3D Printing Of Ceramics And Polymers For Engineering Applications

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3D PRINTING OF CERAMICS AND POLYMERS FOR ENGINEERING APPLICATIONS

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Master’s Program in Mechanical Engineering

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Stephen L. Crites, Ph.D.
Dean of the Graduate School
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by

Jesus Javier Mata

2022
Dedication

To my loving friends and family who have been there for me whenever I needed them the most. My excellent mother who has raised me into becoming a good hard-working man, by guiding with her example and loving kindness along this journey. My gratitude to all those who have been part of my life and have led me to become the person that I am and the person which I aspire to become.
IMPLEMENTATION OF DIW TECHNOLOGY AND EMBEDDED SENSORS

by

JESUS JAVIER MATA, B.S.

THESIS

Presented to the Faculty of the Graduate School of

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of the Requirements

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Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

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Abstract

The Additive Manufacturing industry, in the last years [1] has shown a great push with the development and inclusion of new technologies that have enable the engineering world to achieve great advances. As a consequence of this surge of new technology deriving from the basic principle that conforms additive manufacturing, according to the ASTM a total of seven categories have been defined. The inclusion of these new technologies and the ongoing advances in material implementation has provided the industry with a degree of freedom never seen before, leading to the creation of new solutions to existing problems that seemed impossible only a couple of years ago.

To better understand these technologies, we characterize and analyze the implementation of current Additive Manufacturing techniques that derive from the main 7 categories and how they can be implemented for the creation both ceramic and polymer structures and their respective engineering implementations. Both SLS and DIW have proven to be effective methods when experimenting and characterizing materials for innovative implementations. Testing and experimentation to develop and characterize printing parameters was essential in both instances, as it was the defining factor that dictated the success of the material implemented. This investigation proved the possibility of implementing polymers such as BIM and ceramics like porcelain as unconventional materials for 3D printing that allow for exploration of unique applications.
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Chapter I: Introduction and Background

Introduction

The Additive Manufacturing industry, in the last years [1] has shown a great push with the development and inclusion of new technologies that have enable the engineering world to achieve great advances. As a consequence of this surge of new technology deriving from the basic principle that conforms additive manufacturing, according to the ASTM a total of seven categories have been defined. [2] Each of those categorized technologies take their own approach, while maintaining the same essence that composes AM.

The seven categories that define AM are the following: Binder Jetting, Material Jetting, Direct Energy Deposition, Sheet Laminations, Material Extrusion, Powder Bed Fusion, and Vat Photo-Polymerization [2]. The inclusion of these new technologies and the ongoing advances in material implementation has provided the industry with a degree of freedom never seen before, leading to the creation of new solutions to existing problems that seemed impossible only a couple of years ago.

This ongoing relation between the manufacturing process and material creation has become a critical aspect to the engineering world, as it has allowed for a more efficient and creative way to find solutions using material such as ceramics and polymers in a more reliable and common instance then before. In this paper, we analyze the implementation of current Additive Manufacturing techniques that derive from the main 7 categories and how they can be implemented for the creation both ceramic and polymer structures and their respective engineering implementations.
Background

Section 1.1 AM

Often defined as process of joining materials to make parts from 3D model data, usually layer upon layer, [2] Additive manufacturing has continuously proven to have a major influence since its development in the 1980’s. [3] Deriving from the concept of Rapid Prototyping (PR), which at its core describes the process for rapidly designing and creating a functional prototype part [2], Additive Manufacturing has developed into one of the most lucrative industries in today’s world.

Despite having a total of seven categories, AM has maintained a principal operating process which can be tracked down in any of its categories and subcategories or techniques. This process comes as the result of a compilation of different technologies such as robotics, thermal, CAD software that has allowed for the creation of a very particular and fictional operational method. This method consists in the creation of a model by making use of CAD software, generating a sliced version of such model in order to create and define a toolpath for the part formation, preceding into the part fabrication making use of the layer-by-layer approach that often need to undergo a post processing procedure.

