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Support Structure Development and Initial Results for Metal Powder Bed Fusion Additive Manufacturing

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Abstract

The process of metal additive manufacturing is a relatively new method of fabricating complex parts in industry. Due to the infancy of the technology, limited documentation is available on how to rapidly and efficiently design and fabricate a given part. This paper covers one of the main practical issues of this technology, support generation and design when working with powder bed fusion metal additive manufacturing. This process requires support structures to hold and secure a part being built onto a base plate. The following paper will provide an introduction to the main options of support structure, grid and full support, as well as cover key understanding and developments with support structures for metal additive manufacturing. These support options and their variability will be discussed along with a methodology of rapidly obtaining baseline parameters for their use in fabrication.

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Keywords: Metal Additive; 3D Printing; Powder Bed Printing; Support Structures; Parameters

1. Introduction

Metal additive manufacturing is a new and powerful tool brought to realization by modern technology. The advantages of metal additive manufacturing span from product to process design by eliminating conventional manufacturing constraints to reduced tolerances during manufacture, reduced assembly costs and reduced part

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counts. While the new technology has opened up new possibilities for designers and manufacturers, it is also introducing new challenges to overcome.

One key challenge to this technology is part removal after the build process. In contrast to many plastic printing processes where the part can be simply broken off of 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, there are still significant research efforts needed to optimize the needed quantity and strength of supporting material. In addition, part geometry and orientation can be manipulated to minimize support volume. 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. In order to develop these tools, industries and academia alike are working with many varieties of metals, geometries, and support structures to better understand and refine this technology as it develops.

With technology that has only been in use for a few years, the main obstacle with development is that most research being done is proprietary and not shared outside of a company's engineering team. The goal of this research is to learn and understand the fundamentals of this process then proceed to share and collaborate with industry leaders across the country to expedite metal additive manufacturing integration into the global community. Additive manufacturing in curriculum has only recently gained popularity, and short of high level graduate courses, typically only covers fundamental information. Iowa State University is currently working with industries across the state on projects in new and innovative areas such as metal additive manufacturing. As our knowledge base expands, more and more opportunities and capabilities will arise for companies and the university alike.

Nomenclature

A Additive Manufacturing: A category of manufacturing where an object is fabricated by constructing layer upon layer with a given material.
B SLM: Selective Laser Melting – An additive manufacturing process typically with metals where layers of fine powder are fully melted to build an object.
C EDM: Electrical Discharge Machining – A manufacturing process that utilizes electrical current within conductive materials to erode or burn desired geometries.
D Delamination: A separation of layers due to thermal warping, or insufficient powder distribution during layering.

2. Overview of 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. This means that it is able to achieve enough accuracy that it can 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. The latest technology to gain widespread use is Selective Laser Melting, or SLM. This SLM 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 increase in the 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].

2.1. Industry involvement

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.

2.2. Benefits to Industry

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, SLM is creating parts that will result in material properties very 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 SLM, as long as 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.

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 comparable to a cast 17-4 PH steel with heat treatment.

In order 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. But to advance the knowledge and capability around metal additive manufacturing, new and varied designs and geometries from industry must be tested and shared.

2.3. Support structures

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.

3. Process Description

This process begins with fine metal powder which consists of 5 to 30µm 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 60µm 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. In order 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.

