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Development and initial results for roller-deposition metal powder bed laser fusion additive manufacturing

Dakota Wayne Morgan
Iowa State University

Development and initial results for roller-deposition metal powder bed laser fusion additive manufacturing

by

Dakota Wayne Morgan

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Program of Study Committee:
Emmanuel Agba, Co-major Professor
Pranav Shrotriya, Co-major Professor
Matthew Frank

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NOMENCLATURE

Additive Manufacturing: A category of manufacturing where an object is fabricated by constructing layer upon layer with a given material.

Powder Bed Fusion: A process where powdered metal is spread over a build area before being melted into the required geometry layer by layer.

EDM: Electrical Discharge Machining – A manufacturing process that utilizes electrical current within a conductive wire to burn through metal.

Delamination: A separation of layers due to thermal warping, or insufficient powder distribution during layering.

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ABSTRACT

The process of metal additive manufacturing is becoming increasingly economically viable over traditional subtractive manufacturing processes. However, due to the infancy of the technology, there is a lack of documentation on how to rapidly and efficiently design and fabricate a given part. Our research at Iowa State University aims to aid in the discovery and communication of knowledge on the process as well as increase industry understanding of the modern additive process. Initial focus will be in support structures, as the technology requires a connection between a part and the base plate. This report will give an introduction as well as cover the key understanding and developments with support structures for metal additive manufacturing. A large volume of work has been completed during this research in collaboration with industries around Iowa. Many unique projects and designs have been fabricated utilizing this technology, each with their own unique challenge and outcome. This paper will discuss much of the work completed with these companies around design for additive, and the volume of new insights gained from each project.

CHAPTER 1: INTRODUCTION

Motivation

Metal additive manufacturing is a new and powerful tool brought to realization by modern technology. With metal additive manufacturing, entire new areas are now a possibility for manufacturers. However, with this new technology comes new challenges to overcome.

Initial Goal – Support Structure Generation for Powder Bed Additive Manufacturing

The initial introduction to this system was at its delivery in October of 2015, where a training session was held for those who intended to utilize the system. During the training, we were shown the methods to running a system this complex, and how to set up the software to create a build file. With this software, there were very few given variables to start with. It was found within the first day that the support structures would likely be a challenge for the operator. At this point, the initial goal for this research was outlined to develop an understanding of the different support options provided with the system and how to best utilize them for different geometries.

Developed Goal – Design for Additive

As the understanding of the support structure options and their abilities were improved, it was found that often the likelihood of a failed build could be minimized with slight modifications to the CAD file. When working with companies who had never utilized a metal additive system, the designs that were submitted tended to be vastly over-built for the function. This is largely due to the designs being created with subtractive manufacturing in mind. Once designs began to be modified, the success rate was improved rapidly. While every new design is unique, several core concepts have been discovered to assist with this additive process.

Process for the ProX300 System

The system which was purchased for Iowa State University is a 3D Systems ProX300. Phenix systems initially developed this system before being bought out by 3D Systems. The ProX300 is a metal powder bed fusion printer which utilizes a fine steel powder for the build material and a 500-watt laser to melt the powder into the required geometry.

This system was the largest available at the time of purchase, allowing a 250 x 250 millimeter build area. When considering ~~the~~ purchasing ~~of~~ the system, the larger build area was needed for the planned fabrication of injection mold tooling. Additionally, a core difference between this system and others of similar size is the use of a compacting roller. Where most systems available currently utilize a rigid blade to spread powder over a build area, this system uses a carbide roller. When spreading the powder with this roller, it compacts the powder at each layer which results in a denser material profile. This increased density has the added benefit of enabling larger overhangs, including completely unsupported material where the geometry allows. This compacting ability enables this system to create conformal cooling which has been a large component when developing injection mold tooling with Iowa companies.

What is Powder Bed Fusion Additive Manufacturing?

Most engineers and designers will come across a ‘3D Printer’ at some point in their careers. Typically, these are plastic extrusion printers used to prototype an object or design. When looking at additive manufacturing, there are three main objectives: Form, Fit, and

Function. The plastic printers are typically capable of creating an object that can represent the form of an object to better understand its shape, scale, or relationship to another object when prototyping. Higher quality printers utilizing finer materials are further capable of testing the fit of a part. Using higher quality printers allows users to achieve enough precision to accurately represent a part or component in an assembly or use scenario. The final objective of function has only truly become realized in industry over the past decade with higher precision systems and more robust materials.

Development

The latest technology to gain widespread use in additive manufacturing is Metal Powder Bed Fusion. This technology allows for the creation of fully solid metal and ceramic parts with accuracies under 10 µm (0.0004 inch). This accuracy means organizations can now develop and print designs that can be used functionally in prototypes as well as production parts.

With an estimated threefold increase in additively manufactured production volume expected in the next five years [1], consumers will increasingly find products and components fabricated with this technology in their daily lives and commutes. With these exciting advances projected for the next few years in additive manufacturing, the core drawback remaining is a lack of a collaborated knowledge base between industry, vendors and academic researchers.

Additive manufacturing has been around since the mid 1980’s and as such has had decades of research and learning supporting development. However, with each advancement in materials, from resin to plastic, to metals, the understanding of the process requires an increased understanding of the material in use. It can be safely stated that the fundamentals of Stereolithography (SLA), Fused Deposition Modeling (FDM), and similar technologies are largely understood. Research in these areas are now moving towards new materials and hybrid materials such as composite integration with nylon [2].

Current uses

This technology is currently being utilized by industries across the globe. In any area where design complexity, quality, fabrication speed, or weight is a concern, you can easily find companies beginning research into metal additive manufacturing. One of many recent examples are the advancements in additive manufactured aircraft fuel nozzles. Previously these nozzles would be manufactured through a series of separate procedures on multiple technologies including casting, machining, and welding. At any stage in this process, a small defect in the part could require the producer to rework or even scrap an entire assembly.

Future Market

Metal additive manufacturing has shown to be an exciting opportunity for many companies, as the fast-paced development in the modern market requires rapid advancement in new and efficient designs. When companies develop new products and components, the prototyping stage typically takes weeks if not months. During the process, costs for tooling, machining, and rework can hinder development progress and speed.

Even when considering daily manufacturing, companies are losing money in the form of chips and scrap. When creating a part with subtractive manufacturing, much of what is being removed from the stock material can no longer be used without extensive processing. With metal additive, upon completion of a build, any remaining material is vacuumed within the system before being run through a fine screen and recycled back into the supply. Metal additive manufacturing can provide over 90% powder recovery with minimal material degradation.

When a new technology is developed, its impact on the manufacturing community can be measured by how much faster or easier it can make a process. At its core, powder bed fusion is creating parts that will result in material properties similar to a casting process. The key difference is that manufacturers are no longer limited to geometries defined by sand molds or lost-wax casting processes. With powder bed fusion, if the part adheres to a few basic geometric constraints, nearly any design can be created. In addition to geometric improvements, the process itself can yield a stronger and harder part compared to a cast counterpart. With each layer achieving a full melt of the material, issues such as porosity and inclusions that can invalidate a cast part are minimized. Parts can also now be created with intricate structures such as lattices and complex hollow pathways, which are difficult if not impossible to machine with subtractive processes.

This ability has shown particularly beneficial when considering injection tooling. With the ability to fabricate true conformal cooling, cycle times can be reduced to increase output. The resolution of the print and the understanding of the laser parameters allows for parts to be completed that require minimal post processing when compared to a cast counterpart. Additionally, when comparing to a casting process, the layering resolution and compacting nature of the process minimizes porosity within the fabricated part which will result in a longer-lasting tool.

How does Powder Bed Fusion Additive Manufacturing Work?

This process begins with fine metal powder which consists of 5 to 35 µm diameter metal beads for stainless steel powder. This powder is held in an area within the system next to the build plate. As the layering progresses, a small quantity of powder is raised and transported to the build plate with a blade. Once it is at the plate, a roller spreads the powder onto the plate at 60 µm before returning across the plate at 40µm to compact the material for layering. At this point, the roller and scraper return for the next layer and the melting begins (Figure 1). A 500-watt laser is used to melt the steel powder first to the solid base plate, then to the previous layers of melted material as the build progresses as shown in Figure 2. To obtain optimal melting conditions, the build chamber is maintained at a low oxygen environment with a nitrogen purge. The layering then continues at 40µm layers until the build reaches the top of a part as shown in Figure 3. Once the build is complete, an internal vacuum is used to clean any powder from the build plate and part. At this point, the plate is removed from the system through a bypass door. This bypass allows the system to maintain a clean, dry, low oxygen environment and easily remove a build from the chamber.

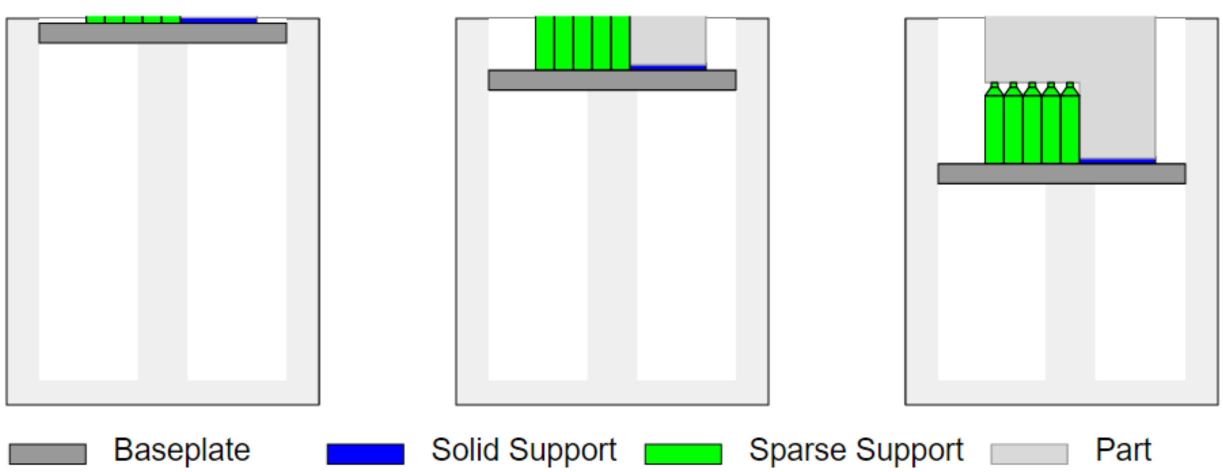


Figure 1: Initial layering pattern

Figure 2: Geometry progress partially through the manufacturing cycle

Figure 3: Geometry with manufacturing mostly complete

Build volume

For the ProX300, the build volume is 250x250x320 mm, which was at the time of purchase, the largest build volume commercially available. The primary driver for purchasing such a large volume system was to give Iowa State University and CIRAS the ability to fabricate injection mold tooling. Since October of 2015, a large portion of the build time for this system has been with injection molds for companies around Iowa.

As shown in Figure 4B, this system utilizes a powder storage area to the left of the build area. This storage can hold up to 400 mm of powder which would allow for several days of build time. The build surface consists of a 250 x 250 x 25 mm base plate as shown in Figure 4F.

Material

The system in use at Iowa State is capable of fabricating with stainless steels, titanium, aluminum, and ceramic. These materials come as a fine spherical powder between 5 and 35 microns in diameter. For the information covered below, the material in use will be a 17-4 PH stainless steel. This material was selected due to its lower cost, frequency of use in industry, and relative safety in handling. The 17-4 PH material is very comparable to a 416 to 430 stainless steel, and the parts fabricated are mechanically comparable to a cast 17-4 PH steel with heat treatment.

Laser

The ProX300 laser is a 500-watt fiber optic CO2 laser which is directed by two galvanometric mirrors. These mirrors swivel rapidly in the X and Y-axis at the same time which allows the system to locate the beam on the build plate to within a few micrometers. Between these mirrors and the build area is a fused silicate lens (Figure 4C) which takes the beam and focuses it to approximately 100 micrometers.

The user-defined settings for the laser will directly impact the part being fabricated. The key two variables that the user will control are the speed and power. Due to this process being so comparable to welding, these inputs will yield similar outputs when varied. By increasing the heat or energy input into the material, the resulting density, hardness, and surface finish can be varied or improved. Additionally, when considering the laser diameter for this process, the resulting dimensional accuracy can be improved with proper testing and understanding of the laser parameters.

Roller

As stated previously, one key difference between the system in use at Iowa State and other commonly utilized metal powder bed systems is the utilization of a roller for the powder deposition. Shown below in Figure 4, powder is first scraped from the supply (B) by a blade (E) until it reaches the build area (A). At this point, the roller (D) will roll counter-clockwise over the build plate at 1.5 times the layering depth to spread the powder over the previous layer. Following this, the build is raised to the proper layering depth and the roller spins counter-clockwise back towards its origin. The purpose of this dual layering is to evenly spread the material over the build area and then compact the material into a dense layer. In contrast, most other systems utilize a rigid blade to deposit the powder over the build plate without the use of a roller. This can potentially lead to a reduction in material density, and an increase in porosity. Lastly, the use of a roller to deposit powder can be more forgiving when working with more complex geometries. For example, if a design required the use of an overhang angle larger than

45°, during the build process, the overhang would create a ‘knife-edge’ or a sharp edge. This occurs whenever a layer has geometry being melted over a previous layer with a smaller footprint. If the angle is extreme enough, the overhang will often warp after the laser has melted the material as the new layer cools. With the compacting roller, the lifted area will be pressed downwards, typically allowing the build to continue. Systems with a rigid blade would instead impact this lifted area, causing the coverage to stall, or build failure.

Plate

As a part is being fabricated, heat will build up within the material. Once layering has progressed further into the height of the part, the lower layers will begin to cool and contract. While it is possible to design a part to reduce this thermal cycle, the non-uniform nature of this additive technology requires more advanced models and tools before it can be truly understood and optimized.

One key drawback to this technology is part removal after the build process. In contrast to many plastic printing processes where the part can be simply broken from a build plate, or have a secondary material dissolved, metal additive technology uses supports of the same material as the part itself. This means that the supporting material must be cut, broken, or machined from the part upon completion of a build. While technologies such as electrical discharge machining can expedite this process, support removal from the part must always be considered during design.

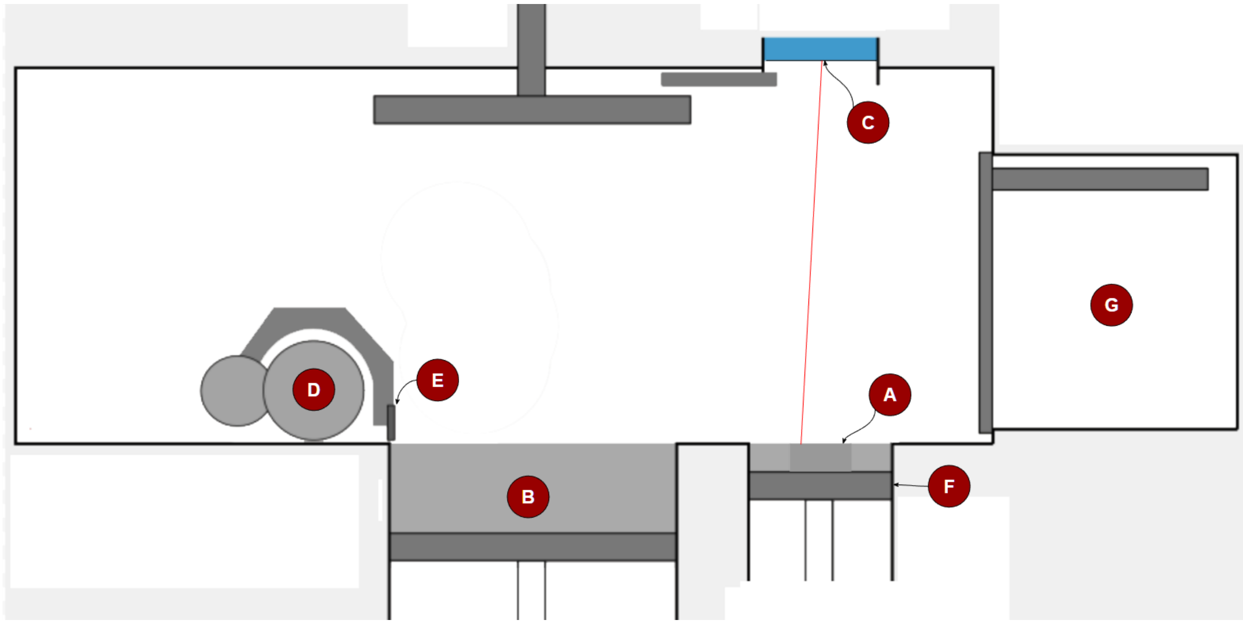


Figure 4: System Layout Diagram

Overview of This Research

This reading attempts to expedite and refine the optimizing of part support structures to minimize post processing requirements. The following documentation covers initial parameter testing followed by sparse and full support parameters. Each type of support has its own benefit and drawback for given part geometries, as well as numerous options for parameter settings within each category. Due to the wide variety within the baseline support structure settings as well as the wide variety of potential part geometries, this research will primarily cover methods to rapidly obtain parameter ranges for a metal additive system. Once baseline results are established for the support options, further work can then be completed to refine and improve designs for individual parts. A large variance of parameters and designs will be gathered to better understand and extrapolate for new and complex geometries. The initial results derived from this research will be presented in this paper, to provide insight for the industry and researchers alike to rapidly understand one of the key obstacles when first learning about this new technology.

