are multiplied as a small scale producer now can test their own material combinations and compounds, without having to order large quantities from a large scale producer.

The future of AM is getting brighter by the day and the possibilities to replace wasteful production methods and supply chains are greater than ever. What is needed now is to move the means of production to the people by increasing the public ability and knowledge to both create both new as well as replacements for worn out parts. This will help decrease waste as fewer new products will have to be built, and new products can be produced at home with materials such as filaments or pellets that are more effective to ship than already made parts.

7.2 Recommendations

Following are a list of recommendations for future projects, which can be performed using this thesis as a starting point:

- Benchmark the throughput and optimise for 3D printing.
- Construct a horizontal casing for the V2 module, with higher torque and better heat control, to enable the creation of filament as well as injection moulding.
- Examine the applicability and usability of coating the barrel or screw in a non stick coating such as graphite, which can withstand temperatures of up to 450°C and could greatly ease cleanup of the module.
- Construct a modular screw, based around a threaded (or hexagonal) rod, where the different parts can be replaced. Make the conveyor parts out of a standard screw, which can be cut, drilled and threaded. (could also 3D print smaller components of a larger screw, which then are assembled into a complete screw) see figure 7.1 for reference. This mimics an industrial extrusion screw design.

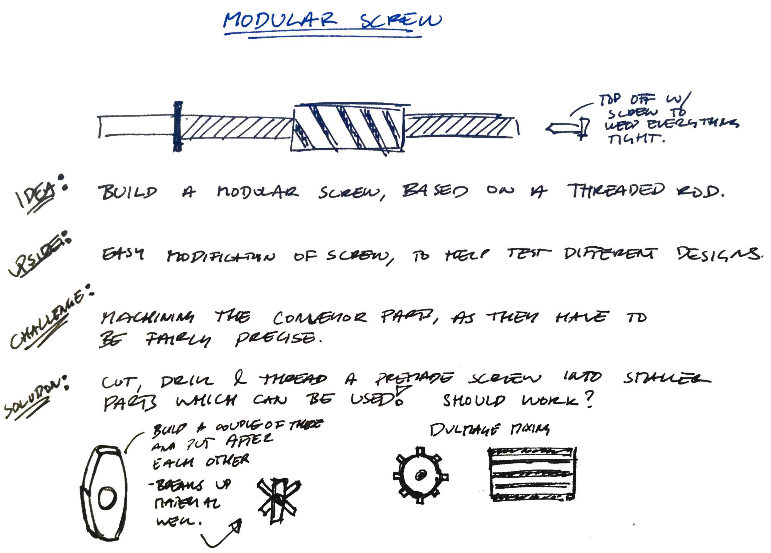


Figure 7.1: Suggestion for modular screw design

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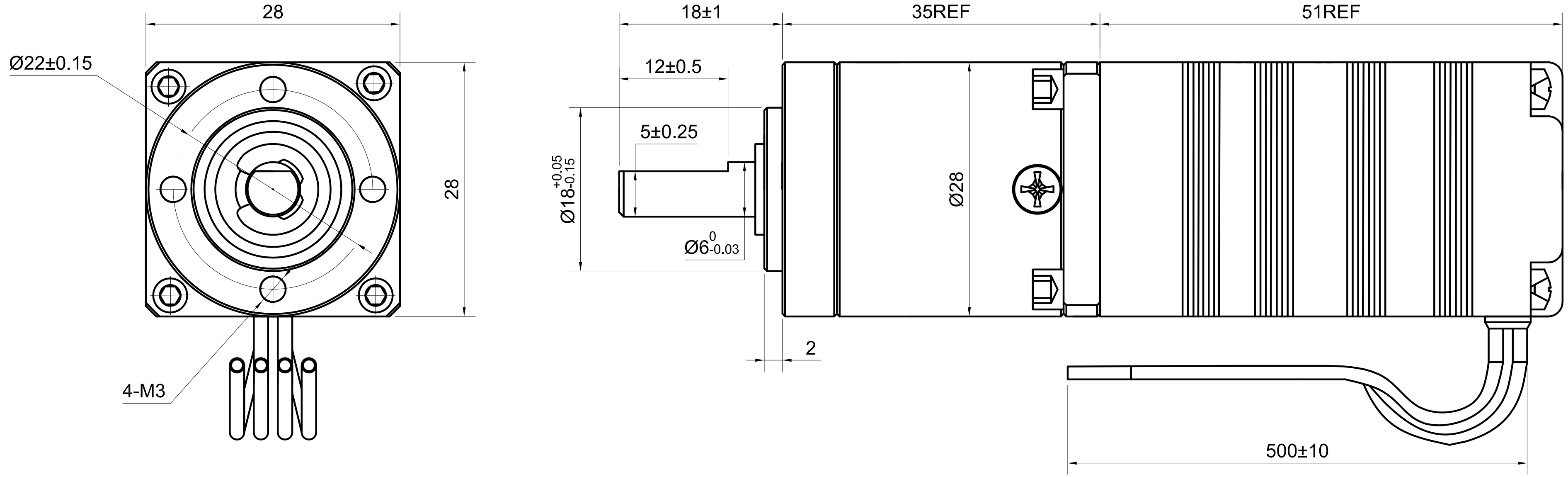
Appendix A

Stepper Motor

This appendix contains a technical drawing and specifications for a *11HS20-0674S-PG27* stepper motor.

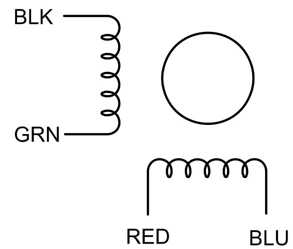


SPECIFICATION / CONNECTION	BIPOLAR
AMPS/PHASE	0.67
RESISTANCE/PHASE(Ohms)@25°C	12.00±10%
INDUCTANCE/PHASE(mH)@1KHz	6.50±20%
HOLDING TORQUE w/o GEARBOX(Nm)[lb-in]	0.14[1.24]
GEAR RATIO	$26\frac{103}{121}$
EFFICIENCY	81.00%
STEP ANGLE w/o GEARBOX(°)	1.80
BACKLASH@NO-LOAD	<=1°
MAX.PERMISSIBLE TORQUE(Nm)	3.00
MOMENT PERMISSIBLE TORQUE(Nm)	5.00
SHAFT MAXIMUM AXIAL LOAD(N)	5.00
SHAFT MAXIMUM RADIAL LOAD(N)	25.00
WEIGHT(Kg)[lb]	0.40[0.88]
TEMPERATURE RISE:MAX.80°C（MOTOR STANDSTILL;FOR 2PHASE ENERGIZED）	
AMBIENT TEMPERATURE -10°C~50°C[14°F~122°F]	
INSULATION CLASS B 130°C[266°F]	

