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Department of Designing and Machine Components

Design modification of extruder of filament for 3D printing

Konstrukční úprava extrudéru filamentu pro 3D tisk

BACHELOR THESES

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Specialization:	Without specialization
Supervisor:	Ing. Václav Čvančara

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

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Konstrukční úprava extrudéru filamentu pro 3D tisk

Guidelines:

The aim of this work is to propose design modifications of the extruder, which guarantee a smooth production of filament with the required properties and in the required tolerances.

Bibliography / sources:

[1] ŠVEC, V.: Části a mechanismy strojů. Spoje a části spojovací. Praha: ČVUT, 2008.
[2] Joseph E. Shigley: Konstruování strojních součástí. 2010. ISBN 978-80-214-2629-0.

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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I confirm that the bachelor's thesis was disposed by myself and independently, under the lead of my thesis supervisor. I stated all sources of the documents and literature.

In Prague ……………… ……………………………………..

Volodymyr Dudavskyi

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ANNOTATION LIST

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Scope of work:	Number of pages: 63 Number of figures: 50 Number of tables: 9
Keywords in Czech:	Výroba filamentu pro 3D tisk, vytlačování
Keywords in English:	Filament production for 3D printing, extrusion
Anotace:	Předmětem této bakalářské práce je návrh úprav existujícího extrudéru pro zvýšení kvality vyráběného filamentu. Zadavatelem této práce je společnost Mubea, která technologii 3D tisk používá pro výrobu různých modelů a prototypů. S ohledem na recyklaci nepotřebných dílů a snížení nákladů na materiál si firma pořídila vlastní extrudér pro výrobu filamentu. Současná kvalita filamentu však není uspokojivá, proto jsou v této práci jsou navrženy dílčí úpravy procesu extruze, následné kontroly průměru a experimentální měření vlastností vyrobeného filamentu.
Annotation:	The subject of this bachelor thesis is a proposal of modifications of the filament extruder to make a smooth production of the filament with the needed tolerances and properties. The main reason to do this work is that Mubea company uses 3D printing for testing specimens and wants to make it cheaper and ecofriendly so the extruder without modifications can’t function correctly. The focus is on the process of production machines for modification of an extrusion process, an inspection of the thickness of extruded filament, and the experimental measurement of the plasticity properties of the filament.

LIST OF ABBREVIATIONS AND SYMBOLS

ABS	-	Acrylonitrile butadiene styrene
ASA	-	Acrylonitrile styrene acrylate
CAM Softwear	-	Computer-aided manufacturing softwear
CHDM	-	Cyclohexanedimethanol
CZK	-	Czech koruna
D	[mm]	Diameter of spool without the material
DC	-	Direct current
DMLS	-	Direct Metal Laser Sintering
EG	-	Ethylene glycol
FDM	-	Fused Deposition Modeling
HIPS	-	High-impact polystyrene
IPA	-	Isopropyl alcohol
L_1	[m]	Length of filament on fully wound first layer
L_{25}	[m]	Length of filament on fully wound spool
LOM	-	Laminated Object Manufacturing
L_r	[m]	Distance that has to be reduced
n	[-]	Amount of windings
PC	-	Polycarbonate
PET	-	Polyethylene terephthalate
PETG	-	Polyethylene terephthalate glycol
PJD-3DP	-	Poly-jet 3D printing
PLA	-	Polylactic acid
PVB	-	Polyvinyl butyral
PVC	-	Polyvinyl chloride
PWM	-	Pulse Width Modulation
SLA	-	Stereo-lithography
SLS	-	Selective Laser Sintering
SSS	-	Single screw extruder
Tg	[°C]	Glass transition temperature
TPA	-	Terephthalic acid
UV	-	Ultraviolet
π	[-]	Mathematical constant number (pi) = 3,14159

OVERVIEW

1 Introduction

The first invention connected with the 3D printing was a Stereo-lithography (SLA) machine that was invented by Charles Hull in 1983 [1]. Nowadays 3D printing has become widely used in different fields such as medicine, engineering, designing, and building of houses and wearables [2][3]. Also, for the 3D printing, a wide range of materials can be used, which makes it accessible to everyone. The most popular material is plastic but also it can be ceramics, paper, concrete, food, metals such as stainless steel and high strength steels, aluminum alloys, copper, and titanium. [4]

The company Mubea has suggested to make design improvements for already existing filament extruder which would make the smooth production of the filament with the needed properties. Mubea uses a 3D printers of company called Prusa to get the specimens of parts connected with the automotive production in order to make some proper tests. Own filament production contributes to a more efficient use of plastic materials and a reduction in material costs and will make the process more ecofriendly.

At the start of the research of this task, some problems that exist were announced by the supervisor. The thickness of the material is not stable and compatible for the 3D printers used by the company and the quality of the filament was not satisfactory because it was hard and brittle.

Therefore, the purpose of this bachelor thesis is to research the 3D printing technologies that is widely used nowadays. Materials that is used in 3D printing and can be produced by extruder will be covered. Also, the filament production will be researched, where all the steps that has to be done to get the sufficient properties of the filament will be researched. In addition, extruders of another companies and their differences will be studied.

By analyzing and synthesizing the knowledge gained, the necessary modifications of the filament extruder will be developed in order to make it work properly. The material that will be extruded after the improvements will be tested on thickness stability, plasticity, rolling quality and printing quality to be sure that it can be used by the Mubea company.

2 3D Printing Technologies

3D printing is a type of additive manufacturing that creates solid objects by building up layers of material. The 3D printing process has two steps: [5]

- Design created using a Computer-Aided Design (CAD) system, where happens creating of the object's individual sections. It is accomplished through the compilation of two-dimensional slices that represent the 3D object. This enables the gradual construction of the object, layer by layer, until it is fully formed.
- Coating and Fusing. Material is applied over a surface, and then it is solidified into layers through the application of a source of energy.

The particular source of energy and the raw materials used may vary depending on the specific type of the 3D printing technology. [5]

Many technologies have been developed for layer-by-layer method part creation: [5]

- Stereo-lithography (SLA),
- Fused Deposition Modeling (FDM),
- Laminated Object Manufacturing (LOM),
- Selective Laser Sintering (SLS),
- Direct Metal Laser Sintering (DMLS),
- Poly-Jet 3D printing.

2.1 Stereo-lithography (SLA)

This technology is widely used for rapid prototyping of polymer components, it should have high precision and accuracy. It was first introduced in 1988 by 3D Systems, Inc. based on the innovations of Charles Hull. [5]

The SLA technology, shown in Figure 1, makes use of a reservoir containing a liquid ultraviolet-curable photopolymer resin and an ultraviolet laser to construct an object's layers sequentially. In each layer, the laser beam follows a cross-section of the part's design on the liquid resin's surface. Exposure to the ultraviolet laser light solidifies the traced pattern and connects it to the layer below. After completing a layer, the SLA's elevator platform moves downward by a distance equivalent to the thickness of a single layer, typically ranging from 0,05 mm to 0,15 mm. Subsequently, a blade filled with resin sweeps across the cross-section of the part, applying a fresh layer of material. On this new liquid surface, the pattern for the next layer is traced, joining with the previous layer. This process results in the creation of complete three-dimensional objects. Stereolithography requires the use of support structures, which have the role of attaching the part to the elevator platform and keeping the object afloat in the basin filled with liquid resin. These support structures are manually removed once the object is finished. The properties of the SLA technology are shown in Table 1. [5] [6]

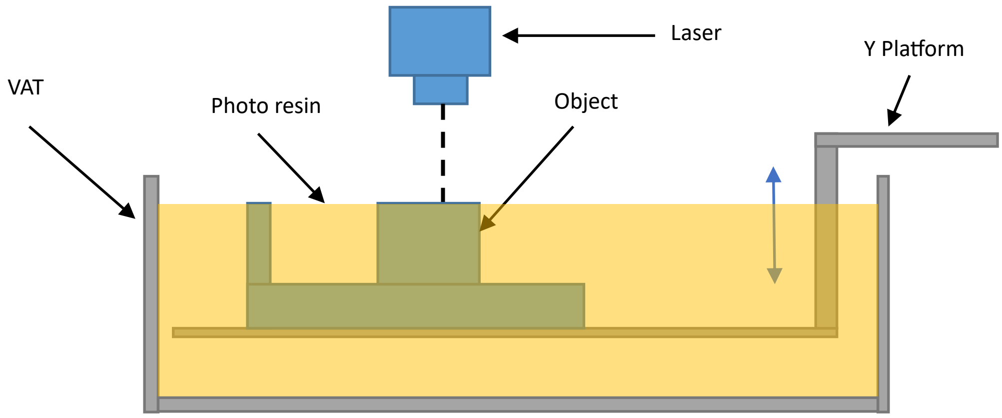

Figure 1: Stereo-lithography Technology Process [6]

Table 1: Properties of SLA [5] (modified)

Material	Principally photo curing polymers which simulate polypropylene, ABS, PBT, rubber; development of ceramic-metal alloys
Min. feature size	0,102 mm
Min. layer thickness	0,025 mm
Tolerance	0,127 mm
Surface finish and build speed	The surface finish is smooth and build speed is average
Applications	Rapid tooling patterns, Snap fits, detailed parts, Presentation models, High heat applications

2.2 Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM), shown in Figure 2, is an Additive Manufacturing process, that constructs objects by depositing material layer-by-layer. This technology is the most popular for commercial use. Initially, it was developed by Scott Crump in the late 1980s. [7]

The core of FDM involves extruding thermoplastic material to form layers. A plastic filament is unwound from a spool, and the extrusion nozzle controls its flow, turning it on and off. A screw drive ensures precise control of the filament's delivery to the nozzle. To melt the material, the nozzle is heated. The extrusion head is versatile and can move in both horizontal and vertical planes under the control of computer-aided manufacturing

(CAM) software. The manipulation of this mechanism is accomplished through numerical control. The final object is created layer by layer, from the bottom up, using stepper motors and an X-Y-Z motion system. The properties of FDM technology are shown in Table 2. [7]

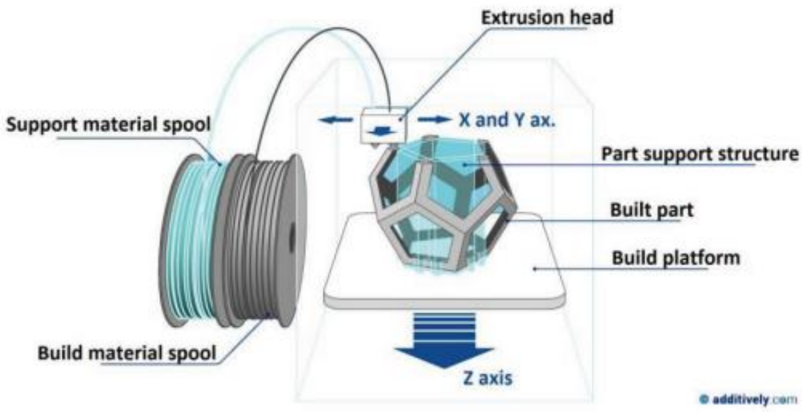

Figure 2: Fused Deposition Modeling Technology Process [7]

