STRENGTH TEST AND ANALYSIS OF ADDITIVE MANUFACTURED GEARS AND THEIR APPLICABILITY FOR EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

THESIS

Sean T. Murphy, Captain, USAF

AFIT-ENV-MS-17-M-204

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENV-MS-17-M-204

STRENGTH TEST AND ANALYSIS OF ADDITIVE MANUFACTURED GEARS AND THEIR APPLICABILITY FOR EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Sean T. Murphy, B.S.

Captain, USAF

March 2017

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-17-M-204

STRENGTH TEST AND ANALYSIS OF ADDITIVE MANUFACTURED GEARS AND THEIR APPLICABILITY FOR EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

Sean T. Murphy, B.S.

Captain, USAF

Committee Membership:

Vhance V. Valencia, PhD, PE, Lt Col, USAF
Chair

Jason K. Freels, PhD, Maj, USAF
Member

Heather J. Chaput, PhD
Member

AFIT-ENV-MS-17-M-204

Abstract

Recent advancements in additive manufacturing have led to a number of fields within the Department of Defense employing this technology. This research determines if additive manufacturing can assist the field of explosive ordnance disposal by manufacturing replacement gears for the micro tactical ground robot. This is accomplished by completing a single-tooth bending test on a number of gear teeth manufactured using two different 3D printers. The ProJet 3500, a $90,000 material-jetting printer, produced gear teeth that proved to be of high strength and quality. The Lulzbot Taz 6, a $2,500 material-extrusion printer, also produced strong gear teeth, but lacked quality dependent on build orientation. The research shows the orientation of layers affected the strength of the gear teeth, but not to a point where the tooth failed before reaching a pre-calculated, required stress. This work provides a starting point for understanding the effect of layering on additive manufactured gears while providing strong evidence toward the efficacy of additive manufacturing within the field of explosive ordnance disposal.

Acknowledgments

I would like to first thank my research advisor, Lt Col Vhance Valencia for all of his guidance and mentorship. His ability to guide me along the right path, while still allowing me the space to learn and grow empowered my success. My two thesis committee members, Maj Jason Freels and Dr. Heather Chaput were also extremely helpful throughout this research effort. I would also like to thank the EOD community locally and across the nation. Your inputs were essential to this research effort. I hope the results from this thesis assist you all in continuing to accomplish the dangerous and essential missions you so often encounter. The Air Force Institute of Technology Machine Shop was also helpful throughout this research effort, and I want to thank them for all of their support. Finally, I would like to thank my new bride Kristen. Thank you for joining the Air Force family, and for putting up with me throughout this first of many Air Force adventures!

Sean T. Murphy

Table of Contents

Page

Table of Figures

Table of Tables

STRENGTH TEST AND ANALYSIS OF ADDITIVE MANUFACTURED GEARS AND THEIR APPLICABILITY FOR EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

I. Introduction

Additive manufacturing (AM), commonly known as 3D printing, continues to develop at an ever-increasing pace. The United States Commander in Chief spoke of AM in his 2013 State of the Union as having the "potential to revolutionize the way we make almost everything" (Obama, 2013). Recent research across the Department of Defense (DoD) points to successful implementations of additive manufacturing across a myriad of applications including: US Navy's 'Print the Fleet' (Tadjdeh, 2014b), satellite manufacturing (Tadjdeh, 2014a), and US Army's Rapid Equipping Force (Army, 2016). An additional application lies in the field of explosive ordnance disposal (EOD). American EOD troops face missions that inevitably require creative solutions. Unexploded ordnances never fall in the same location, two mines are never placed in the same setting, and improvised explosive devices (IEDs) are unique by their nature. As America's adversaries continue to provide creative obstacles for EOD units to overcome, AM may provide EOD units with the capability to produce the innovative solutions they need to accomplish their challenging mission.