Industry involvement

To bring these benefits to a larger segment of manufacturers, communication between industry and educational institutions is vital. Research can always be completed around baselines and ideal cases to get a general idea of what this technology is capable. To advance the knowledge and capability around metal additive manufacturing, new and varied designs and geometries from industry must be tested and shared.

CHAPTER 2: METHODOLOGY FOR DEVELOPING SUPPORT STRUCTURES

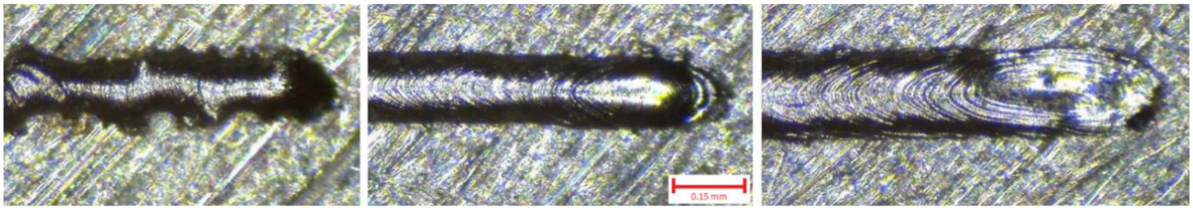
Parameters

There are two types of support structures used to hold printed parts during fabrication; active and passive supports. Passive supports are used for 3D printing of parts in a loose powder. With this method, the parts will 'float' in the powder during the fabrication process. The more common method of supporting a part during fabrication is active supports. Active supports are used to support any geometry that has an overhang or angle beyond what the technology being used is capable of. With active supports, a direct connection is created during the layering process between the base plate and these overhang geometries. This means that the part is fixed to a base and the supports must be later removed. This is simple for plastic printing, as the supports can typically be broken, cut, or dissolved from the part. For metal additive manufacturing, however, these active supports are required to be fabricated with the same material as a part. Additionally, these support structures must be strong enough to keep a part fixed during fabrication. Due to the added heat input during the melting process as the laser is firing, the designs will typically expand or shrink during fabrication. As the layers build up, the lower layers will cool down and begin to contract. This adds an additional level of difficulty when working with metal additive, as this increased tension will readily detach a part from supports during fabrication if the support geometry and strength is not properly set beforehand. The easy solution to this issue would simply be to maximize the strength of these supports. However, once the part is complete, the supporting material must then be removed. If the support geometries are too strong, it can add unnecessary post-processing time to a build. To minimize post processing, it is important to understand how to optimize settings between support structures. The goal is to find a balance between supports being too weak and failing and being too strong to easily remove.

One-Dimensional

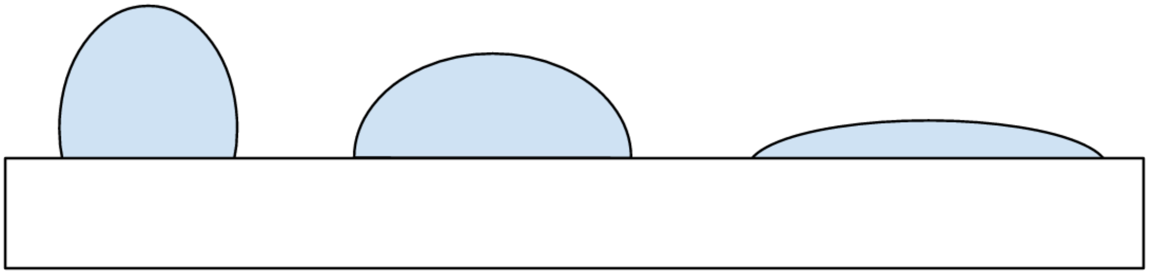
To find a range of parameters for support structure options, a 1-dimensional test was first performed. Due to parts being fabricated with supporting material connecting directly to the base plate, we will start there. The base plate used with this technology is a 25-mm thick plate of a similar material to what is being used in the additive process. To obtain optimal connection strength between the part and base plate, a baseline needs to be established for a parameter range. To accomplish this, the visual qualification of a bead can be used to assist in determining the optimal setting ranges. As the laser passes across the powdered steel, it creates a melt-pool similar to most welding processes. In the same form, the amount of energy being put into the material as well as how fast the energy input point is progressing will have a large impact on the result of the material properties.

To find an optimal range of laser power and speed, we begin with identifying what qualifies as an ‘optimal weld bead’. The simplest comparison would be to observe what a correct weld for standard stick, arc, or wire welding consists of. Several factors will influence the quality of a weld including geometry, consistency, straightness, and smoothness [3]. These factors can be inspected to rapidly determine an approximate range of optimum settings. When determining the quality of a weld bead visually, the standard industry practice is to utilize these visual traits. By understanding how a melt pool reacts to differing power and speed inputs, adjustments can quickly be made to improve the resulting weld. These adjustments translate to an increased penetration, strength, and durability of the weld. It was found that while the scale is significantly smaller, the material melt pool features were comparable to that of a larger scale melt pool. With most common welding systems in use today, a bead width of 5-20mm can be expected depending on the technology and power source. With metal additive, the bead width will typically be 0.1-0.2mm across. As shown in Figure 4, the way a bead will form during the melting process is comparable to larger scale welding. To better understand this interaction, the cross section of a given bead can be visualized for each scenario. In Figure 5, there are three typical cross sections of a weld bead. This understanding is crucial to the next stages of outlining parameters, as the consistency, straightness, width, and height of a bead will directly impact surface quality, porosity, and layering consistency.



a) Low power and high speed	b) 'Optimal' ratio of power and speed	c) High power and low speed
Power: 100 W	Power: 150 W	Power: 200 W
Speed: 250 mm/s	Speed: 175 mm/s	Speed: 100 mm/s

Figure 5: Microscope images of low, median, and high energy input weld bead of 17-4 PH stainless steel powder



a) Too low power input or too fast progression

b) 'Optimal' bead on a flat surface

c) Too much power input or too slow progression

Figure 6: Cross-section diagram of conceptual weld bead model for the initial layer on a plate

A matrix of power and speed settings was created to obtain a full range of results for this experiment. For the test, power was varied from 50 to 200 Watts and speed was varied from 100 to 250 mm/s. In the case of stainless steel on a stainless base plate, an optimum weld bead was formed between 150-200 Watt output and 175-225 mm/s velocity range as shown in Figure 6 below. The quality of each bead was compared and rated on a 0 to 10 scale for bead straightness, consistency, and spatter. Looking at Figure 6, it was clear that anything at 75 watts and below would be suspect due to the inconsistent or incomplete beads. Taking the rating measurements for the remaining values results in the Figure 7 and Figure 8 below. Incorporating trend lines illustrates a clear relation between the three quality factors that were judged.

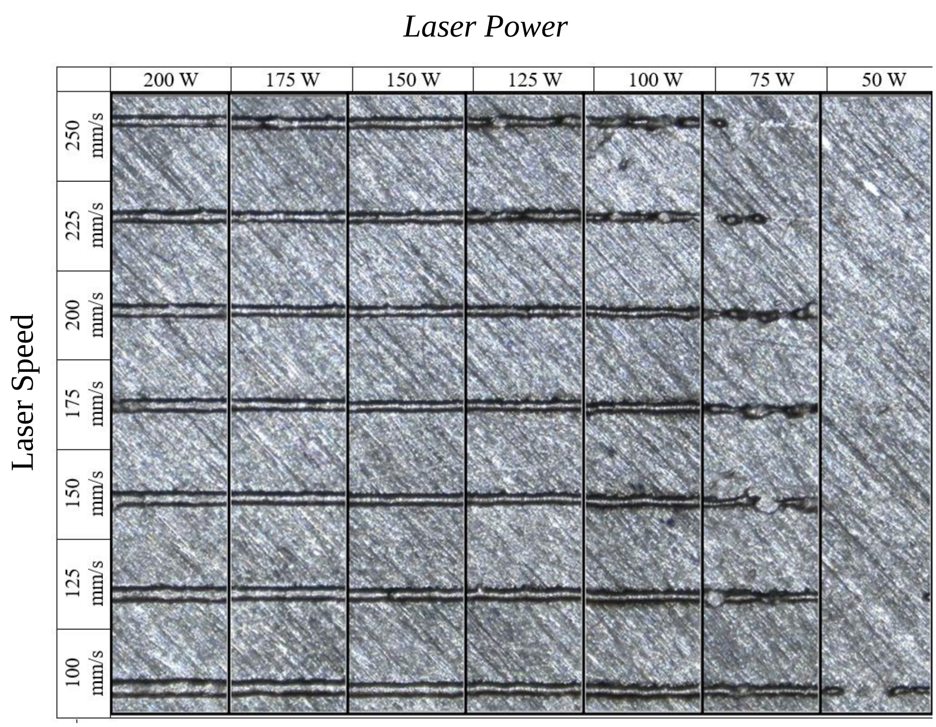


Figure 7: Laser Power and Speed impact on single line melt pool

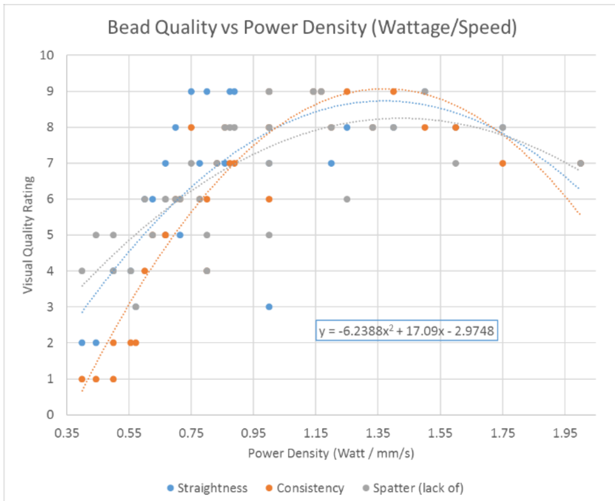


Figure 8: Overall Bead Quality Trend

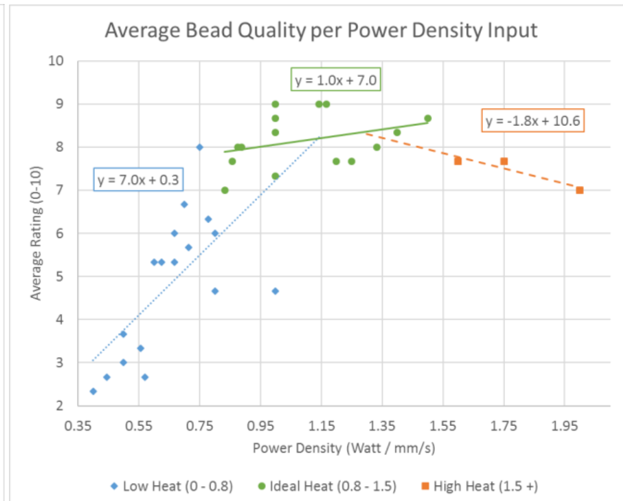


Figure 9: Averaged Quality Trend Regions

The consistency of the trends shown in Figure 7 give several insights that can be utilized in the next steps of determining support structure parameters. First, the data shows a sharp decline in quality when the power to speed ratio drops below 0.8 which covers settings that are higher speed or lower power. At the top of the curve between 0.8 and 1.5 are a larger clustering of high ratings. This area is where a good consistent bead was formed. Finally, the far right of the graph dips back down in ratings beyond a ratio of 1.5 for the power density. These readings are in reference to settings that are slower or higher wattage than the 'good' range. In both figures, equations are shown as derived with the best fit function. Figure 7 utilizes a 2nd order polynomial trend line, then Figure 8 utilizes a linear trend for each section of data points.

To have a more refined method than simply allowing a range for each setting, the data can be averaged across the three ranges to yield a linear equation for our 17-4 PH stainless steel.

Table 1: Averaged bead quality lines

Cold or low melt bead:

$$where\ x = \frac{Power}{Speed} < 0.8 \ \rightarrow 7x + 0.3 \tag{1}$$

Consistent, quality bead:

$$where\ x = \ 0.8 \leq \frac{Speed}{Power} \leq 1.5 \ \rightarrow 1x + 7 \tag{2}$$

Hot or high melt bead:

$$where\ x = \frac{Speed}{Power} > 1.5 \ \rightarrow -1.8x + 10.6 \tag{3}$$

While this method can assist with obtaining a high-quality bead, these results are still purely empirical. As such, they would be used primarily as a methodology to increase the speed at which new material parameters could be found. In addition, there may be cases where increasing or decreasing the heat input to a material can be useful. For example, decreasing the heat input for a sparse support could give a weaker support structure under an area that is not likely to see stress, but would still require support due to geometry limitations. Increasing the heat input would result in a more distributed melt pool, or in the case of a solid area, increase the surface quality or reduce porosity.

Thin Wall Support Structures

Once the baselines of the melt pool are understood, a designer can proceed to finding optimal support geometry parameters. Support structures are required due to the physical nature of the manufacturing process. To melt the material, it must be heated with the laser to at least 1370°C (2500°F). While each bead of material is less than 200 μm across, residual heat coupled with the subsequent cooling between layers can cause a part to warp as much as 1 mm over a 25-mm length. Supports must be selected to maintain a complete and structurally sound connection to the base plate and avoid failure due to warping. [4] [5] These supports primarily consist of sparse and dense geometries. For this study, focus will be on grid or blade geometries as well as a fully solid support.

Working off the data from the previous section, the parameter range from the bead tests can now be utilized in a 2-dimensional design. This sparse design is primarily used in areas where geometry requires support, but also must be removed once a part has been completed. These sparse supports are typically built up as a thin wall up to the part as shown in Figure 1 to Figure 3 in green. These thin wall supports allow a part to maintain connection to the plate while also providing the ability to easily remove structures once a build is complete.

Grid Support

Grid supports are commonly used in areas where there is a curvature that would take excessive time to clean up in a post-fabrication process. Grids utilize a small connection area over many points (Figure 10) to reduce the contact with the part while still maintaining enough support to melt the initial layers of a part. Grids should be optimized to maintain surface quality at any connection area. [6] [7] Additionally, grid support laser settings can be controlled to increase or decrease strength as shown in Figure 11 below.

To find optimal support geometries, it is imperative to understand how the settings found in the 1-Dimensional test will interact when layered over one another. For 17-4 PH, the layering height is typically held at 0.04 mm. This means that at each layer of the process, the laser will be melting through 0.04 mm of powder onto the previous layer. Here, the geometries found in Figure 7 and Figure 8 can be used to better understand interaction between layering, laser power, and laser speed. Consistent material build-up height is critical for a machine using rollers, a factor in this experiment. Beads above this threshold can potentially cause the roller to impact the part or support during the layering cycle. The power density settings must be carefully considered to avoid material building up in uneven layers. This is shown in Figure 10 as shiny areas where the roller would pass over the high spots with enough force to smooth the lighter zones. The benefit for fabricating colder layers is that the grid supports will be weaker and easier to remove from a part [8]. However, this will also increase the likelihood of the support failing during the building process. To increase the strength of these supports, the power can be increased to create a wider, fully melted grid support structure. Comparing the grid supports in Figure 11 shows a clear difference between the hot and cold layering settings.

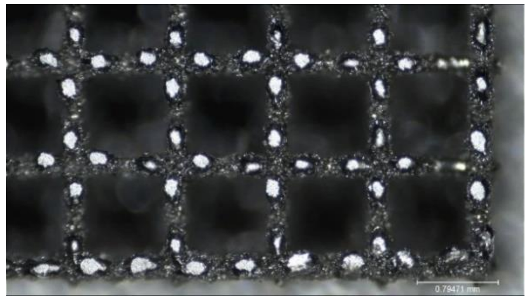


Figure 10: 4x image of grid supports captured in the Z-axis

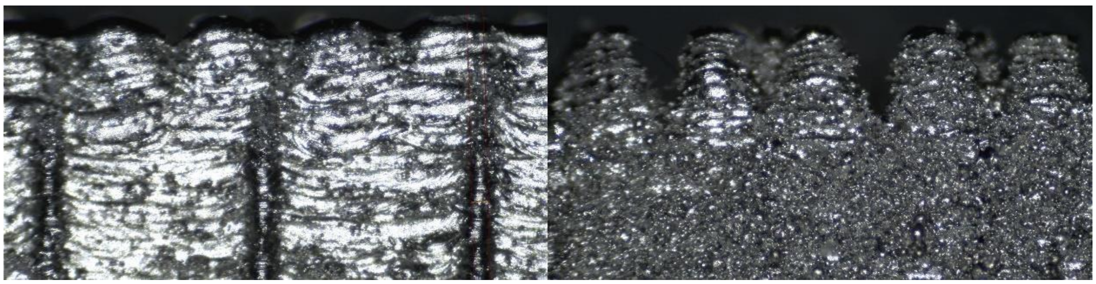


Figure 11: Comparison of high heat input (150W left) vs low heat input (75W right) when building support structures

Solid Support Structures

Continuing from what was discovered in the previous two sections, testing can now be done on the third dimension of support structures, or solid supports. Where grid supports added the layering variable, the solid support adds a spacing or 'hatching' variable. Hatching is the term used for the fill pattern in a design. This is shown in Figure 12in the diagonal lines visible on the structure. The hatching can be varied based on material and layering settings, but for the 17-4 PH, the spacing is set at 0.06 mm between each line. Generally, the laser settings for the solid geometries are set to be significantly faster at a higher power. This decreases the duration of a build while still getting adequate coverage due to the 0.06 mm spacing being significantly closer than the average bead width of 0.15 mm from earlier testing. However, as pointed out with the discussion before Figure 5 of the weld bead diagram, the bead geometry at this stage is integral to several material properties. If the bead layer deviates significantly from 0.04 mm, the layering will become uneven. This can cause issues with porosity and decrease the mechanical strength of a part [9]. To minimize potential layering inconsistencies, the laser settings are constrained to a more specific range than what was available for the sparse supports. The power and speed settings must be controlled in a way that will not allow excess heat to build up within a part and cause potential warping or delamination as previous layers begin to cool.

