DIRECTED ENERGY DEPOSITION ADDITIVE MANUFACTURING FOR PHARMACEUTICAL PRINTLETS

An Undergraduate Research Scholars Thesis

by

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Directed Energy Deposition Additive Manufacturing for Pharmaceutical Printlets

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The goal of this research work is to explore the potential of directed energy deposition (DED) as an additive manufacturing process for pharmaceuticals. DED is a process commonly used in 3D printing of metals, in which a focused energy source such as lasers and electron beams is used to melt deposited powder onto a build plate. This allows for greater control over the customization of prints, including material composition, geometric accuracy, and detail. Such precision is particularly important for patients with specific needs, such as those in the geriatric and pediatric populations. However, the use of DED for pharmaceutical fabrication has yet to be fully explored and tested. To address this gap in knowledge, this research work focuses on developing a working prototype of a DED machine that is specifically tailored for pharmaceutical additive manufacturing. The machine was created by modifying a traditional FDM printer to integrate an enclosed building area, a laser, and a powder deposition mechanism. The resulting prototype was used to produce tablets, demonstrating the impact of various process parameters on print quality. By proving the concept of DED as a viable method for pharmaceutical manufacturing, this research work opens up a plethora of possibilities to aid

patients. In particular, DED could enable greater personalization and flexibility in drug dosage and combination, as well as the potential for more complex geometries that could impact drug release rates. The precision and control offered by DED could also lead to increased efficiency and cost-effectiveness in drug production. Ultimately, the successful implementation of DED in the pharmaceutical industry could significantly improve patient outcomes and contribute to the evolution of personalized medicine.

DEDICATION

To my family who has taught me to chase happiness and never settle for less.

Para mis padres que me dieron todo. Gracias por enseñarme lo que significa el valor de la familia, el trabajo duro, y la fe.

Arriba y adelante.

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The materials used for Directed Energy Deposition Additive Manufacturing for Pharmaceutical Printlets were provided by Dr. Mathew Kuttolamadom and Natalia Garcia. The analyses depicted in Directed Energy Deposition Additive Manufacturing for Pharmaceutical Printlets were conducted by Natalia Garcia.

All other work conducted for the thesis was completed by the student independently.

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1. INTRODUCTION

1.1 Objectives

The pharmaceutical industry is continuously seeking innovative manufacturing methods to produce drugs that are safe, effective, and cost-efficient. One such method that has shown promise in recent years is additive manufacturing. Additive manufacturing, also known as 3D printing, is a process that allows the fabrication of complex 3D geometries layer by layer, using various materials.

The objective of this research work is to develop a directed energy deposition printer capable of producing pharmaceutical printlets and investigate the effects that various process parameters have on the quality of the tablets. The development of the directed energy deposition printer involves the integration of a focused energy source, gas pathways, a powder feeding mechanism, and a reservoir. The printer will be designed to deposit pharmaceutical powder onto a build platform in a controlled and precise manner, with the ability to vary the energy source's power, speed, and position.

Once the printer is developed, the process parameters will be systematically varied and optimized to investigate their effects on the quality of the pharmaceutical printlets. These process parameters may include the energy source's power, speed, and position, as well as the pharmaceutical powder's particle size, shape, and flowability.

The results of this research work will provide valuable insights into the effects of various process parameters on the quality of pharmaceutical printlets produced using directed energy deposition. The findings will help to optimize the manufacturing process and improve the consistency and reproducibility of the pharmaceutical printlets. Furthermore, the development of

a reliable manufacturing method for pharmaceutical printlets using directed energy deposition will have significant impact on the pharmaceutical industry, potentially leading to the development of more effective, individualized and cost-efficient drugs.

The development of a directed energy deposition printer capable of producing pharmaceutical printlets is a promising research avenue. The integration of additive manufacturing techniques in the pharmaceutical industry could potentially revolutionize drug development, leading to more efficient and personalized treatment options. The results of this research work could contribute to the advancement of this field and provide a foundation for further studies in additive manufacturing for pharmaceutical applications.

1.2 Motivations

The development of 3D printing technology has revolutionized the manufacturing industry. In recent years, researchers have explored the potential of using 3D printing technology to produce pharmaceuticals, with the goal of improving patient outcomes through personalized medicine. One promising approach in this area is directed energy deposition (DED), a type of 3D printing that uses focused energy sources to melt and fuse material in a controlled manner.

While DED has been used extensively in the fabrication of other materials such as metals, ceramics, and polymers, its application in pharmaceutical 3D printing is yet to be addressed. The primary motivation behind this work is to prove the concept of pharmaceutical 3D printing using DED and explore its potential benefits. One of the key advantages of DED is the ability to deposit material with high precision, enabling the production of complex and customized pharmaceutical products. This could lead to the individualization of medicine and meet the demands of patients with needs that could be addressed through customization that DED could allow.