General Issue

American EOD units accomplish their mission by using a combination of expert training and cutting-edge technology — including remote controlled robots. Since their invention in Britain during the 1970s, remotely-controlled robots have been used to assist in explosive ordnance disposal around the world (Baker, 2014). These robots have saved many lives and, as the robotic technology continues to develop, these robots will remain an essential component of the EOD unit. These robots often face, at a minimum, a rugged environment and, in extreme cases, a major explosive blast; keeping these robots online is a challenge for EOD units. Furthermore, when the robots go out of commission the mission is not put on pause, but rather an EOD technician must risk their own life to complete the job by hand. Overcoming these challenges might be accomplished through applying new and rapidly developing technology such as AM. The goal of this research to analyze whether AM can provide EOD units with the ability to repair their robots rapidly, saving both time and human lives.

Researchers at the Air Force Insitute of Technology have explored AM applications. Areas include AM use in civil engineering contingency (i.e, wartime) environments (Poulsen, 2015) and AM production of tools and jigs (Shields, 2016). Both areas and the implications on this research effort will be further discussed in the literature review section of this thesis. The literature review provides evidence of a gap in knowledge regarding the field of AM. Although a number of the USAF leaders, including the Chief of Staff, support increasing the use of AM, few actual applications have been proven to be safe and effective (Graham et al., 2014). The search for an application of AM within the EOD field led this research to one specific item—the Micro Tactical Ground Robot.

The United States Air Force (USAF) contracted with an Israeli defense contractor, Roboteam, and ordered 250 newly designed robots known as Micro Tactical Ground Robots (MTGR) (Magnuson, 2016). The MTGR is a state-of-the-art robot, designed to be carried by an EOD technician as a backpack, and is smaller and lighter than other EOD robots. In order to achieve this light-weight design, the majority of the robot is manufactured from plastic. Although designed to be extremely rugged, these plastic parts can be damaged or destroyed during missions. The functionality of these robots is critical, and with delays of replacement part delivery due to logistical challenges in some environments, the EOD units may not be able to complete their missions safely and successfully. Providing these units with the ability to manufacture their own parts would allow for a rapid recovery time of these robots that are so critical to the success of the mission and safety of USAF EOD technicians.

Additive manufacturing (AM) is the formal term for the technology that has also been known as rapid prototyping, three-dimensional (3D) printing, and direct digital manufacturing (Gibson, Rosen, & Stucker, 2009). AM includes manufacturing parts layer by layer, rather than molding, often increasing flexibility and speed of part development (Gibson et al., 2009). As a relatively new process, additive manufacturing (AM) has gained attention across the Department of Defense (DoD) (Insinna, 2014). Multiple United States military services have been steadily increasing their use of AM over the last three years, and research labs and contractors are even further along in using this adaptive technology (Insinna, 2014). By joining the other military fields using AM, EOD units may arm themselves with the ability to perform rapid repair to their robots while in deployed environments.

Problem Statement

This research investigates the effectiveness of using AM to produce replacement gears for the USAF's Micro Tactical Ground Robots (MTGR®). Effectiveness will be measured by the strength and quality of gears designed and manufactured by two separate 3D printers. These parts will be tested for usability and structural integrity through a gear tooth bending test. A market survey of current 3D printers is also included to provide recommendations for which printers will best serve EOD units.

Research Objectives and Questions

The primary objective of this research effort is to determine if additive manufacturing is a viable option for manufacturing replacement gears for the Micro Tactical Ground Robot (MTGR®). To adequately address this objective, this research develops two overarching research questions:

1) *To what extent, if any, are AM gear's tooth bending strength affected by the layering technique used during their manufacturing?*

   By testing gears manufactured at different angles and layouts within the AM machines, this research expects a difference in strength will be observed.

2) *Do either or both of the AM machines used in this study produce AM gears at a high enough quality to be used as replacement gears for the Micro Tactical Ground Robot (MTGR)?*

   By observing the printers and the parts they produce qualitatively, determine the feasibility for use by EOD units currently.

Methodology

The two printers chosen for this study are the Projet® 3500 and the Lulzbot Taz 6. These printers represent two ends of the price spectrum for 3D Printers, priced at approximately $90,000 and $2,500 respectively (Wohler, 2014). The price is certainly not the only difference between these two printers, and the details concerning their design and capabilities will be discussed in Chapters II & III of this study.

