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Investigation of Thermal History in Large Area Projection Sintering, an Additive Manufacturing Technology

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Investigation of Thermal History in Large Area Projection Sintering, an Additive Manufacturing Technology

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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DEDICATION

This work is dedicated to my wife, Caitlin and my parents, Stuart and Debbie. They have loved me unconditionally, supported me and motivated me through the years. I couldn’t have done it without you and I would like to thank you from the bottom of my heart.
I would like to extend my gratitude to the National Science Foundation for funding this research in part through CMMI grant 1563037. I would also like to thank all of the present and past members of the Micro Integration Laboratory for being such great friends and assisting with brainstorming, fabrication and testing throughout our years working together. I’d like to extend my deepest gratitude towards the University of South Florida faculty and staff for the high quality education I received here and their willingness to provide assistance when needed. Most notably, Dr. Rasim Guldiken and Yaricet Ruiz who went out of their way to assist me on many occasions for both academic and personal endeavors.

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ABSTRACT

The goal of this work is to explore the benefits of using long exposure times with polymer powder bed fusion additive manufacturing processes and examine the feasibility of this new application as a manufacturing process. It is well known that the sintering which occurs in these systems are a time and temperature dependent process. However, the most common powder bed fusion systems use a laser which scans and heats the powdered feedstock for microseconds at a time, leaving insufficient time for the polymer to fully melt and/or fuse, leading to reduced mechanical properties. Little has been published on the effects of extended sintering time, especially over large areas. Furthermore, the time-temperature dependent sintering process has not been studied through the direct control of a temporal temperature profile in situ. A new technology was developed to aid in this study, Large Area Projection Sintering, which is capable of using extended exposure times while simultaneously fusing an entire layer of powder, thus preserving high build rates.

The first part of this work introduced the new Large Area Projection Sintering and how it can solve some of the issues plaguing additive manufacturing today. This is followed by a literature review which discusses common additive manufacturing technologies and presented with their advantages and disadvantages. Then, current sintering models are presented to examine the
importance of various material or system properties, such as exposure time/temperature, preheat temperature, melting and recrystallization phenomena, crystallinity and viscosity. This is then followed with a study of the mechanical properties of single layered parts with respect to the sintering time and intensity.

In the first phase, the feasibility of using extending sintering times over relatively large areas with extended sintering times was tested. In this study, single layered parts were fabricated with various time and intensity parameters and were used to gauge the effect on resulting material properties. It was found that current sintering models fail to predict the sintering outcome when sintering with long exposure times due to optical (reflection, transmission) and thermal (convection, conduction, radiation) losses with the environment. Increased energy density levels were shown to have a positive impact on the quality of the part as measured through the maximum achievable tensile force and part density as long as thermal loss effects were minimized by increasing the exposure time or intensity above what is determined through the direct application of the energy density equation.

The following section examines multilayered specimens with a new projection sintering system capable of sintering with closed loop control. This system enabled the study of time-temperature effects and their impact on mechanical properties. Mechanical properties were evaluated through tensile testing and density measurements. A strong correlation was found with small decreases in density causing small decreases in ultimate tensile strength, but with a drastic decrease in elongate at break. The optimal sintering conditions are produced when the material is
held above its peak melting temperature as identified through differential scanning calorimetry. In
this study, the peak melting temperature was found to be 175°C and the highest UTS and EaB
were found with an exposure time of eight seconds and a target temperature of 195°C. This degree
of sintering produced parts with similar strengths (52 MPa) as with similar materials produced on
other powder bed fusion technologies and with extraordinarily high ductility (163%) [1, 2] when
using a temperature target of 195°C for 8 seconds of exposure time. This is believed to be due to
the morphology of the amorphous and crystalline regions but future work will address this through
direct measurement of the crystal structures.

Lastly, Large Area Projection Sintering is evaluated for suitability as a manufacturing
technology and compared against other available powder bed fusion technologies. Equations are
developed that allows the prediction of build rates which are dependent on various print parameters
and the physical capabilities of the machine. This can be used as a design aid to develop new
equipment and estimate performance levels before prototyping begins. Standard practices in
additive manufacturing are still being developed and many manufacturers don’t report build rates
for their systems. If they do, they are often evaluated and reported differently. The collection of
equations formulated in this work provides a means to quantitatively evaluate each system and
provides a level comparison using commonly reported specifications. The results of this work
revealed the large advantages of each of the evaluated technologies. While Large Area Projection
Sintering could provide the highest build rates, it appears impractical to implement in large area
because of the extreme power requirements. However, Large Area Projection Sintering could be
beneficial in sintering materials which need long exposure times or have a very narrow temperature window. Laser sintering was found to be the most beneficial when a small volume fraction is used (such as when printing only a few parts, hollow parts, or lattice structures). Multi Jet Fusion and High Speed Sintering were found to be the most suitable technology for providing large quantities of parts as the requirements scale linearly when printing with larger volumes.
CHAPTER 1: INTRODUCTION TO ADDITIVE MANUFACTURING

Additive manufacturing (AM), also known as rapid prototyping and 3D printing, has been sky rocketing in both popularity and use among all users from the hobbyist to the industrial manufacturer over the last decade. Industrial systems alone have experienced a growth of over 600% in the last ten years [3]. This is due largely to AM’s ability to create complex objects from three dimensional (3D) models rapidly. In addition, new technologies and materials have enabled AM, providing the ability and economics to directly produce end-use components.

Even though commercial AM systems went on the market in the late 1980’s [4], it’s use was minimal and didn’t attract much attention. With the expiration of 225 patents from 2002 to 2014 [5], this opened the industry to competitors who drove prices down and fostered new innovations. In addition, hype from the media is raising the awareness of AM which has now made its way into almost every industry in one form or another. Krippendorf defines three directions for the AM product development process: challenges, opportunities and possibilities [6]. While brains storming provides opportunities and possibilities that can change the world, the real engineering endeavor is finding solutions to these real world challenges. AM offers many opportunities filled with valuable possibilities that can vastly improve the manufacturing landscape. For example, AM can make components much quicker and cheaper than previously thought possible. This thesis
examines two real world AM challenges, long build times and the inherent difficulty of overcoming low mechanical properties with polymer powder bed fusion technologies.

Additive manufacturing (AM) has the ability to create extraordinarily complex shapes which were impossible to make with any other technology [7] and do not require specialized tooling. For example, AM provides the capability to fabricate lattice structures or components with complex interior structures. This ability comes from the layering nature which is typical of most AM systems. Parts are first designed in 3D computer aided design (CAD) software then sliced into many 2D cross sections. Each of these cross sections represents a single layer which the AM system creates, one at a time. AM leverages the conventional and well-established manufacturing technologies (such as multi-axis movement systems, extrusion/laser/2D printing technologies, etc.) to build each layer. Each of these layers are created on top of one another until the final part is formed. Once the part is created, most components require some type of additional post processing, such as support removal, infiltration with a second material, surface treatment, or machining.

1.1 Limitations with Conventional AM Technologies

While AM offers a large variety of advantages, the industry is still in its infancy with the primary focus being on the customization of low volume, high value added products that can be manufactured quickly [8]. While the AM production rates are much quicker than traditional methods, they are still not “rapid” and can typically take multiple days to reach a completed part.
Technologies which rely on fusing powder from a powder bed are typically only able to fuse a few select materials [9, 10] and AM components generally have decreased mechanical properties when compared to their traditionally manufactured counterparts. This may not be an obstacle for those who do not require quick turn-arounds and are not pushing the structural integrity limits of the parts. However, this does make AM ill-suited for a manufacturing environment where a high quality or volume of parts are needed. More recently, a handful of companies (for example, HP, Carbon3D, Stratasys) have released AM systems aimed at tackling these issues [11-13] and improving upon existing technologies. The focus of this work will be on comparing some of these technologies which are discussed in more detail in the following chapters and will evaluate a new AM system capable of overcoming these challenges, called Large Area Projection Sintering (LAPS).

1.2 Large Area Projection Sintering

A novel AM technology developed at the University of South Florida specifically to determine the effects of sintering polymer powders at longer time scales is a layer-wise AM technology. The Large Area Projection Sintering (LAPS) technology is a powder bed fusion technology capable of printing with high strength engineered thermoplastics. However, rather than using the typical method of fusing material at a single point or along a line, the entire layer can be created simultaneously. In LAPS, a uniform layer of dark colored powder is deposited and smoothed to a uniform level with a counter-rotating roller. A custom high intensity projector then projects the image of the desired cross section onto the powder. This provides selective heating in the shape of
the desired cross section, leaving other areas without any incident radiation. Wherever the light strikes the powder, it absorbs the heat energy from the light and melts to fuse the entire layer. Figure 1.1 provides a schematic of one of the LAPS embodiments and demonstrates how this technology works.

The main benefit of this technology is that extended exposure times can be used without sacrificing overall build time due to the entire layer being created simultaneously. This provides additional time for the material to flow and densify, creating parts with highly increased ductility and could allow for other materials to be fused which current powder bed fusion technologies are unable to achieve.

1.3 Objective and Scope

Significant prior work has been conducted on AM technologies from the basic fused deposition modeling (FDM) to nanoscale 3D printing, large format metal printing and everything in between.
However, powder bed fusion systems, which have great potential, are currently lacking an understanding of what occurs during sintering with extended exposure times with a layer-wise fusing fashion. Extended exposure times could be the solution to many problems plaguing this technology, most notably the small selection of material feedstocks and relatively brittle parts. In addition, this could provide the added bonus of dramatically increasing build rates, making this technology quintessential on the factory floor.

The objective of this work is to evaluate the LAPS technology to determine feasibility of this technology for application as a manufacturing system and understand the sintering kinetics which occur with relatively long exposure times. This analysis requires a fundamental understanding of the fusing process and resulting outcomes, as measured by mechanical properties. Further, suitability will be determined by estimating build rates when this technology is scaled up to industrially relevant sizes. These results are then compared to traditional laser sintering (LS) and newer systems which use extended exposure times, such as High Speed Sintering (HSS) and Multi Jet Fusion (MJF). System prototypes will provide test specimens and a method of in-situ testing. While the results found herein could be adapted for application to other powder bed fusion systems (metals, ceramics), the focus of this dissertation is on industrial polymer powder bed fusion technologies.
1.4 Dissertation Outline

The following chapter will present the current knowledge base on polymer powder bed fusion technologies through an in-depth literature review. The various types of polymer powder bed fusion technologies will be introduced along with their advantages and limitations. An introduction into important qualities, both system level and material, will be presented to provide an in-depth understanding of the fundamentals of sintering in these systems.

Chapter 3 will present the first generation prototype used to evaluate extended sintering times. This system was used to provide single layer samples for an initial material study and used as a proof-of-concept system for determining the feasibility of fusing an entire layer of material simultaneously.

Once the proof-of-concept system proved successful, additional prototypes were produced, capable of providing more relevant multi-layered components and is presented in Chapter 4. This system was used to understand the effect of various exposure times, intensities and final temperatures on the mechanical properties. A link between increased tensile strength and remarkably increased elongation to failure is identified through marginal increases in density.

Chapter 5 addresses build rate considerations when scaled up to industrially relevant scales. This chapter establishes equations to model the sintering process for LAPS and other powder bed fusion technologies to addresses physical technology limitations and estimates machine
throughput. This is then compared to existing powder bed fusion technologies where the advantages and disadvantages to each are discussed.

Lastly, Chapter 6 concludes this work with a summary and recommends areas requiring future work.
CHAPTER 2: LITERATURE REVIEW

This chapter outlines the important material properties and system specifications needed to obtain a desirable sintered component. Extensive research has been conducted in this area to gain a fundamental understanding of the sintering process. Sintering has been investigated from both a thermal and physical shape change perspective; the materials morphology, viscosity and composition and temperature stability have all been evaluated; system properties such as laser scan speed, laser power and input energy have also been characterized with the outcome they produce. However, little research has been published on the effect extended sintering time has on the sintering process. This is most likely due to the overwhelming popularity of LS which has been around since the late 1980’s and systems capable economically providing extended sintering times have only recently been developed. This chapter begins with an introduction into other AM technologies which uses polymer feedstocks and discusses the advantages and limitations with each. Then, the sintering process is presented along with the fundamental driving forces in sintering and how they affect the sintering process, both at extremely brief (microseconds) and long time (seconds) scales. Important material properties are also presented to provide a full fundamental background to the sintering process.
2.1 Additive Manufacturing Systems

Each type of AM system can be categorized as creating parts in a point-wise, line-wise or layer-wise fashion [9]. In point-wise processes, material is fused, extruded or bound at a single point, which is then rastered or scanned over the 2D plane until the entire cross section is fused. This is similar to how a large shape can be filled in with a pen. In line-wise processes, material is fused or bound along a 1D line (sometimes consisting of multiple 1D lines acting in parallel) which is then scanned in one direction over the entire cross section. Along this line, the fusing or binding mechanisms can turn on and off as it is scanned, to produce the desired cross section. This process is similar to how laser printers function where each line is formed one at a time as the paper is scanned under the ink transfer drum. In layer-wise processes the entire layer is formed simultaneously without scanning any axis. This process is similar to how an entire area can be selectively cured with a photopolymer, mask and ultra violet (UV) light in photolithography. Examples of each of these system types can be seen in Figure 2.1.

2.1.1 Fused Deposition Modeling

One of the more common AM technologies is Fused Deposition Modeling (FDM) which is described by the American Society for Testing and Materials (ASTM) as a material extrusion technology. While it sometimes goes by other names, this technology is commonly used by hobbyists and professionals alike due to the low cost of the machine and feedstock, which ultimately produces lower cost components. FDM systems use point-wise processing techniques
where polymer filament is fed through a hot nozzle where it melts. It is then extruded from the nozzle as it is scanned over the print bed or previous layer in the shape of the desired cross section as seen in Figure 2.2.

![Figure 2.1: Schematic of AM categories.](image)

While FDM is one of the cheapest AM technologies, it is also able to use a large variety of thermoplastic polymers which contributes to its popularity. However, FDM systems suffer from relatively long print times when compared to other technologies [9]. Print times on these machines usually takes hours to days to complete when printing components on a standard sized printer [17]. This is due largely to the thermodynamic and physical processes which are taking place.

As the material melts in the nozzle, the viscosity becomes lower and is able to flow through the nozzle. However, due to the friction between the molten polymer and the nozzle walls, high pressures would be required to extrude the material at a high rate. The molten polymers typically have a high viscosity and as the molten material contacts the previous layer, it requires a specific
amount of time to flow around the previous layer. It must also be at a sufficiently high temperature and remain molten for long enough to remelt the previous layer in order to create a strong interlayer bond. Otherwise, the deposited line may warp out of position, producing an undesired curled effect or catastrophic print failure. Additionally, the print head which typically houses the nozzle, extruder, and filament driving mechanism has a relatively large mass. Newton’s second law:

\[ F = ma \]  

Equation 2.1

tells us that force (F) equals mass (m) times acceleration (a). This means that the heavy mass of the print head restricts the achievable acceleration. During printing, the print head consistently stops, starts and rapidly changes directions. This means a reduced acceleration capability has a compounding effect on the feasible printing speed. All of these thermodynamic and physical constraints limits the maximum printing speed of this technology [18].
Alternatively, higher build rates can be achieved by using a larger extruder nozzle. However, as the nozzle size is increased, the resolution and accuracy of the system is compromised. Typical nozzle sizes range from 0.3-0.5mm in diameter [18], which correlates to the smallest achievable feature size in the XY plane. Another disadvantage of FDM is that printing parts with features that hang over open air (a.k.a. overhangs) requires a structure under it to support it as seen in Figure 2.2. These supports are typically made of a second material which readily dissolves in a specified liquid. This way, once the part is complete, it can be placed in a bath with that liquid for a few hours to days and then removed. The final component removed from the bath is then free of supports as long as the liquid is able flow around the support material. If support material is required in a closed-off internal cavity, it cannot be removed by simply soaking it in a liquid bath. Typically, these liquids are industrial solvents which are highly caustic and sometimes heated to moderately high temperatures [19].

Figure 2.2: Schematic of a FDM system.
One big advantage of FDM is the wide variety of materials available in the required filament format. These materials range from the commonly used acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) to exotic materials such as high temperature thermoplastics like poly ether ether ketone (PEEK) and polyimides (PI) but also thermoplastics loaded with metals or ceramics. These composite filaments can be used to provide a large range in material properties, both mechanical [20-22] and electrical [23, 24]. When loaded with typically >50 vol% metal or ceramic [25], the component can be placed in a high temperature furnace where the thermoplastic binder is burnt out and the metal or ceramic filler binds together through a sintering process. This provides a full metal or ceramic final part which in some cases can be of relatively high density (~92-99.8% [25-27]).

2.1.2 Powder Bed Fusion

Powder bed fusion technologies are any AM technology which forms the component in a bed of powdered material. This is typically achieved by using an energy source such as a laser, electron beam, or linear lamp which emits heat to fuse a layer of material. Each of the powder bed fusion technologies start by laying down a specified thickness of powder which is often preheated. By preheating the powder, the overall amount of energy require to melt it is reduced and reduces thermal stresses which can cause warping. The powder is smoothed to a uniform level by moving a counter-rotating roller or blade across the surface of the powder. Once completed, the system
selectively fuses the material in the desired cross section. Then, a new layer of powder is deposited onto the previous and the process repeats until the entire component is created.

