THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ELECTRICAL ENGINEERING

THE APPLICABILITY OF ADDITIVE MANUFACTURING IN MASS PRODUCTION AND SPACE OPERATIONS

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A thesis
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ABSTRACT

Additive manufacturing is taking over the mass production industry by storm. More companies are electing to print components of a machine or the entire machine itself. Manufacturing efforts that were thought to be arduous or impossible before the implementation of both plastic and metal additive manufacturing are now possible. The benefits of switching to additive manufacturing from subtractive manufacturing range from less leftover material after machining to cleaner production of the interior of components. With the constant updates of CAD software, it is easier for students and engineers to design parts. The future of additive manufacturing will be applied to industries around the world. As the technology develops, it will become more accessible to the public, eventually allowing every workshop and lab to have a metal additive manufacturing machine to eliminate the barriers to creativity.

This thesis addresses several methods of additive manufacturing and shows how they could be applied to current research with microwave electrothermal thrusters. The MET can be made of materials like aluminum, bronze, or titanium, which can all be used in the additive manufacturing process. Rather than make the thruster through a subtractive process like milling, the thruster can be designed and printed in multiple parts that can be put together in post-processing. The result is a cleaner, more efficient way to maneuver spacecraft while utilizing the most updated additive manufacturing processes.

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I would like to thank my parents for continuing to support me throughout my college career. I am very lucky to have been raised in a manner that allowed me to choose this path in my life. I am appreciative of the financial assistance that I received from Penn State and the Schreyer Honors College so that I could continue my studies without financial issues.

Chapter 1

The Framework of Additive Manufacturing

The first commercial use of additive manufacturing was in 1987 when 3D Systems used stereolithography, a process by which a laser solidifies UV light-sensitive polymers, to produce parts [1]. Additive manufacturing has come a long way since then as the industry has evolved rapidly to support the needs of manufacturers for high-complexity shapes and structures. AM processes use CAD files that are uploaded to the printer to manufacture the part. Some of the various additive manufacturing processes include binder jetting, stereolithography, selective laser sintering, multi-jet fusion, and direct metal laser sintering. Each has strengths and weaknesses that must be considered when designing a part to be additively manufactured. The speeds of the different additive manufacturing methods vary greatly to produce a similar part, from minutes to days.

There are several benefits of using additive manufacturing over subtractive manufacturing for parts with certain features. First, consider a part that requires a design on the inside of an enclosed material. It is much easier to continuously build layers of material from the bottom up instead of going in after the outside is finished. Indeed, some designs are near-impossible to make with subtractive manufacturing. Second, there is less wasted material when using additive manufacturing. The required amount of material can be determined by the volume of the design before the printing begins. With subtractive manufacturing, there is always waste material because the machine has to remove material to make the part. Last, the complexity of each process differs. Ideally, with additive manufacturing, one can press print and it’s automatic. In certain subtractive processes, the part may have to be rotated by the user, or a tool may have to be taken off and a new one may have to be added in the middle of the process. In short, there are a lot fewer problems during the manufacturing stage with additive manufacturing.

While there is a continuously growing list of benefits of additive manufacturing, there are drawbacks that will hopefully be addressed in the future as the technology develops. First, and most importantly, the cost is a factor. For example, printing a part in metal that has the same volume as a shoebox could cost thousands of dollars, which is an order of magnitude more than simply putting a block of metal into a milling machine and milling a part out of the block. However, for certain very expensive alloys, 3D printing may turn out to be less expensive since little material is wasted. Second, post-processing with certain methods of additive manufacturing can be tedious. When a part is manufactured in a milling machine, the part is done when the machine finishes removing the material (although it may need some touching up). This is not the case in additive manufacturing because generally molds and support structures need to be removed at the end of the process. Last, the cost of the machines themselves can be more than $1 million. With the cost of these machines so high, not all companies can afford to have them on-site.

Additive manufacturing is currently being used in multiple industries. For example, in the medical industry, it is being used for prosthetic limbs. A limb can be designed based on the patient’s dimensions, and support structures can be added on the inside depending on the patient’s needs. It is also being used by the defense industry to print aircraft propellors and other components. I have used additive manufacturing to print out a chessboard case. The case was designed to have LED lights attached to the bottom and would light up whenever a piece was on it. It had the separators of a chessboard and had an insertion that would hold an acrylic chessboard on top of it.