Overall, the potential benefits of implementing DED in the pharmaceutical industry are significant, and this work represents an important step towards personalized medicine. With further research and development, DED-based 3D printing could introduce a new drug delivery manufacturing method and treatment.

1.3 Pharmaceutical Additive Manufacturing

In recent years, there has been a growing interest in the use of additive manufacturing techniques for the production of pharmaceuticals. One of the key advantages of this technology is its ability to produce complex geometries and customized drug delivery profiles. With the ability to control the drug release profiles, and composition, personalized medicine can be achieved, which is particularly useful for patients with unique needs.

In addition to the benefits of customized drug delivery profiles, additive manufacturing of pharmaceuticals can also improve the efficiency of the drug development process. With traditional methods of drug manufacturing, the process can be time-consuming and costly, as it involves a series of complex steps. However, additive manufacturing can simplify the process by allowing the drug to be produced in a single step, reducing both time and cost.

Fused deposition modeling (FDM) is a popular additive manufacturing process that has been predominantly used in the production of consumer-level plastic 3D printing. Researchers have expanded the use of FDM into the realm of pharmaceuticals, with promising results. In fact, FDM has been used to 3D print pharmaceutical tablets with good mechanical properties, which has paved the way for further research and development in this field [1].

Despite the success of FDM in pharmaceuticals, this technology has its limitations, including process parameter optimization, which can affect the resolution and precision of the print [1]. As such, the pharmaceutical industry has been working to develop new additive

manufacturing techniques that can overcome these limitations and produce high-quality pharmaceutical products.

The field of additive manufacturing has seen extensive research in the pharmaceutical industry, with binder jetting being a promising technique that has garnered significant attention. Unlike traditional 3D printing methods, this approach involves jetting a binder onto a powder bed, which effectively binds the individual particles together to create a 3D printed object [2]. One of the key benefits of binder jetting is that it offers improved process parameters, including faster print speeds, greater accuracy, lower costs, reduced waste and higher quality prints, thanks to its layer-by-layer binding approach [2]. However, as with any new technology, this process has also revealed limitations, particularly in post-processing requirements and spatial distribution leading to a high degree of porosity, which require further investigation [2].

Finally, the additive manufacturing process of selective laser sintering (SLS) has been investigated as a solution to the issues presented by the previously discussed techniques. SLS is a process that selectively melts powdered material on a build platform with a laser, creating complex geometries [3]. Though typically used for metals, polymers, and ceramics, this technique has also been applied in the research of 3D printed pharmaceuticals. Jamróz and colleagues explored the results of an SLS printed tablet process in their 2018 report [4]. The report highlighted the advantages of SLS, such as customization, dosage personalization, increased print quality, and high accuracy, which addressed previous limitations posed by other additive manufacturing processes [4].

However, similar to the other discussed techniques, SLS also faced challenges in scalability and commercialization, as well as risks in biocompatibility [4]. Despite these challenges, the potential benefits of SLS in pharmaceutical additive manufacturing make it an

attractive area of research for the future of personalized medicine. By continuing to improve and innovate in the additive manufacturing field, the pharmaceutical industry can create more efficient and effective drug delivery methods for patients.

1.4 Directed Energy Deposition (DED)

Directed energy deposition (DED) is an advanced additive manufacturing technology that has gained significant attention and popularity in recent years. The process involves using a focused energy source, typically a laser, to melt and fuse together a range of materials, including metals, plastics, ceramics, and composites [5]. The precision and control offered by DED machines make them ideal for fabricating complex parts with high accuracy and consistency.

One of the main advantages of DED is its ability to address many of the limitations and challenges associated with other additive manufacturing methods. For example, the use of a small focused energy area allows for improved accuracy and detail in the final product. The ability to control the energy source's power also serves as another critical process parameter that can impact the print quality when optimized [5].

Material efficiency is another key benefit of DED. Unlike other additive manufacturing methods, such as binder jetting or selective laser sintering, DED deposits only the necessary material onto the build plate, avoiding material contamination and improper allocation [5]. The unused material can be recycled and used for future prints, making the process more sustainable and cost-effective.

DED machines typically comprise four essential subsystems: the focused energy source, gas pathways to carry the substrate, a powder feeding mechanism, and a reservoir. Together, these components enable faster production rates and greater control over the printing process.

One of the most significant advantages of DED is its design flexibility [5]. The technology enables the creation of complex geometries that are difficult or impossible to achieve with other additive manufacturing methods. With DED, multiple substrates can be utilized in the same print, and the concentrations and distribution of each specific material can be monitored and adjusted to provide greater customization [5].

In conclusion, directed energy deposition is an advanced additive manufacturing technology that offers significant benefits over other methods. Its precision, control, material efficiency, and design flexibility make it ideal for fabricating complex parts with high accuracy and consistency [6]. As the technology continues to evolve and improve, it is likely to play an increasingly critical role in various industries, from aerospace and defense to healthcare and consumer goods.