One large advantage to using powder bed fusion technologies, is that multiple parts can be printed simultaneously, utilizing the entire build volume. For example, an array of components can be printed in the XY axis, but also in the Z axis, on top of the other components [28]. The unfused powder acts as a support for subsequent parts and for overhanging layers that do not have a fused material beneath them to connect to. Once the build is complete, one can simply remove the components from the supporting unfused powder. This has the advantageous effect of requiring less labor during post processing and no support material is wasted. In addition, the unfused powder can be recycled and reused. The reuse may be limited in many cases due to changes in the powder properties during heating and impacts the mechanical properties of the resulting parts. The sensitivity depends largely on the powder bed preheat temperature and the material used, which varies between the different powder bed fusion technologies [29].

2.1.2.1 Laser Sintering

Laser Sintering (LS) is a point-wise variant of powder bed fusion. The LS process involves rastering a small diameter laser over the surface of the build chamber which contains powdered material. As the laser strikes the powder particles, they melt and fuse together into the desired cross section. Rather than scanning a rather heavy and sensitive laser over the powder bed, the laser is reflected off two mirrors which are pivoted in the X and Y axis. This device, called a mirror
galvanometer, uses extremely light weight mirrors which are capable of scanning the laser over the powder bed at rates on the order of meters per second [10]. While the term sintering generally

refers to a fusing process taking place between two solid materials at elevated temperatures over longer time spans (minutes to hours [30]) than discussed here, it is still widely used to discuss metal and polymer powder bed fusion technologies where the material may fully melt. This terminology is widely accepted and used in the AM industry and thus will be used herein. A schematic of the LS process can be seen in Figure 2.3.

Figure 2.3: LS process schematic.

2.1.2.2 High Speed Sintering and Multi Jet Fusion

High Speed Sintering (HSS) and Multi Jet Fusion area relatively new to the AM space and both use a powdered polymer feedstock. HSS was developed by Neil Hopkinson at Loughborough University and refined at Sheffield University. Patents were filed on this technology as far back as
Multi Jet Fusion was released by HP in 2016 and is essentially the same technology as HSS. Due to the similarity, HSS and MJF will be treated together. Both of these technologies are line-wise AM technologies that fuse material along a 1D line which is scanned over the build chamber to cover a 2D area.

To create components, these technologies begin by spreading uniform layers of powder in the build chamber. This powder is typically white and reflective to thermal radiation. An inkjet print head then scans over the powder and deposits a radiation absorbing (black) ink with the shape of the desired cross section. A linear heat lamp is then scanned over the powder bed. The white powder reflects most of the thermal radiation and does not fuse. The ink absorbs the incident thermal radiation and converts it to heat. This heat melts the powder wherever the ink is present, fusing each layer into the desired shape. An example schematic of these technologies can be seen in Figure 2.4.

Figure 2.4 : Schematic of the HSS and MJF technologies.
2.1.2.3 Stereolithography

Stereolithography (SLA) can be either a point-wise or layer-wise AM technology that can create components with extremely smooth surfaces and is capable of making submicron features [14]. SLA uses a liquid photopolymer as its build material. When exposed to ultraviolet (UV) light, the photopolymer solidifies. In the SLA process, a vat or chamber contains the photopolymer which is then is exposed to UV light via a laser or a projector. When a laser is used in the SLA system, it is a point-wise process that functions similarly to LS except using photopolymer instead of a powder bed. The laser is rastered over the surface in the desired cross section via a mirror galvanometer, crosslinking and solidifying the photopolymer as it moves. If a UV projector is used, the SLA system acts as a layer-wise process, solidifying the entire layer simultaneously. Once a layer is complete, fresh photopolymer is deposited on top of the solidified material and the process repeats until the entire component is created. The SLA technology requires supports as well since overhanging areas would not be anchored and may float out of position. These supports are made of the same material as the component and must be manually removed during post processing. Lastly, to finish the curing process, the UV components are typically lightly washed to remove excess photopolymer from the surface of the part and placed inside a UV furnace. In the furnace, the part is exposed to UV light and heat to complete the cross linking process.
2.2 Sintering

Sintering is the process of combing particles into a single solid mass through pressure, heat or a combination of both. The sintering process can be used for both metal and polymer particles with some common applications being electronic capacitors, automotive transmission gears, pacemaker housings and oil-less bearings [30]. Other technologies which use particle sintering are die pressing [32], rotational molding [33] and isostatic pressing [34] to name a few. The typical definition of sintering refers to solid phase sintering, where bonding particles of a predominantly solid structure occurs via mass transport events that often occur at the atomic level [30]. Liquid phase sintering involves the densification of powdered material in which there are both solid and liquid phases present [35] during densification. This work addresses viscous sintering, which falls somewhere between solid and liquid phase sintering and occurs when the volume fraction of liquid is sufficiently high, so that the full densification of the compact can be achieved by a viscous flow of a grain–liquid mixture [36].

Sintering involves particles which are in contact that form a bond at their contact point, called a neck or a bridge. The neck then grows in size until the particles are intimately bonded together and can be considered a single object. Previous work has been conducted to understand the

Figure 2.5: Sintering of two particles under the Frankel sintering model
fundamental principles and effects which drive particle sintering and has been an area of active research [30, 37, 38]. In 1945, Frenkel characterized the morphological change in two crystalline powder particles as they change shape and are drawn together into a single solid agglomerate [39]. This paper is a popular work that is well cited due to its development of an expression to predict the shape change of two spherical particles as they sinter under viscous-flow conditions (Figure 2.5, Equation 2.2):

\[
\left( \frac{x}{r} \right)^2 = \frac{3\gamma t}{2r\eta_0}
\]

where \(2x\) is the width of the neck, \(r\) is the nominal particle radius, \(\gamma\) is the surface tension, \(t\) is time and \(\eta_0\) is the zero shear viscosity. This model is valid for viscous phase sintering and as can be observed through Equation 2.2, a higher degree of sintering occurs with extended sintering time, high surface energy or low shear viscosity. In liquid phase sintering, the first stage involves two particles in contact with each other which first forms a material bridge. The neck thickens and grows as the material flows under viscous forces. The second stage involves the removal of pores to achieve a higher density. Surface tension provides the driving sintering force which is driven by minimizing the surface energy through the reduction in surface area [40]. The flow characteristics of a material are described by its viscosity, or resistance to flow. If a material strongly resists flow (has a high viscosity) sintering will not occur over practical time scales. In the case of crystalline polymers, low viscosities are typically achieved by heating them until the crystalline phase melts, which can happen at a specific temperature or over a temperature range. As the polymer melts, the
viscosity drops by several orders of magnitude creating a sharp change in viscosity over a narrow temperature range which is not typically seen with amorphous polymers.

Newer work has been conducted to further the research conducted by Frenkel. Farzaneh and Tcharkhtchi have shown that increased sintering rates occur with Polymethyl methacrylate (PMMA, acrylic, Plexiglas) particles, when a third particle is in contact with at least one of the sintering particles [41]. They further studied the effect of both temperature and particle size but did not relate this back to a change in viscosity or surface energy. Ashelby noted that the Frenkel equation violated the continuity equation for incompressible fluids and instead proposed the following equation [42, 43] which includes mass conservation [44] and is now referred to as the Frenkel-Eshelby model:

\[
\left(\frac{x}{r}\right)^2 = \frac{\nu t}{r \eta_0} \\
\text{Equation 2.3}
\]

Bellehumeur et al. has shown that this correction better correlates with experimental results [43] but is best described by Hopper’s relation which is an exact analytical solution of the Navier-Stokes equation for two dimensional (implying that circles are used rather than spheres) viscous flow which relates the shape evolution from one circle to two [45]. These studies highlight the importance of a full system level understanding of both material properties and required conditions to achieve a high quality (high density) sintered component.
2.3 Material Properties

The material properties strongly effect the sintering onset, ease of sintering, porosity and mechanical properties. This section will discuss the important material properties used to gauge a material’s suitability for sintering and how to gauge the physical performance of the sintered component. Nylon-12 (Polyamide 12, PA12) is commonly used as a feedstock for polymer powder bed fusion technologies because of a handful of desirable qualities as described in more detail below. The main qualities include sufficiently high mechanical properties [46] and ease of sintering [47]. PA powders are widely available for purchase and are extensively used for both production and research, accounting for over 97% of all materials used in LS [48]. This goes to show that there is a relatively small variety for materials available for powder bed fusion processes. Extensive research has been published on this material and it’s for these reasons that a PA12 powder (PA2202) produced by EOS for the LS industry was selected for use in this study as a benchmark material to provide ample comparisons.

2.3.1 Crystallinity

Polymers can be either crystalline, amorphous or semi-crystalline. In reality, purely amorphous or purely crystalline polymers are extremely difficult (or impossible) to create. In the common terminology, crystalline or amorphous polymers have an overwhelming majority of their structure in an amorphous or crystalline state. An amorphous polymer is a polymer whose polymer chains are disorganized and with each chain in a random orientation. A crystalline polymer has its
polymer chains ordered in a repeatable fashion [49]. Generally, the chains are folded back on themselves in a repeating manner as can be seen in Figure 2.6. These crystalline areas are called lamella and the lamella properties can change the macroscopic properties of the polymer, for example melting temperature. Most polymers have crystalline and amorphous regions throughout the material as shown in Figure 2.6. The degree and type of crystallinity within a polymer strongly effect other properties as well, such as the ductility, strength, melting temperature, and the recrystallization temperatures.

![Crystalline Region](image1)

Figure 2.6: A semi-crystalline polymer whose amorphous regions are seen in green, with its crystalline lamella seen in blue.

### 2.3.2 Melting and Recrystallization

Two important properties in LS is a materials melting and recrystallization temperatures. A highly crystalline polymer tends to have a defined melting temperature where as a highly amorphous polymer has no melting temperature at all, but rather slowly softens and flows as it heats up. Amorphous materials have a glass transition temperature, where the polymer transitions from a more rigid ‘glassy’ state to a more pliable or ‘rubbery’ state [50]. Semi-crystalline polymers, or polymers that have both crystalline and amorphous regions tend to have both a glass
transition temperature and a melting temperature. The melting temperature is when enough energy has been absorbed by the organized crystalline polymer that chains can freely move around, flowing past one another with relative ease. This occurs when the polymer transitions from a solid to a liquid. The melting temperature is determined by the lamella thickness and creates a melting temperature distribution caused by the distribution in lamella of varying thicknesses [40]. In liquid phase sintering, the polymer must be able to flow in order to sinter.

Once a polymer has transitioned to a liquid, and in the case of crystalline polymers, at a specific melting temperature they do not always recrystallize (solidify) when they cool back to that temperature. In some materials, there is a relatively large gap, or difference in temperature between the melting and recrystallization temperature. In laser sintering, this is a desired quality and is

Figure 2.7: The results of a DSC test showing the stable sintering region tested on a 15 mg sample of PA2202 at 5 °C/min.
referred to as the stable sintering region or super-cooling window [51-53]. When a polymer recrystallizes, the polymer chains organize into a more closely packed structure and the bulk material shrinks, causing internal stresses. If the internal stresses become too great, the part will warp and most likely lead to a failed print, highlighting the importance of mitigating this effect as much as possible [54]. Differential Scanning Calorimetry (DSC) is a commonly used method used to determine the stable sintering region.

The results of a DSC test are shown in Figure 2.7 with PA2202. This test heats a polymer sample (typically around 5-15mg to avoid nonuniform temperatures) at a defined rate and measures the additional heat flow into or out of the sample. This heat flow is caused by endothermic (the sample absorbs energy from the surrounding) or exothermic (the sample releases heat into the surrounding) reactions. Melting and evaporation are examples of endothermic reactions and combustion, oxidation and crystallization are examples of exothermic reactions. As the PA2202 sample is slowly heated, it first passes a very small glass transition around 50°C and then a much larger melt transition around 175°C. As mentioned previously, a higher degree of crystallinity leads to a quicker transition from solid to liquid. Once the polymer has fully melted, it is then cooled down and allowed to recrystallize. Recrystallization started in this sample at 153°C. This material has a rather large stable sintering region where the material can cool below the melting temperature without recrystallizing. This is advantageous in LS because it enables the ability to recrystallize an entire part after each layer has been created.

24
Typically, LS sintering has found it difficult or impossible to sinter materials that do not have a large stable supercooling region \((T_m - T_c \gg 0)\) [55]. Researchers have had some success with ultra-high molecular weight polyethylene (UHMWPE), poly ether ether ketone (PEEK) and poly ether keton (PEK) who all have a small stable sintering region [52, 54-56]. In the case of PEEK and PEK, extremely long sintering times were required to reach high tensile strengths, requiring between 80 to 824 seconds to effectively sinter [52, 55]. While this approach works in a lab setting, it does not provide a practical means of producing parts in a timely manner as a large component would require an astronomical amount of time with point-wise processes, such as when scanning a laser extremely slowly over a surface.

In LS, recrystallization is generally delayed until after the entire part has been built. This allows the entire part to shrink uniformly without causing a large buildup of internal stresses which can lead to part warping or cracking. This is achieved by providing a constant temperature to the polymer before and after it is sintered in the form of preheating.

### 2.3.2.1 Preheat Temperature

Preheating the polymer powder bed is required when using PA12 materials (and many others as well). The powder bed is maintained within the supercooling temperature range to keep the sintered material from recrystallizing before the build is complete and also to reduce the input energy required to melt the polymer. Preheating in LS machines is typically achieved through both conductive and radiative heaters. Conductive heaters are attached to the surrounding surfaces of
the metal build volume which conducts heat towards the powdered polymers within. To maintain an even temperature distribution across the surface, radiative heat sources are typically used, such as infrared heat lamps. These heaters are sometimes controlled in zones to achieve a more uniform temperature [57]. If the area which is being sintered is not held at a uniform surface temperature, different degrees of sintering will occur and can lead to part warpage and/or irregular and unpredictable mechanical properties. However, a completely uniform temperature distribution is difficult to achieve and even in an industrial EOS P395 Laser Sintering System, Rusenberg et al. has shown that ultimate tensile strength (UTS) and elongation at break (EaB) can vary by as much as 6% and 43% respectively from parts fabricated in different areas of the build volume [58].

Once the polymer melts, it begins to flow and densify. However, sintering is time and temperature dependent, meaning a part will be fully sintered only after some combination of time and temperature is reached. The required time and temperature are inversely related to each other as less time is required when a higher temperature is reached due to the polymers ability to more readily flow at higher temperatures. A polymer’s ability to flow is measured by its viscosity which lends insight into which materials can be processed with a specific time and temperature profile.

2.3.3 Viscosity

Viscosity is a measure of the resistance to flow. In liquid phase sintering, the material’s viscosity, and more specifically, zero-shear viscosity determines the amount of time or required temperature for the polymer powder to densify. The zero-shear viscosity is a measure of the
material viscosity as the applied shear stresses approaches zero as is found in LS [59]. A low shear viscosity in PA12 materials and their large processing window are the most important factors for their use [47]. A low zero shear viscosity indicates that a material can spend a shorter duration of time in the molten phase and still have sufficient flow to densify within that amount of time. In LS, powder particles are exposed to the laser beam for micro to milliseconds at a time [56, 60, 61]. If the viscosity is too high, then the laser would need to be slowed down and would vastly increase overall build time. Alternatively, the laser power would need to be increased to provide sufficient superheating of the material to decrease the viscosity and increase the time at higher temperatures before the material cools sufficiently to stop effective densification. Increasing the laser power has the effect of applying extremely high heating rates and creates large local thermal gradients. By using typical system parameters, the instantaneous temperature is already estimated to overshoot the melting temperature by over 125 °C in the case of PA12 [53, 62]. This can degrade the polymer, leading to a lower quality sintered component with decreased mechanical performance [53]. It is thus important to understand the amount of time required for a material to sinter and densify under specific input conditions.
2.4 Mechanical Properties

As most applications of industrial AM parts are for engineering applications, understanding their mechanical properties and how to maximize them is critical. A typical measurement of mechanical performance is a tensile test. Tensile testing requires a test coupon that resembles a dog bone, which is a name typically used in the industry. These specimen can be either flat or cylindrical but due to the layering and stair-stepping nature of AM, flat specimens are customarily used. Some typical dog bone geometries are seen in Figure 2.8. These specimens are pulled apart from each end and the force/displacement relationship is recorded. From these values, stress vs strain graphs can be developed and the material’s ultimate tensile strength (UTS), elongation at break (EaB) and Young’s Modulus (E, measure of elasticity) can be determined. These are the primary measurements used to compare results from different AM systems and with different materials. Processing conditions as well as material properties effect the mechanical properties of sintered components. The important processing conditions include the exposure time and intensity of the incident radiation.