TYPE OF CONNECTION (EXTERN)		MOTOR	
PIN NO	BIPOLAR	LEADS	WINDING
1	A —	BLK	A
2	A\ —	GRN	A\
3	B —	RED	B
4	B\ —	BLU	B\

FULL STEP 2 PHASE-Ex.,
WHEN FACING MOUNTING END (X)

STEP	A	B	A\	B\	CW ↓	CCW ↑
1	+	+	-	-		
2	-	+	+	-		
3	-	-	+	+		
4	+	-	-	+		



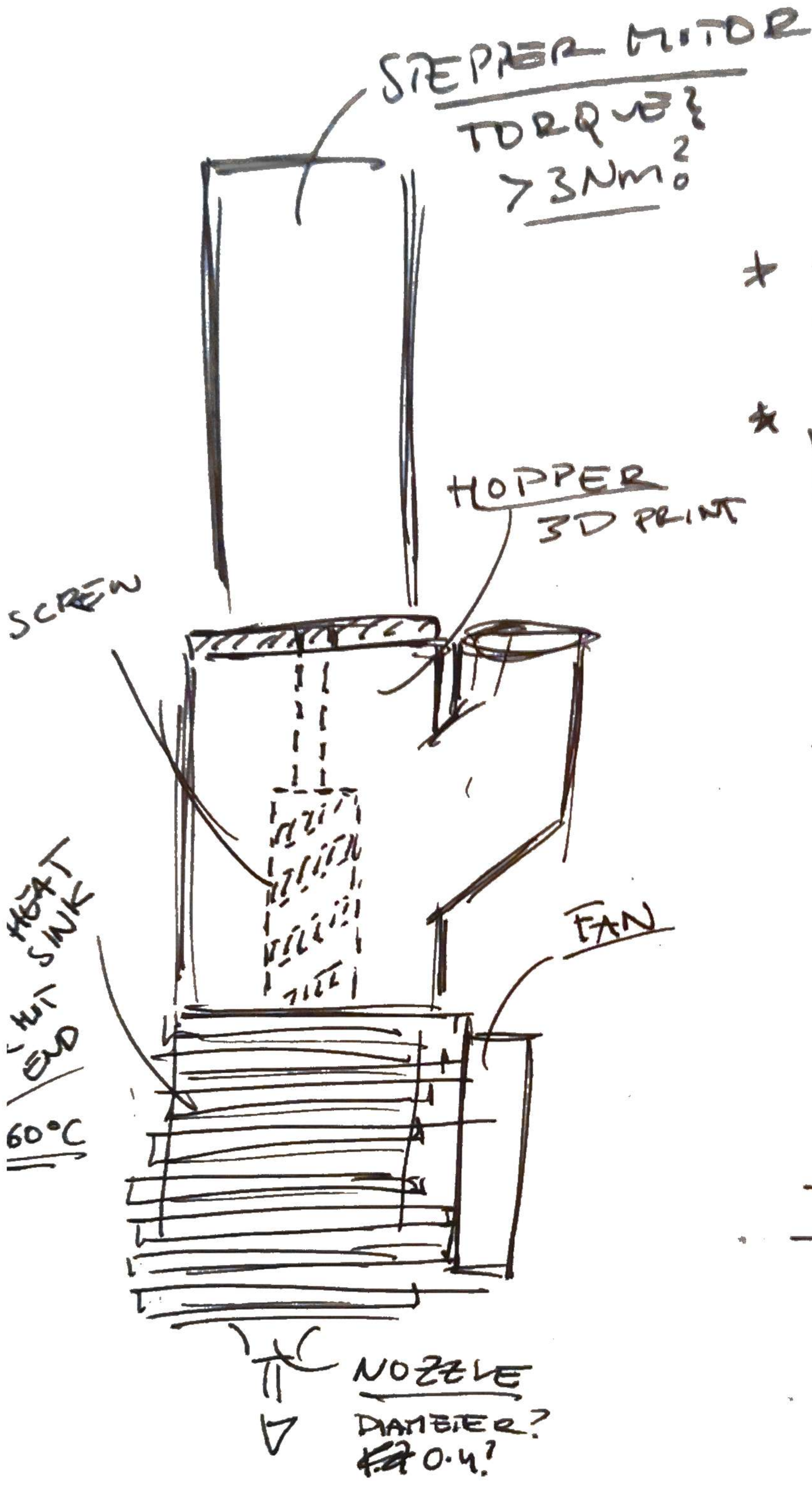
STEPPERONLINE®

	APVD		8.18.2018	STEPPER MOTOR
	CHKD			
1.5:1	DRN			11HS20-0674S-PG27
SCALE	SIGNATURE		DATE	

Appendix B

Sketches of Extruder

This appendix contains sketches and ideas made during the developmental phase of version 1 of the printer head, along with some rudimentary calculations and measurements.



HYREL

* 1 TOOL POSITION HAS 4A OUTPUT. (12VDC)
  - COMBINE 2 IF NEEDED
  - MAX 15A TOT.
* (STEPPER + FAN + HEATER)

$\frac{40W}{12V}$ = 3.3A FOR HEATER

$\frac{0.8W}{5V}$ = 0.16A FAN

0.67A STEPPER

↓

~4.16A,

- USE TWO OUTPUTS
- OR LOWER CURRENTS.
- OR CHANGE FUSE.

DO NOT EXCEED 15A!

HOTEND

260°C MAX TEMP.