1.5 Expected Outcomes

Traditional pharmaceutical manufacturing has faced challenges with processes by limitations that prevent them from meeting the specific needs of certain patient populations, particularly pediatric and geriatric patients. In recent years, there has been a growing interest in additive manufacturing techniques, as a way to address these limitations and provide a more individualized form of care.

This research work seeks to further expand the application of directed energy deposition into the pharmaceutical field. Specifically, the aim is to develop a functional prototype of a DED machine that can produce sample pharmaceutical tablets. These initial trials will serve as the foundation for further research and development, with the goal of advancing the medicinal field and improving patient care.

One of the primary advantages of DED in pharmaceutical manufacturing is its ability to provide greater precision and accuracy. This is particularly important for patients who require highly individualized treatment plans that cannot be met by traditional manufacturing processes. Additionally, DED's ability to fabricate complex geometries with high levels of precision and control could be used to produce tablets with specific drug release rates, potentially leading to improved outcomes. Furthermore, DED's ability to utilize multiple materials in the same process with high levels of precision and control could enable the combination of multiple prescriptions into a single tablet, further enhancing its potential for individualized care. Ultimately, the successful application of DED in pharmaceutical manufacturing represents an important first step towards a future where doctors can prescribe medication with a direct line to individualized pharmaceutical production.

2. MATERIALS AND METHODS

2.1 DED Machine Requirements

In order to prototype a directed energy deposition machine, 4 essential components were designed and integrated to the original Ender 5 3D printer. These subsystems included: the air supply and tubing, the powder feeding mechanism, the laser, and the enclosure. Together, these components effectively demonstrated the principles of directed energy deposition using readily available materials.

The primary objective of this study was to demonstrate the feasibility of using directed energy deposition as a manufacturing method for pharmaceutical printing. To do so, the prototyped DED machine must be able to effectively deliver powder to an established build plate and use a laser as the focused energy source to fuse material together. To achieve this requirement, materials such as 3D printed PLA parts, plexiglass, PE tubing, air pumps, and reservoirs were utilized. The process and modifications made to these materials will be further discussed in the next sections.

2.2 Pharmaceutical Powder

To avoid the improper use of materials, initial trials of the system were done using granulated sugar. Even though the particle weight of granulated sugar is different than that of the drug, the DED machine is customizable and adjustable to varying particle sizes and weights due to the control capacities of the air pump.

The pharmaceutical drug for which the DED machine is meant to be designed for it a combination of 67% Kollidon® SR (KDSR), 30% Carbamazepine (CBZ), and 3% Candurin® NXT Ruby Red Sheen. Kollidon® SR is a mixture of 80% polyvinyl acetate, 19% povidone,

0.8% sodium, and 0.2% silica. Carbamazepine is an API/drug that aids in seizure and epilepsy control. The Candurin® NXT Ruby Red Sheen is typically used a pigment for pulverulent food. It serves as the laser absorbing enhancing agent to prevent any damage to the drug.

3. DESIGN AND CONSTRUCTION OF DIRECTED ENERGY DEPOSITION SET UP

The pharmaceutical DED machine is made up of four distinct subsystems that work in tandem to facilitate the additive manufacturing process. Together they carry powder pharmaceuticals from a reservoir to the building plate where small tablets will be printed (figure 1). Each subsystem and their role will be explained in detail below.

Figure 1: DED set up

3.1 Air Pump

The air pump used in this study served as the fluid through which the powder was carried from the reservoir to the build plate. While a mixture of Argon is a popular choice of inert gas in additive manufacturing, air was used in this study due to the prototyping process and ease of accessibility. To control the flow, an 18L/min, 0.017MPa aquarium air pump from VIVOSUN was used. This pump and its tubing connections can be seen below in figure 2.

Figure 2: Aquarium air pump

The air pump was the only nonintegrated component in the system. To activate the air flow, the air pump must be manually plugged in prior to the initiation of the print to ensure that powder can reach the nozzle before the first layer is printed.

The VIVOSUN air pump was connected to a 6-hole copper diverter valve for adjustable air flow. Each of the 6 adjustable valve outlets allowed for a more precise and controlled flow of the powder through the system. For this study, only two of the six available valves were utilized. One valve was connected to the tubing that served as the powder carrying pathway. This valve was opened to divert 70% of the air to flow. The second valve was connected to the tubing pressurizing the reservoir. The reservoir valve was opened to divert 30% of the airflow. This air flow slightly pressurized the reservoir and prevented back flow. It also allowed for air circulation in the reservoir to keep the powder from solidifying and binding together. The valve openings can be seen below in figure 3.