The future of additive manufacturing is bright, with the machines getting larger and more accessible to the public. We will soon be able to additively manufacture entire car bodies on a single print bed. We will not have to rely on welding, bolts, or screws to attach parts.

This reminder on this thesis is organized as follows. Chapter 2 presents an overview of several types of additive manufacturing. One method of additive manufacturing that will be discussed in more detail is binder jetting. Chapter 3 then addresses the use of additive manufacturing for METs, taking note of changing the method of manufacturing of the nozzle and plate. The printing procedure that the parts went through will be explained in Chapter 4. Chapters 5 and 6 discuss the mass production capabilities of additive manufacturing and material selection. Chapter 7 concludes the thesis with the future marketability of AM.

Chapter 2

Binder Jetting Additive Manufacturing

Binder jetting has advanced significantly since it was initially developed at the Massachusetts Institute of Technology in the early 1990s [2]. Materials available in granular form, such as sand and powdered metals, can be used in this process, which jets binder onto the granules to make them stick together. In metal 3D printing, metals used include tungsten, bronze, steel, and cobalt chrome, to name but a few [2]. With a wide variety of metals available for printing, users should be able to find one that works for them. Another class of materials that can be utilized with binder jetting is ceramics. These can include alumina, carbon, silicon carbide, and tungsten carbide cobalt [3].

The time it takes to work with a part in post-processing after the manufacturing is a factor in evaluating which AM process to use. Especially when working with metals, accuracy is one of the most important factors when evaluating binder jetting techniques. The binder jetting process involves two main steps: 1) create a very thin layer of granules and 2) add a liquid binder through a print head that connects the granules that make up the part, leaving the others unconnected [2]. These two steps are continually repeated until the part is built. Post-processing removes the loose material with a brush or compressed air, usually done by a human [2].

Another main purpose of this technology is to produce parts at a faster rate than other processes, making it an intriguing option for companies. Instead of taking days and weeks to get a newly designed part out, with additive manufacturing it can be done much faster [4]. With the possibility of post-processing automation, there could be nonstop production capabilities. The initial cost of the machines may seem daunting, but any company would only need one or two of these machines [4].

Chapter 3

Additive Manufacturing for METs

Additive manufacturing is currently being used to produce thrusters that use microwave power to produce plasma in a propellant [5]. These thrusters are smaller than the ones we see being used on traditional rockets.

Figure 1 shows a picture of the 17.8-GHz microwave electrothermal thruster (MET) as set up in a vacuum chamber for testing, which is located in the Research East Building at The Pennsylvania State University. Multiple gases can be used in an MET, including ammonia and nitrogen. In Figure 2, one can see the thruster is firing into air. Notice how the plume comes out of the thruster and gets thinner at the top.