Table 2: Properties of FDM [5] (modified)

Material	Thermoplastics such as ABS, Polycarbonate, and Polyphenylsulfone; Elastomers
Min. feature size	0,127 mm
Min. layer thickness	0,127 mm
Tolerance	0,127 mm
Surface finish and build speed	The surface finish is rough and the build speed is slow
Applications	Rapid tooling patterns, Small detailed parts, Presentation models, Patient and food applications, High heat applications

2.3 Laminated Object Manufacturing (LOM)

The Laminated Object Manufacturing process, shown in Figure 3, is used for constructing prototypes using the lamination and laser cutting of various materials, including paper, polymeric films, foils, and metal laminates. The mechanical properties of the materials with the polymeric foils are better than with the paper. These sheets are joined together into solid blocks using methods such as adhesive bonding, clamping, and ultrasonic welding.[8]

The Laminated Object Manufacturing (LOM) system initially was developed in 1991 by Helisys of Torrance, CA. [5]

Each sheet of foil or paper is adhered to the block and forms a new layer using the application of heat and pressure. The material is fed from one side of the machine by a roller and transported to the other side. A heated roller applies the necessary pressure and heat to bond the new layer to the semi-finished prototype part. The working platform is adjusted to the foil's thickness, which typically ranges from 0,07 mm to 0,2 mm. After each layer (foil) is deposited, a laser beam or knife shapes a section of the material into the final product's desired form. The properties of the LOM technology are shown in Table 3. [8]

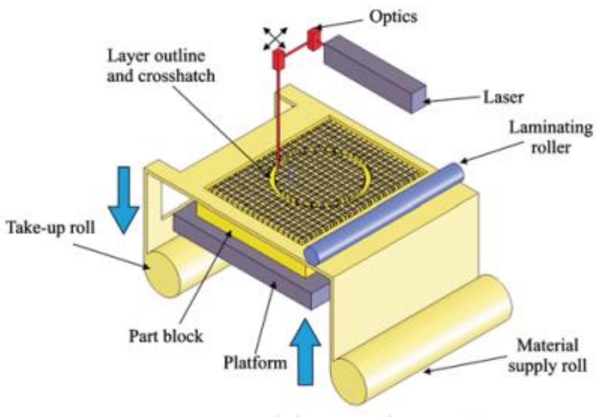

Figure 3: Laminated Object Manufacturing Technology Process [8]

Table 3: Properties of LOM [5] (modified)

Material	Thermoplastics such as PVC; Paper; Composites
Min. feature size	0,203 mm
Min. layer thickness	0,051 mm
Tolerance	0,102 mm
Surface finish and build speed	The surface finish is rough and build speed is fast
Applications	Less detailed parts, Rapid tooling patterns

2.4 Selective Laser Sintering (SLS)

Selective Laser Sintering technology, shown in Figure 4, was developed by Carl Deckard and his team of researchers at the University of Texas in Austin. It was granted a patent in 1989 and was initially sold by DTM Corporation, which was later bought by 3D Systems in 2001.[5]

The printing process starts by lifting the building base to its highest position. Then, a fresh layer of powder is applied, and using a roller is flattened. After that, the laser beam is activated and moves across the powder, sintering it according to the 3D design. This process is repeated for each layer until the printing job is completed. [9]

Once the printing job is finished, the printer needs to cool down for a while. Then, any extra unsintered material is removed using brushing or compressed air, and the finished object is taken out. Sometimes, the final product may need additional adjustments, such as coatings, polishing, or refining the surface to make it stronger and harder, or to improve its size and surface quality. The properties of the SLS technology are shown in Table 4. [9]

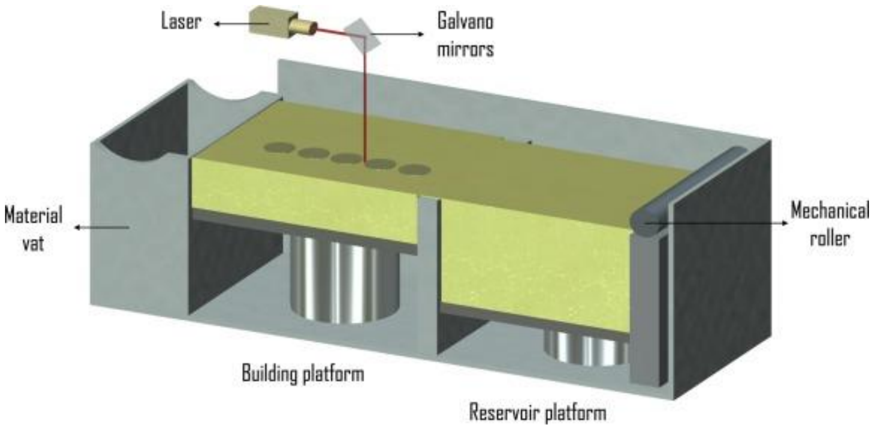

Figure 4: Selective Laser Sintering Technology Process [9]

Table 4: Properties of SLS [5] (modified)

Material	Thermoplastics such as Nylon, Polyamide, and Polystyrene; Elastomers; Composites
Min. feature size	0,127 mm
Min. layer thickness	0,102 mm
Tolerance	0,254 mm
Surface finish and build speed	The surface finish is rough and build speed is fast
Applications	Rapid tooling patterns, Less detailed parts, Parts with snap-fits & living hinges, High heat applications

2.5 Direct Metal Laser Sintering (DMLS)

DMLS, or Direct Metal Laser Sintering, shown in Figure 5, is an advanced 3D printing technology that was developed in collaboration between Rapid Product Innovations (formerly known as Electrolux Rapid Development in Rusko, Finland) and EOS GmbH in Munich, Germany. It's a laser-based 3D printing method that uses 3D design data to create a component layer by layer. [10]

During the process, first, a thin layer of powdered material is applied to the build platform. Then, a high-power laser beam scans over the pattern designed by the user. After each layer, the laser precisely melts the powder in place using a laser scanning optic. At the same time, the build platform continuously lowers, and a re-coater blade spreads the powder on the platform after each scan. DMLS uses liquid-phase sintering to ensure that the metallic particles are effectively bonded together. [10]

One of the benefits of DMLS is its flexibility in terms of materials and shapes. It's able to produce to produce a wider range of shapes, and to form more challenging materials. The properties of the DMLS technology shown in Table 5. [10]

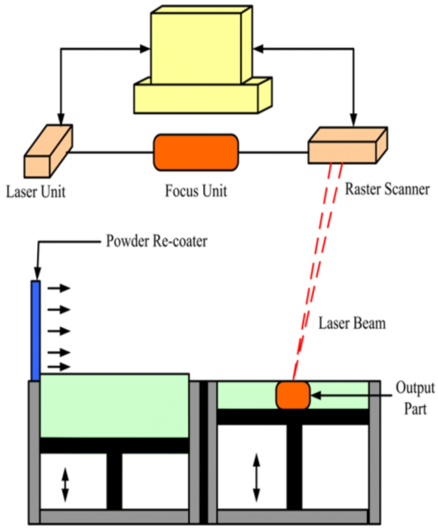

Figure 5: Direct Metal Laser Sintering Manufacturing Process [10]

Table 5: Properties of DMLS [5] (modified)

Material	Ferrous metals such as Steel alloys, Stainless steel, Tool steel; Non-ferrous metals such as Aluminum, Bronze, Cobalt-chrome, Titanium; Ceramics
Min. feature size	0,127 mm
Min. layer thickness	0,025 mm
Tolerance	0,254mm
Surface finish and build speed	The surface finish is rough and build speed is fast
Applications	Rapid tooling, High heat applications, Medical implants, Aerospace parts

2.6 Poly-Jet 3D printing

In the early 2000s, Objet Geometries Ltd., an Israeli company, launched its first machine, which used Poly-Jet technology, shown in Figure 6. This method made possible the creation of complex parts using materials such as photo-curable resins. [5]

In the realm of 3D printing, layers of photopolymer resin are deposited onto a build-tray using inkjet printing. The printing head, equipped with multiple micro jetting heads, dispenses a 16 µm thick layer of resin onto the build tray, matching the object's cross-section's shape. Ultraviolet lamps, attached to the printing carriage, quickly harden the deposited photopolymer droplets. Repeatedly adding and solidifying these resin layers results in a 3D acrylic model with a precision of 16 microns. What's remarkable about the

PJD-3DP process is that it can simultaneously deposit different materials with varying mechanical and optical properties. This technology has applications in various industries, including automotive, electronics, consumer goods, and medical development. Properties of Poly-Jet 3D printing technology shown in Table 6. [6] [11]

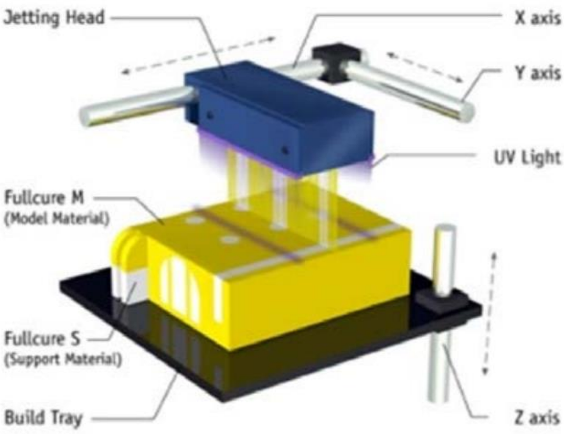

Figure 6: Poly-jet 3D printing Illustration [11]

Table 6: Properties of PJD-3DP [5]

Material	Photopolymer resin
Min. feature size	0,1524 mm
Min. layer thickness	0,01524 mm
Tolerance	0,0254 mm
Surface finish and build speed	The surface finish is smooth and build speed is fast
Applications	Very detailed parts, Rapid tooling patterns, Presentation models, Jewelry, and fine items

3 Materials for 3D printing

Polymers are one of the most popular materials used in 3D printing, they can be broadly classified into two groups: [12]

- thermosets,
- thermoplastics.