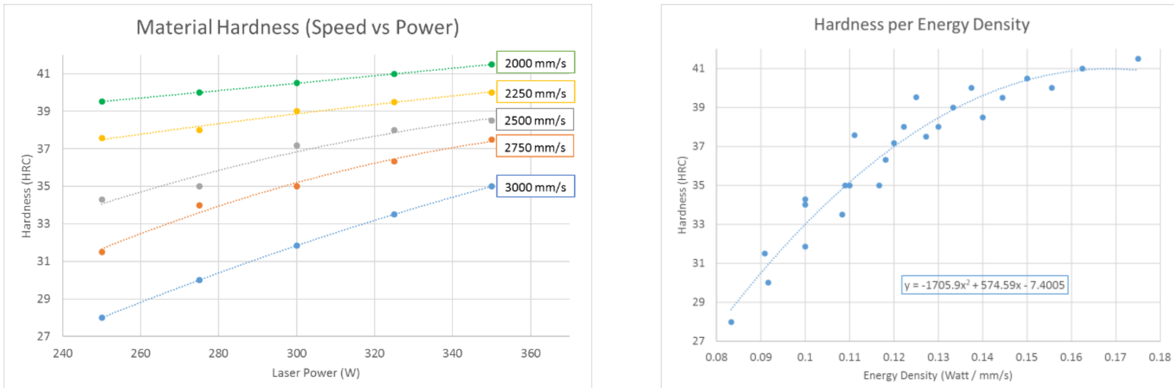
Full Support

Full support is the preferred option for large or flat geometries. Full support is a layer where the laser beam passes in parallel lines to fill in an area as shown in Figure 12, utilizing similar laser settings to that of a part. The main difference is that the power and 'hatching' or beam spacing variables can be controlled to increase connection strength to the base plate or reduce density where the support connects to a part. Providing complete solid connection between the part and the plate allows for reliable material buildup with minimal risk from large or unusual geometries.

Figure 12: 2x image of a solid support layer

Full support and general part parameters can be tested at the same time due to their fabrication similarities. To determine optimal laser settings, an array of 25 values were created around the default settings of 300 Watt at 2500 mm/s given with the system. These settings were then used on 10mm samples and tested for their surface quality and hardness. In the following

Figure 13(a), there is a clear hardness relationship between laser speed and power. These values can further be compared to the energy density, or power divided by laser speed, as shown in Figure 13(b). The results are comparable to a cast and heat treated 17-4 PH which yields hardness values of 33-45 HRC depending on heat treatment temperature and duration.



a) Hardness at different speeds given input power

b) Hardness compared to energy density (power / speed)

Figure 13: Comparison of different laser parameters and their resulting hardness

Parameters and Support Structures

Ease of removal should always be considered during the support design process. The supports are essentially 'welded' to a thick base plate making part removal more complicated than their plastic counterparts. Occasionally, small or thin geometry when used with grid supports may be broken from the part such as the ones shown in Figure 14 below, generally parts must be cut from the plate. This can be accomplished by several means, but the most efficient option by far is with electrical discharge machining or EDM. With access to an EDM, the part and support structures can be easily separated from the build plate with minimal risk of damaging a part. Support structures can further be designed to break off in segments yet still be strong enough to ensure complete connection during the fabrication process. Additionally, designs may include a planar feature or face that can be orientated to be parallel to the plate. In this case, once the part is removed from the plate, there may be little to no post-processing required.

Figure 14: Reducing post-processing by utilizing breakable supports

Combining support options is another method that can expedite post-processing. As shown in Figure 15 below, a part was first created utilizing grid connections, however it failed due to delamination. After review of the failure, a second part was fabricated as shown in Figure 16 with solid support at the extremities of the part. This can be observed in the image where the lighter material is solid support and the darker, shiny material is grid support. The added material worked to both increase connection strengths to the base plate as well as provide further areas for heat dissipation during the manufacturing process.

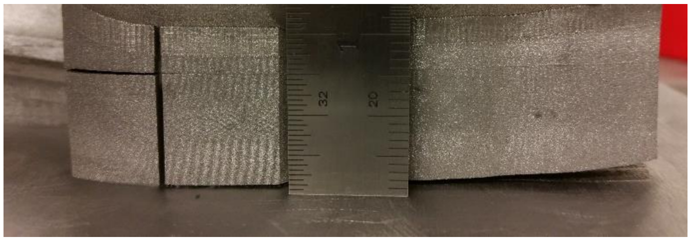


Figure 15: Part delamination due to thermal stress during layering

Figure 16: Full connection by combining solid and grid supports

CHAPTER 3: DESIGN FOR ADDITIVE

Currently in Iowa, a significant portion of industries do not utilize CAD, or will only utilize 2-dimensional drawings. Due to this minimal contact with computer modeling, these engineers and designers will often struggle when transitioning to additive manufacturing. When working with any company who has only experienced subtractive manufacturing, the first step will be to show them examples of what the technology is capable of. Once the designers have a better idea of what the additive system is capable of, work can begin on transitioning design flow from subtractive to additive.

At this point, the first goal is to discuss the limitations of the printer. As discussed previously, there are many factors that must be accounted for when modeling a new design, or modifying an existing design. Below, I will explore a few of the main differences that typically are discussed when first introducing a company to metal additive manufacturing.

Geometry and Accuracy

Melt pool characteristics

In the previous chapter, methods for developing support options were addressed. Using the baselines discovered during these initial tests, a designer can account for the limitations of the additive process. For example, it was shown that on a microscopic scale that the material being melted acts similar to a standard welding process. With this melt pool, there will be a radius where the laser beam stops firing on the material. The laser will stop right where the file states, but where the melt pool ends, there will be a slight radius as shown previously in Figure 5. During the process of slicing the CAD model for export to the printer, the path of the laser is plotted out in a similar style to what is shown below in Figure 17. The specific geometry of the paths can be controlled to account for this added radius. It was found that for the system at Iowa State with the 17-4PH powder, an offset of 75 μm would give the most accurate results for a given part. The offset in this case is 'shrinking' the cad model in the X and Y axis slightly to account for the melt pool end. This results in the finished product measuring within a few tenths of a millimeter in the tests performed.

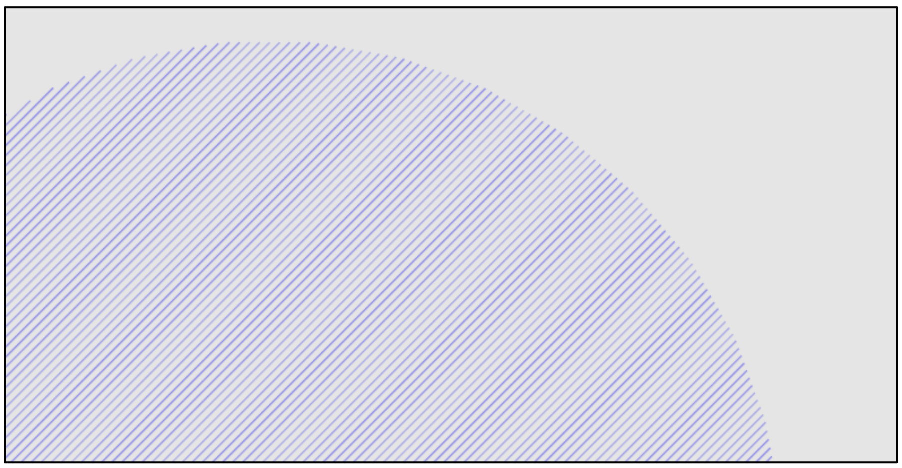


Figure 17: Laser path for normal infill

Wall Geometry

Understanding wall geometry accuracy and how unsupported areas will close was fundamental to the success of conformal cooling. When first taking delivery of the system and getting trained with the software, we were shown the suggested methods for setting up the laser parameters for the build. In this initial case, it was prescribed to utilize an infill pass where the laser would run at a higher speed and power to melt material within a design. In addition to the infill pass, the default setting was to also have a contour or border pass of the laser around each layer. This worked well for any part that had largely vertical geometry. The added contour pass would yield a much smoother outer surface due to the laser following the curve of the file rather than ending at the face as is the case with the normal infill. With the improved consistency and smoothness of the layering at the walls, the contour pass is most often utilized at any friction or bearing surface.

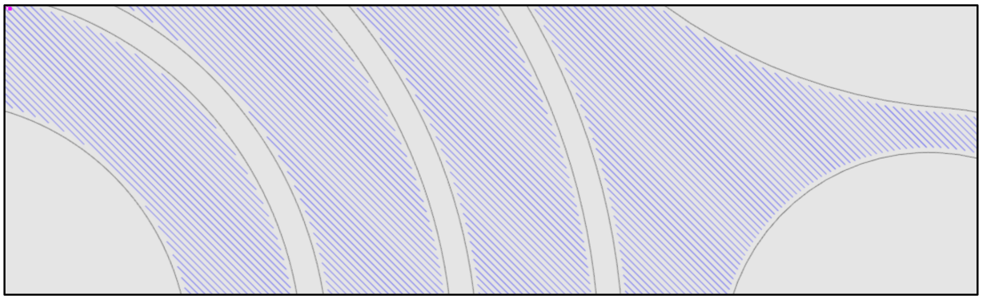


Figure 18: Sliced layer showing normal infill (blue) and contour (black) path for the laser.

Angles

While the contour pass does give a more uniform surface on shallow angles, the opposite is true when unsupported angles are incorporated. When melting material onto a new layer that goes beyond the previous layer’s border, the laser will penetrate the powder below the intended 40 µm layer. When utilizing a contour pass, this can lead to peeling of this outline as shown below in Figure 19. This can be minimized by reducing the programmed spacing between the infill and contour pass in cases where the overhang angles are small enough. When testing this offset, it was found that changing this spacing would reduce both the hardness and the surface quality of the final wall surface.

Figure 19: Peeling Contour pass

Overhangs and Unsupported Features

When creating a CAD file, the melt pool must be accounted for to minimize unsupported areas where possible. As shown in Figure 19, the contour pass should be removed from the settings for any large overhangs. While this will result in a slightly rougher surface, testing has shown that much steeper angles are possible without the contour pass.

The increased angle flexibility can translate to post-processing time savings as well. For example, if a design requires threads, the thread feature can be incorporated directly into the file and printed such as the example below in Figure 20. The thread will need chased afterwards, but there will be no need to drill holes or take the time to tap the stainless-steel material.

Figure 20: Microscope image of ¼-20 thread printed horizontally

Hole and Tube Features

Conformal cooling enables a mold to cool faster and decreases cycle time. As shown earlier, this feature is one of the many aspects to this technology that would not be possible with subtractive methods. However, when creating these cooling lines, attention must be paid to how the layering and melting will occur around the line. If the tube features are not created and orientated properly, it can result in a crashed build or porosity at the layer. As shown in Figure 21, even square conformal cooling lines are feasible with the system. However, looking at the top surface of the tunnel shows how rough the layering will be. This surface is typical for 0° unsupported geometry, and will cause turbulence within the coolant flow.

Figure 21: Interior view of conformal cooling line

This roughness can be minimized if required, by altering the cross-section geometry of the cooling lines. As shown in Figure 22, the 0° overhang will have a very rough surface regardless of how wide the overhang is. The geometry can be modified by rounding the corners or simply utilizing a circular cross-section and give a much smoother resulting surface such as what is shown in Figure 23 below.

Figure 22: Unsupported 0° layering (5-20 mm)

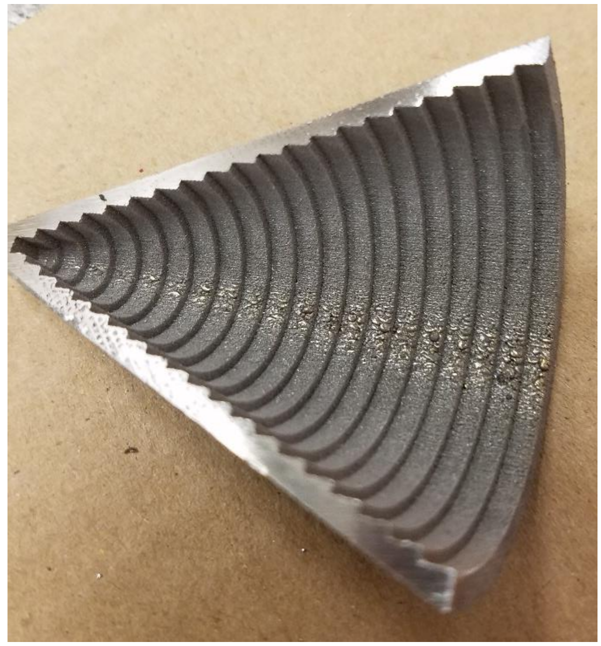
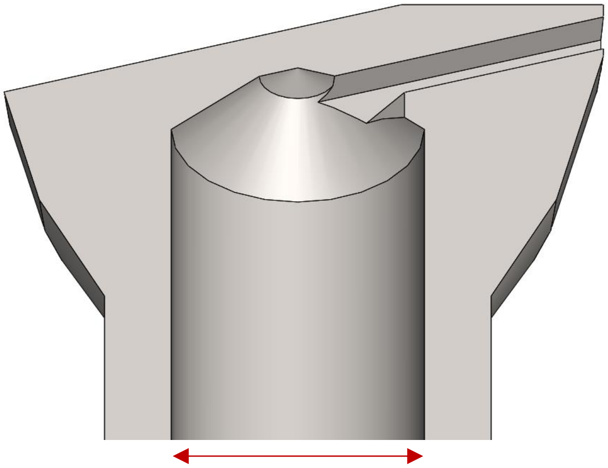


Figure 23: Unsupported geometry with half-circle arc (2-25mm)

Scaling down in size from conformal cooling, another benefit to the additive process is the ability to accurately print nozzles. As shown in the cross-section view in Figure 24, a nozzle with an outlet of 0.2 by 1.6 mm was required for a company product. The method that was currently being utilized was to drill into the head of the nozzle, then broach-EDM from the tip to meet where the drill had stopped. This design had a high failure rate, as it was not possible to accurately position the EDM in relation to the bottom of the drilled hole. Fabricating this design with additive completely removes this issue, and multiple nozzles were printed without issue. No longer requiring complex EDM or high precision machining also enables fabrication of nozzles such as Figure 25. In this nozzle, which was fabricated for faculty at Iowa State, 6 holes with a '+' cross section and a thickness of 0.2 mm was successfully built and utilized in a plastic extrusion system.



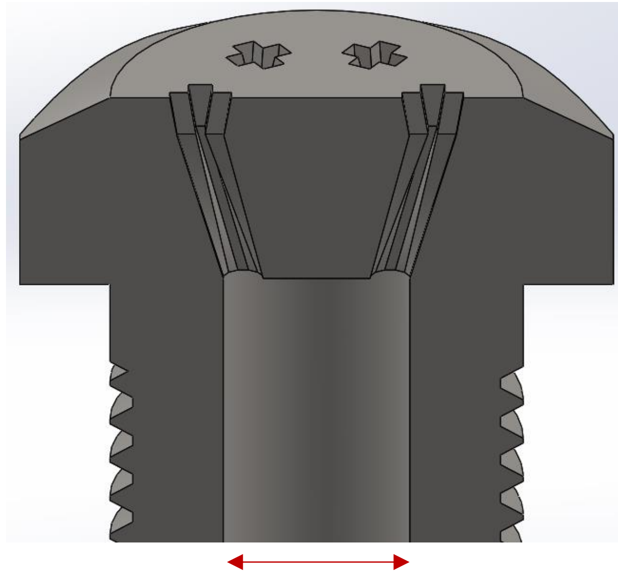


Figure 24: Cross-section view of a nozzle

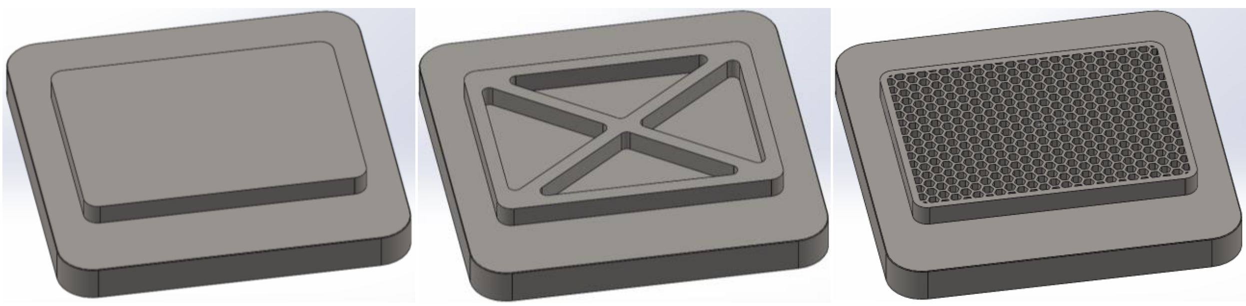
Figure 25: Complex multi-output nozzle

Thermal Warping

Wide Area

Reducing layer surface area of a wide part is the most reliable method to avoid warping or delamination. When modifying the file, consideration must be placed in the important aspects of the design such as holes, aligning faces, and any other clearances. This is a common area where design for additive can be very beneficial, as reducing the volume is not something typically designed into a part to be machined. If the surface area is not considered, however, there will be an increased risk in the layering creating more thermal stress than the material can handle. If this occurs, the design could begin to delaminate from the plate and either cause a failed build, or leave the part warped once it is removed from the plate.