Gears were chosen as the part to test for structural integrity using these different printers due to their universal applicability. A single-tooth bending test was completed on a total of eighteen gear teeth, representing five different layouts. The details of the different layouts and why there were chosen is discussed in detail in Chapter III. Three copies of each tooth layout were tested to allow for a mean and standard deviation to be determined, the results of which are presented in Chapter IV.

Assumptions

There are two primary assumptions used for this research. First, the research was limited by the number of printers available; the two printers represent a small sample of the dozens of 3D printers currently available for acquisition. With a field as new as AM, the technology is constantly shifting directions and improving. If the USAF continues to find interest in AM and is considering purchase of a large number of 3D printers, staying up to date with new printers is essential.

Second, the testing techniques used in this research are not equivalent to real-life field conditions. A pilot study located in a deployed environment is recommended to verify the results of this research. Providing 3D printers to a few EOD units will allow for the results presented in this thesis to be validated, while simultaneously allowing additional requirements to present themselves for further uses of AM within the EOD field.

Document Overview

This thesis follows a traditional five-chapter format. Following this introduction, Chapter II provides a review of relevant literature. The main topics covered include the current status of 3D printing within the DoD, background on the MTGR®, and details of the 3D printers being used and where they fit in the current market. Chapter III covers the methodology utilized for this research. This section includes the design of the test fixture, the printing of the gears, and the testing of the gears. Chapter IV provides a review of the results from the manufacturing and testing portions of the research. Finally, Chapter V offers a discussion on these results, implications of the research effort, and recommendations for follow-on research.

II. Literature Review

Chapter Overview

The main topics covered in this chapter include a market survey of current AM technologies, a review of AM uses within the DoD, an examination of AM within the EOD field specifically, and finally details of the MTGR. Through addressing these four categories, this literature review provides the context under which this research is carried out.

Understanding the Need

AM continues to prove its worth across a number of applications within the DoD and, more specifically, within the EOD field. However, an area of interest, where no research currently exists, is using AM to assist with EOD robot repairs. When EOD robots are damaged and put out of service in deployed locations, long lead times keep these life-saving machines out of service for extended periods of time. Without these robots available, EOD technicians are forced to put their lives at higher levels of risk to complete their mission of ordnance disposal. As described by Ray, a Naval Contract Specialist, AM "presents the potential of local manufacturing that will reduce lead-times and transportation costs" (Ray, 2013). In other words, Ray suggests a potential for a 3D printing machine to provide on-site manufacturing of robot-replacement parts exists, which would provide a decrease in lead times without increasing inventory storage for Air Force EOD units.

With the need of AM in EOD understood, it is important to understand a few terms used throughout the remainder of this thesis and their intended meaning within this context:

Additive Manufacturing (AM): Also referred to as rapid prototyping and popularly known as 3D Printing. AM is the formal name adopted by the ASTM International to encompass the manufacturing process that uses 3D models and a layered 2D construction method to make parts (Gibson et al., 2009).

Explosive Ordnance Disposal (EOD): The cross-service field within the military responsible for the containment and disposal of a myriad of threats including unexploded ordnance (UXO) and improvised explosive devices (IEDs) (Airforce.com, 2016).

Micro Tactical Ground Robot (MTGR®): A lightweight and unique platform designed to aid EOD or Special Operation units around the world (Roboteam, 2016). 250 MTGRs were ordered by the United States Air Force (USAF) from an Israeli company, *Roboteam,* and are being acquired by EOD units around the world throughout the 2016 calendar year—a new update from contracting puts the delivers throughout the 2017 calendar year, a point that will be discussed in Chapter V.

Current 3D Printing Technology

Although AM was first developed in the 1980s, recent years have seen a large advancement in its breadth of use (Yeh, 2014). An increase in desktop 3D printers has allowed interested parties, who are not in large manufacturing companies, expand the ideas and capabilities of AM. As the prices of 3D printers continue to drop, many industries, including the defense industry, will no doubt take advantage of this new opportunity in manufacturing (Tadjdeh, 2014b).