Thermoplastics are polymers that can be melted and reformed after they have formed ones. Polymers known as thermosets are unreformable once they have solidified. Due to the fact, that thermosets cannot be remelted they are not covered in this thesis. [12]

Thermoplastics are widely used in the production of the most consumer products as well as many commercial goods today. Engineers can most accurately forecast an experimental product's final performance by using a material that closely resembles the product during development. This explains why thermoplastic 3D printing is so popular. Engineers can create parts using the most widely used thermoplastics by using Fused Deposition Modeling (FDM) equipment. [13]

3.1 PLA

PLA is a promising alternative to petroleum-based plastics as it is biodegradable, compostable, and made from renewable resources like corn starch, sugarcane. Different methods like direct condensation, ring-opening polymerization, and reactive extrusion are used to polymerize PLA based on the desired properties of the final product.[14]

PLA has many benefits like being biodegradable, recyclable and compostable, meaning it has almost no negative environmental impact when disposed of. Another plus is PLA's biocompatibility. This is especially useful for biomedical uses. PLA won't have toxic or cancer-causing effects on the human body. When PLA breaks down, it turns into water and carbon dioxide, not interfering with tissue healing. PLA also has better heat processability compared to other biopolymers. [15]

However, PLA also has some drawbacks. First, it breaks with less than 10% elongation, meaning it is very brittle and has limitations for various uses. PLA has restricted applications for products needing plastic deformation at high stress levels, like screws and fracture fixation plates in medicine. Second, PLA also has a slow degradation rate. PLA's degradation rate depends on its crystallinity, molecular weight and distribution, morphology, water diffusion rate into the polymer, and stereoisomeric structure.[15]

3.2 ABS

ABS is a widely used thermoplast that is composed of acrylonitrile, polystyrene, and butadiene. These two plastics and one rubber are blended in varying amounts to create different types of ABS plastics, each with unique material properties. ABS plastic typically contains around 50 % styrene along with variable quantities of the other two monomers. [16]

ABS is a robust and enduring polymer characterized by good chemical resistance, yet it shows susceptibility to polar solvents. It possesses superior impact properties and a slightly higher heat distortion temperature. ABS offers a broad processing window and can be shaped using most standard machinery, including injection molding, blow molding, and extrusion. This resin falls in between standard resins (PVC, polyethylene, polystyrene) and engineering resins (acrylic, nylon acetal). [17]

ABS plastic offers several benefits, including high durability, toughness, lightweight, chemical resistance, ease of molding and shaping, cost-effectiveness, and recyclability. However, it also has some disadvantages, such as poor heat resistance, susceptibility to sunlight, lack of biodegradability, poor solvent resistance, and susceptibility to scratches. [18]

ABS is the most commonly used filament in 3D printing, particularly in creating strong plastic parts that need to remain resilient in the face of temperature changes. It is used primarily in FDM (fused deposition modeling) 3D printers. ABS is also much more potent and less brittle than PLA. [19] [20]

3.3 PETG

Polyethylene Terephthalate Glycol (PETG) is a commonly used thermoplastic polyester in the packaging industry due to its excellent mechanical properties, clarity, and toughness. PETG is a modified form of Polyethylene Terephthalate (PET) that contains glycol. [21]

PETG possesses several unique characteristics that make it an attractive material for various applications. It is a flexible, durable material with heat resistance. PETG has a glass transition temperature (Tg) of approximately 80 °C, making it suitable for use in heat-resistant goods. [21]

PETG is formed by polycondensation reactions of Cyclohexanedimethanol (CHDM), ethylene glycol (EG), and terephthalic acid (TPA). The resulting PETG can be further utilized in processes such as injection molding, pressure molding, 3D printing, and thermoforming to produce the desired PETG product. With its favorable thermal properties, PETG is readily moldable and maintains transparency within its operational temperature range of -70 to 70 °C. [21]

PETG is being used in a variety of applications, such as medical and pharmaceutical, machine guards, packaging, retail stands and displays, food and drink containers and 3D printing. [22]

3.4 ASA

ASA (Acrylonitrile Styrene Acrylate) is a thermoplastic that is gaining popularity among users of FDM 3D printers. It is classified as a "terpolymer," which means that it is made up of three distinct monomers. Luran® S, originally introduced by BASF in 1970, is called ASA. [23]

ASA is ideal for outdoor applications due to its exceptional weather resistance and UV stability. It is also chemically resistant and has good mechanical properties, comparable to ABS but more weather-resistant. [24]

ASA is compatible with most FDM 3D printers and can be produced at temperature is around 220 - 250°C. The ideal bed temperature is 90 – 110 °C. However, it is more susceptible to warping than other materials, so a heated bed is recommended. [23] [24]

3.5 PC

Polycarbonate (PC) is a widely used thermoplastic material in 3D printing due to its excellent strength and thermal resistance. Its properties make it ideal for applications that require parts to withstand harsh environments and technical use. [25]

However, due to its high glass transition temperature, which is around 150 °C, PC filament is notoriously difficult to print. It requires high extrusion and tray temperatures, making it challenging to work with. [25]

At room temperature, PC filament is flexible and bendable, allowing it to withstand high tensile stresses that would otherwise cause for example ABS to break or shatter. Additionally, it is more durable than other filaments like ABS or PLA and can withstand typical wear and tear over time. [25]

To enhance its strength and other properties, polycarbonate filaments are usually reinforced with carbon fibers or glass fibers. Additionally, 3D printed items made from polycarbonate are transparent. [25]

PC filament is used in a wide range of applications, including safety equipment, electrical and electronic components, aerospace, electronic display panels, and sporting goods. It is a popular choice in 3D printing for producing robust and sturdy plastic objects with a high melting point. [26]

3.6 PVB

Polyvinyl butyral (PVB) is a unique thermoplastic material that finds its use in 3D printing filaments. It has a natural translucency that makes it an attractive option for constructing see-through objects. However, PVB is not as extensively used for robust components in 3D printing as other plastics like ABS and PLA. Despite this, it is an easily printable material owing to its low melting temperature and is suitable for generating display pieces. [27] [28]

Although, PVB has low warping, it is not temperature-resistant, and its layer adhesion is claimed to be somewhat poorer than that of PLA, rendering it unsuitable for use in mechanically stressed applications. PVB is soluble in isopropyl alcohol (IPA), and its key characteristics are that it can be easily joined with other PVB components and that it can be smoothed. However, PVB's very hygroscopic nature means that it absorbs moisture from the air. [28] [29]

PVB is a perfect choice when printing vases and lamp shades. It is also utilized in the production of display models and transparent parts. [28] [30]

3.7 Comparison of the filaments

For a clear comparison, all the mentioned materials in this chapter are summarised in Table 7. In the first column, the names of the materials can be found, the second and third columns contain general recommendations for printer temperature settings, and the fourth column compares the strength of a material.

Table 7: Summary of properties of plastics mentioned in chapter

Material	Printing Temperature [°C]	Bed Temperature [°C]	Strength [-]
PLA	190-220	20-60	Medium
ABS	220-250	80-110	High
PETG	220-250	70-90	High
ASA	230-250	80-100	High
PC	260-310	80-120	Very High
PVB	200-220	20-60	Medium

4 Filament production

4.1 Influence of the production process on the material

As was mentioned in previous chapters, thermoplastic is a type of plastic polymer that has the ability to form and shape when heated and solidifies when cooled.

In terms of composition, a polymer is a term derived from "poly" meaning "many". It is composed of numerous molecules known as monomers, with "mono" signifying "one." These monomers are capable of forming extensive chains through a procedure termed as "polymerization", shown in Figure 7. This chaining of monomers endows polymers with distinct properties like flexibility or stiffness. [31]

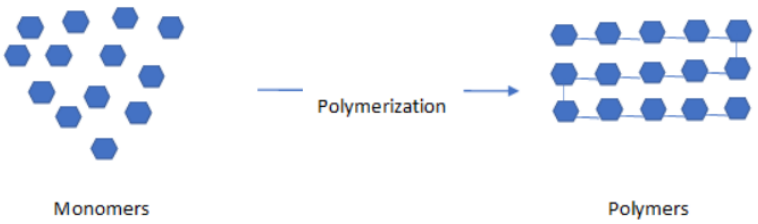

Figure 7: Polymerization [31]

Copolymer, shown in Figure 8, is a material that is composed of various types of monomers bonded together. These copolymers can exhibit different mechanical properties by changing of the type of monomers, making them suitable for certain applications and uses. [31] [32]

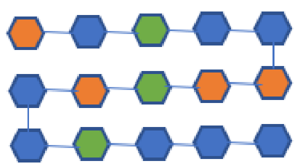

Figure 8: Copolymers [31]

4.2 Filament production process

The filament production process is basically a transformation of plastic resin into slender threads suitable for 3D printing. This production process encompasses various stages, shown in Figure 9, including blending, drying, extruding, cooling, and winding onto spools. [32]

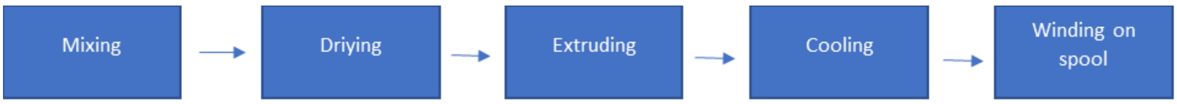

Figure 9: Process of filament production [31] (modified)

All these steps are crucial to get material for 3D printing: [32]

- Mixing: The initial phase involves mixing of the plastic resin pellets with supplementary materials like colorants, impact modifiers, or fillers. These additional components making the filament with distinct features, including color, durability. To guarantee an even dispersal of the additives within the resin, this blending process is carried out using a special blender.
- Drying: The resin with additive mixture undergoes a drying process, which forms the second step. This process goes approximately for two hours and occurs at temperatures ranging from 60 °C to 80 °C. The importance of this step is in the elimination of any moisture present in the mixture and preventing popping and jamming issues during the subsequent extrusion and printing stages.
- Extrusion: Is the third step, in which the blend is transformed into a filament through the use of a single screw extruder (SSS). This machine is responsible for heating and melting the blend before drawing it out through a set-sized die. The filament's diameter, which has to be 1,75 mm or 2,85 mm by standards, is determined by the speed of its extraction. The extruder also maintains the mixture's temperature and pressure to produce a uniform and sleek filament. Subsequently, the filament's tolerance and roundness are verified using for example a laser diameter gauge.
- Cooling: The fourth stage involves cooling down the filament's temperature to stave off distortion and crystallization. This is achieved by first passing the filament through a tank of warm water and subsequently a tank of cold water. The warm water tank mildly reduces the filament's heat while shaping it into a round form. The cold water tank then cools the filament until it reaches room temperature. It's crucial to pay attention to the cooling process to prevent the filament from forming into an oval or irregular shape.
- Winding: The filament's last stage involves spooling, which is carried out on a reel or a spool refill. The process entails winding the filament around a spool at a consistent pace and tension. It's crucial to maintain uniformity during spooling to prevent tangling and filament breakage. After spooling, the filament is vacuum sealed within a plastic bag for protection against humidity and dust.