An example of this process can be found in Figure 26 below. When developing a design such as the option shown in Figure 26a, an engineer would start with the important requirements of the product. In this case, the company needs to fabricate a plate with dimensions of 200 x 150 x 15 mm for a project. While the option shown in a) could work, it would be likely to have a bowl-style warp once it is removed. To reduce the chances of warp occurring, a designer familiar with machining would be tempted to design something more along the geometry of design b). This would work much better than version a), but there will still be thermal stress build-up along the cross-beams. An option that would work well thermally and mechanically would be to implement a geometry similar to a beehive, or a hexagonal infill. With this design, the layer surface area has been greatly reduced, meaning there will be a much smaller risk for the part warping due to thermal stresses.



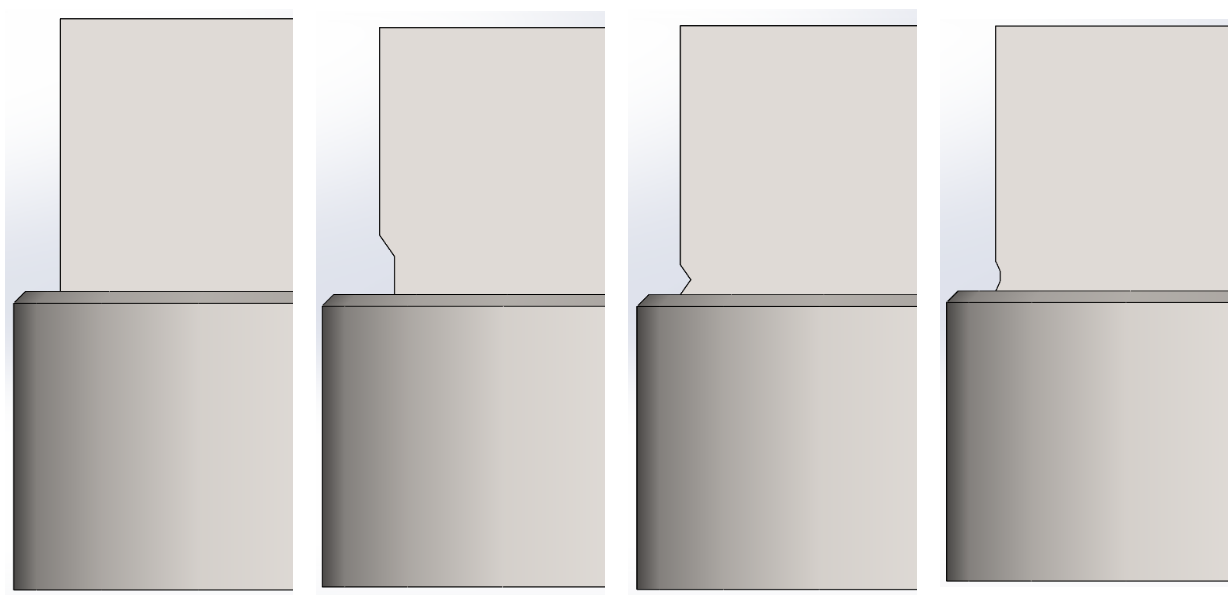
a) Original design b) Reduced area c) Additive only version

Figure 26: Variations of reducing area for a large surface design

High Volume

When fabricating a larger part with metal powder bed fusion, thermal warping must be accounted for. Given the larger surface area and build height of these parts combined with the amount of energy being input into the material, they will warp to some degree during the build process. To minimize issues from this thermal warping, there are a few methods available to a designer.

The first and easiest option is to modify the connection between the plate and the part being fabricated. Over the past year, multiple connection variations have been tested for the system at Iowa State. Four of our main attempts are shown in Figure 27, going from first to latest iteration. It was found that when a part is fabricated with a 90° connection to the plate as shown with a) and b), the thermal stresses can become greater than the mechanical strength of the bond between the plate and first few layers. When this occurs, the part will delaminate from the plate by as much as 2 mm in our worst observed case. The next method attempted was to add an angled start to the base plate connection as shown in c). The idea behind this was to reduce the stress concentration area at the connection to reduce the likelihood of part delamination. This method was successful for smaller designs, but on larger versions, the delamination would begin to occur near the middle of the support where the angle switches back. To resolve this issue, a fillet was added along this crease in the support. This latest method has shown to work well where the other three had failed previously.



a) No modification b) Reduced footprint c) Chamfered d) Radius

Figure 27: Geometry methods for solid material connection to base plate

Advanced Infill Geometry

If the design allows, a reliable option to reduce thermal warping is to exchange areas of solid material with a hexagon or lattice infill as shown in Figure 28 and Figure 29 respectively. By exchanging the solid mass with this sparse geometry, far less material is melted during the firing process. This in turn means that the heat buildup is greatly reduced and the build is less likely to warp or delaminate during the build. The downside to these more complex infill options is that they are more data heavy for a computer. A more powerful computer would be required to utilize these more advanced options.

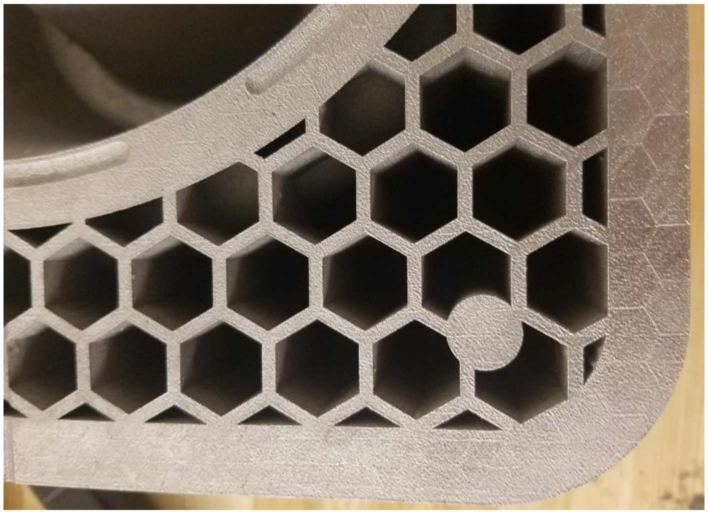


Figure 28: Part fabricated with Hex infill pattern as well as hex space savings

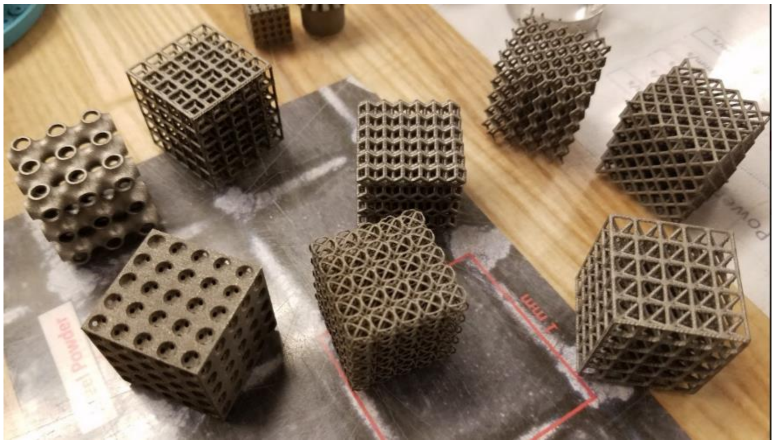


Figure 29: Samples of lattice for testing

Infill Patterns

An additional option for improving the reliability of a build is to alter the pattern that the laser follows at each layer of the part. As shown in Figure 30 and Figure 31 below, a hex pattern can be utilized to extend the duration of the laser firing at each layer. This serves to reduce the speed at which heat is input into the part and can decrease the likelihood of warping. Figure 30 is labeled in order of firing, so the layer will fill in via 1A, 1B, 1C, … then 2A, 2B, 2C, … to make a striped pattern over the area being melted. At this point, it will continue to melt at 3A, 3B, 3C, etc., before finally filling in 4A, 4B, 4C, etc.

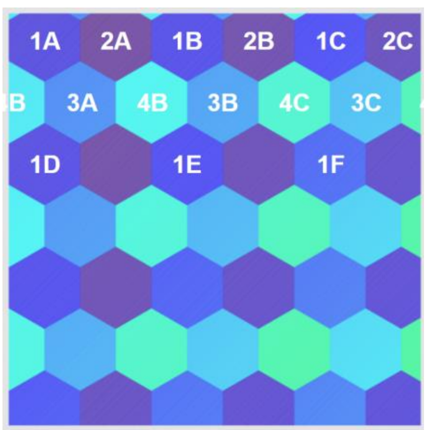


Figure 30: Hex infill pattern with pattern sequence

Figure 31: Part fabricated with hex infill pattern visible

CHAPTER 4: INDUSTRY COLLABORATION

Throughout the previous two years, CIRAS has collaborated with many companies across Iowa. Many of the companies simply wanted to get an idea of what the technology was capable of, and a few appreciated the results enough to consistently return. Below is a list of a few of the companies who were published through the CIRAS Newsletter and willing to share their project success.

List of Companies

Table 2: List of companies and their project durations

	Number of Build Projects	Approximate Build Time	Approximate Volume
American Athletics [10]	16	1000 hr.	26 liter
Quattro [11]	1	60 hr.	0.3 liter
+ 9 additional who have not shared their projects with the public.	23	1300 hr.	18 liter

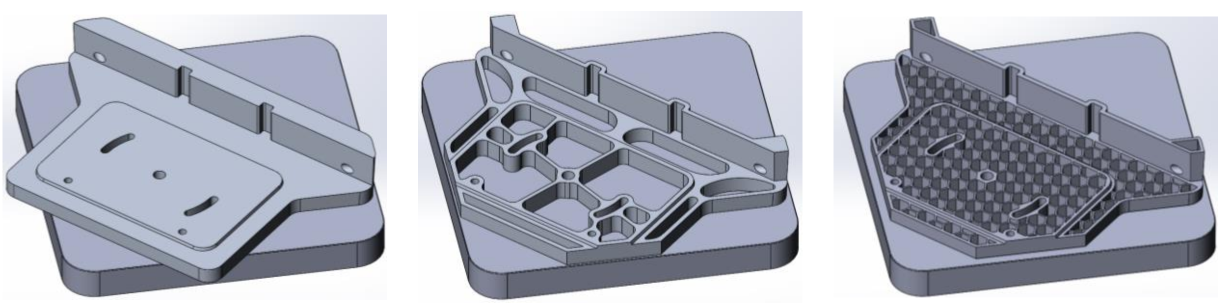
Benefits to Companies

The ProX300 system along with all the additional equipment and supplies needed to run costs just over $1,000,000 dollars. That is an amount that most companies in Iowa cannot justify without having done research beforehand. Given the high cost, metal powder bed systems are frequently used at large global companies or at fabrication shops who complete projects for companies. In both areas, any knowledge on how to efficiently fabricate a part are typically kept within the company. This secrecy benefits the companies, but slows the overall development. Due to this, another primary goal of this research is to ensure any company who wishes to learn more can gain easy access to any of the data within this document and the surrounding tests which were completed.

While working with companies on projects, many new challenges were encountered in relation to fabricating a given design. Many of these challenges were within the area of support structures, so to expedite this process, a paper was written for the 45th SME North American Manufacturing Research Conference [12]. Below are a few of the main case studies that were found to be a challenge, and yielded a notable learning outcome.

Large Area Design

The alignment fixture shown in Figure 32 was one of the very first builds attempted with this system. The part first had to be modified to fit on the build plate as it was too large. The next step was to reduce the area for each layer to reduce the heat input into the build.



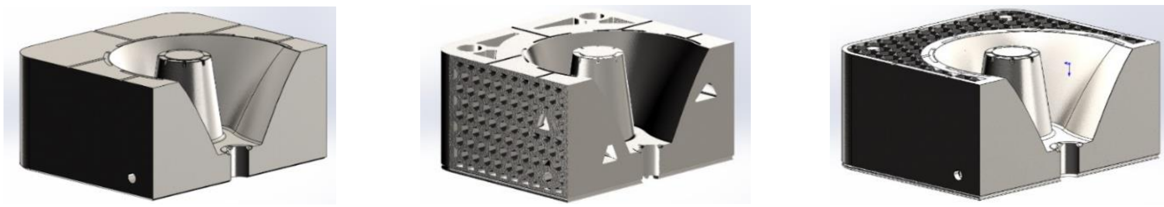
a) Original Design b) Version 1 c) Version 2

Figure 32: Development progression for large area modifications.

	Original	Version 1	Version 2
Layer Area (mm^2)	37,717	11,835	6,416
Layer Area Reduction		69%	83%
Notes	Designed to be machined	Removed corners to fit on plate Reduced volume not integral to function	Further reduced area while increasing strength by utilizing hex pattern

High Volume or Density Design

The largest build yet has been the base cavity mold for the American Athletics [13] injection mold shown below in Figure 33. The material was reduced significantly initially for this mold and was then reduced to 42% of the original volume in the second attempt.



a) Original Design b) Additive Version 2 c) Final Modification

Figure 33: Development progression for injection tooling modifications.

	Original	Additive Version 2	Final Mod
Volume (mm^3) (% reduced)	4,660,809	3,799,345 18%	2,680,760 42%
Build Time (h:mm) (% reduced)	248:58	207:07:42 17%	161:50 35%
Material Cost (% reduced)	$2,698	$2,199 18%	$1,552 42%

Conformal Cooling

Conformal cooling entails fabricating a mold which has cooling channels that flow alongside and below the surface of a design. With conformal cooling, the parts can be removed faster, giving a shorter cycle time and improved daily output. The cooling line shown below in Figure 34 is part of a design for American Athletics. This design is one half of the cavity mold for their ‘Cheer Stand’ product.

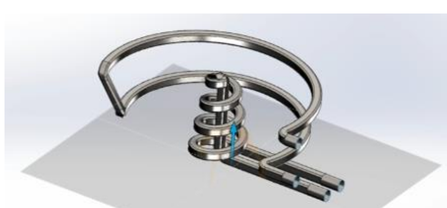


Figure 34: Example of internal cooling channels

CHAPTER 5: CONCLUSION

The information in this report gives an introduction and methodology to support structures for metal additive manufacturing. This study has been for a single material on a single system, but by utilizing these methods, future work on new material or equipment can completed in an efficient manner. With the rapid advancements occurring in the metal additive industry, speed and efficiency will be key to success for anyone wishing to utilize this technology.

By understanding the variations of a single line of material or a 1-dimensional test, an initial set of parameters can be recorded. Progressing from the 1-dimensional parameters and incorporating layer depth allows for a wall of material or sparse supports to be built in a 2-dimensional test. Finally, once thin wall geometry is understood, a solid section or 3-dimensional test can be outlined and tested by incorporating hatching to fill in each layer. These three tests will enable researchers to rapidly develop a set of baseline parameters for any new materials or systems. As with any technology, it is often more efficient to optimize and refine the process itself rather than individual parts.

Once these baseline parameters are understood, the settings can then be manipulated to increase or decrease strength as needed for a given design. When setting up a file to be printed, there are no readily available forms of automatic support parameter setting as there are with many plastic systems. To refine and optimize the settings for a given build, much experimentation needs to be completed to obtain a range of parameters.

Knowledge of laser parameters and support geometry will give an engineer a good understanding of how to design and orient a given part. However, for this technology to become more widely utilized, a design for additive method must be understood. When first working with a new technology, there will be a learning period. Throughout the past two years, many companies have come to CIRAS to fabricate parts on our system. With each of these new projects, designs were modified to be manufactured additively. With few exceptions, the initial design for each project started out as a cast or machined component. But after working with companies, and much trial and error, methods have been developed to fabricate any request to date.

The industry case studies cited above provided me with the opportunity to outline the section regarding design for additive in this thesis. While the information within may stand as a good baseline, it is by no means complete. With each new project comes something learned. The design for additive guide will continue to evolve and improve as companies across Iowa continue to bring new ideas to our students.

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APPENDIX: EXPERIMENTAL RESULTS

One Dimensional

Line Test
Input Variables: Power (200 – 50 Watts) | Speed (250 - 100 mm/s)

		Power (Watt)						
		200	175	150	125	100	75	50
Speed (mm/s)	250							
	225							
	200							
	175							
	150							
	125							
	100							

Laser parameters for each test.

	Plate	Layer 0	Layer 1
Test 1	■		
Test 2	■	■	
Test 3		■	
Test 4		■	■
Test 5			■

Layers fired for each phase of the test.