AM technology spans multiple industries and products ranging from high-end metal prints for the aerospace industry to small trinkets for an office desk. Smaller desktop printers can sell for less than $500, while some large industry printers cost upwards of $2,000,000 (Wohler, 2014). All of these printers use 3D CAD software, and a layering manufacturing technique, but otherwise they can be very different (Gibson et al., 2009). Table 1 shows a review of the seven types of AM techniques named by ASTM International Committee in 2012, along with some of the most popular current 3D printers (Huang, Leu, Mazumder, & Donmez, 2014; Wohler, 2014). Each process category is described briefly in the paragraphs that follow.

Table 1: Types of Additive Manufacturing

Process Category	Company	Model Name	Material	Build Volume (mm)	Cost
Material Extrusion	Aleph Objects	Lulzbot Taz 6	ABS, PLA, HIPS, PVA, wood polyester	280 x 280 x 254	2.5K
	MakerBot	Replicator 2	ABS, PLA	285 x 153 x 155	$2K
	Stratasys	Mojo	ABSplus	127 x 127 x 127	$9K
Material Jetting	3D Systems	ProJet 3500	VisiJet UV curable plastic	298 x 185 x 203	$92K
	Stratasys	Objet1000	100+ proprietary acrylate photopolymers	1000 x 800 x 500	$600K
Binder Jetting	ExOne	Lab Platform	Steel, Bronze, tungsten, iron, ceramics glass	40 x 60x 35	$145K
		Max Platform	Same as Above	1800 x 1000 x 700	$1,600K
Vat Photopolymerization	Asiga	Freeform Pico	Photopolymer	40 x 30 x 75	$7K
		Freeform Pro75	Photopolymer	144 x 81 x 200	$25K
Powder Bed Fusion	3D Systems	ProX 500	Engineered plastic	381 x 330 x 457	$350K
		ProX 300	Steels, titanium, cobalt-chrome	250 x 250 x 300	$684K
Sheet Lamination	Fabrisonic	SonicLayer 7200	Aluminum, copper, steel, combinations	1800 x 1800 x 900	Not available
Directed Energy Deposition	Optomec	LENS 850-R	Titanium, tool steel, stainless steel, others	1500 x 900 x 900	$995K

Material extrusion is one of the most popular methods of 3D printing and is often the method chosen for at-home or desktop printers. It is also one of the most affordable designs, as can be seen in Table 1. The method consists of material being dispensed through a heated nozzle. The material is often stored in spools prior to being heated and placed on the machines build plate. This process somewhat resembles the output of a hot-glue gun (Gibson et al., 2009; Wohler, 2014).

Material jetting consists of droplets of material being placed selectively, and often use UV curable material and a UV light hits each layer to solidify the droplets into a defined layer. Many of these printers have multiple printing heads to decrease manufacturing time, and a convenient wax-support material that easily melts away in post-processing (Gibson et al., 2009; Wohler, 2014).

Binder jetting consists of a powder bed, and a liquid bonding agent that is deposited from a print head to bond the powder particles together to form layers. This 3D printing process was originally developed by MIT, and full color options are commonly available across the market (Gibson et al., 2009; Wohler, 2014).

Vat photopolymerization comprises a vat of light-curable material that is selectively curable by a laser or other light source and a set of mirrors. One form of this process, Stereolithography, was one of the first patented and commercialized process for AM (Gibson et al., 2009; Wohler, 2014).

Powder bed fusion consists of using thermal energy to fuse powdered particles together in a specific designed layer. Many metal 3D printers use powder bed fusion processes, but the extreme heat can lead to warping and other heat-induced structural issues (Gibson et al., 2009; Wohler, 2014).

Sheet lamination includes using cut sheets of material to create a 3D part by layering the sheets. The sheets are coated with an adhesive and inevitably form a plywood-like structure. This simplicity of this process keeps the printer's price point on the low end, while also allowing for many materials to be available for use (Gibson et al., 2009; Wohler, 2014).

Directed energy deposition includes a thermal energy source that fuses materials, often powder, together as the material is being placed. The process is somewhat similar to powder bed fusion but the powder is not in a bed prior to the fusion process. This method has not seen much success in the current AM market, but contains potential for future success due to its flexibility in material input (Gibson et al., 2009; Wohler, 2014).