![AM Production sequence](image)

*Figure 1. AM Production sequence*

Through the implementation of its seven categories and different techniques that derive from them, AM has been able to continuously expand the gallery of material available for implementation. As it continues to further characterize new materials and their possible
applications, industries such as biomedical, aerospace, among others [4] have seen a great benefit in AM.

The extensive range of available technologies in today’s market, has been responsible for the massification and wide availability of suppliers. As a response of this, 3D printers are becoming accessible for public in general that had never experience AM, allowing for a further expansion on the development of new approaches and implementation of this still evolving technology.

Section 1.2 Emerging technology

As a consequence of the ongoing expansion and revolution of additive manufacturing, subsequent technology has emerged deriving from one or more of the main seven categories [5]. These, heavily embrace an aspect of technology that places them within an identifying category, but they differentiate themselves by making use of different processing methods and techniques or simply by having the inclusion of external pieces of technology that sets them apart.

Due to implementation of these subcategories or printing techniques, the user can make use of the vast range of materials that each technology allows the user to work with. As we will discuss in this paper, this range of material is highly influenced by the specific technology that is being implemented.

Section 1.2.1 SLS

Selective Laser Sintering is a technology or printing technique that derives from one of the seven AM categories, Powder Bed Fusion (PBF). PBF is defined as an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed [2], its characterized by utilizing one or more thermal sources to create fusion between the powder
particles. This fusion it’s what generates de layer-by-layer formation allowing to create a part with a very high-grade detail which may be beneficial for the creation of complex geometries. A typical SLS schematic can be seen on Figure 2.

![Selective Laser Sintering (SLS) layout](image)

*Figure 2. Selective Laser Sintering (SLS) layout*

The very first iteration of what is now consider PBF saw light Back in the late 1980’s, as this technology emerged due to the work of a professor at the University of Texas at Austin [6]. This technology would soon spike a lot of interest, as it was a very capable and never seen before approach the creation of complex design. Even though when compared to today’s standards and capabilities these were the very first steps that would allow for the further development and implementation of this technology.

Among the different sources of thermal energy that is implemented with PBF, Laser Sintering (LS) which makes uses of laser technology as a thermal source, is arguably the most used today. LS in the early stages of development was originally developed to produce plastic prototypes using a point-wise laser scanning technique. Today, this approach continues to be
implemented in the creation and development of other materials with the inclusion of metal and ceramic powders.

As SLS has become a more explored area of research due to the great capabilities and features that it has to offer, material characterization and research continues to become more common. Having an increasing library of materials that can be utilized alongside with this technology makes this a very desirable approach to 3D Printing. To further characterize and explore material properties and the overall SLS capabilities and limitations, in this study the Sintratec Kit was acquired and utilized as its capable of producing functional prototypes and provides the user the freedom to modify a variety of printing parameters making it highly versatile.

Among the key aspects to have into consideration when implementing this type of technology, the technical parameters that the Sintratec Kit offers were essential to define, as they play an important role by determining capabilities and the possible limitations the system could
be subjected to. Such parameters like: Print volume, layer height laser speed and temperature as displayed on Table 1.

Table 1. Sintratec Printing Parameters

<table>
<thead>
<tr>
<th>Technical Details</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Volume</td>
<td>110x110x110mm</td>
</tr>
<tr>
<td>Layer Height</td>
<td>100-150μm</td>
</tr>
<tr>
<td>Laser Speed</td>
<td>5-20mm/s</td>
</tr>
<tr>
<td>Temperature</td>
<td>80-150°C</td>
</tr>
</tbody>
</table>

Given that the KIT allows for a customization of parameters such as layer height, hatching offset and hatching spacing, a wide range of possibilities with regards to the polymers that can be used is available. In this instance PA12 which is a well-studied polymer and has a preset printer setting within the Sintratec software was used alongside BMI which is a less studied powder material. Both materials will serve to analyze and study the capabilities that both the Sintratec Kit and SLS technology and their possible applications.

