TUM School of Engineering and Design

Study of Optimal Parameters and Curing Method for a Prototype 3D Printer for Dental Implants

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Bachelor's Thesis
at TUM School of Engineering and Design.

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Task Assignment Bachelor Thesis
„Study of Optimal Parameters and Curing Method for a Prototype 3D Printer for Dental Implants"

The Chair of Carbon Composites (LCC) currently researches the 3D printing of reinforced materials with different fillers. The extrusion process is simple, offers cost and time advantages, and the geometrical accuracy of the dental implants is potentially comparable to the products manufactured with stereolithography technology. For this reason, this project aims to develop an extrusion process, both for high-viscosity and UV-curable materials. As a result, a more economical technique with high-quality standards will be offered compared to the stereolithography process. The aim is to use pastes already commercialized on the market as a highly viscous reaction material to produce dental implants in the extrusion process using UV. In addition to the project management, different subtasks are to be worked out: (1) the material characterization under the process boundary conditions, (2) the print head development, (3) the development of the light-curing unit, (4) the development of a cartridge system for material handling, (5) a color change system, (6) a polishing unit, and exclusively (7) the testing of the component.

The current state of the test bench requires the theoretical investigation of the possible UV-curing units for a further integration – out of scope for this investigation. This work focuses both on the theoretical and experimental study of the key printing parameters using the extrusion test bench for printing commercially available dental resins to investigate their influence on the printed product quality. The results of the work should help to gain insight into the 3D printing for dental protheses applications.

Contents:

- Literature review of UV-curing and UV-sources
- Literature review of key parameters for material extrusion-based additive manufacturing
- Design of experiments for printing parameter analysis
- Experimental planning and execution
- Evaluation of the experiments
- Documentation in English

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Declaration of Honor

I hereby declare on my honor that I have prepared this thesis independently and without the use of other than the indicated resources; the thoughts taken directly or indirectly from outside sources (including electronic sources) are identified as such without exception. The work has not been submitted in the same or similar form to any other examination authority.

Munich, August 7th, 2023

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City, Date   Signature

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To all the individuals mentioned and those who have provided support in various ways along this journey, I express my deepest gratitude. Your contributions have been vital to my academic and personal development.

Abstract

During this thesis project, various investigations and activities pertaining to the development of a 3D printer for dental implants will be undertaken. The focus will be on studying a resin curing method as well as determining optimal printing parameters.

Firstly, concerning the resin curing method employed for printing (Charisma Classic and Charisma Topaz), it is known that UV light is utilized for this purpose. Consequently, an exploration is conducted on the nature of this type of light and the different sources from which it can be obtained. As a result, it is concluded that the Kulzer UV lamp represents the most suitable option for resin curing, with the recommended approach involving post-printing application for a duration of 20 seconds, while maintaining close proximity between the lamp and the printed component. Additionally, the prospect of developing a method for incorporating the light into the printer to facilitate material curing during the printing process is considered.

Secondly, about determining the optimal printing parameters, a fractional factorial experiment has been devised, encompassing twelve individual prints, with three repetitions assigned to each of the four experimental scenarios. Throughout these experiments, selected parameters are varied to discern the values that yield superior outcomes. Specifically, the parameters of Extrusion multiplier, Extrusion rate, and Retraction distance are subject to investigation.

Upon completion of the experiments and subsequent analysis of the results, two experiments demonstrate more favorable outcomes. Unfortunately, certain issues have been encountered in the prototype, thereby influencing the conditions under which these two experiments were conducted and rendering direct comparisons unfeasible.

Moreover, these encountered issues, such as inadequate adhesion or suboptimal distance between the nozzle and the printing bed, have been thoroughly examined, and potential solutions have been proposed within the scope of this thesis.

Contents

Nomenclature

Symbol	Unit	Description
λ	$[nm]$	Wavelength
M_e	$\left[\frac{W}{m^2}\right]$	Spectral radiant existence at λ
T	$[K]$	Absolute temperature of the radiator
A	$[W \cdot m^2]$	Radiation constant
B	$[m \cdot {}^{\circ}K]$	Radiation constant
$FWHM$	$[nm]$	Full Width at Half Maximum

Abbreviations

Abbreviation	Description
ABS	Acrylnitril-Butadien-Styrol
PBF	Powder bed fusion
SLA	Stereolithography
MJ	Material jetting
MEX	Material extrusion
PC	Polycarbonate
PET	Polyethylene erephthalate
TPE	Thermoplastic elastomers
TPU	Thermoplastic polyurethane
PVA	Polyvinyl alcohol
PLA	Polylactic acid
HIPS	High impact Polystyrene
HDPE	High density Polyestyrene
FDM	Fused Deposition Modeling
SEBM	Electron beam selective melting
UV	Ultraviolet
nm	Nanometers
HID	High intensity discharge
LED	Light-emitting diodes
PA	Aliphatic polyamides
PEEK	Polyether ketone
PEI	Polyetherimide

1 Introduction

The recent development of 3D printers has been a huge discovery and advancement in different fields. They are increasingly being used for various purposes and objectives as they are highly flexible and have an enormous number of advantages.

Due to the many advantages that they present, we have set out to research and develop a new application for them. In the field of dentistry, the production of dental implants is a highly time-consuming and expensive process. Therefore, our goal in this project is to design a 3D printer for dental implants.

Thus, we have focused on the creation of this printer and must start by studying the operation of these printers and the different types that we can find in order to select the most suitable one for the application that we are going to give to our product.

We must study the different Additive Manufacturing Technologies used, the different kinematics, and the different materials that are used to produce the object. This work has already been carried out by other members of the project who have selected the most appropriate techniques and modalities for our goal. With these components that make up the printer, a prototype has been.

The main objective of this project will be to study the different parameters that can be modified in the printing process and carry out various prints by varying these parameters.

Once we have different samples obtained from different prints, we can study the properties that the samples present through various tests. To do this, we must better understand the properties we want to investigate and therefore, the type of tests we are looking for.

Thus, it is important to study the properties that we want our implant to have in order to vary the parameters towards approaching these desired properties.

Through the study of properties by means of tests, the objective is obviously to study which are the optimal parameters to obtain the optimal properties and thus establish them as parameters for the printing of the implants.

In addition, we have thought that it may be a good idea to add a material curing process with UV light to achieve a better finish. Therefore, in this thesis, we will also focus on studying UV light and its properties as well as the materials that can be cured with it and the sources from which it can be obtained. After studying UV light and possible sources, we will select the most suitable one and try to introduce it into the prototype, trying to achieve a better finish for the material.

This project not only aims to reduce costs and production times for dentists and patients but also to improve the quality and precision of dental implants. With this 3D printer, we are looking to revolutionize the process of manufacturing dental implants and provide an efficient and precise alternative to conventional manufacturing methods.

2 State of the Art

2.1 3D Printing

3D printing is a relatively new process by which we can obtain different products in a simple, fast, and cost-effective way using as a tool, a 3D printer.

To generate our product, we will use different materials depending on its applications. The most common materials used are polymers such as Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), High impact Polystyrene (HIPS), High-density Polyethylene (HDPE), Polyvinyl alcohol (PVA), Polycarbonate (PC), Polyethylene terephthalate (PET), Nylon, also known as Aliphatic polyamides (PA) or the thermoplastic Ultem. Carbon fibers, metals, or flexible filaments such as Thermoplastic elastomers (TPE) or Thermoplastic polyurethane (TPU) can also be used. Currently, hybrid materials are also available [1].

Regarding the process, these are the steps:

1. Create the CAD design

A 3D design software is used to create a digital model of the object to be printed.

2. File preparation for printing

The CAD file is converted to a format compatible with the 3D printer and prepared for printing.

3. Material selection and printer adjustment

The appropriate material for the object is selected and the parameters of the 3D printer, such as temperature and printing speed, are adjusted.

4. Printing begins

The object is printed layer by layer using the selected 3D printing technique, such as FDM or SLA.

5. Post-processing

Once the printing is complete, the object may require post-processing, such as removing support structures or cleaning the surface.

6. Final object

After post-processing, the final product is obtained, ready for use or further processing if required. [1]

Thus, objects are created through additive processes, where the printer will place successive layers of material to create the product, in other words, it stratifies the material.

This tool was initially created to manufacture prototypes, that is, the actual product would be later manufactured using a different process. Currently, 3D printers are becoming more useful in the industry and are being used not only to create the prototype but also to manufacture the final product.

The main objective of 3D printers is to reduce cost and time. Another very important advantage of this tool is the improvement in the geometric precision that the product created will have, which allows the production of more complex and personalized pieces.

As we have already said, these printers have played a significant role in many areas, both in companies to save costs and time and in the personal sphere, as many people have become fond of them and use them as a hobby.

This makes us wonder what useful and interesting applications we can give this new tool. [2]

2.1.1 AM Technologies

3D printing, also known as additive manufacturing (AM), bases its principle on generating a 3D object from the successive creation of layers of material under a computer-controlled program.

The ISO/ASTM52900-15 standard defines that there are seven types of additive manufacturing (AM) processes: stereolithography (SLA), powder bed fusion (PBF), binder jetting, sheet lamination, material jetting (MJ), material extrusion (MEX), and direct energy deposition. [3]

Now, we are going to explain these different types of AM technologies:

1. Stereolithography (SLA)

A container filled with photopolymer liquid resin undergoes solidification via targeted exposure to a light source, such as a laser or projector, that triggers polymerization and transforms the illuminated regions into a solid component. [4]

In *Figure 2-1* this method is represented:

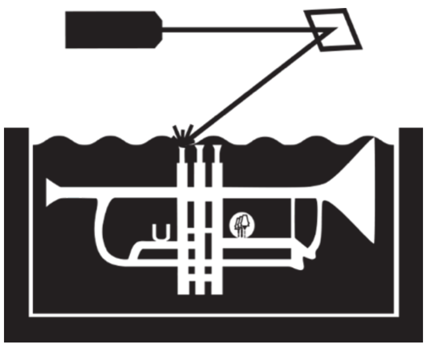

Figure 2-1: Stereolithography [4]

2. Powder Bed Fusion (PBF)

Selective consolidation of powdered material is achieved by melting it using a heat source, such as a laser or electron beam. This process fuses the powder and forms a solid part, while the remaining powder acts as a supporting material for overhanging features. [4]

In *Figure 2-2* this method is represented:

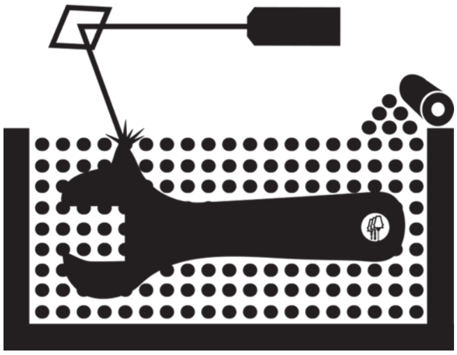

Figure 2-2: Powder Bed Fusion [4]

3. Binder Jetting

The layer-by-layer construction of parts is accomplished through selective printing of liquid binders, which can be organic or inorganic, onto thin layers of powdered material. [4]

In *Figure 2-3* this method is represented:

Figure 2-3: Binder jetting [4]

4. Sheet Lamination

To create the object, sheets of material are stacked and bonded together through a lamination process that can involve adhesives or chemistry, ultrasonic welding, or brazing. After the object is built, excess material is removed by cutting out unwanted regions layer by layer. [4]

In *Figure 2-4* this method is represented:

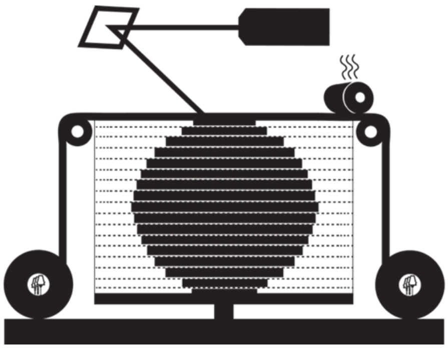

Figure 2-4: Sheet lamination [4]

5. Material Jetting

Parts are fabricated by depositing droplets of material layer by layer. This can be achieved through various methods, including jetting a photocurable resin and exposing it to UV light for curing and jetting thermally molten materials that solidify in ambient temperatures. [4]

In *Figure 2-5* this method is represented:

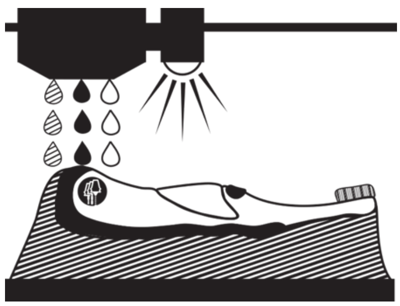

Figure 2-5: Material jetting [4]

6. Material Extrusion (MEX)

A multi-layer model is built by extruding material through a nozzle or orifice in the form of tracks or beads, which are combined. This process can be accomplished through various methods, such as heated thermoplastic extrusion (similar to a hot glue gun) and syringe dispensing. [4]

In *Figure 2-6* this method is represented:

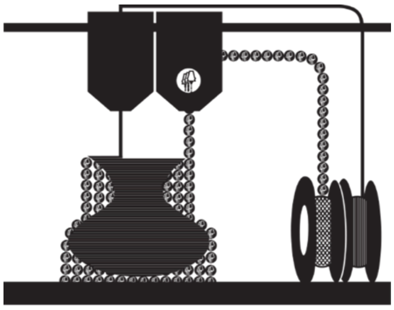

Figure 2-6: Material extrusion [4]

7. Directed Energy Deposition

A melt pool is generated on the part's surface using an energy source, such as an arc, laser, or electron beam. Powder or wire is tfed into the melt pool, where it adheres to the underlying part or layers. This process is essentially a form of automated build-up welding. [4]

In *Figure 2-7* this method is represented:

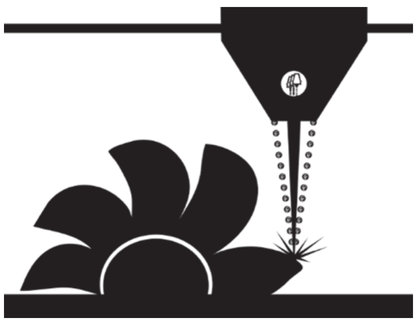

Figure 2-7: Directed energy deposition [4]

2.1.2 Kinematic

Each 3D printer uses its kinematics that controls the movement of the mechanical parts, the print head, and the platform.

Fused Deposition Modeling printers (FDM), also known as Fused Filament Fabrication (FFF) printers, are a type of 3D printer that uses thermoplastic plastic filaments as printing material. These printers are popular for their accessibility and the wide variety of materials they can use. They can also produce large parts and can be used in a wide range of applications, from prototyping to the mass production of final parts.

That is why our printer prototype will be based on this technology, and for this, we studied the different types of kinematics that FDM printers can have. These possible kinematics are Cartesian kinematic, Delta kinematic, Polar kinematic and H-Bot kinematic and we will briefly explain them below. [5]

1. Cartesian kinematic

Cartesian printers are the most common FDM printers on the market.

Cartesian technology uses three axes (X, Y, Z) to determine the movements of mechanical parts, so they move in the axes according to the coordinates.

There are possible ways for platforms and print heads to move, but the most common one is when the platform moves horizontally (Z) and the extruder moves two-dimensionally along the X and Y axes [6] as you can see in *Figure 2-8*:

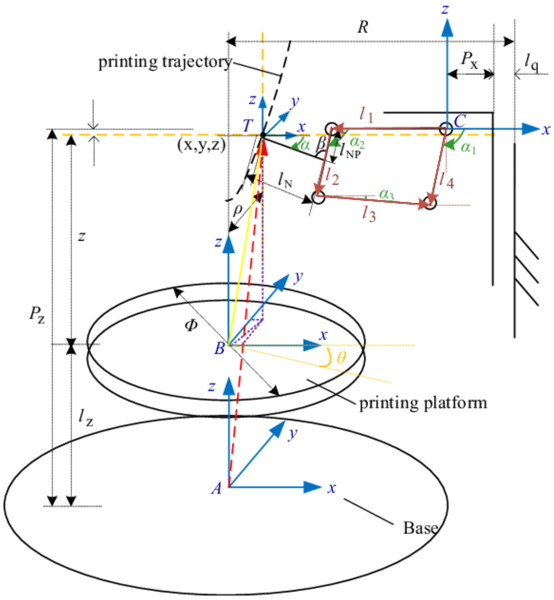

Figure 2-8: Cartesian kinematic [7]

2. Delta kinematic

The most significant difference between Delta printers and Cartesian ones are the extruder movements concerning the print bed.