4.3 Thickness of the filament

Initially, the 3D printing industry favored the 3 mm filament. However, over time, the preference shifted towards the 1,75mm filament due to several benefits. [33] [34]

Filament of 3 mm diameter, while more robust, was prone to breakage under strain, such as when moving along the curved path in a 3D printer towards the extruder's hot end. This issue became particularly noticeable towards the end of a spool when the filament's natural curvature was at its peak, often causing additional friction along the filament path and resulting in printing problems. [33]

On the other hand, the 1,75 mm filament, with its increased flexibility, is more suited for spooling and maneuvering through curved tubes towards the extrusion and heating point. The 1,75 mm filament is also known for producing prints of higher quality, characterized by their smoothness, glossiness, and intricate detail, whereas prints produced with 3 mm filament may appear less detailed, rougher, and potentially more susceptible to warping. [33]

Therefore, the extruder that has to be modified will also require filament of 1,75 mm diameter with a tolerance of ±0,02 mm.

5 Analysis of existing filament extruders

5.1 Filament extruder

In the procedure of plastic extrusion, wherein the plastic is melted and shaped into a continuous profile. The ram extruder, depicted in Figure 10, serves as the most straightforward example to comprehend this process. The piston is subjected to pressure, leading to the ejection of the extrudate from the die. The material's viscosity decreases as heat is applied to the barrel, subsequently melting the material. Provided the heat and ram movement pressure are correctly calibrated, the polymer is expelled from the die in the desired form. [35]

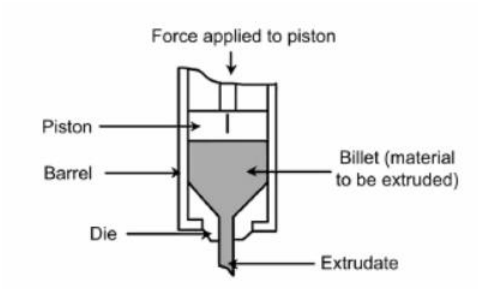

Figure 10: Ram Extruder Scheme [35]

These years one of the most popular extruders for filament production became screw ones. According to the number of screws, they can be divided into 3 main types: [36]

- single screw extruder,
- twin screw extruder,
- three screw extruder.

Each type of extruder has its pros and cons, and they are used in different fields with different applications. For instance, a twin screw extruder, shown in Figure 11, has much better stability and mixing properties than single screw one, but three screw extruder, shown in Figure 12, has improved the "mastification effect", it means that it has the best

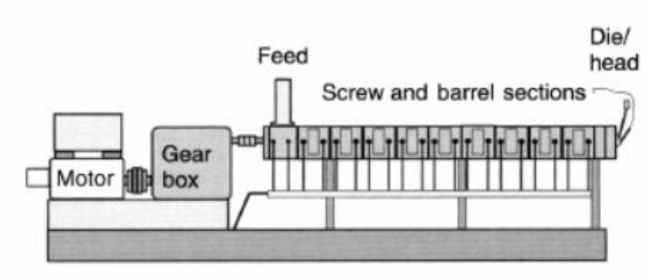

Figure 12: Twin-Screw extruder Scheme [35]

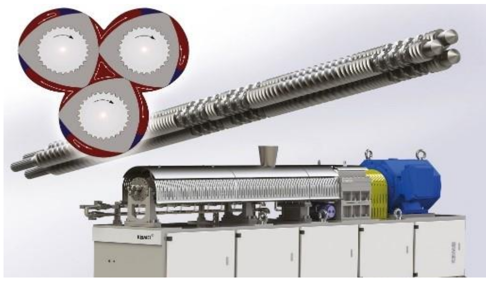

Figure 11: Three screw extruder scheme [59]

mixing and breaking down properties of raw materials to create a filament, but it is the most expensive to produce. [37] [38]

5.1.1 Extruder components

In this chapter, the single screw extruder, shown in Figure 13, will be more discussed, because it is the most popular and it is a type of extruder that has to be modified during this work.

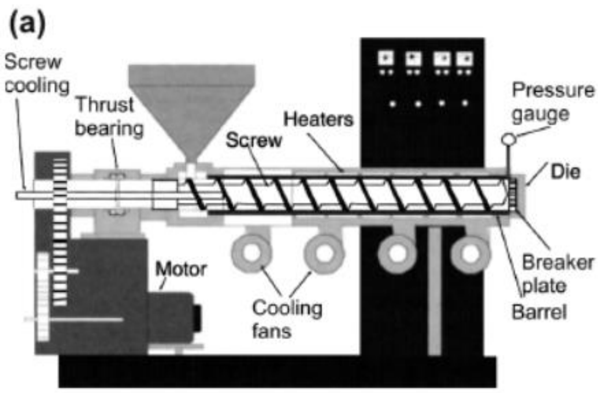

Figure 13: Single screw extruder scheme [35]

A single screw extruder has five major equipment parts: [39]

- drive system,
- feed system,
- screw, barrel, and heaters system,
- head and die assembly,
- control system.

The drive system comprises the motor, gear box, bull gear, and thrust-bearing assembly. There are also direct drive systems that do not need a gear box. [35]

The feed system is the feed hopper, feed throat, and screw feed section. The screw, barrel, and heating systems are where solid resin is conveyed forward, melted, mixed, and pumped to the die. The extrudate is transported through the adapter and shaped in the die. [35]

Finally, the control system controls extrusion process conditions such as motor revolutions per minute and barrel temperatures. It can also monitor other process conditions such as melt temperatures and pressures. Computer-based controls not only run and monitor the extruder but they can also control the entire extrusion process with feedback loops that automatically change feeder settings, puller speeds, screw speeds, etc. to maintain product quality. [35]

5.1.2 Feeding Polymer systems

Extruders rely significantly on their feeding systems, as these components play essential role in determining the quality of the material produced after extrusion. The feeding system's influence extends beyond controlling the output of the extruder; it also impacts the stability of the process and the condition of the melt. The feed rate, which affects the fill degree in the remaining part of the screw, has impact on both the temperature and uniformity of the melt, given a particular screw design. [40]

There are for main types of the feeding systems: [35]

- flood feed,
- starve feed,
- crammer,
- melt feed.

In the process of flood feeding, shown in Figure 14, the screw consumes the maximum amount of material it can manage, resulting in the lower portion of the hopper being completely filled with the material. On the other hand, during starve feeding, shown in Figure 15, the material is carefully pushed into the machine using a feeder, which results in the bottom section of the hopper not being entirely filled with the material. [41]

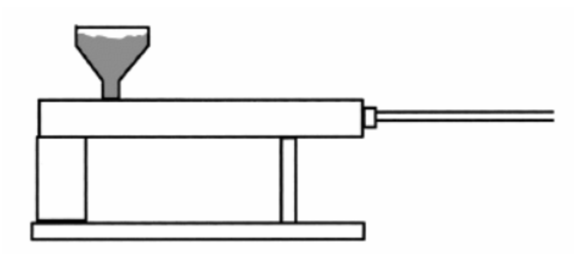

Figure 14: Flood feeding [35]

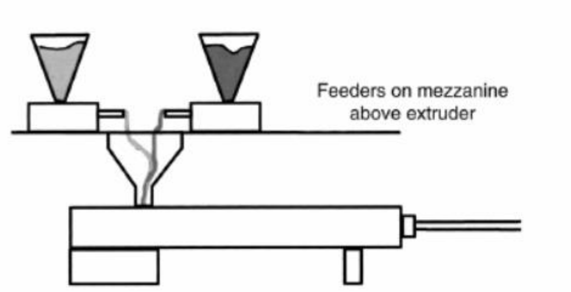

Figure 15: Starve feeding [35]

The process of starve fed extrusion boasts multiple benefits when compared to flood fed extrusion. It offers lesser pressure build-up along the screw, reduced chances of agglomeration and potentially enhanced mixing action. Furthermore, the melting process is expedited as the pellets aren't compacted into a solid, dense bed, allowing polymer granules to maintain their distinctness as they melt. [41]

A significant feature of starve fed extrusion is the flexibility it offers in controlling the screw speed and output. One can alter the screw speed while maintaining constant output or vice versa, providing a higher level of process control. This makes it suitable for more complicated operations, despite its drawbacks. [41]

It's important to note that while using starve fed extrusion, the throughput of the extruder is lower than its capacity. Additionally, the process is more complex as it requires an external device to feed the material into the machine. However, these challenges are often outweighed by the advantages it brings to more demanding operations. [41]

The feeding method known as crammer feeding, depicted in Figure 16, is a positive feed system that is particularly effective for materials with low bulk density, those prone to bridging, and other challenging-to-feed substances. The feed system operates by using a screw mechanism in the crammer to actively transport material to the extruder. [35]

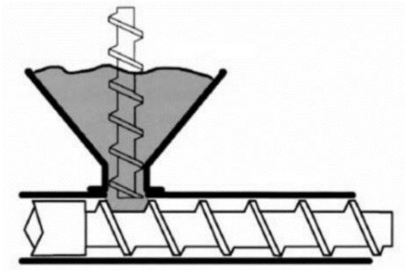

Figure 16: Crammer [35]

This approach significantly enhances the extruder's throughput rates by forcing extra material into it. However, initial stages require careful attention to avoid overfilling the extruder to the point where it cannot melt the polymer, which can result in unmelted resin being thrust into the metering section. Overfeeding in severe cases can lead to the extruder screw breaking. While this positive feed system is an excellent way to boost throughput rates, it's essential to exercise caution during the initial stages to mitigate potential issues associated with overfeeding. [35]

5.2 Comparison of existing machines

When undertaking the task of creating filament, it's crucial to weigh certain elements while evaluating diverse product types. One essential feature of a filament extruder is its filament production speed. Naturally, the more rapidly an extruder can generate a coil of filament, the more advantageous it is. Typically, the standard speed of a filament extruder can be found in the machine's description, although it can fluctuate based on the quality required and the filament material being processed.

Equally significant is the compatibility with various materials. It's not a given that every filament extruder can work with all kinds of materials. The materials that can be used are determined by the machine's maximum heating temperature, but other factors such as cooling capabilities can also influence this. Fortunately, most filament extruders are capable of dealing with ABS and PLA pellets, which is beneficial since these are two of the most commonly used filament materials.

Another crucial thing about the properties of the extruders is the thickness of the material that they can produce. The closer the tolerance of the diameter to standard which it ±0,05 mm the better the machine.