The current 3D printing market is expanding and dynamic in nature. Each year, more printers are introduced, with new capabilities and often at lower price points. Over the last few years, the DoD has also began to take advantage of this exciting new technological trend.

3D Printing Across the DoD

The Navy first introduced 3D printers in March 2013, with their Print the Fleet initiative. The initiative places 3D printers on ships with six sailors trained in maintenance, repair, and basic CAD skills. The sailors also have the ability to send more complicated design requests to skilled design engineers stateside (Insinna, 2014). The ability to coordinate designs from around the world, followed by immediate on-site manufacturing, is an exciting opportunity. A problem can be realized, designed, manufactured, tested, modified, and re-manufactured in a fraction of the time, and the Navy is realizing the impact (Insinna, 2014).

Defense contractors across the United States realized the potential of AM in providing flexibility and advancement in their fields. The Air Force Research Laboratory has implemented a project titled *America Makes* to look further into the capabilities of 3D

Printing (Lonardo, Conner, & Gorham, 2015). This is a public-private project that demonstrated how leveraging this new technology could help American companies and the defense partners.

A few companies involved in expanding their capability in the AM field include: Lockheed Martin, Caterpillar, GE, and LMI. LMI, a Virginia-based company that provides consulting to the Defense Logistics Agency, specializes in the implications of 3D printing and claims AM "provides an opportunity for turning the supply chain on its head" (Harper, 2015). As the technology in this field continues to improve, it is logical to assume more companies will take advantage of both simplified supply chains and decreased complexity in manufacturing.

Additive Manufacturing within the EOD Field

As AM proves its worthiness across the DoD, it has begun to find its way into many specific areas of the military — one of which is explosive ordnance disposal (EOD). One inventive way this technology has helped a non-combat EOD unit is through Advanced Ordnance Teaching Materials (ATOM) kits. The ATOM kits have recently been sold to the United Nations, PeaceTrees Vietnam, and Switzerland's International Committee for the Red Cross. These intricate land mine kits cost $7,000 but can be carried on a plane (unlike traditional training aids in this field) and contain many interworking parts to help teach how land mines work. The creators, a MIT processor and a retired Army EOD technician, develop and manufacture all the training aids using 3D printing. Their goal is to help rid the world of its 110 million active landmines, which monthly account for over 800 deaths. These AM hands-on training tools prove to be widely more affective teaching measures when compared to traditional books and pamphlets (Grunewald, 2015). The Advanced Ordnance Teaching Materials kit takes a step beyond trinkets and static training-aid replicas. The moving parts and detailed design prove AM's ability to create complicated and usable products.

The graduate school providing this thesis, the Air Force Institute of Technology, has worked alongside a local EOD unit on a several different projects. Plastic training aids, not unlike those in the ATOM kits, were manufactured for the local Wright-Patterson Air Force Base EOD unit using the Projet® 3500. Students also designed and printed shaped charges, used by EOD troops to slice through metal, and multiple hook tools used to cut wires for the EOD technicians. These advances expand the capabilities of AM to assist EOD units and helped provide a starting point for this thesis's research (Alwabel et al., 2017).

EOD Robot Design and Use

The vast span of mission sets an EOD unit accomplishes requires a broad set of training and tools. One of the most often used tools are EOD's remotely controlled robots. Robots—specifically those that can be remotely controlled—have saved countless lives in the field of Explosive Ordnance Disposal since their inception in the 1970s (Baker, 2014). The first of its kind was a simple rope-pulley system attached to a wheel barrel. The inventor, Lieutenant Colonel Miller, was losing EOD technicians to car bombs placed by the Irish Republican Army (IRA) and knew there had to be a better way. Technological advancements in the remote-control field, as well as others have allowed for these robots to progress from rope-controlled-bulky products to advanced tactical machines.