Delta kinematics allows a higher speed but at the same time provides less accuracy. The reason because this happen is that these extruder movements require three motors working simultaneously, leading the errors in coordinate positioning. [6] In *Figure 2-9* this type of kinematic is represented:

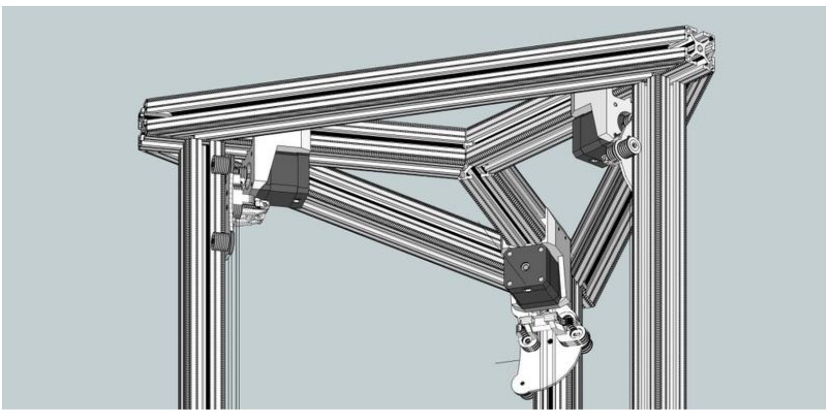

Figure 2-9: Delta kinematic [8]

3. Polar kinematic

As can be seen in *Figure 2-10*, Polar kinematic uses polar coordinates so the positioning is determined by radius and angle instead of commonly used axes. In this case, the platform is circular, and it moves horizontally in one dimension. At the same time the extruder moves up and down. [6]

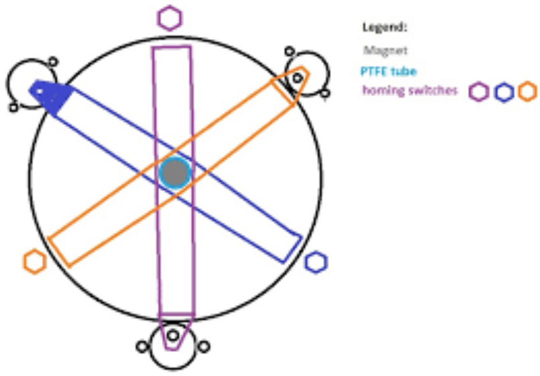

Figure 2-10: Polar kinematic [9]

4. H-Bot kinematic

This kinematic moves vertically and uses two motors and a belt drive system, in which one belt is mounted to a frame with an H-shape. [6]

When both motors rotate in the same direction, the extruder moves along the X-axis but when they turn in different directions, the extruder moves along the Y-axis. When one of the motors doesn't rotate, then the extruder moves diagonally.

In *Figure 2-11* the H-Bot kinematic is represented and can be understanded better:

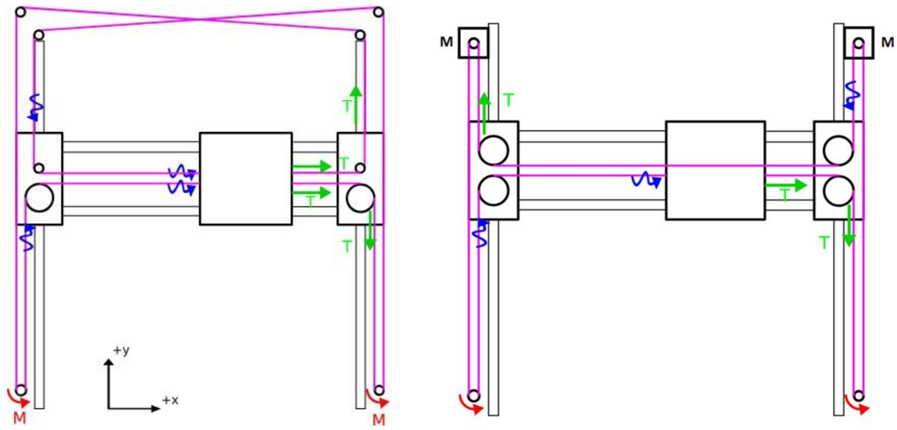

Figure 2-11: H-Bot kinematic [8]

2.1.3 Printing Parameters

For 3D printing, it is necessary to consider different parameters, which must be established in software programs or the printer before starting the printing process.

These parameters must be chosen consciously according to the application of the object to be printed and the printer, as they will affect the properties and quality of the print.

Some of the most critical parameters, in the case of Material extrusion technology and UV assited, are the following:

1. Temperature (ºC)

Each material is associated with various temperatures at which it can be extruded.

The extrusion temperature is related to the fluidity that the material will exhibit. Thus, we know that the higher the temperature, the more fluidity it will have, and less force is required to extrude it.
However, too much fluidity causes the material to slide too much, and the layer loses consistency.

We must also consider that if the nozzle temperature is too high, it can re-melt the deposited material, deforming the piece.
Therefore, the temperature stability of the nozzle is crucial. [10]

2. Extrusion rate (mm/s)

The speed limit is indicated by both the motor's capacity and the extruder's capacity to move the required amounts of material.

In addition, other factors can affect this parameter, such as inertia, vibrations, instability of the structure, or failures in the precision of the belts. [10]

3. Aceleration (mm/s^2)

This parameter sets speed time from 0 to the defined value or vice versa, when it brakes. This directly affects on both the printing time and the quality, as abrupt angles and movements will be cushioned, reducing vibrations.[10]

4. Layer height (mm)

The layer height corresponds to the size of each layer that is being printed.

The thickness of the layers affects both the printing speed and the quality of the product. Thus, an object printed with many layers offers a higher quality result with a smoother surface, even though it takes longer to print.
In other words, the object's height is the same as if it had been printed with few layers, but it has many layers of lower height or thickness, offering higher quality.
Therefore, the layer height is inverse to the quality and printing time. [11]

5. Nozzle's diameter (mm)

The nozzle is responsible for determining the amount of material deposited per second. The standard diameter is 0.4mm but it can range from 0.2 to 1.2mm.

A larger diameter allows for more material, faster printing speeds, higher layer heights, and requires less force from the extruder.

A smaller diameter results in slower printing speeds but allows for finer surface finishes and better surface detail. It also requires more force from the extruder.[10]

6. Extrusion volume (mm^3/s)

The extrusion volume considers the speed, nozzle diameter, layer height, and material density.

It is used to gain precision in the amount of material deposited on each layer by calculating the pressure inside the nozzle.
It is essential because it allows for adjusting the extruded material flow, thus avoiding under or over-extrusion. [10]

7. Exposure time for UV curing (s)

In printing techniques that use UV light curing, it is essential to establish the exposure time of each layer of material to the light.

The standard time for the target resins, i.e., Charisma Topaz, is usually 6 seconds to go to its gel point and 20 s to achieve its maximum curing degree. This time can vary depending on the resin used, as its physical properties may vary and may require more or less exposure time to become solid. [11]

8. Anti-distorsion

Distortion is the stair-step effect that occurs when a diagonal or curved line is rendered on a monitor with square or rectangular pixels.

Anti-distortion is used to smooth the curve of these objects, reducing the number of jagged lines and vertical artifacts that may appear in your print.

The standard levels of anti-distortion are 2, 4, and 8. [11]

2.1.4 Under- and Over- Extrusion

To better understand the rest of the project, we will explain two common phenomena that can occur in a 3D printing process: under-extrusion and over-extrusion.

2.1.4.1 Under-Extrusion

Under-extrusion is a phenomenon where the 3D printer does not extrude an adequate amount of material, resulting in gaps between extrusions in each layer. [12]

So, gaps between layers indicate under-extrusion, while their seamless connection suggests a different issue. Under-extrusion phenomenon is shown in *Figure 2-12*:

Figure 2-12: Under-Extrusion [12]

This phenomenon can be caused by multiple factors, with the most common being that the software is unaware of the filament diameter. If the diameter is correct, to address the under-extrusion issue, you can increase the extrusion multiplier parameter in PrusaSlicer by 5% or more if needed. [12]

2.1.4.2 Over-Extrusion

Printer may extrude more material than expected, resulting in over-extrusion that can distort the dimensions of the printed object.

The software and printer work together to ensure precise material extrusion, but most 3D printers cannot directly measure the amount of material being extruded. Over-extrusion could be because of printer extrusion settings are misconfigured. [13]

Over-extrusion phenomenon is shown in *Figure 2-13*:

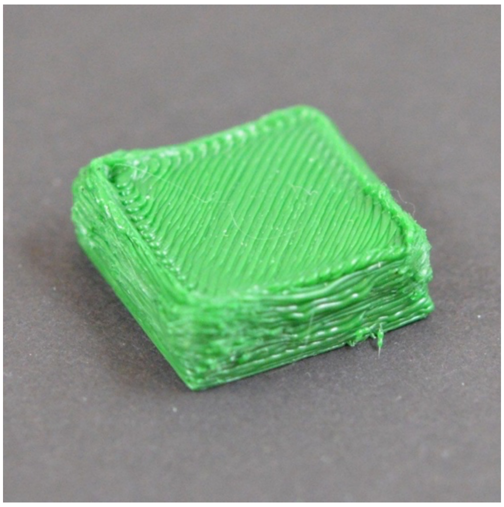

Figure 2-13: Over-Extrusion [13]

In order to solve this phenomenon, if increasing the extrusion multiplier is effective in addressing under-extrusion, then decreasing the extrusion multiplier would be advisable for addressing over-extrusion problems.

2.2 Dental Implants

Dental implants are medical devices designed to replace one or more missing teeth. They are surgically placed in the maxillary or mandibular bone and provide a stable base for attaching artificial teeth or dental prostheses.

The materials used in dental implants include titanium and titanium alloys, ceramics, and polymeric materials. Titanium is the most used material due to its corrosion resistance, biocompatibility, and ability to bond with the bone through a process called osseointegration directly.

Dental implants can improve masticatory function, aesthetic appearance, and patient self-esteem. They can also prevent bone loss in the jaw and improve overall oral health by avoiding the need to shave down adjacent teeth to support a dental bridge.

Like everything else, the production technique of these implants has been evolving and improving. In addition to improving their production, with the help of navigation technology and digital guidance, the implant placement technique has also been improving. The dentist can precisely plan the placement of the dental implant and minimize the risks associated with the procedure, thus allowing for minimally invasive surgery, which means the patient may experience less pain and a faster recovery. [14]

2.2.1 Conventional Production

Conventionally, dental implants have been manufactured through a machining process on micro-precision computer numerically controlled lathes of high specialization. During the procedure, each piece of titanium, or the selected material, is meticulously inspected in the laboratory with micrometer magnifying glasses that allow for complete quality control. [15]

The process begins with taking impressions of the patient's teeth, which are used to create a plaster model of the patient's mouth. From this model, a wax structure is built to serve as a pattern for the implant manufacture.

The wax structure undergoes a casting process, in which the wax is melted, and the implant material is injected in its place. Once it has cooled, the metal structure is machined to create the appropriate shape and size for the dental implant.

Finally, the implant is placed in the patient's mouth, in the appropriate position to replace the missing tooth. The implant placement process may vary depending on the patient's needs and the technique used by the dental surgeon. [16]

This conventional production of dental implants may have some drawbacks, including:

1. Cost

Conventional production of dental implants can be expensive due to the required manufacturing processes, materials, and specialized equipment.

2. Time

The production process can be lengthy and take several weeks or even months for the implant to be ready for placement.

3. Size and shape

Conventional implants are available in a limited variety of sizes and shapes, which can limit the dentist's ability to customize the solution for a specific patient.

4. Material limitations

Conventional implants are often made of materials such as titanium, which may not be suitable for all patients.

5. Risk of rejection

Although conventional dental implants have a high success rate, there is a risk that the patient's body will reject the implant.

6. Placement difficulties

Placing conventional dental implants may require invasive surgery, which can lead to complications and postoperative pain. [17]

In summary, the conventional production of dental implants has some limitations and disadvantages that can make the process difficult for patients and dentists.

It is also important to highlight that the production of dental implants is a constantly evolving field, so it is essential to stay current on the latest advances and trends in the industry.

2.2.2 Innovative Production (3D Printing)

As previously explained, the conventional production of dental implants presents various drawbacks, which is why new production methods are being developed for these implants. Additionally, the dental sector is a market that constantly faces the need to manufacture customized and geometrically optimal products.

Thus, we can say that the production of dental implants is advancing in 3D printing technology.

3D printing of dental implants is a method that allows us to reduce cost and time, as it will be in dental clinics and the dentist will be responsible for manufacturing the implant without the need to outsource it to an external company. This will generate savings for both the dentist and the patient, both economically and in terms of time, as the implant will be ready for application within a maximum of half an hour.

In addition to the advantage above, another crucial one is the improvement in the geometric precision these implants will have since conventional manufacturing methods present some limitations. This technology allows dentists to create custom-made implants tailored to each patient's individual needs. Custom implants not only improve the effectiveness of the implant but can also reduce recovery time and increase patient comfort. [14]

Considering all these advantages, the reduction in time and cost, the reduction of human error in the manufacturing process, as well as the reduction of material waste and the greater geometric perfection of the pieces, which allows the production of more complex and personalized components, leads us to consider the use of this new technology in the field of dentistry.

In the dental field, some 3D printing methods stand out, such as stereolithography (SLA), fused deposition modeling (FDM), electron beam selective melting (SEBM), laser powder bed fusion, and inkjet printing. [18]

2.3 UV Curing

In this project to create a 3D printer for dental implants, we want to develop a method of additive manufacturing technology in which we include material extrusion and curing through a UV light source. Our goal is to merge two methods to try to achieve an optimal result for our product.

To do this, we need to understand better the properties of UV light, the materials that can be cured with it, and the sources from which it can be obtained.

2.3.1 UV Light

Regarding the discovery of UV light, in 1672, Isaac Newton demonstrated, thanks to his glass prism, that light is composed of a spectrum of radiations ranging from red to violet, including orange, yellow, green, blue, and indigo.

In 1800, Frederick William Herschel discovered invisible rays beyond red, which were named "infrared".

Likewise, in 1801, the German physicist Johann Wilhelm Ritter discovered invisible rays beyond the violet spectrum and named them "ultraviolet rays". He also contributed to the invention and evolution of the spectroscope. [19]
ultraviolet (UV) light is electromagnetic radiation with a shorter wavelength than visible light, meaning its frequency and photon energy are higher than visible light.

In the electromagnetic spectrum, we can place UV light between visible light and X-rays.

UV light is produced naturally by the sun and provides some benefits, such as t vitamin D production in the skin or tanning. However, excessive exposure to this type of radiation can be harmful to health, as it can cause burns or skin aging and can also trigger mutations in skin cells that can later develop into skin cancer.

In technology, the use of UV light has also been introduced for various applications. The most common ones are the sterilization of medical equipment, the manufacturing of electronic products, and the curing of resins in 3D printing.

UV light has a wavelength between 100 and 400 nm. However, it's important to note that between the 100 nm and the 10 nm that mark the difference with X-rays, there is Vacuum UV light, which we had not mentioned before.

Therefore, the wavelength of UV light is shorter than visible light and more prolonged than X-rays, and it falls on the spectrum between these two.

As for X-rays, their wavelength is between 0.01 nm and 10 nm, and that of visible light is between 400 and 700 nm, as shown in *Figure 2-14.* [20], [21]

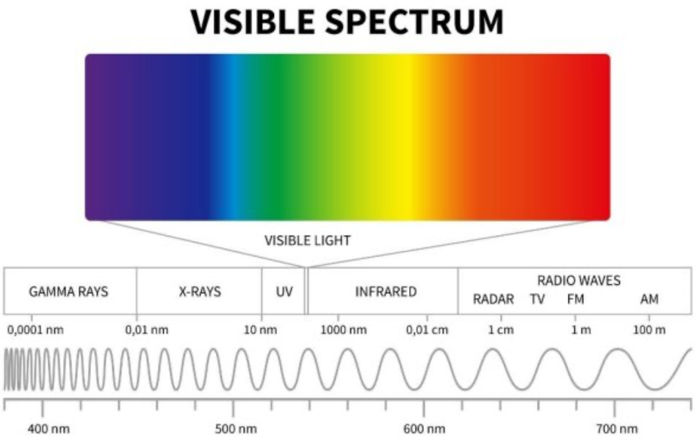

Figure 2-14: Wavelength diagram 1 [21]

Now, analyzing the UV light diagram shown in *Figure 2-15* we see it is divided into four sections: Vacuum UV or VUV, UV-A, UV-B, and UV-C.

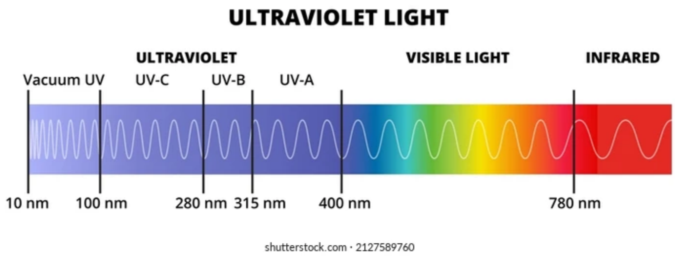

Figure 2-15: Wavelength diagram 2 [22]

The Commission Internationale de l'Eclairage (1970) [23], among others, has divided wavelengths between 400 and 100 nm into three regions:

- UV-A: 400 - 315 nm.
- UV-B: 315 - 280 nm.
- UV-C: 280 - 100 nm.

On the other hand, we have VUV (Vacuum UV), which is in the wavelength range of approximately 10 to 100 nm.

It is called vacuum because the shortest wavelengths are strongly absorbed by air and can only be observed in a vacuum.

VUV is used in various fields such as spectroscopy, electronic device manufacturing, and research in physics and chemistry. [20]

2.3.1.1 The Production of Ultraviolet Radiation

Ultraviolet radiation may be produced either by heating a body to an incandescent temperature or by the excitation of a gas discharge (Henderson and Marsden 1972).

