DEVELOPMENT OF A PROCESS PLANNING MODULE

FOR METAL ADDITIVE MANUFACTURING

A Thesis in

Industrial Engineering

by

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ABSTRACT

Producing metallic parts using Laser Engineered Net Shaping (LENS™) additive manufacturing allows for a wide range of flexibility and customization while reducing waste material compared to traditional manufacturing methods. One of the important aspects of additive manufacturing is process planning, and there are many decisions that must be made in order to convert a CAD representation of a desired component into a finished part. These include determining the build orientation, generating support structures for necessary areas, slicing the model into layers, and creating the toolpath that the machine will follow for each layer. The interdependence of these tasks is complex, and traditional methods that only consider individual parameters can yield an inferior end result.

This thesis develops a process planning module to select an optimal parameter set for the construction of a part using additive manufacturing. A framework is created to determine the settings that are of interest to a designer for metal additive manufacturing. A series of steps are outlined to reduce build time and cost while ensuring high quality components. Commercial software packages are examined for compatibility and usability in the process planning framework. The current procedures used by companies to determine parameter values are assessed, and a new three-stage approach is developed and validated. This approach involves the identification of important parameters to the construction of the part, the creation of a test design to examine the relationship between these settings, and the analysis of multiple parameters simultaneously to determine optimal values. The objectives of the process planning module are established, and the inputs and outputs are defined to allow for interaction between other design modules and to ensure success in the creation of a part using metal additive manufacturing.
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Chapter 1

Introduction

1.1 Motivation

On February 12, 2013, President Barack Obama gave the first State of the Union speech of his second term. One of the central themes of this speech was the need to make America a key player in the manufacturing sector and draw jobs back from other countries that have been steadily increasing in production over the past years. He mentioned several companies that have already began this movement, stating that the country still needs to do more to accelerate this growth by advancing technology through manufacturing innovation institutes. One such institute is in Youngstown, OH, where they are using “3D printing that has the potential to revolutionize the way we make almost everything” [1]. It is this fact that is the driving force behind research in metal additive manufacturing (AM).

When used properly, metal additive manufacturing provides the ability to produce near-net shaped parts that are impossible to create using traditional manufacturing. Although there is great interest in advancing these techniques, because they are so new there has been very little research done into optimal parameters and settings for these metal additive processes. Many companies are content to make only one or two specific parts using a process, which does not allow the technology to be used to its full potential. However, in order to become a revolutionary manufacturing technique, it is necessary to produce a wide variety of products across many different fields and applications. Additionally, there has been no comprehensive study to establish the relationships between the various parameters so that complete testing and optimization of these parameters can occur. The development of a
processing planning module to bring together simulation and production of final parts using this technology is the next step to show how designers and manufacturers can work together to produce reliable parts without wasting material or time.

1.2 Scope

The Applied Research Lab (ARL) at Penn State has established a research facility funded by DARPA at Innovation Park in State College, PA, consisting of numerous additive manufacturing machines. One of these machines is the Optomec LENS MR-7, which is the major focus in this thesis. Although the procedures and experiments explained can be related to other additive manufacturing processes, some of the comparisons made and the explanations provided are specific towards this machine. The process planning module that is established can also be used for many types of additive manufacturing processes as long as the design rules and proper optimal values are changed and experimentation is done to assure that the simulations performed reliably match the output obtained from the machine.

1.3 Objectives

The goal in the research is to analyze the processing planning functions that would allow for successful integration with design, simulation, and subsequent metal additive manufacturing. For example, given a part model, process model, and material properties, the predicted build microstructure and layer dimensions can be determined. The strength and mechanical properties can also be related to other attributes such as build geometry, layer thickness, and orientation of the part. Support structures might need to be generated in the
model to support the build. In order to determine optimal parameters for these activities, a new form of experimentation is proposed and examined to demonstrate the relationships between numerous process parameters. A process planning module is also developed that is able to integrate with other designed tools in order to effectively create parts using metal additive manufacturing.

1.4 Organization

Chapter 2 provides an examination into the relevant literature in the area of additive manufacturing. This includes an overview of all additive manufacturing processes and the establishment of the technique, how the processes have been used in industry, the research that has been done on the LENS process specifically, and processing planning among metal additive manufacturing machines. Chapter 3 examines the flow from CAD design to final part, the major processing parameters in LENS additive manufacturing, and the need to establish a relationship between these parameters. The various choices of software for process planning are also evaluated. Chapter 4 describes how these processing parameters are determined today and why this procedure does not result in the best values for the parameters to be set. A new approach to determine these parameters is also proposed and validated using the Optomec LENS MR-7. Chapter 5 explains the process planning module in detail, including the inputs and outputs of the module itself. It also shows a sample part being brought through the entire process and evaluated for production purposes. Chapter 6 summarizes the contributions of the research and explores areas for future development.
Chapter 2

Literature Review

2.1 Additive Manufacturing Overview

The field of additive manufacturing encompasses a wide range of processes with different characteristics and materials that can be used, and an overview of the development of the processes is given in [2]. In its most basic form, additive manufacturing is the creation of a part layer-by-layer. This idea was developed from topographical relief maps and photosculpture, which attempted to create a 3D object by photographing it from different angles and then creating only specific portions in a medium by using a silhouette of each photograph. The technology was transposed into using metal powders by Ciraud in 1971, where as a consequence of laser-localized heating the metal particles would stick to each other to form a continuous layer. This was further extended by Housholder in 1979, who patented a laser sintering process in which each of the layers was individually deposited and solidified selectively in order to form a part. Kodama brought this technique into photopolymers where the exposed area was related to a cross-section of the model. In 1979, Herbert developed steps for the process such that mirrors were used to direct a laser across the layers, the build platform was lowered by a specific amount, and additional photopolymer was added to create a new layer. This technique is still used in some of the applications of additive manufacturing [2].

Most of the AM processes that are used today were developed in the late 1980’s and early 1990’s. Some of these include material jetting, powder bed fusion, and directed energy deposition [3]. Many of the machines are constructed to create plastic parts, while some use
metals. Each process and machine differs in its speed, the accuracy of the built part, the quality of the completed product, and the final material properties that are produced. Although the primary market for these machines was originally rapid prototyping using plastics, it has transformed into a field that is beginning to compete to create direct parts for manufacturers around the world [3].

Although many of the technologies using the same material type have similarities between them, there are key differences in selecting which one to use for a particular application [4]. Specifically, these differences occur in geometry and performance. The geometrical freedom over traditional methods is one of the big advantages of using AM, as overhangs and undercuts can be made easier. The size of the part is a limitation, as medium-sized parts can be made without much trouble but larger pieces must be divided and then attached together after processing. This would greatly add to the cost of using AM to create a part. On the other end of the spectrum, tiny parts can actually be made with more accuracy using AM processes than almost any other traditional method due to the precision that is possible with a computer controlled system. In examining the performance possible using AM, each process and machine has different maximum scan speeds and thus different productivity rates. In general, using this technology is slower than traditional methods [4]. Multiple beam systems can greatly speed up this processing time. Some of the AM technologies also require post-processing to remove supports or increase the durability of the part produced. Each process also promises different amount of accuracy from the original model, and thus those dimensionally critical parts would need to be done using only specific AM technologies. The largest difference between the processes concerns the materials that they can use, and the link between material and machine is strictly defined. Therefore if a
designer wishes to use a particular material to manufacture a part, it greatly limits the selection between the different processes [4].

There are currently many challenges that need to be addressed in using the technology. The first is the vast amount of material databases that must be collected to engineer and design parts properly. If the properties for a specific material are not available, then customers might not consider using AM if they also need to perform research and development in order to produce a proper design. However, at this time it is unclear who should be collecting and distributing this data [3]. Individual machine manufacturers treat some of this information as trade secrets and are not willing to share specifications without payment. There is also the need to develop additional materials to use for processing, which would open the door for more applications [3].

Aside from the technological issues, there are also challenges for companies that wish to adapt additive manufacturing technology into their businesses. In order to examine which aspects are important for improvement, a survey was conducted across academic, industry, equipment, and service providers regarding their opinions on six processes that are directly able to make parts using metals [5]. Build speed and surface roughness were each ranked in the top three most important aspects for improvement in the majority of the technologies. Except for electron beam melting, in-process monitoring was ranked in the bottom half of importance for the other technologies. The results for maximum part size were split in the responses, as the results for three of the processes indicated that it was very important while it was unimportant in the others. Respondents across all technologies did not place raw material variety high on their list of priorities, but it is suspected that this was due to more
than half the participants using the machine for research and development instead of manufacturing [5].