![Figure 2.8: Tensile test coupon. A (ASTM E8-11 subsize specimen) and B (ASTM 638-10 type IV) are common tensile test coupons used for metal and polymer tensile testing respectively and C is the coupon used for tensile tests with the LAPS process. Size shown is not to scale.](image-url)
2.4.1 Exposure Time and Intensity

The degree of sintering is proportional to the sintering temperature and the amount of time the powder particles are heated. Both the exposure time and intensity dictate the temperatures reached. In LS and HSS, heating and cooling is a dynamic process. In LAPS, a control temperature can be set and maintained for a specific time. In LAPS, either intensity or temperature can be considered an independent variable, whereas in LS or HSS, only intensity and time can be controlled. This is why for LS, energy input is a primary variable which is evaluated, even though many sintering models depend on viscosity, which is directly dependent on temperature and not energy input. Increasing either the exposure time or intensity of the incident light has the effect of increasing the energy input. The energy input \((E, \text{ Joules})\) is related to the exposure time \((t, \text{ seconds})\) and intensity \((I, \text{ watts})\) through the following equation:

\[
E = It
\]

Equation 2.4

This equation can alternatively be defined for energy density, or the amount of energy flux through a plane:

\[
\Phi = It
\]

Equation 2.5

where \(\Phi\) is the energy density \((\text{J/m}^2)\), \(I\) is the power density \((\text{W/m}^2)\) and \(t\) is time \((\text{s})\). These relationships have been used in determining the ideal amount of energy density required to obtain a high quality sintered part. Once known, either exposure time or intensity can be varied to achieve the same end result. One method of using this technique is by evaluating the energy melt ratio.
The energy melt ratio relates the amount of energy input, with the theoretical energy required to fully melt the powder. However, it assumes 100% of the applied energy is absorbed uniformly by the material. It does not take into account thermal losses or uneven energy absorption. Thermal losses include the partial reflection of the incident radiation and convection/conduction losses to the surroundings. In the case of LS, these assumptions are typically accepted as the extremely short exposures allow little time for heat losses to occur and a CO$_2$ laser is typically used, which provides a long wave infrared wavelength that is highly absorbed by the PA12 powder. Starr et al. has shown that increasing material properties will result with increasing energy melt ratios until this value equals unity and then an increase in mechanical properties beyond this point will not occur [63]. If no losses are present, the energy melt ratio is the exact amount of energy required to fully melt the material. However, LS components show evidence of incomplete melting [46, 64], indicating that the thermal losses and/or uneven absorption of the radiation must be significant (more energy is absorbed at the surface rather than evenly throughout the volume). Thus, the ratio should not be taken as an absolute rule, but a guideline that was specific to the energy absorption and thermal loss condition studied. An energy melt ratio of unity is suspected to be when 100% of the volume of powder melts. If an energy melt ratio increases further, the excess energy may degrade the material (>6.2 in the test conditions for LS using PA12 [63]). Insufficient energy to bond the material occurs with an energy melt ratio below 0.5 [65]. These values represent a system parameter set which exposed the powder for between 18 to 89 microseconds [65, 66].
A more commonly cited value is Andrew’s number ($A_n$) which is useful in LS systems because it allows the operator to select common machine parameters to achieve a specific outcome [63, 67]. Andrew’s number is defined as:

$$A_n = \frac{P}{V \cdot HS}$$  \hspace{1cm} \text{Equation 2.6}

where $P$ is the laser power, $V$ is the laser’s scan velocity and $HS$ is the hatch spacing, or distance between scan lines. Andrew’s number is a flux based value, determining how much energy is input onto a surface.

Another approach used to quantify this process is called the degree of particle melt and is a volumetric approach. It is defined as the fraction of crystals in the powder which melted during sintering compared to the total crystal content. This approach separates itself from the energy melt ratio and Andrew’s number as those methods depend on process inputs while the degree of particle melt quantifies the sintering outcome which eliminates assumptions about thermal (convection, conduction, radiation) and optical (reflection, transmission) losses.

The degree of particle melt is determined by comparing percent crystallinity of the raw powder and the final part and is determined by a DSC study. Hopkinson et al. and Zarringhalam et al. have shown that an increased degree of particle melt increases mechanical properties and correlates well with an increased degree of sintering [64, 68]. They further confirmed this through cross sectioned images that showed a bulk of material which had resolidified after melting but also contained particle cores which never fully melted during sintering. The degree of particle melt in LS was
then found to have a linear correlation to Andrew’s Number over the range of 8.5 to 12 kJ/m² [64].
As observed by the authors, densification is a time dependent process and for a high-quality part
to be made, porosity should be kept to a minimum. However, as LS is known to produce porosity,
the degree of particle melt method does not take into account the porosity as the DSC results
strictly report intrinsic material properties and cannot identify inadequate extrinsic part properties.
Additionally, Andrew’s number does not account for time dependent densification, or thermal
losses. The following chapter evaluates the mechanical properties for LAPS by using the energy
density approach to determine its validity for longer exposure times.
CHAPTER 3: EVALUATION OF PROCESSING VARIABLES IN LARGE AREA POLYMER SINTERING OF SINGLE LAYER COMPONENTS

This chapter has been accepted in the Rapid Prototyping Journal and is awaiting publication.

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3.1 Abstract

Projection sintering, a system for selectively sintering large areas of polymer powder simultaneously with a high power projector is introduced. The paper evaluates the suitability of laser sintering process parameters for projection sintering as it uses substantially lower intensities, longer exposure times, and larger areas than conventional laser sintering (LS).

The tradeoffs in sintering outcomes are evaluated by creating single layer components with varied exposure times and optical intensities. Some of these components were cross-sectioned and evaluated for degree of densification while the single layer thickness and the maximum tensile force was measured for the rest.

Shorter exposure times and higher intensities can create thicker and therefore stronger parts than when equal energy is applied over longer exposures. This is different from laser sintering in which energy input (Andrew’s Number) is accepted as a reliable process variable. This difference
is likely because significant thermal energy is lost from the sintering region during the exposure time—resulting in reduced peak temperatures. These thermal losses can be offset by imparting additional energy through increased exposure time or light intensity.

Most methods for evaluating LS process parameters, such as the energy melt ratio and Andrew’s Number, estimate energy input from basic process parameters. These methods don’t account for thermal losses and assumes the powder absorbs all incident light. These methods become increasingly inaccurate for projection sintering where exposure times are much higher (>1s) and a larger portion of the light is reflected from the power’s surface. Understanding the appropriate sintering criteria is critical for the development of long-exposure sintering.

3.2 Introduction

Additive manufacturing (AM) is a rapidly growing technology that enables fabrication of components directly from digital models without part-specific tooling. Many industries are adapting AM into their manufacturing processes because it is able to quickly create complex and functional components. Laser sintering (LS) is an AM method that produces high quality parts suitable for end-use [9, 69]. In LS, a focused laser scans across a preheated powder bed to locally fuse particles. A new layer of powder is then deposited on top of the first, and the process repeats as shown in Figure 3.1. Partially crystalline polymers with a well-defined melting point typically perform best because the powder bed can be heated near the melting point so that relatively little energy input is required to melt them [40, 70]. Part distortion is reduced if the material has a small
crystallization shrinkage and/or a large gap exists between the recrystallization and melting temperatures [71]. While LS has been demonstrated with a wide range of materials [71], the vast majority of all polymer LS components are produced with polyamide 12 (PA12) because it best meets these stringent constraints [72].

![Figure 3.1: Schematic of the LS process. A laser and laser scanner sinters the powder in the X-Y axis while the recoating roller and refill piston supplies powder for a new layer.](image)

LS systems are typically composed of a laser, a galvanometer for steering the laser, and a powder spreading system contained within an inert environment [9]. In order to produce parts economically with high spatial resolution, commercial systems generally have a small laser diameter (~0.5 mm) with high scanning speeds (~1-5 m/s) [56, 60, 61] and high optical intensities (900 - 4,500 W/cm²) [73, 74]. A single area is typically exposed for micro to milliseconds at a time [56, 60, 61]. During the brief exposure, high local temperatures are generated which can degrade the polymers. Area-based patterning could provide an alternative for economical processing of
materials while providing longer exposure times at each location. Longer exposure times could be beneficial by limiting the peak temperature which will decrease degradation effects, providing additional time to ease the use of closed loop process control, and by providing a longer time period for the polymer particles to sinter and densify.

Polymer sintering typically occurs through a time and temperature dependent viscous sintering process. This two-stage process starts with particle coalescence, followed by pore shrinkage and removal. The early stages are described by a simple viscous sintering model developed by Frenkel as seen below in Equation 1 [59, 75]:

\[
\left( \frac{a}{R} \right)^2 = \frac{3}{2} \left( \frac{\gamma t}{R \eta_0} \right)
\]

Equation 3.1

where \( a \) is the radius of the growing neck between two spherical particles of radius \( R \), \( \gamma \) is the particle’s surface energy, \( \eta_0 \) is the zero-shear viscosity, and \( t \) is time. Liquid phase sintering is driven by the minimization of surface tension forces through reduction of the surface area [40]. The zero-shear viscosity decreases with increasing temperature—reducing the required sintering time. In order to fully fuse and coalesce these particles, the polymer must have sufficiently low viscosity to allow the material to flow before cooling [43]. Low strength components with high porosity will result if viscosities are too high or if heating times are too short. Prior polymer sintering work has focused on point processing with a scanning laser. This work addresses criteria for densification of polymer powders with longer exposures and larger areas to cure an entire layer simultaneously.
3.3 Experimental Setup for Projection Sintering

A system was designed which enabled sintering of large areas with relatively low intensities and longer than typical exposure times when compared to LS. A schematic of the test system is presented in Figure 3.2. In this system, an Optoma X316 projector was modified to decrease the exposure area from a maximum of 278,709 cm$^2$ to 3.7 cm$^2$ and provided a pixel resolution of 20 μm at the target. Decreasing exposure area concentrated and increased the intensity of the projected image. Additionally, the optical power was boosted from 1.8 W to 7.3 W, as measured from a fully white projected image on a Thorlabs S310C thermal power sensor which measures the heat energy of the input light with a flat absorption spectra from the visible to beyond the medium wavelength infrared spectrum. Overall, this provides an intensity increase from $6.5 \times 10^{-6}$ W/cm$^2$ to 2 W/cm$^2$. This makes the modified projector an effective area-based heating tool with high thermal contrast.

Figure 3.2: Schematic representing the sintering process. In this experimental setup, an aluminum plate holds a 1.5 mm layer of PA12 powder at a uniform temperature. A high power projector applies patterned light to sinter the powder through a borosilicate window.
An example of a part created with this system and a thermal image demonstrating the high thermal contrast can be seen in Figure 3.3. The projector’s optical power is provided by a 190 W ultra-high pressure mercury vapor (UHP) bulb. UHP bulbs produce a broad spectrum of light that ranges from the ultra violet (UV) to infrared (IR) spectrum, though a majority of the energy is contained within the visible spectrum (400-700 nm) and produces a mostly white light. The projector’s optics and lamp are optimized to transmit light in the visible spectrum, filtering out the UV and IR light. Because of the poor transmission and high absorbance of UV and IR light in the projectors optics, it is assumed a negligible amount of these wavelengths remain in the projected image.

![Figure 3.3: Left) example part created with a single, large area exposure, right) example thermal image of the University of South Florida logo on a PA12 powder bed created with the projection sintering system.](image)

A PA12 powder layer 1.5 mm thick was spread onto an aluminum platform using a blade. Similar to LS, PA12 powder was preheated to 170°C as measured by a thermocouple placed in the center of the platform halfway through the thickness of the 1.5 mm layer of powder. The test platform was placed 5 cm from a transparent window in a modified convection oven. The
convection oven provided even heating from all directions through convection rather than through conductive and radiative heaters as is commonly used in laser sintering systems. As white powders reflect most of the visible light away from the surface, absorbing only a small portion of the optical energy from the incident light, a black PA12 powder (part number PA2202), provided by EOS was selected for testing to maximize the energy absorbed by the powder. The PA2202 is manufactured for the AM industry and is commonly used in LS systems to create black components.

Measurement of the visible light absorbance was conducted by measuring the total amount of light and subtracting out the measured transmitted light and degree of reflected light. The total amount of light was measured with a Thorlabs S310 thermal power sensor. The transmitted light was measured by placing a photodiode under a layer of powder at various thicknesses and measured the transmission of light from the projector’s lamp. To find the degree of reflected light, light was reflected off the powder’s surface and into a photodiode. A ratio of reflected light was calculated by comparing the results from a white PA12 to a black PA12. Using the assumption that white PA12 reflects 100% of the light yields an absorption for the black PA12 of 65% and 95% after transmitting through 100 μm and 200 μm of powder respectively. By removing this assumption, we find that the absorbed light drops to 45% and 76% for 100 μm and 200 μm of powder respectively. These results are promising because a majority of the light would be absorbed in one standard 100 μm layer and almost all of the light is absorbed after transmission through two standard layers. This could assist in fusing and bonding each newly sintered layer to the layer
below it. This system provides a method of effectively sintering single layer parts to assess the impact of varied exposure conditions on density, thickness, and strength of the exposed layers.

### 3.4 Analysis of Single Layer Parts

#### 3.4.1 Degree of Densification

To analyze the degree of densification and layer thickness, four test coupons were sintered under varying degrees of exposure time at the maximum optical intensity of 2 W/cm². After cooling, the parts were removed from the unsintered powder. They were cooled in liquid nitrogen and broken to create a brittle fracture with a nearly flat fracture surface. These components were then sputter coated with gold-palladium to create a conductive surface and imaged with a Hitachi S800 scanning electron microscope as seen below in Figure 3.4.

![Figure 3.4: Cross sectional images of tensile bars. All components were sintered with 2 W/cm² and are shown at 100x magnification. The exposed surface is on top in all images. a) 1.5 s exposure b) 1.75 s exposure c) 2.0 s exposure d) 3.0 s exposure.](image)

Exposure times below 1.5 s produced parts that were too weak to be handled and therefore, were not imaged. As seen in Figure 3.4a, short exposure times produced limited particle necking.
with individual particles clearly visible through the entire part thickness. This resulted in a low degree of densification and low strength. The bottom surface shows little evidence of sintering even though the parts were lightly brushed to remove any loose powder before imaging. As the exposure time is increased, a continuous dense layer is formed (Figure 3.4b) which increases in thickness as exposure times increase (Figure 3.4c,d). The exposed top surface becomes smoother as well. Oliveira Setti et al. [76] has shown that a smooth surface finish represents a high density and tensile strength, indicating good particle coalescence and therefore, good sintering quality. After 3.0 s the fully dense layer is approximately 100 μm thick. This is encouraging for the formation of multilayer parts as this is the standard layer thickness in LS and many other AM processes. A highly dense layer is a fundamental necessity and quality indicator for high component strength.

3.4.2 Component Strength

In order to effectively analyze the impact of exposure time and intensity, single layer tensile test specimens were created using a single exposure. The components were tested in accordance to ASTM standard D638-10. The tensile specimen geometry used in this study is similar to the standard. However, it was scaled down to fit the maximum achievable exposure size and the gauge width was increased to increase the maximum achievable force for ease of measurement by the force sensor. The specimen had an overall length of 23.0 mm, a gauge length of 8.0 mm, a gauge width of 4.6 mm, a grip length of 4.2 mm, a grip width of 6.6 mm and a transition radius of 2 mm.
After removal from the powder bed, the back of each specimen was lightly brushed then cleaned with compressed air to remove loose non-load bearing powder. The specimen thickness was measured with a dial micrometer whose contact tip was replaced with a blunted needle. The blunt needle contact tip was used to facilitate measurement of curled samples. The specimens were measured on the long axis centerline at three locations and averaged. Tensile testing was conducted on a MTS 810 hydraulic tensile testing machine.

During these tests, the components that were sintered at low energy densities (short exposure time or low intensity) showed a low degree of sintering and remained flat but were also of insufficient strength to be handled. The specimens that were well sintered exhibited some degree of curling at the edges directly after exposure in the powder bed. This made it difficult to measure the cross-sectional width in the gauge length. The forces recorded during tensile testing could not be converted to stress values because of this. Since forces do not demonstrate a material property, they are used here only for relative comparison.

Multiple methods exist for parameterizing and evaluating sintering conditions in LS that are successful in accurately predicting sintering outcomes during the short exposure times in LS. For example, Andrew’s Number is cited extensively and relates various processing parameters to the overall energy input into the powder [38, 53]. Another effective parameter is the energy melt ratio, which is a comparison of the amount of energy input into a specific volume of powder divided by the actual amount of energy required to melt that volume of powder [63]. Both methods would
predict that process performance would be independent of exposure time/intensity as long as total energy input remains constant.

To see if this holds true in projection sintering, a constant energy density was maintained by increasing exposure time as the light intensity was decreased. Three different energy density values were chosen for testing, 4.0, 6.0, and 8.0 J/cm\(^2\) representing a low, medium and high amount of energy input for projection sintering.

Figure 3.5 shows that process outcomes clearly vary with exposure time for constant energy input. Increasing exposure time and decreasing intensity creates weaker parts. While they had less warping, the load carrying capacity is also reduced as shown in Figure 3.6. It is evident from the pictures shown in Figure 3.5 that less sintering occurred in the parts that were exposed for a longer period of time at a lower intensity but with the same overall input energy. The specimens with 4.0 J/cm\(^2\) energy input had a very rough surface finish, were very weak, and showed significant variation due to the difficulty of handling the weak specimens. At higher energy inputs (6 J/cm\(^2\), 8 J/cm\(^2\)), both thickness and strength varied significantly with changes in optical intensity, even though the overall energy input remained constant. This shows that energy input alone is not a sufficient metric for characterizing the process. At each optical intensity, both strength and part thickness also increased with energy input. As seen in Figure 3.5, the lower strength when using a lower optical intensity (longer exposure time) is attributed to losing more energy to the
surrounding powder and the environment when it is input over a longer time—decreasing the peak temperature and increasing the viscosity during sintering.