A body heated to a high temperature radiates because its constituent particles become excited by numerous interactions and collisions. Planck's law dictates that the power emitted per unit area from a perfect black body at any given wavelength is solely dependent on its temperature as we can see in *Formula 2-1*:

$$M_{e\lambda} = \frac{A}{\lambda^5[exp\left(\frac{B}{\lambda T}\right) - 1]}$$

Formula 2-1: Planck's law [20]

M_e is the spectral radiant exitance at wavelength λ.

T is the absolute temperature of the radiator.

A and B are radiation constants, their values are $A = 3.7418 \cdot 10^{-16}\, W \cdot m^2$ and $B = 1.4388 \cdot 10^{-2}\, m \cdot {}^{\text{o}}K$. [24]

When the temperature of an object goes up, the amount of power radiated increases and the peak of the emission curve shifts towards shorter wavelengths. The sun is a well-known source of ultraviolet radiation, but artificial sources like tungsten filament lamps are not very efficient at emitting UV light. (Summer 1962). [20]

2.3.2 UV Resins

In this project, we aim to use a material extrusion method with UV light curing in our 3D printer. Therefore, we investigated which materials can be cured with UV light, and the answer is photopolymer resins, or UV resins.

UV resins are very common in 3D printing due to their numerous advantages over other materials. Among these advantages, we highlight their printing speed, as these resins cure quickly with UV light, allowing for much faster printing than with other materials.

Another advantage is their high printing resolution, allowing for detailed and precise models.

It is worth noting their versatility, as UV resins come in a wide variety of colors and types, including transparent ones, allowing for printing parts with a high level of transparency and clarity, which is very useful for applications in specific industries such as dentistry.

Furthermore, they are highly resistant to wear and heat, providing great durability, and their post-processing is simple, as they are easy to sand, polish, and paint, allowing for a very good finish. [25]

Regarding curing these resins with UV light, the light that hits our product generates the polymerization of functional monomers, quickly transforming a solvent-free resin into a highly resistant polymeric product at room temperature.

The viscoelastic and mechanical properties of UV-cured polymers can be precisely controlled through the chemical structure and functionality of the monomer used and curing conditions, depending on the application considered.

The hardening of organic coatings by light is generally achieved by a polymerization reaction with a radical mechanism, for example in acrylic resins, or by a cationic mechanism, as in the case of epoxy resins.

A typical formulation of a UV-curing resin consists of a photo initiator, a functionalized prepolymer that will constitute the three-dimensional skeleton of the polymer and a monomer used as a diluent and viscosity adjuster simultaneously.

The photo-initiator plays a key role, controlling on the one hand the degree of initiation of the reaction, as well as the penetration of the incident light and therefore, the depth of cure. The degree of polymerization will depend on the reactivity of the functional group, the viscosity of the resin, and naturally, the intensity of the UV radiation.

Furthermore, dual-action cures have been developed for poorly illuminated product areas. This is based on combining UV and thermal curing and contain some additional functionalities, generally isocyanates and hydroxyl groups, intending to achieve effective cross-linking in dark areas through heat. [26]

2.3.3 UV Sources

As mentioned, the sun is the best ultraviolet radiation source. Still, we also know that artificial UV sources exist despite not being as efficient as the earlier ones.

A few decades ago, science and technology allowed the invention and construction of artificial sources of ultraviolet rays such as UV lamps, commonly used for disinfecting water, air, food, and sterilizing medical instruments. Ultraviolet radiation is a germicide capable of sterilizing by preventing the reproduction of harmful microorganisms in humans.

More recently, ultraviolet rays have been used in the laboratory thanks to the invention of electromedical instruments for cell study in forensic medicine to search for evidence to highlight biological traces and DNA profiles.

In industry, UV technology has introduced great innovation for the "drying" of lacquers, varnishes, inks, and adhesives. In chemical product polymerization, ultraviolet light is widely used in graphic arts, wood, and fiber optics. It is also commonly used in automotive, medicine, consumer electronics, and renewable energy, among others.

In more recent times, in which the invention and development of 3D printers stand out, manufacturers can print prototypes using these 3D printers that use ultraviolet ray lamps to quickly dry the raw material. [27]

We are going to mention some of the artificial sources of ultraviolet radiation used in these different applications:

1. Mercury UV lamps

These lamps use an electric arc within an ionized gas chamber as is showed in *Figure 2-16*. Thanks to the arc, it emits photons after the decomposition of atoms, producing a constant flow of light.

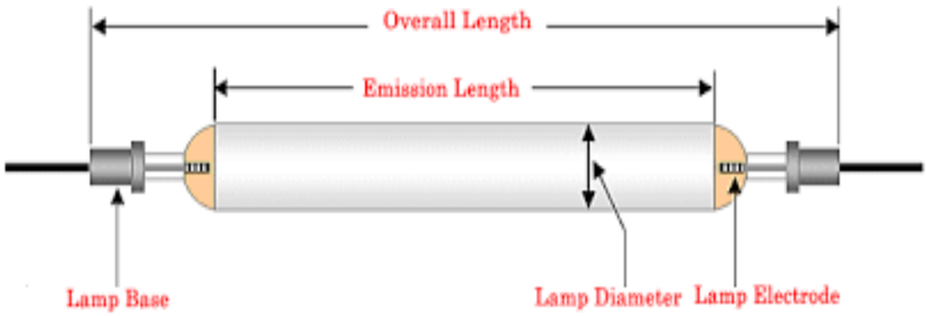

Figure 2-16: Mercury UV lamp [28]

There are different types of Mercury UV lamps:

1.1 Low-pressure mercury lamps

These lamps emit short-wave UV-C light and are commonly used for surface disinfection, water, and air treatment, and in medical phototherapy applications.

1.2 High-pressure mercury lamps

These lamps emit long-wave UV-A and UV-B light and are used in industrial, scientific, and specialized lighting applications, such as in the manufacture of computer chips, curing coatings, and illuminating stadiums.

1.3 Plasma lamps

These lamps produce short and medium-wavelength UV radiation by exciting gas through an electric arc, as we have said before. [29]
Regarding advantages, we must mention that these lamps are very efficient in energy, that is, they generate a large amount of UV light with a relatively small amount of electrical energy. Their lifespan is also long, as they are very durable. It is worth noting that they are relatively easy to install and maintain.

They also have disadvantages, including the emission of short and medium wavelength UV radiation, but not long wavelength, which means they are not effective for all applications. We must also consider the material they are composed of, mercury, a toxic heavy metal that can harm the health and environment if handled or disposed of improperly. Mercury vapor UV lamps can emit significant heat, which can be a problem in certain applications where precise temperature control is required. Finally, it is worth noting that these lamps can be expensive compared to other UV light sources. [30]

2. Fluorescent lamps

Some fluorescent lamps emit small amounts of UV-A and UV-B light as a byproduct of their normal operation. However, special fluorescent lamps that emit UV-A and UV-B light for phototherapy and reptile lighting are specifically designed to emit UV light. Most fluorescent lamps contain mercury inside. When electricity passes through the gas in the tube, the mercury is ionized and produces ultraviolet light. This ultraviolet light causes the phosphor inside the tube to emit visible light. However, fluorescent lamps also contain other metals, such as tin, indium, and lead, used in the electrodes and phosphor coating. [31]

Fluorescent lamps's structure is represented in *Figure 2-17*:

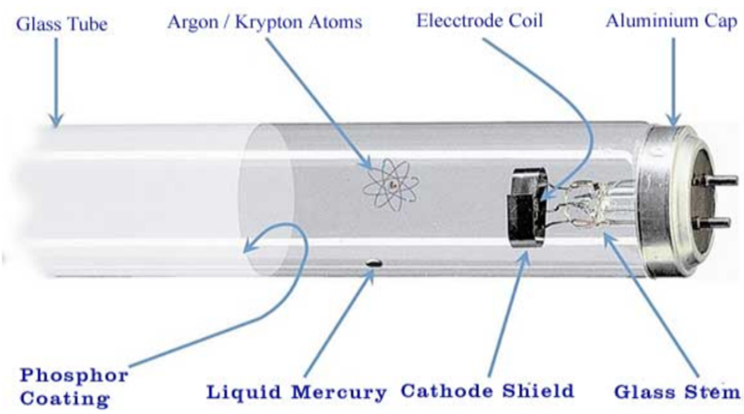

Figure 2-17: Fluorescent lamp [32]

Fluorescent UV lamps are relatively energy-efficient and generate a large amount of UV light with a relatively small amount of electrical energy, like mercury lamps. Their lifespan is also long, and they require little maintenance. They are a source of short and medium-wavelength UV light, making them effective for most disinfection and material curing applications, and relatively inexpensive compared to other sources. Still, it means that they are not effective for all applications.

Another disadvantage of these lamps is that they contain mercury, which, as we have already mentioned, can be harmful and emit a significant amount of heat. It is worth noting that they have a limited emission spectrum compared to other UV light sources, which means they may not be effective for certain applications. [33]

3. High Intensity Discharge (HID) lamps

These lamps emit UV-A and UV-B light. They are a type of lamp that uses a mixture of metal halides inside to produce light. When electricity passes through this mixture, it ionizes, producing a very bright and high-intensity light. In *Figure 2-18* this structure can be seen.

HID lamps are used primarily in applications where the most critical factor is creating as much visible light per watt as possible. Major applications include streetlights, gymnasiums, warehouses, large retail facilities, and stadiums, and plant growing rooms. Recently, these lamps have also been used in some high-end vehicle headlights.

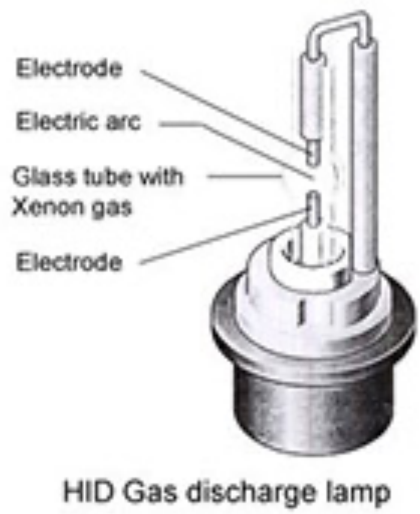

Figure 2-18: High density discharge lamp [32]

These lamps are very energy efficient and can produce a large amount of light with a relatively small amount of electrical energy. Additionally, they have a long lifespan and are relatively easy to maintain.

However, they also have some disadvantages. For example, they may take some time to reach their maximum brightness after turning on. They can also be expensive compared to other light sources, and their UV light emission spectrum may be limited compared to other UV light sources, so they may not be effective for all applications. [34]

4. LED UV lamps

These are ultraviolet spectrum emitting diodes. LED UV lamps emit short and medium-wave UV radiation by exciting a semiconductor material within the lamp. These LED UV lamps are used in various applications, such as water and air disinfection, curing adhesives and resins, leak detection, and material inspection. [35]

Figure 2-19 represents LED UV lamps:

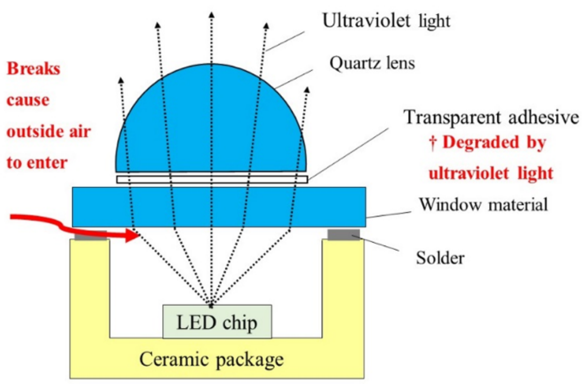

Figure 2-19: LED UV lamp [36]

LED UV lamps have some advantages over other UV light sources, such as mercury vapor lamps and UV fluorescent lamps. Firstly, LED UV lamps do not contain mercury or other hazardous materials, making them safer and more environmentally friendly. Additionally, LED UV lamps have a longer lifespan and consume less energy than other UV light sources, making them more energy efficient.

However, it is important to note that LED UV lamps can have a higher initial cost than other UV light sources. Additionally, the quality and intensity of the UV light emitted by LED lamps can vary depending on the manufacturer and model, so it is important to ensure that a high-quality and reliable LED UV lamp is used for the intended application.

As we have already mentioned, some 3D printers already use UV light curing to achieve a better finish. The sources used in 3D printers have a wavelength close to 405 nm, which is responsible for curing or solidifying the resins used.

Currently, the most commonly used sources are light-emitting diodes (LEDs) that emit in the specific wavelength band for the resin used.

Some 3D printers also use UV light sources with a wavelength close to 365 nm, which is the wavelength used in most low-pressure UV lamps. These 365 nm UV lights are less common but are used in some 3D printers. [37]

As a summary, we can visualize in *Table 2-1* the advantages and disadvantages of the different types of UV light sources explained above:

Table 2-1: Summary of advantages and disadvantages of UV light sources

Characteristics	Mercury UV lamps	Fluorescent lamps	HID lamps	LED UV lamps
Advantages	Energy efficent. Long lifespan. Easy to install and maintain.	Energy efficient. Long lifespan. Cheap. Easy to maintain.	Energy efficient. Long lifespan. Easy to maintain.	Do not contain mercury. Energy efficent.
Disadvantages	Short and medium wavelength, not long. Mercury is a toxic metal. Emits heat. Expensive.	Short and medium wavelength, not long. Mercury is a toxic metal. Emits heat. Limited emission spectrum.	Slow start. Limited emission spectrum. Expensive.	Expensive. Quality and intensity depend on the manufacturer and model.

3 Current Test Bench

In this section, we will define how the project has progressed and what decisions have been made regarding the material to be used and the printer prototype. That is, what AM technology and what kinematics have been integrated to the test bench.

3.1 Charisma Classic and Charisma Topaz

The possibilities of 3D printing are limitless, with a wide range of materials being used, from plastics and metals to organic materials and food. Each material is carefully chosen to meet the technical requirements of the final product.

In our 3D printing project for dental implants, we will be using a material that has already been validated for use in dentistry.

We have chosen Charisma Classic and Charisma Topaz, which are radiopaque composites that cure with light, designed for use in dental restoration. They are composed of a mixture of inorganic and organic fillers, resins, and pigments, giving them good mechanical strength, stability, and high aesthetics. [38]

The University of Regensburg in Germany conducted a study to study the properties of this material. In this study, the same material was subjected to different aging conditions. All of them were subjected to the same mechanical load, allowing for studying the flexural strength of the different materials generated after curing.

At the end of the study, significantly different results were found among the various materials. A considerably stronger decrease in flexural strength was observed after the combination of storage and thermal cycling. [39]

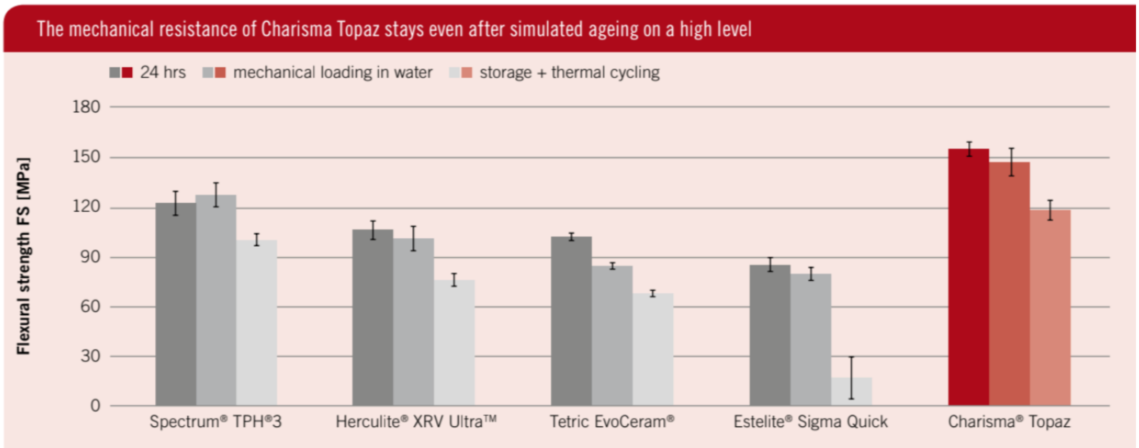

Figure 3-1: Results of the strength test [39]

During aging, the mechanical strength of a resin-based composite decreases. However, for the intended use of the material, it should still exhibit high flexural strength even after aging to withstand masticatory forces.

As seen in *Figure 3-1*, the flexural strength of Charisma Topaz remains at a high level, indicating that it is useful and resistant to dental applications. [39]

Dentists currently use these materials to create different implants and pieces manually. This makes us wonder if these same materials could be used to create the same pieces but in a 3D printer.

In addition, dental implants require the use of specific biocompatible materials that meet certain safety and efficacy requirements. As these materials have been tested and used before, we know that they are biocompatible. [3]

3.2 Material Extrusion

In the case of our 3D printer for the manufacture of dental implants, we will use the material extrusion method, where the 3D object is created by extruding the polymer into various layers, which are then cooled and solidified.