The cost of the machines, materials, and maintenance is also an obstacle, as many companies require a specific return on investment in order to purchase into the technology. For companies that already use existing processes and are thinking of changing to AM, it is believed that they must receive a gain of at least 30% to 40% when replacing what they currently use [6]. This cost reduction could also come in the form of time, in that the consolidation of parts or ease of additive manufacturing could allow for companies to produce complex parts faster and reduce much of the machining cost. For some industries, the lack of available materials is also an issue. As it stands now, for most mass produced parts additive manufacturing is not viable. This is due in part to the need for machines, operators, and facilities to produce consistent parts very quickly, which is not always possible using the current technology. Process standards must be established and distributed, the testing of parts should be standardized, and a better system to create larger parts using AM should be researched and developed [6].

Predictions have been created as to where advanced manufacturing technology will be globally in the next 10 to 20 years, and it appears poised to take advantage of an international market space [7]. In the 10 year range, advanced manufacturing processes are expected to be more energy efficient as sustainable methods become integrated with design [7]. There will be an increase in demand for flexible and customized parts, which could allow for local manufacturers to adapt to the needs of their customers quickly. Biological-inspired designs will be integrated into manufacturing processes, and AM can create and change these designs quickly [7]. In 20 years, it is expected that manufacturing innovations
will replace many of the labor-intensive processes that are used today. Robots and sensors will continuously monitor processes to reduce human intervention while still recording the data necessary to create advancements in design and technology. Advanced and custom-designed material will be used across many fields, and accelerated testing techniques are therefore needed to be able to obtain parameter values for these new metals and plastics in a timely manner [7].

2.2 Applications of AM Technology

Despite some of the issues mentioned in the previous section about the general manufacturing population adapting the technology, there has been a trend towards acceptance in certain industries. A survey was conducted with the users of over 10,000 metal and plastic solid freeform fabrication machines installed worldwide in 2003, and Figure 1 indicates how those customers indicated were planning on using the technology.

![Figure 1: Uses of Solid Freeform Fabrication Machines (adapted from [8])](image)
Many new applications have developed over the years for using the technology in both metal and plastics. Although visual prototypes were the main use for the original processes, functional prototypes are becoming more and more prevalent, as shown in Figure 1. These prototypes are able to reproduce such results as the final strength of the product. Several machines are also suited for application in CAD offices as visual aids for engineers being used as concept modelers. These machines are relatively small and cheap and are able to create parts very quickly without worrying so much about the quality of those parts. The software used with these machines is not very complex and works similar to a desktop printer, but some definition of supports and then removal of those supports might be necessary in order to create the visual aid [9].

The technology has also been used in tool making, where the delay to produce dies and molds can be greatly reduced by using this “rapid tooling” technique. This can be achieved through more direct methods such as the dies being produced by the additive machines, or by indirect methods where a master model is first made and then reproduced using other processes [9]. Additive manufacturing has also been used for die repair because when dies are used repeatedly, they begin to wear out. By depositing material in specific locations, these dies can be repaired and used again instead of being replaced every time, which is quite expensive. This requires extensive knowledge of the process and precise control during the repair; otherwise, the die will not turn out as dimensionally perfect as a completely new purchase would have been [9].

Some other typical applications of the repair process for AM are discussed in [10]. Low-wattage repair of titanium components has many potential aerospace and Department of Defense applications, such as the repair of the housing for a gas turbine engine. In the
particular housing mentioned in [10], the bearing seating area was worn out. Metal material was deposited using the LENS process and then machined to meet tolerances again. It was estimated that the repair saved the company 50% compared to manufacturing the housing again, and the delivery time was much quicker [10]. Another example included a user who utilized the process to repair a drive shaft. This drive shaft had been repaired before using sprays and chromes, but the mechanical bond would consistently wear off. However, because the deposits using additive manufacturing are metallically bonded to the surface, the user was able to use AM to fix the part with only a single one-time cost instead of a continuous application of the spray. A comparison between the two repairs can be seen in Figure 2.

Figure 2: Comparison of Thermal Spray Repaired Shaft and LENS Repaired Shaft (adapted from [10])

One of the most popular applications of AM is medical modeling, in which parts such as implants for humans can be made [11]. Implants are typically created with a milling process, but an alteration to the surface of the part would then need to be made. The implants are coated to improve the stability and increase the bone integration into the stable parts of the limb. The use of additive manufacturing has allowed for the joining together of very thin sections of metal, which changes the density of the final produced part. This density difference allows for the implant to have the same stiffness as human bone, and the stresses
that would be present across a traditional implant are then dispersed. Two artificial hips were created from stainless steel using the LENS process, but there were restrictions noted on the maximum overhangs that the researchers could achieve without the use of support structures [11]. This was addressed by slowing the machine during the contour building phase such that more material was deposited on the overhang portion [11].

There are also parts that cannot be made using the current AM technology, but designers are working towards the creation of new processes every day. Williams, et al. [12] set out to create a metallic mesostructure using additive manufacturing, which is a low-density cellular material with divided space into closed cells. This structure has good energy absorption characteristics and high compression strength. It was found that there were numerous issues that could not be overcome using direct metal AM processes due to poor resolution, an inadequate surface finish, a limited selection of material, and the need to remove supports in between the complex internal geometry. Instead, they proposed the creation of an additive manufacturing process after carefully stating why all of the current alternatives would not be desirable to produce their part. This new process would allow the designer to fully specify the part macrostructure using layer-based additive fabrication of metal oxide powders and combine it with post-processing in a reducing atmosphere. This process is currently under development [12].

2.3 LENS Process Research

LENS is an acronym for Laser Engineered Net Shaping and is one of the AM technologies classified as laser cladding. It was commercialized by Optomec in 1997 to
create original parts made from titanium alloys [13]. In the LENS process, metal powder is brought to the surface of part through gas jet powered nozzles directly at the focal point of a high-energy laser beam which creates a molten pool. This powder is then attached to the part in layer-by-layer fashion. The powder feeder and the laser beam are usually located perpendicular to the substrate, but they may also form an angle if the part requires a smaller amount of material in a particular area. Some of the powder bounces off of the part surface while some becomes trapped in the melt pool. The solidification of the powder happens very quickly because the heat is moved away from the interaction area. The entire process occurs in a closed chamber with a controlled atmosphere of nitrogen or argon. Many of the machines that use this process are only able to move the laser and build platform in the X, Y, and Z axes. Therefore, complex parts with overhangs cannot be produced without the use of supports. This is different from some of the other AM processes because powder beds can offer natural assistance in building parts with overhangs. Nickel alloys, titanium alloys, steels, cobalt alloys, and aluminum alloys are the main choices for materials used in the process. There are also two powder feeders on many machines so that different combinations of powders can be used simultaneously to create a graded finished product. Finishing might be required depending on the use of the part and the quality of key surfaces that the process is able to produce [13].

Keicher, et al. [14] tested the feasibility of the LENS process to fabricate shapes directly from CAD models. Although early constructions had created machines with non-uniform and non-steady powder deposition, the authors noted that improvements have created reliable deposition and consistency in newer models. Mechanical testing found that parts that were obtained from the LENS process exceeded the performance in yield strength
and ultimate strength compared to those that were produced using similar techniques. It was estimated this was due to the larger grain size within the LENS created structures compared to those that were annealed. It was also observed that the surface finish was a function of the powder particle size and was currently of lesser quality than that required for most manufacturing operations. This indicated that finishing would be necessary on the test pieces if they were to be used by a company [14].

The interface between the CAD design and rapid prototyping systems is a main component of the quality of produced parts. It is very important that the interaction between the two is as clean as possible to allow the part to be appropriately sliced and produced inside of the machine. The STL (STereoLithography) format is the standard input to an additive manufacturing process planning system, and it divides the CAD model into a series of triangular pieces [15]. In a STL file, the triangular facets are described by a series of X, Y, and Z coordinates and a unit normal vector to show which face is outside of the object. This became the standard due to its ease of use and independence from specific CAD modeling systems, and therefore STL files could be produced using many different programs that could be customized by the designer.

