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**Grau d'Enginyeria
de Materials**

Treball Final de Grau

**Improving the mechanical properties of acrylic resin through
optimized curing and enhancement with alumina**

**Millora de les propietats mecàniques de la resina acrílica mitjançant
el curat optimitzat i la millora amb alumina**

Guillem Serra Verdager

June of 2023



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Marie Curie

A, Dr. Pol Barcelona Pons, tutor meu en la jornada del TFG, qui amb la paciència d'un rellotge de sorra m'ha guiat durant aquest semestre tan intens i m'ha ajudat a tota hora durant la investigació i redacció d'aquest treball. Agrair també els meus pares, Dolors i Carles, que m'han donat suport quan les coses es veien fosques i m'han motivat quan el meu ànim estava cansat.

REPORT

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1. GLOSSARY

AM – Additive Manufacturing

DLP – Digital Light Processing

DMA – Dynamic Mechanical Analysis

DSC – Differential Scanning Calorimetry

FDM – Fused Deposition Modelling

LCD – Liquid Crystal Display

SLA - Stereolithography

SDG – Sustainable Development Goals

TT – Thermal Treatment

Tg – Glass Transition Temperature

UV – Ultraviolet

WT – Weight Percent

3D – Three Dimensional

2. SUMMARY

By offering a more versatile and cost-effective approach for creating complex three-dimensional objects, 3D printing technology has revolutionized various industries such as automotive, aerospace, healthcare, and fashion. In line with this transformative impact, this work focuses on optimizing the mechanical properties of acrylic resin Spot-HT, a commonly used material in vat photopolymerization. The primary challenges associated with using acrylic resin are its suboptimal curing process, which often degrades its properties, and the resultant object's inadequate mechanical properties, even when the resin is fully cured. This scenario demands robust solutions for the production of high-quality 3D-printed objects.

This project is segmented into two core sections. The first section focuses on optimizing the curing process of acrylic resin in 3D printing through photopolymerization, where it has been substantiated that post-processing treatment through overexposure to UV radiation or thermal post-curing significantly enhances the resin's mechanical properties. The second section involves formulating suspensions with alumina in the same resin for 3D printing. The aim is to achieve a stable material that allows the printing of a composite with improved properties. To evaluate the mechanical properties of the resin in different processes, flexion and tension tests have been conducted, allowing us to compare the flexural moduli and maximum stresses. However, the post-processing treatment appears to be more efficient than the addition of alumina and the subsequent post-treatment. By using a curing time of 27 seconds per layer with the 3D printer LCD and a thermal post-treatment, we have achieved a maximum modulus increase of 15% compared to the resin without post-treatment.

3. RESUM

La tecnologia d'impressió 3D ha revolucionat diverses indústries com l'automoció, l'aeroespacial, la sanitat i la moda, oferint un enfocament més versàtil i econòmic per a la creació d'objectes tridimensionals complexos. Amb aquest context transformador, aquest treball té com a objectiu optimitzar les propietats mecàniques de la resina acrílica Spot-HT, un material freqüentment utilitzat en la impressió 3D per fotopolimerització. Els principals desafiaments associats a l'ús de la resina acrílica són el seu procés de curació, molts cops insuficient, que sovint degrada les seves propietats, i les propietats mecàniques inadequades de l'objecte resultant, fins i tot quan la resina està completament curada. Aquest escenari demana solucions robustes per a la producció d'objectes impresos en 3D d'alta qualitat.

Aquest projecte està dividit en dues seccions clau. La primera part tracta sobre l'optimització del procés de curat de la resina acrílica en la impressió 3D per fotopolimerització, on s'ha corroborat que un tractament de post-processat per sobreexposició de radiació UV o post curat tèrmic millora significativament les propietats mecàniques de la resina. La segona part implica la formulació de suspensions millorades amb alúmina en la mateixa resina per a impressió 3D. L'objectiu és obtenir un material estable que ens permeti la impressió d'un compòsit amb propietats optimitzades. Per avaluar les propietats mecàniques de la resina en els diferents processos, s'han realitzat assajos de flexió i tracció, que ens han permès comparar els mòduls de flexió i les tensions màximes. No obstant això, sembla que el tractament post-processat és més eficient que l'addició d'alúmina i el post-tractament subseqüent. Obtenint amb un temps de 27 segons de curat per capa amb la impressora 3D LCD i amb un post-tractament tèrmic un màxim increment de mòdul en un 15 % respecte a la resina sense post-tractament.

4. PREFACE

4.1 MOTIVATION

During my Erasmus program in Austria at the Montanuniversität, I had the opportunity to take a course on additive manufacturing under the guidance of Dr. Clemens Holzer. The course provided me with a comprehensive overview of the subject and sparked my interest in the field.

Hence, when the time came for me to choose my research topic for the next semester, Dr. Pol Barcelona explained me the different lines of research they were pursuing at the University of Barcelona. I found Pol's research on Vat photopolymerization particularly intriguing and decided to join his team.

In addition, the additive manufacturing market is currently experiencing tremendous growth and expansion, making it an exhilarating and dynamic field to be a part of. As an individual who is keen on gaining experience in this industry, I perceive this growth as an excellent opportunity to learn about the latest developments in 3D printing and to explore potential opportunities that may emerge as the market continues to expand.

I am confident that by staying informed about the latest trends and innovations in additive manufacturing, I can strategically position myself to leverage future opportunities in this field. Moreover, I believe that my experience in this area will enable me to develop new skills and insights that will be valuable across a broad range of industries.

In conclusion, I am thrilled to be a part of the additive manufacturing group and I am eager to contribute to the growth and development of this critical field. With the market size of AM projected to continue expanding, I am enthusiastic to see where this journey leads me and what new opportunities may surface as a result of my involvement in this vibrant field.

5. INTRODUCTION

5.1 GENERALITIES

Additive manufacturing, also known 3D printing, has revolutionized the manufacturing industry, providing a more versatile and cost-effective approach to create three-dimensional objects. This technology offers unparalleled precision, allowing to produce complex geometries and intricate designs that would be difficult or impossible to achieve with traditional manufacturing methods. The ability to create customized pieces that meet the specific requirements of each individual customer has made 3D printing particularly attractive to various industries, including automotive, aerospace, healthcare, and fashion. (Shahrubudin et al., 2019)

One of the significant advantages of 3D printing is its ability to reduce production costs and manufacturing time. The cost savings are particularly significant for customized pieces, where 3D printing can cut the production costs by up to 50 % compared to traditional manufacturing methods like injection moulding. Additionally, 3D printing is much faster, with an average reduction in manufacturing time of up to 90 %. (Spectroplast AG, 2022)

This reduction in production costs and manufacturing time is crucial in today's fast-paced business environment, where companies are constantly seeking ways to reduce their operational costs and increase their efficiency.

Overall, 3D printing is a game-changer in the manufacturing industry, offering a more sustainable and efficient way to create three-dimensional objects while reducing costs and lead times. As the technology continues to improve and become more accessible, the possibilities for 3D printing are endless.

Additive manufacturing has radically transformed the process of object and component creation. As illustrated in Figure 1 there exists a variety of 3D printing techniques, each presenting its own distinct benefits and constraints.

One of the most popular methods is Vat photopolymerization, which uses a liquid photopolymer resin that solidifies when is exposed to an energetic light. Another method is Powder Bed Fusion, which uses a laser or electron beam to melt and fuse layers of powder material. Binder Jetting, on the other hand, involves depositing a binder onto a powder bed to form layers, while Material Jetting uses inkjet printheads to deposit droplets of material onto a build platform. Sheet Lamination involves bonding sheets of material together, while Material Extrusion, also known as Fused Deposition Modelling (FDM), melts and extrudes thermoplastic filament to form layers.