The Micro Tactical Ground Robot (MTGR®) is the newest and most adaptable robot the USAF's EOD units have ever used. At approximately 18" in length, and under 20 pounds, the MTGR is designed to be carried like a backpack by a single EOD technician. This weight is dwarfed by other EOD robots, which usually weigh closer to 300-400 pounds. The MTGR shown in Figure 1 has extendable arms, which allow for the robot to climb stairs and maneuver around countless obstacles.

The adaptability of this new acquisition will lead to uses around the world as a work-horse within AF EOD units. The MTGR has an operating range of 1,600 feet, a 360-degree camera, and many other features. It is also protected from dust and considered to be "ruggedized" by military standards (Roboteam, 2016).

Figure 1: Micro Tactical Ground Robot (www.robo-team.com, 2016)

Summary of the Literature

By explaining the main areas of relevant literature: AM market survey, AM use in the DoD, advancements in EOD's use of AM, and the MTGR, the problem statement for this thesis should be better understood. The men and women who deploy within EOD units are in need of a rapid repair method for their remote-controlled robots. Additive manufacturing has proven itself as an adaptive technology for the military, and may prove to be an asset for EOD units in the near future.

III. Methodology

Chapter Overview

In order to attain a better understanding of the feasibility of using AM parts on EOD robots, this thesis assesses the strength of AM developed plastic gears. Specifically, a single-tooth bending test was used to find the strengths of AM gears printed by both the Projet® 3500 and the Lulzbot Taz 6. This chapter provides the methodology for the single-tooth bending test. Specifically, it will cover the materials and equipment used for this test, details on how the gears were manufactured, and details on the testing procedure.

Materials and Equipment

This thesis required multiple pieces of equipment: two AM machines, a compression machine, and a gear-bending fixture. The AM and compression machines were already located within the research labs at the Air Force Institute of Technology and the neighboring Air Force Research Labs (AFRL), while the gear-bending fixture had to be designed and manufactured as part of this research effort.

3D Printers

As detailed in the literature review, a plethora of 3D printers are available in today's market. The two 3D printers chosen for this research effort were the Projet® 3500, which is a material jetting printer, and the Lulzbot Taz 6, which uses material extrusion technology. Both receive ".stl" file formats, which can easily be output from most CAD software programs—including Solidworks, which was the primary 3D software program used for this thesis. By using two printers that incorporate different processes, and reside near the ends of the price spectrum, the results attained may provide a more complete look at the capability of AM than simply using one printer.

The ProJet® 3500, pictured in Figure 2, is a professional 3D printer that costs approximately $90,000 (3D Systems, 2016). This high-end printer includes touchscreen controls, UV-curable structural-plastic, and a melt-away wax support layer. A heater, pictured in Figure 3, is included as a separate component provided by the machine's manufacturer, *3DSystems,* and provides optimal conditions for melting away the support material. The ProJet 3500 has a build volume of 298mm x 185mm x 203mm (11.75" x 7.03" x 8") and a layer thickness of 32µm (3D Systems, 2016).

Figure 2: ProJet 3500 at Air Force Institute of Technology

Figure 3: ProJet 3500 Post-Processing Heater

The Lulzbot Taz 6, pictured in Figure 4, is made by *Aleph Objects*. The build volume for this printer is 280mm x 280mm x 250mm (11” x 11” x 9.8”) and can have a layer height down to .05 mm (Aleph Objects, 2017). Capable material inputs include but are not limited to: ABS, PLA, HIPS, PVA, wood filled filaments, Nylon, Copper, and Alloy 910. Acrylonitrile butadiene styrene (ABS) is an inexpensive and strong material that is commonly used for material extrusion printers, and was also used for this research effort. The post processing of this printer is similar to most extrusion printers includes removing support material by hand.

Figure 4: Lulzbot Taz 6 at Air Force Research Lab's MakerHub

Compression Machine and Gear Bending Fixture

In addition to the 3D printers, two other pieces of equipment utilized for this research were the compression machine and the gear bending fixture. The American Gear Manufactures Association (AGMA) requires specific steps to be taken when testing gear strength (Shigley, Mischke, & Budynas, 2004). However, the AGMA does not provide a design for the equipment needed to complete this test. There are a variety of methods to complete the test—all with their own positive and negative aspects. For this research, a design was adapted from the fixture shown in Figure 5, which was detailed by Ravai, Nagy, & Lobontiu (2015). .