Over time, it has been discovered that this format has numerous drawbacks. There is a large amount of redundancy in the files because of duplicate vertices and edges, as every point that two triangles meet is actually contained in the data of both of the triangles at that intersection. It is possible that holes and cracks could also form when converting models into this specific file type, and it is work-intensive to find these errors and correct them. Kei, et al. [15] suggest that, due to these drawbacks, AM machines should move to a different file format that offers numerous advantages and enable precise modeling in additive
manufacturing designs. However, the inferior STL file type is still used by the LENS process, and therefore these disadvantages must be taken into account when creating parts. This could have an impact on process planning due to support structures and other portions of the parts not generating and being produced on the machine correctly [15].

Research has also been done to understand the microstructure of components that are created using the LENS process. The desired geometric and material properties can be designed into parts through the fabrication parameters if they are able to be properly defined through experimentation. It was found that if the part requires high yield and ultimate tensile values, then low power and high traverse velocity should be selected while if the part needs significant ductility, high power and a slow traverse value should be chosen [16]. In this way, deposition parameters can be selected for both the part geometry and the material performance desired. Models can be developed to predict the microstructure evolution of parts. The ultimate goal would be to monitor the thermal signatures during the process itself and then alter the build of the part accordingly, but the data used to create the toolpath is not able to be changed currently in this manner [16].

Another method to determine the thermal behavior of a part during the LENS process was given by Ye, et al. [17]. Heat equilibrium equations were implemented into a simulation model which was then verified using a video camera recording the actual production of a part. The camera could record a temperature range from 1500 to 2500 K and allow for tracking of the melting pool at all times. They found that the molten pool is not circular but rather elliptical. Additionally, as the distance from the molten pool increased, the temperature would gradually decrease even while the part was being made. The numerical simulation data that was programmed was able to correctly predict this change, and it was
concluded that the simulations have the potential to give the information of the entire thermal behavior throughout the construction of a part. Predicting the thermal distribution and resulting microstructure before creating a part could allow for designers to alter toolpaths so that the correct product is produced correctly on the very first attempt [17].

2.4 Process Planning Overview

Process planning is defined as a series of decisions that are made after the creation of a model to establish a completed part in an accurate and efficient manner. Each of these choices could involve selecting values for multiple parameters on an AM machine or in the slicing process in order to obtain the desired result. Various papers classify these steps in different manners. Kulkarni, et al. [18] specifically addresses layered manufacturing and focuses on the transition from the model domain to the layer domain. They classify process planning being grouped into four tasks: (1) slicing, (2) orientation determination, (3) support generation, and (4) path planning. The model domain consists of the selection of orientation and the generation of supports, the layer domain consists of path planning, and the slicing task is the relationship between the two domains as shown in Figure 3.

Figure 3: Mapping from Model Domain to Layer Domain (adapted from [18])
Orientation determination is deciding the direction in which the model is going to be built, while support structures are the material underneath the part to reinforce any overhangs or sections that require a starting point to deposit metal. These supports might be removed in post-processing, or left on the part if they are not disrupting its final use. Slicing refers to the procedure in which planes are intersected with the CAD model in order to determine the 2D images that display the deposition of material for each layer. When the toolpath itself is considered on this plane, it is labeled as a 2.5D image. Stacking the planes on top of each other would therefore represent the completed part. Path planning is defined as the plotting of the physical movement of the build platform in the X-Y plane in order to create the final part. The relationship between orientation and support structures is shown by the arrow between the tasks in the figure; however, there is no suggestion to deal with this issue other than to state that all tasks must be considered when creating a part [18].

Other process parameter work has attempted to look at how changing some of the values could affect a single quality of a final part, such as the height of one line or one layer produced using additive manufacturing. Averyanova, et al. [19] attempts to compare two different techniques used in selective laser melting in order to produce parts. The “1 zone” manufacturing strategy uses one laser beam pass over the powder with a constant hatch distance, which is the difference between successive travels of the laser in a single layer. In this way, the laser beam melts the previous track and the new powder layer at the same time and joins them together. The “2 zone” manufacturing strategy is actually a two-step process. First, the powder layer is processed with a hatch distance equal to that of a single track of metal deposited. Afterwards, the beam passes between the previously melted tracks of the same layer in order to join them together. It was found that in changing multiple parameter
settings such as the height of the dilution zone and the width of the tracks that the “2 zone” strategy was more robust in producing good adhesion inside of the layers. The “1 zone” technique demonstrated that input parameter variation more significantly affected the output parameters of interest and therefore would not be a preferable method. However, the authors did not consider other key outputs, such as the amount of time that it would take to create a single layer. Due to the double pass over the layer that must occur, it is suspected that the “2 zone” method takes significantly longer to produce a part. Without a proper process planning module, this shows the difficulty in analyzing only certain parameters while not considering the full set of properties [19].

Some modeling software programs are actually able to assist with the calculation of key output parameters such as the amount of material needed to create a part, the amount of material needs to create the supports, and the amount of time the part would take to manufacture. Udroiu and Nedelcu [20] describe a case study of an airfoil that is built using inkjet technology and the importance of selecting proper orientation. The virtual model of this part is shown in Figure 4 below:

![Figure 4: NACA Airfoil Virtual Model (adapted from [20])](image)
Three different orientations were considered on the build tray by placing the largest model dimension, labeled $l$ in the figure, along the X, Y, and Z directions. The smallest amount of supports was needed in the Z direction because the part was standing up on its end. However, it also required the largest amount of building time – almost 6 hours – since the part is being made layer-by-layer in the Z direction. Placing the airfoil with the largest dimension in the X or Y direction reduced the estimated build time but doubled the amount of supports needed. This was due to the downward shaped curve of the airfoil that needed to be supported underneath. This case study demonstrates the need for rules to be developed for selecting orientation and illustrated that a trade-off could be necessary between some of the output parameters that are going to be calculated. It would be up to the user to decide in this situation whether the extra processing time for the part to be produced would be preferable to not having to remove the extra supports [20].

The orientation selection and choice of build direction are so important that research has been done in order to improve this one specific task in parts. Frank and Fadel [21] described a specific study in which surface finish, build time, and support structures were chosen as key parameters of evaluation when choosing an orientation. Experts in AM were used to classify various parts into categories through an iterative process, and it was determined that certain geometric features were more important than other. Some examples of these features included holes, rounded surfaces, thin structures, planes, and overhangs. In the developed system, the user would select two geometric features and define the relationship between them, such as making the feature axes parallel or perpendicular. The program would then indicate if the designer was creating rules that were impossible, or place
the part in the proposed orientation if there were no conflicting directions. The authors also incorporated calculating the build time of the part using a program written in C. This was some of the first work done in orientation management to give help to designers, but now many software packages have features like this included as an option inside of the program [21].

Specific areas of focus in process planning include individual metals, AM processes themselves, and specific process parameters across multiple applications. An examination of the process parameters necessary to deposit nickel powder with a small amount of titanium using direct metal deposition was performed [22]. The titanium was added to the pure nickel because historically nickel has been difficult to weld, resulting in cracks. It was determined that gas flow rate, laser power, and traverse rate had the largest impact in determining the quality of the finished test part. Quality of the finished part in this experiment was determined by mechanical strength, visual inspection, and an examination of the microstructure that was formed. However, the specific parameters that were chosen were simply based on what the machine offered as settings, which does not encompass the full scope of process planning. It was possible that some of the parameters used in the formation of the part itself could have been found to be important in the development of any of the outputs. Those parameters not of interest were also placed at their preset machine settings, which might not have been optimal for that part type or material [22].

Research in process parameters was also performed specifically for direct metal laser sintering (DMLS), which uses liquid-phase sintering to bind metallic products together [23]. A metallic powder cylinder is filled up with two types of mixed metallic components, namely, a binder and a structural metal. This composition is provided to the working
cylinder in a fixed thickness. The powder surface is then scanned with a laser system, and then another new layer is added and printed in this manner. One of the results from the research by Yu [23] was a genetic algorithm based intelligent hatch spacing module in order to improve the homogeneity of the process. This was measured by the percentage of shrinkage obtained in the final parts. It was found that varying hatch lengths resulted in a worse final product, and thus designers should attempt to prevent short hatch lines in this process and reconfigure any toolpaths which create tiny hatches [23].
Chapter 3

Process Planning Framework

3.1 Introduction

In order to identify the process framework and the parameters that would need to be changed in order to produce parts of high quality using the LENS process, it is important to understand the machine itself. Figure 5 is an image of the Optomec LENS MR-7.