Figure 3.5: Tensile specimens made with the same energy density (4.0 J/cm²), a) 4.0s of exposure time with 1.0 W/cm² power density, b) 3.33s of exposure time with 1.2 W/cm² power density, c) 2.0s of exposure time with 2.0 W/cm² power density. The degree of sintering is decreased as exposure time increases as evident by the rougher surface finish.

The traditional LS process parameters (Andrew’s number, energy melt ratio) assume all input energy is absorbed into the powder and used in the melting process. Short exposure times (<1 ms is typical in LS) at long wavelengths (10.6 μm is typical) where the powder heavily absorbs the light, provides little time to allow for thermal losses during the heating process. Recently, Drummer, Drexler and Wudy [77] have studied this effect and evaluated exposure times from 0.06 to 0.77 ms. While this is significantly faster than with projection sintering, they revealed a similar trend that higher quality sintering occurs with increased heating rates. Higher degrees of sintering (higher strength and density) occur with both slower heating rates and additional energy input. However, an upper bound exists as the resulting higher temperatures begins to degrade the polymer, resulting in weaker parts. Currently, no research has studied the limit to the increased degree of sintering gained with slower heating rates, especially at the time scales presented in this work. An ideal system would allow the powder to be raised to a specific sintering temperature and
maintain that temperature for a specified amount of time. A second generation system with this capability is currently under development at the University of South Florida which should yield additional insights into the effect constant predictable heating rates will have on the mechanical performance of the material.

![Graphs of testing conditions and results for tensile bars created with constant energy density at three different values.]

Figure 3.6: Testing conditions and results for the tensile bars created with a constant energy density at three different values.

Projection sintering samples with greater than 4.0 seconds of heating times and 4.0 J/cm² were too weak to be handled because excessive thermal losses prevented the powder from fully melting.

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This varies from literature values for LS where the Andrew’s Number necessary to produce high strength dense parts with PA12 vary from 2 to 3.5 J/cm² [53, 78, 79]. This difference in energy input is attributed to the reduced absorptivity of the powder to the projector’s visible light and the increased thermal losses which occurs during heating.

In order to create components with equal degrees of sintering, as would be indicated by equal values of part thickness and breaking force, the energy density must increase as exposure time increases to make up for the lost thermal energy. However, predicting the energy input required for different exposure times in order to achieve a constant material output is based on thermal losses and would be a function of geometry, powder, bed position, and environmental variables. Additional research is needed to develop an appropriate process control criteria for long heating times to assure consistent part outcomes. One possible approach would be to track and control the temperature at the bed’s surface.

3.5 Conclusion

A new area-based sintering technology is used to analyze the role of exposure time and optical intensity in polymer sintering. This system is capable of sintering entire 2D cross-sections with a single exposure. This work evaluated single layer PA12 components to understand the interaction between the PA12 powder and visible light absorption. The single layer parts evaluated in this study could act as the foundation for future 3D parts. They also show that with projection sintering, layer thickness can be controlled and layers much thicker than the industry standard of 100 μm
can be produced. Components created with this system show that increased light intensity or exposure time increases the degree of sintering but part properties are not directly proportional to the energy input as assumed in LS. With the longer exposure times typical with projection sintering, thermal losses can become significant and must be accounted for. Common evaluation methods that do not account for losses fail to predict sintering outcomes. Development of new process parameters is critical in the development of long exposure polymer sintering processes.

Projection sintering can potentially expand the range of materials that can be sintered by permitting more control over the peak temperature and sintering time. This system aids to the understanding of sintering kinetics outside the realm of high heating rates. Previous research and these results suggest that this technique could be extended to create stronger 3D parts. However, many obstacles exist including overcoming warping due to sintering shrinkage and correction of a nonuniform distribution of light across the exposure field. Future work will evaluate the effect long exposures have on the minimum feature size that can be obtained with this technology.
CHAPTER 4: IMPACT OF SINTERING TIME AND TEMPERATURE ON MECHANICAL PROPERTIES IN PROJECTION SINTERING OF PA12

4.1 Abstract

Additive manufacturing (AM) provides the means to create both prototype and end use parts quicker and cheaper than conventional manufacturing processes for small volumes. In addition, it unlocks the ability to create components which were previously impossible and without the need for any special tooling. Powder bed fusion is a popular AM technology used to meet these demands. The sintering process which governs how the material is fused in these systems is well known to be a temperature and time dependent process. However, little work has been performed in situ which allows the direct application of varied exposure times and temperatures with longer sintering times than are typical in common LS systems. To apply this concept, Large Area Projection Sintering (LAPS) is used which is a system capable of sintering entire layers of material simultaneously over the course of a few seconds. This work evaluates the effect of time and temperature on sintering through the characterization of the PA2202 (polyamide 12) powder and sintered tensile test specimens through thermal and mechanical analysis. It was found that the highest toughness can be achieved with lower sintering temperatures for extended periods of time and that relatively small changes in density can produce drastic changes in the parts ductility.
4.2 Introduction

Additive manufacturing (AM) has worked its way into the manufacturing industry and is becoming a staple. Earlier in its years, AM was typically used for rapid prototyping but the focus is now shifting to creating end user parts. This is due to the many benefits AM can offer in geometry, lead time, and customization, but also because the material options are expanding and the properties of the parts are approaching the quality desired by design engineers. However, parts created by AM typically suffer from anisotropy [80, 81] and reduced mechanical properties when compared to well-established manufacturing processes, such as injection molding (IM) [82].

Laser sintering (LS) is an AM technology which is commonly used and is capable of creating components for prototyping and end use. LS typically uses the popular Polyamide 12 (Nylon 12, PA12) powdered feedstock which is an engineering thermoplastic capable of producing quality parts with high strength, chemical resistance, resistance to abrasion and a moderately high melting temperature [83, 84]. LS is a powder bed fusion technology as defined by ASTM [85] that uses a high power laser which scans over the surface of the powder bed. LS rasters the cross sectional image at high speeds (~1-10 m/s [86, 87]), fusing powder particles as it scans. While providing decent quality and resolution, the rapid scanning required for economical build times are known for producing parts with porosity [88] and unsintered particle cores [64, 68] which Hopkinson et al. has shown decreases the strength and ductility. Furthermore, sintering is well understood to be a time and temperature dependent process, but these time-temperature effects haven’t been studied in situ. This is due to the difficulty of controlling the temperature when the heating process occurs.
rapidly as by a scanning laser. In LS, as the laser scans over the powder for microseconds at a time, it follows a sharp heating curve with significant gradients through the layer thickness and even powder thickness and after it passes, uneven cooling occurs. As such, a stable sintering temperature is never reached \([89]\). A new AM technology developed at the University of South Florida, Large Area Polymer Sintering (LAPS), sinters powder particles at orders of magnitude slower exposure times (~2-8 s in this work, compared to μs with LS). This is achieved by utilizing a high intensity projector which projects a thermal pattern on the surface, heating and fusing an entire layer simultaneously in the desired shape. A new layer of powder is then deposited and spread by a blade or roller mechanism. A thermal camera provides closed loop feedback control, updating the image being projected to obtain a specified final temperature. The use of closed loop feedback control allows temperature targets to be set and maintained for a specified time and to correct for spatially varying thermal boundary conditions in the plane of the bed or into the depth. A schematic of the system can be seen in Figure 4.1. This system will be utilized to understand the time-temperature sintering relationship at longer than typical sintering times and with much lower intensities when compared to LS. The exposure time and temperature will be correlated with the resulting mechanical properties and part density through tensile testing and Archimedes density experiments respectively.

In commercial polymer powder bed fusion systems, the powdered feedstock is generally semi-crystalline and has both a glass transition temperature, where the material softens, and a melting temperature range over which the polymer melts. In these systems, the melting transition is
relatively sharp with a decrease in viscosity of several orders of magnitude as the crystalline regions transitions from a solid to a liquid over just a few degrees Celsius (~10°C). In these systems, viscous sintering of the polymer occurs. This occurs when there is sufficient liquid volume to flow and densify [90]. The viscous flow which occurs in viscous sintering is a time and temperature dependent densification process. The time and temperature dependence arises primarily from the polymer’s viscosity change during the phase change from solid to liquid, though viscosity continues to decrease with higher temperatures. Viscous sintering is driven by surface tension forces which seeks to minimize surface energy through the reduction in surface area [40].

Figure 4.1: Schematic of Large Area Projection Sintering (LAPS) system.
As the material flows, densification occurs as the particles are drawn together and pores are eliminated [43]. Longer time spent in the molten state allows more time for the polymer to flow and densify while lower viscosity decreases the required time to densify. This is evident in the basic sintering model developed by Frenkel [39] and later corrected by Eshelby [43] to satisfy the continuity equation and defined as:

\[
\left(\frac{a}{R}\right)^2 = \frac{\gamma t}{R \eta_0}
\]

Equation 4.1

where \(a\) is the radius of the growing neck between two spherical particles of radius \(R\), \(\gamma\) is the particle’s surface energy, \(\eta_0\) is the zero-shear viscosity, and \(t\) is time. The amount of time required for a material to densify is based on its zero-shear viscosity, which is the viscosity used in viscous sintering as there are negligible external forces [59]. The zero shear viscosity is in turn dependent on the temperature. As higher temperatures are reached, lower viscosities can be achieved. At extended time periods (often measured in minutes and hours [62]) the PA12 powder is known to post-condensate which is an aging effect that increases the molecular weight of the polymer which increases the viscosity [91]. However, in the short time spans evaluated in this study and minimal temperature increase above the melting temperature this is assumed to contribute a negligible effect. While the time and temperature effect of polymers are well documented, little work exists which directly studies various time and temperature effects on sintering in situ.

The goal of this work is to correlate LAPS extended exposure times, intensity of incident light, and the sintering temperature to part quality. This is of interest as the extended exposure times
could allow more time for the polymer to melt and flow, leading to decreased porosity (increased density) and fully melted polymer particles. In this study, tensile test specimens were created under various time and temperature regimes to compare density and mechanical properties.

4.3 Methods

4.3.1 Thermal Control of LAPS System

The LAPS system in this study has the capability of sintering entire layers with a single exposure from a high intensity projector. The projector was modified to produce an intensity of 2.4 W/cm$^2$ with a maximum image size of 2.1 cm by 1.6 cm. A FLIR A325sc long wave infrared thermal camera is mounted to the system to observe the sintering area. The thermal camera is used in a feedback control loop with the projector to maintain the set temperatures and obtain a uniform temperature distribution through PID control. Before sintering occurs, the projector creates a uniform temperature distribution ($\Delta T < 1 \, ^\circ\text{C}$ over sintering area) over the course of three seconds with a target temperature of 169 °C.
After modifying the projector, the projected image was found to only have a uniformity of less than 68%, meaning that some areas had considerably higher or lower intensity when compared to other sections of the image. This nonuniformity would cause the areas with the highest intensity to increase in temperature at a quicker rate and maintain the desired sintering temperature for a longer period of time. This can be seen in Figure 4.2, where the highest intensity is on the right side (located at the red arrow). However, if a target temperature is set, the system will attempt to maintain that temperature by decreasing the intensity in each area once it is reached. When specific areas hit the temperature target, the heating rate was drastically reduced but in cases where there was sufficient sintering time remaining, the system typically overestimated the required intensity and those areas overshot the target temperature. In most cases where this occurred, the overshoot

Figure 4.2: A) Temperature distribution after 4 seconds of exposure time when the projector is set to bring the entire image seen in B) to the highest possible temperature (open loop control). The hottest temperature in the gauge area and located on the gauge width centerline is located at the red arrow and the coolest temperature is located at the blue arrow.
was minimal (5 °C in the worst case). With a majority of the cases, the material either didn’t have enough time or enough intensity to reach the target temperature and is discussed in more depth with the results of each experiment. Since the variation in intensity over the gauge area of the tensile specimens produced varied temperature profiles, the final temperature is recorded along the center of the gauge width for the areas with the lowest and highest temperature, depicted by blue and red arrows in Figure 4.2 respectively. These pixels will be referred to as the hot and cool pixel in the subsequent sections.

4.3.2 Optical Resolution

The images formed by the projector and thermal camera are constructed by individual pixels from the camera’s sensor or the projector’s digital micromirror device (DMD). The DMD is a microelectromechanical system where each pixel can be turned on or off by a mirror which reflects the light out of the front of the projector lens or towards an internal light absorber. The Optoma X316 projector uses a 1024x768 DMD. At the image plane of the projector, each pixel is 21 μm across. However, the actual resolution is most likely higher than this due to aberrations caused by modifying the projector’s optics. The FLIR A325sc thermal camera uses an uncooled 320x240 pixel microbolometer detector. The thermal camera is mounted at an angle and thus produces a warped image of the sintering region. This image is post processed through a MATLAB program which correctively warps the image to appear as if it was taken orthogonally. The image is then cropped to the size of the projected image where each pixel represents an area that is 364x280 μm
in size. The temperature recorded by each pixel is an average of the temperature within the area it is observing. This means that the image produced in the control loop will only have an effective resolution similar to that of the thermal camera.

4.4 Tensile Testing

Since sintering is known to be dependent on both time and temperature, two experiments were conducted to gauge the effect of each of these variables. In addition, a third experiment tested the system in open loop control to evaluate the effect of the addition of closed loop control. The testing parameters used for each of these experiments are shown in Table 4.1. In the first experiment, the effect of various target temperatures with a constant exposure time is evaluated. Experiment two is the opposite, where the temperature target is maintained constant while varied exposure times are used and is evaluated at two different temperature targets. In the third experiment, the projector was run in an open-loop control mode. In this mode, it maintains full intensity over the entire image for the duration specified.
For each of the tests, tensile bars were created with the dimensions described in Chapter 3 which are similar to ASTM standard D638-10. Each specimen is composed of ten 100 μm thick layers, creating a final component approximately 1 mm thick. All test specimen were tensile tested with a displacement rate of 1 mm/min. Strain was measured with a MTS LX 500 Laser Extensometer, capable of measuring strain without contacting the sample.

For the first two types of tests conducted, tensile test specimens were created one at a time and with a minimum of three specimens for each parameter set. For the third experiment where the projector was run in open loop control, three samples at each parameter set was created in each build. For all tests, each part was anchored to the silicone build plate with two layers that used the

| Table 4.1: Test conditions for the three types of tensile and density tests conducted. |
|-----------------------------------|-----------------------------------|-----------------------------------|
| **Experiment 1** | **Experiment 2** | **Experiment 3** |
| **Exposure Time (s)** | **Temp Target (°C)** | **Exposure Time (s)** | **Temp Target (°C)** | **Exposure Time (s)** | **Power Flux (W/cm²)** |
| 2.5 | 185 | 1.5 | 195 | 1.5 | 2.4 |
| | 190 | 2 | | 1.75 | |
| | 200 | 3 | | 2 | |
| | 205 | 5 | | 4 | |
| | 215 | 8 | | | |
| | 1.5 | 205 | | | |
highest possible exposure power for five seconds irrelevant of the test conditions. Additionally, external radiation from a 60W incandescent spot light was used for the first three layers. Without the anchoring layers, many of the specimens would warp and cause the build to fail. The ambient air above the build surface is heated through convection by the preheated powder and heated side walls of the build piston. It maintains a temperature of approximately 120 °C as measured 5 mm above the powder surface. While the tensile specimens were created, the spatial and temporal temperature was recorded on the ninth layer with the thermal camera. The ninth layer was chosen because it was sufficiently far from the bottom few layers where differences may occur due to the foundational anchor layers. During printing, the powder would occasionally not be spread uniformly (either too thick or too thin in different areas), causing the layers to warp and create areas which wouldn’t fully densify. These components were discarded, although density measurements could assist in identifying parts with a large amount of pores.

4.4.1 Density Determination

If a material has pores in its internal structure, these act as non-load bearing areas and thus decreases the mechanical properties and reduces density. Thus by measuring the density of a sample, an estimation of the pore volume may be obtained. However, this is only true for conditions where the crystalline structure between each sample is similar. Different structures provide different densities, these structures include a purely amorphous phase (0.99 g/cm³), an α phase crystal polymorph (1.034 g/cm³) or a γ phase crystal polymorph (1.085 g/cm³) [92]. Thus it
is difficult to correlate pore volume directly to density. However, an increased density in polymers typically translates to higher tensile strengths and elongation to failure [93, 94]. More on the crystal structure is discussed in the following section.