5.2.1 FelFil Evo

The Felfil Evo filament extruder, shown in Figure 17, is available in both a pre-assembled model and a kit version. Despite its extrusion rate of 100-150 grams per hour not being the fastest in the market, but it is reasonable for its price point of 900 euros. This rate allows production of slightly over two 1-kilogram spools in a day. [42]

Figure 17: FelFil Evo [42]

Felfil asserts that their extruder produces filament with a tolerance of ±0,07 mm. Although this might not initially seem impressive, it provides the perfect tolerance for most 3D printers, given the extrusion settings are correctly adjusted. [42]

It's noteworthy that the Felfil Evo kit is available in both 1,75 mm and 2,85 mm filament versions, accommodating different printer requirements. However, the Evo's maximum heating temperature is capped at 250 °C, sufficient for producing PLA, ABS filaments. Unfortunately, it is not enough for PETG production which necessitates slightly higher heat. [42]

For the completing of the filament production process with this extruder also needed a hopper and spooling device as additionally bought devices. [42]

5.2.2 Noztek Pro Desktop Extruder

Noztek, a company specializing in 3D printing filament production, offers the Pro Desktop extruder, shown in Figure 18. This impressive machine not only costs less than many other fully assembled alternatives, but it also boasts a quick setup time, allowing to start extruding filament in 15 minutes. [43]

Figure 18: Noztek Pro Desktop Extruder [43]

The Pro Desktop extruder's base model from Noztek can reach a peak temperature of 300 °C. This feature enables the production of various plastics such as ABS, PLA, and PET. The extrusion speed of Noztek pro is 1 kilogram of filament per 2 hours and this this company gives the option to upgrade machine with Noztek's extended vertical hopper and filament winder. This enhancement allows for greater pellet storage and facilitates the spooling of the filament as it is produced. [43]

One standout feature of the Noztek Pro is its precision. It can maintain a diameter tolerance of just ±0,04 mm - a level of accuracy that surpasses many filaments produced by pricier professional machines. Additionally, with Noztek's interchangeable output nozzles, both 1,75 mm and 2,85 mm diameters can be produced.[43]

5.2.3 3devo precision

3devo is a company that specializes in creating filament extruders and shredders. The Precision 350, their device, has a maximum temperature of 350 °C, allowing for the production of various filaments such as PLA, ABS, PET, PETG, and more. What sets the Precision 350 apart is its four heating zones, which provide a more precise and controllable plastic melting process. [44]

Figure 19: 3devo precision [44]

Additionally, the device features a well-designed cooling system with two fans on either side of the filament line, ensuring accurate filament production. Unfortunately, the company's website does not provide information regarding the speed rate of filament extrusion and the diameter of the filament that can be extruded. [44]

5.2.4 ReDeTec ProtoCycler+

ReDeTec is yet another popular manufacturer of filament extruder products, and the ProtoCycler+, shown in Figure 20, is their flagship product.

ProtoCylcer+ is an advanced filament extruder system that includes all the parts, such as extruder screw and heater, spooling but also it can take a failed print and turn it into printable filament because it has its own built-in shredder. This mechanism turns large metal grinders to mash up plastic parts and turn them into pellets that can moved through the filament extruder system.

The extruder is fully assembled and has some great features. First off, it can produce filament with a diameter tolerance of ±0,05 mm, the same as most consumer printing filaments.

ReDeTec states that the ProtoCycler+ can make PLA, ABS, PETG, HIPS, nylon, and over 10 other materials using the company's patented MixFlow technology. However, this extruder can only reach 250 °C, which means that the high-temperature materials can be extruded but on a very small speed.

But the impressive speed of 1 kilogram every 2 hours and the spectacular diameter precision of ±0,05 mm certainly make up for it because this means you can make high-quality filament very fast. [45]

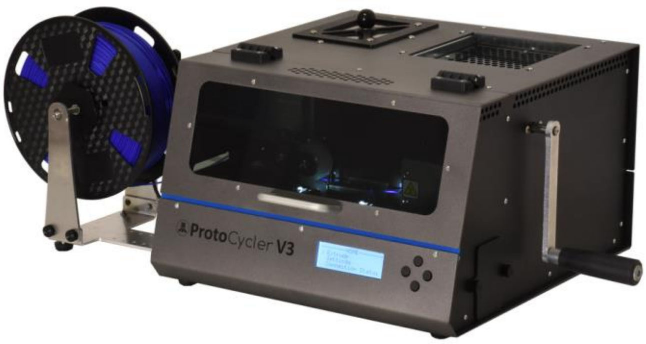

Figure 20: ProtoCycler+ [45]

5.3 Overview of extruder to be modified

The extruder which has to be modified, shown in Figure 21, pertains to single screw extruders that was created by one of the employes of Mubea Company, that specializes in the development and production of components for various sectors of the automotive industry such as engine belt tensioners, stabilizer clips, headrests, seats, springs, carbon components etc. The Prague branch of the Mubea uses two original Prusa MKS3+ 3D printers for various purposes, such as production of parts for better visualization of design tasks, as well as parts for testing and production. The extruder had to cover the consumption of both printers if they were to be operated continuously. Since one printer consumes 10 grams of plastic per hour, the daily plastic consumption was 480 grams per day. [46]

Figure 21: Our filament extruder [46]

It was concluded that machine is working and can process materials up to 300 °C so it could be materials such as ABS, PLA, and PET and more, which gives a good opportunity to use varied materials for different needs. The speed of filament extruding is 800 grams per hour. [46]

6 Modifications for the extruder

An assignment that has been received from Mubea is to finalize the fully automated process of production of plastic for 3D printing. The extruder for this assignment is already exists and functions but to get the full process of filament creation some tasks must be fulfilled:

- the diameter of the material has to be 1,75 mm with a tolerance of ±0,05 mm,
- the elasticity of the filament has to be improved,
- the whole process of filament creation has to be automated,
- the finished material has to be rolled evenly on the spool.

To accomplish these tasks some additional machines have to be created:

- cooling machines,
- thickness calibration machine,
- spooling mechanism.

Figure 22 below shows the complete process and the arrangement of the additional machines that improve the plastic filament production process. The order of all machines was made especially for the existing extruder. First, after the extruder a cooling part is placed where the quality of the material should be reached. The second part is the calibration of the thickness, where the pulling mechanism and thickness checking mechanism are placed. The last part is rolling, where the rolling mechanism is placed by which the even winding should be reached.

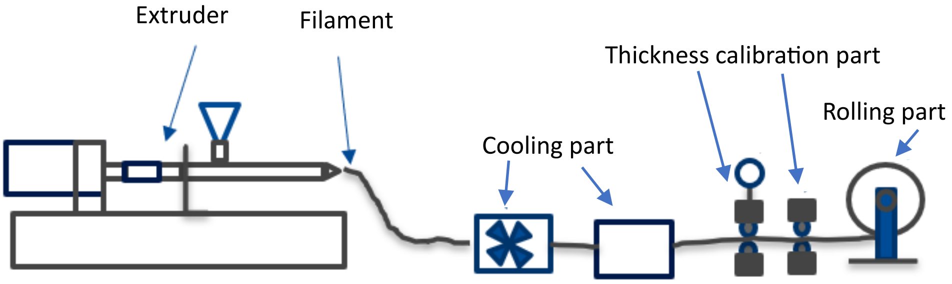

Figure 22: Process of filament production

For this work, a free two-tier table was given, so enough space to place all the machines after the extruder. In addition, the task to create these machines for not more than 10000 CZK was given. To achieve this task models for all the machines will be printed on 3D printers of the company called Prusa, which are placed in the Mubea office.

7 Cooling system

Cooling of the material has to be placed after the extruder because during this process, material that is pulled from the extruder has to be hardened and a round shape cross-section should be reached [32]. For this task, two ways to cool the plastic were prepared:

- the fully air-cooling,
- the combined cooling.

The fully air-cooling method supposes two propellers located after the extruder on both sides of the plastic filament as shown in Figure 23.

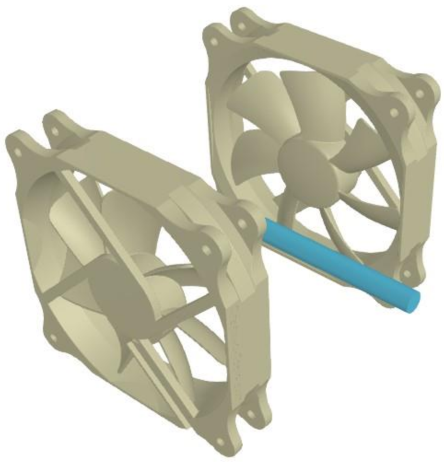

Figure 23: The fully air-cooling method

The combined cooling method shown in Figure 24 means that the plastic first pre-cooled by air stream and then passed through the water cooling.

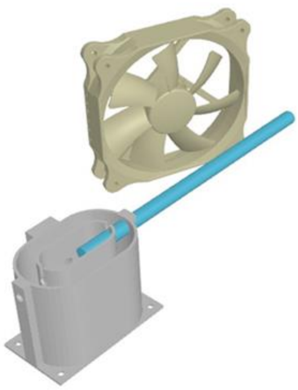

Figure 24: The combined cooling

During the initial testing of the extruder, without the modifications, the problems with the flow of the material from the nozzle was detected. The material that passed through the nozzle of the extruder was falling and stretching due to its weight and low pressure inside of the extruder, because regardless of the set temperature of the extruder when it was set to the lowest melting temperature of PLA plastic, which is 170 ˚C, It was still impossible to move the material even to the cooling part. So, the material first had to be a bit hardened after it comes off from the nozzle of the extruder to move it further. That is why, as a final solution, combined cooling was used. [46]

7.1 Pre-Cooling

For the pre-cooling, the propeller was used. It was placed near the nozzle of the extruder to start the hardening of the material after it was extruded and to make it possible to push the filament further to the final cooling in the bathtub. To get the direct stream on the filament used an addition, shown in Figure 25 that was found in the Mubea office.

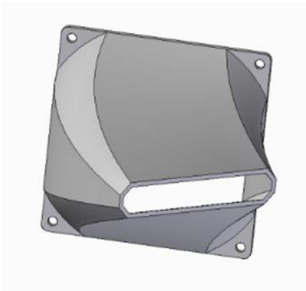

Figure 25: Direct stream addition

7.2 Finishing cooling

The finishing cooling has been done by the water-cooling in the bathtub, shown in Figure 26, where the water is circulating from one vessel to another to keep the room temperature of the water, that is necessary for final cooling of the filament. Cooling of the plastic during molding by water was chosen because it can remove heat more effectively than air cooling. Furthermore, it can prevent warping of the plastic filament. [47]

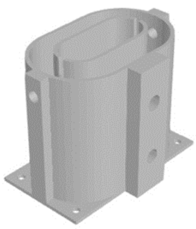

Figure 26: Bathtub for water-cooling

7.2.1 Equipment for the cooling part

The water pump, as shown in Figure 27, has been purchased to transfer water from one vessel to another. Due to the fact that bathtub is small the only two needs had to be fulfilled:

- it has to be a surface water pump,
- it has to be suitable for the extruders power supply, which is 12 V.