![Figure 5: Optomec LENS MR-7](image)

In order to create a part using Optomec’s LENS MR-7 laser-based direct digital manufacturing system, a 3D CAD file of the desired product is sliced into layers by one of several computer programs. A toolpath is generated for each layer while outputting code for the machine to use as instructions on how to build the desired part. The materials fed into the machine are fine particles that are nanometers in size, and the machine has a process work...
envelope of 300 mm x 300 mm x 300 mm. The powder is ejected out of four nozzles at a speed of up to 100 grams per hour directly under a laser that has a maximum power setting of 500 W. The laser melts the powder together on the metal substrate, which can move at a maximum speed of 60 millimeters per second in the X and Y directions as determined by the toolpath [24]. The machine is equipped with dual powder feeders that hold up to two liters of powdered material as shown in Figure 6.

![Dual Powder Feeders](image)

Figure 6: Dual Powder Feeders

Once the first layer has finished printing, the laser and nozzle move in the Z direction the distance equivalent to one layer of printed material and the second layer begins to be deposited. This activity takes place in an environmentally-controlled chamber maintaining oxygen at less than 10 parts per million which is optimal for the melting process [24]. After the final layer is printed and the part is removed from the substrate, the output is ideally a part consistent with the original 3D design. Figure 7 labels the major portions of the powder delivery system.
Although the process begins with a CAD file, the operations performed to convert that file into a finished design are quite complex and not well defined in the literature. There are many parameters that need to be established including settings on the machine, the material properties, the method in which the file is sliced, and the toolpath options. This chapter classifies those parameters into groupings and details how they should be considered. It also provides an overview of the creation of the toolpath file that is used on the machine, and the various software programs that can be used to create that file format.

3.2 LENS Process Overview

When creating a 3D part from a CAD file, there are many steps that need to be completed, and each stage has its own options that need to be selected as well. In order for the output to successfully be the desired 3D part, the flow from design to part and the choices
to be made in each step need to be fully understood. Even one small error at any step could create a finished part that is far from satisfactory.

Figure 8 shows the CAD design to finished part flowchart highlighting the major steps in the process. A part begins as a CAD file in the STL file format as discussed in Section 2.3. Once the desired material is selected, then the STL file is sliced into individual layers to be printed one at a time. In order to do this, a slicing software package needs to be selected and used. Since different packages have different capabilities and compatibilities with machines, this choice is quite important. The selected machine also has its own settings which must be chosen, including the speed at which the machine prints, the laser power, and the rate at which the material is deposited. When slicing the file, the desired build orientation and the layer thickness need to be selected because the output of the slicing step is a SLIce (SLI) file. Next, a toolpath for each layer needs to be generated by the software. This step contains many decisions in order to create the desired part such as the algorithm chosen for the direction of the toolpath (i.e. spiraling towards the center, linear patterns), the spacing between each line of the toolpath (i.e. hatch spacing), if the outer contour of the toolpath will be thicker than the inside, and many other options. The output of the toolpath generation step for a LENS system is a toolpath file called the DMC code. Once all of these choices are made, then the file is uploaded to the LENS system. It is also possible to generate DMC code without following this procedure by using a word processor or a program like Mathematica, but this requires manual programming skills and a complete understanding of the language so that the correct properties are obtained.
There are many choices and settings that must be determined in order to use metal additive manufacturing process. In order to make these decisions not only does the flow of information from CAD design to finished part need to be understood, but how the process parameters that are chosen affect the output obtained also needs to be defined. These parameters not only change the final product, but they affect each other as well. Without proper knowledge of the relationships between process parameters and their effects on the part, a successful output cannot be created. Therefore, a detailed framework needs to be created to determine optimal settings and parameters for metal additive manufacturing to be an effective tool.

### 3.3 Parameter Framework

There are many parameters that need to be defined in order to follow the flowchart in Figure 8 and obtain the desired results. A comprehensive framework was created to detail
each of the settings that need to be entered so that a metallic part can be produced, as well as classifying each of those decisions into various stages. This framework was determined by examining the creation of parts and noting every decision made, as well as looking at the options available for each stage. Figure 9 contains this proposed framework, and each of the parameters is defined in detail in the following sections.

<table>
<thead>
<tr>
<th>Material Parameters</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Size</td>
<td>Alloy Type</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Machine Parameters</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Beam Power</td>
<td>Travel Speed</td>
<td>Deposition Rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orientation Selection</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height in Build</td>
<td>Quality of</td>
<td>Area of Base</td>
</tr>
<tr>
<td>Direction</td>
<td>Surfaces Desired</td>
<td>on Which Part Rests</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Support Generation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Shape</td>
<td>Pillar Size</td>
<td>Support Distance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slicing Options</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Layer Thickness</td>
<td>Maximum Layer Thickness</td>
<td>Slicing Algorithm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Toolpath Generation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Contours</td>
<td>Contour Start Location</td>
<td>Toolpath Algorithm</td>
</tr>
</tbody>
</table>

Figure 9: Additive Manufacturing Process Parameter Framework for LENS Systems (adapted from [25])
The material parameters should be the first to be defined since the CAD design has presumably been created with a typical material in mind. It is necessary to determine the particle size and the alloy type of the metal to be used, since different metals have different properties and produce varying results depending on many of the other options selected.

The machine parameters would be the next options to be chosen. The laser beam power is the maximum power that the laser will achieve during the operation of the machine. The travel speed determines how fast the build platform moves during the procedure. The deposition rate is set depending on the velocity that the user would like the powder to move from the powder feeder through the nozzle. The gas chamber settings such as the oxygen and moisture levels are set and adjusted by the influx of argon or nitrogen, which prevents oxidation.

There are many additional considerations that need to be made when selecting an orientation for a part to be produced. The most important is the height in the build direction, as this has a direct impact on the length of time it will take to make the part. The volume of support structure that would need to be used in order to produce a part in this orientation is also related. Other decisions that must be made revolve around the quality of surface finish that is desired, and the area of the base on which the part will be built. The base must be larger than the first layer of the selected orientation, and therefore the selected substrate and the build envelope itself could limit the orientation options. The distortion or curl produced in the part should also be taken into account, as it could cause parts to be out of tolerance if not addressed.
Once the build orientation has been selected, some of the features in the part may require supports. This could include things like overhangs and holes in the part. In a LENS benchmarking experiment, it was found that an angle of approximately 26 degrees was the largest that could be achieved without the use of support structures [11]. Since the LENS machine uses metal powder, the supports will need to be created out of the metal itself. There are many choices for support structure designs. They could be a block, where the support is created exactly the same as the part with a contour and hatch lines. The supports could also be a line, in that only a contour line is used to support a particularly key edge of the build. If the part comes to a point, then a crossed support underneath that area might be the best selection. Gusset supports connect to the part itself rather than the substrate. A web design can also be used for larger parts. After the shape of the supports is selected, then the size of the pillars and the distance between successive supports must also be decided. Figure 10 demonstrates a part with block and gusset supports, in red, added to those features that would require them using a powder bed process.

Figure 10: Support Example (adapted from [26])
Slicing options involve the segmentation of the CAD file into horizontally stacked slices, which are produced by the machine one layer at a time. These slices could be a variable layer thickness in which both the maximum and minimum allowable would need to be set, as well as the algorithm to be used to determine the thickness of the individual slices. Alternatively, the layers could be a single fixed thickness that would not change as the part is being built. The hatch width is the distance between successive hatches in the production process, while the hatch styles refer to the different ways that the hatches can be deposited. They can be placed perpendicular to each other or always in the same direction, but the hatch angles must be set if successive hatches are to be done at differing slopes. Figure 11 shows the key hatching parameters on an example layer.