This method uses a continuous filament of thermoplastic material as the base material. The filament is fed from a coil through a heated and moving printer extrusion head, often abbreviated as an extruder. The melted material exits the extruder nozzle and is first deposited onto a 3D printing platform, which can be heated to achieve greater adhesion. Once the first layer is completed, the extruder and platform separate in a single step, and the second layer can be deposited directly onto the growing piece. A computer controls and moves the extruder's head and the layers are going to be deposited above the previous ones until the process is completed.

A wide variety of materials can be extruded, with the most popular being thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU), aliphatic polyamides or nylon (PA), and more recently, high-performance plastics such as polyether ketone (PEEK) or polyetherimide (PEI). In addition, pasty materials such as ceramics, concrete, and chocolate can be extruded using this 3D printing technique, and composite materials are also becoming increasingly common.

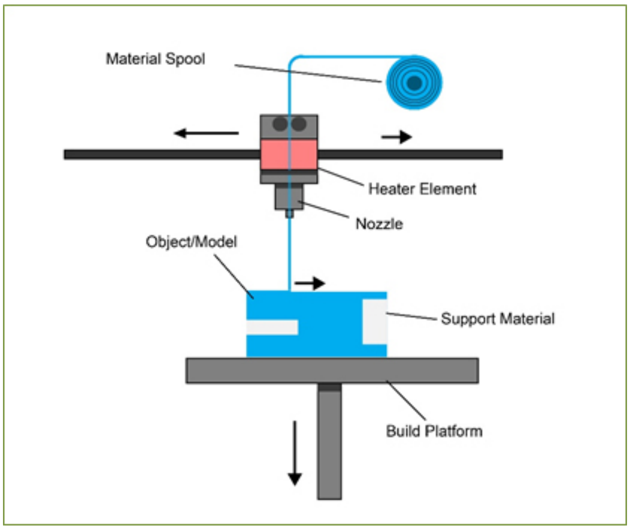

Figure 3-2: Material extrusion method [40]

The MEX 3D-printing technology (represented in *Figure 3-2*) uses a low-cost process and equipment, as the extrusion process is quite simple. Additionally, the incremental technique reduces the shrinkage occurring during polymerization, which reduces the deformation and microcracks of the finished object. [41]

However, compared to other additive manufacturing technologies, MEX remains relatively underdeveloped in dental. Using gamma radiation, the FFF technique can produce significant anisotropy in terms of properties. But MEX can strengthen parts and reduce anisotropy, while thermal treatment can also reduce anisotropy.

Usually, this method does not involve curing with UV light. Still, we want to study if it's possible to merge these two techniques, material extrusion and UV light curing, to obtain a better product from our print.

Therefore, we can say that an alternative to the usual use of this method is to use viscous resins as a material that can be solidified by applying our UV light since viscosity is the property of resins that allows the filament we use to be extruded.

3.3 H-Bot Kinematic

In our 3D printer prototype for dental implants, we will use the H-Bot kinematic that we have already explained before.

The advantages and disadvantages of different kinematics have been compared for the selection process, and the H-Bot kinematics has been chosen for its fast acceleration, positioning, and high speed, making the system and therefore the printing process faster. Another advantage is that it uses a single distribution belt, which reduces costs and simplifies construction. Additionally, it has high dynamic performance.

On the other hand, it should be mentioned that the H-Bot kinematics may have some disadvantages, such as potential issues with transfer and/or multidirectional effects. However, the other kinematics have more significant problems that could have a more definitive impact on our printing process.

In *Table 3-1* a comparison of kinematics and the final decision is shown:

Table 3-1: Summary and comparison of the kinematic models based on their properties [5]

Characteristics	H-Bot	Core XY	Delta Kinematic
Advantage	Fast acceleration High accuracy Fast positioning High dynamic performance High speed Single timing belt Low cost Simple construction	High speed High acceleration High resolution Low cost High precision	Good dynamic performance High speed High precision Strong bearing capacity Workplace along z-axis
Disadvantage	Racking problems Multi-directional effect	Large moving mass Low weight ratio Sensitivity to error Small workplace Ensuring tension belt	Small workplace Time consuming Iterative process

To implement the H-Bot kinematic, a theoretical demonstration was carried out to ensure that the method worked correctly and then a practical demonstration was carried out, meaning that the necessary parts were constructed with Solidworks and 3D printers.

Finally, also the prototype was built as it is showed in *Figure 3-3:*

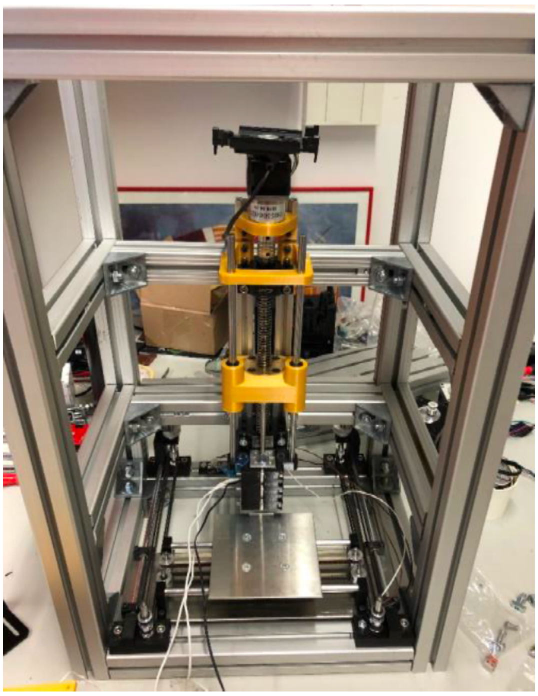

Figure 3-3: Prototype [5]

4 UV Light Source for Resins Curing

As mentioned before, we have decided to use the material extrusion method in our printing, adding a UV light curing for material compaction.

In this research process, we will address the different aspects necessary to develop this photopolymerization unit, analyzing UV light and the source from which it can be obtained and choosing the best option to achieve our goal. We will also design how the UV light source can fit into our printer prototype and conduct experiments to study when we should apply the light. Finally, we will experimentally test the functioning of this unit concerning our 3D-printed dental implant product.

Thus, the goal is to incorporate a UV light source into our 3D printer prototype for dental implants that fulfills the function of curing and compacting the material that forms the implant.

4.1 UV Light Source Options

We have decided to use LED UV lamps as the source of UV light source for curing resins in our 3D printer prototype. As we have explained before these lamps emit ultraviolet radiation of specific wavelength, around 405 nm, by exciting a semiconductor material within the lamp.

As we have just explained in *UV* Resins*,* UV light cures resins, transforming them into highly resistant polymeric products at room temperature. The properties of the cured polymer can be controlled by the chemical structure and functionality of the monomer used and the curing conditions. The formulation of a UV-curing resin includes a photoinitiator, a functionalized prepolymer, and a monomer. The photoinitiator controls the initiation of the reaction and the degree of polymerization. Dual-action cures have been developed for poorly illuminated areas, combining UV and thermal curing. [26]

LED UV lamps are used in various applications, but the one that interests us is the application in 3D printers, as this is the most used source in this application.

LED UV lamps have some advantages over other UV light sources. LED UV lamps do not contain mercury or other hazardous materials, making them safer and more environmentally friendly. Additionally, LED UV lamps have a longer lifespan and consume less energy than other UV light sources, making them more energy efficient.

However, we must take into account that as a disadvantage of this source, the quality and intensity of the UV light emitted by LED lamps can vary depending on the manufacturer and model, so it is important to ensure that a high-quality and reliable LED UV lamp is used for the intended application.

Thus, we have concluded that it is the best option due to its only disadvantage, which is that we must find the suitable model to achieve the desired results, and its numerous advantages that can help us achieve the goals we are looking for.

To search for the ideal UV LED light source, we are looking for a set of properties:

1. Wavelength of approximately 405 nm
2. High precision
3. Easy to assemble and maintain
4. Size compatible with the printer, preferably medium or small
5. Economical
6. High-quality and intense curing capability
7. Energy-efficient

We have found several options for UV LED light sources.

In addition, we need to consider the current dimensions of our prototype in order to choose an LED light option that can be adapted to it and reach the product for curing. In *Figure 4-1,* we can see that space is limited, specifically we currently have a distance of approximately 1 mm approximately between the board and the printer nozzle:

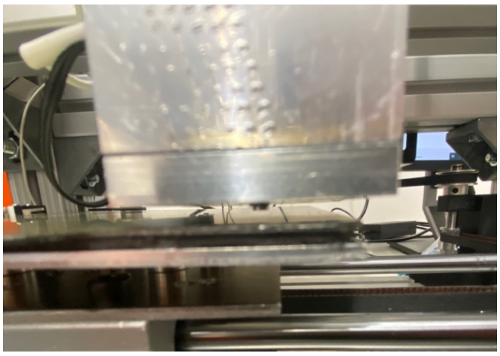

Figure 4-1: Space for working angles

Thus, in *Table 4-1* the requirements we are looking for in our UV LED light source have been gathered to simplify the search and decision-making process:

Table 4-1: Requirements our UV LED lamp must have

Requirements (Unit)	Values
Minimum wavelength (nm)	405
Stability level	It must have a high stability level; the angle and distance can't change
Maximum weight (g)	500
Temperature withstands capacity (ºC)	65
Connection method	Cables to connect the light to the printer
Minimum intensity (W/cm2)	1
Focus diameter (mm)	The minimum possible
Approximately budget (euro)	500
Working angle (º)	7.59

To calculate the range of angles, we must consider that the light beam cannot be in contact with the nozzle, we want to cure the resins when they are in the bed.

Therefore, as you can see in *Figure 4-2*, we will use the Pythagorean theorem, in which we will calculate the angle based on the two legs, one of them being the horizontal distance between the point where the material is printed and the location where the lamp will theoretically go (x), and the other leg will be the vertical distance between the control box and the point where the material is printed (y).

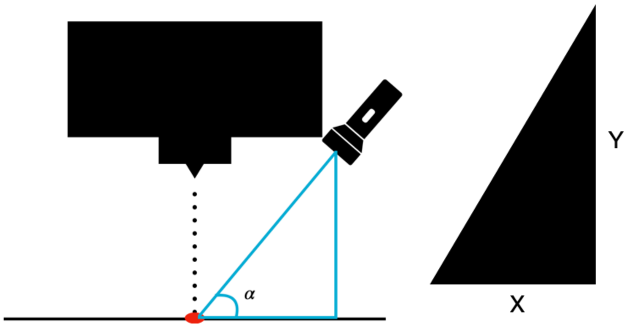

Figure 4-2: Working angles

$$\tan\alpha = \frac{y}{x} \quad ; \quad \alpha = \tan^{-1}(\frac{y}{x})$$

Formula 4-1: Obtain Alpha

With *Formula 4-1*, we solve for alpha and thus obtain the range of possible angles, from 0º to αº.

After measure x and y in the prototype, we have obtained the following values: $x = 15\,mm$ and $y = 2\,mm$.

So, inserting these values in the formula, the range of possible angles obtained is [0º, 7.59º].

As for the budget, we must consider that besides the UV light source or spotlight, we need to purchase an adapter lamp and cables for some of the options, so we must ensure that the budget for all necessary equipment does not exceed our budget. Additionally, as we will discuss later, acquiring some products intended for worker protection will also be necessary since UV light poses a health risk if proper protection is not used.

In *Table 4-2,* we will compare the different options and their most important properties to decide which can be the best option for the application it will have:

Table 4-2: Compation of UV LEDs lamps

Model	LTCLHP023-B	LED-Modul 28mm	High Power Top Led	Collimated LED for Olympus BX & IX	Nichia LED NVSU233B UV
Wavelength (nm)	460	470	405	405	405
Storage temperature (ºC)	50	-	100	70	100
Working angle (º)	-	6	34	-	35
Price (euro)	656	55	-	575.92	36.97
Weight (g)	152	25	5	220	10
Diameter (mm)	28	28	-	58.9	-
Large (mm)	96.8	45	2.06	131.3	1.23
Size (mmxmm)	-	-	3.45x3.45	-	3.5x3.5

As we can see, options 1 and 4 are outside of our budget and, furthermore, this budget does not include any of the extras previously mentioned such as clamping structure, cables, and safety equipment.

On the other hand, options 3 and 5 correspond to chip-type UV LED lights which do not use cables, making it impossible to connect them to the printer and control everything from the same control box.

Thus, the option that best fits the requirements mentioned is option 2. This option costs 55 euros for the light. Now we need to find out what else is required for its installation.

As we can see on the manufacturer's website, this light is sold with two accessories:

- LED-Machine light IL300-24V

This is the structure in which we should insert the light, an aluminum housing. This offers several advantages as it allows for quick change of the light source, has threaded caps and a protective glass for high requirements, allows for flicker-free light and brightness adjustment. The light will be powered directly through the machine connection. The cost of this product is 155 euros.

- Connection cable for 24V via M12

Necessary cables to connect the light source to the printer, allowing for control. The cost of this product is 27 euros.

Therefore, if we finally choose this option, to start with the installation of this lamp, we will need to place an order for these three products, at a total cost of 237 euros.. [42]

Despite this study of the ideal UV light source and having found a good option, we are aware that there are UV LED light lamps for curing dental resins on the market, which are used in clinics, so we will also study this option.
The Kulzer group, also the manufacturer of Charisma resins, produces the Translux Wave lamp, whose properties can be found in *Table 4-3*:

Table 4-3: Translux wave lamp propierties

Properties (Unit)	Values
Power density (mW/cm2)	1,200
Wavelength (nm)	440-480
Dimensions (mm)	L210 mm, max. ø 23 mm
Weight (g)	145
Power supply	Rechargeable lithium-ion battery, 3.6 V/2000 mAh.
Light source	Single high-power LED
Light guide	ø 8 mm, 70°

Considering that these specifications are exactly what we are looking for, this may be the best option we will find for curing UV resins. [43]

4.2 Application of the UV Radiation

Various options for applying UV radiation to the printed object have been analyzed and studied, some options for UV material curing include:

1. Concurrent curing

Radiation is applied during the 3D printing process, meaning it is constant. This allows the light to penetrate more deeply into the material, improving mechanical properties and enabling rapid and controlled solidification.

2. Post-printing curing

UV radiation is applied after the 3D printing process is completed. This improves mechanical properties and water resistance.

3. UV curing combined with other methods

UV curing is applied along with other curing methods such as chemical cross-linking or thermal curing.

This prompts us to consider which curing type will be optimal for our objective. Therefore, it would be great to study the material's properties after subjecting it to concurrent curing and post-printing curing and, based on the results, decide which type of curing is suitable for 3D printing of dental implants.

We have ruled out the UV curing method combined with other ways, such as heat application, and it will not be tested on our prototype. This is because the resins we will use in the printing process cannot be cured with heat, rendering it ineffective and yielding no results.

However, we must consider that the UV lamp (Translux Wave lamp, Kulzer) works with a battery, so a system must be developed to connect the lamp to the printer motor and hold the lamp in place to cure the resins during printing.

As this process is complex and time-consuming to develop, we will manually cure the resins with this lamp after printing for the study of printing properties.

5 Changes in the Prototype

The existing prototype presents a significant problem that limits us during printing. This problem consists of the nozzle being pushed down too forcefully by the piston during the extrusion process, causing it to touch the printing bed, which prevents proper resin extrusion.

Therefore, instead of designing a piece in CAD and requesting a quote, as this involves a significant investment of time and money due to the company's waiting times, we have decided to create a piece in the workshop.

Firstly, we took measurements of the different holes and distances, using the existing piece as a reference.
Subsequently, we searched for some parts that could be used to create a similar piece, but this time more securely so that the force applied by the piston during the extrusion process would not move the piece containing the nozzle.

We found a good system by combining three different pieces, two of them new and one of them existing (into which the nozzle is inserted), and we joined them together using screws.