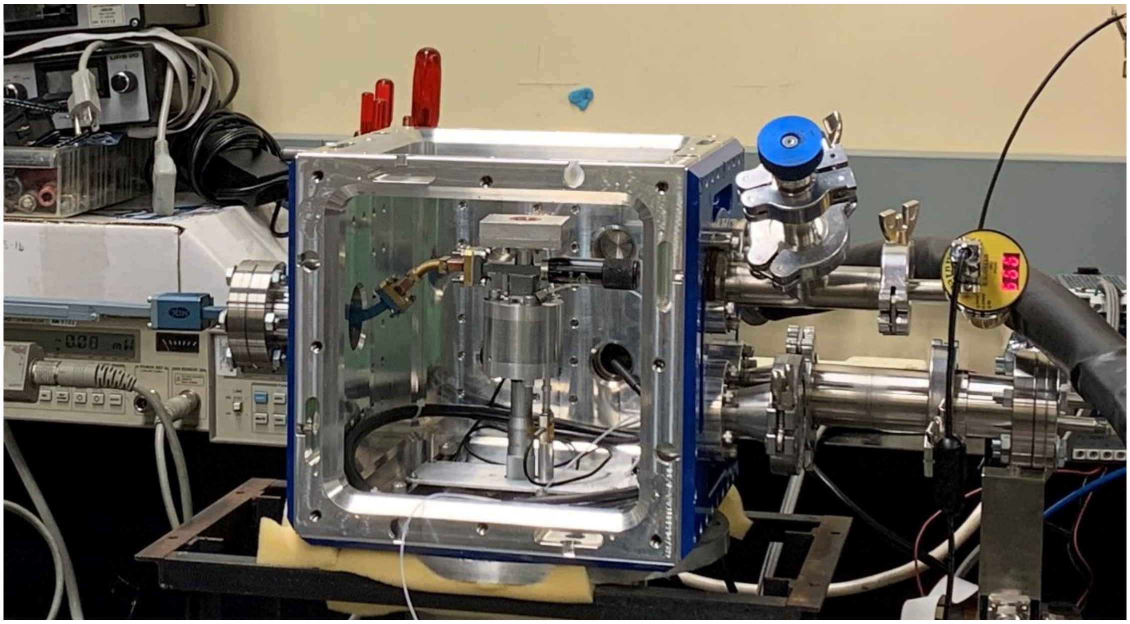

Figure 1: 17.8-GHz ammonia propellant microwave electrothermal thruster.

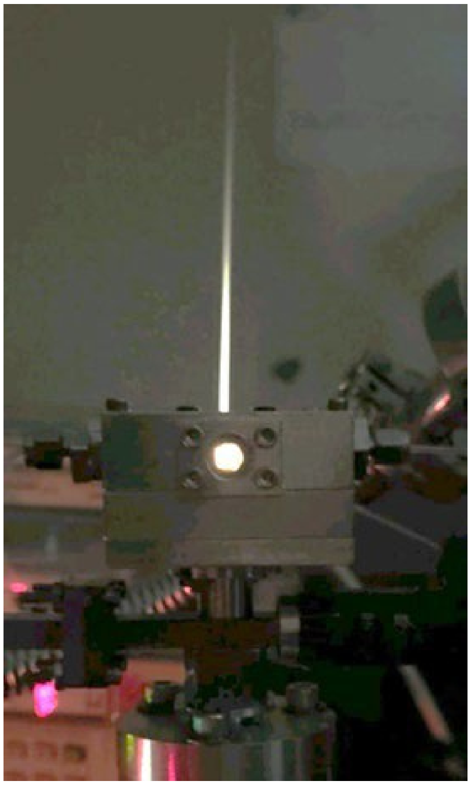

Figure 2: 17.8-GHz MET firing into air (courtesy of Matthew Beckerle).

The data in Table 1 summarize prior tests of the 17.8-GHz MET. As shown, the specific impulse rises with an increase in input power. The increase in the stagnation pressure ratio is also an indicator of the performance of the thruster [5]. In the MET, “once formed, the plasma becomes a very efficient absorber of the microwave energy due to being very resistive in nature and having a high rate of electron collisions with neutrals and ions; thus, the plasma can be sustained at high pressures” [5]. As stated, “A higher chamber pressure results in a more coalesced plasma, improving the heating of the propellant gas flowing around the plasma before passing through the nozzle. Decreasing throat diameter also increases the throat Reynolds number for the same mass flow, reducing the discharge coefficient of the nozzle” [5].

Table 1: 17.8-GHz MET test summary (Biswas).

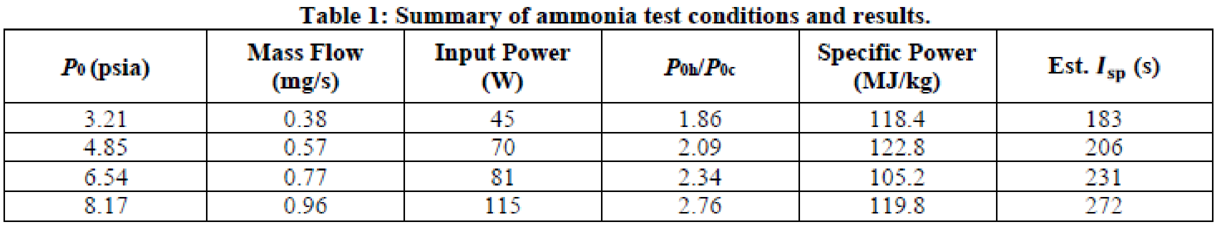

Table 1: Summary of ammonia test conditions and results.