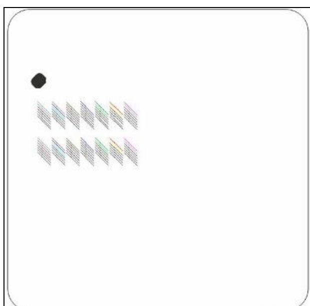
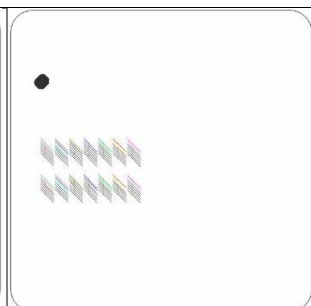
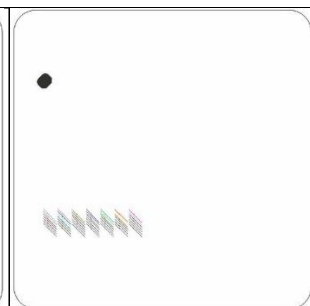
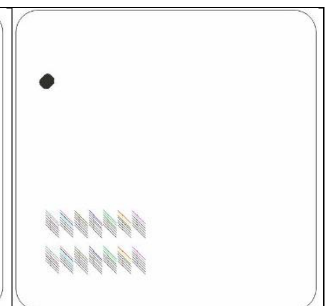
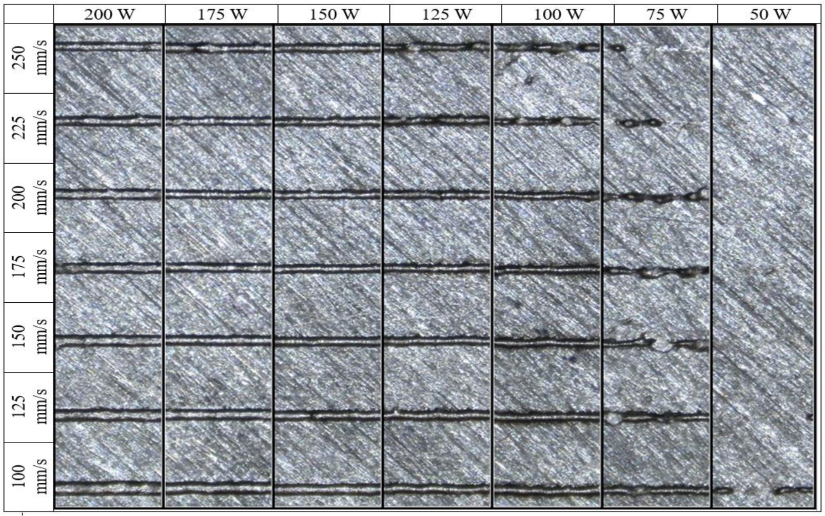
			

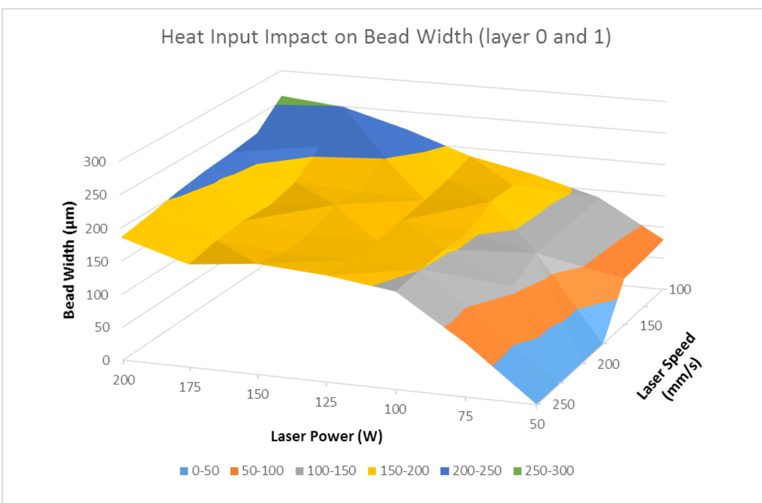
Plate Only	Layer 0	Layer 0	Layer 1

Output Variables: Melt Pool Width | Melt Pool Visual Quality | Stall Areas
Description: This test was to determine the bead quality during the initial layering and material melting of a build. The drive for this test was to better understand part adhesion to the plate, especially when considering sparse supports.

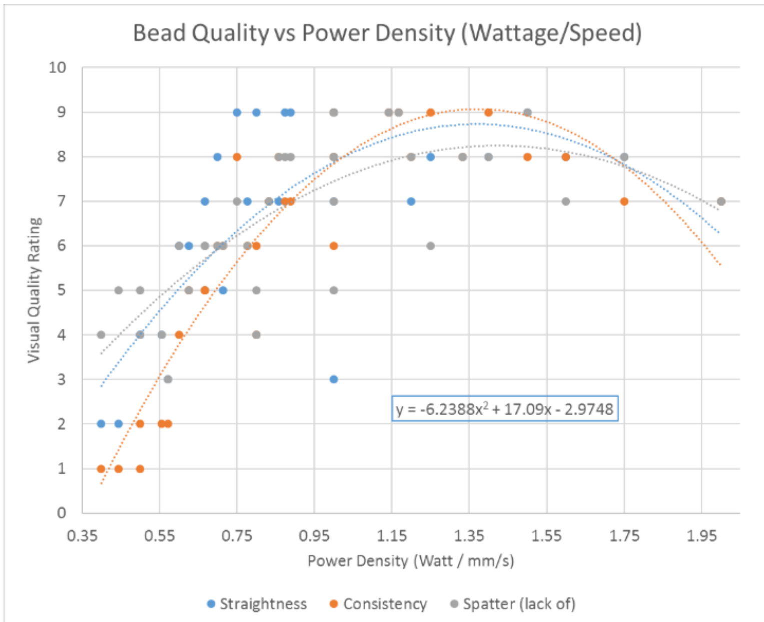
Results: The test was completed on just the plate, the plate and layer 0, layer 0 only, layer 0 and layer 1, then layer 1 only. The following chart shows the visual results for layer 0 and 1 which yielded the best results and is standard procedure for a build. All testing variations yielded similar outcomes to this layer 0 and 1 result.



Melt Pool Width: Melt pool width turned out to be somewhat difficult to measure given the inconsistency of the lines for some inputs. Below are the averaged widths measured with an optical microscope.

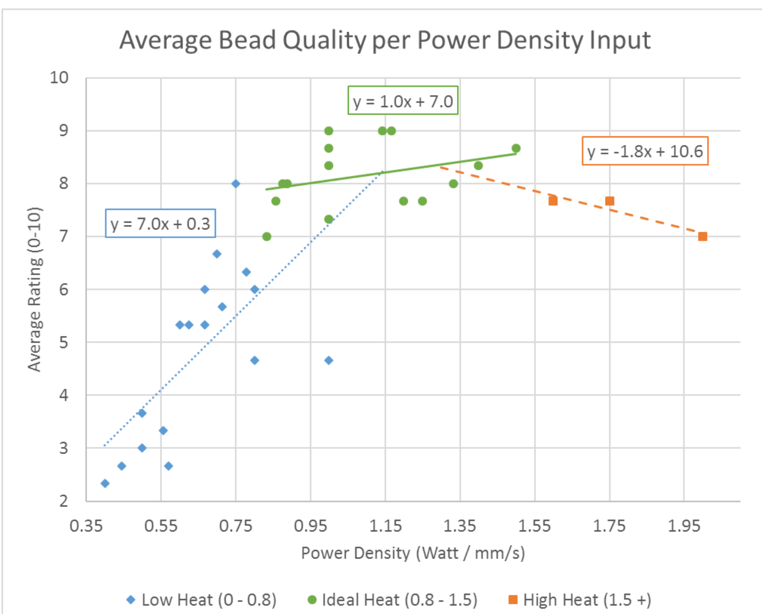


Melt Pool Quality: To contrast the various results for this test, the visual quality was compared for each result. With the visual quality, comparisons were made between all samples and rated on a scale of 0-10 for worst to best. This is a method like what is utilized for inspection of weld beads.



Comparison of common weld bead visual qualities

Averaging out these bead qualities yields three zones for use with sparse supports.



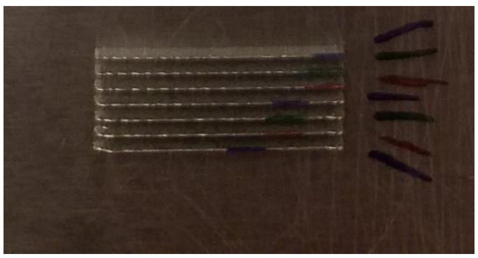
Averaging visual qualities to get a range of settings for later use.

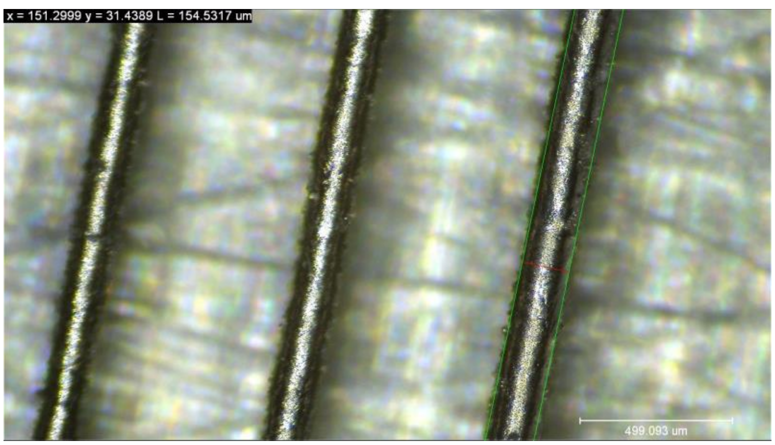
Stall Areas: N/A – None of the testing points resulted in a stall, however, there were some areas that 'smeared' when the roller crossed. Additionally, most of the melting at the 50-watt level did not adhere to the plate.

Two Dimensional

Wall Test

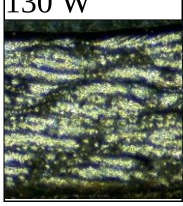
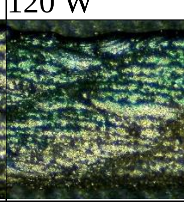
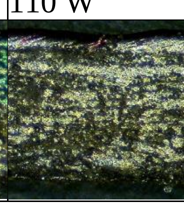
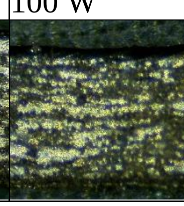
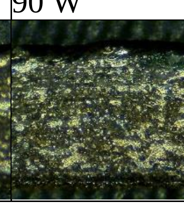
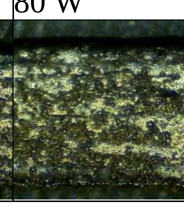
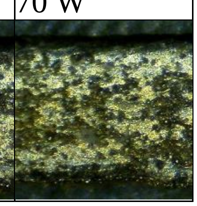
Input Variables: Power and Speed
Output Variables: Consistency
Description: This test was to be a more isolated test for two-dimensional supports. The main goal was to determine the impact of laser power and speed on the consistency and quality of a thin wall.
Results: The results for this test were as expected, where each of the 7 options for support were built up in a clean and consistent manner.


Top-down image of the wall samples.



Microscope imaging showing measurements being taken.

Consistency:
As expected, the consistency of each wall depends on the power level for the process. Below shows the side view of seven samples completed for this test. The center value of 100 Watts is the default value, surrounded by +/- 2, 4, and 6 % laser power.

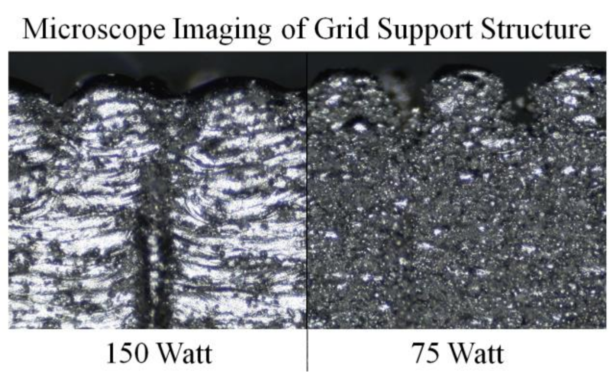
130 W	120 W	110 W	100 W	90 W	80 W	70 W
						

Grids Test

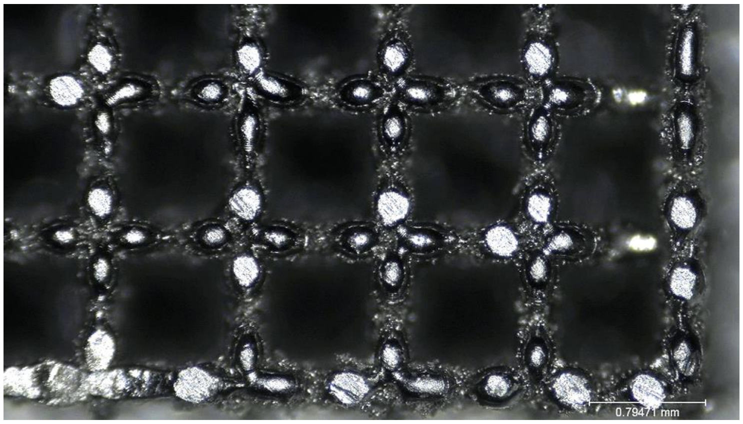
Input Variables: Laser power and speed
Output Variables: Structure quality
Description: The aim of this test was to obtain a comparison between different speeds and powers of sparse supports. This test was completed early in the project to better understand why some components were building easily and others were not.
Results: The first item noted during this test was that several of the parameters were too ‘hot’ for the sparse supports. These grid patterns gave very wide beads that impacted the roller at each layer, eventually causing it to stall enough that they were removed from the build a few layers in. The more functional outputs are shown in the image below. The left image shows grid supports with a higher power input, which shows as a smoother and more defined wall. The image on the right shows a much lower power wall support where the material was only lightly sintered. The main outcome for this test shows a physical difference between the settings. This difference can be utilized as an outline when selecting which support power to utilize for a build. In the case of the higher power support, the material bond would be stronger, and as such have a stronger connection to the base plate. If strength was not an issue, and there only needed to be material supported for surface quality, the weaker ‘sintered’ support could be used.
In addition to the strength during the build, these outcomes would also translate to post-processing. When removing the grid supports from a curved surface of a part, there are limited tools which can be used. In the case of grid support, the hotter the support, the harder to remove. In these cases, areas where access is limited, could greatly benefit from the weaker support.

	175	125	75
220	129.0121	168.8307	144.713
160	192.1894	190.1707	152.0552
100	249.0997	210.3654	183.1671

Typical wall width for each test in µm based on input speed (mm/s) and power (W).



Visual comparison of strong and weak support structure options.

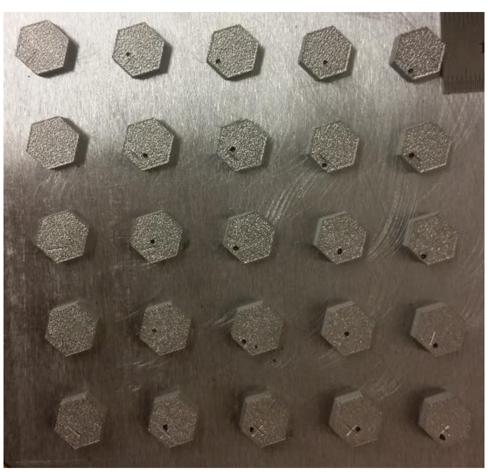


Z-orientation image of grid support option.

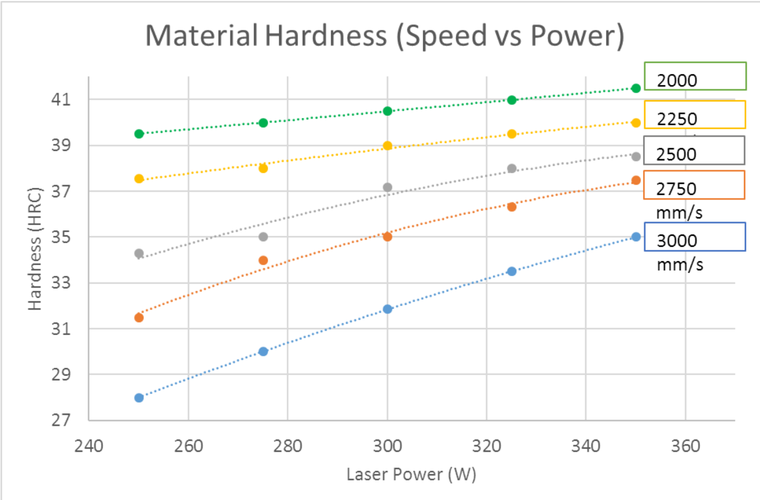
Three Dimensional

Hex Cupons (V1 Lens)

Input Variables:
Fill Power: 50, 55, 60, 65, 70 %
Fill Speed: 2000, 2250, 2500, 2750, 3000 mm/s
Contour Power: 19, 17, 15, 13, 11 % Contour Speed: 245, 205, 165, 125, 100 mm/s
Output Variables: Hardness | Geometry
Description: The idea behind this test was to better understand the three-dimensional material settings. The primary goal for this test was to determine how much the part would expand or shrink given a range of laser parameters. In addition to this geometry offset, understanding the hardness values would allow us to understand if it were possible to increase the durability of a design or reduce the porosity. At this stage in testing, most designs utilized a contour pass, as we had not discovered the benefits to withholding the feature.
Results: Each sample fabricated for this test yielded good data. Following are the main tests performed on the batch.



Hardness:



Material hardness in relation to speed and power

Geometry:
Overall, the geometry was reasonable for results. As shown in the table below, there is an expansion at either end where the material was hotter or colder. We believe this is due to the addition of the contour pass which had a variable heat input as well. It can be seen however, that our smallest differences occur in the middle range where our default settings for contour pass typically lay.