These three pieces are shown below in *Figure 5-1*:

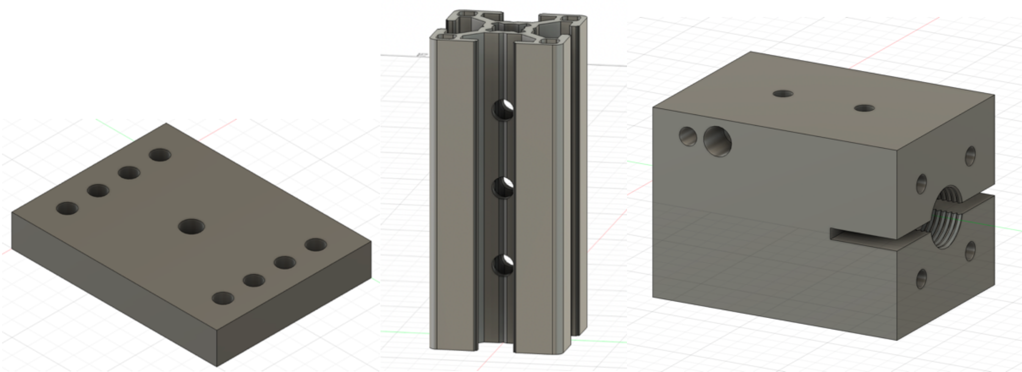

Figure 5-1: Separate pieces that are part of the updated piece for fixing the nozzle and cartridge to the main structure of the printer; On the left, the silver

fixation; In the center, the aluminum profile with holes; On the right, the piece in which the cartridg and nozzle are inserted

The resulting piece is shown in *Figure 5-2* and *Figure 5-3*:

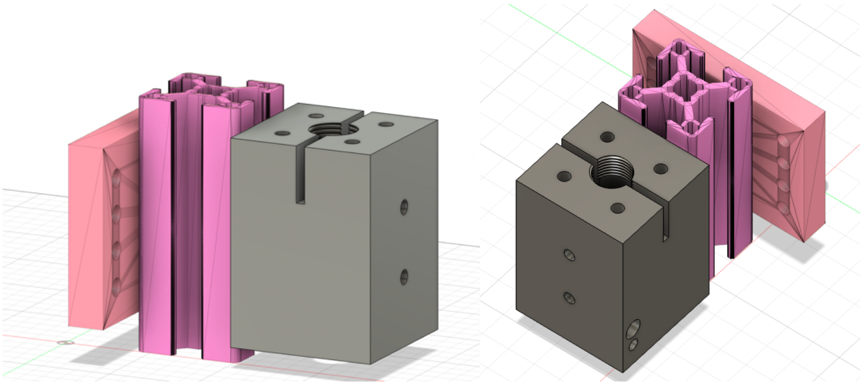

Figure 5-2: Updated piece for fixing the nozzle and cartridge to the main structure of the printer (CAD version)

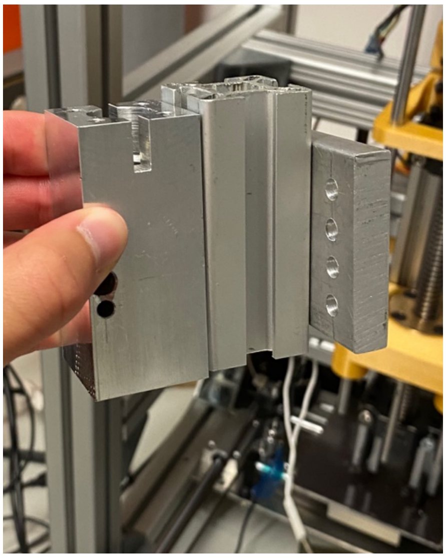

Figure 5-3: Updated piece for fixing the nozzle and cartridge to the main structure of the printer

Finally, once we have the piece, we attached it to the prototype using additional screws, and it ended up looking as we can see in *Figure 5-4*:

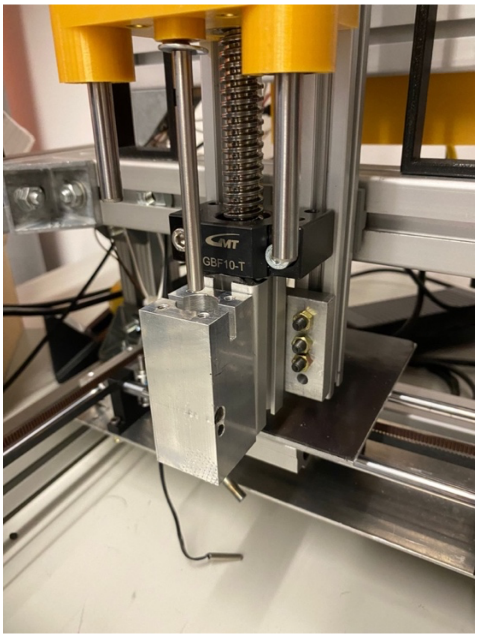

Figure 5-4: Actual protoype after changing the piece for fixing the nozzle and cartridge to the main structure of the printer

After making some initial test impressions, we noticed other flaws in the prototype.

One of them was the issue of material adhesion to the printing bed. The material was unable to stay fixed on the printing bed even after applying the special 3D printing adhesive DimaFix.

As a solution to this problem, we found a 3D printing adhesive that requires a lower temperature (40-60 ºC) to activate, as opposed to Dimafix, which needed slightly higher temperature (65 ºC) and perhaps that's why the adhesion wasn't working.

This new adhesive is called Magigoo, and just like Dimafix, it is applied on top of the printing bed before each print.

Additionally, to help address this issue, we have also requested two new printing beds, but this time with a rough surface instead of a smooth one, which theoretically should help improve resin adhesion.

Another problem that arose was that when changing the aforementioned part, the nozzle was too close to the printing bed, causing the material to get stuck to the underside of the part while being extruded. This made it very difficult for the material to be deposited correctly.

Therefore, we designed new parts in CAD using the Fusion 360 program with the aim of replacing some existing parts in the prototype. These parts are located beneath the printing bed and provide height, measuring 9 mm in height.
So, we designed the same parts with heights of 8 mm and 7 mm to replace the 9 mm ones and create more space between the nozzle and the printing bed, thus achieving better printing quality.

The parts were subsequently 3D printed, and finally, the 8 mm ones were used.

In *Figure 5-5* relevant parts are shown:

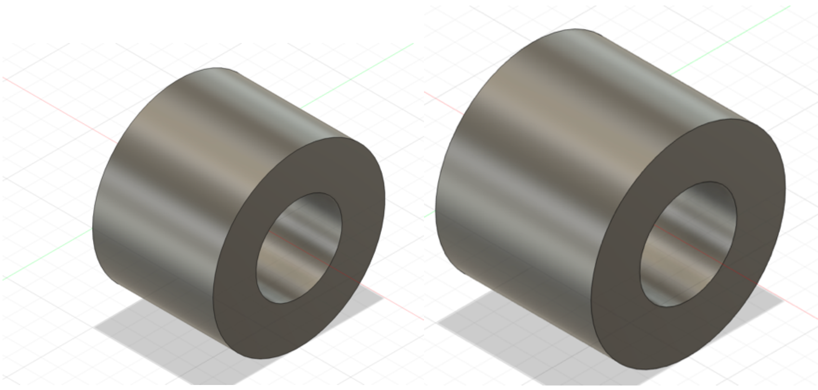

Figure 5-5: New spacers to place between the printing bed and the base of the printer; On the left, 7 mm in length; On the right, 8 mm in length

6 Experimental Method

6.1 Fractional Factorial Method

We need to establish a method to conduct the experiments most efficiently, that is, trying to minimize the number of prints required, thereby saving time and material.

To achieve this, we have decided to use a fractional factorial method, which involves varying multiple parameters in each print instead of keeping all parameters constant and varying only one. Additionally, for each set of conditions established, we need to perform three repetitions of the print to obtain more meaningful results.

To apply the fractional factorial method, it is necessary to first understand and analyze it in depth.

Fractional factorial designs are designs in which the number of experiments is a fraction of the number of experiments for the corresponding full factorial design. In other words, the 2^{k-p} fractional factorial design is a fraction of the full 2^k factorial design. This method is employed when conducting 2^k experiments is too demanding in terms of time and resources.
The 2^{k-p} design will consist of k factors, where $k > 2$, and p can take any value.
This method is based on the idea that it allows sacrificing less important information by reducing the number of experiments required. It also relies on the assumption of factor diversity, which suggests that a small fraction of the factor effects is significant for a process. In contrast, the rest of the effects are negligible for practical purposes.
This allows for obtaining the information with the minimum number of experiments and with the least possible uncertainty. [44]

To conduct an experiment using the fractional factorial method, we must follow the following steps:

1. Identification of the parameters to be studied and the experimental domain

For example, in a 3D printer, the factors can be temperature, printing speed, etc. Besides knowing which factors will be studied, we must understand the possible values they can take.

If the factors are continuous, their experimental domain will be expressed with the maximum and minimum values they can take. The most common encoded notation for continuous factors consists of using the value -1 for the lower end of the experimental domain and the value +1 for the upper end. Often, only - and + are indicated for simplicity. It is necessary to define the correspondence between real and encoded variables because the design of experiments describes optimal experimentation using encoded variables $(x1, x2, \dots)$ without dimension. This way, mathematical and statistical tools are general and can be applied to each problem. [45]

2. Creation of a design matrix that contains all possible combinations

Has we have already mentioned, the 2^{k-p} design will consist of k factors, where $k > 2$, and p can take any value.

The matrix for this design will be constructed considering that the p number of factors will be combinations of the remaining factors. This is called the design generator, and the experimenter will choose it.

For example, for a design with seven factors $(A, B, \dots, G)$ and $p = 2$, which means $2^{7-2} = 25$, the matrix is constructed in such a way that the columns for the first five factors are the same as in a complete 2^5 design, while the last two factors, F and G, combine of the other factors. The most commonly used design generator for this design would be $F = ABC$ and $G = ABD$. [44]

As a clarification, we can say that design generators are specific combinations of factors used to construct the design matrix. They are chosen carefully to ensure that the factors' most relevant interactions and main effects are captured while reducing the total number of experiments.

3. Experiment planning and execution

Next, the matrix of experiments is refined for our study by replacing the + and - values of the encoded variables with the values of the real variables. This results in the experimental plan, which comprises a structured and easily understandable list of experiments to be conducted. Once it has been verified that all experiments are feasible, they are carried out. [45]

4. Analyze the obtained results

You can use statistical techniques to evaluate each factor's impact and their interactions. For example, an analysis of variance (ANOVA) can help determine the significant influence of each factor and if there are relevant interactions. [45]

Once we have analyzed the method and know how to apply it, we proceed to apply it to our experiment:

6.1.1 Identification of the Parameters to be Studied and the Experimental Domain

In this project, we are searching for optimal printing parameters to obtain an optimal product.
To do this, we have studied those printing parameters that are variables and that affect the printing. Based on the values of these parameters already used in previous prints, we will make some prints by varying some of these parameters to study the changes that the material presents and, with this, possible improvements in the print quality. [44], [46]

Firstly, the parameters that affect the product quality and that we are going to analyze are the following:

1. Temperature (ºC)

It is set to 65ºC because it was determined in Özge Özoy's work. [5]

It is important to know that with a higher temperature, the material will be extruded more quickly, because of the viscosity dependence on the temperature.
It is also important to know that with a higher temperature, there is not only one change, an increase in printing speed, there are some issues, such as poor adhesion.

Higher printing speeds can reduce contact time between the material and the printing bed, potentially leading to weaker adhesion. Finding the right balance between speed and adhesion is essential to ensure successful prints.

Considering the adhesive problem has already been solved with the Magigoo adhesive, then it is not necessary to change the parameter temperature in PrusaSlicer and it is going to be set to 65ºC for all the experiments.

2. Extrusion multiplier

This parameter determines how much plastic the printer is going to extrude.

It is possible that there may be more or less material exiting the nozzle than what the software expects, otherwise known as Over-Extrusion or Under-Extrusion.

For PLA it is typical to print with an extrusion multiplier near 0.9, ABS tends to have this parameter closer to 1.0.

If we see Over-Extrusion in the sample we will try to decrease the extrusion multiplier by 5%, and in the same way, if we see Under-Extrusion, we will try to increase the extrusion multiplier by 5%. [47], [48]

In the first print we notice Under-Extrusion with a value 0.9 so we are going to try to print with 1 and 1.1 as values.

3. Extrusion rate (mm/s)

In PrusaSlicer, this parameter is set to 20 mm/s by default.

It should be noted for this parameter that with a higher extrusion rate, the material is extruded more quickly, resulting in greater flow. We must also take into account that with faster printing, the quality of the product may deteriorate because the material is not squeezed with the same accuracy.

Similarly, as happens with extrusion multiplier, we can try changing this parameter and analyze the variations. Whether the only thing that changes is an increase or decrease in printing speed or if we encounter any advantage or change.

We are going to use as the low value 10mm/s and as the high one 20 mm/s.

4. Retraction distance (mm)

It is a technique in which the material is moved backwards in the extruder to prevent it from continuing to extrude while the nozzle moves to another area of the print. This helps prevent the appearance of material strings between the print areas and improves the surface finish quality of the printed piece. [49]

This parameter, retraction, is configured in the slicer software. In general, both the retraction distance and retraction speed can be adjusted. Therefore, we will conduct tests by varying these parameters and analyzing the results until we obtain an optimal product and optimal values for these parameters.

In PrusaSlicer, this parameter is set to 2 mm by default. We are going to use 2 mm as the high level and 1 mm as the low one.

5. Curing method

Before the UV source was studied in this project, the samples were manually cured with a UV lamp after the impression.

A way to introduce the lamp into the test bench is being studied, and when it is possible to introduce it, then it will be possible to study what curing method is optimal for the samples. As we had already mentioned, there are different curing methods, like curing the material during or after the impression.

For a manual use of the lamp, is important to held it on as close as possible to the sample and during approximately 20 s.
Also, it is essential that the person who cure the sample wears the protective glasses, as it is said before, UV light can be dangerous for human health.

The maker of the lamp just determines these two parameters so we are not going to study them.

6. Adhesion of the extruded material

It is important that the material already deposited on the printing bed can adhere correctly to the extruded material, thus favoring the uniformity and consolidation of the implant.

To facilitate good material adhesion, it is important to consider the properties of the printing bed, such as its roughness or temperature, as they can affect adhesion.

In previous projects, it was observed that the material did not adhere properly, so it was decided to use a suitable adhesive glue for 3D printing beds (Dimafix pen, Dimafix). For these new experiments we are going to use a different printing bed adhesive (Magigoo adhesive, Magigoo). Thanks to its use, the material adheres better to the surface.

Regarding this factor, we have observed that in cases where it has been printed without the use of adhesive on the printing bed, the samples have shown very poor results. Therefore, we believe that this parameter would be optimal at its highest level, which means using the adhesive.

So we will not study this parameter in the experiments and will use the adhesive in all of them.[5]

In *Table 6-1*, we can observe the k factors that will be studied in this experiment ($k = 3$):

Table 6-1: Fractional factorial method factors

Factors $(x_1, \dots, x_k)$	
x_1	Extrusion multiplier
x_2	Extrusion rate (mm/s)
x_3	Retraction distance (mm)

In *Table 6-2*, we can also observe the experimental domain of each factor, which includes the level - (minimum possible value) and level + (maximum possible value):

Table 6-2: Fractional factorial method experimental domain

Experimental domain	Level -	Level +
x_1	1	1.1
x_2	10	20
x_3	1	2

6.1.2 Creation of a Design Matrix that Contains All Possible Combinations of the Factor Levels

Table *6-3* shows the experiment matrix obtained by combining the two levels of the 3 factors. To carry out the experiment using the fractional factorial design method, we have used the value 1 in place of p, so the employed design will be 2^{3-1}.

The number of combinations and therefore the number of experiments we need to perform is 4, and the design generator will be $x_3 = x_1 x_2$.

Table 6-3: Fractional factorial method design matrix

Experiments	x_1	x_2	x_3

1	-	-	+
2	+	-	-
3	-	+	-
4	+	+	+

6.1.3 Experiment Planning and Execution

In *Table 6-4,* we have replaced the + and - values of the encoded variables in the Design matrix in *Table 6-3*, with the values of the real variables:

Table 6-4: Fractinal factorial method real values design matrix

Experiments	x_1	x_2	x_3
1	1	10	2
2	1.1	10	1
3	1	20	1
4	1.1	20	2

We are going to name the four experiments based on the influence of various factors, with Experiment 1 as the reference. Thus, in *Table 6-5*, we can observe a more technical name for the previously mentioned experiments:

Table 6-5: Technical names of the experiments

Experiment Number	Experiment Name
1	Baseline experiment
2	Influence of extrusion multiplier and retraction distance on the baseline experiment
3	Influence of extrusion rate and retraction distance on the baseline experiment
4	Influence of extrusion multiplier and extrusion rate on the baseline experiment

After the complete experiment is planned, we assess the feasibility of all the experiments before proceeding with their execution.

In addition to verifying the feasibility of conducting the experiments, a list of necessary materials is required to proceed with the printing.
To create this list, we need to consider that each experiment must be repeated three times, which means we will perform 12 prints.

To calculate the required quantity of Charisma resin cartridges, we need to consider that each cartridge contains 4g of material, and the density of this material is 2.1g/cm³.
Since we will be printing 2x2cm squares with a height of 0.5mm (inner nozzle's diameter), each square will have a volume of 0.2cm³ and weigh approximately 0.42g.

We will need 5.1g of resin. Now including some material waste between prints, we would need around four cartridges, as shown in *Table 6-6*:

Table 6-6: Materials required to perform 12 prints of a square measuring 2x2 mm

Material	Units
Resin cartridge (Charisma Topaz, Kulzer group)	7
Nozzle with 0.5 mm inner diameter	2

6.2 Softwares

In addition to studying the parameters and conducting experiments, it is crucial to understand how the printer and the necessary software work.

The following programs we explain below are essential, as they are used to carry out the design process of the piece, program the desired printing parameters, and establish the connection and control of the printer.

6.2.1 Autodesk Fusion 360

The first step consists of designing the part that is to be printed in a CAD program. In the case of this project, the program Autodesk Fusion 360 is used. It is also common using Solidworks.