Finally, Directed Energy Deposition involves the use of a focused energy source, such as a laser or electron beam, to melt and fuse material together, while Hybrid 3D printing combines two or more of the above methods to create complex parts. (Hybrid Manufacturing, 2021)



Figure 1: Different types of additive manufacturing printers

5.2 MARKET TRENDS

By 2020, 40 years after the development of the first commercial machines, analysis of the AM sector showed it had grown to a USD 13.4 billion industry with a 22 percent annual growth rate. The sector remains extremely dynamic, with more than 200 players competing to develop new hardware, software, and materials. Rapid innovation is driving major improvements in the performance of AM technologies. The newest generations of machines are overcoming many of the perceived limitations of their predecessors, such as by allowing the production of overhanging parts without the need for elaborate printed support structures or creating stronger parts by controlling the alignment of fiber reinforcements using magnetic fields. The range of materials available for AM systems continues to expand, including high-strength aluminium alloys and medical-grade polymers. (Bromberger et al., 2022)

As it shows Figure 2, This market is expected to increase to reach USD 83.56 billion by 2030, with an annual growth of 21.2 %. This implies that several opportunities will be presented in the 3D printing sector and that the coming years will be key for the different lines of research and for companies wishing to increase their market share. (PR Newswire, 2022)

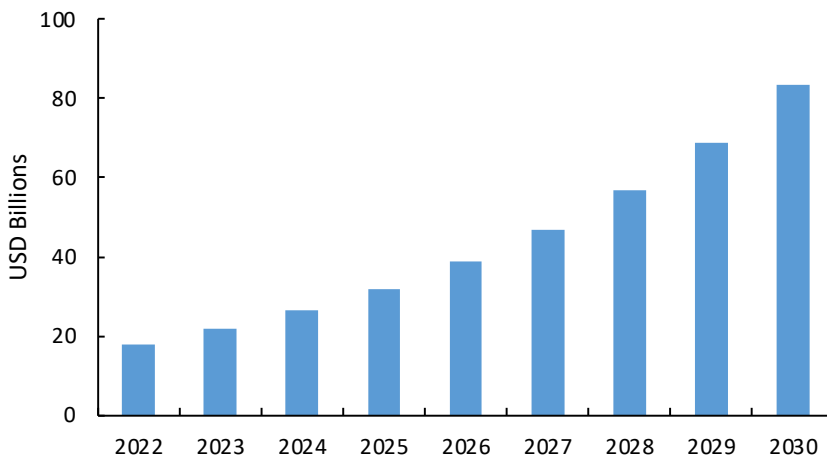


Figure 2: Forecast of the market size of additive manufacturing. (PR Newswire, 2022)

5.3 3D PRINTING TECHNOLOGIES: VAT PHOTOPOLYMERIZATION

In this project, the focus will be on Vat photopolymerization, and its principles advantages and limitations will be explored in-depth. By offering a comprehensive understanding of this 3D printing method, the aim is to contribute to the advancement of this technology and its utilization in various fields. Vat photopolymerization is a 3D printing technology that uses light to cure liquid resin into a solid object. This process involves a vat or tank that is filled with a liquid photopolymer resin. A light source, typically a UV laser, is used to selectively cure the resin, layer by layer, to create a 3D object. The build platform is lowered into the vat after each layer is cured, allowing the next layer of resin to be added on top of the previous one until the object is complete. There are three types of Vat photopolymerization technologies as Figure 3 illustrates: Stereolithography (SLA), Digital Light Processing (DLP), and Liquid Crystal Display (LCD). SLA uses a laser to cure the resin, and the laser is directed by mirrors to trace the shape of each layer. DLP uses a projector to project the entire layer onto the vat of resin, curing the entire layer at once. LCD works in a similar way to DLP but uses an LCD screen to project the image onto the resin.

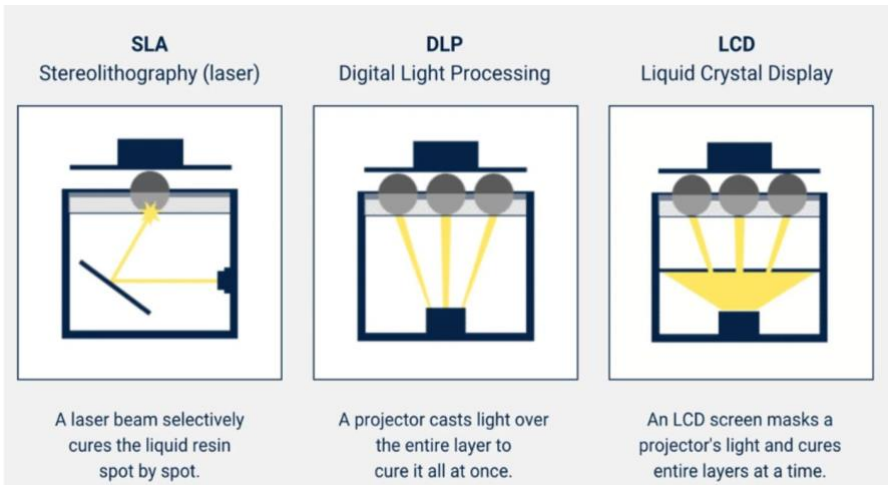


Figure 3: Vat Photopolymerization technologies (Alfattni, 2022)

Specifically, the type of Vat photopolymerization technology that is going to be used in this project and available at the University of Barcelona is the Liquid Crystal Display (LCD) method.

LCD-based 3D printing works by projecting an image of each layer of the 3D model onto a vat of photopolymer resin using an LCD screen. The screen is made up of an array of tiny pixels that can be selectively turned on or off, allowing the light to pass through and cure the resin in the desired pattern, therefore, the resolution of the print is limited by the size of the pixels on the LCD screen. One of the benefits of LCD-based 3D printing is that it is faster than some other types of Vat photopolymerization, such as SLA, because it can cure an entire layer at once. Additionally, LCD screens are relatively inexpensive and widely available, making them a popular choice for desktop 3D printers. LCD-based 3D printing can be a versatile and cost-effective option for producing high-quality, detailed 3D objects. By selecting the appropriate type of photopolymer resin and optimizing the printing parameters, it is possible to create objects with a wide range of properties and characteristics, making this technology a valuable tool for research and development in a variety of fields. (H. W. Chen et al., 2018)

In the market, acrylic resins are widely used in Vat photopolymerization for several reasons. Firstly, Vat photopolymerization relies on light-sensitive polymers, including acrylates, epoxies, and vinyl ether, making acrylic resins a suitable choice. These resins offer a range of variations with different properties such as hardness, flexibility, and strength, allowing for customization based on the specific requirements of the printed object. Despite not being the strongest polymers in terms of mechanical properties, acrylic resins remain popular due to their commercial availability and affordability. They are widely accessible, making them a convenient choice for many additive manufacturing applications. Additionally, their low viscosity contributes to smoother printing processes. (Cui et al., 2022)

However, it is important to note that there are limitations associated with Vat photopolymerization. The range of materials suitable for this process is relatively limited, with a focus on light-sensitive polymers. Recycling these materials can be challenging, and there are concerns about their potential toxicity. Moreover, some specialty acrylic resins can be costly, adding to the overall expenses of the printing process. Considering these factors, acrylic resins continue to dominate the market for their ease of use, cost-effectiveness, and

versatility in various applications, despite their limitations in mechanical strength and recyclability. (Pagac et al., 2021)

6. OBJECTIVES

The main objective of this project is to increase the mechanical properties of acrylic resin obtained by LCD printer. By collecting empirical data, the optimal factors that yield the best results in terms of mechanical enhancement of the acrylic resin will be pinpointed.

As previously noted, the project will approach the enhancement of properties in two ways.

The first approach focuses on the curing of the resin with the objective of enhancing its mechanical properties. This approach involves a comprehensive examination of various factors:

- Analyse the impact of layer curing time of the LCD printer on the mechanical properties of the resulting product.
- Explore whether UV radiation or thermal treatment could enhance the product's mechanical behaviour.
- Ascertain the impact of curing durations and post-processing alternatives on the material's glass transition temperature and its mechanical properties.

The second approach revolves around the creation of a new alumina suspension in acrylic resin to improve its attributes. This requires:

- Formulate resin suspensions of alumina with good stability and printability.
- Assess if adding different amounts of alumina to the resin could improve the starting mechanical properties of the LCD printer's output.

Furthermore, a beneficial global impact is aspired to be achieved by improving the quality and efficiency of materials used in various industries (Sustainable Development Goals 9). The aim is to lead the way in developing more efficient, sustainable production methods, ultimately improving the lifespan of the material (Sustainable Development Goals 12).

7. REFLECTION ON THE SUSTAINABLE DEVELOPMENT GOALS

Aligned with the United Nations' Sustainable Development Goals (SDGs), this project seeks to enhance the mechanical properties of acrylic resin. The primary SDGs relevant to this project are Goal 9: Industry, Innovation and Infrastructure, and Goal 12: Responsible Consumption and Production. This report reflects the project's alignment with and contribution to these goals.