P_0 (psia)	Mass Flow (mg/s)	Input Power (W)	P_{0h}/P_{0c}	Specific Power (MJ/kg)	Est. I_{sp} (s)
3.21	0.38	45	1.86	118.4	183
4.85	0.57	70	2.09	122.8	206
6.54	0.77	81	2.34	105.2	231
8.17	0.96	115	2.76	119.8	272

To explore the use of AM in the manufacture of the MET, two thruster parts were designed: the nozzle and plate and nozzle combination. Figure 3 shows the nozzle, whereas Figure 4 shows the design for the nozzle and plate combination. This is the final design for the nozzle and plate in that same thruster. A simple assembly file was used to merge the nozzle and plate that were created. The dimensions of each part were smaller in design as compared to previous designs, but the ratios of measurements between the throat and the point of exit were kept relatively the same.

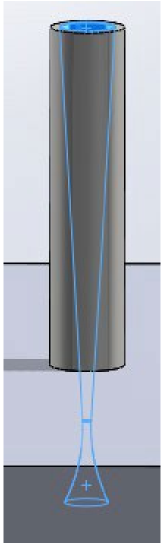

Figure 3: Nozzle design for microwave electrothermal thruster.

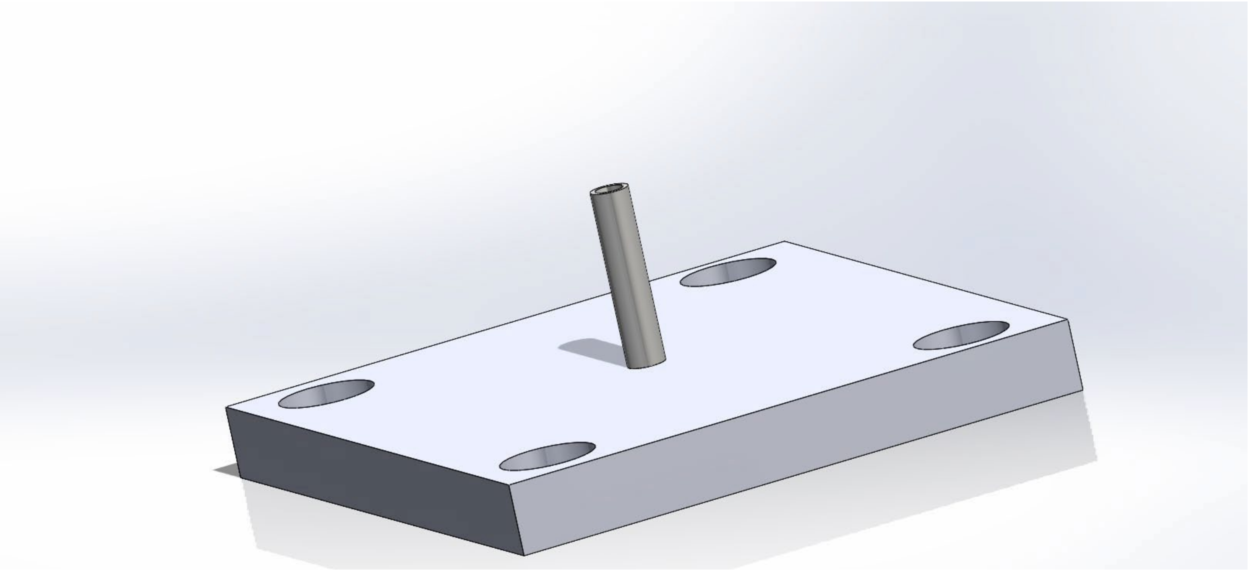

Figure 4: The nozzle and plate attached.

In the future with these thrusters, AM could be the primary method of production for more than just the plate and the nozzle. The expansion of the AM industry into more fields will continue to cement the technology as the new normal of manufacturing. While expensive right now, the machine knows how much material it needs to produce the part and then produces it layer by layer. As a reminder, AM of the parts was chosen for the thrusters because it does not leave as many, if any, leftover materials as subtractive manufacturing. The only thing that would be needed is support structures if necessary. It might not be a huge problem, but cleaning up a little bit at a time makes a large difference when added together.

Chapter 4

Printing Process

The printing process used for the nozzle was direct metal laser sintering. The printing was done by The University of Texas at El Paso in their Convergent Microsystems Laboratory. The 3D printer used was a Xact Metal XM200C 3D Metal Printer, with 316L steel powder. Figures 5 and 6 show that the nozzle had to be ground because the nozzle throat was not open after printing.