As stated before, there are many aspects that must be considered when utilizing SLS in order to generate a successful print, as it can have a major influence in the end result of the experimentation. For this specific KIT the assembly process is a major aspect to keep in mind, as a proper assembly and parameter calibration will be responsible for the success of the study.

Section 1.2.2 DIW

Direct Ink Writing (DIW) is a technique that derives from the main principle of material extrusion, and it was developed in 1997 with the intention to process ceramic slurries [7]. Despite emerging as a technique designed for a specific purpose, DIW has since then been classified as a computer aided material extrusion process that relies on the deposition of material
through a nozzle to create a structure using the layer-by-layer approach. Having also the notable advantage of being able to process highly viscous materials. [8]

In comparison to other forms of material extrusion, the process for printing using DIW as seen on Figure 4, consist of having material pushed through a feeding tube connected to the printhead which then is deposited on the printing platform by making use of an inner screw controlled by a motor.

![Figure 4. Schematic Representation of DIW printing technique.](image)

Due to the ability to utilize high viscous material, DIW in comparison to other techniques allows the user to make use of the benefits of AM and combine them with high viscous materials such as ceramics, enabling the creation of creative printed parts with unique properties that derive from using these types of materials. These unique properties and distinguished benefits such as high degree of permeability [9] can lead to the creation of new and innovative solutions such as humidity regulation within an enclosed environment.

To further investigate the capabilities of DIW and analyze the mechanical properties of different ceramics such as clay, the Delta Wasp 2040 Clay was acquired and implemented. Given that the printer in comparison to other competitors allows to print and produce a wider range of
parts thanks to the available nozzle sizes that can be implemented and the spacious build area, the Delta Wasp can help further characterize and define parameters for clay printing.

Figure 5. Delta Wasp 2040 Clay Setup

This specific model has a set of printing parameters as seen on Table 2, that are optimal for quick sampling and prototyping. These parameters facilitate the printing process and material characterization as they provide a wide range of printing options.

Table 2. Delta Wasp 2040 Clay Printing Parameters

<table>
<thead>
<tr>
<th>Technical Details</th>
<th>200x4000mm</th>
<th>0.5mm</th>
<th>150mm/s</th>
<th>3L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer Height</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Printing Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Travel Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Storage Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Section 1.3 Printing Materials (Ceramics/Polymers)

In today’s industry, the selection and implementation of material has taken a major role in the research areas for 3D printing. As it has been stated before, the development of new and more efficient methods for 3D printing has enable the use of more materials that had not been available before. For instance, characterization and further investigation of ceramics and polymers in the last years has taken a major role as they have shown to have a great versatility and material properties that most industries can benefit from. [10,11]

By making use of 3D printing methods, material like this and their potential, can be studied and implemented as they won’t be bound to the limitations and boundaries of conventional manufacturing. The degree of freedom that AM offers in combination with these materials make for a very effective and desirable combination

Section 1.3.1 Ceramics

Ceramics over the years have developed into being among the most studied and implemented materials for complex solution because of the excellent properties they can display. All though, there are some limitations due to the nature of traditional fabrication methods that have proven to be expensive and time consuming, their mechanical properties alone were unique that industries would often overlook all the limitations that represent the inclusion of these type of materials.

As discussed previously, the emergence of 3D printing technologies provided a pathway for the inclusion and development of new techniques capable of using a wide range of materials such as ceramics, neglecting some of the major drawbacks of using this type of materials. As a response of this surge in technology, we can see major industries such as aerospace, metallurgy,
biomedical, electronics and chemical take a more active role in the development and characterization of ceramic materials for 3D applications.