40W, 12A, 3.3A

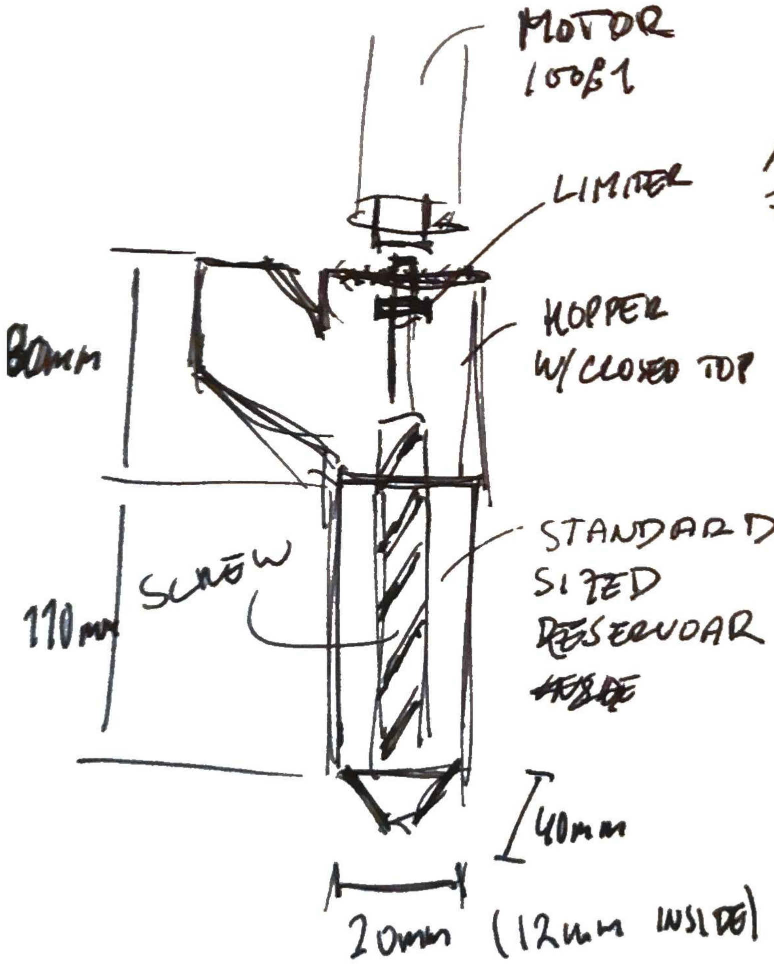
DOES IT NEED A HEATSINK & COOLING FAN?

USE OLD HOTEND, GOOD SIZE & LESS WORK
- CONNECT IT TO CIRCUITBOARD

COULD A MODIFIED VOL-25/OTHER HEAD BE USED? ADDING A HOPPER AND AUGER IN THAT CASE.

IF THE EXISTING HEAD COULD BE HEATED TO 250°C, A MODULAR DESIGN COULD BE USED.

+ LESS WORK AND CHEAPER.



NEED TO PROTECT STEPPER FROM AXIAL FORCE.
- USE THE HOPPER-TOP TO LIMIT SCREW MOVEMENT

SCREW CONNECTOR 9.7mm SQUARE.
9mm HIGH

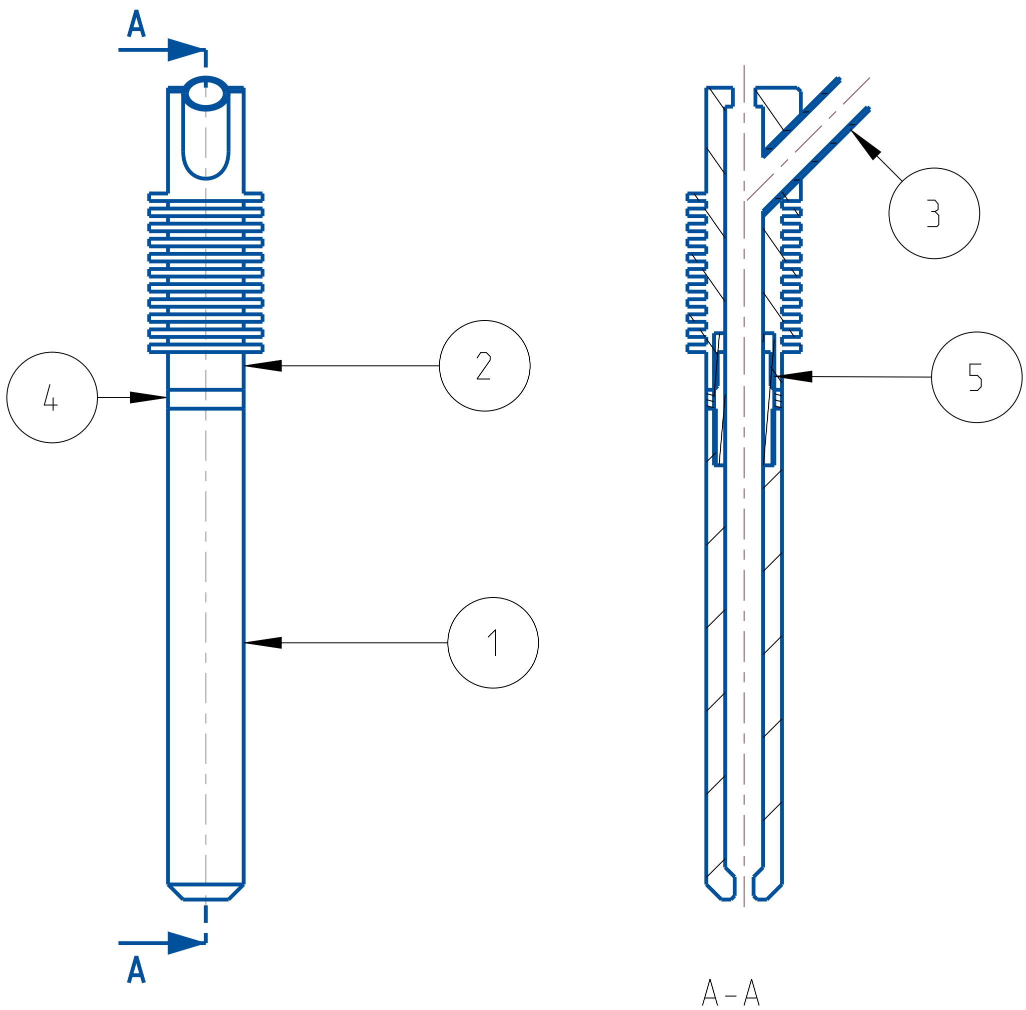
RESERVOAR CASING:

3×M3 NO THREADED HOLES ON EACH SIDE
40mm DISTANCE.
USE FOR FAN??

Appendix C

Machine drawing of V1 module

This appendix contains the technical drawings for the V1 module



Pos	Ant	Artikel/Modell	Benämning	Material	Dimension
1	1	CYLINDER		Aluminium	130 x 20
2	1	FEEDER		Aluminium	80 x 30
3	1	FEEDER-TUBE		Aluminium	40 x 12
4	1	MIDDLE-RING		Stainless steel	5 x 20
5	1	MIDDLE-SECTION		Stainless steel	35 x 10

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:2	A4	1(1)