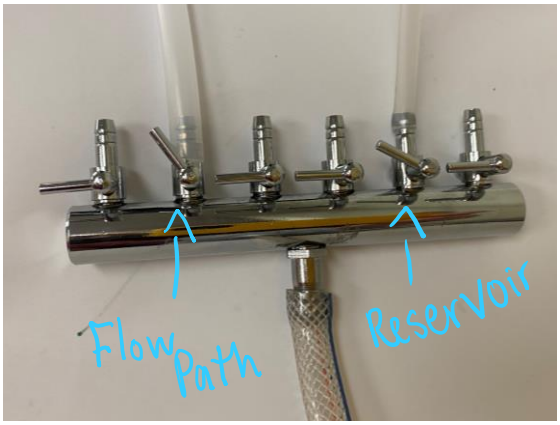

Figure 3: Valve openings

For prototyping purposes, the use of only two of the six valves was ideal due to the simplicity of the process. In the future, if more powders were to be introduced to the tablet prints, the remaining four valves can be utilized. A similar set up to the one described above could be used to pressurize the reservoirs and provide the powder carrying gas pathway. This system would centralize the air flow. The control and precision of the powder delivery process facilitated by the six control valves could lead to the creation of more complex and individualized pharmaceutical tablet compositions.

3.2 Tubing

In this study, 3/16” inside diameter EZ-FLO polyethylene tubing was used to carry the powder and air from the pump and reservoir. This FDA approved low-density polyethylene tubing, typically used for food and beverage lines, provided the corrosion and chemical resistance necessary for the handling of pharmaceutical powders. Compared to other popular tubing options, silicone and polyurethane, polyethylene has low air permeability. This quality allowed for the powder to be carried with air without clogging the pathways or retaining moisture.

The complete air flow pathway throughout the system can be seen in figure 4. As stated previously, the air coming from the air pump was controlled by two control valves. One of the valves led to the top of the reservoir while the other led to one of the inlets of a union tee tube connector. The union tee connector allowed for the powder carrying airpath to be formed. The right-hand side inlet was the tubing coming directly from the air pump, the top inlet came from the reservoir feeding the powder into the system, and the third opening serving as an outlet directing the powder to the build plate. In order to properly connect the tubing to the union tee connector, 3D printed size converters were utilized. The union tee connector was rated for a ¼" outside diameter tubing. The tubing used in this study had a 5/16" outside diameter, meaning that the tubing would not be able to sit properly into the union tee. The 3D printed attachments were designed for one side to sit inside of the 3/16" inside diameter tubing and then transition into a ¼" outside diameter opening that would sit perfectly inside of the union tee. This attachment was also placed inside of the funnel, as the funnel opening also had a 3/16" inside diameter for better powder deposition control. Using a union tee connector at this location allowed for the powder to be carried to its ideal location in a simple pathway.

The second control valve coming from the air pump led to the top of the reservoir. This valve served as a slight pressurization system of the reservoir. By pressurizing the reservoir, powder backflow was prevented and ensured air circulation inside the reservoir to promote granule movement. This second valve maintained the centralization of the system and prevent any potential issues with contamination.

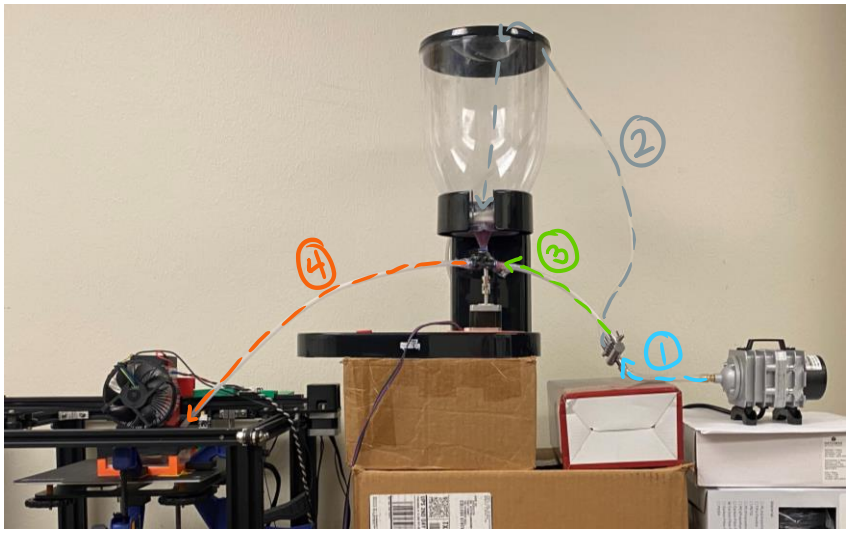

Figure 4: Air flow path of system

3.3 Reservoir

In DED machines, a reservoir is needed to house the powder in a centralized unit. The reservoir used in this study was a modified cereal dispenser. Adjustments to the cereal dispenser were made in order to prepare the reservoir for finer substance dispensing compared to larger cereal pieces. The choice of repurposing a cereal dispenser was made so that if more reservoirs were needed for future testing, these could be added easily due to their large availability and their low price point. The modifications made to the cereal dispenser can be seen in figure 5.