	95	85	75	65	55
245	158.9167	161	172.5833	165.5833	183.25
205	103.75	104.0833	137.375	101	101.75
165	113.6667	105.1667	104	91.25	99.5
125	135.1667	124.625	114.3333	92.625	112.625
100	138.5	135.25	120.3333	108.5833	105.5

Required Geometry Offsets in µm based on input laser power (watts) and speed (mm/s).

Hex Cupons (V2 Lens)

Input Variables: Laser power and speed, contour or no contour pass
Output Variables: Geometry offsets
Description: The goal of this test was to determine how much the laser power and speed would impact the geometry of a part. In this test, three batches were fabricated. The first batch was fabricated with the original lens for the system, which we are referring to as 'Lens V1', then another two tests were performed after a lens upgrade which we are referring to as 'Lens V2'. In the first test, a 5x5 matrix of power and speed was tested with the use of a contour pass. In this test, the main output would be the difference between the speed and power for the contour only.

In the second and third test, a slightly wider laser power and speed matrix was constructed, but sill with the 5x5 samples.
Results: All samples in this test were functional and gave expected results. Below are the values found for each of the two variants of geometry. All numbers are in terms of required geometry offset from CAD design.


V2 Lens samples with no contour pass

Lens V2 Geometry offsets (No Contour Pass)

Offset	70	60	50	40	30
3000	37.66667	-7.33333	14.66667	13.16667	-2.66667
2750	89	42.83333	36	27.5	15.58333
2500	128.9167	92.41667	75.08333	60	60
2250	188.0833	157.3333	139.8	127.0833	111.8333
2000	305.4167	238.75	192.9167	195.1667	179

Required geometry offsets in µm based on input speed (mm/s) and power (% of 500 W)

Porosity Samples

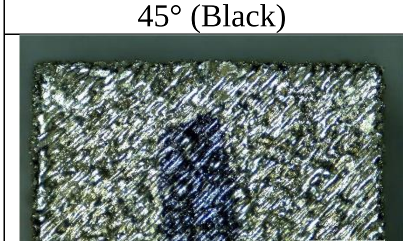
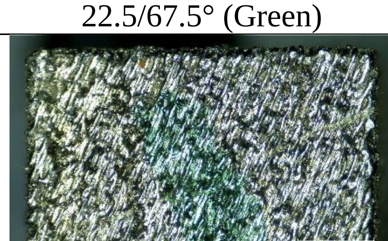
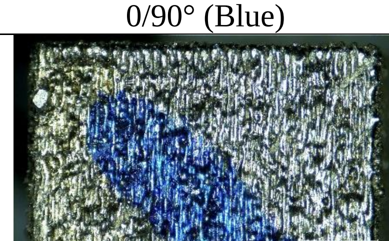
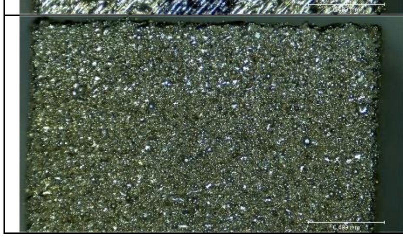
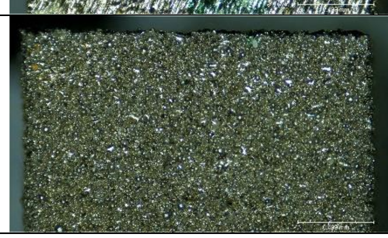
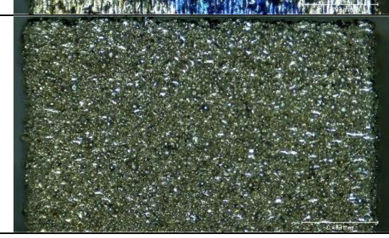
Input Variables: Laser Power (standard 65% power 2500 mm/s)
Output Variables: Porosity
Description: The goal for this test was to determine a baseline for porosity with this system.
Results: Several samples with varying power and speed were tested through CNDE at Iowa State. One larger baseline sample of 25 x 25 x 10 mm was tested initially, followed by the hex samples from an earlier test. While the first large sample could yield good data, the smaller size of the hex samples showed no visible porosity. The testing engineer perform further tests, but the equipment was not able to give any notable results.
However, for the first large sample, the results were given as **0.56%** porosity by volume for a sample of standard size and laser parameters.

Geometry

Orientation Geometry

Input Variables: Orientation on build plate
Output Variables: Geometry
Description: The idea of this test was to determine if there was notable difference between different angles for a part. The main outcome in question was if the direction of the laser would impact the surface quality when it impacted at a 45, 22.5, or 90-degree angle. The test was performed on multiple samples of a 5-mm cube.
Results: Visually, there were negligible differences in surface between the samples. In each case, the wall and top surface showed nearly identical results.

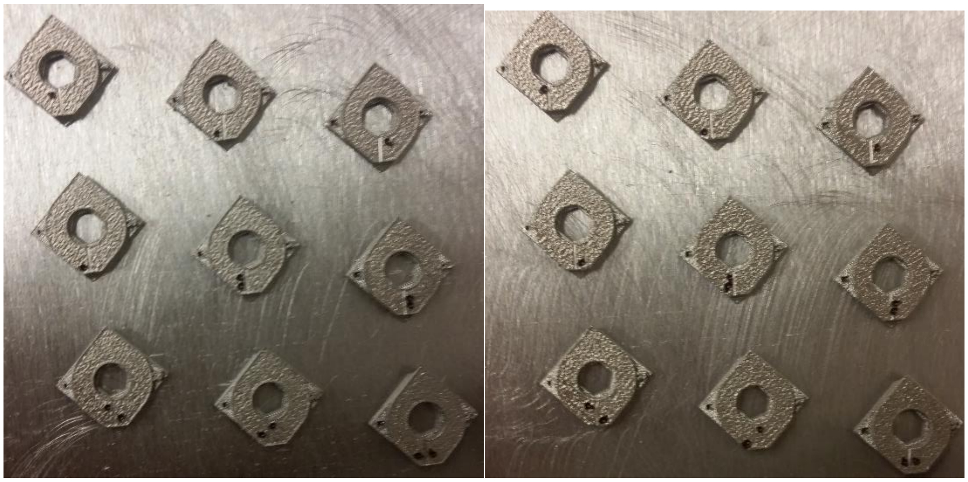

Image of geometry orientation samples.

45° (Black)	22.5/67.5° (Green)	0/90° (Blue)
		
		

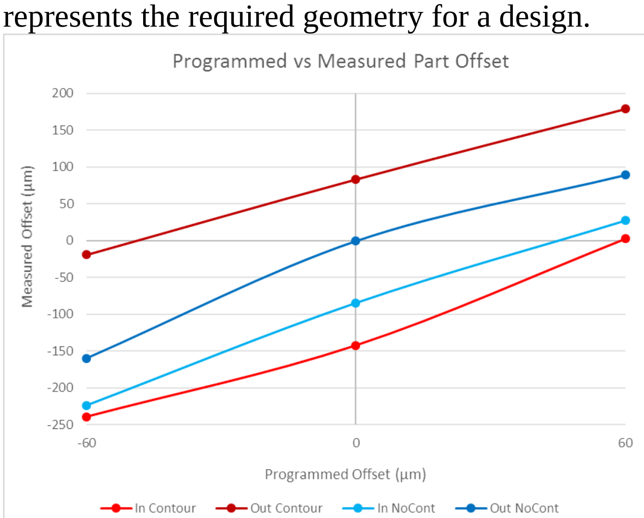
For each of the samples, the difference in measurement showed no consistent trend. This would be attributed to the roughness of the surface due to powder connecting to the ends of each melted line. This test would give a result however, if there were a requirement for specific geometry at the top surface of a design.

Geometry Testing (V1 Lens)

Input Variables: Geometry Offset
Output Variables: Dimensions
Description: This test was performed early in the process of developing parameters for the system. With the software in use at Iowa State, there is an option to modify laser geometry offsets from the part. With this geometry offset, it is possible to fine-tune the end geometry outcome for a given component. In this test, values were gathered for contour and no-contour.
Results:



When measuring the values, there was a clear trend shown by shifting the offsets for the inside and outside geometries by -60, 0, and +60 µm as shown by the chart below. From this data, we can quickly get an idea of where settings should be placed to obtain a part that most accurately represents the required geometry for a design.



Measured offsets vs offset set in software

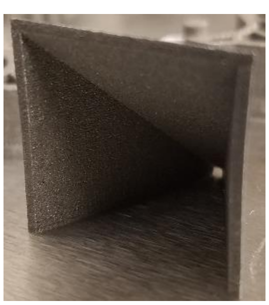
180° Overhang

Input Variables: Geometry
Output Variables: Functionality
Description: This test was simply to observe if a flat overhang was feasible with this system, and if so, what its limitations were for width.
Results: As shown in the image below, the test was fully functional for all samples from 1 to 15 mm overhang. As is shown in the right of the image, the first few layers will require several layers to 'heal' beyond the initial layer. This method has proven to work in many of the conformal cooling applications for this system where cooling lines of 10-15 mm wide were utilized. There were some situations where if the line was orientated perpendicular to the roller, it would possibly stall for the first layer or two after closing up over this flat area, but would heal within 3-8 layers typically.

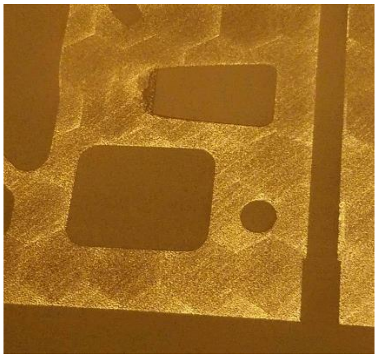
Image of an unsupported flat overhang for use in conformal cooling.

Angle Overhang

Input Variables: Geometry
Output Variables: Functionality
Description: In order to minimize the quality posed by the previous example, a simple addition of an angle was tested for a small sample. In this test, a part was fabricated with a 45° angle overhang.
Results: As shown, it was fully functional and shows no visible surface imperfections. The test was further utilized with a few of the initial injection mold tools as a method to top geometry over volume reducing cavities. This is shown below in an image taken during a build. Here, the overhang was taken down to around 15° and the image shows the rough zone at the right side of the hole where the surface will have a rougher surface.



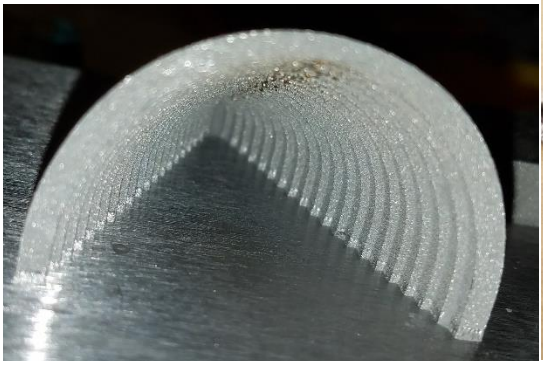
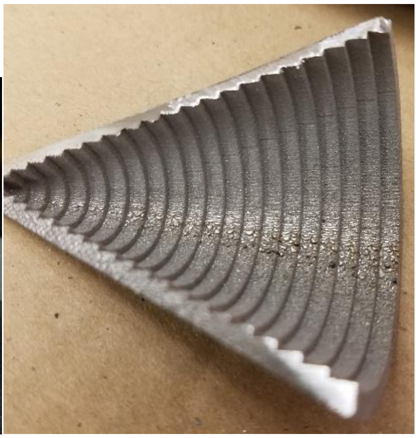
Sample fabricated with a 45° overhang and no support.



Utilization of angle support for volume reducing geometry.

Curved Overhang

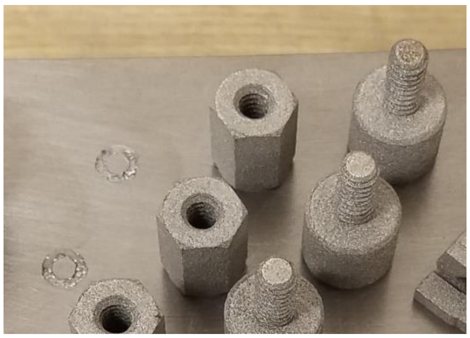
Input Variables: Geometry
Output Variables: Functionality
Description: After understanding what the system was capable of with flat overhangs, further improvement was theorized if a curvature was utilized.
Results: To improve the width possible for unsupported overhang, a test was performed with a half-circle arc from 2 to 30 mm overhang. As shown in the images below, this test performed well, with minimal surface imperfections along the length of the design. This translates into use with both cooling lines as well as any geometry that may have a larger overhang. If any unsupported or inaccessible geometry is required for a design, adding the proper curvature or angles to it can increase the likelihood of functionality for the design.

Unsupported overhang utilizing a radius for self-support.

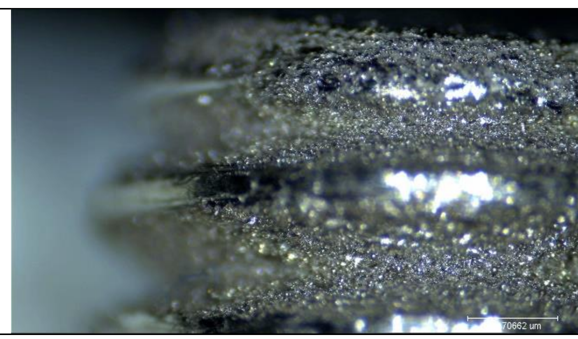
Threaded Features

Input Variables: Geometry
Output Variables: Function
Description: The goal for this test was to determine the feasibility of printing threads directly into a design. In the first test, male threads were printed vertically, accompanied by vertical female threads and horizontal female threads. In each case, the geometry was altered from the default option to determine how deep surface imperfections would penetrate.
Results: For each test, the printed design was followed up with a tap or die to clean up the surface of the threads.



Threaded samples fresh from printer.

As shown in the images below, the geometry offset was integral to obtaining accurate thread re-creation. In the image on the left, the threads were expanded by only 60 micrometers, when in contrast to the right image was adequate to result in a consistent thread.

	
Sample with geometry expanded by 60 μm	Sample with geometry reduced by 30 μm

While it is possible to recreate bolts that could be found at the hardware store, the better use for this feature is to create threads in more complex components. In the example below, ½”-13 threads were printed into a custom extrusion nozzle. The image shows the original design on the right, and the metal additive version on the left which utilizes 12 complex hole features.


Comparison of additive vs. original nozzle design.

Nozzle Features

Input Variables: Geometry
Output Variables: Functionality
Description: The goal for this test was to determine if complex cross-sections were feasible with this technology. In the example below, a nozzle was fabricated with a three-sided shape cross-section.
Results: While the test was a success for the fabrication of the design, it was found that the die swell for the plastic was slightly larger than the distance between the features. To accommodate for this, a second option was fabricated which utilized only 6 features.

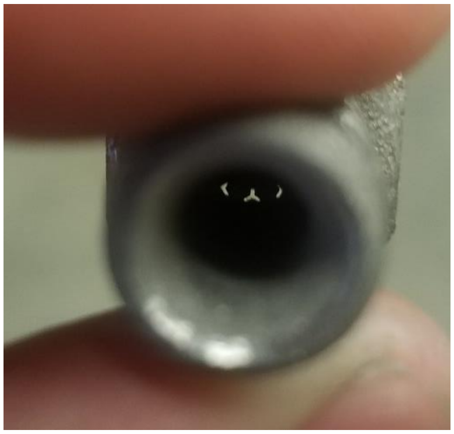
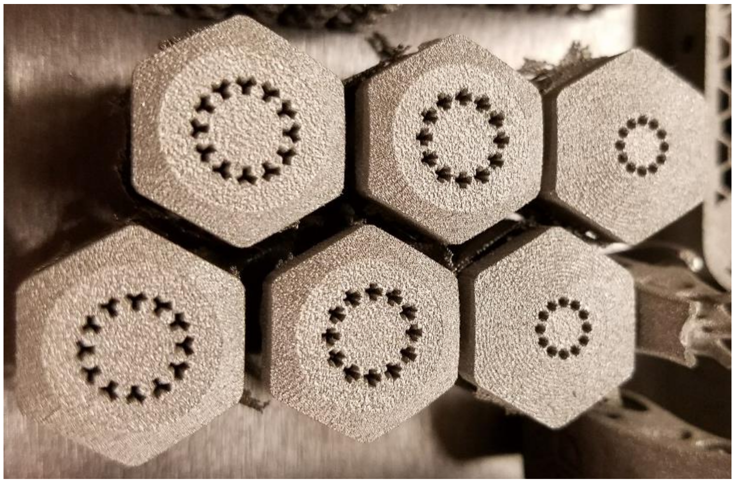


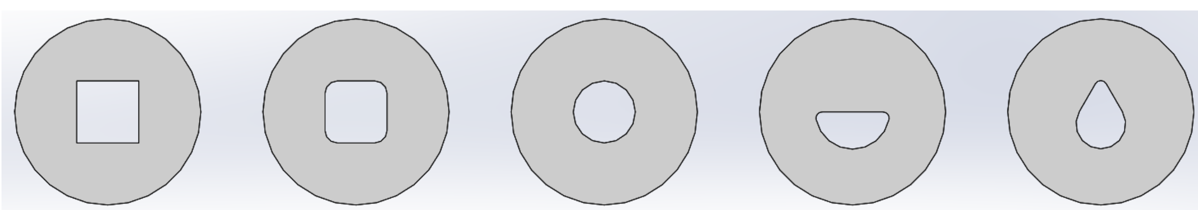
Image of the cross section of a complex extrusion nozzle.