Among the many possible materials that are classified under ceramics, clay has remained one of the most used. Dating back to ancient times, clay has proven to have very reliable and durable material not only for arts but for water storage and other substances as well. Its unique properties such as high level of density, high degree of permeability are key aspects that allow the material to retain high levels of moisture and regulate humidity in the air. [12] All these distinctive properties that belong to clay in combination to all the mechanical properties that ceramics exhibit, places clay in a very desirable position for different applications.

When trying to compare clay to other most used materials for 3D printing it has some advantages due to the nature and chemical composition of the material such as being widely availability, unexpensive and environmentally friendly. These advantages further enhance the incentive for using clay as a material for 3D printing.
Due to vast availability of clay, porcelain is being studied in this paper to identify all possible benefits and limitation when implementing this material in combination with DIW techniques.

**Section 1.3.3 Polymers**

As stated before, one of the benefits of AM is the ability to create complex geometries making use of a variety of materials with special or unique properties that can be essential to certain application. This has enabled polymers to become among the most implemented and therefore researched materials for 3D printing [13,14]. Because of this research, polymers are found in variety of forms such as thermoplastic filaments, reactive monomers, resin or powder, and are used across all industries.

Among the most used and studied polymers for SLS applications Polyamide 12 or PA12 stands out as is a very desirable material for prototyping as it has great mechanical properties such as heat resistance alongside flexibility and a convenient narrow melting point [15,16]. In contrast a thermoset material such as bismaleimide (BMI), which possesses excellent thermal, mechanical and chemical properties is very desirable for aerospace applications [17,18].
Chapter II: Experimental Data Testing Analysis

Section 2.1 SLS

Looking back at the many types of printing technologies available nowadays, in comparison to other more common and available printing techniques such as material extrusion, selective laser sintering or SLS has a very distinguished set of components that allow it to approach the layer-by-layer additive process differently. A build bed, supply bed, powder distribution roller, and laser as power source are the main components that make this possible.

Section 2.1.1 Sintratec Kit

To adequately research of the many capabilities that SLS and the Sintratec Kit has to offer, the printer was used to produce a set of characterization samples. These samples were printed making use of two different materials, PA12 and BIM. Since the Sintratec Kit offers default printing parameters for the use of PA12, it granted the opportunity to use it as a control sample while BIM was implemented to further investigate the capabilities of the printer.

Section 2.1.2 Sintratec Kit Assembly

Among the many technical parameters that must be considered for the implementation of the Sintratec Kit, the assembly process and calibration play a major role as they can be a decisive element that defines the overall success of print. The overall assembly process is divided into a total of 6 segments corresponding to different base aspects of the machine. Such segments are, Door, Base, Core, Lamp, Hat, and Electronics all from which have an individual set of instructions that must be closely followed.

Door
Despite being the first and easiest to assemble as there is no electronics within this segment, the door plays a major role as is responsible for keeping an isolated printing environment. This has a big significance as it keeps external impurities from interfering with the powder sintering process, at the same time it allows for the temperature within the chamber to be easily regulated and keep a constant and precise temperature level throughout the printing process. On the other hand, it serves to keep the user safe by keeping the laser, temperature, and high temperature exposure contained as the printing process is happening.

In conjunction to the isolation and UV light protector that the door has in order to preserve the internal environment of the printing chamber, as seen in figure x a small magnetic switch is also placed to further expand the safety of the user. This switch is responsible for detecting when the door is open, stopping the laser from functioning if triggered. This could also be a negative aspect as it has the potential for moving or misaligning with respect to the sensor triggering a false signal of an open door stopping the laser from functioning and stopping the print from happening.

*Figure 7. Sintratec door assembled*
Base

The base is responsible for encasing the printing chamber and providing structural support of the printer. Just like the door, is well isolated to help maintain a steady temperature throughout the printing process. Due to the simple role, it plays with respect to the other segments of the assembly the materials and overall design that goes into the base as seen on figure x focusses to achieving the maximum amount of isolation.