Goal 9 focuses on constructing resilient infrastructure, encouraging inclusive and sustainable industrialization, and promoting innovation. The proposed modifications and enhancements in this project directly support this goal. Improving the mechanical properties of acrylic resin signifies innovation in the material science industry, thereby paving the path for more durable, efficient, and sustainable products. Given its versatility, acrylic resin is employed across various industries including automotive, construction, and consumer goods. Enhancing acrylic resin translates to stronger and more resilient infrastructure and products. A longer product lifespan, thanks to the improved resin, diminishes the necessity for frequent replacements and repairs, contributing to infrastructure resilience. Furthermore, this innovative approach could stimulate the industrial sector to explore more sustainable materials, encouraging progress towards the industry's sustainability transition. Thus, the project significantly contributes to SDG 9.

Goal 12 aims to ensure sustainable consumption and production patterns. By enhancing the mechanical properties of acrylic resin, the project reduces the frequency of product replacements, thus lowering waste generation and encouraging responsible consumption. Moreover, with enhanced acrylic resin, fewer resources are needed over time, which could reduce raw material extraction and processing. This could potentially diminish the ecological footprint of industries that use acrylic resin, thereby promoting more sustainable production practices. In addition, the extended lifespan of the enhanced acrylic resin implies less waste

ending up in landfills, consequently reducing environmental impact. This directly addresses Goal 12's target of significantly reducing waste generation through prevention, reduction, recycling, and reuse.

In conclusion, the project illustrates a strong alignment and contribution to the achievement of SDGs 9 and 12. By improving the mechanical properties of acrylic resin, it facilitates sustainable industrial growth, promotes responsible consumption and production, and supports the overarching objective of the SDGs – building a more sustainable future. (United Nations, 2023) (Martin Schaaper, 2022)

8. OPTIMIZATION OF THE ACRYLIC RESIN CURING PROCESS IN ADDITIVE MANUFACTURING

As previously commented, this work on improving acrylic resin mechanical properties consists of two parts: optimization of the acrylic resin curing process in additive manufacturing and formulating alumina-enhanced resin for 3D printing. Next, the first part of the study will be presented.

8.1. PRINTING THE BASE MATERIAL SAMPLES

For this project, it has selected the "Spot-HT - Hard and Tough," an acrylic resin manufactured by Spot-A Materials, a local provider based in Barcelona. This choice reflects a commitment to sustainability, as the local sourcing reduces transportation-related carbon emissions, while its affordability at 72 €/kg suits with project's economic considerations.

Spot-HT is well-suited to creating solid, robust objects that can withstand some degree of stress, making it a fitting candidate for prototyping and creating design and marketing samples. However, while it offers certain advantages, it's also worth noting that the mechanical properties of Spot-HT leave room for improvement - a key objective of this study.

One of the features of Spot-HT is its high cure speed, allowing for a rapid polymerization process. This is adjustable to the specific power output of the UV printer used, providing a certain degree of flexibility in the experimentation. Additionally, Spot-HT's low viscosity, marked at 400 mPa·s/cPs, can enhance the efficiency of the 3D printing process by reducing the buffer time between layers. It operates effectively at room temperature, negating

the need for additional heating, and its low viscosity simplifies post-processing by making cleaning more manageable.

The polymerization of acrylic resins, such as Spot-HT, is an intricate process. When exposed to ultraviolet (UV) light, the photo-initiators within the resin absorb energy, transitioning from a ground state to an excited state. Upon returning to the ground state, these photo-initiators release energy, producing free radicals. These radicals are highly reactive, and they initiate the polymerization reaction by interacting with the carbon-carbon double bonds present in the monomers of the acrylic resin. The energy released by the photo-initiators triggers a three-step process: initiation, propagation, and termination. In the initiation step, the free radicals bind to the monomers, creating primary radicals. During the propagation step, these primary radicals react with other monomers, leading to the formation of polymer chains. The termination step occurs when two active chains collide, resulting in the formation of a stable, cross-linked polymer network. (Scranton et al., 1997)

The depth and uniformity of the cured resin depend on the duration and intensity of UV exposure. This is directly related to the curing time per layer in the 3D printer, which serves as a critical variable in the project.

In order to examine the influence of curing time on the mechanical properties of the printed samples, a series of reference samples will be fabricated, with each set subjected to a different curing time per layer. Specifically, as it shows Table 1, five samples will be printed with a curing time of 3 seconds per layer, five with a curing time of 9 seconds per layer, and another five with a curing time of 27 seconds per layer. This range allows us to investigate the correlation between curing time and the ultimate properties of the cured resin, enabling us to optimize the process for the best mechanical performance.

Table 1: Summary of the reference samples

Curing time per layer	No Post-treatment (reference samples)
3 s	x5
9s	x5
27s	x5

This project employs the Anycubic Photon M3 Plus (Figure 4), an LCD-based 3D printer renowned for its high precision and dependable performance in additive manufacturing. LCD, short for Liquid Crystal Display, is a technology used in 3D printing to accurately and uniformly polymerize a photosensitive resin layer by layer. The Anycubic Photon M3 Plus boasts a high-resolution LCD, offering finely detailed and accurate prints.

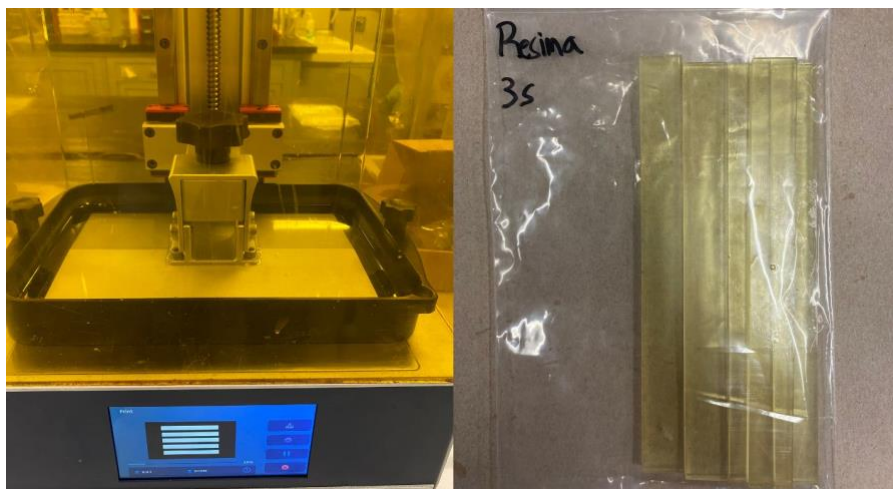


Figure 4: 3D LCD printer and 5 test tubes of 3 seconds of exposure UV light from the printer.

Proceeding to the printing process, it commences by pouring the Spot-HT acrylic resin into the printer's vat. The model of sample is then loaded into the printer's software, where the curing time per layer is set according to the group (3, 9, or 27 seconds). The dimensions of the sample are set to comply with the article (ASTM, 2015), which specifies a width of 12.5 mm, a thickness of 3.5 mm, and a length of 125 mm. The layer thickness of 75 micrometres is further specified in the print settings.

With the acrylic resin in place and the print parameters set, the Anycubic Photon M3 Plus begins its work. The printer projects UV light through the LCD screen to cure each layer of resin, constructing the sample layer by layer until the final part is complete. After printing, each sample is carefully removed, cleaned and ready for testing.

8.2. CHARACTERIZATION OF THE BASE MATERIAL SAMPLE

From this point, it commences the flexural test, also known as the three-point bending test, is a common method used to evaluate the strength and stiffness of a material. In this test, the sample is supported at two points, creating a span length [L] of 53 mm. A force is then applied at the center of the sample, perpendicular to its longitudinal axis, causing it to bend. To perform the flexural test, the sample was positioned on the supports, ensuring that the loading point was aligned with the midpoint of the span length. The testing machine then applied a gradually increasing load until the desired strain level of 5 % was reached. At this point, the machine automatically stopped, allowing us to record the corresponding force applied to the sample. Stopping at 5% flexion helps avoid permanent deformation or damage to the material, which could influence the accuracy of the results.