Figure 27: Water pump.

This pump can be powered by a DC power supply of 12 V and has a flow rate of 2 liters per minute. It is versatile and can be used for various applications such as irrigation, fountains, aquariums, and cooling systems. The power supply of the extruder is used to power this pump. [48]

7.2.2 Regulator

To regulate the speed of circulation of water in the bathtub, a regulator for DC motors, shown in Figure 28, was purchased. This decision was made because due to the fact that for higher temperature materials the speed of the extrusion will have to be reduced and more power for extrusion will be needed, during such situation the high speed of circulation of water in the bathtub will not be needed, furthermore, there is no need to use the power of the extruder. The additional advantage of this regulator is that it can function with voltage ranging from 12 to 36 V and can handle a continuous current of up to 3 A, so it can be used with the power supply of the extruder, which is 12 V and 3 A. Such controllers are commonly used to adjust the speed of DC motors or to alter the brightness of power diodes.[49]

Figure 28: PWM Regulator of DC motors

8 Thickness calibration

The thickness calibration process involves a pulling mechanism and a thickness measuring device. The pulling mechanism must operate smoothly to maintain a stable material thickness of 1,75 mm with a tolerance of ±0,05 mm. It is responsible for pulling the material from the extruder nozzle through the cooling system and the thickness measuring device, all the way to the rolling part. The thickness measuring device should be able to measure the diameter of the filament in real time.

8.1 Pulling mechanism

To ensure correct operation of the pulling mechanism, certain properties must be achieved:

- smooth and stable rotation,
- adjustable distance between the rollers,
- friction between the rollers and the filament.

A suitable stepper motor has already been purchased by Mubea for this mechanism, and the decision was made to use it due to its ability to provide smooth movement. The pulling mechanism, shown of Figure 29, was designed to use this motor. This mechanism has two 26 mm rollers that are covered with rubber, which thickness is 4 mm. The distance between the rubber-covered rollers is 1,5 mm, that is less than the standard material diameter – 1,75 mm. This decission was made because the friction coefficient of rubber and plastic is 0,19, which is quiet small, means that additional forces has to be applied to increase the friction. By the normal forces during moving of the material through the pulling mechanism the friction is increased. The thickness calibration machine is placed after the cooling part, where the material is already formed and hardened. Therefore, the shape and the thickness of the material will not be affected by this mechanism.

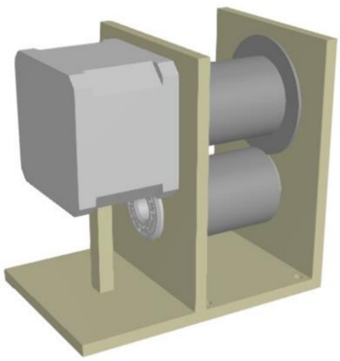

Figure 29: Pulling mechanism

8.1.1 Equipment for the thickness calibration

Mubea has provided the Nema 17 stepper motor, which is shown in Figure 30. Unlike traditional DC motors, this stepper motor can ensure a smoother rotation to maintain the stability of filament thickness. The specifications of this stepper motor are: [50]

- Step angle: 1,8° for 200 steps,
- Holding torque: 42 N · cm,
- Nominal current: 1,6 A,
- Nominal voltage: 2,5-3 V.

Nema 17 is a motor that is widely used in 3D printers, CNC machines, robotics, and laser cutters. [51]

Figure 30: Nema 17 - stepper motor [50]

In order to control the stepper motor, a stepper motor driver called A4988, as shown in Figure 31, was purchased. This driver was used because the maximum amount of microsteps that it can handle is 1/16, which is the same as what is commonly used in 3D printers.[52]

Figure 31: A4988 - stepper motor driver [52]

The reason that this driver making the motor smoother is that stepper motor by standard has 200 steps per revolution, but because of this drive each step of stepper motor will can be converted to 16 microsleeps which mean that the motor will have 3200 steps per one revolution, which means that it will become smoother but the rotational speed will be lost. The device requires two power supplies, one for the stepper motor ranging between 8 – 35 V and another for the driver electronics 3 – 5,5 V. [52]

To operate the A4988 driver, an Arduino UNO was used and connected according to the scheme shown in Figure 32. The driver was powered by the 5 V output of the Arduino, while the motor was powered by a separate 12 V and 5 A power supply to achieve a higher torque.

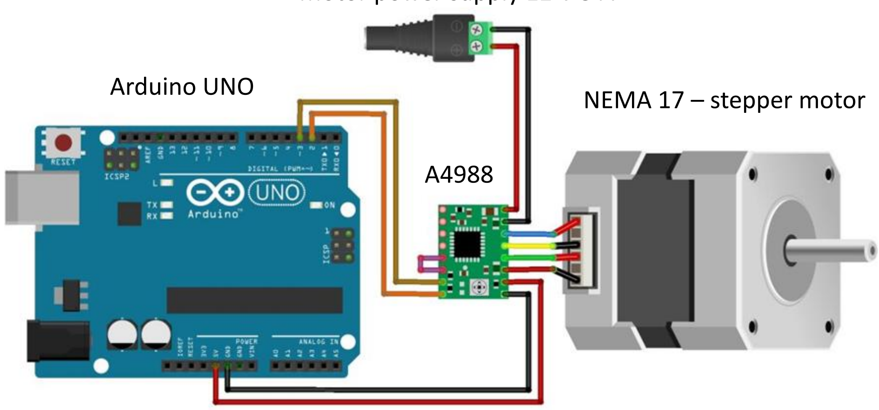

Figure 32: Electric Scheme of motor controlling

8.2 Thickness calibration

To automate the calibration of plastic thickness the thickness measuring mechanism, shown in Figure 33, was made. It has to be placed between the cooling part and thickness calibration machine.

Figure 33: Thickness measuring machine

The idea of this mechanism is that filament that is already hardened after cooling part pulled through this mechanism by force applied by the thickness calibration machine. This mechanism measures the thickness of the plastic in real-time as it passes through the two bearings by using a digital gauge.

A digital thickness gauge, shown in Figure 34, was used for this mechanism, which had already been purchased by Mubea. It has a tolerance of ±0,01 mm. The material requirement had a tolerance of ±0,05 mm, so by the “Rule of ten” the measuring device tolerance should be at least ±0,005 mm. Digital thickness gauges with the accuracy 0,005 mm and resolution 0,001 mm could be used for this machine. However, since the device was already purchased, it was used for this machine. [57]

Figure 34: Digital thickness gauge

9 Rolling machine

The primary function of the rolling machine is to wind filament evenly onto the spool. It must work using only one motor, while transmitting movement in two directions. Proper guidance of the material is required to obtain even spooling.

The first solution, that was found, is used by the filament producing industries. They use the screwed shaft which is connected to the motor and making a constant movement of the guiding. With each roll of filament the position of the guiding is changing on the distance of the filament diameter along the length of the spool. The disadvantage of this idea is that 2 motors will be needed, the first one for the spool and another for the guiding. Also, to make the movement of the guiding two-sided the motor movement has to be programmed, which makes this mechanism complicated.

The second solution, shown in Figure 35, was the rolling machine that can work from one motor, and could be printed on 3D printer, was found on Prusa forum. [53] The way this machine works is that motor rotates the pinion and transfers the rotation on the shaft that is connected to the worm transmission, which moves the guiding, and on the pulley. The inventor made a video, where shown that this machine works properly. [54] In addition, since almost all parts of this machine could be printed on a 3D printer, this made this machine quite cheap and suitable for the set task.

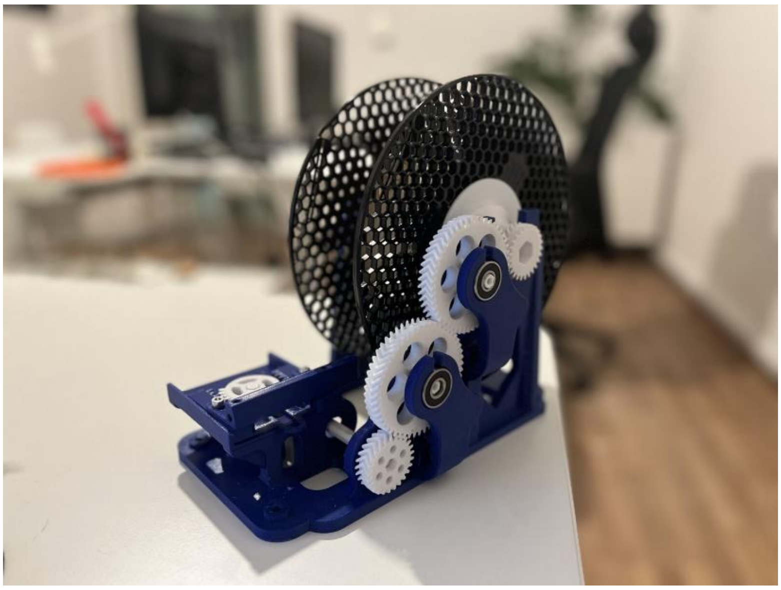

Figure 35: Rolling machine

9.1. Spool moving gearbox

A simple transmission, as shown in Figure 36, was used to move the spool. The transmission transfers the torque of the motor to the spool using four herringbone gears which reduce the axial forces from the bearings. These gears are known for their ability to handle powerful transmissions. In the case of the rolling machine, these gears are ideal because the material being spooled needs to be under tension to ensure an even winding. [55]

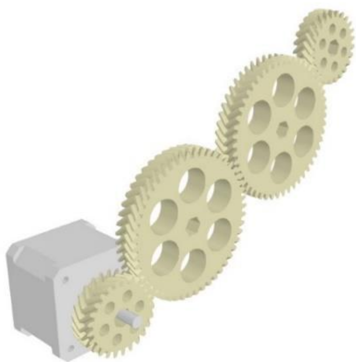

Figure 36: Spool gearbox

9.2 Guiding table gearbox

To achieve smooth movement and to change the direction of rotational motion of the gearbox on 90°, a worm transmission was used. This type of transmission is typically used with high rotational motors to reduce the speed of rotation and to increase the torque. Figure 37 shows the worm transmission that was used. [56]