To determine the density of each sample, loose powder was removed with a nylon brush and compressed air. An Archimedes’ principle density determination kit was used to find the density. For this test, knowing the volume is not required, only the part’s dry weight and weight submerged in a fluid (includes buoyancy force) is required. With these, the density of the fluid and the density of the air, the density of the sample can be measured with the following equation:

\[
\rho = \frac{m_d - m_w}{m_d} (\rho_f - \rho_a) + \rho_a
\]

Equation 4.2

where \( m_d \) is the mass of the dry sample in air, \( m_w \) is the mass of the sample wet (submerged), \( \rho_f \) is the density of the fluid and \( \rho_a \) is the density of air. For these tests, 2-propranol anhydrous was used as the fluid due to its large difference in density than that of the PA12. Three sample sets were created for density measurements at eight of the nineteen sample sets to determine repeatability of the experiments. In the results which follow, these sample sets are indicated by the ± symbol. These tests were found to be highly repeatable, where a majority of tests varied by less than 0.4% with the highest variation of 0.6%. Due to the high repeatability of these tests, it was deemed acceptable to report values for a single test. However, due to only have one sample for the remaining 11 sample sets, it should be noted that many of the samples could have higher deviation not captured in the results.
4.5 Material

4.5.1 Effects of Crystallinity

Each of the specimens was created from PA2202, which is a dark colored polyamide 12 powder (PA12, Nylon 12) produced by EOS for the LS industry [1]. To determine the proper preheat temperature and required sintering temperature, a differential scanning calorimetry (DSC) test was conducted on virgin powder with a TA Instruments Q20 DSC system. A DSC test heats or cools a small sample of material while measuring the heat flow into or out of the sample. Decreases in heat flow represent an endothermic reaction, signifying melting or a glass transition temperature. Increases in heat flow represent an exothermic reaction, such as recrystallization. The results can be seen in Figure 4.3 where a rather large window exists between the melting temperature and recrystallization temperature. In LS, the preheated powder bed is maintained at this temperature so that the polymer remains in a liquid state until the entire part is printed. As recrystallization and reordering of the semi-crystalline structure occurs, bulk shrinkage adds internal stresses to the part and can cause warping which can lead to a failed print. By postponing the shrinkage until after the entire part is finished, it can be cooled slowly and uniformly, minimizing the internal stresses [53, 65]. It should be noted that in LAPS, the fresh powder is held in a hopper which is not preheated and during powder deposition, the bed moves into a lower temperature region of the build chamber. While the previously sintered layer stays molten after being sintered, it most likely recrystallizes to some degree when a new layer of powder is spread.
Figure 4.3 shows a melting onset temperature around 175 °C with a sharp transition. However, this is not an instantaneous change. PA12 powders for the AM industry are well known to be a multiphase polymer [95] consisting of an α (monoclinic) and γ (hexagonal) phase with the α phase forming under slow cooling rates or high temperatures and the γ phase forming under fast cooling rates or low temperatures [37]. Each of these crystal phases melt at different temperatures. Additionally, the thickness of the layered crystallite lamella can further change the melting temperature. This leads to a melting temperature range rather than a specific melting temperature. The peak of this range is located at 185 °C but the melt isn’t complete until around 200 °C. To further illustrate this effect and understand how this effects densification, a thermomechanical analysis (TMA) test was run on virgin PA2202 to measure the densification over the melting temperature range.
Figure 4.3: DSC results of PA2202 under nitrogen purge at 5 °C/min. The processing window is identified by the region which is hotter than the recrystallization temperature but lower than the melting temperature. The preheat temperature should be within this window while the sintering temperature must be above the melt temperature.

4.5.2 Temperature Dependency on Densification for PA2202

A TMA measures a dimension change with a linearly variable displacement transducer attached to a probe which contacts the sample. The sample is then heated or cooled while the displacement of the sample is recorded. The powder was placed inside an alumina sample cup and filled to a height of 8.2 mm. The TMA probe was coated with a 2 mil thick high temperature polyimide tape to prevent the probe from being damaged. The probe was then placed on top of the powder column with a force of 0.005 N. This force is sufficient enough to provide high sensitivity
height measurements but not high enough to overcome surface tension forces and sink into the powder when it melts. The sample was then heated at 5 °C/min, slowly expanding, up to 170 °C and then held at that temperature for 30 minutes. The temperature was then ramped up 5 °C and held for another 30 minutes. This process was repeated until 200 °C and the results can be seen in Figure 4.4. Slight densification occurs at 175 °C but with a vast majority occurring at 180 °C. It appears that even if the peak melting temperature of 185 °C (indicated by the melt peak as seen in Figure 4.4) is maintained for extended periods of time, full melting/densification does not occur.

In LS, the powder particles are only exposed to the laser’s energy for microseconds at a time. With this quick exposure, the particles are brought well above their melt temperature, which can

![Figure 4.4: Densification results from virgin PA2202 powder ran on a TMA with 50 ml/min nitrogen purge, a sample height of 8.2 mm in an alumina sample cup, with a 5 °C/min heating rate and 30 minute isothermal holds at 170 °C and every 5 °C above that.](image)

63
degrade the polymer [56, 96]. While this isn’t sufficient time for the polymer to reach full density [88, 97], high strength parts can still be achieved. This is due to PA12 temperature dependence on the zero-shear viscosity.

4.5.3 Zero Shear Viscosity

As previously shown in Equation 4.1, a material’s zero shear viscosity is one of the main driving components in determining if a material will display a high quality of sintering during the printing process. The zero shear viscosity is heavily dependent on temperature and at elevated temperatures, less time is needed to obtain a high strength sintered component due to the decreased viscosity. Further, if an elevated temperature is maintained, the PA12 powder will post-condensate, causing an increase in molecular weight which increases the material’s viscosity [91, 98].

![Graph showing zero-shear viscosity of PA2202 at various temperatures.](image-url)

Figure 4.5: Zero-shear viscosity of PA2202 at various temperatures.
effect can be seen in Figure 4.5. Since the current embodiment of LAPS is only capable of reaching temperatures moderately above the melt temperature of PA12, relatively long exposure times are required (2-5 s compared to tens to hundreds of μs for LS) in order to reach high strength and full density. The viscosity present during sintering is shown for three different temperatures in Figure 4.5. The material viscosity during sintering would be the value near zero time, as there is little change in the viscosity over the few seconds of sintering. It is evident that sintering at higher temperatures produces a lower viscosity melt.

4.6 Results and Discussion

4.6.1 Impact of Target Sintering Temperature

This experiment consists of multiple temperature targets with a constant 2.5 seconds of exposure. Since the projector is only capable of supplying 2.4 W/cm² of intensity, as higher temperature targets are set, it takes progressively longer for the material to reach the target temperature. The temperature target for each set of tensile bars was 185, 190, 200, 205 and 215 ºC. The sintering temperature profile is shown in Figure 4.6 for the case of the highest and lowest temperature targets (185 ºC and 215 ºC) with a 2.5 second exposure time. These profiles show how with lower temperature targets, the temperature is brought to the target temperature quicker than with high temperature targets and have less spatial variation. It also shows that for the higher temperature targets, the projector doesn’t have enough intensity available to bring the material to the target temperature in the specified amount of time.
The results of the tensile testing can be seen below in Figure 4.7 and tabulated with density measurements in Table 4.2.

In order to identify trends, the ultimate tensile strength (UTS), which is the maximum stress the component endured during testing, and elongation at break (EaB), which is a measure of how much the sample stretched with respect to its initial length when it broke (identified as the vertical line at the end of each stress strain curve) were graphed versus the target temperature. These results are shown in Figure 4.8.

Figure 4.6: Temperature profile for the hot and cool pixels indicated in Figure 4.2 for the 185°C and 215 °C temperature target with 2.5 seconds of exposure time.
Figure 4.7: Tensile test results for experiment one, where the exposure time was held constant at 2.5 s and the temperature target was varied between 185 and 215 °C.

Figure 4.8: Temperature profile for the hot and cool pixels indicated in Figure 4.2 for the 195 °C and 205 °C temperature target tests with 8 seconds of exposure time.
While the exposure time was held constant at 2.5s for each sample set, increasing the temperature target shows a general trend of increased density, ultimate tensile strength (UTS) and elongation at break. The hot and cool pixel reference the pixels identified in Figure 4.2 for the hottest and coldest spot along the gauge width center line located in the gauge area.

Table 4.2: Tensile testing and density results for samples created with 2.5s exposures and varying temperature targets. Density values with ± indicate three samples were made for repeatability testing. The hot and cool pixel reference the pixels identified in Figure 4.2 for the hottest and coldest spot along the gauge width center line located in the gauge area.

<table>
<thead>
<tr>
<th>Exposure Time (s)</th>
<th>Temp. Target (°C)</th>
<th>Final Temp. at Hot Pixel (°C)</th>
<th>Final Temp. at Cool Pixel (°C)</th>
<th>Density (g/cm³)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation at Break</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>185</td>
<td>186.2</td>
<td>185.1</td>
<td>0.999</td>
<td>39.30</td>
<td>11.7%</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>187.8</td>
<td>183.2</td>
<td>1.016</td>
<td>42.6</td>
<td>31.1%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>197.5</td>
<td>193.6</td>
<td>1.019</td>
<td>42.4</td>
<td>49.5%</td>
</tr>
<tr>
<td></td>
<td>205</td>
<td>201.5</td>
<td>196.2</td>
<td>1.021</td>
<td>45.1</td>
<td>52.0%</td>
</tr>
<tr>
<td></td>
<td>215</td>
<td>209.3</td>
<td>200.3</td>
<td>1.020 ± 0.002</td>
<td>48.1</td>
<td>88.6%</td>
</tr>
</tbody>
</table>

Figure 4.9: Tensile test results for the constant exposure time of 2.5s with target temperatures varying between 185 and 205 °C.

While the exposure time was held constant at 2.5s for each sample set, increasing the temperature target shows a general trend of increased density, ultimate tensile strength (UTS) and
elongation at break (EaB). The data sheet for the PA2202 lists the UTS at 50 MP, the EaB at 12% and with a density of 0.98 g/cm³ for LS parts. While the resulting UTS for all samples was below that of the data sheet values, the density was higher. This implies that a morphological difference within the material is strongly impacting material properties or that micro pores exist and is an area for further study. Only a few percent porosity is known to have a considerable effect on the mechanical properties of a material, most notably in the reduction of ductility [99, 100]. This occurs because reducing the effective load-bearing cross-sectional area introduces stress concentration sites for strain localization and damage, decreasing both strength and ductility [101-103].

As seen in Figure 4.3 and Figure 4.4, unless the sample reached at least 200 °C it would still have some unmelted regions which could cause porosity. Between the two extreme temperature targets (ΔT = 23.1 °C at the hot pixels) the UTS increases by 22% while the EaB increases by 657% with a density change of just 2%. This suggests that these samples exhibited porosity levels which decreased (increased densification) at higher sintering temperatures.

4.6.2 Impact of Exposure Time

In experiment two, two different target temperatures (195 °C, 205 °C) are used while the exposure time is varied from 1.5 s to 8.0 s for a total of 10 parameter sets. During these tests, the desired tensile bar shape is projected onto the powder, bringing the powder up to the specified target temperature and maintaining that temperature for the remaining sintering time. The specified
sintering time includes both the heat up and isothermal hold periods. The resulting temperature profile for both the 195 °C and 205 °C target temperature cases are shown in Figure 4.9.

The results seen in Figure 4.9 are for the eight second trials, and final temperatures of the other trials are similar to those found at those respective times in the longer eight second test. For these tests, at approximately one second, the projector overestimates how much it needs to reduce the intensity by, resulting in a ripple. The PID control of the projector makes up for this but takes approximately two and four seconds for the target temperature to be reached in the hottest and coolest areas for the 195 °C target temperature respectively. When the target temperature is 205 °C, this occurs at three seconds for the hottest pixel and five seconds for the coolest pixel. This varies slightly for each test as the PID control adjusts the intensity as it approaches the target. When insufficient sintering time is defined, the projector isn’t able to bring the powder up to the target temperature. The resulting tensile test results are shown above in Figure 4.10 and the results are tabulated with the density measurements below in Table 4.3.
Figure 4.10: Tensile test results for specimens created with 1.5 to 8 s exposure times with a constant target temperature of top) 195 °C and bottom) 205 °C.
When the temperature target is maintained constant in these tests and the exposure times are varied between 1.5 s to 8 s, the density, UTS and EaB all increase with increasing exposure time. These results show that the UTS increases by 29% and 23% respectively for the 195 and 205 °C temperature target tests while the EaB exhibits an increase of over 9x and 6x respectively. This is due to the large range in resulting temperatures which resulted in a large range of sintered quality based both on sintering time and the reached temperature. In the case of 1.5 seconds of exposure, parts of the gauge area on the tensile bar didn’t even reach the melt temperature peak. These porous areas would act as strain concentrators and would most likely be the first place to fail, resulting in a low UTS and EaB. This large change in material properties occurs with only a 1-2% change in density of the material. This could be due to differences in porosity but may also be caused by morphological differences. However, these results do show that in all cases, EaB values above the 12% listed in the PA2202 data sheet for LS parts was achieved and confirms that extended exposure times above what is typical in LS creates highly ductile parts with increased toughness.
By viewing the trends present in Figure 4.11, it appears that the UTS and EaB increase at a reduced rate with longer exposure times, particularly in the case of the 205 °C temperature target tests. This could be due to the component reaching its highest quality of sintering and full density which would occur at lower viscosities (higher temperatures). While some density difference could be present due to varying degrees and types of crystallinity, future work would need to directly identify the porosity levels in these samples to confirm this. These results suggest that using a lower temperature target is more effective at creating a high quality part due to the minimal change in UTS but highly increased EaB at longer exposure times. This could be due to differences in the

<table>
<thead>
<tr>
<th>Exposure Time (s)</th>
<th>Temp. Target (°C)</th>
<th>Final Temp. at Hot Pixel (°C)</th>
<th>Final Temp. at Cool Pixel (°C)</th>
<th>Density (g/cm³)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation at Break</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>195</td>
<td>187.8</td>
<td>183.4</td>
<td>1.009</td>
<td>40.10</td>
<td>15.4%</td>
</tr>
<tr>
<td>2</td>
<td>195</td>
<td>191.3</td>
<td>186.3</td>
<td>1.010 ± 0.003</td>
<td>43.10</td>
<td>39.5%</td>
</tr>
<tr>
<td>3</td>
<td>195</td>
<td>194.1</td>
<td>192.2</td>
<td>1.022</td>
<td>45.40</td>
<td>57.2%</td>
</tr>
<tr>
<td>5</td>
<td>195</td>
<td>198.6</td>
<td>195.6</td>
<td>1.031 ± 0.004</td>
<td>47.60</td>
<td>117.2%</td>
</tr>
<tr>
<td>8</td>
<td>195</td>
<td>199.2</td>
<td>196.9</td>
<td>1.026 ± 0.006</td>
<td>51.70</td>
<td>163.1%</td>
</tr>
<tr>
<td>1.5</td>
<td>205</td>
<td>189.2</td>
<td>183.4</td>
<td>1.016</td>
<td>40.20</td>
<td>17.1%</td>
</tr>
<tr>
<td>2</td>
<td>205</td>
<td>192.8</td>
<td>184.0</td>
<td>1.017</td>
<td>41.20</td>
<td>53.5%</td>
</tr>
<tr>
<td>3</td>
<td>205</td>
<td>201.1</td>
<td>192.4</td>
<td>1.019 ± 0.001</td>
<td>44.20</td>
<td>60.3%</td>
</tr>
<tr>
<td>5</td>
<td>205</td>
<td>206.8</td>
<td>204.2</td>
<td>1.021 ± 0.004</td>
<td>50.20</td>
<td>101.8%</td>
</tr>
<tr>
<td>8</td>
<td>205</td>
<td>209.7</td>
<td>207.0</td>
<td>1.026 ± 0.006</td>
<td>49.40</td>
<td>122.7%</td>
</tr>
</tbody>
</table>

Table 4.3: Tensile properties and density for a target temperature of 195°C and 205°C with varied exposure times from 1.5 to 8 s. Density results with a ± symbol indicates three density samples were created with this parameter set for repeatability testing. The hot and cool pixel reference the pixels identified in Figure 4.2 for the hottest and coldest spot along the gauge width center line located in the gauge area.
degree of melting and the following cooling conditions. Further work is needed to characterize the resulting structures to further investigate these differences.

Figure 4.11: Tensile test results graphed against exposure time for the UTS (top) and EaB (bottom).
4.6.3 Impact of Open Loop Control

For experiment three, the tensile bars were created using a target temperature of 500 °C with sintering times between 1.5 s to 4 s. Since the projector is not able to bring the powder to this temperature, it effectively applies the full intensity of light (average of 2.4 W/cm²) to the entire desired area and does not reach the levels required to use the feedback control loop. Since the feedback control loop wasn’t used, irregular heating and cooling patterns occurred. This can be viewed in the resulting temperature profile shown in Figure 4.12. For these tests, an upper temperature limit was not achieved as this would take exceedingly long periods of time. After approximately six seconds of exposure, the melt pool spread extensively and a gauge area with a constant length couldn’t be formed due to the growth of the melt pool in those areas. This demonstrates the benefit of the closed loop control and ability to sintering at lower temperatures as seen in the previous experiments.

The resulting tensile properties, temperatures and density are recorded in Figure 4.13 and Table 4.4. As seen in the previous experiment, increased exposure time leads to both increased density, UTS and EaB. However, the final temperatures in these experiments are much higher than in the previous experiments and with a larger variation in temperature throughout the part. In the previous experiments, as the temperature of the powder approaches the target temperature, the heating rate
slows down. In this case, the powder is heated with the full intensity for the duration of the test.