The formulas (Eq 1) used to calculate the flexural modulus and the force are the following, which were extracted from report (ASTM, 2015). In these formulas, [w] is the width, [t] is the thickness, [L] is the span length, [F] is the force applied by the machine, and [δ] is the deflection.

$$\sigma = \frac{3 F L}{2 w t^2} \quad \text{Eq 1a: Flexural stress equation}$$

$$\varepsilon = \frac{6 \delta t}{L^2} \quad \text{Eq 1b: Flexural strain equation}$$

$$E = \frac{\sigma_{0.25\%} - \sigma_{0.05\%}}{\varepsilon_{0.25\%} - \varepsilon_{0.05\%}} \quad \text{Eq 1c: Chord modulus equation}$$

When calculating the modulus, the specific range considered is from 0.5 % to 2.5 %. This range is typically where the material behaves elastically, with deformation directly proportional to the applied load, following Hooke's Law. Selecting this specific range, as it shows Figure 5, helps ensure that the material remains within its elastic region, where stress and strain have a linear relationship. Measurements outside this range might reflect plastic deformation or could involve non-linear or unpredictable behaviour, potentially making the modulus calculation less reliable.

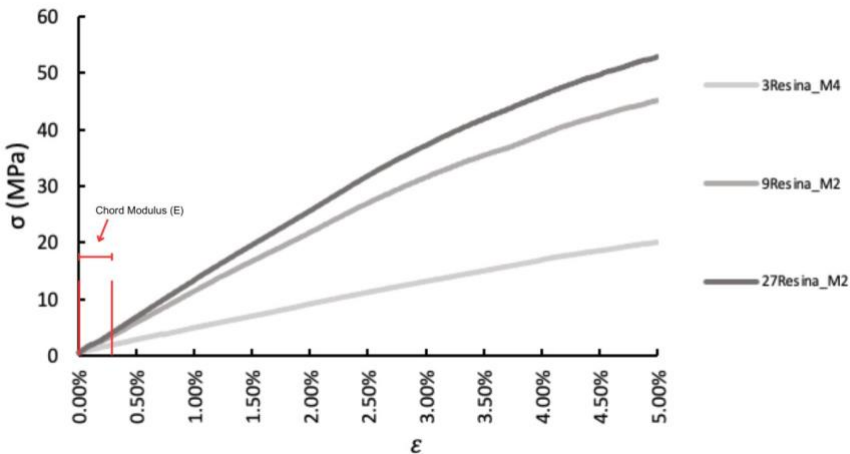


Figure 5: Stress-strain diagram where the parameters for calculating the Chord Modulus are marked.

The chord modulus is a crucial parameter in the field of materials testing and characterization, particularly in flexural testing. It represents the slope of the chord line drawn between two points on the stress-strain curve within the elastic region of the material. The chord modulus provides valuable information about the material's stiffness or resistance to deformation under bending stress. A higher modulus indicates that the material has a greater ability to resist bending and maintain its shape. This is important for mechanical properties as it implies enhanced structural integrity, increased load-bearing capacity, and reduced susceptibility to deformation or failure. A higher modulus is desirable in applications where strength, rigidity, and dimensional stability are critical factors.

Now, the results obtained from the flexural testing of the moduli are presented. These results shed light on the material's performance and mechanical properties, specifically

focusing on the modulus and its significance in evaluating the material's behaviour under bending stress.

The results, depicted in Figure 6 , reveal a clear trend regarding the relationship between exposure time and the modulus. At an exposure time of 3s per layer, the modulus was measured to be 470 MPa (± 40). With an increased exposure time of 9s, the modulus significantly increased to 1010 MPa (± 10). Further extending the exposure time to 27 s resulted in a higher modulus of 1230 MPa (± 40). These findings demonstrate a positive correlation between the exposure time of UV light per layer in the 3D printer LCD and the resulting modulus. The observed increase in modulus can be attributed to the enhanced curing of the resin, leading to improved mechanical properties. Notably, the modulus exhibited a remarkable 162 % increase when comparing the 3s vs 27s exposure times.

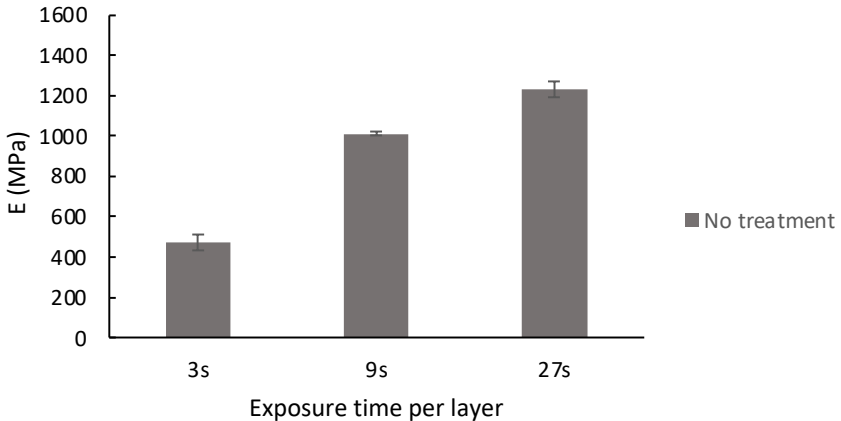


Figure 6: Chord Modulus vs Exposure time per layer

At this stage, the focus shifts to the tensile strength analysis. Tensile strength refers to the maximum stress or force a material can withstand before it fractures or breaks under tension. It is a critical mechanical property that characterizes a material's resistance to being pulled apart or stretched. During a tensile strength test, a sample is subjected to an increasing tensile force in a controlled manner. The test measures the material's response to the applied force, allowing for the determination of its mechanical properties. The key parameters assessed in a tensile strength test include the maximum force or load at which the material

breaks, as well as the corresponding cross-sectional area of the sample. To conduct a tensile strength test, the sample is clamped into a testing machine, the machine applies a steadily increasing tensile force to the sample until it reaches its breaking point. During the test, various parameters such as load, displacement, and strain are recorded. These measurements are then used to calculate the tensile strength of the material by dividing the maximum force by the cross-sectional area of the sample. The tensile strength test provides valuable information about a material's ability to withstand stretching or pulling forces. It helps in assessing the material's overall structural integrity and suitability for specific applications where strength and durability are crucial factors. In this project, determining the maximum tensile strength will be instrumental in assessing the mechanical properties of the acrylic resin. By obtaining this crucial parameter, insights can be gained into the resin's ability to withstand stretching or pulling forces.

The maximum stress is calculated using the following Eq 2, where the [w] is the width, and the [t] is the thickness.

$$\sigma_{\max} = \frac{F_{\max}}{w \cdot t}$$

Eq 2: Engineering stress equation

The results of the maximum tensile stresses are presented in Figure 7 . At an exposure time of 3s, the maximum stress measured was 15 MPa (± 3). Increasing the exposure time to 9s resulted in a higher maximum stress of 25 MPa (± 1), while at 27 seconds, the maximum stress further increased to 31 MPa (± 1). Similar to the conclusions drawn from the flexural modulus analysis, a positive correlation is observed between the exposure time and the maximum tensile stress. Longer exposure times lead to higher maximum stress values, indicating improved mechanical properties. This can be attributed to the fact that the resin is more fully cured at 27 seconds compared to 3 seconds. These findings highlight the significance of sufficient resin curing in achieving higher tensile strengths and improved mechanical performance. The results demonstrate that a longer exposure time positively impacts the resin's mechanical properties, leading to higher maximum stresses. This information is valuable for optimizing the 3D printing process and ensuring the production of components with enhanced strength and reliability.

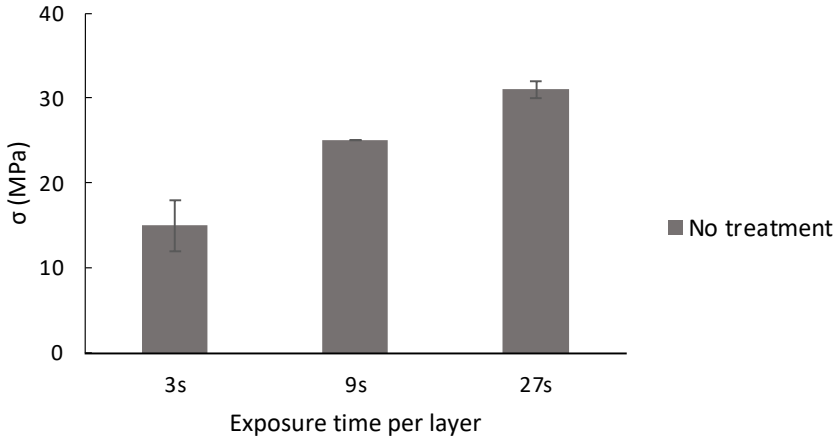


Figure 7: Maximum tensile strength vs exposure time per layer

To conclude the characterization of the reference sample specimens, it has performed a dynamic mechanical analysis (DMA) to determine the glass transition temperature (T_g). DMA is a testing technique used in materials science to study and characterize materials. It applies a varying force, such as a periodic stress or strain, to a sample and measures the sample's response as a function of time, temperature, or frequency. It's often used to study polymers but can also be used for other types of materials. The key output of DMA is a material's modulus (E) and damping (tangent delta), which can provide information on a material's viscoelastic properties. These properties can give clues about the material's ability to store and dissipate energy, which can be important in understanding the material's behaviour under different conditions. One of the important properties that can be determined using DMA is the glass transition temperature, or T_g . The T_g is the temperature at which an amorphous material (like a glass or a polymer) transitions from a hard, brittle state to a soft, rubbery state. This is a key factor in determining a material's properties at different temperatures. The T_g can affect the modulus (E) of a material significantly. Below the T_g , the material behaves more like a glassy solid, with a high modulus, meaning it resists

deformation. Above the T_g , the material behaves more like a rubber, with a low modulus, meaning it's easier to deform. (PerkinElmer & Inc, 2013)