To prepare the reservoir for use in the DED machine, the dispensing knob was removed, and the bottom opening was cut off to the point where a circular plate could sit inside without any air gaps. The removal of these features allowed the funnel section of the rotating powder feeding mechanism to sit inside the reservoir. The funnel will be discussed in a later section. Furthermore, as mentioned previously, in this study, the reservoir was pressurized by 30% of the air flow provided by the air pump to avoid the back flow of powder. To allow air to come into

the reservoir, a small hole was made to the lid of the reservoir for the tubing to be placed through. This tubing was then sealed into the lid with adhesive.

Figure 5: Reservoir with rotating powder feeding mechanism and powder

3.4 Powder Feeding Mechanism

The rotating powder feeding mechanism plays a crucial role in the DED process as it is responsible for regulating the amount of powder that enters the flow path towards the build plate. For this study, the powder feeding mechanism was placed inside of the enclosure and controlled by the Ender 5 3D printer that holds the build plate. This system can be seen in figure 6, which shows the powder feeding mechanism mounted in the reservoir.

Figure 6: Mounted powder feeding mechanism

The entire powder feeding mechanism was comprised of 3 main elements: the funnel, the rotating plate, and the rotating shaft. As previously discussed, the funnel sat at the bottom opening of the reservoir. This funnel fed the powder directly into the union tee valve. The small funnel diameter regulates the powder delivery rate so that only small amounts are pushed through to the build plate at a time.

The rotating plate sat on top of the funnel fixture. The plate was attached to the extension of the motor shaft. As the printer sent commands to the extruder motor to rotate, the plate rotated along with it. The rotating plate can be seen in figure 7. Six ¼" diameter holes around the plate serve as the escape route for the powder. As a hole lines up with the funnel opening, powder is brought down by gravity and pressure and is let through the funnel and into the powder deposition path.

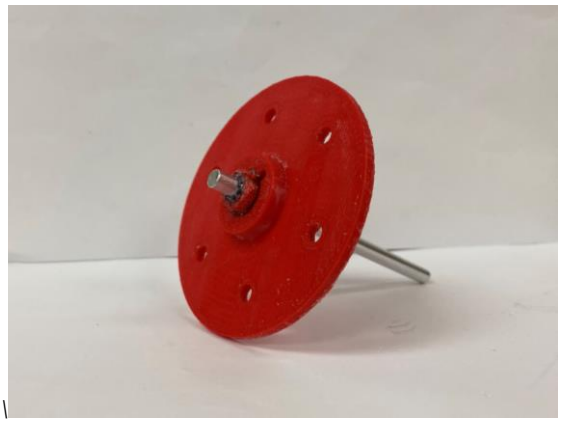

Figure 7: Rotating plate

Lastly, the shaft previously mentioned is connected to the rotating plate. Because the funnel is permanently fixed to the enclosure, when the shaft rotates, only the rotating plate rotates along with it. The shaft is an extension of the extruder motor shaft. This extension is

connected by a universal joint shaft coupler that allows flexibility in angle due to alignment while maintaining the same rpms.

The rotation of the plate is controlled by the repurposed extruder motor from the Ender 5 printer. Because the extruder nozzle was replaced by a laser which will be discussed in a later section, the extruder motor was no longer necessary for operation. The extruder motor was repurposed to serve as the rotating driving force as it would keep the tablet building system centralized and unified. To get the motor functioning in a way that benefited the study, modifications to the slicer G code had to be made. These modifications will be discussed in a later section as multiple components required g-code modifications.

3.5 Laser and Powder Deposition

Briefly mentioned previously was the repurposed extruder motor. In a traditional FDM 3D printer, the extruder motor controls the speed at which the filament is fed into the nozzle. Due to the nature of the DED process, filament was no longer needed and therefore the extruder motor remained unused. The nozzle was then also removed and replaced with a 10 Watt Endurance laser to serve as the focused energy source of the DED printer. The laser was connected to the 3D printer by replacing the connection that previously controlled the nozzle fan.

This was a single connection labeled “FAN1” on the printer’s computer board accessible by removing the bottom plate of the printer. By doing this, the laser was able to be controlled from the centralized g-code of the tablet print originally controlling the fan speed. The changes to the g-code pertaining to the fan speed will be discussed in a later section. The set up of the laser on the printer can be seen in figure 8. The laser was held in place by a 3D printed holder clip. This clip not only held the laser, but also served as an anchor point for part of the build plate enclosure.