When compared to the previous tests, the resulting temperatures are considerably higher.

Figure 4.1212: Temperature profile during the application of 2.4 W/cm² of light for 4 seconds of exposure time.
Additionally, the change in EaB (ΔEaB = 87%) over the density range (Δρ = 2%) is much less than with the previous experiments. These parts reached higher temperatures quicker and had less time to sinter when compared to previous tests at similar temperatures, resulting in a lower quality part.

Figure 4.13: Tensile test results for the full intensity tests with exposure times from 1.5 to 4 s.
When graphing the tensile results versus the exposure time as seen in Figure 4.14, it is difficult to correlate a trend for UTS or EaB. The density measurements follow the expected tendency; increasing exposure time leads to increased density but does not fit with the measured UTS and EaB as was found with the previous experiments. This is most likely due to the large variation in heating and cooling conditions caused by the lack of PID control and/or the creation of all 3 samples in each build. Due to the small exposure area, each sample was created in a separate exposure within a single build. This means that compared to making one sample at a time, these samples went through different thermal conditions as each had varying amounts of time to cool before or after being fused. This may be the reason behind some of the large scatter bars and

Figure 4.13: Tensile results versus the 1.5 to 4 seconds of exposure time when the intensity is set to the maximum 2.4 W/cm² for the sintering duration.
change in trends. Future work should be completed here to remove the additional variable between each test, and remake these samples with a single part in each print.

Table 4.4: Tensile and density properties for the full intensity tests without a control loop and 1.5 to 4 s exposure times. The hot and cool pixel reference the pixels identified in Figure 4.2 for the hottest and coldest spot along the gauge width center line located in the gauge area.

<table>
<thead>
<tr>
<th>Exposure Time (s)</th>
<th>Power Flux (W/cm²)</th>
<th>Final Temp. at Hot Pixel (°C)</th>
<th>Final Temp. at Cool Pixel (°C)</th>
<th>Density (g/cm³)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation at Break</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.4</td>
<td>193.8</td>
<td>187.9</td>
<td>1.005</td>
<td>45.4 ± 0.8</td>
<td>36.3%</td>
</tr>
<tr>
<td>1.75</td>
<td></td>
<td>196.0</td>
<td>189.0</td>
<td>1.007</td>
<td>47.1 ± 1.5</td>
<td>21.2%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>197.3</td>
<td>188.8</td>
<td>1.009</td>
<td>44.9 ± 0.1</td>
<td>17.8%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>223.4</td>
<td>209.5</td>
<td>1.025</td>
<td>48.9 ± 0.7</td>
<td>67.7%</td>
</tr>
</tbody>
</table>

4.7 Conclusion

It is well understood that sintering rates depend strongly on both time and temperature but in LS systems, the sintering temperature wildly fluctuates which makes the direct application of current sintering models difficult. Further, only the input laser power or energy can be defined. This work evaluated the effect of both time and temperature in situ of a novel large area sintering process capable of directly controlling these variables. It has been shown that full melting and possibly densification does not occur until the end of the melt peak (200 °C for PA2202). Resulting small changes in density (1-2%) displayed moderate changes in UTS but with a drastic change in EaB. Tensile testing of samples with various exposure times and temperature targets revealed that a higher toughness may be achieved with longer exposure times and lower temperature targets. Additionally, closed loop PID control of the sintered part demonstrated a higher quality of sintering
is obtained over applying the full intensity. Future work will need to address the effect of the crystal polymorphs on the mechanical properties of these parts and how they can be controlled.
CHAPTER 5: COMPARISON OF BUILD RATES FOR POLYMER POWDER BED FUSION TECHNOLOGIES

5.1 Abstract

Additive manufacturing (AM) is establishing itself as a staple in many industries and is becoming the go-to technology when a limited number of prototypes or end-use parts are required quickly. One such technology that is driving this transition, is powder bed fusion, a classification of additive manufacturing that uses a powdered feedstock. Powder bed fusion technologies are seeing many new innovations from a large variety of companies and research institutions alike. When trying to compare these systems it can often be a difficult task due to the lack of standards for reporting system specifications. The system specifications are commonly reported differently and can be misleading to the viewer. This work addresses this issue by providing a method to evaluate three different types of powder bed fusion technologies, laser sintering (LS), Multi Jet Fusion/High Speed Sintering (MJF/HSS), and a new technology capable of sintering entire layers simultaneously, Large Area Projection Sintering (LAPS). These technologies are evaluated on the basis of feasibility with respect to the desired build rates and exposure times. LS was found to be the most efficient when creating parts that have a low volumetric fill ratio (such as hollow objects or lattice structures) but is incapable of reaching build rates to that of MJF/HSS or LAPS for large
areas and/or with high volumetric fill ratios. LAPS is shown to provide the highest build rates with large areas and is capable of economical build times when a material requires extended exposure times. However, it is shown that overcoming the feasibility of the required power levels for fusing large areas will be difficult and it is here that MJF provides the best method for achieving high build rates.

5.2 Introduction

Additive Manufacturing (AM) is breaking the paradigm of traditional manufacturing and is truly a disruptive technology to the industry. This is because AM has many advantages to offer a consumer over traditional manufacturing methods, such as the ability to create highly complex objects, rapidly manufacture prototypes and functional end use components, and reduce inventory and waste to name a few [9, 104]. AM is impacting almost every industry and it’s for these reasons that AM is experiencing compound annual growth rates of 34% over the last four years [4]. Much of this growth is based on the transition from prototyping to true manufacturing of parts. However, when transitioning into true manufacturing applications, machine throughput is a major driver to the production cost of the components. Powder bed fusion technologies have great potential to contribute in this space due to high mechanical properties and fast production rates.

Powder bed fusion technologies utilize a bed of powdered material which is often preheated. Then, a laser or other energy source imparts heat to bring the powdered material above its melting point, fusing it into the desired cross section. A new layer of powder is then deposited and recoated
to a uniform thickness with a blade or counter rotating roller. In the case of metal powder bed fusion technologies which directly melt the metal particles during printing, support structures are needed to prevent high internal stresses from warping the part [105]. For polymer powder bed fusion, unfused powder acts as a support structure for subsequent layers so no post processing is required to remove posts or physical supports from the models. Without support structures, the entire print volume can be utilized as components can be placed anywhere in the 3D build volume without interfering with support structures for other parts.

These technologies typically have a high build rate when compared to other AM technologies because of the high speed of powder spreading and many fusing methods [10, 11, 86, 106]. However, there has been little examination of the potential build rates of these processes. This paper develops equations to predict the scaling rates as a function of scaling parameters. The powder bed fusion technologies that will be evaluated in this work is Large Area Polymer Sintering (LAPS), Laser Sintering (LS) and Multi Jet Fusion (MJF)/High Speed Sintering (HSS). These processes are briefly summarized below.
Laser Sintering (LS) is a commonly used industrial AM technology which has the capability of creating strong components with high detail. LS uses a high power laser which is typically focused to a 0.2-0.4 mm spot [107-109] and steered across the powder bed using mirror galvanometers. The laser fuses material as it is scanned and must raster the entire cross section to create a fused layer. Since LS only fuses material at a single point which must be scanned over the entire powder bed, it is considered a pointwise technology [9]. An example schematic can be viewed in Figure 5.1.

Figure 5.1: Schematic of laser sintering, a point-wise AM technology.
Multi Jet Fusion (MJF) and High Speed Sintering (HSS) are two similar technologies that use a bed of powdered polymer that reflect away incident light energy. An inkjet print head scans over the powder bed, printing the desired cross section into the powder using a radiation absorbing ink. A linear lamp is then scanned over the powder bed, fusing only the areas which contain the radiation absorbing ink. MJF and HSS are considered line-wise technologies [9] as they fuse powder along a line which is scanned over the powder bed. These technologies sinter at time scales orders of magnitude larger than LS and are shown schematically in Figure 5.2. This may contribute to the more complete melting of the powder particles [64, 68], increased density [110], and higher elongation to failure [111] compared to LS.

![Diagram of MJF and HSS](image)

Figure 5.2: Schematic of Multi Jet Fusion and High Speed Fusion, similar line-wise AM technologies.
Large Area Projection Sintering (LAPS) is a relatively new technology developed at the University of South. LAPS uses a high intensity projector to project an image of the desired cross section on the powder bed. The high intensity light fuses the powder while adjacent unexposed areas don’t absorb any incident light. LAPS falls under the layer-wise AM category [9] as it is capable of fusing entire layers simultaneously as seen in Figure 5.3.

![Schematic of Large Area Projection Sintering (LAPS)](image)

Figure 5.3: Schematic of Large Area Projection Sintering (LAPS), a layer-wise AM technology.

LAPS is the only technology evaluated herein that is not commercially available. LAPS is currently a lab based technology which has proven the ability to successfully sinter PA2202, which
is a dark colored polyamide-12 (Nylon-12, PA12) produced by EOS [1] for laser sintering. The current LAPS system (Figure 5.3) consists of a heated build chamber and build volume, a recoating hopper and blade, an IR camera to observe the sintering region and a modified X341 Optoma projector. The projector has been modified to concentrate the light from a maximum diagonal image size of 7.73 m (4:3 aspect ratio) to 2.64 cm and the intensity of the light was increased from approximately 3.1 W to 9.8 W as measured by a Thor Labs S310C thermal power sensor. Overall, this provides an increase in the intensity of the light by 2,650 times, making it an effective tool to spatially control the thermal profile over the current 1.6 cm x 2.1 cm exposure area. This system typically uses exposure times from approximately two to five seconds which minimize high local temperature gradients, known to cause warping and possibly even material degradation [96].

As a user evaluates different polymer powder bed fusion technologies for use in various applications, it can often be difficult to compare systems from different companies. This is because each manufacturer chooses to report the machine specifications differently. Build rates, which defines how much material can be formed over time, are typically not reported. If they are, the conditions under which that number was found is not supplied and can be misleading to reviewers.

LS has been around since the late 1980’s [112] and has been well documented in literature. LAPS and MJF are relatively newer technologies and little research has been conducted in the academic community. However, even with LS, no standard has been developed for reporting the
build rate. This work details a method to use commonly reported specifications to calculate build rates for LS, MJF and LAPS for a quantitative comparison.

5.3 Build Rates

As AM is beginning to shift towards producing large quantities of parts, the build rate becomes an important factor. As higher build rates are achieved, large numbers of components can be created quickly, making them more economical.

The build rate is a significant specification which can be used to evaluate different systems. For this work, the build rate is defined as the amount of material that can be fused per unit time for a given geometry. The amount of material that can be fused in a specific amount of time varies depending on both the technology and what is being printed. For example, when using LAPS or MJF, the time it takes to complete a layer is nearly independent of the cross sectional area of the part, but for LS, the build rate is highly dependent on the area of the cross section of each layer as the laser needs more time to traverse the larger area. To achieve the highest build rates with MJF or LAPS, 100% of the build volume should be used (a solid cube the size of the build volume), but LS is more competitive for low area fills.

The ideal part size to be printed for the highest build rate depends on the ratio of recoating time versus time spent sintering. This means that LAPS and MJF are most likely to be fastest when large area fractions must be fused, otherwise LS may complete a layer in the least amount of time. Since the build rate is dependent on what is being printed, it is important to know the conditions
used to determine the build rate. However, build rates aren’t commonly reported and if they are, the build conditions are not listed [10, 11, 86, 107].

This study will propose a relationship to predict the maximum build rate achievable by each system given a few basic parameters. This can be useful for comparing existing systems or evaluating the tradeoffs between competing technologies. The build rate can be calculated as the total volume of parts \( V_{total} \) printed divided by the length of time it takes to print them \( T_{total} \). The occupied volume of all of the parts is determined by:

\[
V_{total} = V_{build} \cdot \varepsilon
\]

where \( V_{build} \) is the maximum build volume and \( \varepsilon \) is volume fill ratio, or the ratio of the volume occupied by the parts divided by the build volume and varies between zero to one. Alternatively, when printing large batches of a single part, \( V_{total} \) can be calculated as:

\[
V_{total} = \left( \frac{H_{BV}}{H_p} \right) \cdot \left( \frac{W_{BV}}{W_p} \right) \cdot \left( \frac{L_{BV}}{L_p} \right) \cdot V_p
\]

where \( V_p \) is the volume occupied by the part, \( H_{BV} \), \( W_{BV} \) and \( L_{BV} \) represent the height, width and length of the build volume respectively. \( H_p \), \( W_p \) and \( L_p \) represent the part’s bounding box height, width and length respectively. Each of these fractions represent the number of parts which fit along their respective axis and together represent the total number of parts which fit inside the build volume.
In a real system, the number of parts which fit into each build dimension should be rounded down to the nearest integer because only a discrete number of parts will fit along the respective axis. This study assumes basic part packing where each part is arranged parallel to each other and in a simple side-by-side 3D array where the bounding box of each part has no gap between it and the adjacent bounding boxes. To take part spacing into account, the space desired on each side of the bounding box should be added to the dimensions of the bounding box (for example $H_p = H_p + \text{spacing}$) to calculate the number of parts which fit along each dimension. Then, the number of parts are multiplied by the volume of each part. Part spacing can have a significant effect on the maximum achievable volume fill ratio and therefore, build rates. In actuality, some systems use more complex part packing algorithms which will change the angle of each part in all 3D dimensions to fit the maximum number of parts. The total time it takes to print each layer can be determined by the following equation:

$$T_{total} = \frac{H}{t} \cdot (T_{recoat} + T_{sinter})$$

Equation 5.3

where the first fraction represents the total number of layers in a print, represented by the total height of all of the parts in the build volume plus any unprinted height represented as $H$, divided by the layer thickness ($t$).

The time required to sinter each layer for a technology is given below their respective subsequent sections. The length of time it takes to sinter each layer differs between each
technology. In this work, it will be assumed that a similar recoat speed will be used for each technology as the recoating methods are similar and was calculated with the following equation:

\[ T_{\text{recoat}} = T_d + \frac{W_{\text{BV}} + W_{\text{recoater}}}{v_{\text{recoat}}} \]  

Equation 5.4

where \( W_{\text{recoater}} \) is the width of the recoating carriage plus any features off the bed that must be traversed during spreading, and \( T_d \) represents dead time, or time not spent spreading a layer. This occurs when new powder is being deposited in front of the blade/roller or during a pause between the sintering and spreading. In this work, \( T_d \) is taken as 2.15 seconds which was calculated empirically from videos of the spreading process [113, 114]. \( V_{\text{recoat}} \) is the velocity of the blade/roller assembly which uniformly spreads a new layer of powder. The width of the build volume (\( W_{\text{BV}} \)) dimension is the axis of which the recoating mechanism spreads a new layer of powder and is assumed identical for each technology for the purpose of comparison.

### 5.3.1 Laser Sintering

In laser sintering (LS), the laser is scanned with high speed mirror galvanometers which are capable of changing speeds and direction extremely quickly. To achieve uniform sintering, the laser must expose each area of powder for a similar time period and is achievable by having a constant velocity while sintering the powder. Given the fast scan speeds and quick accelerations, a constant velocity is assumed. Travel moves of the laser, when the laser is moving from one location to another without sintering, are also neglected.
The important variables which effect both the print quality as well as the build rates include the laser beam size, scan speed and hatch spacing (distance between each scan line). Larger beam sizes can sinter more material with each pass but the minimum feature size is increased. The scan speed determines the exposure time of the powder. As the laser is scanned at higher rates, a higher laser power is required in order to elevate the temperature of the powder above its melt temperature. Andrew’s number \( (A_n) \), a measure of input energy density [67], is used to correlate beam velocity \( (v) \), hatch spacing \( (HS) \) and laser power \( (P) \) with the following equation:

\[
A_n = \frac{P}{v_{beam} \cdot HS}
\]

Equation 5.5

As the hatch spacing is reduced, more energy is imparted to the build area due to an increase in beam overlap. Beam overlap is necessary to assist the fusing together of each scan line [74]. Starr et al. [63] has shown that an ideal energy density of 0.018 and 0.025 J/mm\(^2\) exists for 0.1 mm and 0.15 mm layer thicknesses respectively. There is a range of speed, power and hatch spacing parameters which can be changed while maintaining a constant Andrew’s number to produce similar sintering results [67].

In order to calculate the build rate in laser sintering the amount of time it takes to sinter a layer \( (T_{sinter,LS}) \) must first be found:

\[
T_{sinter,LS} = \left( \frac{V_{part}}{v_{beam} \cdot HS \cdot t} \right) \left( \frac{t}{H_{part}} \right) = \left( \frac{V_{part}}{v_{beam} \cdot HS \cdot H_{part}} \right)
\]

Equation 5.6
The first term calculates the total sintering time and the second divides by the number of layers to find an average sintering time per layer for consistency with the other process formulations. For convenience of comparing different laser beam diameters, the hatch spacing (HS) can be assumed to be 1/4 of the laser beam size [115-117] and is discussed in section 5.4.1 in more depth.