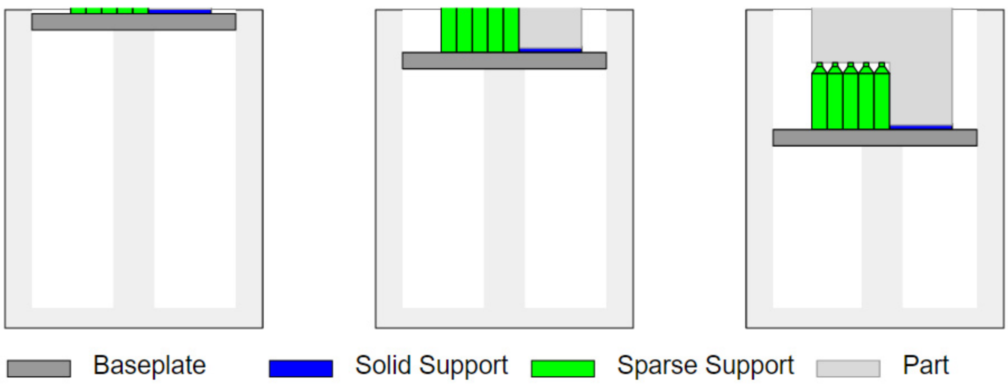


Figure 1: Initial layering pattern

Figure 2: Geometry progress partially through the manufacturing cycle

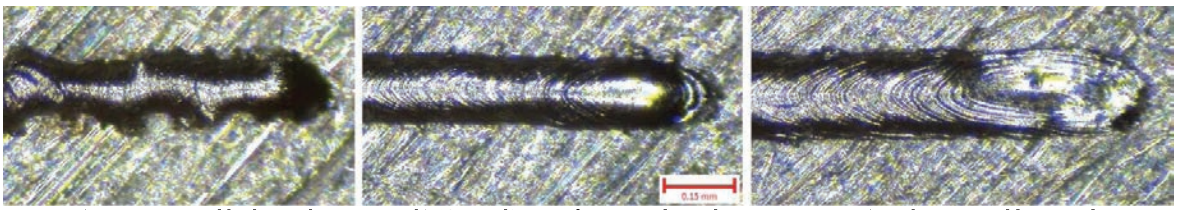
Figure 3: Geometry with manufacturing mostly complete

3.1. Parameters and Support Structures

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 will have to be later removed. This is fairly 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 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 increase the strength of these supports to the maximum possible. 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. In order to minimize post processing, a core task when working with this technology is 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.

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. In order 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 very similar to most welding processes. In exactly 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 end 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 the aforementioned 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 4: Microscope images of low, median, and high energy input weld bead of 17-4 PH stainless steel powder.

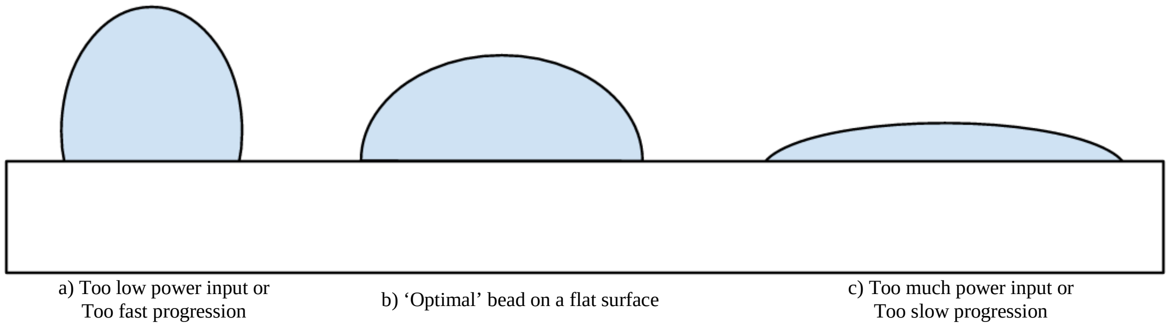


Figure 5: Cross-section diagram of conceptual weld bead model for the initial layer on a plate.

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.