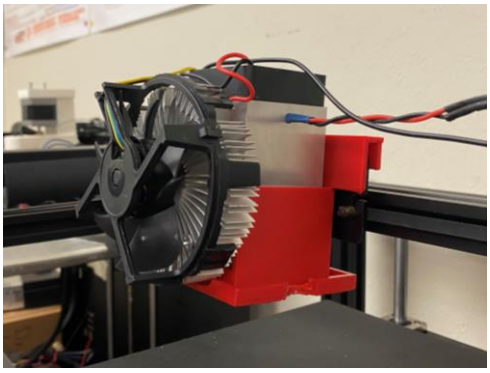

Figure 8: Laser set up

The Endurance laser, just like the original nozzle fan, is controlled through pulse width modulation. Pulse width modulation is a way to control the strength of a signal through duty cycles. The laser turns on and off at variable width pulses that represent the amplitude of the desired signal.

When working with lasers, the focal point distance is an essential parameter for optimal performance. For this application, the laser's focal point had to be at the build plate's surface. The focal point is the distance at which the laser will have its greatest energy focus. This provides the most heat and accuracy. The exit point of the powder deposition tubing was directly aimed at the laser's focal point to ensure that the powder was being deposited right at the focal point for the greatest heat efficiency.

3.6 Enclosure

To maintain a clean workstation, the steel build plate was enclosed in a 3D printed structure that kept the powder inside for reduced contamination and easier clean up. For this study the enclosure was composed of four different materials: PLA 3D printed filament, plexiglass, an air filter, and a balloon. The four-sided enclosure had 3 sides holding plexiglass for

viewing purposes and one side holding the air filter. A Filtrete MPR 2500 air filter with a rating of MERV 14 was utilized in this study as this would allow the air to escape the enclosure while maintaining all the powder particles inside of the enclosure. The enclosure can be seen in figure 9.

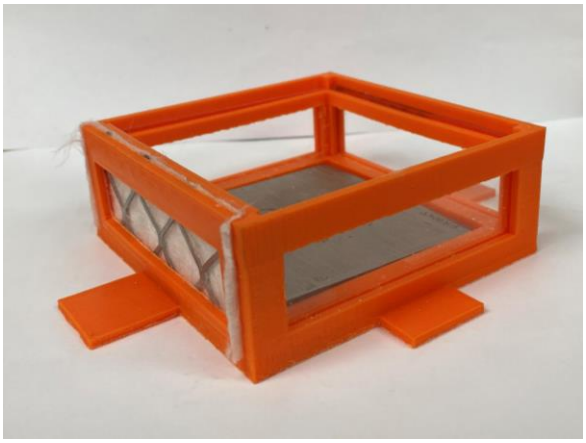

Figure 9: Enclosure

To allow the laser to move freely inside the enclosure, the top of the enclosure is covered with a large balloon. The elastic nature of the balloon provides flexibility for the necessary movement while also making the build plate easily accessible for tablet retrieval or cleaning. The balloon can also be replaced when needed within a few seconds, saving time and money while keeping the enclosure's functional and structural integrity. The balloon was stretched over the sides of the 3D printed structure and around the laser clip holder. This set up kept the powder inside of the enclosure while not blocking the powder flow path or the laser's focal point (figure 10).

Figure 10: Full enclosure set up

Due to the small size of the prints produced by the DED printer, the build plate and enclosure were scaled down from the original Ender 5 printer bed. In order to keep the laser inside of the enclosure and prevent any collisions between any part of the enclosure, 3D printer, or laser, modifications were made to the slicer settings, which will be discussed in the next section, and limit switch trigger extensions were attached. The limit switch trigger extensions (figure 11) were mounted on the Ender 5 3D printer to trigger the limit switches, reducing the build plate space and redirecting the laser head inside of the enclosure.

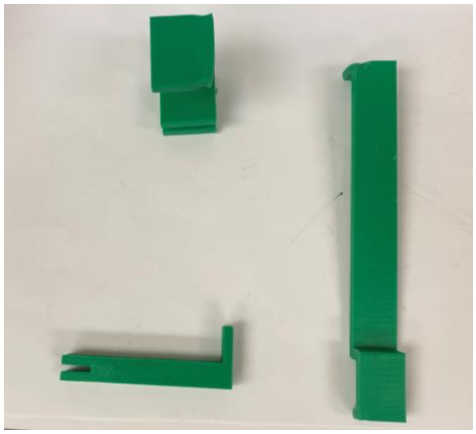

Figure 11: Limit switch trigger extenders

4. SOFTWARE AND CODE MODIFICATIONS

4.1 Creality Slicer 4.8.2

Previous sections mentioned slicer modifications made to accommodate the changes for the directed energy deposition printer. The slicer software used in this study was Creality Slicer 4.8.2 as it is extremely compatible and recommended for Ender 5 printer usage. The user-friendly interface aided in the ease of customization of the software.