5.3.2 Multi Jet Fusion

In current commercial MJF systems, a carriage containing two linear heat lamps and the inkjet print heads are scanned over the build area. This has the effect of scanning the print bed with a linear lamp once, printing the radiation absorbing ink and scanning a lamp over the bed three more times. All of these processes are captured in the time it takes to sinter a layer \( T_{\text{sinter,MJF}} \) as seen below:

\[
T_{\text{sinter,MJF}} = 2 \cdot \frac{W_{\text{BV}} + W_{\text{edges}}}{v_{\text{carriage}}}
\]

Equation 5.7

where \( T_{\text{sinter,MJF}} \) is represented by the time it takes for the carriage moving at velocity \( V_{\text{carriage}} \), to cover the distance of the width of the build volume \( W_{\text{BV}} \) and width of the edges \( W_{\text{edges}} \) that the carriage must pass as well. This is multiplied by two because the carriage scans the build area twice for every layer. In this work, it is assumed that if the bed area is increased, the width of the edges and the velocity of the carriage will stay constant. It was found that the carriages moves at approximately 40 cm/s and the width of both edges are approximately 816 mm.
5.3.3 Large Area Projection Sintering

For LAPS, the time to sinter is independent of all other variables and is equal to the set exposure time for the powder bed. From previous work using PA2202, four seconds of sintering time with an intensity of ~2.5 W/cm² was found to produce quality layers. For the demonstration LAPS system, the sintering consists of two steps. First, a preheat \( T_{\text{preheat}} \) exposure, where the projector preheats the exposure area to the proper temperature and eliminates temperature gradients. Once preheated, the desired image is projected for a specified time \( T_{\text{exposure}} \), completing the sintering process for that layer as seen in Equation 5.8:

\[
T_{\text{sinter,LAPS}} = T_{\text{preheat}} + T_{\text{exposure}}
\]

Equation 5.8
5.4 Discussion

By graphing the build rate for each of the three technologies, additional insight into the effects of various machine specifications and print parameters can be gained. These graphs provide useful information into design considerations for LAPS, LS and MJF. For each of the following discussion points, the parameters in Table 5.1 were used unless otherwise stated.

Table 5.1: Assumed machine parameters unless otherwise stated.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Build height</td>
<td>H\text{BV}</td>
<td>310</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Layer thickness</td>
<td>t</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Recoater velocity</td>
<td>v\text{recoat}</td>
<td>109</td>
<td>mm/s</td>
</tr>
<tr>
<td></td>
<td>Dead time</td>
<td>T\text{d}</td>
<td>2.15</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Width of recoater</td>
<td>W\text{recoater}</td>
<td>75</td>
<td>mm</td>
</tr>
<tr>
<td>LS</td>
<td>Beam velocity</td>
<td>v\text{beam}</td>
<td>6000</td>
<td>mm/s</td>
</tr>
<tr>
<td></td>
<td>Beam diameter</td>
<td>d</td>
<td>0.4</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Hatch spacing</td>
<td>HS</td>
<td>0.3</td>
<td>mm</td>
</tr>
<tr>
<td>MJF</td>
<td>Edge width</td>
<td>W\text{edges}</td>
<td>820</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Carriage velocity</td>
<td>v\text{carriage}</td>
<td>400</td>
<td>mm/s</td>
</tr>
<tr>
<td>LAPS</td>
<td>Preheat time</td>
<td>T\text{preheat}</td>
<td>2</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Exposure time</td>
<td>T\text{exposure}</td>
<td>4</td>
<td>s</td>
</tr>
</tbody>
</table>

Build rates over an increasing build area are shown in Figure 5.4 and shown at various fill ratios for each of the technologies. The sintering time is independent of bed area for both LAPS and MJF and thus the build rate increases with a mostly linear trajectory. There is a slight curvature in the build rate estimations due to the marginally increased time to recoat and sinter a layer with...
progressively larger build volumes. For LS, it is the most time effective technology when printing small cross sectional areas (low fill ratios) such as a low density lattice structure or hollow structure. As the cross sectional area increases, the time to sinter a layer increases by the square of that increase in area. With a 5\% volume fill ratio, this occurs with LAPS and MJF when the bed area reaches approximately 700cm\(^2\) (~26x26cm). It becomes increasingly efficient to use LAPS or MJF as the bed area increases to larger values. When considering 50\% volume utilization, MJF and LAPS are quicker than LS over areas larger than just 65 cm\(^2\) (~8x8cm ).

To evaluate the upper build limit of each technology, the volume fill ratio is set to unity, with the results shown in Figure 5.5. While the build rate asymptote for LS is reached much quicker,
the build rate for LAPS and MJF is many times higher because a much larger volume is sintered in the same amount of time. As previously mentioned, the build rate increases at an almost linear rate as the build area is increased due to the layer sintering time being independent of the area being sintered. This occurs with MJF even though it takes longer to sinter a layer as the width becomes larger. The lost time is made up as additional area is added to the length, causing the build rate to increase further. MJF provides a quicker build rate due to the short exposure times used for smaller areas but as the area is increased, LAPS becomes the most efficient at approximately 1500 cm$^2$ (~39x39cm). This is because MJF must scan the entire build area every layer, increasing the time spent sintering as the build area increases. The LS build rate has a logarithmic increase up until approximately 200 cm$^3$/hr where it approaches an asymptote. This occurs because as the length and width increases linearly, the area to be covered by the laser increases by the square of that increase. This makes it progressively more time prohibitive as the exposure area increases.

5.4.1 Laser Sintering

LS includes a few variables which are not related to LAPS or MJF but can have a considerable effect on the build rate. In LS, the beam diameter is defined by the optics within the system and typically are not dynamically adjustable but different systems come with a variety of beam sizes. The beam velocity and hatch spacing are machine settings, which for most LS technologies, can be changed for each build or varied within the print process itself.
Both the beam diameter and hatch spacing determine the number of scan lines required to complete a layer. The limit of the hatch spacing is dependent on the beam diameter. If the hatch spacing is larger than the beam diameter, then unexposed powder will exist between the layers, producing an undesirable effect, as this would decrease the mechanical properties. If the hatch spacing is less than the beam diameter then there will be overlap for each scan line, leaving an area which is exposed twice. This is a desirable effect as it fuses each of the scan lines together. The beam overlap is defined as the beam spot size (calculated in Equation 5.9) minus the hatch spacing distance which is typically 1/4 of the beam spot size [115-117]. It is evident from Figure 5.6, which uses the variables in Table 5.1 and only changes the one respective variable for each line, that as the beam diameter increases, the build rate also increases as more material can be sintered for each

Figure 5.5: Build rate as a function of bed area when the entire volume is filled, representing the upper build limit for each technology.
pass of the laser and less scan paths are required. Increasing the beam velocity also increases the build rate but with a lesser effect because in the defined range, the overall change in velocity is smaller than the overall change in the number of scan lines produced. By increasing the beam diameter or decreasing the beam velocity, the exposure time is increased and can be calculated with:

\[ T_{\text{exposure,LS}} = \frac{d}{v_{\text{beam}}} \]

Equation 5.9

where \( d \) is the diameter of the laser beam and \( v_{\text{beam}} \) is the scan velocity of the beam. Most lasers in LS exhibit a Gaussian distribution. Therefore, the diameter of the beam is typically taken as the diameter at which the intensity of the beam has decreased to approximately \( 1/e^2 \) (\( \approx 13.5\% \)) [118].

In order to obtain exposure times similar to that of LAPS or MJF, LS would require extremely slow scan speeds (<0.1 mm/s) which would lead to astronomical build times. Alternatively, a very large beam spot size could be used but this would require a high power laser and would produce very poor quality parts due to the inability to make small features.
When scaling up the build area (X and Y dimensions), the area covered by these dimensions increases by the square (X times Y) of the dimension change. This can be viewed in Equation 5.10 and Figure 5.7, where the current intensity of the light is approximately 2.5 W/cm$^2$.

$$P_{optical} = W \cdot L \cdot I = W^2I$$  

Equation 5.10
where \( P_{\text{optical}} \) is the required optical power (Watts) to reach an intensity of \( I \) (W/cm\(^2\)) over an area of width (W, cm) times length (L, cm). To simplify the description for explanation, the width is set equal to the length in this work. Further, \(~1.5 \) W/cm\(^2\) has been identified as the lowest intensity which can sinter quality parts.

![Graph showing optical power requirements](image)

Figure 5.7: Example of how scaling over an area impacts the required optical power at the sintering plane as the build edge width (width=length) increases for multiple exposure intensities.

While Equation 5.10 and Figure 5.7 show how much optical power is required, this does not take into account the efficiency of the lamp or light path, which occurs as the light is homogenized, focused, shaped, and filtered. In the current setup with the X341 projector which uses a 195W lamp, the efficiency from lamp input power to optical power out of the lens is 5% with a brand new lamp. However, with higher end lamp based projectors, it may be possible to achieve a higher
efficiency. To see how this effects the required lamp power, the required optical power is divided by the efficiency of the light path. When taking this into account, the resulting required lamp power can be seen in Figure 5.8.

With the application of Equation 5.10 and considering light path and lamp efficiencies, Figure 5.8 demonstrates that the biggest limiting factor of layer-wise technologies is that to keep the intensity of the light the same when doubling the exposure area, four times the intensity is required due to the physics of scaling [119]. The required intensity of the light source becomes increasingly prohibitive, if not impossible, to directly scale-up LAPS to larger build areas.

![Figure 5.8: Required lamp power for the lowest working intensity of 1.5 W/cm² as a function of build area edge length (width = length).](image)

**5.4.3 Implications for Future Development**
In this work, various parameters have been shown to have an effect on both build rate, build time and in the case of LAPS, the required optical and source power. However, while the process can be optimized for the maximum build rate, this is not always feasible. In the case of LAPS, the ideal system would be extremely large to maximize the build rate. However, since the required power increases by the square of the increased bed dimensions this is not feasible. Furthermore, the required power from the light source vastly increases when the efficiency of the light path is considered. Some of the highest end, most powerful lamp based projectors available today use 6-7 kW Xenon lamps. Assuming these projectors are capable of transferring 10% of the electrical power of the lamp to the screen as light, this leaves 600-700 W of optical power. In order to maintain the minimum intensity to sinter a part of 1.5 W/cm$^2$, this implies that the largest area that can be sintered is 467 cm$^2$ or a build area that measures ~22x22 cm. For a more ideal intensity of 2.5 W/cm$^2$ this leaves an area of 280 cm$^2$ or a build area that measures ~17x17 cm. While this area represents an area much smaller than most commercial machines [11, 86], it also represents the base case scenario and the cost of the projector alone may make this cost prohibitive.

One advantage offered by LAPS is that a sintering temperature can be maintained for any length of time. This could provide sufficiently long sintering times to sinter many materials which are currently difficult with powder bed fusion technologies and is shown for a variety of exposure times in Figure 5.9. LAPS is compared to an EOS Formiga P100, which is an entry-level industrial LS, an EOS P500 which is quoted as a high productivity system and an HP MJF 3D 3200 which a relatively new system aimed at high production rates. The build rate for each system was developed
from their respective specification sheets and is listed as the highest achievable build rate [11, 120, 121]. For LAPS, high build rates can be achieved with short exposure times, however, the most notable feature is that economical build rates can still be reached, even when using extremely long exposure rates, such as 30 seconds. While the build rates are still not considerably high, the ability to fuse materials which is currently impossible with other powder bed fusion technologies could be a great benefit to LAPS. Again, however, the primary difficulty to overcome in this situation is reaching the required intensity levels over such a large area.

For LS, as seen in Figure 5.4 and Figure 5.6, as the ratio of the area to be sintered to the build area becomes larger, the asymptote of the build rate is reached at a quicker pace. This means, that

![Graph showing build rates for LAPS with various exposure times compared to existing AM systems.](image)

**Figure 5.9:** Build rates for LAPS with various exposure times compared to existing AM systems.
as the build area or area to be sintered is further increased, the build rate will only marginally increase and at very large sizes, it becomes time prohibitive for these large builds. It can be seen that the benefit of increased build area on build rate strongly subsides after a build area of approximately 1000 cm$^2$ or ~31x31cm is reached.

Further insight can be gained by analyzing the process limitations on a fundamental level, where the technology is broken down to its fusing mechanism and analyzed by how much material is fused per unit of time. By plotting these conditions from the quickest exposure times capable by each of the technologies (10 μs LS and 2 s for LAPS & MJF) to 30 seconds, the related build rates can be found with various exposure areas. These results are shown in Figure 5.10. The commonly used PA12 powder has been successfully sintered over a large range of exposure times.

![Figure 5.10: Fundamental fusing rates for LS, MJF and LAPS over their feasible exposure times with their exposure area (for LS the beam diameter is listed for comparison).](image)

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(microseconds to seconds and longer). This is due largely to their thermal stability and low viscosity when melted. However, most other materials which don’t have a sharp melt transition are difficult to sinter with conventional LS due to the material’s affinity to bind together during preheating and requires extended exposure times to densify.

As shown in Figure 5.10, the rapid scanning speed of the laser makes it economical as long as the scan speed is kept high (low exposure time) and can achieve higher fusing rates than MJF or LAPS. However, to reach exposure times similar to those in LAPS and MJF, even with a one millimeter beam diameter and two seconds of exposure, the laser scan velocity must be slowed down to less than 500 μm/s. This brings the build rate to levels which are almost useless unless very small parts are desired. MJF and LAPS scale well as they are able to provide reasonable build rates even when the exposure time is drastically increased. LAPS shows the most promise for producing parts quickly with materials that require extended sintering times. LAPS becomes even more beneficial as the build area is increased. However, as shown previously, achieving these exposure areas would be a difficult task.

MJF, a line-wise AM technology, scales to larger sizes most efficiently as the required power, build rate and build time only increases at a linear rate. Since MJF only has a higher build rate with high volume fill ratios, it would be most useful to those who primarily print large volume parts or batch prints of many smaller parts which take up a large portion of the build volume.
5.5 Conclusion

This work evaluated three different powder bed technologies which encompassed a technology from each of the layer-wise (LAPS), line-wise (MJF) and point-wise (LS) categories. A system of equations was presented to provide build rate estimations based on various machine specifications and print parameters. The resulting build rates and physical requirements were then investigated for feasibility. The point-wise technology, LS, was found to provide the highest build rates for low volumetric fill ratios and moderately sized build areas. However, LS was found to approach an asymptotic build rate limit which is reached at quicker rates as the cross sectional area increases.

For batch prints where many components or large components fill a large volume, LAPS and MJF provide the highest build rates, with LAPS being slightly higher at large build areas. However, as the required power was shown to increase by the square of the build area increase, a physical limit is reached around 280-467 cm^2 with existing projection technology. LAPS gains its true advantage of providing economical build times when extended sintering times are required, such as would be needed to fuse materials with a high zero shear viscosity. MJF was shown to provide both high build rates and a feasible scaling model to reach large build volumes. These results provide a universal approach to compare powder bed fusion technologies on the basis of desired build rates, exposure times and feasibility.
CHAPTER 6: CONCLUSIONS AND FUTURE WORK

The objective of this dissertation was to explore effects of extended sintering times in polymer powder bed fusion AM technologies. This would enable optimization of the polymer sintering process with longer than typical exposure times and determine the feasibility of the LAPS process to be scaled up to industrially relevant scales. The following discussion highlights the main conclusions and contributions of this work.

6.1 Key Contributions

6.1.1 Implementation of LAPS Technology

LAPS is a novel polymer powder bed fusion technology developed through this work to study the effect of extended sintering times. Through this work, several generations of LAPS systems were developed to maximize the intensity of light produced and control the process. In Chapter 3, a proof of concept system was initially developed to test the hypothesis of sintering an entire layer of powder simultaneously with a high intensity projector. This system proved the concept and provided a means to create single layered parts for an initial material property study. This study yielded insights about thermal losses at extended exposure times and established comparisons to existing methods used for evaluating and controlling the sintering process. Later, two more
generations were created to provide full 3D functionality in a controlled manner, including the addition of a heated build volume and closed loop sintering control through feedback with a thermal camera.

6.1.2 Solution to the Low Toughness of AM Components

The single layer components created with the proof of feasibility system were not able to yield UTS or EaB material properties but provided a relative measurement to evaluate the effects of light intensity and exposure time in which it was found that increased energy input in the form of extended sintering times or higher intensities lead to an increase in the degree of sintering. However, it was found that thermal losses can become significant which is not accounted for in existing sintering models and fails to predict outcomes with extended sintering times.

New generations of the system were developed to provide multilayered tensile bars for the measurement of thermal, physical and tensile properties. These tests determined the proper time and temperature conditions for processing the PA2202 powder into a high strength component. Components created with AM have long suffered from a lack of toughness due to low ductility, causing part failure to be more catastrophic. It was found that when creating components with extended exposure times, that highly increased ductility could be achieved which is many times greater than with any other powder bed fusion technology. Further, this was achieved without compromising the component’s strength, providing much tougher and resilient parts. Additionally,
a strong correlation was established between slight increases in density and its dramatic improvement on the ductility of the part.