To conduct the experiments, a simple shape such as a square will be employed. Therefore, the desired size square is designed in the Fusion 360 program.
For the square to be printed, we have used dimensions of 2x2 cm, as shown in *Figure 6-1*:

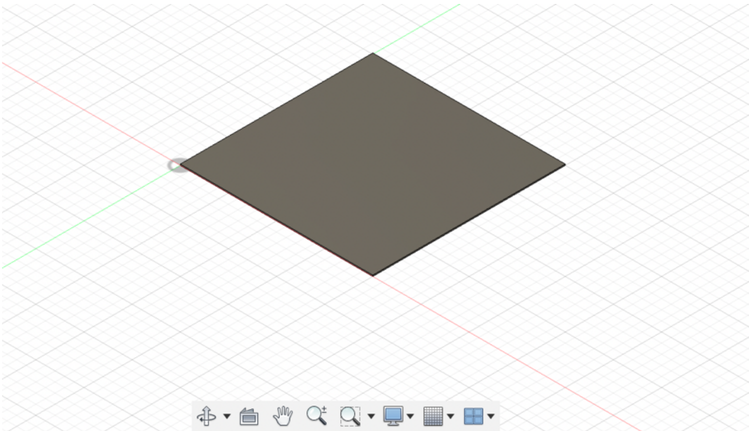

Figure 6-1: Square in Autodesk Fusion 360

6.2.2 PrusaSlicer

After designing the product to be printed, the file in which it is located must be sliced in software such as PrusaSlicer.

PrusaSlicer does not support Autodesk Fusion F3D file format, so we export the file to a compatible format such as STL, OBJ, or 3MF, then import it into PrusaSlicer. In our case, we have exported it in STL format.
The slicing process defines the printed layers and generates the G-code, which will be sent to Pronterface, the next program we will use.

In this program, we will change the parameters for the different experiments. For each parameter, we must follow the following path within the program:

1. Temperature

Filament settings: Filament: Temperature: Nozzle.

2. Extrusion multiplier

Filament settings: Filament: Filament: Extrusion multiplier.

3. Extrusion rate

Print settings: Speed: Modifiers: First layer speed.

4. Retraction distance

Filament settings: Filament Overrides: Retraction: Length.

6.2.3 Pronterface

The Proterface software is used to control the 3D printer. It has a control panel that can be manually operated, allowing you to select parameters such as the movements performed by the extruder, temperature changes, or the start and end of the printing process.

Therefore, it is in this program that our previously generated slicers, using Prusaslicer, will be uploaded along with the necessary G-code to carry out the printing.

In *Printing steps*, the steps to follow for printing with this program will be explained.

6.3 Printing steps

Once we have the necessary files on our computer, we proceed with the printing process using the following steps:

1. Spread the 3D printing bed adhesive (Magigoo adhesive, Magigoo) over the entire surface of the printing bed to ensure proper material adhesion. It is important to clean the printing bed with isopropyl alcohol after printing to remove any adhesive residue.

2. Connect the prototype to the computer using a USB connection, and use the *Connect* button in the Pronterface program to establish a connection with the printer as you can see in *Figure 6-2*:

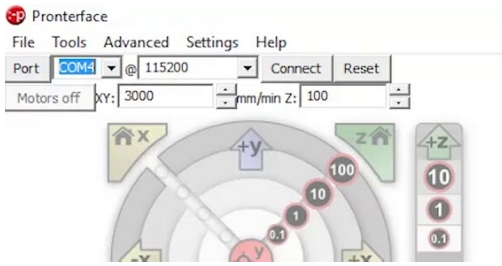

Figure 6-2: Pronterface commands I

3. Use the *Reverse* button to retract the extruder, allowing us to place the Charisma Topaz resin cartridge. In *Figure 6-3* you can see this button:

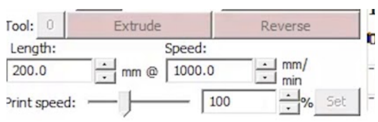

Figure 6-3: Pronterface commands II

4. Once the cartridge is in place, reinsert the metal extruder and tighten it securely to ensure strong extrusion.

5. In Pronterface, select a temperature that will be 60ºC to 65ºC, use the *Set* button (shown in *Figure 6-4* and wait approximately 5 minutes for the temperature to reach the desired level.

Figure 6-4: Pronterface temperatre commands

6. Load the slicer we previously edited with Prusaslicer in Pronterface using the *Load file* button, and configure the temperature settings in that file.

7. After the 5 minutes, we can proceed with the printing process by clicking the *Print* button in Pronterface (see *Figure 6-5*).

Figure 6-5: Pronterface commands III

8. Once the printing process is complete, the resin should be cured using a UV light lamp. To do this, we must put on UV protective glasses and apply the light as close as possible to the resin for 20 seconds. We should do this in all areas of the printed piece until the piece is completely cured.

6.4 Properties to Analyze

To determine which experiment, and therefore, which parameters, yield a better product, it will be necessary to examine some of its important properties, paying particular attention to those that have the greatest impact on the product due to its application. [50]

1. Print quality

First, we will determine the print quality by analyzing the piece through observation, using a microscope if necessary. This will allow us to assess factors such as accuracy, details, presence or absence of defects, smooth surface, etc.

2. Print time

We will also consider the print time of the piece in each of the experiments, as this will help us evaluate whether certain parameters offer greater efficiency and productivity or if this is independent of the selected parameters.

3. Material consumption

Just as minimizing time is important for a more effective process, minimizing material consumption is important for both cost reduction and waste reduction.

According to various dental clinics that perform dental implants, dental implants must have excellent biocompatibility and viable fixation between the alveolar bone and mucosal tissue. [51]

4. Biocompatibility

We know that our product exhibits biocompatibility as it has already been approved for this use and is currently used in the dental field for implant applications.

5. Stable fixation

A stable fixation between the bone and the mucosal tissue will be the responsibility of the dental professional who places the implant in the patient.

7 Results and Discussion

After designing the experiments and determining the parameters to be varied in each of them, we proceed with their execution and the analysis of the obtained results. We are going to analyze the 12 prints and draw conclusions that will help us understand the effect of each parameter.

7.1 Experiment One: Baseline Experiment

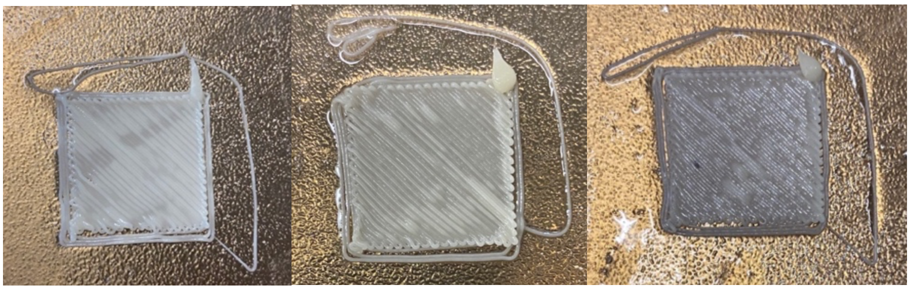

Figure 7-1: Baseline experiment (Experiment 1), T_65_EM_1_ER_10_RD_2_; On the left side, repetition 1; In the center, repetition 2; On the right side, repetition 3

After conducting Experiment 1, in which the values for the three varying factors were set at 1 for extrusion multiplier, 10 mm/s for extrusion rate, and 2 mm for retraction distance, we can observe the results of the three repetitions in the previously shown figure (*Figure 7-1*).

Regarding print quality, we can observe that the perimeter is printed quite straight, following the square pattern. As for the infill, it is fairly uniform without any folding, indicating that the nozzle-to-printing bed distance is appropriate, as well as the extrusion multiplier parameter, which prevents the Under-Extrusion phenomenon observed in some previous prints with the prototype.

In terms of details, we can see that the outer square designed to protect the part is not printed in any of the repetitions. This may be due to the fact that, being a single resin filament and the first one deposited, it lacks material to adhere to on the printing bed, causing it to drag and leave a trail of resin outside the square. To address this issue, the adhesion of the resin to the printing bed should be improved, despite changing the adhesive to one that activates at a lower temperature and switching from a smooth printing bed to a rough one.

Another detail that can be observed in all repetitions of this experiment is the blob of resin deposited when the printing is finished in the right corner. This is obviously due to the extruder applying pressure on the cartridge even after the print is completed, causing the material to continue oozing out.

One manual way to solve this imperfection is to press the *Reverse* button in Pronterface for a minimum value of 2 mm. This retracts the extruder and prevents resin from dripping, which also helps to conserve material during printing.

Another more technical and professional way to prevent this from happening would be by adjusting the retraction distance parameter in PrusaSlicer. As we have explained, by doing so, it is possible to prevent the occurrence of material leftovers and improve print quality.

As for the printing time, it has remained constant at a value of 60 seconds for all three repetitions of this experiment.

For this experiment, one cartridge of resin (Charisma Topaz, Kulzer Group) was consumed, and there was no need to switch to a second cartridge during the experiment. This facilitated both the execution of the experiment and material savings. Additionally, more material could have been saved if the *Reverse* button had been pressed after completing the print, as mentioned earlier.

7.2 Experiment Two: Influence of Extrusion Multiplier and Retraction Distance on the Baseline Experiment

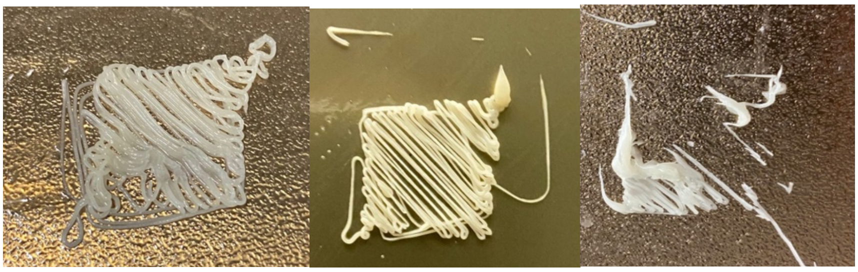

Figure 7-2: Influence of extrusion multiplier and retraction distance (Experiment 2), T_65_EM_1.1_ER_10_RD_1_; On the left side, repetition 1; In the center, repetition 2; On the right side, repetition 3

After conducting Experiment 2, in which the values for the three varying factors were set at 1.1 for extrusion multiplier, 10 mm/s for extrusion rate, and 1 mm for retraction distance, we can observe the results of the three repetitions in the previously shown figures (*Figure 7-2*).

Regarding print quality, we can observe that the perimeter is printed only in repetitions 1 and 2, and it is not straight. Additionally, the perimeter is formed by two filaments, and in these repetitions, the filaments do not align in the same space, each one is printed in a different location. As for the infill, in repetition 1, it is not uniform and exhibits some folding, while in repetition 2, although it is more uniform, the lines forming the infill are not properly connected, leaving large gaps between them.
Despite maintaining the appropriate nozzle-to-printing bed distance from the Baseline experiment, the extrusion multiplier parameter, with a value of 1.1, likely had an impact as increasing it by 10% resulted in a significant decrease in the Under-Extrusion phenomenon.

Regarding the material buildup in the upper right part, it is still present, indicating that the change in 1 mm of retraction distance has had no effect.

As for the details, we can see that the outer square designed to protect the part is not printed in any of the repetitions, just like in the Baseline experiment.

In repetitions 1 and 2, a figure similar to the intended one (square) is achieved. However, in repetition 3, it appears that only the bottom-left part starts to print, and the rest of the area is empty. This is because during this experiment, there was more material waste, and by the time repetition 3 was reached, the cartridge ran out of resin, preventing the square from being completed.

As for the printing time, it has remained constant at a value of 60 seconds for all three repetitions of this experiment.

One cartridge of resin (Charisma Topaz, Kulzer group) was used for this experiment, but as can be seen, it was not sufficient, and an additional cartridge would have been needed to print a third square. In this experiment, there was greater material wear as we had to conduct preliminary tests before the official prints since the material was not adhering properly to the surface.
Finally, through trial and error with both the rough printing bed (repetitions 1 and 3) and the smooth printing bed (repetition 2), the necessary adhesion was achieved to carry out the prints.
This leads us to believe that the adhesion is still not optimal, as all the experiments should be able to be conducted using the same printing bed.

7.3 Experiment Three: Influence of Extrusion Rate and Retraction Distance on the Baseline Experiment

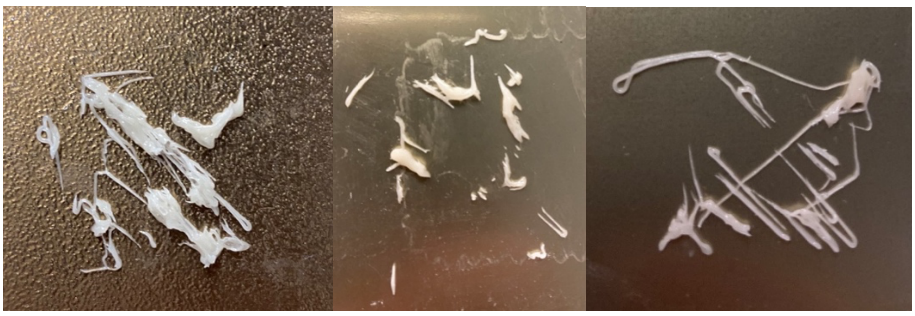

Figure 7-3: Influence of extrusion rate and retraction distance (Experiment 3), T_65_EM_1_ER_20_RD_1_; On the left side, repetition 1; In the center, repetition 2; On the right side, repetition 3

After conducting Experiment 3, in which the values for the three varying factors were set at 1 for extrusion multiplier, 20 mm/s for extrusion rate, and 1 mm for retraction distance, we can observe the results of the three repetitions in the previously shown figures (*Figure 7-3*).

Regarding print quality, we can observe that the perimeter is not printed in any of the three repetitions. As for the infill, in repetition 1, it is not uniform, there is only infill in a few areas, and it exhibits folding and overlapping material. As we suspected that this could be an adhesion issue, similar to experiment 2, we decided to switch to a smooth printing bed to see if the adhesion would improve.
However, in repetition 2, we mainly observe some resin fragments that have stuck to the printing bed.
In repetition 3, we can see that the movement to generate the square has been executed correctly, but there is not enough material deposited. This may be due to the increased extrusion rate, which does not allow for proper material deposition, as the nozzle-to-printing bed distance is appropriate, consistent with the Baseline experiment.

As for the printing time, it has remained constant at a value of 50 seconds for all three repetitions of this experiment.

Two cartridges of resin (Charisma Topaz, Kulzer group) were consumed for this experiment. In this experiment, there was greater material wear as we had to conduct preliminary tests before the official prints due to the material not adhering correctly to the surface and not achieving the desired figure. Finally, we have concluded that this may be due to the parameter changes or an unknown external factor.

7.4 Experiment Four: Influence of Extrusion Multiplier and Extrusion Rate on the Baseline Experiment

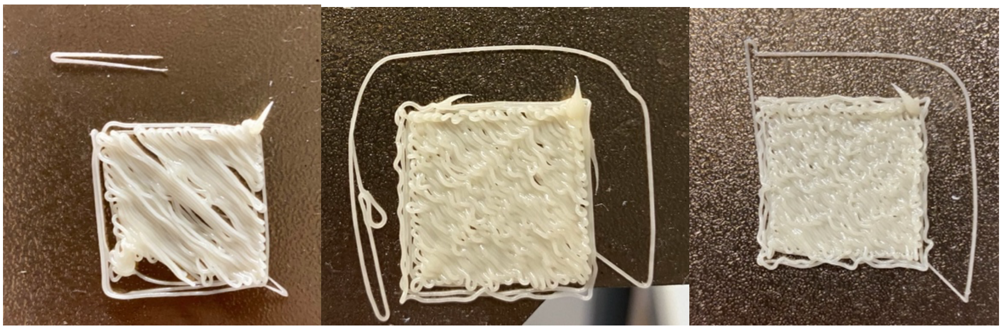

Figure 7-4: Influence of extrusion multiplier and extrusion rate (Experiment 4), T_65_EM_1.1_ER_20_RD_2_; On the left side, repetition 1; In the center, repetition 2; On the right side, repetition 3

After conducting Experiment 4, in which the values for the three varying factors were set at 1.1 for extrusion multiplier, 20 mm/s for extrusion rate, and 2 mm for retraction distance, we can observe the results of the three repetitions in the previously shown (*Figure 7-4*).

Regarding print quality, we can observe that the perimeter is printed following the square pattern. As for the infill, it is fairly uniform, leaving some gaps in repetition 1, but completing the entire square for repetitions 2 and 3. As for the folds observed in all repetitions, which increase in repetition 2 and even more so in repetition 3, they may be due to the nozzle-to-printing bed distance not being appropriate. However, this distance has remained unchanged at 2 mm, so it raises the question of what could be causing these folds.

We dismantled the piece containing the nozzle to examine if anything has changed inside that could be causing the excess of material. As we can see in *Figure 7-5*, the resin has not only exited from the cartridge to the nozzle but also around it. We believe that this may be associated with the significant force, approximately 70 kg, exerted by the extruder on the cartridge and nozzle, displacing them downward and shifting the part that holds the nozzle and creates a sealed area. As a result, the material has managed to escape, and we believe that this issue is the source of the excessive material and folds factor observed in the samples.

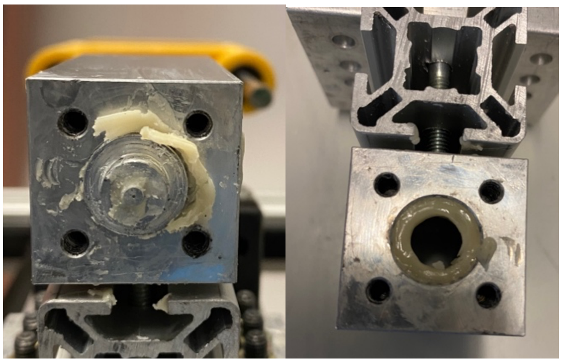

Figure 7-5: Resin leaking from the sealed area

Regarding the details, we can see that, just like in the Baseline experiment, the outer square designed to protect the piece is not fully printed in any of the repetitions. As mentioned before, this could be due to a lack of adhesion.