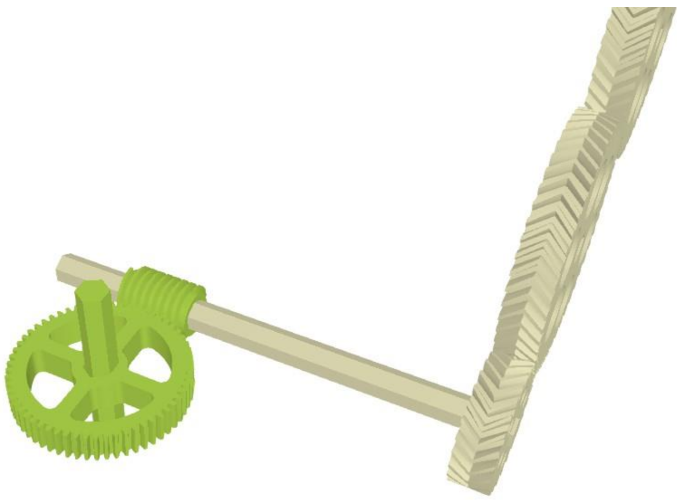

Figure 37: Worm transmission

In order to achieve the two-sided movement required for guiding of the filament, a rack and pinion drive system was used, shown in Figure 38. These types of transmissions are commonly used in linear drive mechanisms. For the filament guiding application, a half-toothed pinion was used to enable the two-sided movement. [57]

Figure 38: Filament guiding transmission

To get this machine working the same equipment as for thickness calibration machine was used, such as NEMA 17 stepper motor, driver A4988, Arduino UNO and two additional power supplies 5 V and 2 A for Arduino and for motor 12 V and 5 A power supply.

10 Problems occurred and final placement

After the rolling machine and the thickness calibration machine was assembled and placed in correct order, the problem between these machines was figured out. In order to get continuous and even winding of the rolling machine, the speed of the rolling of the filament and speed of the feeding filament from the thickness calibration machine has to be equal. If at the start of rolling of the material these speeds will be the same, then with each layer the diameter of the spool will increase, which will cause an increase of the speed of material rolling and increase of the tensile force between the machines and may cause the changings in the thickness of the filament. So, the possible solutions for this case can be:

- to reduce the speed of the rolling,
- to change the distance between the machines.

The first idea for this problem was to decrease the speed of the rotation of the spool with each layer of the filament. Since the maximal diameter of spool filled by the filament is 177 mm which makes 23 layers of 1,75 mm filament diameter, the rolling speed will have to be changed 23 times, which makes the process of the filament creation more complicated, because operator would be needed.

Next Idea to reduce the speed of rolling was to create an additional rolling mechanism, shown in Figure 39. This mechanism has two shafts of small diameter, that are powered by one motor and connected by the belt. The spool is just laying on these two rotational shafts and rotating due to the friction force. This machine is supposed to do the winding process, in case if tension between the thickness calibration machine and spool is increasing and tensional force become bigger than frictional force which will mean sliding of the spool on these two shafts. The disadvantage of this mechanism is that the winding of it will be rough and ugly, because it won't be under the control, and that means that there will be needed one more process of respooling of the material from one to another spool.

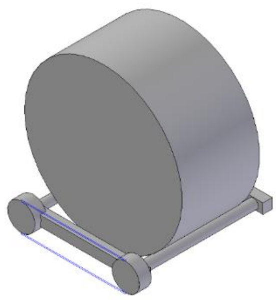

Figure 39: Laying rolling machine

The next possible solution was to increase the distance between the rolling machine and thickness measuring machine to reduce the tensional force. Before deciding how this task can be solved the calculation of the distance that will have to be reduced has to be done. To solve this problem, it is known that if the winding on the spool is even the final length of the filament is approximately 340,25 m, as it was calculated in Table 9 in Appendix A. The length of the filament of fully wound first layer can be calculated by formula (1).

$$L_1 = \pi \cdot D \cdot n \div 1000 \quad (1)$$

Where: L_1 [m] is a length of filament of fully wound first layer,
D [mm] is a diameter of spool without the winding,
n [-] the maximum number of windings on the width of spool.

The diameter of spool without the material is 100 mm, the width of the spool is 60 mm which means that there can be placed 34 layers of the filament of the thickness 1,75 mm. The amount of layers that can be wound on spool equals to 23. So, to get the distance, which has to be reduced, the next formula can be used (2).

$$L_R = L_{25} - 23L_1 = L_{25} - 23(\pi \cdot D \cdot n \div 1000) \quad (2)$$

Where: L_R [m] is a distance that has to be reduced,
L_{25}[m] is the length of the fully wound spool,
L_1 [m] is the length of the material on the first layer.

Basically, the distance that has to be reduced is the difference between the length of the material of fully wound spool and the length of the material that is all the layers wound but as the first layer and it equals to.

$$L_R = L_{25} - 23L_1 = 340{,}25 - 23(\pi \cdot 100 \cdot 34 \div 1000) = 94{,}57\ m \quad (2)$$

Due to the fact, that distance which should reduce the tensioning equals to 94,57 m, it is impossible to place the rolling mechanism and thickness calibration mechanism on a such distance but the next suggestion, shown in Figure 40, was to use the two-tier table for placement of these machines.

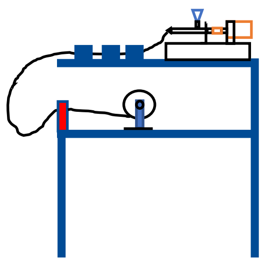

Figure 40: The scheme of placement

This placement of the machines gives an opportunity to reduce the distance. And operator of this process doesn't have to change any settings during the filament creation process. The way this idea will work is that rolling machine is turned off during the filament creation and the filament falls down in some box from the second tier of the table. After that operator has to turn off the extruder and to start rolling of the material. The extruders feed rate is 800 grams of filament per hour and the mass of the filament of the fully wound spool is 1 kilogram, that means that on extrusion of the filament, to fulfill one spool, 1 hour and 15 minutes will be needed, after that extruder has to be turned off and rolling of the filament has to be started. [46] For organization of correct rolling of the filament, at the start of the filament creation, the end of the filament has to be clamped on spool in order to prevent the knots during the process.

11 Results

Finally, the machines were positioned as shown in the Figure 41. Where the distance between the pulling mechanism and rolling mechanism was increased. The placement of the propeller near the nozzle of the extruder made an opportunity to move the material further to the other parts of the filament creation process. During the testing to reduce the axial movement of the filament along the axis of bearings in thickness calibration machine, the thickness measuring machine was brought closer to the pulling mechanism.

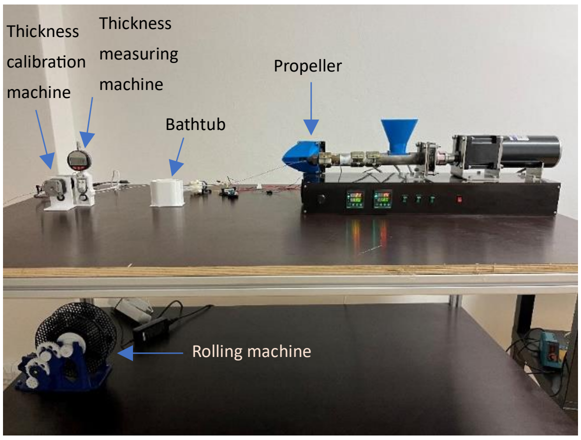

Figure 41: Final placement of the machines

In the following chapters, the results of the materials will be compared to the results of the filament previously extruded without the improvements made in this work. PLA plastic granules will be used for this test. The temperature setting for the filament creation will be the same as was mentioned in [46]. The preheating temperature will be set at 130 °C, and the final temperature will be set at 190 °C. The extruded material will be assessed for thickness stability, plasticity, winding quality, printing quality.

Before the improvement, the placement of the extruder and rolling machine was as shown in Figure 42, the cooling was done also by one propeller placed near the nozzle.

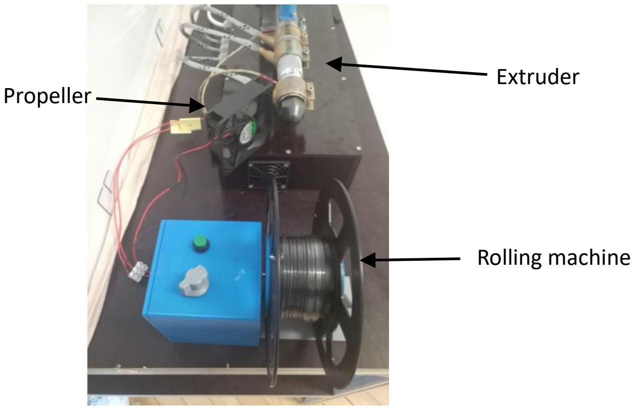

Figure 42: Placement before the modifications [46]

11.1 Material thickness and quality results

The thickness stability of the material was tested by moving the extruded filament through the thickness measuring machine, as shown in Figure 43. The thickness of the material was measured on each half of the meter, and the results of the measuring are presented in Table 8. The difference was calculated between the diameter of filament after the modifications and standard thickness of the filament, which is 1,75 mm with the tolerance of ±0,05 mm.

Figure 43: Thickness measuring process

Table 8: Thickness measuring results

Length from start [m]	Diameter before the improvements [mm]	Diameter after improvements [mm]	Standard thickness [mm]	Difference [mm]	Deviation [mm]
0,5	2,10	1,74	1,75	-0,01	0,013
1	2,05	1,75		0	
1,5	2,13	1,76		0,01	
2	2,21	1,78		0,03	
2,5	2,06	1,75		0	
3	2,03	1,73		-0,02	
3,5	2,03	1,74		-0,01	
4	2,13	1,76		0,01	
4,5	2,05	1,75		0	
5	2,07	1,74		-0,01	

The thickness stability of the filament before the improvements was low, it was because the filament was spooled without the guiding and directly from the extruder, so the diameter of spool was different and the tension between the extruder and the rolling mechanism was changing, and it was hard to control. The lowest diameter of the filament was 2 mm and the reason for that was incorrect electrical part, where motor didn't have enough power to stretch material to the diameter lower than 2 mm.

The plasticity testing was done by the experiment, where one piece of the filament before the improvements and after the improvements with the length of 150 mm was taken. The specimens were clamped at the one of ends and in the middle. The force was applied on the second end of the specimen and pushed on 180˚. Ones it was bended on 180˚, the force stopped to act. After that, the angle during the resting condition was defined and the thickness in the place of bending was measured.