Understanding the glass transition temperature (T_g) is essential in the project as it directly impacts the material's mechanical properties. A higher T_g indicates a more brittle behaviour, resulting in better mechanical properties. On the other hand, a lower T_g indicates a softer material with poorer mechanical properties. It is important to note that T_g is not a specific point but rather a temperature range. In the work, it was considered T_g as the midpoint of this range, as shown in Figure 8. The figure also presents a comparison between the DMA curves of the 3s exposure time and the 27s exposure time. Notably, the further to the right the curve extends, the higher the T_g and, consequently, the better the mechanical properties. This correlation is due to the higher the modulus achieved at the same temperature.

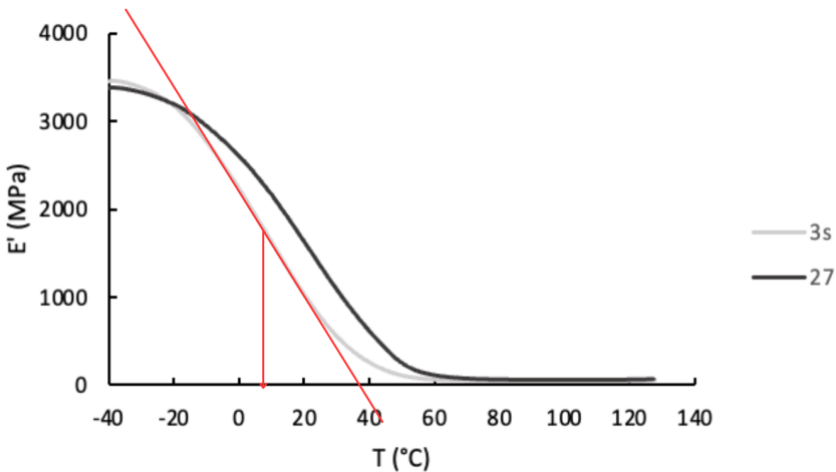


Figure 8: DMA analysis at 3s exposure time vs 27 exposure time

The T_g studies presented in Table 2 not only validate the results of the flexural test and tensile strength analysis, but also demonstrate that as the exposure time increases, the T_g tends to be higher, leading to improved mechanical properties. Additionally, the significance of considering room temperature during testing is emphasized, as higher temperatures correspond to lower mechanical properties in the acrylic resin. The tests were conducted within a room temperature range of 19 to 22 degrees Celsius. In conclusion, the findings in section 8.1 indicate that longer exposure times in the 3D printer LCD result in enhanced mechanical properties due to improved resin curing. The T_g analysis further

supports the correlation between exposure time and mechanical performance, underscoring the importance of resin curing in achieving superior mechanical properties.

Table 2: Variation of Glass Transition Temperature (T_g) with Exposure Time

Exposure Time	3s	9s	27s
T _g (°C)	7.94 ± 0.8	20.8 ± 1.0	27.1 ± 1.6

8.3. POST-TREATMENT OF THE SAMPLES

As has been observed seen in section 8.2, exposure time is crucial in increasing the mechanical properties of the specimens. However, even with a 27s exposure time yielding favourable results, it is possible that the specimens are not fully cured. Therefore, in this section, two post-treatments will be performed on the specimens to further enhance their mechanical properties by achieving complete curing. The first post-treatment involves UV treatment. It is important to note that the specimens will be reprinted following the guidelines outlined in section 8.1. Once printed at different exposure times, they will undergo a 15-minute UV treatment using the Anycubic Wash & Cure Plus Machine in an attempt to achieve 100 % curing of the specimens. The second treatment will involve a thermal treatment. In this case, a thermal initiator, Luperox® 531m60, will be added to a solution of Spot-HT acrylic resin prior to printing.

A thermal initiator is a key component used in polymerization processes to initiate and accelerate the curing or polymerization reaction. It plays a vital role in facilitating the conversion of monomers or reactive species into a polymer network by providing the necessary energy to initiate the chemical reaction. Thermal initiators are composed of molecules that are sensitive to heat. When the thermal initiator is exposed to an appropriate temperature, it undergoes a decomposition process known as thermal decomposition. This decomposition releases free radicals or reactive species, which are highly reactive and capable of initiating the polymerization reaction. These free radicals or reactive species can

react with the monomers or other reactive components present in the resin solution. By initiating a chain reaction, the thermal initiator triggers the cross-linking or bonding of monomers, resulting in the formation of a polymer network. (Bonardi et al., 2020)

To determine the precise temperature required to activate the thermal initiator and therefore cure the samples in the oven, the Differential Scanning Calorimetry (DSC) was utilized, a thermal analysis technique commonly used in laboratories to investigate the thermal properties of materials. In a DSC experiment, differences in heat flow between a sample and a reference are compared while both are subjected to a controlled temperature program. Both the sample and the reference are placed in two adjacent cells and are subjected to the same temperature profile. Throughout the DSC experiment, changes in heat flow occurring in the sample relative to the reference are recorded and analysed. These changes can signify various thermal transitions and properties of the material. (Dr. J. Schawe, 2000)

In this case, as mentioned, this is used to determine the curing temperature that needs to be set for the oven to ensure that the sample cures with the initiator. The following are graphs where the x-axis represents temperature in degrees Celsius and the y-axis represents the heat flow. Figure 9 displays a sample cured with an activator, where it can be observed that the reaction requires minimal energy as the resin is nearly fully cured.

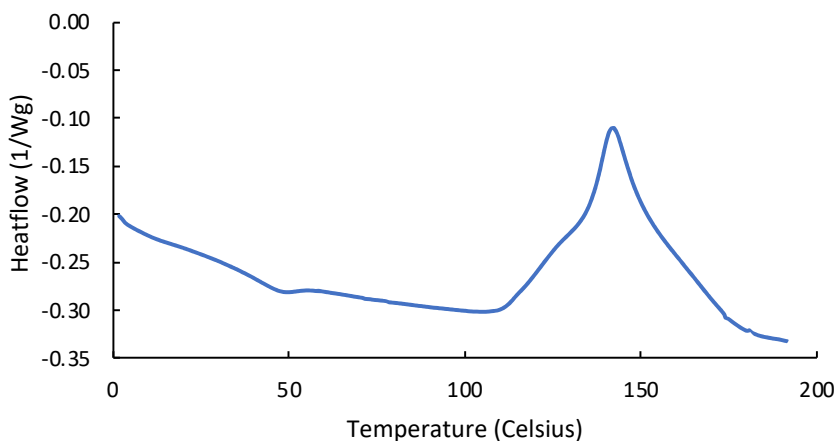


Figure 9: DSC of cured resin with thermal activator

Conversely, Figure 10 illustrates an uncured sample with an activator, where it is observed that the peak is much larger, requiring almost ten times more energy for curing.