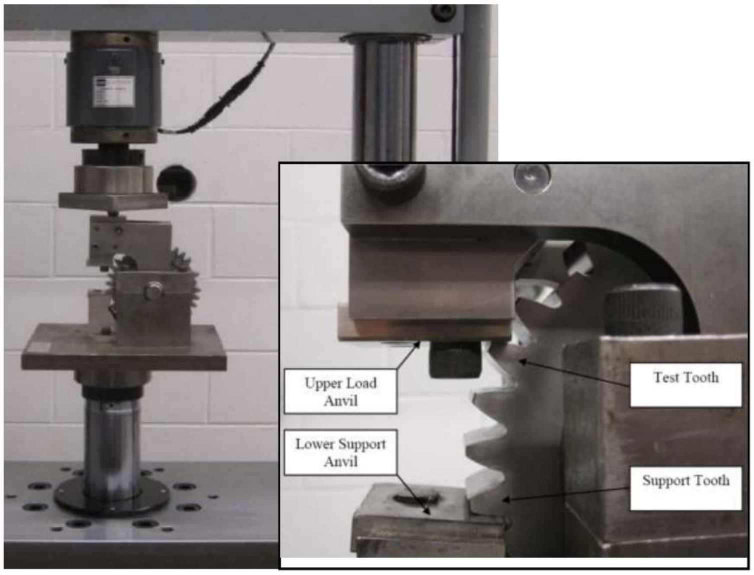


Figure 5: Gear-Bending Test Fixture (Ravai Nagy & Lobontiu, 2015)

Such a fixture is designed to be attached to a compression machine, pictured in Figure 6. By replacing the clamps shown in Figure 6 with the gear-compression fixture shown in Figure 7, a proper single-tooth bending test can be accomplished. The compression machine, manufactured by MTS Systems Corporation, is able to record detailed data outputs consisting of force applied to the gear over time and the distance of deformation during each test.

Figure 6: Compression Machine at Air Force Research Laboratory

Figure 7 shows one of the final iterations of the test fixture designed for this research effort. Although not needed for this thesis, the design allows for gears of different diameters to be tested. The lower piece of the fixture (which will attach to the compression machine) is designed in a way that future researchers can use it as a platform for countless research efforts. By using a plug-and-play method, the gear-focused parts of the design can be removed, allowing for other compression tests to be competed on the same base.

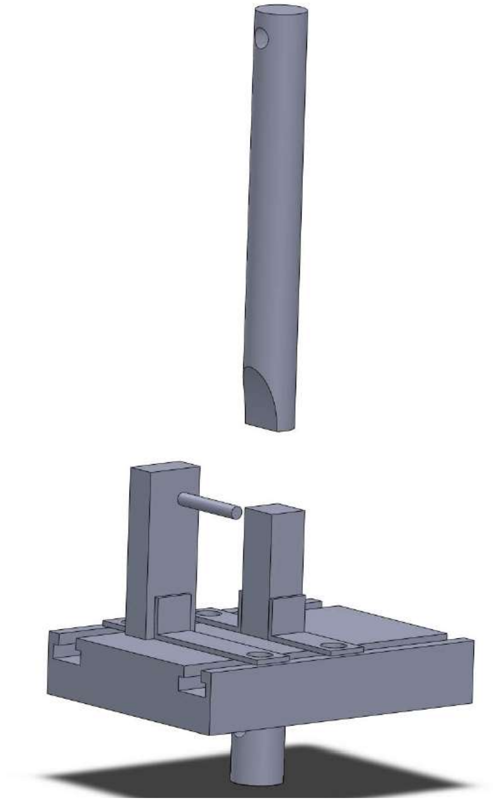


Figure 7: Final Gear Bending Test Fixture, 3D Model

Figure 8 shows an image of the gear bending test fixture, as it sits in the compression machine. Note a slight variation between the model shown in Figure 7 and the final test fixture in Figure 8: the t-slots were replaced with small screw holes, but to the same effect. The bottom piece can be used for any assembly designed to attach to it, and the diameter of gears can be adjusted if necessary for this current setup. The entire assembly was constructed by the AFIT Model Shop using all scrapped parts.