Within the machine settings of the Ender 5 printer, the build plate dimensions were adjusted to closer reflect the boundaries of the build plate and enclosure previously described. The build plate was modified to be 15mm wide by 15mm deep and 15 mm tall. These dimensions prevented the laser from crashing into the edges of the enclosure and overextend its distance causing other issues to the printer. The checkbox indicating a heated bed was also unchecked to remove any commands directing the printer to heat up the original ender 5 build plate. A non-heated build plate is essential to the directed energy deposition process as all the energy must come directly from the focused energy source.

As for the print settings, a few parameters were modified and adapted to meet the requirements of DED. To begin with, a standard quality of 0.2mm thick layer was chosen. The first parameter that was changed was the printing temperature. This parameter checks the nozzle's temperature and prevents the print from starting until that temperature has been reached. The print temperature was set to 25℃ as this is close to the room temperature where this study was being conducted. Even though the nozzle was not in use, the thermistor was kept plugged into the printer to allow easier modifications from the pronterface program that will be discussed

momentarily. The build plate temperature, although “heated bed” had been unchecked, was also selected to be 25℃ for the same reason as the nozzle.

Next, the fan speed under “Cooling” was adjusted. As previously mentioned, the connections that previously controlled the cooling fan were replaced by the laser. This signified that any changes to the parameter “Fan Speed” affected the laser. By changing the fan speed percentage, the pulse width modulation of the laser was directly affected and therefore the g-code and strength of the laser. For testing, the fan speed was set at 100%.

Lastly on the slicer end, the build plate adhesion type was changed from raft to none as this would not be necessary for test printing. Having any sort of build plate adhesion could have also led to wasting powder.

The changes made to the Creality slicer aided in the customization and of the DED machine. By making these changes, the printer can maintain a safe distance from the enclosure boundaries and avoid any potential collisions that could result in damage to the printer or the enclosure.

4.2 Pronterface

Pronterface was another software that was utilized in this study. By using this software, direct g-code commands were able to be sent to the printer and specific printer settings inaccessible through the hardware were able to be modified. For the Pronterface program to be functionable, the system had to be able to receive temperature readings from the nozzle and from the heated bed. Although neither one of these components were used in the study, the temperature sensors for them were kept connected for the ease of making modifications.

Through pronterface, the main setting that affected the extruder motor’s performance was modified. With the Ender 5 printer connected, the command “M503” was sent to check the print

settings stored in the system configuration. The E-Step setting controls the number of steps taken by the extruder stepper motor per millimeter. This setting is represented through the M92 command. The command “M92 E300” was sent in order change the extruder’s E-steps to 300 steps per mm, effectively proportionally increasing the distance that the extruder motor rotated according to g-code indicated by the slicer. For a better comparison, a line of code that would previously result in a $1/6^{th}$ of a turn would be increased to ½ a turn because of the “M92 E300” command. This setting was then saved by sending the “M500” command.

4.3 G-Code

The use of modified G-code allowed for greater control over the rotation of the powder feeding mechanism, which in turn affected the amount of powder being deposited onto the build plate. This level of control is essential for the success of the DED process as it allows for precise customization of prints, including material composition, geometric accuracy, and detail.

Two main direct g-code changes were made: the edit of the starting g-code, and the addition of extra extruded material before every layer. The original starting g-code can be seen in figure 12. This was simplified to the code seen in figure 13. As the set up of other machine settings were redundant since they were already saved to the printer’s main settings code, and extra drawn lines were not necessary for the type of printing that was being tested. The last line in the edited g-code “M302 P1” allows cold extrusion. This means that the nozzle does not have to reach the established melting point of PLA before beginning the print.

```
M201 X500.00 Y500.00 Z100.00 E5000.00 ;Setup machine max acceleration
M203 X500.00 Y500.00 Z10.00 E50.00 ;Setup machine max feedrate
M204 P500.00 R1000.00 T500.00 ;Setup Print/Retract/Travel acceleration
M205 X8.00 Y8.00 Z0.40 E5.00 ;Setup Jerk
M220 S100 ;Reset Feedrate
M221 S100 ;Reset Flowrate

G28 ;Home

G92 E0 ;Reset Extruder
G1 Z2.0 F3000 ;Move Z Axis up
G1 X10.1 Y20 Z0.28 F5000.0 ;Move to start position
G1 X10.1 Y200.0 Z0.28 F1500.0 E15 ;Draw the first line
G1 X10.4 Y200.0 Z0.28 F5000.0 ;Move to side a little
G1 X10.4 Y20 Z0.28 F1500.0 E30 ;Draw the second line
G92 E0 ;Reset Extruder
G1 Z2.0 F3000 ;Move Z Axis up
```

Figure 12: Original starting g-code

Start G-code

```
G28 ;Home

G92 E0 ;Reset Extruder
G1 Z2.0 F3000 ;Move Z Axis up
G1 X0 Y0 Z0.28 F5000.0 ;Move to start position
G1 Z2.0 F3000 ;Move Z Axis up
M302 P1 ;Allow cold extrusion
```

Figure 13: Edited starting g-code

Lastly, three lines of g-code were added before every layer started printing to ensure that powder was going through the nozzle in time to reach the build plate before every new layer was started. Figure 14 shows an example of the three lines added. The only difference between each layer was that the last line instead of resetting the extruder back to 0, the value was reset back to what the previous line stopped at so that the print would resume as normal.