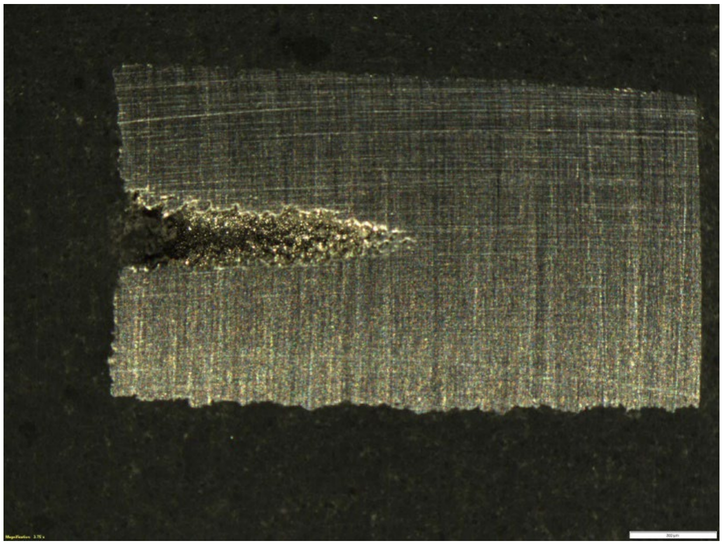

Figure 5: Grinding of the nozzle (courtesy of Dr. Robert Roberts and Bhushan Lohani).

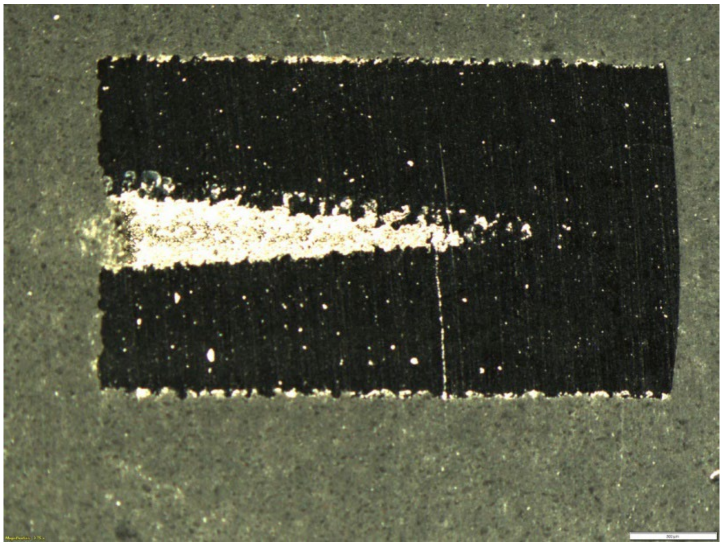

Figure 6: More grinding of the nozzle (courtesy of Dr. Robert Roberts and Bhushan Lohani).

The grinding process was performed by Michael Lopez-Duran and Dr. Brian Schuster in the Metallurgy and Materials Department at UTEP. The CAD file also was modified to simplify the printing process. The modifications are shown in Figure 7 with an accompanying picture of the nozzles in Figure 8. The printed nozzles are shown in Figure 9.

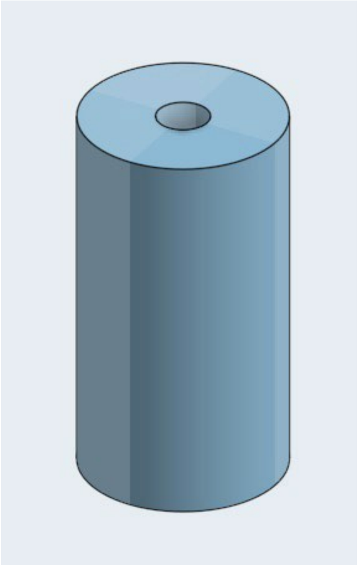

Figure 7: The outside of the nozzle (courtesy of Dr. Robert Roberts and Bhushan Lohani).