The specimen that was taken from the material that was tested before the improvements was cooled not properly, due to the air cooling done by just one propeller and by the testing the material shown brittleness, after the first try to bend it, the filament cracked. Anyway, this test was done and after bending of another specimen on 180˚ it is changed angle on 80˚ without any change in the diameter, see in Figure 44.

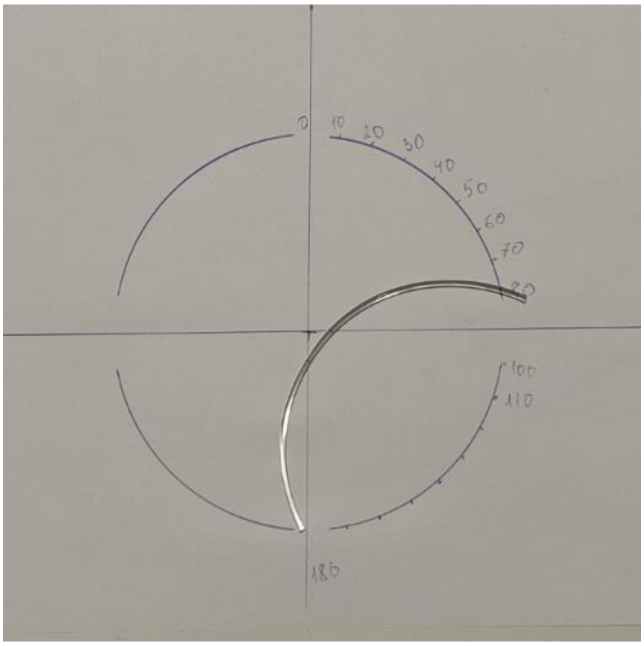

Figure 44: Bending result before Improvement

The specimen of the material that was extruded after the improvements after bending changed its angle on 160˚, shown in Figure 45, and the diameter in place of bending became 1,46 mm, shown in Figure 46. So, the filament after the improvements reached more plasticity.

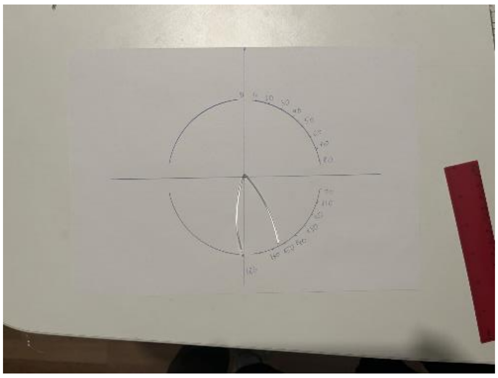

Figure 45: Bending test after improvement

Figure 46: Thickness after bending

11.2 Spool winding

Previously the winding on spool was done directly from the extruder. It was pretty hard to make a good winding without the guiding and make a continuous diameter of the filament as the rolling machine was connected directly to the extruder. The result is shown in Figure 47.

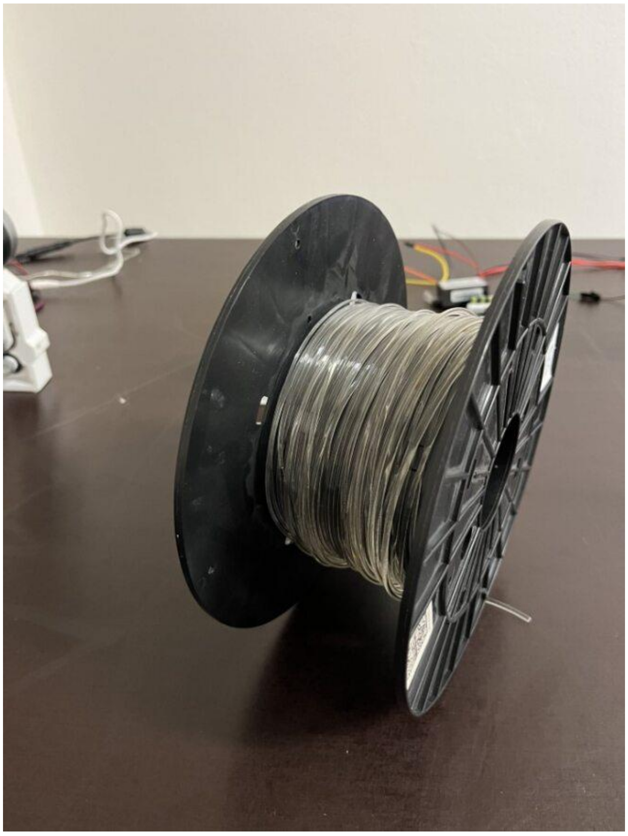

Figure 47: Previous winding

After the improvements and new rolling machine all the process was automated and rolled evenly see in Figure 48.

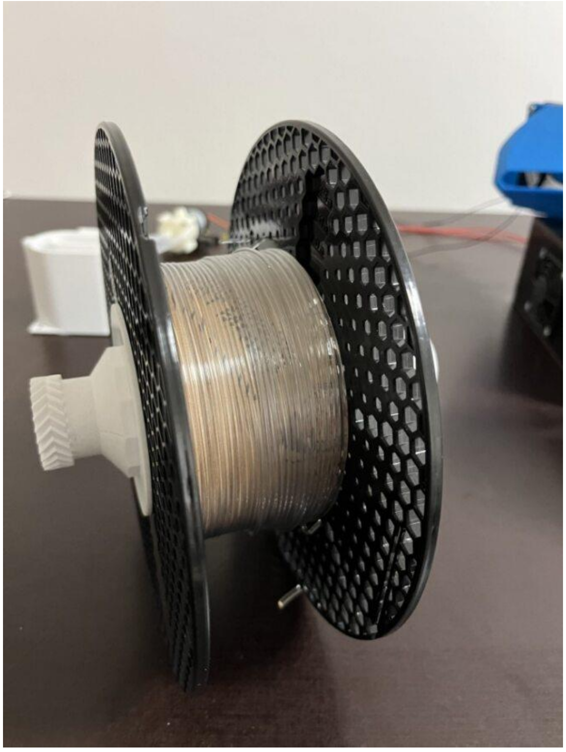

Figure 48: Winding on new rolling machine

11.3 Printing test

Simple model of boat, shown in Figure 49, was used to test the printing from the extruded filament. This model was chosen because it has 3 different types of surfaces such as round, flat and non-contiguous, where the printing was done not on the surface but in the air. The printing took one hour, and 4 meters of PLA plastic was used. The set temperature of the extruder during the printing was 210 ℃ as a standard temperature. The filament that was extruded before improvements was not sufficient to be used for 3D printers because diameter of the filament was sometimes bigger that 3D printer couldn't work with it.

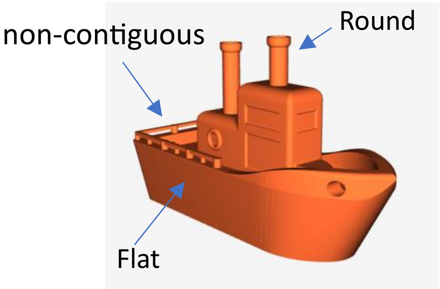

Figure 49: Model of boat [58]

In Figure 50, the important places were matched by the red rectangles because these areas have different types of surfaces. In the right red rectangle, there is a gap between the railing at the stern of the ship, this means that in that part the printing took place not on the surface but in the air, this indicates that the material has a good stretching property in the state of melting. Other rectangles are placed in places where are round and flat surfaces and filament handled them well.

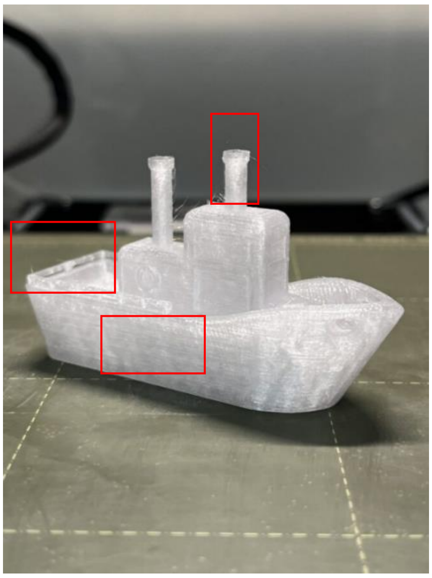

Figure 50: Printing test

12 Conclusion

The main objective of this thesis was to propose modifications for the extruder that will make a possibility to make a smooth production of the filament with the needed properties to be sufficient and to be used by Mubea company. New machines were proposed for improvement of the process of the filament extrusion, based on theoretical knowledge. The needed material's properties were reached.

The thesis is divided in two parts, the first part is a research part where information about the 3D printing technologies, materials for 3D printing that are widely used, the process of filament production and main steps which result the changes of the quality of the filament were studied. The information about what is the most important in filament extruder and the properties that show the quality of extruder was discussed. The second part is practical part, which is based on the theoretical knowledge got from the research, the new purposes was discussed and new machines such as cooling machines, thickness measuring machine, thickness calibration machine were designed. All the modifications are introduced and described.

The filament that was extruded after the improvements was tested on thickness stability, plasticity, printing quality, and rolling quality, all the results was described in the Chapter 11.

In conclusion, the filament production was made, the modifications were purposed, the results were tested, but this was just a small part that had to be done to get more ecofriendly filament production.

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APPENDIX A

Table 9: Filament length calculation

Layer [-]	D [mm]	D · π [mm]	D · π · width of spool [m]	Sum of the length of the filament [m]
1	100	314,1592654	10,68141502	10,68141502
2	103,5	325,1548396	11,05526455	21,73667957
3	107	336,1504139	11,42911407	33,16579364
4	110,5	347,1459882	11,8029636	44,96875724
5	114	358,1415625	12,17681313	57,14557037
6	117,5	369,1371368	12,55066265	69,69623302
7	121	380,1327111	12,92451218	82,6207452
8	124,5	391,1282854	13,2983617	95,9191069
9	128	402,1238597	13,67221123	109,5913181
10	131,5	413,1194339	14,04606075	123,6373789
11	135	424,1150082	14,41991028	138,0572892
12	138,5	435,1105825	14,79375981	152,851049
13	142	446,1061568	15,16760933	168,0186583
14	145,5	457,1017311	15,54145886	183,5601172
15	149	468,0973054	15,91530838	199,4754255
16	152,5	479,0928797	16,28915791	215,7645834
17	156	490,088454	16,66300743	232,4275909
18	159,5	501,0840282	17,03685696	249,4644478
19	163	512,0796025	17,41070649	266,8751543
20	166,5	523,0751768	17,78455601	284,6597103
21	170	534,0707511	18,15840554	302,8181159
22	173,5	545,0663254	18,53225506	321,3503709
23	177	556,0618997	18,90610459	340,2564755