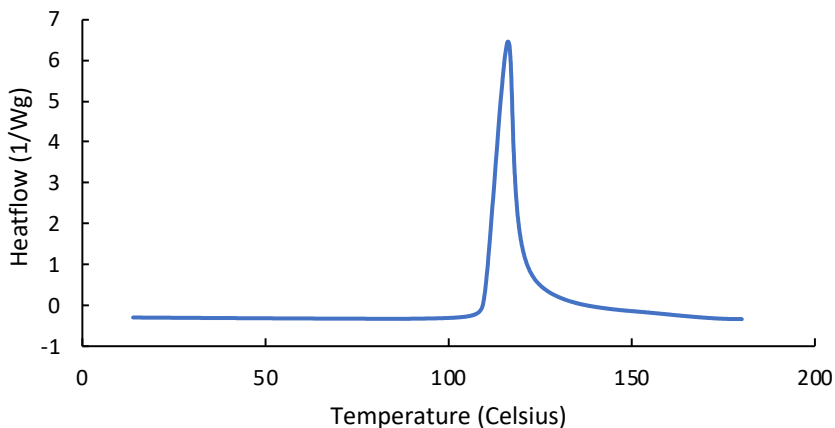


Figure 10: DSC of uncured resin with thermal activator

In the results Table 3 , it can be deduced that the curing temperature for the samples should be around 120 degrees Celsius since the peak temperature of the not cured resin with thermal activator is 119.96 °C and the aim is to cured the resin that has not been already cured for the UV light of the LCD.

Table 3: DSC results

With thermal activator	Results DSC	
	Cured	Not Cured
Integral	398.40 mJ	3709.45 mJ
Normalized	33.99 Jg ⁻¹	351.94 Jg ⁻¹
Peak	142.11 °C	116.17 °C

To conclude, specimens were printed at exposure times of 3s, 9s, and 27s for each of the different post-treatments involving UV and thermal treatment. However, two groups were subjected to thermal treatment using different concentrations of thermal initiator solution: one group with 0.25 wt% and the other with 0.5 wt%. This comparison allows us to assess which concentration yields better results in terms of enhancing the mechanical properties.

The schematic representation in Table 4 shows the number of samples printed for each post-treatment. It is important to emphasize that the untreated samples serve as reference specimens, as they have already undergone characterization in section 8.2.

Table 4: Summary of the different post-treatments and number of samples to be tested.

Exposure Time	No Post-treatment	UV (15 min)	Heat treatment with 0.25% activator	Heat treatment with 0.5% activator
3 s	x5	x5	x5	x5
9s	x5	x5	x5	x5
27s	x5	x5	x5	x5

8.4. CHARACTERIZATION OF POST-TREATED SAMPLES

For the characterization of the post-treated specimens, the steps and formulas described in section 8.2 will be followed. The samples were tested at a temperature of 19 degrees Celsius. In this section, the variables to consider will be the UV radiation exposure time per layer of the printer, which includes 3 seconds, 9 seconds, and 27seconds, as well as the type of post-treatment (UV or thermal). In the case of the thermal treatment, the amount of initiator will be taken into account, which can be either 0.25 wt% or 0.5 wt%.

In Figure 11 , the results of the flexural testing are presented. The y-axis represents the Modulus in MPa, while the x-axis groups the different treatments based on the UV exposure time per layer of the printer, namely 3 seconds, 9 seconds, and 27 seconds. The grey colour corresponds to the reference sample that was tested in section 8.2. The blue colour

represents the UV post-treatment for 15 minutes, the yellow colour represents the thermal post-treatment at 120 degrees Celsius for 24 hours with a 0.25 wt% thermal initiator, and the green colour represents the thermal post-treatment with a 0.5 wt% thermal initiator.

In general, there is a positive trend where longer UV exposure time per layer results in higher Modulus values, indicating improved curing of the resin. The implementation of post-treatment in all cases leads to a higher modulus compared to the reference sample. On average, post-treating the specimens with a 3-second UV exposure per layer yields a 125 % increase in modulus, a 23 % increase at 9 seconds, and a 9 % increase at 27 seconds. It is worth noting that as the curing time per layer increases, the effectiveness of the post-treatment diminishes. Lastly, the post-treatment that has demonstrated the best results is a thermal treatment with a 27-second UV exposure per layer and a 0.5 wt% thermal initiator concentration, resulting in a modulus of 1410 MPa with an error margin of ± 130 . This combination exhibits superior enhancement in the mechanical properties of the specimens.

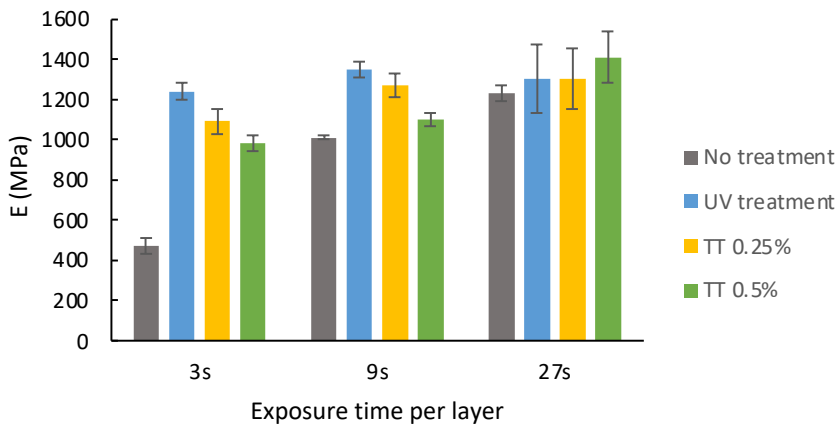


Figure 11: Chord modulus vs different post-treatments at different cure times of printing

Regarding the Figure 12, similar conclusions can be drawn, where the trend of the uncured resin is that the greater the exposure, the greater its maximum tension. It can also be seen that performing a thermal post-treatment always has a positive effect on the tensile strength.

In the case of an exposure time of 3 seconds, it is observed that the best post-treatment is the thermal one with 0.5 wt% thermal activator, increasing the maximum tension by 113 %.

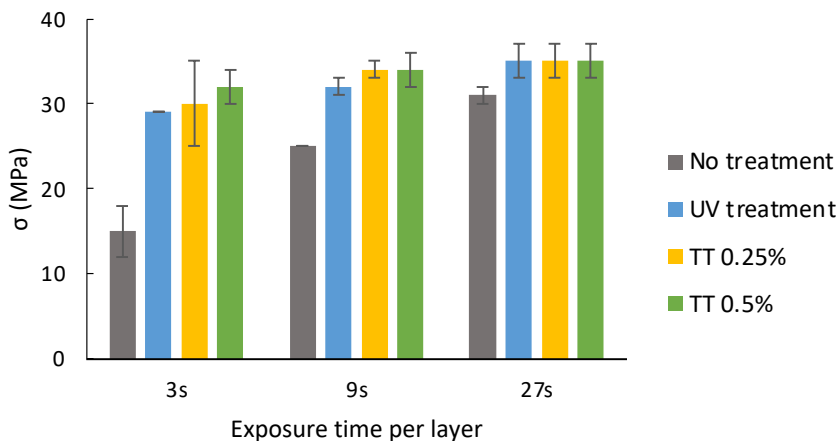


Figure 12: Tensile test results vs different post-treatment at different cure times of printing.

In the case of 9 seconds, the best post-treatments are thermal ones with a modulus increase of 36 %, and finally for 27 seconds, there is a modulus increase of 13 %, with all three post-treatments being equally effective. It can also be concluded that with longer exposure times, the trend is towards poorer performance.

Another conclusion that can be drawn from Figure 11 and Figure 12 is that increasing the thermal initiator concentration does not significantly impact the mechanical properties. In this case, there is no substantial benefit in using a 0.5 wt% thermal initiator concentration compared to a 0.25 wt% concentration, as the resulting mechanical properties are similar. Therefore, it is more cost-effective and practical to utilize the 0.25 wt% thermal initiator concentration, which yields comparable properties to the higher concentration.

The results obtained from the DMA (Table 5) analysis reinforce the relationship between curing time and T_g (glass transition temperature), highlighting the improved mechanical properties associated with higher T_g values. The findings demonstrate that increasing the curing time leads to an elevated T_g , indicating that the material possesses better temperature

resistance at higher temperatures. This correlation is significant because the experiment was conducted within the range of T_g temperatures, emphasizing its influential role. Furthermore, the post-treatment of the specimens consistently results in a higher T_g , validating the observed improvements in mechanical properties. The higher T_g values indicate that the material exhibits enhanced performance at elevated temperatures. Given the experimental temperature range's relevance to practical applications, the T_g values play a crucial role in determining the material's suitability. These conclusions emphasize the importance of optimizing curing time and implementing post-treatments to achieve desirable mechanical properties and temperature resistance in the acrylic resin. The correlation between curing time, T_g , and mechanical performance provides valuable insights for enhancing the material's application potential.