![Figure 11: Hatch Angle and Hatch Width (adapted from [25])](image)

The final set of process parameters relate to toolpath generation. The number of contours for each layer can be defined at this stage as well as the start location for each of the layers. For many parts, starting at the same location for every layer presents some difficulties; therefore, either a random location can be selected or a small move can be made on the contour so that a different beginning position is chosen. The toolpath algorithm can also be selected to determine which one of the hatches is constructed first and how the program will progress from one hatch to another. Additionally, there are parameter options dealing with disconnected hatches due to holes and “blocking” groups of similar hatches together.
There are numerous commercial software packages that allow many of these parameters to be chosen during the conversion process from the STL file to the DMC code. However, each one has slightly different settings and customization options that allow the user more options for process planning. The next section details some of the packages available as well as their strengths and weaknesses in the overall process planning methodology.

3.4 Software Comparison

PartPrep is the program suggested by Optomec to be used with the LENS MR-7, and it presents the fewest issues in terms of compatibility. It is also quite simplistic in its design and is the easiest to use to begin producing parts quickly. Unfortunately, it also offers the fewest options for customization and does not allow for variable slice thicknesses, as one value must be selected for each of the slices in the SLI file. The distance and angle for up to six different hatches can be defined by the user, but there is no assistance by the software to choose any optimal settings for these values. There are only two different choices for defining the toolpath and contours, although it can be selected that each layer begins in a different location on the contour either randomly or through a small move to a new position. It also offers the option of predicting how long the build will take based on the values entered by the user and its calculated toolpath [27].

Compared with PartPrep, VisCAM has many more options for users in terms of parameter customization. The program allows changes of the part orientation directly by using options such as the least height or the highest mass on the bottom. It will automatically
generate supports when the proper settings are entered, which is a very useful feature to have in a process planning program. Otherwise, it would be necessary to alter the CAD file after the orientation step to add these manually. The program can account for distortion using its shrinkage compensation feature, which is calculated based on the type of material that is selected by the user. It can also vary the slice thicknesses by using the maximum and minimum value entered. The program can predict the total cost of producing a part when information about this is entered into the software. Some of the hatching options are a bit lacking, as only a single defined angle can be entered and layers are differentiated using that angle. Although Optomec does not directly endorse the use of this program, there have not been issues in using it to create SLI files to use with the process [28].

Netfabb presents a middle ground software package between options and ease of use. It allows for the distance and angle of the hatching to change between layers, and users can completely customize every layer if they so desire with the Slice Commander add-on. It also allows variable slice thicknesses to be selected, and combining these two options creates the most customizable slicing package available. Unfortunately, it falls behind in other key areas. It does not allow for supports to be generated or for shrinkage to be taken into account. There are no prediction parameters included with the program, which does not allow a user to determine whether one group of settings would be preferable over others based on time or cost. In order to use this program, a prediction methodology would need to be developed. A major disadvantage is that the package is not currently supported by Optomec, but this might change in the future [29].

Magics provides the best software package out of those that Optomec advises is fully compatible with LENS due to its ability to combine functionality and ease of use. The
program allows for supports to be generated, and shrinkage is taken into account via a multiplicative factor entered by the user. Variable slicing thicknesses are supported, and the prediction parameters can take both time and cost into account. It does lack hatching options compared to the other programs since the layers are only allowed to be alternated by 90 degrees every time. In this way, completely perpendicular hatches must be created in successive layers, and there is no option to change this selection. However, the program is more robust than PartPrep and should be the dedicated software for those users who wish to have the most process planning options immediately after the machine is operational [26].

There are some features that are believed to be useful that do not appear in any of the commercial packages. Having the ability to set a pause time between various layers would allow for cooling to occur and would drastically increase the range of parts that could be produced. This would also allow for easier changes to the microstructure that is formed inside the part. The programs are also limited in the options that each present in dealing with multiple powders fed into the system at the same time. Since LENS machines can have up to four powder feeders, these should be able to work concurrently not only in an individual layer but also in creating a gradient in the X-Y direction. Currently, any modifications such as this must be made directly to the DMC code after generation, which is a tedious process. A summary of the features of interest and the software that can be used in the LENS manufacturing process can be seen in Figure 12.
<table>
<thead>
<tr>
<th>Feature</th>
<th>PartPrep</th>
<th>VisCAM RP 4</th>
<th>Netfabb Studio Professional 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(with Slice Commander add-on)</td>
</tr>
<tr>
<td>Support Generation</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Shrinkage Compensation</td>
<td>NO</td>
<td>YES, depending on entered material</td>
<td>NO</td>
</tr>
<tr>
<td>Orientation Options</td>
<td>None, must be re-sliced if changed</td>
<td>Least height, least footprint, highest mass on bottom</td>
<td>None, must be re-sliced if changed</td>
</tr>
<tr>
<td>Hatching Options</td>
<td>Distance and angle, up to 6 hatches</td>
<td>Alternate layers based on single defined angle</td>
<td>Distance and angle, change rotation by set amount each layer</td>
</tr>
<tr>
<td>Variable Slice Thicknesses</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Prediction Parameters</td>
<td>Time</td>
<td>Cost</td>
<td>None</td>
</tr>
<tr>
<td>Current support with LENS</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>

Figure 12: Software Comparison Matrix
Chapter 4

Parameter Relationship Analysis

4.1 Introduction

Although the proposed framework identifies the major decisions that need to be made in order to create a part, it is still difficult to determine what values should be set for these parameters. Even with the various options available in the software packages that are compatible with the LENS process, not all of the parameters can simply be calculated. Some must be determined using experimentation due to the variety present from designers using different processes, materials, and machines. This chapter emphasizes that determining optimal values for individual parameters without taking into consideration how they affect each other will yield poor results. A discussion on the methodology used by companies and designers today to determine these parameters is provided, as well as some examples showing the relationship between various parameters of interest. A methodology is then presented and validated using the LENS MR-7 that incorporates multiple parameters at the same time in an attempt to find the best combinations to produce repeatable results using the desired AM process.

4.2 Current Methods of Parameter Analysis

With so many values that need to be selected for parameters as discussed in the previous chapter, designers and engineers that are attempting to determine optimal parameter selections to build a specific part face a difficult task. In order to achieve the knowledge
necessary to select the proper values, it could require companies to create many parts and test different settings in order to see which are ideal for that process for that part. This is time-consuming and could be financially draining on a company that wishes to only make one specific part using additive manufacturing. Many AM machine manufacturers have attempted to ease the burden on the individual company in determining these values by presenting parameter sets that are available for purchase. For example, EOS offers customers the option to buy these sets for particular materials with their machines.

There are numerous issues with this method. The first is the connection between the designed part and the AM process that is being used to make that specific item. As explained, some processes are able to handle tasks like supports easier than others due to the way the powder is deposited. Therefore, it would be ideal that the designer of the part realize the limitations of the machine and created the part keeping in mind those restrictions. Another issue is that these parameter sets are tailored towards a particular material for a specific process using a defined processing speed. While the parameters will most likely allow non-critical parts to be created in the machine for a customer, the part could be such that precise depositions by the nozzle are very important. Every machine will be slightly different, and these small corrections could have a large impact on the final surface finish or material properties that are obtained. It is also important to remember that the cost for all of these different parameter sets that would need to be purchased could drastically raise the amount that companies would need to quote a customer. This could cause that company to lose the bid for a specific part over other processes. A final more serious issue is that the Optomec LENS MR-7 has a dual powder feeder, and the ability to grade materials gives it a
large advantage over other AM processes. However, there might be no perfect parameter set available to purchase for making a part composed of some defined percentage of each metal.

Therefore, it has become far more common to use a designed methodology in order to determine the process parameters when a new powder is being used on a machine. While this would certainly take longer to create the very first completed part, it would make sense to use because of the possibility of wasting materials and resources in attempting to create the desired part repeatedly until a satisfactory result is reached. The method currently used is to first select a process parameter that the designers believe is the most important in the creation of the final product and then conduct experiments changing only that parameter. A single test part would be used for this purpose, and ideally multiple rows of test pieces could be made in one build with each row changing this single parameter. The test parts would then be removed from the machine and subjected to non-destructive and destructive testing. An examination of the microstructure formed is typically done, and the strength of the resultant part would be examined.