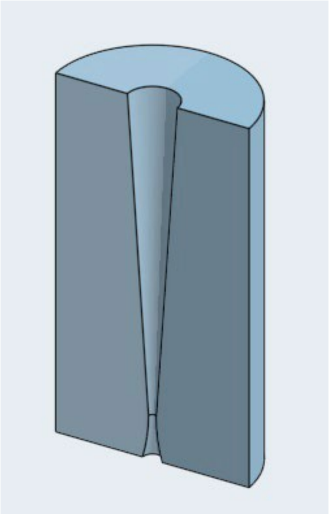

Figure 8: The inside of the nozzle (courtesy of Dr. Robert Roberts and Bhushan Lohani).

Figure 9: The printed nozzles (courtesy of Dr. Robert Roberts and Bhushan Lohani).

As per Dr. Roberts, the initial print run was performed while grinding some of the samples in half to have a look at the internal structure. Test structures were also built to test the printer performance on different hole sizes to determine the smallest optimal size for this nozzle.

Chapter 5

Mass Production Capabilities

Before the invention of faster printing machines with larger print beds, mass production was not as practical. For AM to be competitive, it must keep up with the more traditional methods of manufacturing. Fortunately, what was thought to take weeks and months to create using AM is now taking hours.

Specifically, binder jetting differs from other processes like sintering and lasering because it does not build the parts with a single point [2]. It does not have to weld material together with a single nozzle [2]. With the use of CAD files, it can lay grains of material on the print bed and apply a liquid binder that attaches every required grain at a high speed [2]. This is being done with metal and sand, so the question of material is already answered.

The CAD files are uploaded into the machine and the machine already knows how much material is needed. A lot of costs come from excess material that is purchased to be put into the milling or drilling machines, so if millions of parts need to be made, the only answer to save costs is to use additive manufacturing. The question of where the excess material goes during the subtractive manufacturing process is also a concern. It would not be a surprise if the material gets thrown out and contribute to landfills. The leftover material might not always be recycled because it might be damaged beyond reuse.

The future for binder jetting will involve projects like printing entire car bodies at once so that supercars look even better than they do now. The machines are not yet large enough to do this, but they can already make the parts for them. There are hardly any metals too difficult to be used in binder jetting. The possibilities are endless with this futuristic technology. The speed only gets faster, and the process only gets more accurate. Within a decade, there could be binder jetting printers in every workshop.

If mass production is to be implemented using AM, then there has to be a capability for 24/7 production. Some subtractive manufacturing methods require human supervision because the tooling methods could fail and cause serious damage to the part and the surrounding area. Additive manufacturing is the clear winner in terms of the safety factor. Not only does it not include rapidly spinning tools, but it also does not use sharp objects that can detach during operation. The ability to keep production running without human supervision is a key component of mass production in the future.

The ExOne S-Max Pro is one of many examples of advanced printer technology. It is an enclosed case where the entire printing process occurs. The part is extracted once completed and is ready for post-processing. The maximum build rate for this specific machine is around 125 l/h or 125,000 cubic centimeters per hour [6]. That is an unprecedented speed for binder jetting. This speed will undoubtedly increase in the future. The machines are now so advanced that they can detect issues in the process early so that less material can be wasted [6]. There is less post-processing and less cleanup because the entire process is enclosed in the machine, not to mention that the part is immediately ready to be removed after completion [6]. Whether it is one part made on the entire print bed or multiple parts of the same design being printed at once, binder jetting is the clear choice for high-quality mass production of industrial or commercial components.

Chapter 6

Material Selection

When selecting AM as the choice of production, it was once only for tabletop plastic operations. The projects being made could range from small figurines to phone cases. Now, with a larger selection of machines and materials, some projects can only be made through AM. Figure 10 shows an example print using plastic additive manufacturing.

Figure 10: Plastic boats made using additive manufacturing.

While the main discussion is about metal being implemented in additive manufacturing, there is still a wide variety of plastics for different applications. A common plastic to use in plastic additive manufacturing is PLA plastic. PLA plastic is easy to obtain and is one of the plastics that does not run a large cost on the expenses sheet [7]. For any projects that might need a quick prototype on a low budget with a large volume, PLA plastic will get the job done. A drawback to PLA plastic is that it is not resistant to heat and will melt when exposed to high temperatures [7].

If there is a need for stronger plastic in additive manufacturing, ABS plastic is the next choice available. This plastic withstands higher temperatures and is stronger overall in comparison to PLA plastic [8]. It does cost more than other plastics, but it can also be used for prototypes before using metal. Any serious projects that plan on using metal AM could take this path first to get a working prototype with high-quality material before moving to metal.