Sample pre-layer g-code:

```
G92 E0 ;Reset Extruder
G91 E0.75 ; Rotate 1.125 turns
G92 E0 ;Reset Extruder
```

Figure 14: Sample pre-layer additional g-code

5. RESULTS

In this study, a directed energy deposition machine was effectively able to be prototyped using easily accessible and repurposed materials. Figure 15 once shows the full DED set up with its four main components mid print. The blue light coming from component number 4, the enclosure, is the light produced by the laser. With modifications, the feasibility of DED was demonstrated. Its benefits like adaptability and precision could also be seen through the multiple customizations available to change if needed.

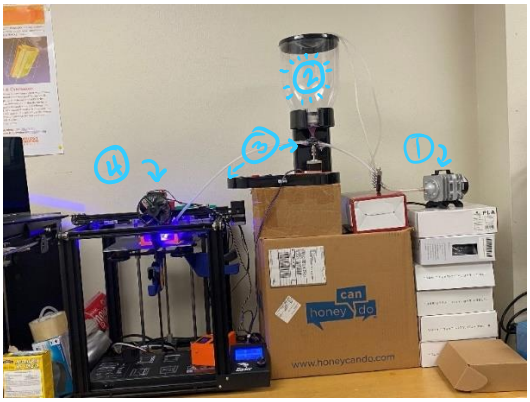

Figure 15: Complete DED set up

The effectiveness of the powder deposition system was the main system to be tested. If no powder reached the build plate and did not land on the focal point, test layers would not be able to be produced. In figure 16, excess powder can be seen bouncing off the steel build plate as the laser bonds sugar granules together. This process demonstrated that the designed system worked and is feasible for a greater expansion into varying material testing.

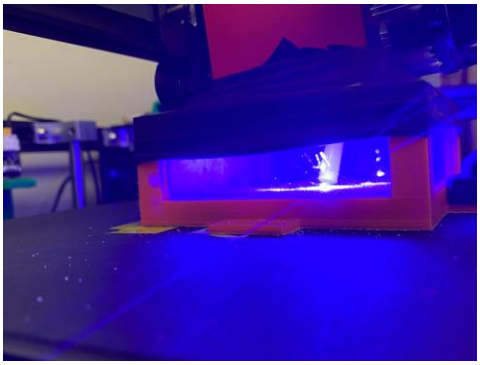

Figure 16: Powder reaching the build plate and focal point

When a print of a 1cm diameter, 0.5 cm tall tablet was printed, the 2-minute-long print resulted in approximately 4.5 grams of granulated sugar being deposited to the build plate (figure 17) and an initial first outline was able to be bonded together (figure 18). All the powder was properly contained within the enclosure. Due to the precautions and modifications made, no collisions occurred, and the entire printing process was controlled.

Figure 17: Measured deposited granulated sugar

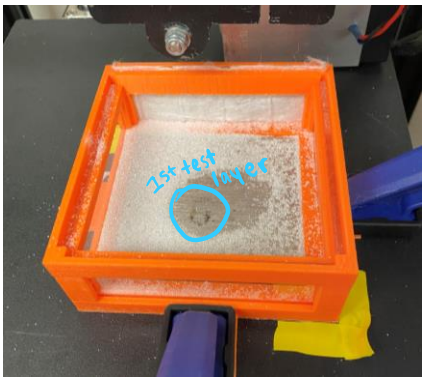

Figure 18: First test layer

6. CONCLUSION

The feasibility of directed energy deposition in the pharmaceutical field was effectively modeled. With structural and software modifications, a prototyped DED machine composed of accessible materials was tested. The principles of directed energy deposition were implemented as the four main components worked together to produce the desired results. The air pump supplied ample carrying gas to flow through the tubing. The powder deposition mechanism successfully transferred powder from the reservoir to the build plate. At the build plate, the powder was deposited at the focal point, at which the powder was then fused together. Each component performed its function and cohesively formed a prototype of a directed energy deposition machine.

Further research in this field is necessary to investigate the possible impact DED could have on the pharmaceutical industry. Initial trials demonstrating the feasibility of pharmaceutical DED printing is the first step towards a more customizable and individualized pharmaceutical industry. Other industries have already taken advantage of the benefits that DED provides. The process has been perfected to print metals, ceramics, and other materials. Adding pharmaceuticals to the list would not only be an advancement in manufacturing but also better the lives of millions of geriatrics, pediatric, and individual patients who’s needs could be better met through personalized medicine.

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