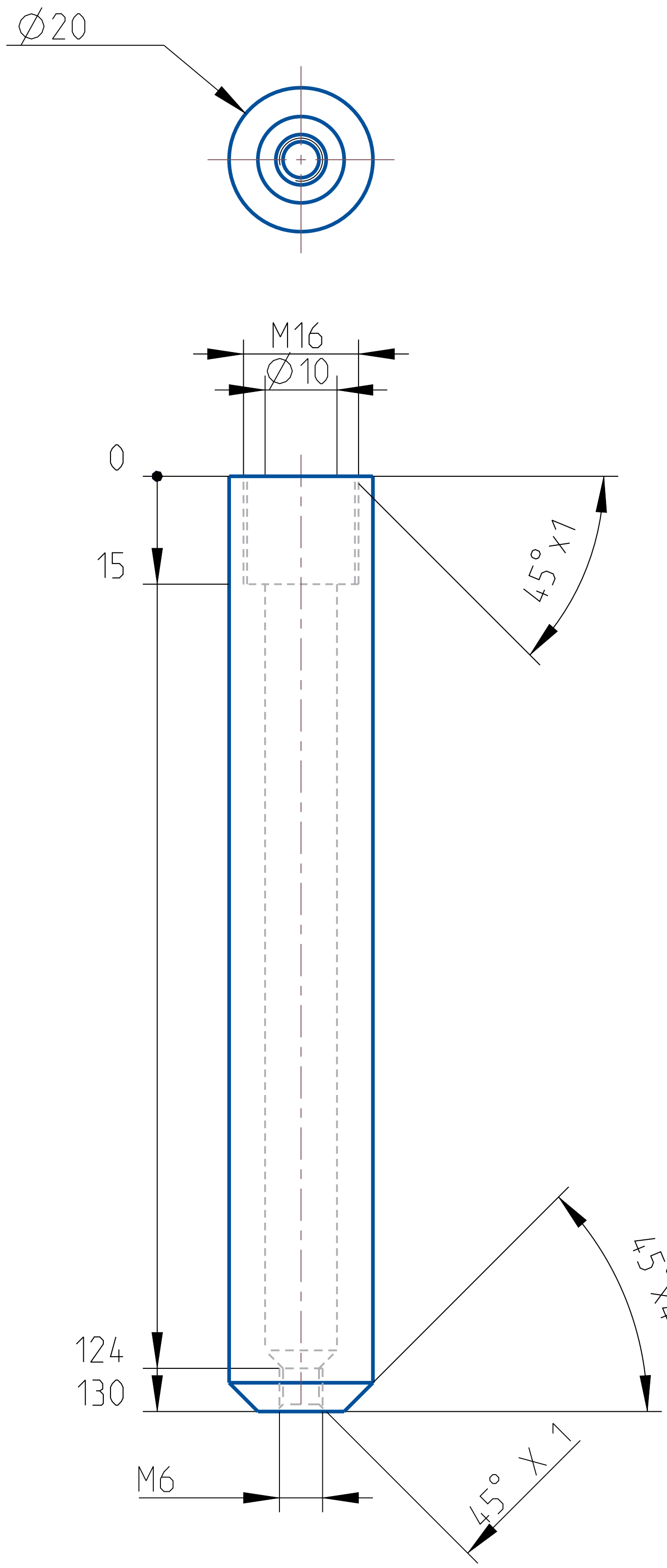
Machine Design LTH

Artikel/Modell: MODULE

Datum: 18-Feb-21

Benämning:

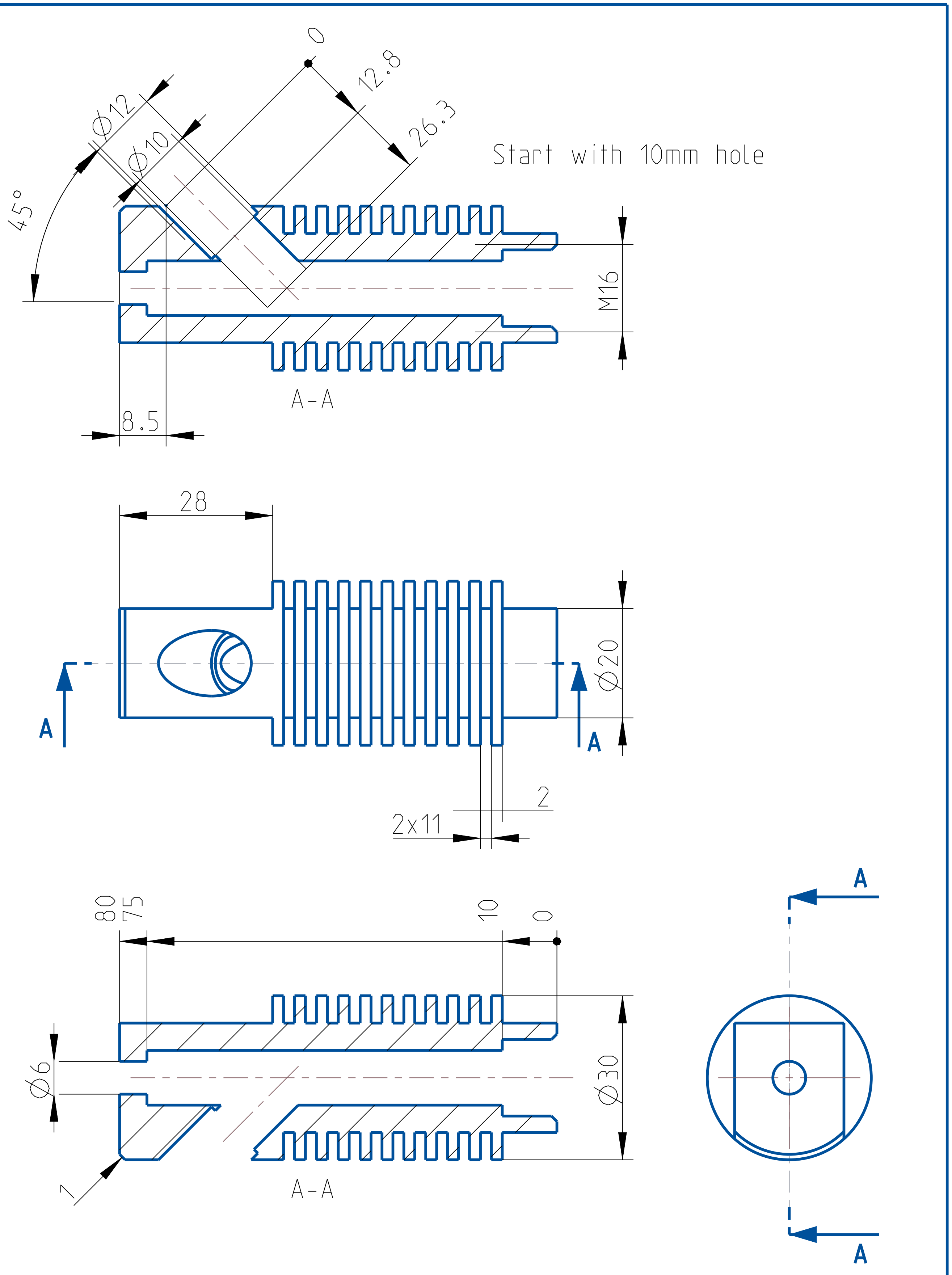
Ritning: MODULE



				Aluminium	130 x 20
Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr OSCAR R.M	Ritad OSCAR R.M	Revision	Vikt	Skala 1:1	Format A4	Blad.nr 1(1)