Table 5: Variation of Glass Transition Temperature (T_g)

T_g (°C)	No post-treatment	UV treatment	Thermal treatment (0.25 %)
3s	7.9 ± 0.8	37.6 ± 6.4	31.6 ± 3.7
9s	20.8 ± 1.0	42 ± 1.2	33.1 ± 1.1
27s	27.1 ± 1.6	42.5 ± 4.9	40.6 ± 2.2

9. FORMULATING ALUMINA-ENHANCED RESIN FOR 3D PRINTING

The aim of this section is to present a comprehensive study on formulating alumina-enhanced resin for 3D printing applications. The goal is to develop a stable, printable, and reproducible composite that improves the mechanical properties of the Spot HT acrylic resin. By incorporating alumina, a ceramic material known for its excellent mechanical properties and affordability, is pursued to enhance the performance of the resin in terms of strength, stiffness, and durability. Alumina, also known as aluminium oxide (Al_2O_3), possesses a range of desirable characteristics that make it a suitable additive for enhancing the properties of the acrylic resin. Firstly, alumina exhibits excellent mechanical strength, making it highly resistant to deformation and fracture. This characteristic is crucial for ensuring the structural integrity and longevity of the 3D-printed objects. Additionally, alumina has a high melting point and exceptional thermal stability, enabling the printed objects to withstand elevated temperatures during post-processing or demanding operating conditions. (Z. Chen et al., 2019) Furthermore, alumina is chemically inert, rendering it compatible with the resin matrix without adversely affecting the printability or stability of the composite material. Its non-reactive nature ensures that the composite maintains its integrity and performance over time. Moreover, alumina is readily available in various forms, allowing for the selection of particle sizes and distributions to optimize the mechanical properties of the composite. The cost-effectiveness of alumina further enhances its attractiveness as an additive for resin formulation. (Yathish Narayana Rao & Mohamed Kaleemulla, 2018)

9.1. FORMULATING AND PRINTING ALUMINA-ENHANCED RESIN

In this section, the focus will be on the formulation and printing of the test samples. Several factors will be considered during this process. Firstly, based on the previous findings in section 8 of this study, the selected post-treatment method will be the thermal treatment with a 0.25% thermal initiator concentration. This choice is made because the mechanical properties did not significantly differ from those obtained with a 0.5 wt% initiator concentration. Therefore, utilizing a lower initiator concentration offers a more cost-effective approach without compromising the performance of the composite. Furthermore, the test samples will be printed with different UV exposure times per layer: 3 seconds, 9 seconds, and 27 seconds. Additionally, various alumina loadings will be employed, including 2.5 wt%, 5 wt%, 7.5 wt%, and 10 wt% alumina. This will allow for the investigation of the influence of alumina content on the mechanical properties of the composite. Moreover, each combination of alumina loading and UV exposure time will be tested with and without the post-treatment, as indicated in Table 6. By systematically exploring these variables, the aim is to establish the optimal formulation and printing parameters for the alumina-enhanced resin. This approach will enable a comprehensive understanding of the impact of alumina content, UV exposure time, and post-treatment on the mechanical properties of the 3D-printed samples.

Table 6: Summary of the samples to be tested, a total of 120 samples.

Alumina	No treatment			TT 0.25%		
	3s	9s	27s	3s	9s	27s
2.50%	x5	x5	x5	x5	x5	x5
5%	x5	x5	x5	x5	x5	x5
7.50%	x5	x5	x5	x5	x5	x5
10%	x5	x5	x5	x5	x5	x5

To create a stable, printable, and reproducible mixture, it is essential to ensure that the alumina particles have a stronger affinity for the medium rather than for each other. Otherwise, particle agglomeration may occur, leading to uneven dispersion and poor performance. This is where the importance of a dispersant comes into play. A dispersant is a chemical additive that promotes the uniform distribution of particles within a liquid medium by reducing the

attractive forces between them. In this case, the dispersant BYK-105 was utilized. This particular dispersant is designed to enhance the compatibility and stability of the alumina particles in the resin matrix. It accomplishes this by forming a protective layer around the particles, preventing them from clumping together and facilitating their dispersion throughout the resin. The dispersant achieves this by reducing the surface tension and increasing the repulsive forces between the particles, thereby promoting their uniform distribution. Normally, the amount of dispersant is calibrated by measuring the viscosity of different solutions, and the less viscous solution is selected as it indicates better dispersion. However, in this case, since it was required a relatively small amount of dispersant, the viscosity differentials would be minimal, making this approach less effective. Instead, it was opted to evaluate the alumina retention over time in the test samples. The dispersant that exhibits the highest level of alumina retention proves to be the most effective in providing stable dispersion.

To optimize the dispersant, five test tubes were prepared, each containing 27 grams of acrylic resin and 3 grams of alumina. Each tube had a different concentration of dispersant: 0 wt%, 1 wt%, 2 wt%, 3 wt%, and 4 wt%. The purpose of this optimization was to determine the optimal amount of dispersant needed to achieve a well-dispersed solution.

To assess the dispersion quality, with the machine Turbiscan, backscattering measurements on each sample were performed. Backscattering involves measuring the amount of light reflected from the top surface of the sample. A higher reflection indicates a higher concentration of alumina at the top and signifies good dispersion without sedimentation. The backscattering measurements were conducted at regular intervals, starting with frequent measurements and gradually reducing them to once every 24 hours.

The results revealed that over time, some samples exhibited sedimentation of alumina, causing light to pass through during backscattering. This indicated inadequate dispersion and poor performance of the dispersant. On the other hand, samples that retained more alumina at the surface exhibited higher reflectance, indicating better dispersion and effective dispersant performance. Therefore, the longer the particles remained suspended at the surface, the more efficient the dispersant was deemed to be. In this Figure 13 it can be observed the samples prepared for testing.

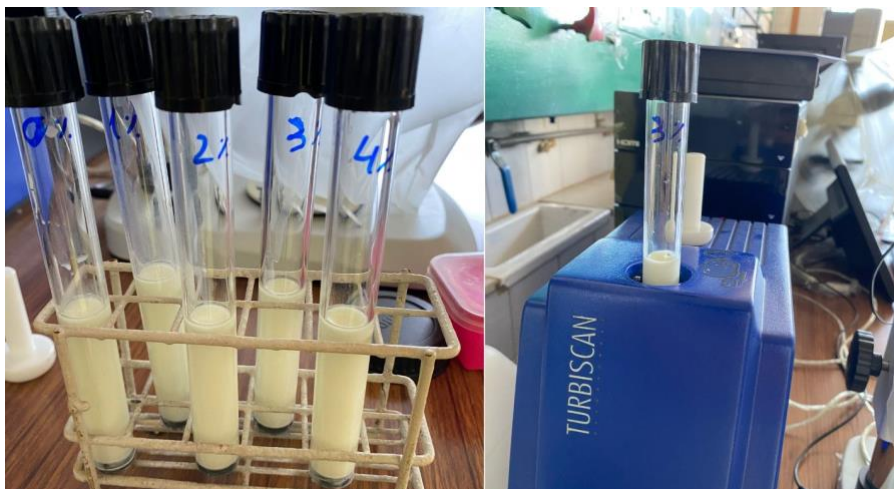


Figure 13: Samples ready to be tested in the Turbiscan.

In Figure 14, the retention of alumina over time is presented, with the dispersant concentration plotted against the retention percentage. From the graph, it is evident that the sample with a 1 wt% dispersant concentration demonstrated the highest retention of alumina over time. This indicates that a 1 wt% dispersant concentration achieved the most homogeneous solution with improved dispersion characteristics.