Another detail that has changed compared to the Baseline experiment is the resin blob in the right corner. The amount of deposited resin has significantly decreased by retracting the extruder immediately after completing the print (retraction speed value ist he same).

As for the printing time, it has remained constant at a value of 50 seconds for all three repetitions of this experiment.

For this experiment, one cartridge of resin (Charisma Topaz, Kulzer group) has been used, and there was no need to switch to a second cartridge during the experiment. This has facilitated both the execution of the experiment and material savings.

7.5 Discussion

Thus, after thoroughly analyzing all the experiments, we can compare experiments 1, 2, and 3 among themselves. However, experiment 4, despite successfully printing the squares, cannot be compared to the others because it was not carried out under the same conditions due to the issue that arose with the resin and the piece.

It is evident that, based on the factors we have analyzed, the Baseline experiment is the best of the three, considering the print quality and the minimal material waste, which can be further reduced.

Regarding the parameters we have modified, we will conduct an analysis to determine the optimal values.

Referring to the extrusion multiplier parameter, which we have tested with values of 1 and 1.1, it can be deduced from the experiments that a better result is obtained with a value of 1 for this parameter. This can be inferred from experiment 1, where a uniform figure is observed, while in experiment 2, using 1.1, there are significant gaps between the resin strips.

As for the extrusion rate parameter, it can be considered that a good value is 10 mm/s based on experiment 1, as in experiments 3 and 4, where the speed is increased to 20 mm/s, the results are not as satisfactory. This may be because increasing the speed, which affects the force exerted, amplifies the force exerted by the extruder on the nozzle, leading to the issue observed in experiment 4. The time, which is also related to this factor, is set at 60 seconds for 10 mm/s and 50 seconds for 20 mm/s. It does not vary much for now because it is a small piece, but when printing larger quantities or larger pieces, it may be important to save time. It would be necessary to study if it is possible to print at 20 mm/s without encountering the mentioned issue.

For the retraction distance parameter, a higher value is better to eliminate the material buildup observed at the end. Therefore, it would be preferable to try a value of 2 or even higher.

Therefore, we have taken its measurements to further analyze the perfection of the different repetitions. We have measured the length, width, and thickness at three different points on each sample. Considering the desired values, 20 mm for both length and width and 0.5 mm for thickness, we can observe the existing variations for each of these measurements in the different repetitions.

Baseline experiment (experiment 1) results are shown in *Figure 7-6, Figure 7-7* and *Figure 7-8:*

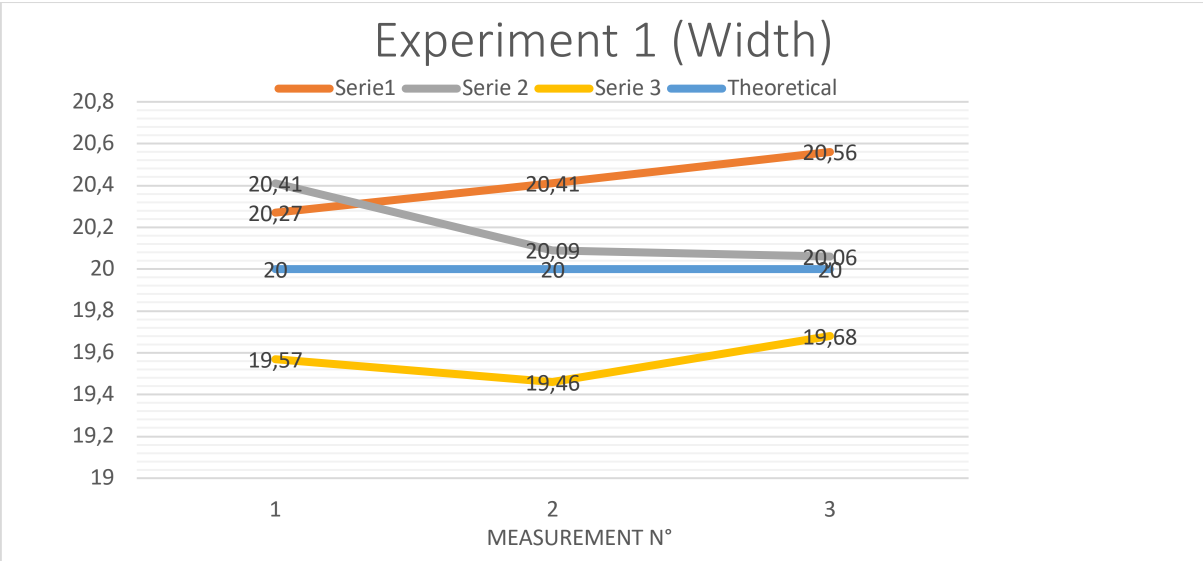

Figure 7-6: Variations in width (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 1)

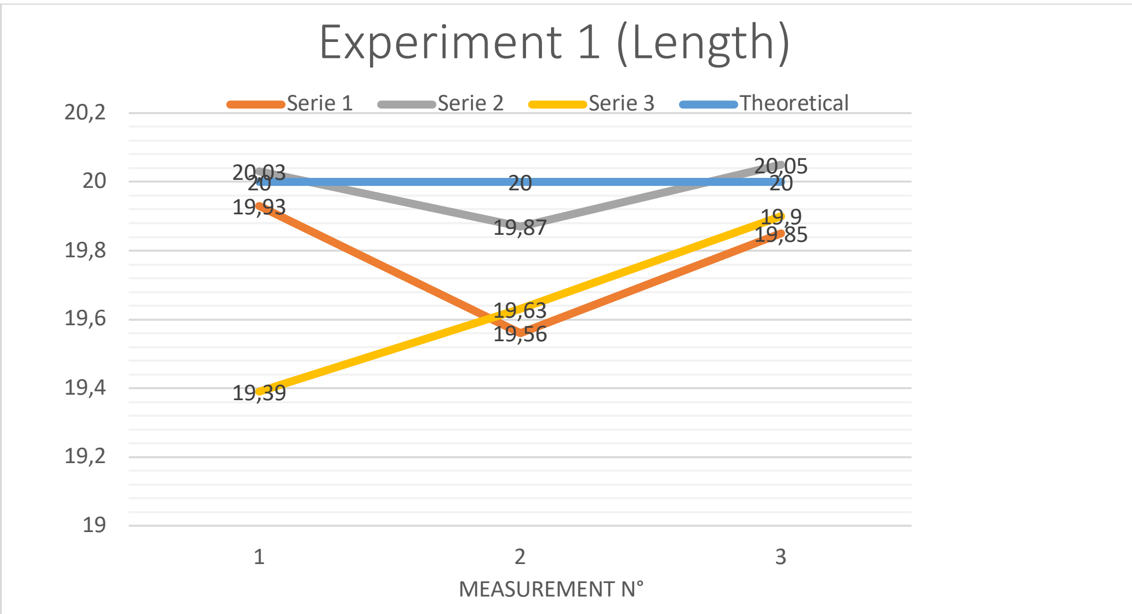

Figure 7-7: Variations in lenght (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 1)

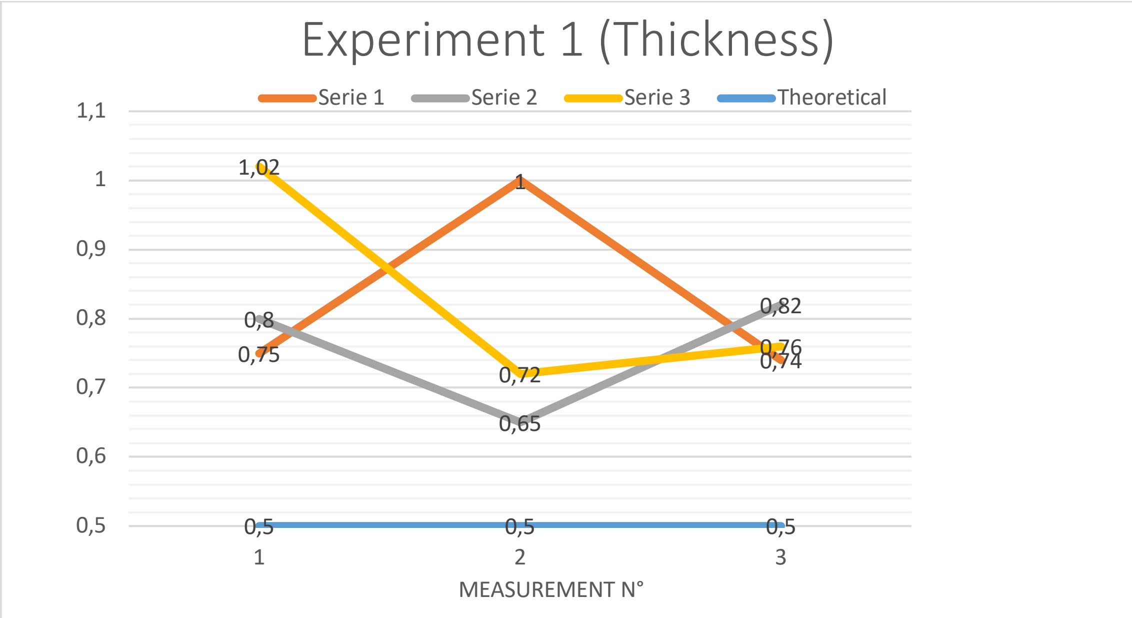

Figure 7-8: Variations in thickness (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 1)

Despite the failure encountered in Experiment 4, measurements have also been taken for the different repetitions, and the results are shown in *Figure 7-9, Figure 7-10* and *Figure 7-11*:

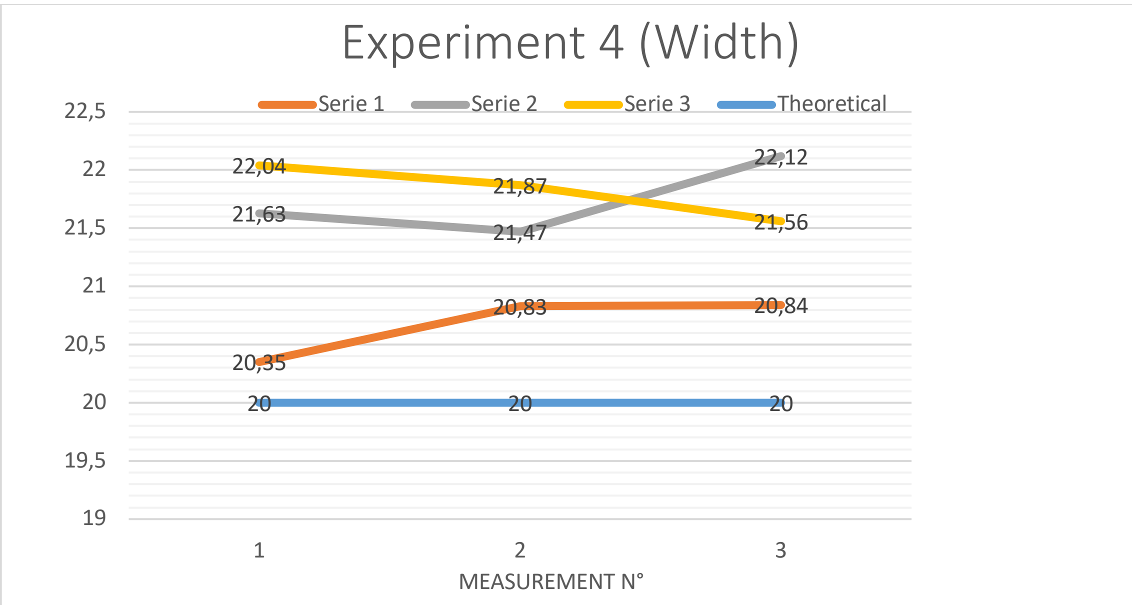

Figure 7-9: Variations in width (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 4)

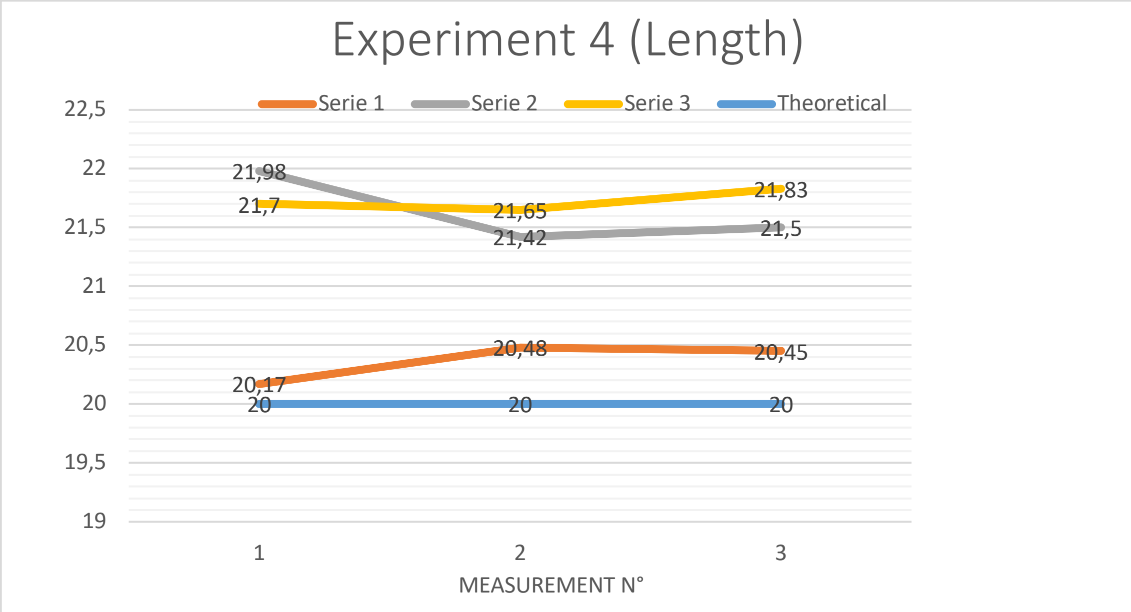

Figure 7-10: Variations in lenght (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 4)

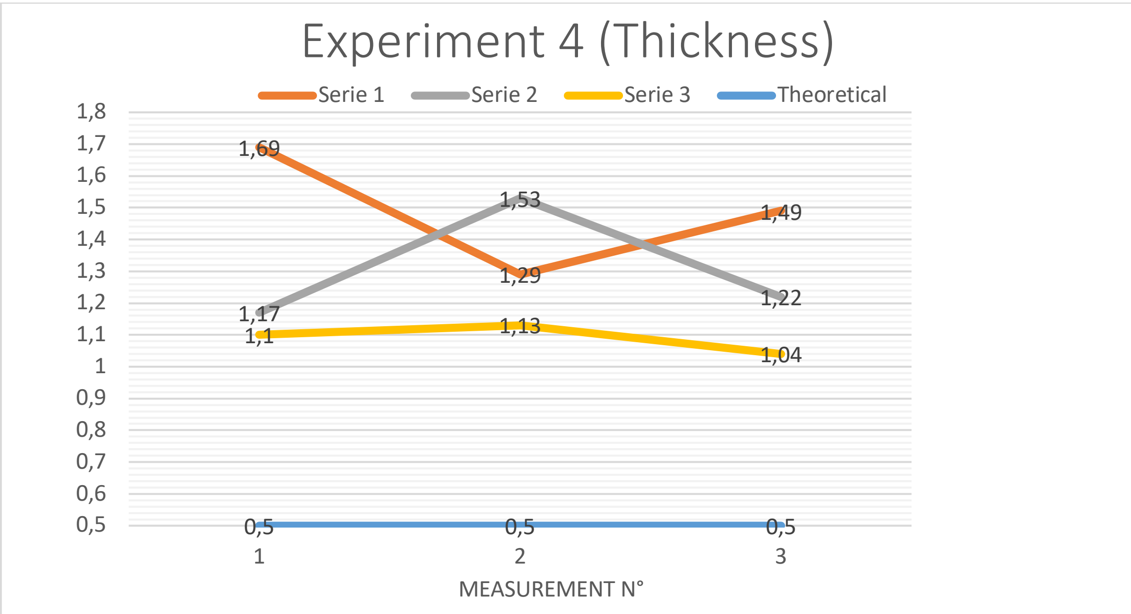

Figure 7-11: Variations in thickness (mm) at three different points of the squares of repetitions 1, 2, and 3 (Exp 4)

After analyzing all the graphs, we can state that, although the measured values are close to the desired ones, they vary significantly and cannot be considered stable. Regarding the Baseline experiment (Exp 1), all the measurements are below the desired values, whereas in the experiment where we studied the influence of the extrusion Multiplier and extrusion Rate (Exp 4), all the measurements are above them.

Obviously, as we have already mentioned, the excess material in experiment 4 is due to the issue related to the output and, therefore, abundance of material. As for the slight lack of a few thousandths of mm in the different measurements of the Baseline experiment, it may be due to the material not adhering correctly, resulting in the printed figure not reaching the desired outcome.