Once the tests are conducted and the results are obtained, the engineers would agree on the parameter value that gives the best results from all of the assessments together. This value is then set in the use of that particular material for the process and is considered to be optimal. The designers would then select the next process parameter that they think to be the most important out of those remaining to be tested, and perform the same experimentation. The value obtained from the last examinations for the previous parameter would be used at this time. This cycle continues until there are no more process settings that are deemed important by the designer, and the values that are calculated are used as the parameter set when a part needs to be made using that material on that machine.
There are many reasons why this procedure is not ideal to properly identify optimized machine parameters. If the AM process is completely new to the designers, then there might not be known limits to set the parameters when examining them. This is important because the entire process range would need to be tested to find the optimal value. There is also no reason besides designer experience that would lead towards the identification of the most important process parameter. It would also be difficult to decide when to stop considering the rest of the parameters and allow them to remain with the suggested values that the machine gives automatically. The final reason why this procedure is not optimal is that the relationships and interaction between the parameters is completely ignored, despite the fact that it is known that changing one value can have a profound effect on the resulting properties of the part. This could lead to not finding the actual optimal parameters for that material, and the data set received could be a local optimum point rather than a global one due to the successive nature of the design. It might be possible to adjust another process parameter to achieve the same result or better if the first decided parameter value was able to be changed instead of set at the beginning. Without a complete understanding of the relationship between certain parameters for the process, this would be missed using the current experimental design.

4.3 Determining Parameter Relationships

The difficulty in determining the relationships between certain parameters is the choice of property to measure for the test part. In general, certain key parameter values would alter the part properties obtained more than others. For example, if the scan speed in a
build is increased but the laser beam power remains the same, then it is possible that a proper part would not be formed due to the lack of a bond between the powder and the previous layers. The choice of what value is going to be measured in order to determine this relationship is therefore very important.

If *surface roughness* is the property of interest, then the laser power, scan speed, hatch distance, layer thickness, and toolpath generated would all have an effect. This is true because if the thickness of the layers increased and the hatch distance did not change, tracks would be created too close to each other due to the large deposition of material in one area. If *mechanical strength* was of interest to the designer, then the laser power, scan speed, hatch distance, and layer thickness would all affect the final part. Proper fusion must occur between the layers in order to obtain a strong part; so, decreasing the laser power and not decreasing the thickness as well would result in a weaker bond being formed.

If *process time* was deemed to be the most important property, then the laser power, scan speed, hatch distance, and layer thickness would have the largest effect. Specifically, slicing the file into larger layers would reduce the number of passes necessary by the nozzle but the laser power would need to be increased to take this additional powder into consideration. If *dimensional accuracy* was the major feature of interest, then scan speed, laser power, layer thickness, hatch distance, and the scan path would be the primary parameters. The scan path that is followed by the nozzle and the speed in which this route is traced could result in certain dimensions experiencing shrinkage. Finally, if *cost* was the deciding factor, then scan speed, the hatch distance, and the layer thickness would be the major process parameters. Depositing more material every layer and not increasing the laser power would result in wasted powder, as this extra material would not be captured by the
melt pool. Although it is recognized that the relationships between these parameters have profound impact on part properties that are obtained, designers have struggled with determining how to use this information to relate the parameters to each other. A defined testing methodology is required in order to perform the proper tests to ensure that the correct relationships are determined between the parameters to make a part.

4.4 Proposed Testing Methodology

In order to propose an alternative to the current testing procedure, a three-stage methodology has been developed. The first stage is quite similar to the current methods used by companies and researchers in order to determine optimal process parameter sets. All of the process parameters that are of interest to the designer should be tested using layers of deposited material, and the effect of each parameter should be examined one at a time while leaving the others constant. There would be an evaluation of the test pieces to determine the process range for each parameter for all of the usable parts that were created. As many test parts as possible should be done during each build as long as the proper settings can be established for each, and the replicates would allow the variability to be quantified. Note that one particular value is not selected in this stage, but it is discovered that the optimal value for every parameter occurs somewhere in the defined parameter window. The second stage is the design and execution of a factorial experiment using these parameters. Depending on the number of factors, levels, and time available, either a full or fractional factorial experiment could be performed. In this way, the effect on the specific property of interest is measured using different levels in the parameter window for each of the parts. The final stage is the
evaluation of the new interaction parameter parts for the property of interest, and the
determination of the optimal process parameter values for the tested material using the
specific AM process.

A validation of this methodology was conducted using the Optomec LENS MR-7
machine housed in the Applied Research Lab at Penn State. A T-shaped test piece was
selected to examine the effect of hatch spacing on the desired thickness of the final part.
Hatch spacings of 0.005 inches, 0.010 inches, and 0.015 inches were chosen to represent the
entire process window. Since the other parameters must remain constant during this process,
Table 1 details some of the settings for the machine during the creation of this test piece.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>450 W</td>
</tr>
<tr>
<td>Scan Speed</td>
<td>25 in/min</td>
</tr>
<tr>
<td>Powder Flow Rate</td>
<td>5.4 g/min</td>
</tr>
<tr>
<td>Track Height</td>
<td>0.006 in</td>
</tr>
<tr>
<td>Track Width</td>
<td>0.031 in</td>
</tr>
</tbody>
</table>

Figure 13 shows the results of the experiment using Stainless Steel 431, with each
one of the parts representing a different hatch spacing amount.

![Figure 13: Hatch Spacing Test Parts - Top View](image_url)
Based on Figure 13, it is clear that the hatch spacing has a large impact on the desired layer thickness as well as other properties that are not being measured for this particular experiment. The values labeled “t” in the figure are the average part thicknesses that were achieved, and a wide range between them was noted. This becomes even more evident as shown by the cross-sections of the pieces in Figure 14.

![Figure 14: Hatch Spacing Test Parts – Cross Section](image)

Typically, at this point a designer would indicate that a particular value for the hatch spacing was the optimal value for this material using this process and select the next parameter to be tested. No such decision is made using the new methodology. Instead, experiments the same as this one would then be performed for other parameters of interest. The results would then be compiled and examined to identify the process parameter window for each. In the hatch spacing test piece, all of the parts were able to be created; therefore, the window for this parameter should be between 0.005 inches and 0.015 inches.

With the results from the individual parameter tests, the second stage of the methodology is to establish a fractional factorial experiment to study the parameters of interest and their interactions. For this example, in addition to hatch spacing, the designers could be interested in the laser power and the powder flow rate of the machine. The goal of the combined test piece would then be to examine the effect that hatch spacing, laser power,
and powder flow rate have on layer thickness. Two levels are selected for each of the parameters, as shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Level</th>
<th>High Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>400 W</td>
<td>500 W</td>
</tr>
<tr>
<td>Powder Flow Rate</td>
<td>3.0 g/min</td>
<td>6.0 g/min</td>
</tr>
<tr>
<td>Hatch Spacing</td>
<td>0.005 in</td>
<td>0.015 in</td>
</tr>
</tbody>
</table>

An elbow-shaped test part was created that was 0.5 inches long, 0.5 inches wide, and 0.3 inches high. Using a half fractional factorial design, four test parts were created because there were eight different combinations of parameter settings. The parts were produced from the same material and using the same machine and settings as the previous experiments. The order that these parts were created was randomized. Table 3 displays the parameters for each of the four test pieces and the parameters determined for each part number.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Laser Power</th>
<th>Powder Flow Rate</th>
<th>Hatch Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500 W</td>
<td>3.0 g/min</td>
<td>0.005 in</td>
</tr>
<tr>
<td>2</td>
<td>400 W</td>
<td>6.0 g/min</td>
<td>0.005 in</td>
</tr>
<tr>
<td>3</td>
<td>500 W</td>
<td>6.0 g/min</td>
<td>0.015 in</td>
</tr>
<tr>
<td>4</td>
<td>400 W</td>
<td>3.0 g/min</td>
<td>0.015 in</td>
</tr>
</tbody>
</table>

All other parameters remained constant at the settings shown in Table 1. PartPrep was chosen as the software used to create the SLI files to produce these parts. Figure 15 is an image of the toolpaths, in yellow, that would be followed for each of the parts with different hatch settings. As expected, the smaller hatch spacing requires more passes by the nozzle in order to complete the build.
Figure 15: Toolpath Images for Interaction Test Pieces

Figure 16 shows one of the test parts during processing, where the laser is active and the stainless steel is being deposited through the four nozzles.