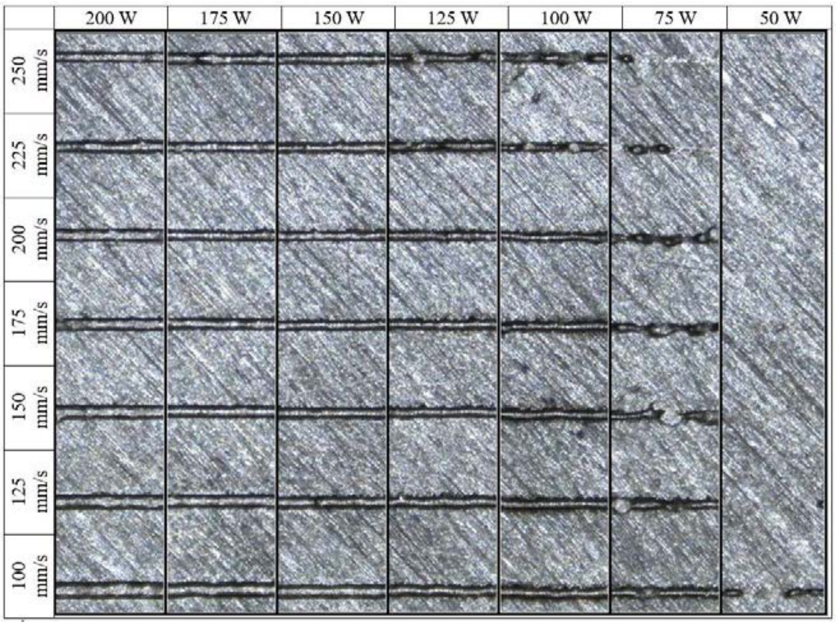


Figure 6: Laser Power and Speed impact on single line melt pool.

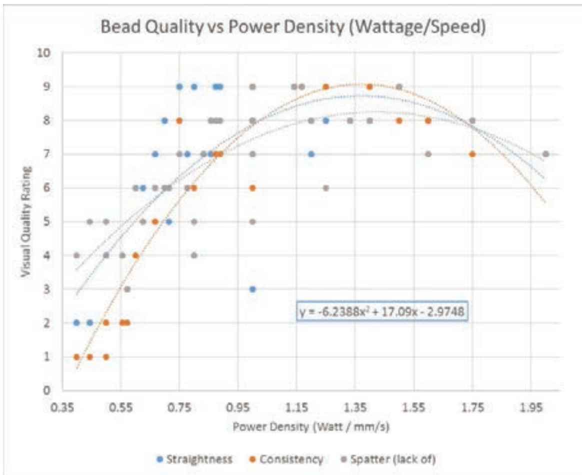


Figure 7: Overall Bead Quality Trend

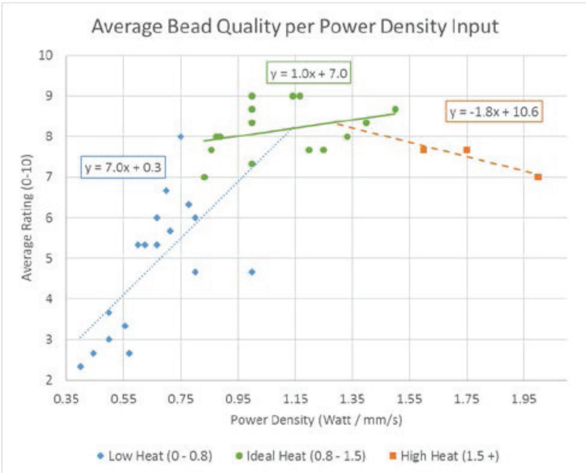


Figure 8: Averaged Quality Trend Regions

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.

In order 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.

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.

3.2. Thin-Wall Support Structure Patterns

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. In order 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 has to 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 9) to reduce the contact with the part while still maintaining enough support to melt the initial layers of a part. Grids should be optimized in order 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 10 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 in Figure 5 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 9 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 support, the power can be increased to create a wider, fully melted grid support structure. Comparing the grid supports in Figure 10 shows a clear difference between the hot and cold layering settings.