Core

The core assembly is the most extensive segment as its responsible for the assembly of the build bed, supply bed, their respective platforms and chambers, the powder spreader, initial placement of magnetic switches, heater and thermistor placement and wiring, and providing the printer the most amount of structural support. All this composition of assembly parameters makes this one of the most precise segments to take into consideration due to several factors:
1. The misalignment of the build and supply chambers could lead to a leak of powder material between chamber or the bottom of the printer.

2. Unbalanced fit of the roller used for the chamber platform of the powder spreader could lead to mechanical malfunction and lead to applying more unnecessary load to the motors implemented.

3. Unproper alignment of the powder spreader could have an influence in the layer formation.

Figure 9. Sintratec base isolation

All these factors are responsible for a proper mechanical functioning of the printer, on the other hand as stated before this segment is also responsible for the placement of magnetic switches which serve to control the positioning of the build and feed platform and the connections and routing for the heater and thermistor which control the heat in the printing chamber.
Lamp

For SLS systems, this assembly represents a major functioning aspect as this lamp is reasonable for heating and keeping the powder at the right temperature prior and during the sintering process. This segment must be done with major care as the lamps are susceptible to breaking do to their glass composition.
Hat

What is defined as the hat is the segment on top of the printer which houses all the electronical components and wires that the printer needs. As is to be expected, this segment must be well isolated as it sits on top of the main printing chamber and houses all electronical devices that can be affected if exposed to high temperatures.

Careful placement of this segment are essential as it will help the routing process for all the electronic devices an easier process to undergo. Is important to keep this area as clean and isolated as possible to avoid any interaction or misplacement of small parts by error.

Figure 12. Sintratec base isolation

Electronics

The electronics and wiring process can be among the most challenging and important segments as this is where all the components interact with the motherboard and a power source.
Through this process the most important aspect is the isolation, labeling, and constant testing of all cables which can help speed the process while helping to avoid any misplacement that could lead to a failure of the system.

Isolation and routing routes to differentiate between communication cables, high voltage suppliers are recommended as the interaction between them could lead to a negative interaction between them affecting the operation and communications of the printer.

![Sintratec base isolation](image)

**Figure 13. Sintratec base isolation**

**Section 2.1.3 Calibration process**

Once the assembly process is complete, a detailed calibration of the laser alongside with the build bed and supply bed platforms is needed to ensure all aspects of the printing process will be successful. Both calibrations were performed following specific guidelines and safety protocols set by Sintratec that can be seen on their assembly manual. [19]

**Laser Calibration**
As stated before, the Sintratec KIT utilizes a laser as a main source of power for initiating the sintering process, which creates the formation of the layers that form a final product. Nowadays, there is two different types of lasers that are commonly used for SLS applications, the most used for high end printers carbon dioxide laser, and the more practical diode Laser. [20] The Sintratec Kit makes use of a small 2.3W diode laser that must be perfectly aligned with respect to two galvanometers Figure 14 responsible for guiding and controlling the laser.

![Sintratec base isolation](image)

Figure 14. Sintratec base isolation

To easily calibrate the laser by making use of the galvanometers, the Sintratec interface “Sintratec Central” which regulates the printing process must be utilized. The interface allows the user to display a calibration pattern as seen on Figure 15 that must match exactly to a printed pattern placed on top of the build platform.
Figure 15. Sintratec base isolation

To accommodate and obtain the desired results the two galvanometers controlling x and y should move accordingly to adjust the image of the pattern, once the pattern resembles the overall position of the printed pattern its needed to expand or collapse the laser reach depending on the pattern shown.