Figure 16: Creation of Interaction Test Parts

Figure 17 is an image of the labeled final interaction test parts after the substrate has cooled and been removed from the LENS machine.
Since the result of interest is the average height of the entire part, calipers were used to measure the height of each elbow at three different points as labeled in Figure 18.

The height of the substrate was measured to be 0.265 inches and the height of the part in the model was set at 0.3 inches, which was a desired total of 0.565 inches. This value was subtracted from each of the measurements to obtain the height differential for the part at each of the desired points as shown in Table 4. A positive differential indicated that the part was built taller than expected at the measured area, while a negative differential indicated that the part was created smaller than expected. The average of the absolute value of the differentials is also displayed because having the part taller or smaller is equally undesirable.
The third stage is the identification of the response surfaces and coefficients that would be used to determine the optimal values for this material using the LENS process on this Optomec machine. The calculated average differentials in Table 4 were then entered into Minitab\textsuperscript{®} Statistical Software to perform this analysis. The software is able to estimate the coefficients for the equation to measure height differential, as shown in Table 5.

### Table 4: Height Differentials for Interaction Test Pieces

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Height Differential 1</th>
<th>Height Differential 2</th>
<th>Height Differential 3</th>
<th>Average Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.214 in</td>
<td>0.146 in</td>
<td>0.122 in</td>
<td>0.161 in</td>
</tr>
<tr>
<td>2</td>
<td>0.168 in</td>
<td>0.131 in</td>
<td>0.125 in</td>
<td>0.141 in</td>
</tr>
<tr>
<td>3</td>
<td>0.146 in</td>
<td>0.132 in</td>
<td>0.130 in</td>
<td>0.136 in</td>
</tr>
<tr>
<td>4</td>
<td>0.018 in</td>
<td>0.000 in</td>
<td>-0.029 in</td>
<td>0.016 in</td>
</tr>
</tbody>
</table>

### Table 5: Estimated Coefficients for Height Differential

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>0.03492</td>
</tr>
<tr>
<td>Powder Flow Rate</td>
<td>0.02525</td>
</tr>
<tr>
<td>Hatch Spacing</td>
<td>-0.03758</td>
</tr>
<tr>
<td>Constant</td>
<td>0.11342</td>
</tr>
</tbody>
</table>

The parameter of hatch spacing having the largest magnitude indicates that it is the most important setting in order to obtain a part with the desired layer height. The sign of the coefficients also reveal that in order to minimize the height differential, the engineer should minimize both the laser power and powder flow rate while maximizing the hatch spacing. Response surfaces can also be used, as in Figure 19, to show the interaction between each of the parameters and how they affect the final height differential that is obtained. The values that should be selected by the engineer are those that are closest to zero, since the height differential should be minimized in the creation of the part. Based on both the estimated coefficients and the response surfaces, for using Stainless Steel 431 on the ARL's Optomec LENS MR-7 the values that proved optimal were a laser power setting of 400 W, a powder
flow rate of 3.0 g/min, and a hatch spacing of 0.015 inches. This was a change from what the laboratory believed to be the optimal values before the experiment was conducted.

![Figure 19: Surface Plots of Height Differential](image)

If there were more complex parameters involved in the interaction experiment, then examining these response surfaces would allow for the discovery of a global maximum since these equations and relationships can be modified to determine individual parameters. This method also uses the procedure itself to determine which of the parameters is the most important without assigning weights to them because the modeling and response surfaces can provide those results. The process parameters have then been optimized using a particular metal for this process and on the particular machine that the designer owns. It is important to remember that some of the tasks, like orientation and supports, need to be done on a part-specific basis; however, many of the machine parameters have been determined using a specific alloy and particle size range. This information is necessary to have during the implemented process planning module, as it requires a database of optimal parameters to allow the designer to consider all options for orientation and support.
Chapter 5

Process Planning Module

5.1 Introduction

The goal in this chapter is to discuss how the analysis of process planning and process parameters is positioned in a larger group of capabilities for additive manufacturing. This collection of modules is currently under development at the Center for Innovative Metal Processing through Direct Digital Deposition (CIMP-3D) through the Applied Research Lab at Penn State. This manufacturing demonstration and research facility includes the Optomec LENS MR-7 machine, and research is being done to develop tools to allow designers to create better additive manufacturing parts. The creation of the modules is being performed to increase the effectiveness and utility of the AM processing that is happening in the facility on a daily basis. This chapter explains the steps in the production of an additive manufactured part and shows how the addition of the modules provides increased capabilities to the design and manufacturing process. The creation of models from the initial design to the finished part is examined, and an explanation is provided of how the modules attempt to ensure that the machine code obtained from the process is going to correctly produce a part using the particular AM machine. This prevents a cycle of failed parts and experimentation until a final design is reached, which saves companies money when direct manufacturing is their preferred use for the machine. Although most companies purchase an AM machine for a specific use or component to be made, the machines at the Center are also being used for research so that new designs and parts will continually be imagined and created using the
processes. It is important to have a consistent procedure through the entire process so that these parts can be made reliably and without prototyping or testing at every single stage.

5.2 Process Planning Module Inputs and Outputs

In order to incorporate the discovered optimal process parameters into a part creation methodology, a process planning module is necessary to interact between the designer and software program. Additionally, the inputs and outputs of the process planning module need to be clearly defined. Figure 20 shows the flowchart of the proposed process planning module, detailing both the inputs and outputs of this module.

![Process Planning Module Flowchart](image)

The inputs to the module include the part model, the process model, and the material properties of the selected part. The part model would be the CAD representation of the object that is desired to be built, which would be in an STL file format if LENS is being
used. It is assumed that by the time the model arrives at this stage it is able to be produced in some orientation by the process. This would work in collaboration with the process model, which would have defined exactly what the specific AM technique chosen is capable of producing. The material properties would be those parameters that are particular to the type of metal used, as well as an understanding of which metals interact well together and which are proper for the type of AM process selected for the part.

Inside of the process planning module itself, the results from the previous parameter experiments are crucial in the decisions that are made. Many of the parameters such as hatch spacing and laser power would have predefined settings that were determined to be optimal, while those related to orientation and support structures would need to be configured at that time. Optimal orientation selection depends on the preference of the designer in relation to three different factors: (1) the amount of support structures, (2) the height of the build, and (3) the amount of space in the X-Y plane the part would occupy. The last factor is very important in direct component production for companies, as it would be desirable that parts had a small profile on the plane so that many parts could be produced at one time. The various options for path planning would also be decided in the module, such as the number of contours and the algorithm used to create the toolpath.

The outputs of the process planning module need to be carefully defined because they must be connected with the other modules that are being developed. The most important output is the machine code itself, which would be a DMC file if the LENS process is selected. The final product characteristics would be recorded in this module but could be tested and evaluated in other modules in the future. The cost and time estimates to create the desired part are important outputs for the designer, as it allows for comparison to easily occur.
between different orientations. The goal is to minimize build time while not causing geometric errors or potentially leaving a section of the build unsupported. As referenced in the software comparison in Section 3.4, many of the programs have the ability to provide time or cost estimates, but the cost estimates tend to be more unreliable since much of the data needs to be entered by the user.

5.3 Module Development

The proposed process planning module is supported by others which are currently in development. In order to create a part using additive manufacturing, a designer would follow a series of steps to progress from an idea to a final part. The design of the product would need to be done using CAD software, keeping in mind the limitations that each AM process has in its ability to produce parts. The toolpath would then need to be generated to allow the machine to follow a specific set of commands. This step would also involve the addition of any support structures necessary and many of the other parameter decisions. The part could then be produced using the AM machine, and then any post-processing such as the removal of supports, separation of the part from the substrate, or increasing of the durability of the part through treatment would occur. The flowchart in Figure 21 demonstrates these steps in a linear fashion.

![Figure 21: Traditional AM Production Flowchart](image)
There are some issues with this flowchart for creating manufacturing parts. It is completely a feed-forward approach and pushes towards the creation a final object which, if any parameters are defined incorrectly, could fail to produce the part. If the part was unable to be created, then there would also be no feedback as to where there was an issue in the process. The design could simply be impossible to make using the chosen AM process, there could have been a machine setting that was incorrect, or more supports could have been necessary in order to make the part. There is also no consideration of the microstructure of the final part or other possible problems that could occur if the part was being made with two different metals [16]. Thermal effects such as distortion and curl could also be occurring in the part which would lead to undesirable results [18].