Several improvements that need to be implemented in the prototype should also be considered to avoid issues like those encountered in experiments 2 and 3, related to adhesion, or in experiment 4, related to weight.

After working with the printer and observing its behavior, I propose some changes that I believe will help achieve better results:

- Material Adhesion to the Printing Bed

The lack of material adhesion to the printing bed remains a problem in the prototype, despite changing to a glue that activates at a lower temperature and experimenting with different textures of the printing bed (smooth and rough).

While there has been a significant decrease compared to the initial tests thanks to these changes, it is still necessary to adjust, such as changing the printing bed or the amount of glue, in some of the repetitions to achieve the desired adhesion.

This parameter should be consistent throughout the process, meaning the same glue and the same quantity should always be applied, and the same type of printing bed texture should be used. This would save time and material since pre-printing adhesion tests would not be necessary.

Some proposed improvements for this issue could include:

1. Testing different printing bed surfaces

As we have already mentioned, the textures of the printing bed are crucial. In addition to the ones already tested, we could investigate if there are any other alternatives in terms of texture or even material. Some printing beds are made of glass for example. Since each material will have its own properties, it's possible that another one may enable resin adhesion.

2. Testing different adhesives

If the glue we are currently using is still not optimal, we can try one that provides sufficient adhesion. In addition to adhesive glues like the one we are currently using, there are other types such as spray adhesives or adhesive films.

3. Adding temperature to the printing bed

A slightly more complex option would be to add temperature to the printing bed so that it also heats up like the nozzle. This way, the problem of adhesion could undoubtedly be improved.

- Weight Applied by the Extruder

As observed during the execution of Experiment 4, there is an issue related to the weight exerted by the extruder on the cartridge and the nozzle. This causes the nozzle to gradually move downward with increasing force after several prints, leading to a separation between the end of the cartridge and the beginning of the nozzle, resulting in material loss around the piece.

This is a significant problem as it leads to material waste and, as reflected in the three repetitions of Experiment 4, it prevents optimal and high-quality printing.

Some proposed improvements for this issue could include:

1. Optimize print settings

Reducing parameters such as print speed or flow rate may also reduce the tension on the extruder, thereby eliminating the downward displacement of the nozzle.

2. Implement regular maintenance and cleaning

One option, although it requires effort and manual work, could be to establish a maintenance and cleaning routine after each print. This routine can involve removing the extruder using the *Reverse* option in Pronterface and disassembling the nozzle component for cleaning and reassembly, ensuring it is tightly secured. This way, the strain does not accumulate with each print, preventing the point at which the weight becomes too much and causes the nozzle displacement.

3. Reinforce the support structure

The structure should be analyzed to identify the areas that contribute to the extruder movement. Once identified, reinforcing structures could be added to these areas to hold the extruder in place, distributing the force away from it and, consequently, away from the nozzle.

These are some improvement proposals for the prototype. Some of them have already been studied, but further investigation could lead to finding an optimal solution. Due to limited time, my research has been restricted, but I believe that the proposed ideas can be highly beneficial for future students working with the prototype.

8 Summary and Outlook

To conclude, we must highlight the use of the Kulzer UV light lamp (Translux wave lamp, Kulzer group) for resin curing, which provides optimal results and an excellent finish to the product. Its manual usage is sufficient to achieve the desired curing.

However, studying a structure that allows its attachment to the prototype to enable curing during printing is a good idea and a significant improvement in the prototype.

We must also highlight the various changes and improvements that have been made to the prototype. Among them, the ones that stand out the most for their impact on the results are: the replacement of the part that holds the cartridge and the nozzle, which has improved their fixation to the structure; the adjustment of the height of the washers lifting the printing bed, allowing us to achieve the desired distance between the nozzle and the printing bed; and the changes made to improve adhesion, such as using the printing bed adhesive (Magigoo adhesive, Magigoo) and the rough texture of the printing bed.

Despite solving some problems, other issues have been detected during the execution of the experiments, such as the high pressure and weight exerted by the extruder on the nozzle, causing material leakage and printing failures. Therefore, the project has proposed some solutions to this problem that could be highly useful for future work. These problems can be resolved, and then the experiments 1 and 4 can be conducted again to see if we obtain a perfect result with the established parameters.

We have also analyzed the influence on the print of three studied parameters, which we have modified in the PrusaSlicer software. These parameters are extrusion multiplier, extrusion rate, and retraction distance.

Using a fractional factorial method, we designed four experiments in which these parameters were varied with different values, and we conducted three repetitions for each of these experiments.

Based on the observed results, we have established 1 as the optimal value for extrusion rate, as with the value 1.1, we observed under-extrusion, and with 0.9 (used in previous tests), we observed over-extrusion.

For extrusion rate, we obtained better results with a value of 10 mm/s, but we are unsure if this is due to external factors. Therefore, this parameter would need to be analyzed individually. It is possible that the lack of good results with a value of 20 mm/s is because the increase in speed affects the force and, consequently, the structure of the prototype, hindering proper execution of the print.

Lastly, for the retraction distance value, 2 mm is the selected value, but not the optimal one, as we still observe material drooping at the end of the print. Thus, it would be a good idea to use a higher value such as 3 or 4 mm.

In conclusion, this project has been highly useful in developing many improvements both in the prototype and in the parameters used for printing. Thanks to these enhancements, progress has been made in the design of the 3D printer for dental implants, as well as identifying potential future improvements in order to achieve an optimal final product.

BIBLIOGRAPHY

[1] X. Rodríguez Campillo, “PROYECTO DE DISEÑO DE PIEZAS MODELADAS CON UNA IMPRESORA 3D PARA LA REALIZACIÓN DE PRÁCTICAS DE LABORATORIO DE LA ASIGNATURA DE RESISTENCIA DE MATERIALES Y TEORÍA DE ESTRUCTURAS,” 2018. Accessed: May 25, 2023.[Online].Available:https://upcommons.upc.edu/bitstream/handle/2117/126329/xavier.rodriguez.campillo_130960.pdf?sequence=1&isAllowed=y

[2] A. Blanco Prieto, “Estudio comparativo entre la obtención de piezas mediante impresión 3D y su obtención mediante moldes u otros procesos de fabricación.,” 2020. Accessed: May 25, 2023. [Online]. Available: https://riunet.upv.es/bitstream/handle/10251/153236/Blanco%20-%20Estudio%20comparativo%20entre%20la%20obtenci%C3%B3n%20de%20piezas%20mediante%20impresoras%203D%20y%20su%20obtenci%C3%B3n%20m....pdf?sequence=4&isAllowed=y

[3] W. Zhang, “Conceptualization of an UV-Curing Unit for 3D Printing of High-Viscosity Dental Resins,” 2022. [Online]. Available: www.lrg.tum.de/lcc

[4] Dr. Jason B. Jones, “AM Basics - Additive Manufacturing (AM).” https://additivemanufacturing.com/basics/ (accessed May 25, 2023).

[5] Ö. Özsoy, A. Margarita, and E. Bello, “Design and Kinematic Integration of an H-Bot System for 2D Extrudate Laying of High-Viscosity and UV-Curing Resins in 3D Printing Applications in Garching near Munich,” 2023. [Online]. Available: www.asg.ed.tum.de

[6] Top 3D Media, “3D Printer kinematic types,” 2019. https://top3dshop.com/blog/3d-printer-kinematics-explained (accessed May 25, 2023).

[7] “Kinematic model of the 3D printer | Download Scientific Diagram.” https://www.researchgate.net/figure/Kinematic-model-of-the-3D-printer_fig1_340311998 (accessed Jun. 01, 2023).

[8] “3D Printer kinematic types.” https://top3dshop.com/blog/3d-printer-kinematics-explained (accessed Jun. 01, 2023).

[9] “file.php 856×584 píxeles.” https://reprap.org/forum/file.php?4,file=105709 (accessed Jun. 01, 2023).

[10] Martínez Solè Andreu, "¿Qué parámetros afectan a la calidad de la impresión 3D?" https://capasobrecapa.com/parametros-calidad-fdm/ (accessed May 25, 2023).

[11] "Cómo parametrizar y optimizar una resina," 2023. https://filament2print.com/es/blog/165_parametrizar-resina-impresion-3d.html (accessed May 25, 2023).

[12] "Under-Extrusion | Simplify3D Software." https://www.simplify3d.com/resources/print-quality-troubleshooting/under-extrusion/ (accessed Jul. 12, 2023).

[13] "Printer Parts Update." https://chat.openai.com/ (accessed Jul. 12, 2023).

[14] "Avances en implantología dental | Instituto CIMEV," 2023. https://cimev.es/avances-implantologia-dental/ (accessed May 25, 2023).

[15] Adminodril, "¿Cómo se hacen los implantes dentales? – Red Implantologia Viña," 2020. https://redimplantologia.cl/2020/03/12/como-se-hacen-los-implantes-dentales/ (accessed May 25, 2023).

[16] Adana Dental, "Así se fabrican coronas, puentes e implantes en Straumann, líder en producción odontológica - YouTube," 2015. https://www.youtube.com/watch?v=oxu0Ok_K40c (accessed May 25, 2023).

[17] P. C. Manrique Holguín, "'Precisión de impresiones convencionales vs digitales intraorales de arcada completa sobre implantes dentales: Revisión de la literatura,'" 2022. Accessed: May 25, 2023. [Online]. Available: https://repositorioacademico.upc.edu.pe/bitstream/handle/10757/667073/Manrique_HP.pdf?sequence=3&isAllowed=y

[18] "La impresión 3D en odontología," 2020. https://www.owandy.es/la-impresion-3d-en-odontologia/ (accessed May 25, 2023).

[19] "Origen de los rayos UVA | Quién descubrió los rayos UVA |." https://curiosfera-historia.com/historia-de-los-rayos-uva-y-su-descubridor/ (accessed May 25, 2023).

[20] B. L. Diffey, "Ultraviolet radiation physics and the skin," *Phys. Med. Biol*, no. 3, pp. 405–426, 1980.

[21] "adhere academy: can you see UV light? - Intertronics." https://www.intertronics.co.uk/2023/03/adhere-academy-can-you-see-uv-light/ (accessed Jun. 01, 2023).

[22] "6642 imágenes de Radiación electromagnética - Imágenes, fotos y vectores de stock | Shutterstock." https://www.shutterstock.com/es/search/radiaci%C3%B3n-electromagn%C3%A9tica (accessed Jun. 01, 2023).

[23] "SCIENTIFIC COMMITTEE ON CONSUMER PRODUCTS SCCP Opinion on Biological effects of ultraviolet radiation relevant to health with particular reference to sunbeds for cosmetic purposes," 2006, Accessed: Jun. 01, 2023. [Online]. Available: www.europa.eu.int/eur-lex/en/treaties/selected/livre221.html

[24] "2. Física de la radiación | Temas de Ecologia." https://fjferrer.webs.ull.es/Apuntes3/Leccion02/2_fsica_de_la_radiacin.html (accessed May 25, 2023).

[25] J. D. Moreno Cubaque, " FORMULACIÓN DE UN PROTOTIPO DE RESINA CALCINABLE PARA LA ELABORACIÓN DE PIEZAS DENTALES EN IMPRESORAS 3D SLA-DLP DE 405 nm," 2021. Accessed: May 25, 2023. [Online]. Available: https://bibliotecadigital.udea.edu.co/bitstream/10495/20837/1/MorenoJulian_2021_PrototipoResinaCalcinable.pdf

[26] J. J. Manso García, "Curado ultrarápido por radiación UV - Plástico," 2009, Accessed: May 25, 2023. [Online]. Available: https://www.interempresas.net/Plastico/Articulos/32435-Curado-ultrarapido-por-radiacion-UV.html

[27] "Tecnología UV - Qurtech." https://www.qurtech.com/es/tecnologia-uv-2/ (accessed May 25, 2023).

[28] "images 409×123 píxeles." https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcTUYBDdsarbW91RJM89O1tTyAN5LA_GmbrGGySuhfyjopmZc-2imRRZnhVZ08b9qfwkzA&usqp=CAU (accessed Jun. 01, 2023).

[29] "Curso de iluminación." https://grlum.dpe.upc.edu/manual/sistemasIluminacion-fuentesDeLuz-LamparasDeDescarga-LamparaVaporMercurioAltaPresion.php (accessed May 25, 2023).

[30] H. B. Wright and W. L. Cairns, "DESINFECCION DE AGUA POR MEDIO DE LUZ ULTRAVIOLETA".

[31] "How Fluorescent Lights work – Reliable Lighting Solutions." https://www.reliablelighting.ca/2020/07/22/how-fluorescent-lights-work/ (accessed May 25, 2023).

[32] "fluorescent+tube.PNG 1000×417 píxeles." https://images.squarespace-cdn.com/content/v1/5af9d5c9620b85ba8d048268/1528297681805-VV5NNQJTUS1CBAMFMA1Z/ke17ZwdGBToddI8pDm48kFJC_hCI-D-mahgAI9LnIL4UqsxRUqqbr1mOJYKfIPR7LoDQ9mXPOjoJoqy81S2I8N_N4V1vUb5AoIIIbLZhVYxCRW4BPu10St3TBAUQYVKcsixUjAvrKIzUuiNejB1Tc0iBCKR_jZ-vReOtOeP_7_U9vSq0_vGMBtSgSrgdjB9_/fluorescent+tube.PNG?format=1000w (accessed Jun. 01, 2023).

[33] "Curso de iluminación." https://grlum.dpe.upc.edu/manual/sistemasIluminacion-fuentesDeLuz-LamparasDeDescarga.php (accessed May 25, 2023).

[34] "HID (High Intensity Discharge) | Light Bulb Types | Bulbs.com." https://www.bulbs.com/learning/hid.aspx (accessed May 25, 2023).

[35] "2. How do artificial lights work? - Comisión Europea." https://ec.europa.eu/health/scientific_committees/opinions_layman/artificial-light/es/l-3/2-technologies.htm#0p0 (accessed May 25, 2023).

[36] "02e.png 819×500 píxeles." https://www.agc.com/en/news/detail/__icsFiles/afieldfile/2018/01/15/02e.png (accessed Jun. 01, 2023).

[37] All3DP, "Tipos de impresoras 3D: las 7 technologías de impresión 3D | All3DP," 2022. https://all3dp.com/es/1/tipos-de-impresoras-3d-tecnologia-de-impresion-3d/ (accessed May 25, 2023).

[38] Kulzer, "Charisma Topaz." Accessed: May 25, 2023. [Online]. Available: https://www.kulzer.gr/media/webmedia_local/downloads_new/charisma_9/charisma_topaz_1/CharismaTopaz_IFU_20160630.pdf

[39] Kulzer, "Scientific_Info_Charisma_Topaz_Strength_Testing_GB_WEB.pdf - Google Drive." Accessed: May 25, 2023. [Online]. Available: https://drive.google.com/file/d/1T0cgQV90SqGFKfardO5kemL0zu9EGMgL/view

[40] "Material Extrusion | Additive Manufacturing Research Group | Loughborough University." https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/ (accessed Jun. 01, 2023).

[41] A. Y. Davis, Q. Zhang, J. P. S. Wong, R. J. Weber, and M. S. Black, "Characterization of volatile organic compound emissions from consumer level material extrusion 3D printers," *Build Environ*, vol. 160, p. 106209, Aug. 2019, doi: 10.1016/J.BUILDENV.2019.106209.

[42] "LED-Modul 28mm | StarLight Online-Shop." https://shop.starlight-oe.com/de/led-modul-28mm.html (accessed May 25, 2023).

[43] Kulzer, "Translux ® Wave," 2017.

[44] S. Fernández and B. Director, "DISEÑO DE EXPERIMENTOS: DISEÑO FACTORIAL Memoria y Anexos Autor".

[45] J. Ferré, "EL DISEÑO FACTORIAL COMPLETO 2 2".

[46] Goméz Monzón Jesús, "RPubs - Diseño Factorial Fraccionado," 2021. https://rpubs.com/JESUS-GM-99/835927 (accessed May 25, 2023).

[47] "Under-Extrusion | Simplify3D Software." https://www.simplify3d.com/resources/print-quality-troubleshooting/under-extrusion/ (accessed May 25, 2023).

[48] "Over-Extrusion | Simplify3D Software." https://www.simplify3d.com/resources/print-quality-troubleshooting/over-extrusion/ (accessed May 25, 2023).

[49] J. O'Connell, "3D Printer Retraction Speed – Simply Explained | All3DP," 2021. https://all3dp.com/2/3d-printer-retraction-speed-what-does-it-mean/ (accessed May 25, 2023).

[50] P. Sevilla Sánchez, "Propiedades mecánicas y degradación de implantes dentales de circonia estabilizada con itria."

[51] "Materiales de los implantes dentales - Nart Clínica Dental." https://nartclinicadental.com/materiales-de-los-implantes-dentales/ (accessed Jun. 16, 2023).

LIST OF FIGURES

LIST OF TABLES

LIST OF FORMULAS

APPENDIX

A Folder

The folder: "TULR/lcc/Freigaben/Studentenprojekte/artesi_camilla_(etchegaray_bello_bt_20231001)" contains the following data:

- Thesis in PDF and Word format
- Literature
- Diagrams and Figures
- Design, preparation, execution, and evaluation of Experiments
- CAD pieces