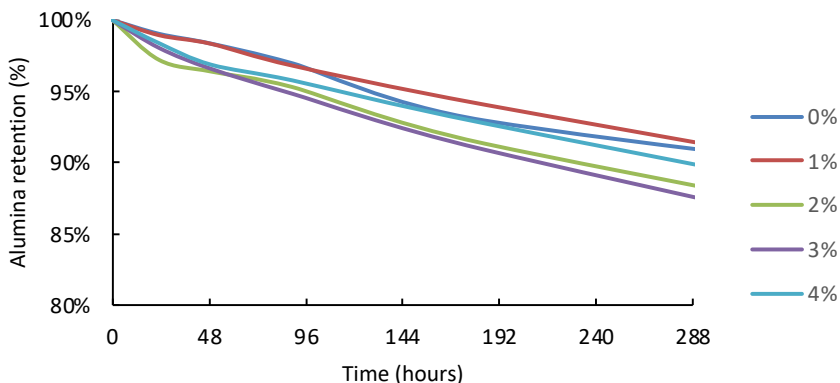


Figure 14: Time vs Alumina retention

To prepare the mixture, the aim was to create a 300 mL mixture for each percentage of alumina with some excess volume to account for potential flaws encountered during printing, such as malfunctioning pixels or detachment from the LCD screen, which can lead to deformations. The process began by adding 0.25 wt% thermal initiator to a 1L bottle of acrylic resin and manually mixing it. Next, in a dark and inert 500 mL container, the selected amount of dispersant, in this case, 1 wt%, was added. Subsequently, the appropriate quantities of acrylic resin with initiator and alumina were added to maintain a total volume of 300 mL. The specific amounts depend on the desired alumina concentration in each mixture. For instance, for a 2.5 wt% alumina concentration, 8.4 grams of alumina particles were added to 327 grams of resin. Similarly, for a 5 wt% alumina concentration, 17.11 grams of alumina particles were added to 325 grams of resin, and so on. Once all the components are combined, small alumina balls were introduced into the mixture and allowed to rotate for a minimum of 24 hours. This rotation process aids in the dispersion and homogenization of the mixture. Afterward, the alumina balls were filtered out, resulting in a ready-to-print mixture. With the desired concentration of alumina evenly dispersed, this prepared mixture is now suitable for the printing process. The printing and post-treatment procedures are detailed in previous sections.

9.2. CHARACTERIZATION OF ALUMINA-ENHANCED RESIN

Before discussing the results of the flexural and tensile mechanical tests conducted on the formulated samples, it is important to note that the testing procedures followed those outlined in previous sections. However, it should be mentioned that the ambient temperature of the testing room was 22 degrees Celsius instead of 19 degrees Celsius.

In Table 7 , the flexural modulus results of the various specimens are shown. The greener colours represent higher modulus values, while the lighter colours represent lower modulus values. As clearly seen from Phase 1 of the project, the application of a treatment considerably improves the material's properties, and the best combination is 27 seconds of exposure to the printer and 2.5 wt% alumina with give us a flexural modulus of 1230 MPa.

Table 7: Flexural modulus (MPa) of the different sample.

E (MPa)	No treatment			TT 0.25%		
Alumina	3s	9s	27s	3s	9s	27s
2.5%	670 ± 50	790 ± 60	950 ± 10	870 ± 30	1120 ± 50	1230 ± 140
5%	760 ± 30	910 ± 50	910 ± 60	980 ± 40	1070 ± 50	1020 ± 50
7.5%	610 ± 50	910 ± 70	980 ± 40	940 ± 60	1060 ± 40	1080 ± 50
10%	780 ± 20	860 ± 80	970 ± 70	960 ± 20	950 ± 40	1110 ± 20

However, although post-processing has improved the properties of the material, if Table 7 the columns of the TT 0.25% with Figure 11 are compared, it can be observed that the modulus of the treated samples without alumina is higher. For example, the resin with alumina, exposed for 27 seconds with a resin percentage giving us 1230 MPa, is surpassed by all UV-treated specimens without alumina, both at 9 and 27 seconds of exposure and with both 0.25% and 0.5% of thermal activator. Therefore, it can be concluded that, regarding the flexural modulus, adding alumina in none of the cases gives us a higher modulus. One of the determining factors in this loss of modulus could have been the temperature. Working near the glass transition temperature (T_g), any increase in temperature can affect the degradation

of the modulus. Indeed, the work was carried out chronologically, which means that these tests were conducted closer to summer and temperatures were higher than during the initial tests.

The second test conducted was the tensile test, where the results were quite similar to the flexural test. As can be seen in Table 8, undergoing a thermal treatment with 0.25 wt% thermal activator positively influenced the maximum stress values. When comparing each result one by one, there's not a single instance where the thermal treated sample with 0.25 wt% thermal activator had a lower tensile strength than the untreated ones. Furthermore, it can be observed that the highest tensile strengths are found in samples with a 27-second 3D printer exposure time and that have either 2.5 wt% or 10 wt% alumina. However, another factor to consider is that there isn't a specific alumina percentage that stands out against the others. Hence, it makes more sense to use the 2.5% alumina, as it implies a lesser expenditure on alumina.

Table 8: Maximum tensile strength of the different samples

σ (MPa)	No treatment			TT 0.25%		
Alumina	3s	9s	27s	3s	9s	27s
2.5%	20.1 ± 0.4	24.1 ± 0.8	28.2 ± 0.6	26.9 ± 0.9	32.4 ± 0.9	32.7 ± 0.7
5%	23.2 ± 8.0	24.1 ± 2.9	29.0 ± 0.4	29.8 ± 0.5	30.0 ± 0.5	31.5 ± 1.3
7.5%	17.2 ± 1.2	24.3 ± 1.8	28.3 ± 0.9	27.2 ± 0.9	30.8 ± 0.4	31.1 ± 0.5
10%	20.5 ± 2.0	24.6 ± 2.8	27.5 ± 0.8	28.0 ± 0.7	28.4 ± 1.8	33.9 ± 1.5

However, upon comparing the results obtained from the post-processing with alumina as shown in Table 8, to the results obtained without alumina post-processing from Figure 12, it is observed that every post-treatment without alumina results in higher tensions compared to those with alumina. This leads us to conclude that the addition of alumina particles neither benefits the flexural modulus nor the maximum tensile strength. As previously noted, it's essential to consider the test room temperature as a significant influencing factor. To elaborate, the goal of adding alumina to the resin was to improve the material's mechanical

properties, given that alumina is known for its high hardness and strength. This process is commonly used in the field of composite materials, which combine two or more materials to achieve properties that the constituent materials don't have individually. However, the experiment results suggest that the addition of alumina in this case did not bring the expected benefits to the flexural modulus and maximum tensile strength. This discrepancy could be due to various factors, including the processing conditions, such as the mixing procedure, the concentration of alumina, or the application of thermal treatment. Another critical factor is the testing conditions, particularly the test room temperature. Given that the tests were conducted chronologically and therefore during different seasons, the variation in room temperature could have influenced the results, particularly because the tests were conducted near the glass transition temperature (T_g) of the resin, where the material's mechanical properties can significantly change. Hence, it's crucial to carefully control and monitor these factors in materials testing.

10. CONCLUSIONS

The primary objective of this study, which was to enhance the mechanical properties of the acrylic resin used in 3D printing, has been accomplished.

The conclusions extract from the optimization of the acrylic resin curing process in additive manufacturing were:

1. The mechanical properties of the acrylic resin improve with longer UV exposure per layer during the 3D printing process.
2. Implementing both UV and thermal post-processing enhances the mechanical properties of the resin.
3. The application of post-processing drastically enhances the mechanical properties of the resin, thus aligning with the objectives of the Sustainable Development Goals 9 and 12. At the longest printing time, which is 27 seconds per layer, the modulus of the resin is approximately 1230 MPa, with a deviation of 40. However, with thermal post-treatment, the modulus increases to 1410 MPa, with a deviation of 130.
4. The relationship between the T_g value (glass transition temperature) and mechanical properties has been confirmed; a higher T_g leads to a higher modulus. This is related to the fact that the T_g ranges are within the temperature ranges in which the tests have been conducted.

The conclusions extracted from the Alumina-Enhanced resin for 3D printing were:

1. The optimal formulation to obtain the most stable alumina suspension contains a 1 wt% of BYK-P 105 dispersant.
2. The most effective formulation to achieve the optimal mechanical properties of the Alumina-Acrylic resin consists of 0.25 wt% thermal activator, and 2.5 wt% alumina. This composition, when applied with a 27-second exposure per layer and a thermal post-processing at 120 degrees Celsius for 24 hours, yields the best results, with a

bending modulus of 1230 ± 140 MPa, and a maximum tensile strength of 32.7 ± 0.7 MPa.

3. The addition of alumina and the subsequent post-processing do not enhance the mechanical properties more than post-processing without alumina. Hence, at present, it can conclude that treatment without alumina yields superior properties compared to treatment with alumina.

Nevertheless, questions have arisen from the final stages of the experiment, where the inclusion of alumina appeared to compromise the properties compared to post-processed samples without alumina. One possible explanation for this outcome could be fluctuations in temperature control during the treatment. Hence, future research focusing on alumina could consider maintaining a constant temperature in the testing room as a promising new hypothesis. This perspective also ties in with the expectation that the introduction of alumina could provide stability to the acrylic resin. Such stabilization could inhibit degradation from radiation exposure, consequently preserving the resin's mechanical properties for a longer duration. This expectation, aligning with the results of temperature control, suggests a coherent path forward for continued research in this area.

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