However due to the safety precautions of having to turn off the laser every time an adjustment had to be done, this task can be time consuming, therefor a different initial approach was taken. To avoid the constant alignment of the galvanometers while the laser is on displaying the pattern as seen on Figure 16, a source of light was placed inside the chamber on top of the pattern that way the light would travel from the inside of the chamber into the galvanometers and ending near the laser. This method despite not replacing the process for calibration it allows to reach a close proximity to the position needed in order to match the pattern. After this initial process was done, the manual instructions were followed to make some corrections and have the perfect pattern alignment therefor ending the laser calibration process.
Platform Calibration

The platform calibration plays a major structural job, as its responsible for property defining the maximum amount of movement the platforms must have. If not done property it could risk and dimmish the lifespan of the motors controlling both platforms by adding additional stress and workload that it should not be subjected to it. Unlike the laser calibration, there are no instructions detailing the correct approach for calibration all was based on testing different parameters until the desired operational system was obtained.

The Sintratec Kit makes use of magnetic sensors or switches that upon activation serve to identify the position of specific sections. As seen on Figure 17 the placement of the magnetic switches is essential for the printer to identify the limitations and the printing process by delimitating space constrains. The system makes use of a total of six magnetic switches that serve to identify the placement for the build and supply platform, the powder spreader travel distance, and the door status.
To obtain the best results, as seen on Figure 18 the placement of the sensors was being tested by making use of the “Sintratec Central” which allows to independently control each platform and rise or lower them to a specific value. In this instance both platforms were placed at the upper and lower limit with respect to the build and supply beds, then the respective switch would be alight with respect to the actuator making sure that at that position they would make contact allowing to define the upper and lower limits that the platforms can travel.
Section 2.2 DIW

Direct ink write could be consider among the earliest examples of 3D printing technologies that were developed, nowadays despite having a seemingly simple approach to AM and the 3D printing process, it can distinguish itself due to its capabilities and implementations which can be unique. With today’s standards and capabilities DIW doesn’t excel on precision part quality finish but it does allow the user to implement materials with much higher viscosity levels, feature that other printing techniques fails to achieve.

Section 2.2.1 Delta Wasp 2040 Clay

The Delta Wasp 2040 Clay as stated before, is a DIW 3D printer with the capability of 3D printing using high viscous materials with a focus on implementation of clay. The 3-liter tank in combination with the 200mm x h400 mm printing volume, allows for the creation of a wide range of structures that range in volume and size.
The Delta Wasp provides a straightforward printing process that relies on the interaction of the user throughout. From preparing the material all the way to adjusting the printing parameters the Delta Wasp and DIW in general is often defined by the hands-on experience that the users are subjected to. For this specific printer the process is defined in a total of six steps:

1. Material Preparation
2. Tank Loading and pressurization
3. Printer Setup
4. Material Extrusion
5. Printing Parameters
6. Printing Initiation

For this paper the printer was implemented to establish a base foundation that can be used for the creation of 3D structures utilizing clay as a material. All printing aspects that were utilized for the creation of the prints were recorded analyzed and duplicated to achieve a constant standard process that can be duplicated.

Flow Control

As stated, given the nature of DIW and its unique approach to 3D printing, to successfully implement the Delta Wasp a conjunction of internal and external aspects such as pressure and material density in relation to the printers printing speed and flow deposition rate, had to be consider. To facilitate the deposition rate and number of variables within the printer, it
was essential to perform print under the same external conditions leaving the printing parameters such as printing and speed and flow deposition rate, as the main variables to control. The Delta Wasp was loaded with total of 2kg of material and pressurized at a steady 4bars while using a 1.5mm nozzle.

On the other hand, while external factor was made into a constant the printing speed and flow of the printer had to be controlled. Given that the Delta Wasp makes use external slicing software to generate a gcode, most of the controlled setting were customized by the slicing software to later be refined using the printers “Tune” setting.

Ultimaker Cura Settings

Unlike other printers which make use of their own software to interpret an STL file for printing, the Delta Wasp must make use of an external slicing software. In this specific instance Ultimaker Cura slicing software was implemented as it allows for the creation of custom printers, material profiles and printing profiles that will adjust to the needs of the Delta Wasp. As seen on *Figure 19* a profile was set up containing the dimensions of the Delta Wasp, as well a printing profile was adjusted to accommodate for the larger nozzle sizes used with higher viscosity materials like clay.
Section 2.2.2 Clay Selection

Through characterization and implementation of new technologies it has been shown that ceramic materials exhibit unique and interesting properties that can be implemented for variety of manufacturing processes and research. Clay among the benefits of its natural composition, wide availability, and low cost, has a set of unique properties that make it a great candidate for the creation of enclosures to encase and protect an object from the exposure to harsh
environmental conditions that could potentially diminish or compromise the lifespan of such.