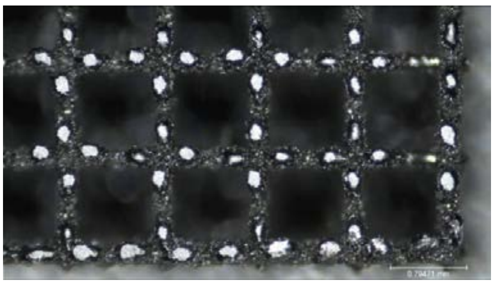


Figure 9: 4x image of grid supports captured in the Z-axis

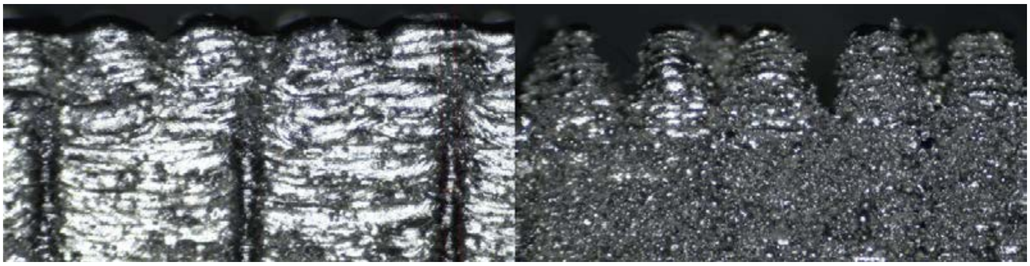


Figure 10: Comparison of high heat input (150W left) vs low heat input (75W right) when building support structures.

3.3. Solid Supports

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 11 in 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 11, 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.

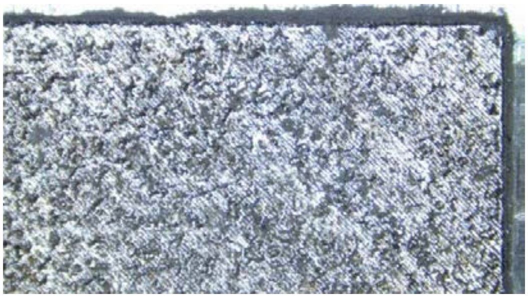
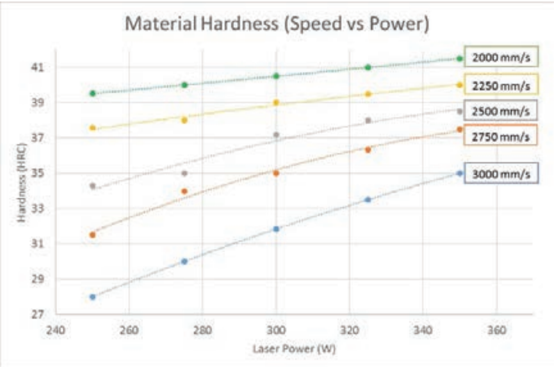
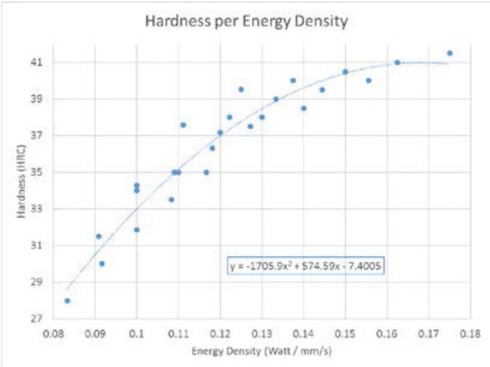


Figure 11: 2x image of a solid support layer

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 12 (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 12 (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 12: Comparison of different laser parameters and their resulting hardness

4. Discussion

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 13 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 13: Reducing post-processing by utilizing breakable supports

Another possibility that is not often discussed is combining support options. As shown in Figure 14 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 15 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.

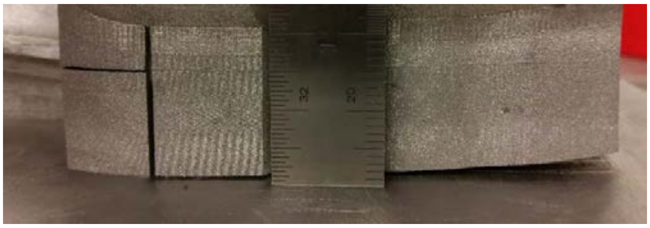


Figure 14: Part delamination due to thermal stress during layering

Figure 15: Full connection by combining solid and grid supports

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 the 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 generation and parameter setting as there are with many plastic systems. In order 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, in order for this technology to become more widely utilized, the systems supporting it must improve. Once the academic research models have been integrated into CAD software, designers will be able to rapidly develop and optimize designs for manufacturing. The possibilities that this technology brings will take years to fully research and understand. Establishing the baseline parameters of this process is the first step in learning how to fully utilize metal additive manufacturing as the technology advances.

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