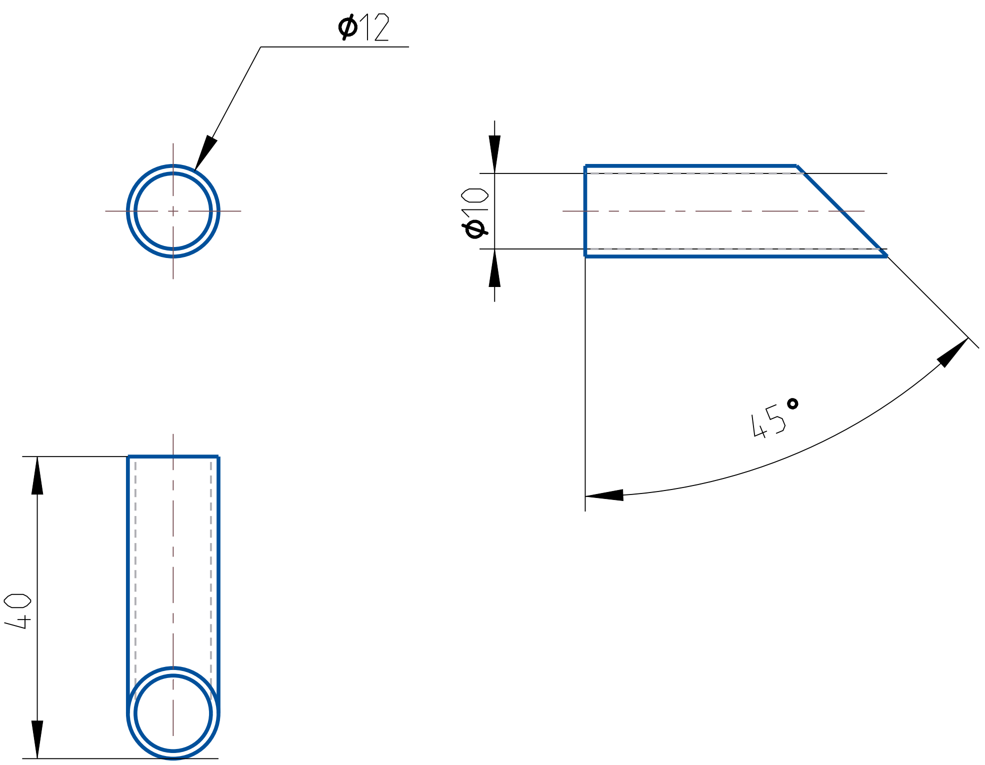
Machine Design LTH	Artikel/Modell CYLINDER	Datum 18-Feb-21
	Benämning	Ritning CYLINDER



				Aluminium	80 x 30
Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

Machine Design LTH	Artikel/Modell FEEDER	Datum 18-Feb-21
	Benämning	Ritning FEEDER



				Aluminium	40 x 12
Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

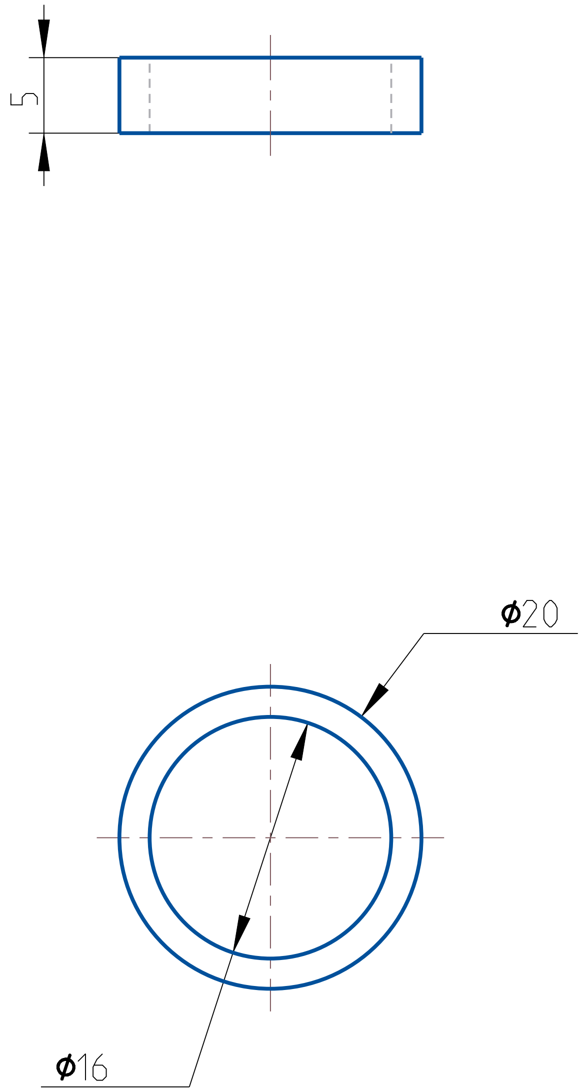
Machine Design LTH

Artikel/Modell: FEEDER-TUBE

Benämning:

Datum: 01-Mar-21

Ritning: FEEDER-TUBE



Pos	Ant	Artikel/Modell	Benämning	Material	Dimension
				Stainless steel	5 x 20

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			2:1	A4	1(1)

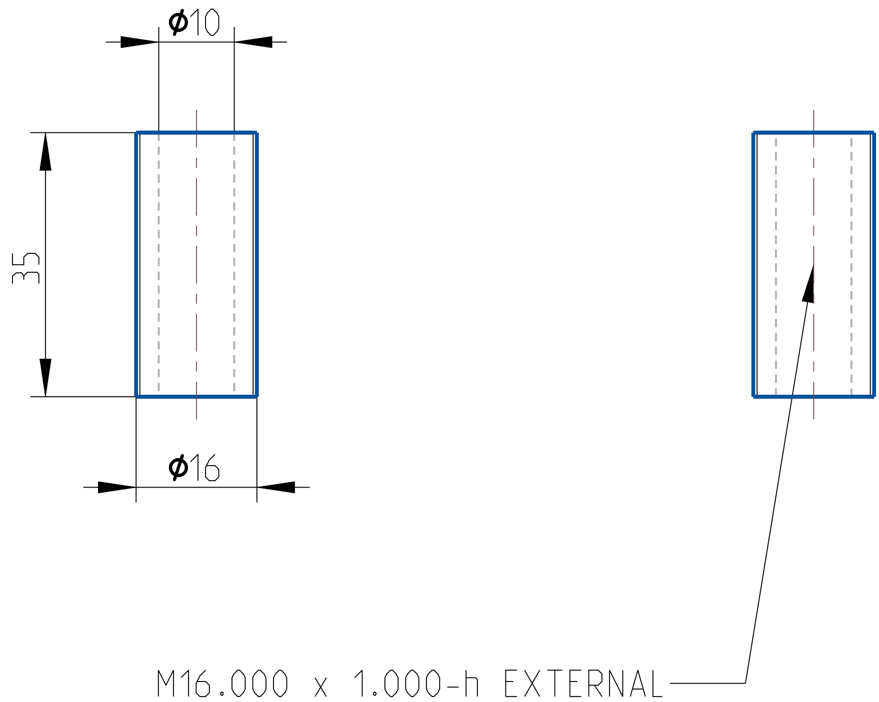
Machine Design LTH

Artikel/Modell: MIDDLE-RING

Benämning:

Datum: 21-Apr-21

Ritning: MIDDLE-RING



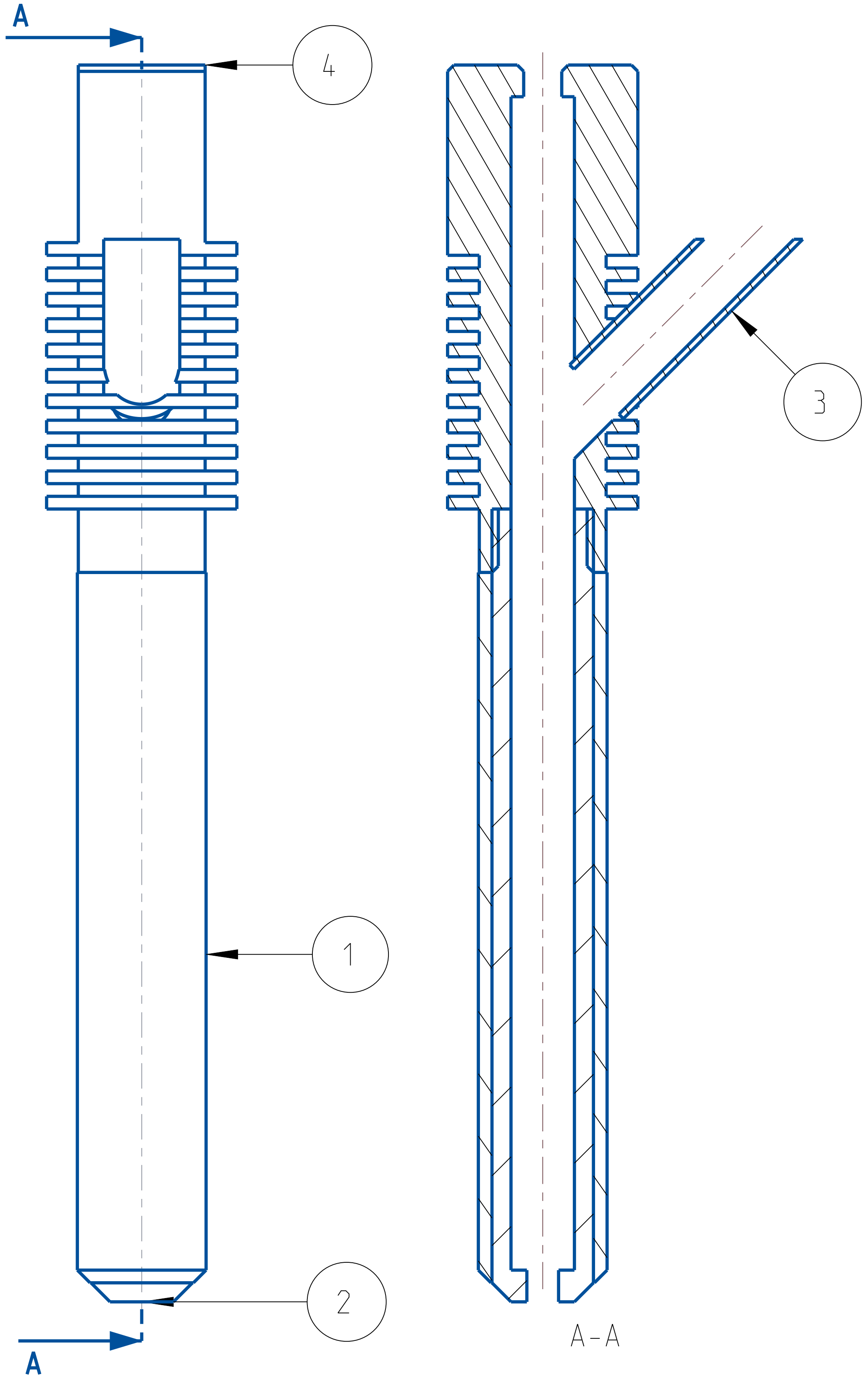
				Stainless steel	35 x 10
Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr OSCAR R.M	Ritad OSCAR R.M	Revision	Vikt	Skala 1:1	Format A4	Blad.nr 1(1)
Machine Design LTH		Artikel/Modell MIDDLE-SECTION			Datum 21-Apr-21	
		Benämning			Ritning MIDDLE-SECTION	

Appendix D

Machine drawing of V2 module

This appendix contains the technical drawings for the V2 module

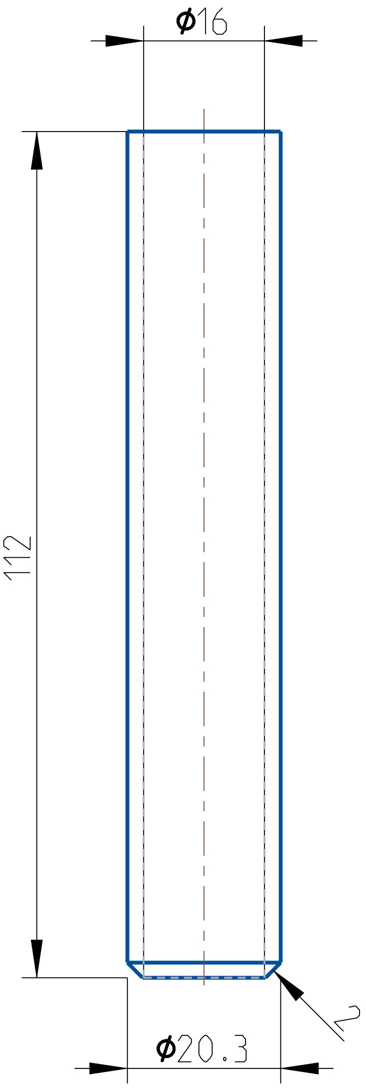


Pos	Ant	Artikel/Modell	Benämning	Material	Dimension
4	1	FEEDER-V2		Stainless steel	80 x 30
3	1	FEEDER-TUBE-V2		Stainless steel	40 x 12
2	1	BARREL-STEEL		Aluminium	125 x 10
1	1	BARREL-ALUMINIUM		Stainless steel	112 x 20