[21,22]

In order to test the material properties of clay and its possible implementation to the creation of embedded sensors, porcelain 5 clay was implemented as it is known to exhibit great water absorption and low shrinkage percentage in comparison to other clay materials. [23,24] The porcelain was further softened by making use of water until reaching toothpaste consistency, enabling the implementation of 3D printing in the form of DIW. Afterwards the porcelain was fired at and glazed by making used of a kiln.
Chapter III: Results

Section 3.1 SLS Printing Results

Once the Sintratec Kit was successfully built and calibrated, a set of prints were commissioned using PA12 as a reference to test the printing conditions of the Sintratec, and BIM to characterize the powders settings while using this printer.

Section 3.1.1 PA12

Pa12 which is described as an industrial grade polyamide Nylon powder, is among the most widely used materials for printing using SLS. For this reason, the Sintratec Kit utilizes this material to create the calibration print, which help define the proper operational conditions for the printer. A total of two prints were created using PA12 including the calibration print. As seen on Figure 21 the Sintratec Kit was able to successfully print a fully dense part utilizing the preset parameters and dimensions appointed by the manufacturer. A minor fracture can be seen on one side of the part mostly due to improper handling of the object.

Figure 21. PA12 Calibration part

Following the success of the print, the preset parameters for PA12 were implemented once again to test quality and presession of the printer by attempting more complex parts. The design
implemented was a floating cup and it was an attempt to see the benefits and capabilities of SLS to fully print a dense part without the need for support material.

![Figure 22 PA12 Calibration part](image)

Figure 22 PA12 Calibration part

The part was printed but it showed an excess in the hardness of the material surrounding it, making it impossible to fully remove all the excess powder by conventional means, thereby compromising the structural integrity of the part. In Figure 23 we can see the printed part after several attempts to fully remove the excess harden powder led the part to break.
Section 3.1.2 BIM

Unlike PA12, BIM powder is not as commonly used for SLS applications, for this reason there is a lack of predetermined settings that can be followed to obtain a successful print. To overcome this issue, several printing attempts with different settings were performed in an attempt to create a fully dense part using this material. The first print which was considered successful, as displayed on Figure 24 was a fully dense piece with some minor cracking close to the edges, leading to the idea that the setting could further be refined.

Further changes to the printing setting lead the second successful print which as seen on Figure 25 was an improvement on the previous attempts. The printer sample shows a better density and interlayer bounding in comparison to the previous attempts but with signs of burnt material near the edges.
Figure 25. PA12 Calibration part

Section 3.2 DIW Printing Results

Different characterization sample were designed and printed considering the designed Cura parameters with the purpose of analyzing and determining the behavior of the porcelain during and after the printing process. As seen on Figure 26 the sample designs were simple shapes that could allow to better understand the basic capabilities of the printer, at the same time allow for a reliable analysis of those samples.

Figure 26. Sample designs
The initial printing process as seen in Figure 27 presented overflow of the material which caused a big deformation and change in dimensions of the original design. This can be attributed to the printer’s printing speed and flow control which had to be tuned to accommodate to the set pressure and material density.