Additional nozzle geometries tested.

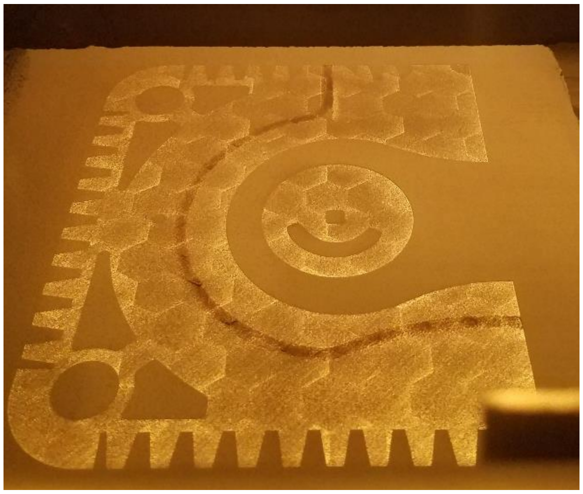
Conformal Cooling

Input Variables: Geometry
Output Variables: Functionality
Description: Conformal cooling is the use of cooling channels in a mold design that conform to the molding surface. With this method of cooling, injection parts can be fabricated with reduced cycle times.
Results: With a large portion of the build time put towards the system being in injection mold tooling, conformal cooling has been in use for over a year. With these cooling lines, several geometries were considered and utilized for different projects. When designing the conformal cooling, the main consideration was with the orientation of the line in regards to the roller for layering, followed by the distance between the cavity and the mold surface.



Cross-Sections considered and utilized during conformal cooling fabrication.

As mentioned in the section with the 180° overhang, consideration must be made to how layering will occur with cooling line design. If the geometry includes a flat section, adequate layering must be possible beyond this flat section to allow the material to regain consistent quality layering. During the process, if a flat overhang is included, it will show as a dark layering for the first few layers beyond the closing of the line as shown below.



Dark area where a flat overhang closed.

Surface Quality

Laser Power Impact (Top)

Input Variables: Laser Power and Speed
Output Variables: Roughness
Description: The goal of this test was to determine the typical surface roughness given different laser power and speed. For this test, a 2D surface roughness profile was found for the extents of the Lens V2 5x5 test.
Results: As shown, there is an increase in roughness as the heat input to the material varies too far from the default heat input ratio.

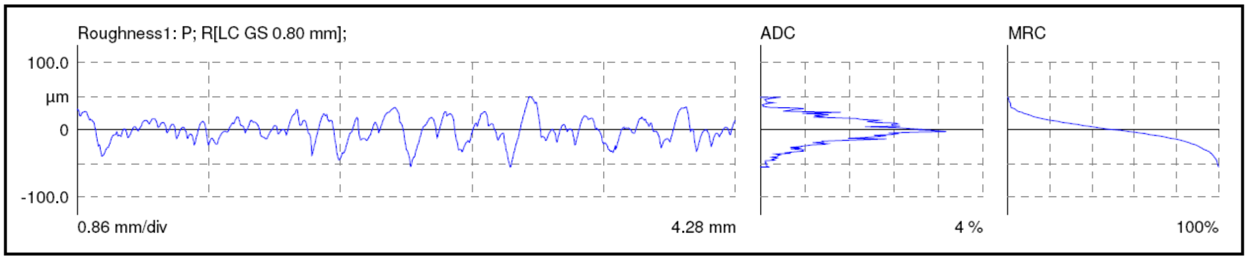
Values measured in (Ra) with results based on input laser power and speed.

Perpendic	210	195	180	165	150
3000	12.873		12.241		14.441
2750					
2500	14.313		11.462		13.998
2250					
2000	17.43		13.678		11.804

Measurement taken perpendicular to laser scan direction.

Parallel	210	195	180	165	150
3000	14.077		9.365		13.274
2750					
2500	15.163		11.084		16.035
2250					
2000	13.346		13.319		10.027

Measurement taken in-line with laser scan direction.



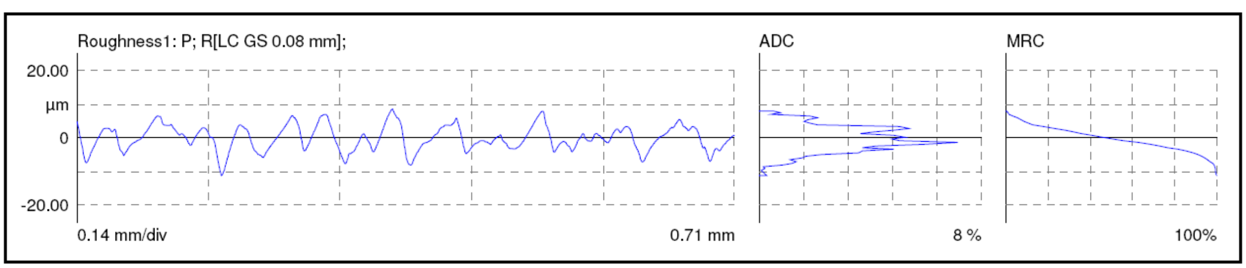
Roughness profile for sample 13 (180 W @ 2500 mm/s) in the perpendicular direction.

Laser Power Impact (Contour)

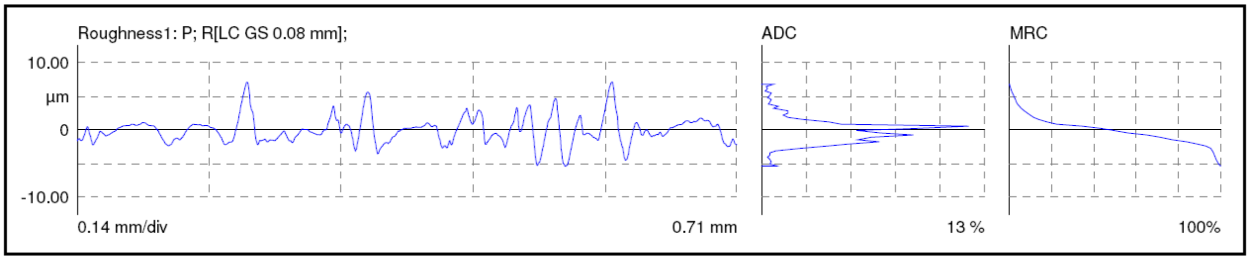
Input Variables: Laser Power and Speed
Output Variables: Roughness
Description: The goal of this test was to determine the typical surface roughness given different laser power and speed. For this test, a 2D surface roughness profile was found for the extents of the Lens V2 5x5 contour test.
Results:
The results for this test were somewhat opposite of what would be expected. My hypothesis is that this is due to the wall being melted either higher or lower than a typical layer, similar to the results for the grid test. In the situation where the parameters were 'good', the layering would be fairly even, and still have a good melt pool, which would result in ridges of roughly 40 µm across.

Ra	55	75	95
100	2.986	1.865	2.318
165	2.827	2.957	2.146
245	2.601	2.611	1.457

Surface roughness along the vertical direction of a contour pass sintered wall.



Roughness profile for sample 13 (75 W @ 165 mm/s)



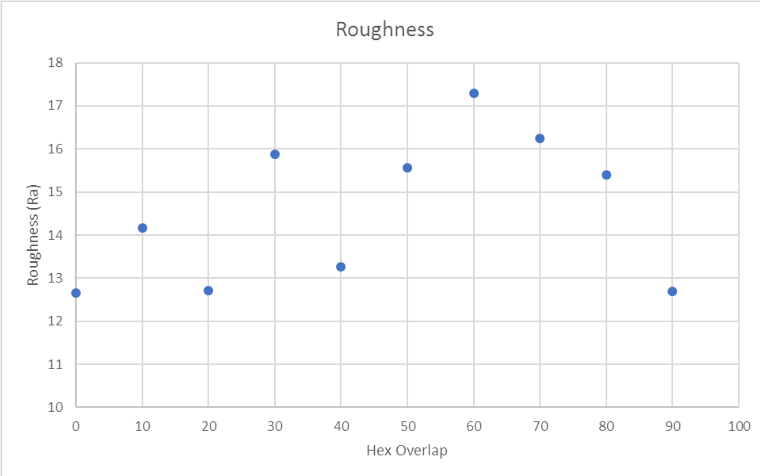
Roughness profile for sample 25 (95 W @ 245 mm/s)

Hex Overlap Test

Input Variables: Hex pattern infill overlap (0-90 µm)
Output Variables: Roughness, visual quality
Description: The goal of this test was to determine if there is a notable difference between the overlap dimension of the hex pattern infill. With this test, the overlap was varied between 0 and 90 µm. The result was to determine if there is a notable difference in the surface quality for each sample. The surface pattern is important, especially when used for molding, as the pattern will show up on the final product for any flat area designs.
Results:
The results for this test showed less difference in roughness than would have been expected. With these tests, the 2D roughness profile was found in several different lengths over a 20 mm sample. The sample length of 10 mm with the overlap in the center yielded the best results.


Hex overlap samples.

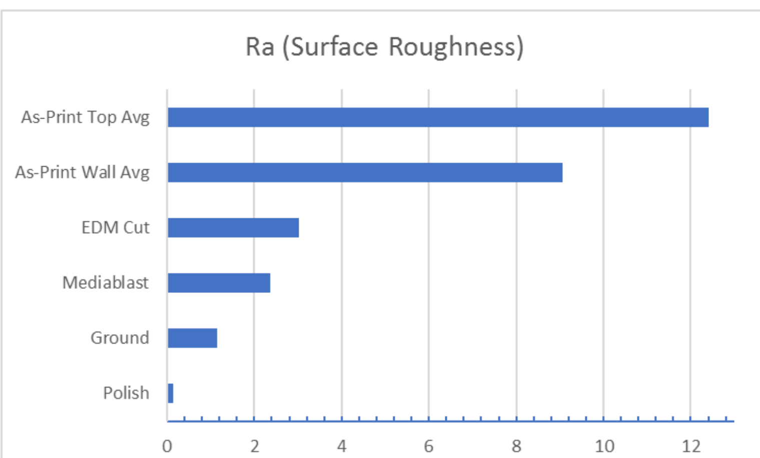
As shown in the chart below, there was minimal difference in surface roughness for each sample. There is a slight arc trend to the results, and this may be due to the amount of material being hit with the laser twice. For the far left, where the overlap is minimal, there would be minimal areas where the laser would be firing twice. Then for the center of the data, the laser would be firing with a similar overlap to the normal hatching spacing, which could cause an uneven melt area. Finally, for the far right, the laser would be melting material over a wider area, and as such, the impact would smooth out more than if it were closer to the beam width.



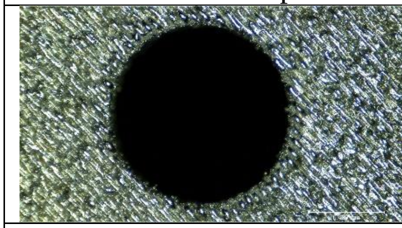
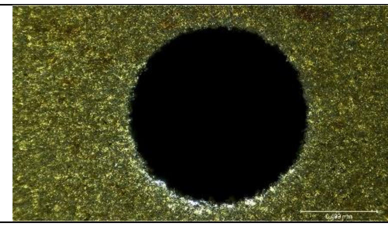
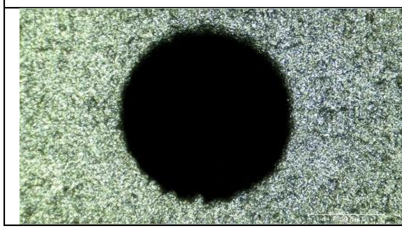
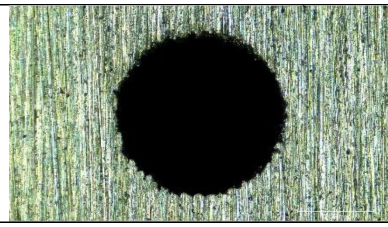
Surface roughness for different hex overlap.

Post-Processing

Input Variables: Modification of post-processing method
Output Variables: Surface roughness (Ra)
Description: To establish and visualize a baseline for different post-processing methods, a sample was created and processed with several methods. The sample consisted of a 15 mm square cube with baseline laser parameters. The cube was then left as-printed on two faces, ground with a file, polished, and media-blasted all on a side of the cube. The resulting roughness values are displayed below.
Results: Overall, the surface roughness for the as-printed faces were within the range of what would normally be found with baseline settings. It was found that the glass media finishing yielded a significantly smoother surface, reaching near the level of grinding.



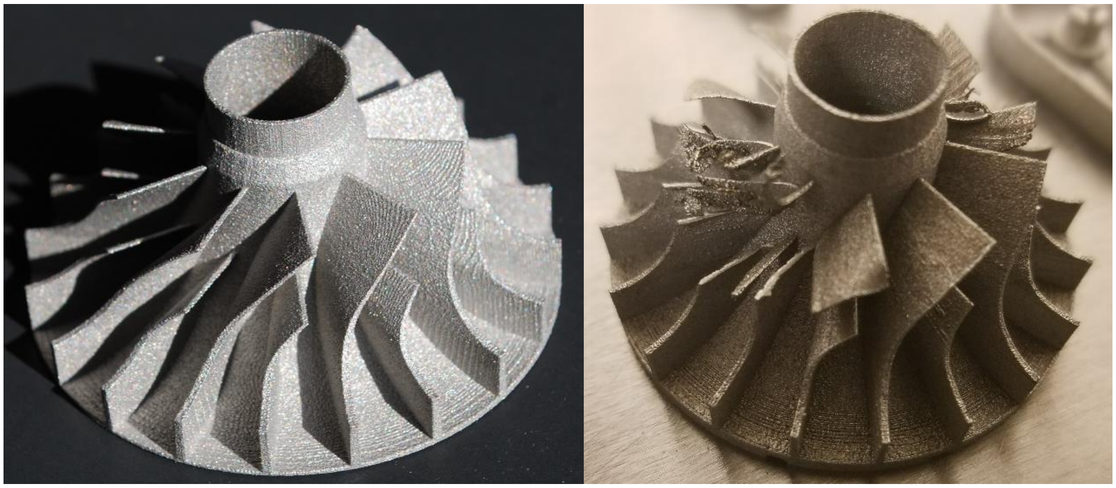
Detail Finishing Methods:

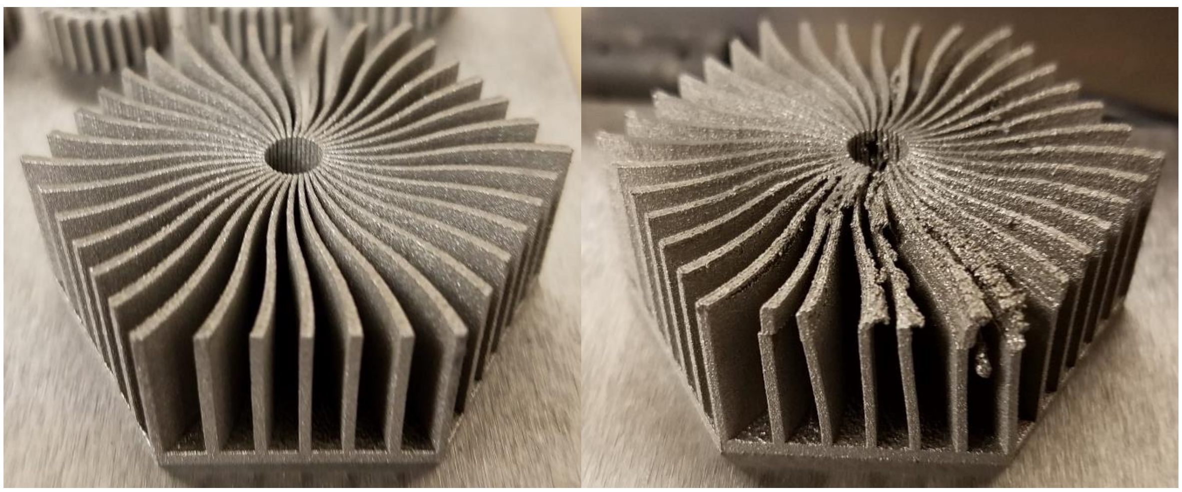
As-Print Top	As-Print Side	EDM Cut Base
		
Mediablast Side	Ground Side	
		

As-Print – Left to be tested with no post-processing. This surface would be comparable to what would be found fresh from the system.
EDM Cut – This surface is the result of the electrical discharge machining to separate the part from the plate.
Mediablast – A fine glass bead media was sprayed over the surface at high velocity which causes any uneven surface to smooth down.
Ground – Any notable surface roughness was filed down to a consistent height. The roughness in this case would be attributed to the grit of the file used.
*Polish*ed – This surface utilized a 'scotch-brite' buffing wheel to attain a reflective finish.

Contour Pass Inclusion

Input Variables: Contour Pass
Output Variables: Functionality
Description: One key finding during this research was with the inclusion of a contour pass for a build. The idea of the contour pass is to give a more consistent or uniform side surface or shell to a part. The downside to this option is there will be an increased likelihood of a part having issues during the fabrication process due to overhang geometries.
Results: Results will vary based on each design, but for thin geometry or large overhangs, it was found that the inclusion of the contour pass can rapidly deteriorate the quality of a design. As shown in the four images below, the contour pass resulted in the roller 'pushing over' the thinner geometries of the part. This resulted in escalating issues as the part progressed through the layering. In contrast, having just the normal infill pass yielded a design that was fully functional and stable through the duration of the build.