6.1.3 Build Rate Models for Polymer Powder Bed Fusion

A standard or method to compare build rates of various technologies did not exist. This made it difficult to estimate productivity and throughput of machines from different manufacturers or product lines. This work provided models for three powder bed fusion technologies to estimate build rates based on a variety of commonly reported machine specifications and can be used as a guide for the design of future systems. Each of these technologies were also evaluated to determine scalability of the technology from both a build rate comparison and a feasibility perspective. It was found that LS is only quicker at fabricating parts when a relatively low volumetric fill ratio is used, such as creating single parts or components with sparse structural material. The primary limitation for the LAPS technology was found to be the required power levels required by the light source. However, if this could be overcome, the technology has the capability to provide build rates much higher than any of the other evaluated technologies when long sintering times are needed. This could provide a means to create AM parts with materials not currently capable in the powder bed fusion space.
6.2 Future Work

6.2.1 Porosity and Crystallinity Considerations

In the previous work it was found that the density has a drastic effect on the ductility of the material. Changes in density can be caused by various crystal structures or from pores within the structure. Determining the porosity would complete the link between the EaB and density changes by determining if pores or the crystal structures have the largest impact. PA12 was shown to be semi crystalline and it is well known that different crystal structures form depending on the recrystallization conditions. The greatly increased ductility of the parts is believed to be caused by the amorphous content and these resulting crystal structures. The optimum sintering time and temperature can be determined by conducting similar tests seen in Chapter 4 and paired with the resulting crystal structure. This would then allow for optimization of the sintering process to achieve the best possible outcome.

6.2.2 Material Study with Additional Polymers

LAPS is capable of providing long sintering times which could provide enough time for highly viscous materials to flow and create a high quality sintered part while still producing economical build times. This was benchmarked with the PA2202 powder and compared with existing literature. Further studies with other polymer powders could yield valuable insights about the optimum sintering temperature and sintering times for polymers that require extended times to densify.
REFERENCES


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APPENDIX B: EXAMPLE MATLAB CODE FOR BUILD RATE CALCULATIONS

clc
clear all
close all
Request User Input
dlgTitle = 'User Question';
dlgQuestion = 'Clear Graphs?';
choice = questdlg(dlgQuestion,dlgTitle,'Yes','No','Yes');
switch choice
case 'Yes'
close all
clear all
legend_reqd_pwr = {}; 
legend_source_pwr = {}; 
case 'No'
hold on
end
Initialize
disp('All units are in Si units, cm, W, J')
disp('')
User Defined Variables
disp('-------------------ASSUMPTIONS-------------------')
disp('1) Build volume of every technology is identical')
disp('2) Layer thickness of every technology is identical')
disp('3) The recoating time of LS and LAPS is identical')
disp('4) There are no travel movements for the laser')
disp('5) The laser does not scan past the sinter path to accelerate')
disp('6) The laser instantly accelerates')
disp('')
disp('Simulation 1: Exposure Area vs Optical Power');
disp('Simulation 2: Exposure Area vs Source Power')
disp('Simulation 3: Case Study - 3D Benchy')
disp('Simulation 4: Case Study - Full Volume Print')
disp('')
simulation = input('Please input simulation number:\n\n');
desired_intensity = 5; W/cm^2
desired_intensity = [1.5:.5:5]; W/cm^2

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desired_intensity = [1.5 2 2.5 3 4 5]; W/cm^2

efficiency = .03; Values range from 0 to 1, current system is approximately 3-5 efficient. Andy Delong thinks he can get up to 30 efficiency
efficiency = [.03 .05 .1 .2 .3];
efficiency = [.05 .1 .2 .3];
exp_time = 4; exposure time in seconds
recoat_time = 4; recoating time in seconds
preheat_time = 2;
layer_thickness = 0.12; units are in mm
bed_height = 33; units are in cm, 31cm = 12.2”
beam_velocity = 5; velocity of laser beam in m/s
beam_diameter = 0.4; diameter of laser beam in mm
hatch = beam_diameter*0.25; hatch spacing, or stepover distance between beam paths in mm
hatch = beam_diameter*1; hatch spacing, or stepover distance between beam paths in mm

The following values are used to scale the output plots
bed_area_min = 0; units are in cm
bed_area_max = 1000; units are in cm
reqd_pwr_ymin = 0; units are in cm
reqd_pwr_ymax = 1000; units are in cm
source_pwr_ymin = 0; units are in cm
source_pwr_ymax = 1000; units are in cm
part_name = ‘3D Benchy’; Name of
part_real_volume = 15.55; units in cc
part_cell_length = 6; units are in cm
part_cell_width = 3.1; units are in cm
part_cell_height = 4.8; units are in cm
part_number_height = floor(bed_height/part_cell_height); number of parts that fit along the height axis
build_height = bed_height; total height that will be reached by all the parts in the build volume
layers_total = build_height/(layer_thickness/10); number of layers required to print entire volume encompassed by parts
layer_time = exp_time + recoat_time + preheat_time; total time it takes to fuse and recoat a layer
equivalent_volume = part_real_volume; equivalent volume of a rectangular bar has the same volume as the original part
equivalent_height = part_cell_height; equivalent height of rectangular bar is the same as the height of the original part so that the same number of layers are required
equivalent_length = (equivalent_volume/equivalent_height)^.5; equivalent length and width are the same and so they can be calculated from the volume and height
equivalent_width = equivalent_length; all units are in cm
scan_lines = ceil(equivalent_width/(hatch/10)); number of scan lines equals the number of beam paths that fit along the width of the part, multiplied by the number of parts
distance_traveled = scan_lines*equivalent_length*part_number_width*part_number_length; distance traveled equals the number of total scan lines multiplied by their length
LS\_layer\_time = (distance\_traveled/(beam\_velocity*100)) + recoat\_time; time to fuse a layer equals the amount of time to scan the distance traveled

LS\_print\_time = LS\_layer\_time*layers\_total;

LS\_build\_rate = bed\_real\_volume/(LS\_print\_time/3600); build rate for MJF in cc/hr

LS\_print\_time\_max = layers\_max*LS\_layer\_time;

LS\_advantage = (LS\_print\_time-print\_time)/print\_time; advantage of LAPS over LS

LS\_build\_rate\_max = bed\_volume/(LS\_print\_time\_max/3600);

LS\_advantage\_max = (LS\_print\_time\_max-print\_time\_max)/print\_time\_max;

MJF\_edges = 81.6; units in cm

MJF\_velocity\_printhead = 40.0; units are cm/s

MJF\_velocity\_recoat = 10.86; units are in cm/s

recoater\_width = 7.5; units are in cm

percent\_fill = [.05 .2 .75];

percent\_fill = 1;

dead\_time = 2.15;

bed\_width = [10 20 40];

bed\_length = bed\_width;

for i = 1:25 31 cm is 12.2”

for n = 1:length(percent\_fill)

bed\_width(i) = (i); Creates a 1x31 matrix of width values from 1 to 31

bed\_length(i) = (i); Creates a 1x31 matrix of length values from 1 to 31

bed\_area(i) = bed\_width(i)*bed\_length(i); Creates a 1x61 matrix of area values from for each of the dimensions

recoat\_time(i) = dead\_time + ((bed\_length(i)+recoater\_width)/MJF\_velocity\_recoat);

layer\_time(i) = exp\_time + recoat\_time(i) + preheat\_time; total time it takes to fuse and recoat a layer

print\_time\_i = layer\_time(i)*layers\_total; amount of time in seconds it takes to finish a LAPS print

printed\_volume(i,n) = bed\_width(i)*bed\_length(i)*bed\_height*percent\_fill(n); total volume of space occupied

MJF\_width(i) = MJF\_edges + bed\_width(i);

MJF\_sinter\_time(i)=(2*MJF\_width(i))/MJF\_velocity\_printhead;

MJF\_layer\_time(i) = MJF\_sinter\_time(i) + recoat\_time(i);

build\_rate(i,n) = printed\_volume(i,n)/(print\_time(i)/3600); build rate for LAPS in cc/hr

MJF\_layer\_time\_i = (10.91+10.97)/2; time it takes to print 1 layer for MJF, averaged from two videos of the process

MJF\_print\_time\_i = MJF\_layer\_time\_i*layers\_total; time in seconds it takes to finish a MJF print

MJF\_build\_rate\_i = printed\_volume\_i,\_n/(MJF\_print\_time\_i)/3600); build rate for MJF in cc/hr

scan\_lines(i,n) = (bed\_width(i, hatch/10))\*percent\_fill(n);

distance\_traveled\_i,\_n = scan\_lines\_i,\_n*bed\_length\_i; distance traveled equals the number of total scan lines multiplied by their length

LS\_sinter\_time\_i = distance\_traveled\_i,\_n/(beam\_velocity\_100);

LS\_layer\_time\_i,\_n = (distance\_traveled\_i,\_n)/(beam\_velocity\_100) + recoat\_time\_i; time to fuse a layer equals the amount of time to scan the distance traveled

LS\_print\_time\_i,\_n = LS\_layer\_time\_i,\_n*layers\_total;

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LS_build_rate(i,n) = printed_volume(i,n)/(LS_print_time(i,n)/3600); build rate for MJF in cc/hr
LS_ratio(i,n) = LS_sinter_time(i,n)/LS_layer_time(i,n);
fprintf('Bed area: %f cm^2, LS sintering time: %1fs, Recoating time: %2fs, Ratio: %2f.
',bed_area(i),LS_layer_time(i,n),recoat_time(i),LS_ratio(i,n))
end
end

current_area = 1.6*2.1; units are in cm
fprintf('The current bed area is %2f cm^2',current_area)
Calculated Variables
disp('---------------CALCULATED VARIABLES-------------')
fprintf('Case study for %sn',part_name)
for i = 1:9
desired_intensity(i) = ((i/2)+0.5); Creates a 1x9 matrix of intensity values from 1.5-5 with 0.5 steps increases
end
for i = 1:30
efficiency(i) = (i); Creates a 1x30 matrix of efficiency values from 1 to 30
end
Calculations
for r = 1:length(bed_area)
    for c = 1:length(desired_intensity)
        for z = 1:length(efficiency)
            reqd_pwr(r,c) = bed_area(r)*desired_intensity(c);
            source_pwr(r,c,z) = reqd_pwr(r,c)/efficiency(z);
        end
    end
end
for i = 1:length(bed_area)
    for n = 1:length(efficiency)
        reqd_pwr(i,n) = desired_intensity(n)*bed_area(i);
        source_pwr(i,n) = reqd_pwr(i)/efficiency;
    end
end
disp(reqd_pwr)
build_rate2 = (part_number_height*print_time)/(part_number_width*part_number_length*layer_thickness*part_real_volume)/(print_time/3600); build rate for LAPS in cc/hr
MJF_print_time = MJF_layer_time*layers_total; time in seconds it takes to finish a MJF print
MJF_build_rate = bed_real_volume/(MJF_print_time/3600); build rate for MJF in cc/hr
MJF_advantage = (MJF_print_time - print_time)/print_time; advantage of LAPS over MJF
MJF_print_time_max = layers_max*MJF_layer_time;
MJF_build_rate_max = bed_volume/(MJF_print_time_max/3600);
MJF_advantage_max = (MJF_print_time_max-print_time_max)/print_time_max;

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equivalent_volume = part_real_volume; equivalent volume of a rectangular bar has the same volume as the original part

equivalent_height = part_cell_height; equivalent height of rectangular bar is the same as the height of the original part so that the same number of layers are required

equivalent_length = (equivalent_volume/equivalent_height)^.5; equivalent length and width are the same and so they can be calculated from the volume and height

equivalent_width = equivalent_length; all units are in cm

scan_lines = ceil(equivalent_width/(hatch/10)); number of scan lines equals the number of beam paths that fit along the width of the part, multiplied by the number of parts

distance_traveled = scan_lines*equivalent_length*part_number_width*part_number_length; distance traveled equals the number of total scan lines multiplied by their length

LS_layer_time = (distance_traveled/(beam_velocity*100)) + recoat_time; time to fuse a layer equals the amount of time to scan the distance traveled

LS_print_time = LS_layer_time*layers_total;

LS_build_rate = bed_real_volume/(LS_print_time/3600); build rate for MJF in cc/hr

LS_print_time_max = layers_max*LS_layer_time;

LS_advantage = (LS_print_time-print_time)/print_time; advantage of LAPS over LS

LS_build_rate_max = bed_cycle_volume/(LS_print_time_max/3600);

LS_advantage_max = (LS_print_time_max-print_time_max)/print_time_max;

Results

disp('---------------------RESULTS---------------------')

fprintf('For a sintering time of .0fs and a recoating time of .0fs...n...the total LAPS printing time is .2fhrs\n\nexp_time, recoat_time, print_time/3600)

fprintf('For the s, LAPS has a build rate of .0f cm^3/hr \n\n.part_name, build_rate)

fprintf('MJF prints the exact same volume in .2fhrs\n\nMJF_print_time/3600)

fprintf('For the s, MJF has a build rate of .0f cm^3/hr \n\n.part_name, MJF_build_rate)

fprintf('For a sintering time of .0fs and a recoating time of .0fs...n...the total LS printing time is .2fhrs\n\nLS_layer_time-recoat_time, print_time/3600)

fprintf('For the s, LS has a build rate of .0f cm^3/hr \n\n.part_name, LS_build_rate)

fprintf('For the s, LAPS is .1f faster than MJF\n\n.part_name, MJF_advantage*100)

fprintf('For the s, LAPS is .1f faster than LS\n\n.part_name, LS_advantage*100)

fprintf('Assuming the entire build volume is 100 filled...n')

fprintf('...0f layers are required and...n', layers_max)

fprintf('...the total LAPS print time is .2fhrs\n\n.print_time_max/3600)

fprintf('...the total MJF print time is .2fhrs\n\n.MJF_print_time_max/3600)

fprintf('...the total LS print time is .2fhrs\n\n.LS_print_time_max/3600)

fprintf('This gives a build rate of...n')

fprintf('...2f cm^3/hr for LAPS\n\n.build_rate_max)

fprintf('...2f cm^3/hr for MJF\n\n.MJF_build_rate_max)

fprintf('...2f cm^3/hr for LS\n\n.LS_build_rate_max)

for i = 1:length(bed_area)

fprintf('Required optical power for a bed area of .3f cm^2 = .3f W\n\n.bed_area(i), reqd_pwr(i))

end
Plotting Results
The following code plots the required power versus bed area
if exist('f1') == 0
    f1 = figure;
else
    figure(f1)
end
plot(bed_area, reqd_pwr)
xlabel('Bed Area (cm^2)') label for x axis
ylabel('Required Optical Power (W)') label for y axis
axis([bed_area_min bed_area_max reqd_pwr_ymin reqd_pwr_ymax]) Comment out this line to not set axis limits
movegui('northwest')
desired_intensity_str = {};
for r = 1:length(desired_intensity)
desired_intensity_str = [desired_intensity_str num2str(desired_intensity(r))];
desired_intensity_str(r) = strcat(desired_intensity_str(r), {' ', 'W/cm^2'}); add units to string
end
legend(desired_intensity_str)
hold off
The following code plots the required source power versus bed area
[X, Z] = meshgrid(source_pwr(:,1,1), source_pwr(1,:,1)); only create the meshgrid from the portion you need
E = source_pwr(:,:,1);
E = X.^2 + Z.^2;
surf(X, Z, E)
graph = input('nWhich desired intensity would you like to view? (1->8,1.5:.5:5), \n');
graph = 1;
if exist('f2')==0
f2 = figure;
else
figure(f2)
figure;
hold on
end
source_pwr_eff = [source_pwr(:,graph,1) source_pwr(:,graph,2) source_pwr(:,graph,3)
source_pwr(:,graph,4)];
plot(bed_area,source_pwr_eff(:,:)) xlabel('Bed Area (cm^2)') ylabel('Required Source Power (W)') axis([bed_area_min bed_area_max source_pwr_ymin source_pwr_ymax]) Comment out this line to not set axis limits
movegui('northeast')
for r = 1:length(efficiency)
efficiency(r) = efficiency(r)*100;
end
efficiency_str = {};
for r = 1:length(efficiency)
efficiency_str = [efficiency_str num2str(efficiency(r))];
efficiency_str(r) = strcat(efficiency_str(r), ' efficiency'); add units to string
end
legend(efficiency_str)
hold off
if exist('f3')==0
f3 = figure;
else
figure(f3)
hold on
end
[r,c] = size(build_rate);
colors = ['r', 'g', 'b', 'm'];
for ii = 1:c
plot(bed_area,build_rate(:,ii),'color',colors(1), 'LineWidth',2)
grid on
plot(bed_area,MJF_build_rate(:,ii),'--','color',colors(1), 'LineWidth',2)
plot(bed_area,LS_build_rate(:,ii),'-','color',colors(1), 'LineWidth',3)
disp(ii);
end
plot(bed_area,build_rate4,'LineWidth',2)
plot(bed_area,build_rate5,'LineWidth',2)
xlabel('Bed Area (cm^2)') label for x axis
ylabel('Build Rate (cm^3/hr)') label for y axis
axis([0 1000 0 300]) Comment out this line to not set axis limits
movegui('north')
technology = {'LAPS' 'MJF' 'LS'};
technology = {'5 Volume Filled' '50 Volume Filled' '75 Volume Filled'};
technology_str = {};
for r = 1:length(percent_fill)
    percent_fill(r) = percent_fill(r)*100;
technology_str(r) = strcat(num2str(percent_fill(r),'')); add units to string
    technology_str = [technology_str num2str(percent_fill(r))];
end
legend(technology_str)
legend(technology)
    hold off