Figure 27. Initial printed samples

Afterwards printing setting were adjusted to overcome the overflow of material and obtain a consistency between printed samples enabling the creation of characterization samples such as in Figure 28. These samples were printed to assure the consistency, effectiveness, and repetitiveness of the printing process. The end results showed very good material consistency and part accuracy in relation to the original design dimensions.
Once the printing process was mastered, the prints samples had to be analyzed for their change in volume and mass due to the drying process the material implemented undergoes and the post processing techniques to which it is subjected. To obtain a control set of values, sample disks seen on Figure 29 were printed and analyzed in a set of four stages: original, dry, sintered and...
glazed. As presented on Table 3 the results indicate there was a change in the dimension and volume of the disks, averaging a total of 13.77% change between the dry value and the sintered.

![Successful Prints](image)

**Figure 29. Successful Prints**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Dimensions (in)</th>
<th>Volume (in^3)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
<td>0.370697</td>
<td>-</td>
</tr>
<tr>
<td>Dry</td>
<td>0.98</td>
<td>0.4310138</td>
<td>16.271186</td>
</tr>
<tr>
<td>Sintered</td>
<td>0.92</td>
<td>0.3757234</td>
<td>-12.827988</td>
</tr>
<tr>
<td>Glazed</td>
<td>0.91</td>
<td>0.37163945</td>
<td>-1.0869565</td>
</tr>
</tbody>
</table>

As seen in **Figure 30** the results exhibit an increase in the volume from the original stage to dry stage due to the printing process not being fully refined. Afterward the part exhibits a decrease in the volume due to sintering and glazing post processing techniques implemented.
As well, on Table 4 we can identify a change in the mass of the printed samples due to the same process.

Table 4. Mass Change

<table>
<thead>
<tr>
<th>Stage</th>
<th>Weight(g)</th>
<th>Density(g/cc)</th>
<th>Mass(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>2.8</td>
<td>2.6</td>
<td>18.36</td>
</tr>
<tr>
<td>Sintered</td>
<td>2.9</td>
<td>2.6</td>
<td>20.48</td>
</tr>
<tr>
<td>Glazed</td>
<td>2.9</td>
<td>2.6</td>
<td>20.48</td>
</tr>
</tbody>
</table>

After analyzing the values for all stages, we can see an increase in the mass for the sample part. As better depicted on Figure 31 there is an increase in mass after sintering, meanwhile subsequent postprocessing in the form of glazing does not represent any change in the mass of the parts.
Figure 31. Successful Prints
Chapter IV: Conclusion and Future Work

Current additive manufacturing techniques such as SLS and DIW have proven to be effective methods when experimenting and characterizing materials for innovative implementations. Testing and experimentation to develop and characterize printing parameters was essential in both instances, as it was the defining factor that dictated the success of the material implemented.

SLS proved to be an effective approach for the implementation of a thermoset polymer such as BIM. The correct processing and treatment of the material with the inclusion of SLS has the potential to make use of the unique properties of BIM and the complexity in parts design achievable with SLS for the development of unique parts.

The development and characterization of the printing parameters for the Delta Wasp proved successful by obtaining consistent prints with consistent properties. The post processing techniques proved successful as it allowed for the printed samples to become stable structures that can be used for different purposes.

In conclusion, this investigation proved the possibility of implementing polymers such as BIM and ceramics like porcelain as unconventional materials for 3D printing that allow for exploration of unique applications.

4.1 Future Work

The success of the research has enabled the possibilities to make use of their specific properties for the further development and research on the process of embedded sensors. Given clay special properties and distinctive behavior with relation to humidity alongside with the implementation of DIW, it can be used to create special safe enclosures.
References


Vita

Jesus Javier Mata attended the University of Texas at El Paso where he received Bachelor of Science in 2019. During his educational career, he was granted the opportunity to be a fellow member of the Mickey Leland Energy Fellowship (MLEF) with the National Energy Technology Laboratory (NETL) where he helped develop a fault prevention system for a Solid Oxide Fuel Gas Turbine system. While attending UTEP, he was hired to conducted research for the Center for Space Exploration and Technology Research (cSETR) while being part of the Consortium of Hybrid Resilient Energy Systems (CHRES). He has accepted a full-time position with Kansas City National Security Campus upon graduation as an engineer.