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

Machine Design LTH

Artikel/Modell: V2	Datum: 14-Apr-21
Benämning:	Ritning: V2



Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

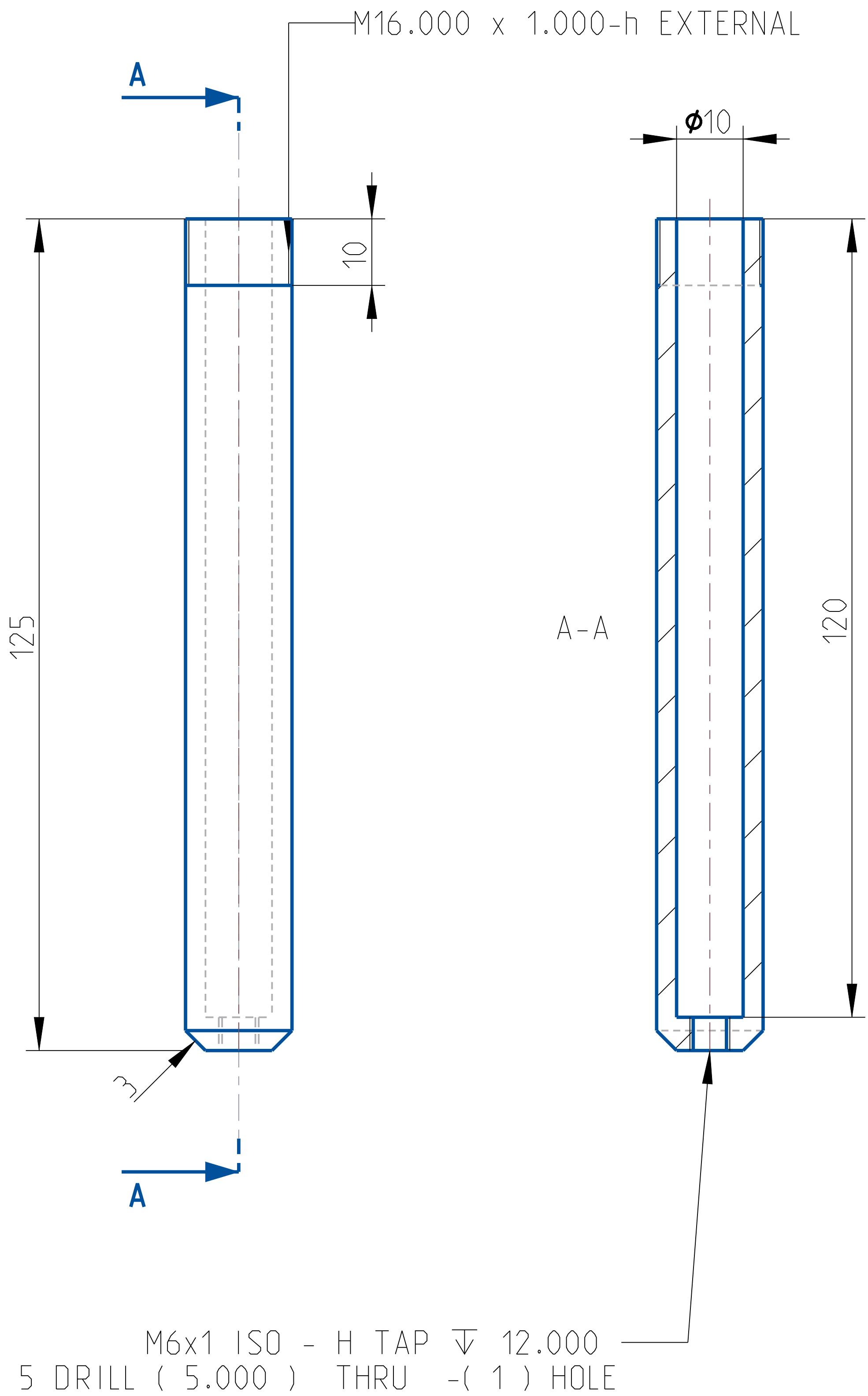
Machine Design LTH

Artikel/Modell
BARREL-ALUMINIUM

Datum
14-Apr-21

Benämning

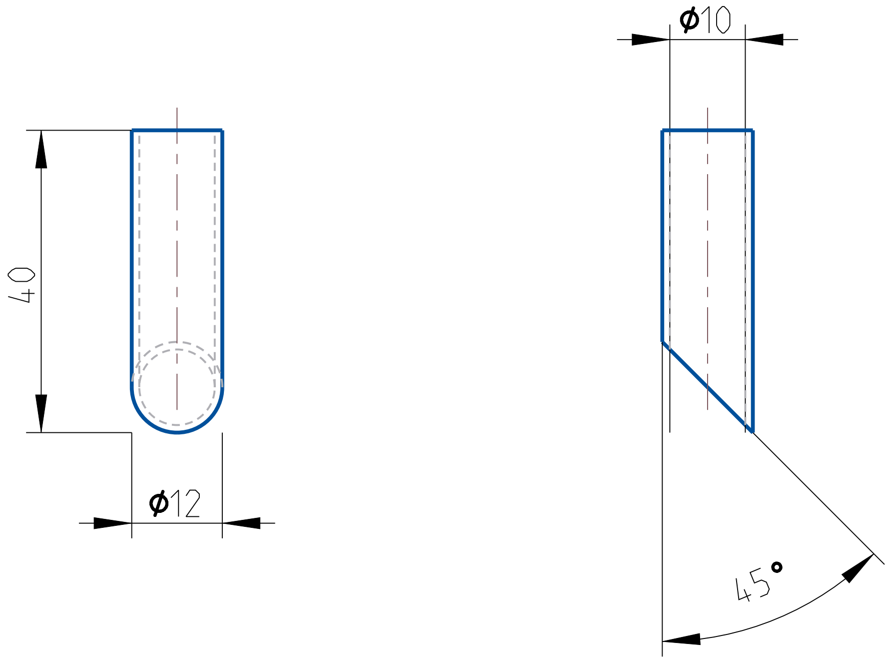
Ritning
BARREL-ALUMINIUM



Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

Machine Design LTH	Artikel/Modell BARREL-STEEL	Datum 14-Apr-21
	Benämning	Ritning BARREL-STEEL