Turbine created with identical geometry offsets, but with the left having no contour pass.


Heatsink created with identical geometry offsets, but with the left having no contour pass.

Strength

Pull Test (Grids)

Input Variables: Laser power level
Output Variables: Force / elongation, tensile strength
Description: This test aimed to test a sample of grid supports to determine the impact that laser power has on sparse support strength. With this test, two main variants of support were tested with the ‘spikes’ being at the top of all samples, and on the bottom on half the samples. It was found during the process that the samples with the spikes at both the top and the bottom failed to build properly on the lower power levels. The options that started as a full wall were functional in all tests.

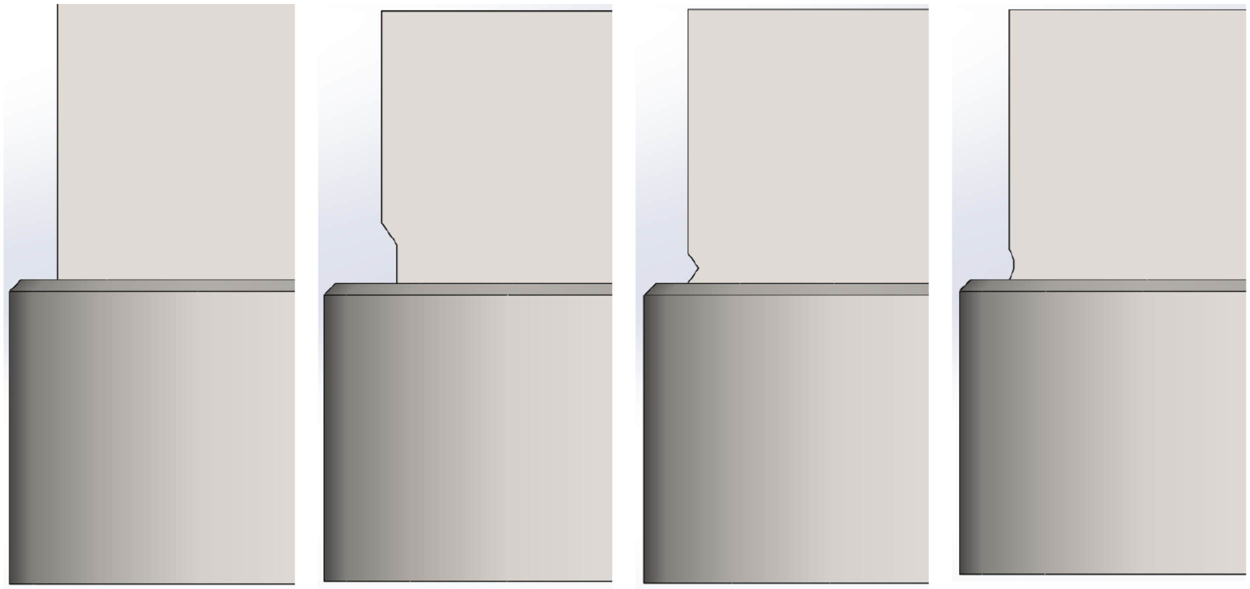
Results: After removing the three samples that were non-functional, 7 options remained. These samples were pulled in the build-orientation, which would most closely represent their real-world strength.
It was found that overall, the tests performed as expected, where the higher power level grids were stronger than the lower power grids. It should also be noted that with the geometry selected for this test, the weaker options were not sufficient to adequately support the top clamping feature, and may be why they tested as weaker.

	kgf	mm
Top Spikes	Peak Load	Displacement
50	290.84	0.07719
62.5	793.246	0.23769
75	1427.228	0.27249
87.5	1919.748	0.35891
100	2447.804	0.74979
Both Spikes		
87.5	230.0358	0.03188
100	1385.274	0.02107

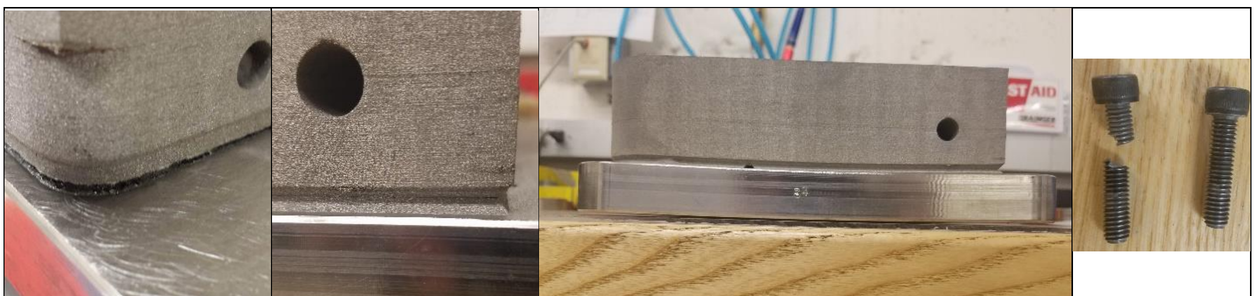
Peak load before fracture and maximum displacement given input laser power level.

Mold Base Geometry Testing

Input Variables: Geometry
Output Variables: Functionality
Description: Through the several large volume projects, the primary issue encountered was part delamination at the base plate. The first route to try and alleviate these issues was to alter the way the parts contacted the build plate.
Results: Initially, builds were fabricated with support directly shadowing the build. This resulted in part delamination for most designs. In a few cases, the build was able to complete quickly enough for the part to only fully separate once the layering was complete. This would give a part that was bowed, which would typically have to be scrapped. Moving on to reducing the footprint, the next idea was to reduce the surface area where the part connected to the plate. While this was functional in the goal of reducing heat transfer, it decreased the connection strength to the plate. This is shown in image h) where the entire mold delaminated during the build. While the result was largely flat at the top surface, this outcome requires that additional material be supplied at the base to be machined beyond the bowing. To reduce this delamination from the plate, a chamfer was added to the next few mold designs like what is shown in c). This design was much more functional, but if the design were too large, it could lead to tearing such as in image f). So finally, to minimize the chance of tearing and delamination, a radius was added to the design. This radius served to minimize stress concentration zones between a cooling part and the plate. The downside to the increased strength was then the added ability to handle thermal warping while the part was being fabricated. As shown in image g) and e), thermal warping during the fabrication process can be extreme enough to warp a 25mm plate to the point that it will cause a grade 12.9 (1220 MPa) bolt to fail.



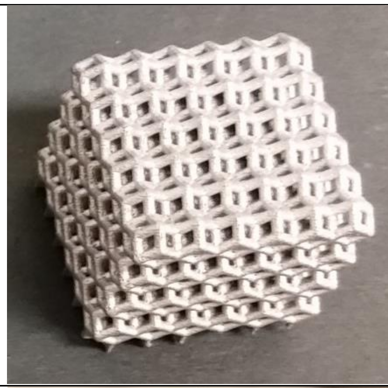
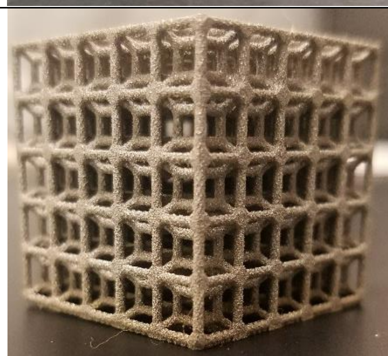
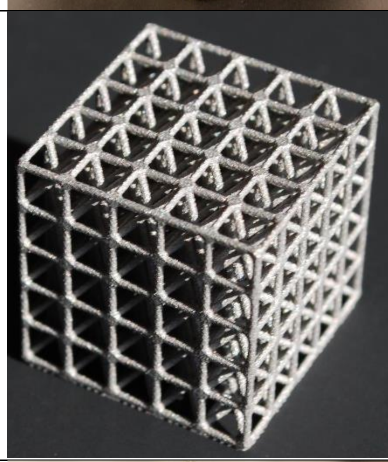
a) No modification b) Reduced footprint c) Chamfered d) Radius

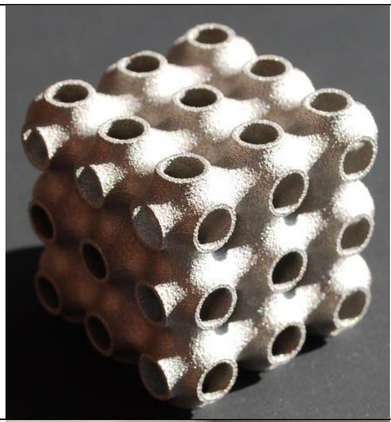
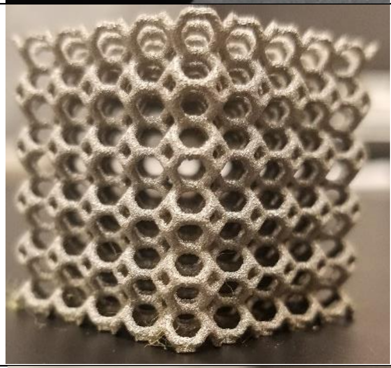
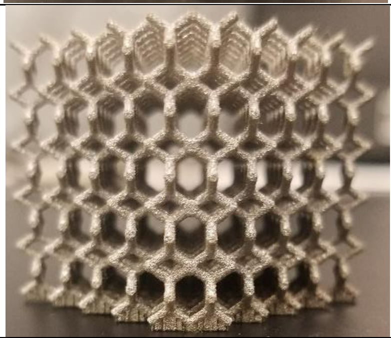
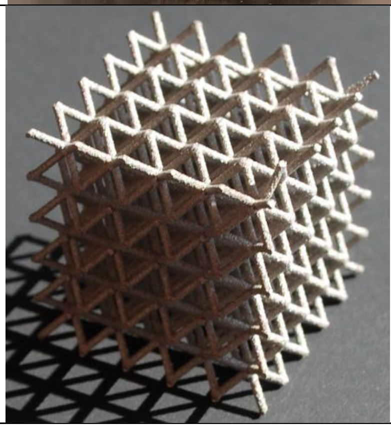


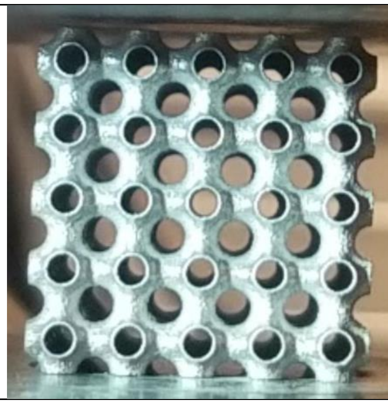
e) Design Delamination | f) Chamfered Split | g) Radius Plate Warp | h) Sheared bolt

Lattice Crush Testing

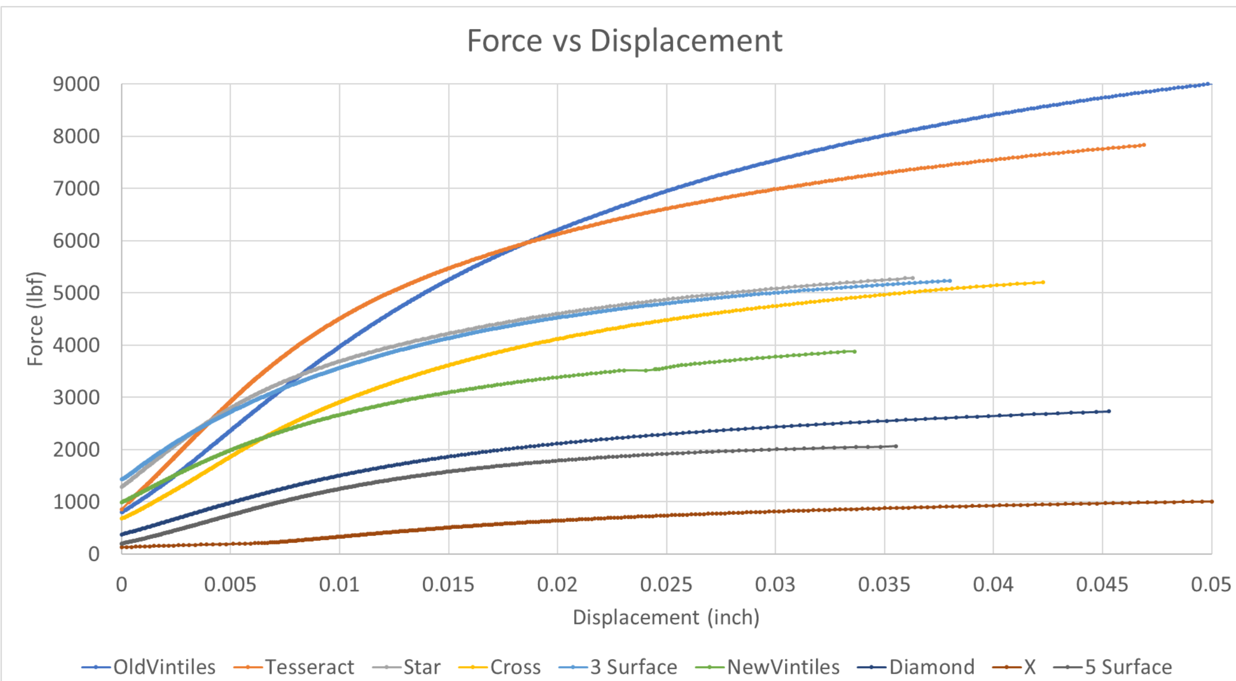
Input Variables: Geometry
Output Variables: Force and Displacement
Description: With advances in CAD software, more complex infill options are becoming available. With the latest version of layering software available from the printer manufacturer, a wide variety of lattice infill is available along with finite element analysis of the resulting designs. To assist with verification of these designs, testing was performed on various samples of lattice created with software called Rhino and an add-on called Grasshopper.
Results: The main use for lattice incorporation into a design is to reduce the volume of the component which reduces the overall laser time. Additionally, lattice can be incorporated in many areas that do not need full volume strength.

Old Vintiles	
Tesseract	
Star	
Cross	

3 Surface	
New Vintiles	
Diamond	
X	

5 Surface	

For the force test, results were trimmed once the sample reached its yielding point and shifted to account for sensor jitter during the initial contact with the samples.



Plot of force and displacement for various lattice samples.

To complete this test, values were computed for the typical material reduction for each sample.

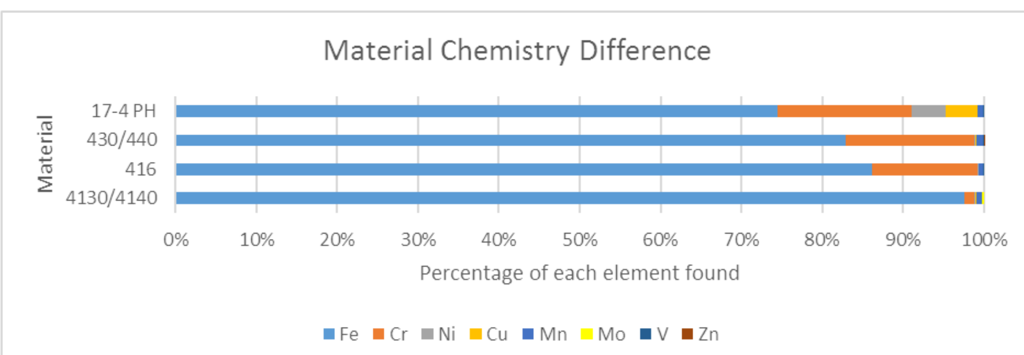
	Volume	Volume Reduced	Weight	Weight Reduced	Max Force	Yield Displace
Solid	15625		4.2188			
OldVintiles	4900	68.6%	1.3230	68.6%	9436.159	1.528623
Tesseract	3372	78.4%	0.8873	79.0%	7842.844	1.191006
Star	2716	82.6%	0.7115	83.1%	5290.08	0.922147
Cross	2450	84.3%	0.6580	84.4%	5201.813	1.07348
3 Surface	2372	84.8%	0.6404	84.8%	5234.594	0.965378
Vintiles	2322	85.1%	0.6525	84.5%	3883.147	0.853999
Diamond	1774	88.6%	0.4893	88.4%	2730.851	1.150493
X	1712	89.0%	0.4890	88.4%	1146.979	2.022983
5 Surface	1495	90.4%	0.4026	90.5%	2068.983	0.901878
	mm^3		oz		lbf	mm

Volume, weight, force, and displacement values for each lattice sample tested.

Material

X-Ray Material Testing

Input Variables: Batches of plates
Output Variables: Chemical material properties
Description: Early in the process of learning how the system works, it was noted that some plates would work better for larger or taller parts than others. Additionally, it was observed that some plates would rust where others would not.
Results: After comparing the similarities, it was found that of the four batches of 10 plates each, there were 3 different plate materials found. Batch 1 and 2 were of a 4130/4140 stainless steel which as shown in the chart below has a high concentration of iron. These plates were the ones which tended to rust and have a poor connection to the parts at layer zero. Batch 3 was of a 416 steel, which would show minimal to no rust when compared to the initial two batches. The parts fabricated with this plate would also tend to be more reliable than with the first two batches. Finally, batch four was a 430/440 stainless steel. With this batch, no rust was observed, and even the larger parts would have good connection to the plate. Upon scanning a batch of plates and parts, the following results were found. The chart shows how similar the 430 steel is to the 17-4 compared to the 4130.



Chemical comparison of each option for base plate material as well as powdered metal.