It would be far better to have a series of checks and balances throughout the flowchart to ensure that the part that is being produced is able to be made with the chosen AM process. In order to establish this, modules were developed to interact with each other to provide a more intelligent design. This proposed AM production flowchart can be seen in Figure 22.

![Figure 22: Proposed AM Production Flowchart](image)

Notice how a direct progression through this flowchart is not always assured, but rather there are opportunities to proceed back to a previous stage in order to correct a potential issue or rework the product. However, in order to manufacture the part, every design must still pass through each of the different modules. Information flow between the
various developed modules is very important, as ultimately the designer should use these as a tool in order to ensure success in the production of the part. The design for manufacturing module does not have any inputs besides the desire by a designer to create a part for manufacturing. Inside of this module, design guidelines would be present to help guide the production of a part to be made using additive manufacturing. Since CIMP-3D contains multiple AM processes, this module would indicate which machines could be used to feasibly make the part by analyzing the design features in the model. Some of the features of interest to the designer would be the minimum hole diameter, the maximum height to width ratio, and the minimum radius of curvature [18]. If none of the processes were able to make the designed part, it would offer detailed suggestions about how to change the model so that the part could be produced. It would also need to be compatible with a design package, such as SolidWorks. The outputs of this module would be the part in an STL file format which passes all of the feature tests for a particular process.

The primary focus of the thermal simulation module in Figure 22, which is utilized after the process planning module described in Section 5.2, is to describe the transfer of energy from the laser beam of the process to the deposition material. It is also able to calculate the temperature dependent properties of the part. The input for this module would be the toolpath code that would be used to make the part on the machine, which would be the DMC code in the case of the LENS process. An example of the output for this module is seen in Figure 23.
It is possible to examine how the temperatures are predicted to change over time by continuing to move through the toolpath in the simulation. This module would alert the designer to any issues in the creation of the part, such as distortion in a particular area due to repeated high temperatures. This information could then be returned to the process planning module, where the toolpath could then be altered. For example, if one section of the contour in the part was experiencing abnormally high temperatures, then it could be changed so that the contour would start in a random area of the part every time. This could prevent the rapid increase in temperature and ensure that the part would be able to be created. The output of this module would be the temperature distribution over the build time for the part.

The last module before the part could be manufactured is the microstructure and phase prediction module, which would take the thermal history data and simulate the evolution of the microstructure of the metal over time. The phase prediction portion of the module is useful when two metals are going to be combined and the grading of the materials needs to be observed to ensure that no intermetallic phases are formed. The outputs of this module would be a pass or fail notification, and a failure would have the designer identify the issue in the thermal distribution and then adjust the process parameters accordingly. For
example, scan speed has a direct impact on the liquid phase of the melt pool and therefore the microstructure that is formed. If the part passes, then it could be produced using the toolpath established in the process planning module. Any post-processing would then occur after the part was created.

5.4 Demonstration Part

In order to examine how this module enhanced flowchart would function, a sample part could be constructed using a rescaled version of the Nittany Lion Shrine, one of the major symbols of campus life at Penn State. Figure 24 is a photograph of the lion in its location in the northwest portion of the college grounds.

![Figure 24: Lion Shrine Image](image)

If a designer wanted to create this object using additive manufacturing, the first step as outlined in the flowchart in Figure 22 would be the design for manufacturing module. A digital scan of the statue could be performed and placed into a CAD program, and the CIMP-3D name could be added to the front of the part as shown in Figure 25.
The design for manufacturing module would examine the scanned geometry to determine if there were any areas of the part that would not be able to be created using additive manufacturing, as well as examine the geometry for any defining features that could cause difficulties in processing. Although there is a space underneath the stomach that would not be supported when constructing the part layer-by-layer, it can be filled in with support structures that would be removed in post-processing. There are also no strange angles, cavities, or holes in the part to be particularly concerned about when conducting the manufacturing process. If the model passed all of the design guidelines, then it is converted into an STL file for the next stage.

The process planning module then examines the STL file and load the specific parameter set for the machine and material that the part was going to be made out of, which would be stainless steel in this example. The orientation would be selected as shown in Figure 25, because turning the part over to the curved back or standing it up on either the tail or head would result in more support structures than the flat base on the bottom. Although support structures would be suggested by the software for the lettering in the front of the base, these would be too small and would be eliminated from the model before slicing. There would also be a large amount of support structures needed under the head of the lion,
and when those supports would be extended directly downwards they would end inside the base of the model. This group of support structures would be brought forwards and outward to allow for easier removal. The STL file would then be converted into an SLI file, which would contain the information for each of the layers. The SLI file would then be changed into a format that could be read by the machine and used in the future modules. An estimation of the processing time would be calculated and checked if it was acceptable to the designers. If not, then they would need to reconsider the slice parameters or orientation of the part during the construction.

The machine code would then be entered into both the thermal simulation and microstructure and phase prediction modules. Assuming no issues with the thermal history data or microstructure development, the part could then be constructed. A completed part would look as shown in Figure 26. Post-processing would then need to be done to remove the supports by the head and those smaller areas located under the body.

Figure 26: Completed Lion Shrine using AM at CIMP-3D
Chapter 6

Conclusions and Future Research

This research has demonstrated the development of a process planning module for use with LENS metal additive manufacturing. Additive manufacturing is able to create near-net shapes that are impossible to make using other processes, and it has applications in many fields including prototyping, tooling, direct part manufacturing, and maintenance and repair [9]. Through its international growth since being introduced two decades ago, AM is poised to allow designers to create parts in many different industries including the aerospace [10] and medical fields [11].

The flowchart from CAD file to finished part was created, and every file format in the process and the conversion between each was mapped. Due to the numerous decisions that designers need to make in order to use additive manufacturing to produce parts, a process parameter framework was necessary in order to organize these into a series of tasks that could be followed. A description of each of the parameters was provided, as well as a discussion of the various software programs that could be used with the LENS process. Each of the programs presented had strengths and weaknesses, and a matrix was created to show the choices that designers have in the creation of their parts.

The methodology that companies currently use to determine processing parameters for AM machines was discussed, in which one parameter at a time is examined using a series of test pieces. These test parts would then undergo experimentation to determine which value for the parameter was best, and this setting would be established for that material and that machine. It was noted that due to the interaction between the parameters, the values that
were obtained might not be optimal for the machine. A new methodology was presented in which three steps would be followed in order to determine optimal parameter settings: (1) a series of test pieces would be examined to determine the process window for key parameters, (2) an experimental design would be formed that tested these parameters and their interactions at the same time, and (3) response surfaces and equations would be created with these results. From these response surfaces, the relationship between the parameters can be assessed and a set of values can be chosen that would give an optimal result for the designer.

The inputs and outputs to the process planning module were defined, and it was discussed how the module would use the experiments conducted and the optimal parameters determined in order to manufacture parts. It was also established how this module would be connected with others in development in order to revolutionize the typical linear flowchart in which parts are created today. Using simulation techniques to determine the microstructure of the part before creation would allow for the identification of potential defects that could form in the production process. A demonstration part was also discussed and guided through this flowchart to show the responsibilities of the various modules and the potential to identify issues before the part fails in the AM machine.

In the future, research in this field should be developed to ensure that companies continue to embrace the technology and integrate it into their products. This includes the creation of less expensive machines and continuing to simplify the procedures needed to construct designs. It is possible that the manufacturing plant of the future consists of a warehouse with AM machines creating every component needed in the final assembly for a part. Comprehensive work should also be done on the environmental impact in using additive manufacturing, as a focus on sustainability would be of interest to companies. With
the introduction of smaller machines intended for home use, the average consumer is also becoming aware of the technology and beginning to find innovative ways to implement it in their own lives [3].

In order to use the equipment to its fullest potential, the engineer of the future must be able to understand both the process and the limitations. More individuals need to be trained not only in the types of products that can be created on the machines, but also on the material properties and process capabilities so that models can be made that are truly designed for manufacturing. This goal can be obtained through information distribution in research and development as well as designer experience with many different kinds of AM processes. Every day that users continue to advance the technology and produce new designs, society is closer to saying for certain that “if you can dream it, we can build it”.

REFERENCES