Pos	Ant	Artikel/Modell	Benämning	Material	Dimension

Konstr	Ritad	Revision	Vikt	Skala	Format	Blad.nr
OSCAR R.M	OSCAR R.M			1:1	A4	1(1)

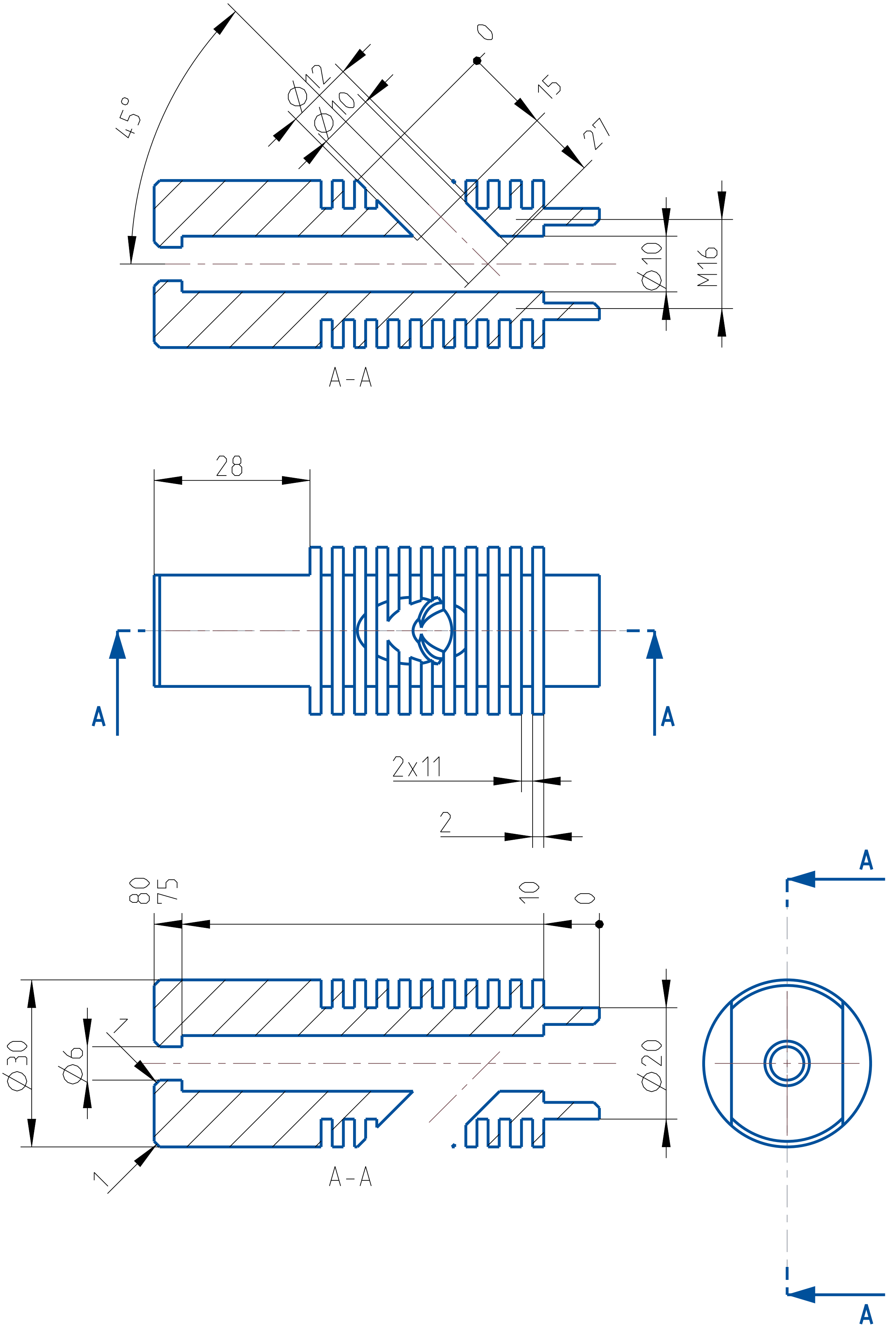
Machine Design LTH

Artikel/Modell: FEEDER-TUBE-V2

Datum: 14-Apr-21

Benämning:

Ritning: FEEDER-TUBE-V2



Pos	Ant	Artikel/Modell	Benämning		Material	Dimension
Konstr OSCAR R.M	Ritad OSCAR R.M	Revision	Vikt	Skala 1:1	Format A4	Blad.nr 1(1)
Machine Design LTH		Artikel/Modell FEEDER-V2			Datum 14-Apr-21	
		Benämning			Ritning FEEDER-V2	

Appendix E

Raw data from tensile strength test

This appendix contains the raw data and code used to calculate tensile strength.

```
%-----------------Matlab-------------
clc
clear all

%% Rate of the machine
rate = 2; %mm/min

%% Load the data
[file,path] = uigetfile('.txt');
data = importdata([path,file]);

if file == 'Sample 1.txt'
    width = 3.6
    length = 36;
    F_shift = 0;
elseif file == 'Sample 2.txt'
    width = 4
    length = 34;
    F_shift = 0.08;
elseif file == 'Sample 3.txt'
    width = 4.5
    length = 39;
    F_shift = 0.08;
else
    width = 3.7
    length = 37;
    F_shift = 0.085;
end

time = data.data(:,1); % Time in ms
force = data.data(:,2); % Force in N
force = force/((width/2)^2*pi); % Force in MPa
disp = time/1000/60*rate;
        % Calculate the displacement using
        the time and rate
disp = disp - disp(1); % Make the
        displacement start at 0
disp = disp / length;
```

```
%% Shift the curves horisontally to coincide
        at the force F_shift
try
    [~,idx] = min(abs(force - F_shift));
    disp = disp - disp(idx);
catch
    disp('Can''t shift curves, check F_shift')
end

%% Plot
figure(3)
hold on
plot(disp-F_shift,force,'-b',
        'Displayname',file, 'linewidth', 1)
xlabel('Strain [\epsilon]')
ylabel('Stress [\sigma]')

%-----------------DoE Testing-----------

clc
clear all
close all

generators = fracfactgen('a b',2);
[dfF,confounding] = fracfact(generators)

y =     [   55.28, 47.01, 45.29, 27.86]; %A1B1, A1B2, A2B1, A2B2

group = [   180, 9      %A1B1
            180, 12     %A1B2
            200, 9      %A2B1
            200, 12];   %A2B2
figure(1)
interactionplot(y,group,'varnames',{'Temperature','Speed'}); %Plot

figure(2)
[~,~,stats] = anovan(y, group, 'varnames',{'Temperature','Speed'});
figure(3)
results = multcompare(stats,'Dimension',[1 2]);
```