When deciding to use metal AM for a project, it is important to choose a material that can handle the project's application. The most common material used for printing with metal is aluminum due to its low cost in comparison to other alloys, its strength, its conductivity, and its resistance to extreme temperatures [9]. If a dense material is needed, nickel, titanium, and steel are also available to be used [9]. The materials thought to be too strong to print with are now available for use.

If neither plastic nor metal work for the application, printing with sand is also available. Binder jetting offers a variety of binders that pair well with ceramic and silica sands. One type of binder that works with both these sands is furan binders. The main quality of this type of binder is its strength [10].

Lastly, an inorganic binder can be used if the part should not have an acid or chemically cured binder. Inorganic binders with sand binder jetting are water-based and require more post-processing than the other binder types [10]. Regardless of the type of binder that is chosen, sand binder jetting stands as a reliable option for additive manufacturing.

Chapter 7

Future Marketability and Conclusion

Marketability is another aspect of additive manufacturing that is under a microscope. Even if all of the possible improvements are made, the question of who will adopt it over other methods of manufacturing still needs to be answered.

Companies in different industries that use subtractive manufacturing and companies that are recently aware of additive manufacturing are the most likely to take the first step. Since exposure is in its early stages, there is an abundance of opportunities that are yet to be taken advantage of. Current market conditions have allowed for the market capital values of additive manufacturing companies to fall low enough that larger additive manufacturing companies are buying the smaller ones to strengthen their base. For example, consider Desktop Metal buying out ExOne in November of 2021 [11]. To put the company in a better position, they purchased a smaller company before someone else could. They now own a larger share of the additive manufacturing world. One of their main points is to focus on mass production, so acquiring another company with a similar focus was a pivotal step to success [11].

When the companies that do not use additive manufacturing start buying companies that do is where the market share of additive manufacturing will start to grow exponentially. The moment one company is bought by an industry leader so that their technology can be implemented, others will catch on, and eventually, there will be no more companies left to buy. The lists of clients are sometimes listed on the company website, so it is only a matter of time before a client turns into an owner. From a sheer monetary perspective, because every person is looking for the next undervalued buying opportunity, someone is eventually going to take the risk.

The difference between buying a company outright and having them as a client is the intellectual property that comes with the purchase. Instead of crediting the manufacturing company that aided in the project, the company logo now replaces it. The other previous clients may have been competitors, and now the company that bought the entire additive manufacturing intellectual property can choose to keep the technology for themselves, giving them an edge over everyone else.

In conclusion, while this technology is continuing to develop at an alarming rate, additive manufacturing is still in its primitive stages in comparison to what the future holds. It will take time for change to take place, but the future is bright for additive manufacturing.

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- **Updated and develop scripts** for array startup and performed RF hardware calibration analysis
- **Supported maintenance** of solid-state radar components and support equipment
- **Obtained a Final Government Secret Clearance**

Michael Baker International Pittsburgh, PA

Electrical Engineering Internship, May 2021 – August 2021

- **Lighting systems design** for highways and bridges throughout Pennsylvania, Ohio, Georgia, and New York, to meet architectural planning goals and the design standards required by the department of transportation in each jurisdiction
- **Cost-benefit engineering analysis** evaluating equipment availability, operating costs, and capital costs, while meeting sustainability and safety goals
- **Proficient in AutoCAD, AGI 32, and MicroStation** to analyze road conditions and determine the proper lighting ratios to satisfy the luminaire requirements of each project
- **Effectively communicate** project progress via presentations, reports, and e-mails to senior engineers, architects, and project managers in multiple company departments

McDonald's Restaurant

Guided Experience Leader, 2017 – 2019

- Improved the customer experience by combining my technical expertise and customer service excellence to instruct patrons how to use McDonald's new computer ordering technology

Professional Skills

- AGI 32, Autodesk AutoCAD, and MicroStation
- Bluebeam Revu 20 and Adobe Acrobat DC
- C++, Verilog, Multisim, and Ultiboard
- myDAQ and oscilloscope proficiency
- Autodesk Inventor and Fusion 360
- SolidWorks
- Microsoft Word, Excel, Outlook, PowerPoint
- Desktop computer assembly with an Nvidia GeForce 1060 GPU

Enrichment Programs

Iceland Engineering Enrichment, *April 2017*

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