Figure 8: Final Gear Bending Test Fixture

Printing Parts

Using the equipment and materials detailed earlier, this study was well equipped to complete the gear-bending test. However, before the bending test could take place, the gears needed to be manufactured. The additive manufacturing process is lean and condensed by design, but it is a process and some of the steps differ significantly based on the machine and printing technology being used.

The first step to design an AM part is creating a 3D model in a CAD software program. These models can be imported through scans of objects or made from scratch by the designer. Solidworks was the program of choice for this thesis and is considered a leader in the current field of 3D design. A very simple, and repeatable gear was chosen for this test. Pictured in Figure 9, this gear's design details are included in Table 2.

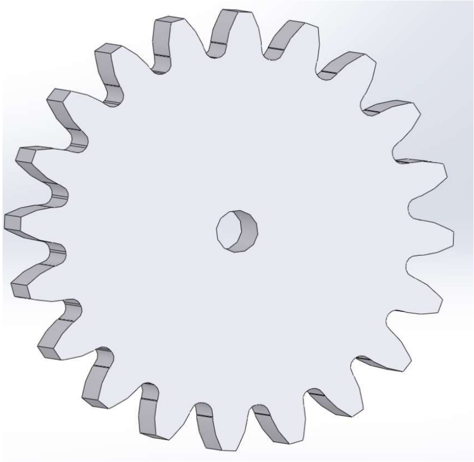


Figure 9: Full Gear Design

Table 2: Gear Design Parameters

Number of Teeth	20
Diametral Pitch (1/mm)	.2353 (1/mm)
Face Width	20 mm
Pressure Angle	20 degrees
Pin Diameter	8.5 mm
Lewis Factor	.32

For the single-tooth bending test, the gear tooth, rather than the entire gear, is the primary focus. Therefore flexibility is allowed in the final design of the gears themselves. As seen in the design in Figure 5, when metal gears are tested, one or more teeth are removed for the gear to fit in the test fixture. In the case of AM gears however, an entire gear does not need to be made for the test. Due to the nature of the test, gear segments—or pie pieces—were used for testing. One such pie piece is shown in Figure 10, with two teeth present, concluding part design.

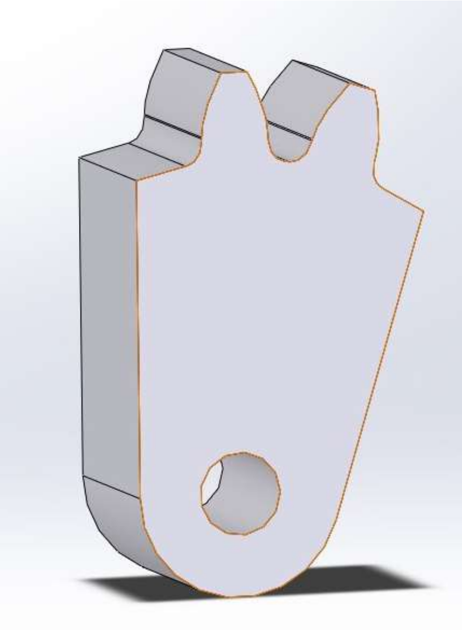


Figure 10: Gear Pie Piece for Printing and Testing

After completing the part design, the AM process requires the designer to reformat the parts into a file type readable by AM machines. Currently, the field of AM, utilizes the ".stl" file format as the standard input for AM machines (Gibson et al., 2009).

These ".stl" files are loaded into the AM machines' software programs and the printers can begin manufacturing — or printing — the parts.

The pie piece design also allowed for different orientations to be printed, to better represent an entire gear. The five orientations included: On Surface, 0°, 45°, 90°, and 135°. Figure 11 provides a visual to better understand the layouts tested. The highlighted gear segments show two of the 90°-orientation test specimens. Three of each orientation test specimen were printed to facilitate means and standard deviations to be calculations from the testing results.

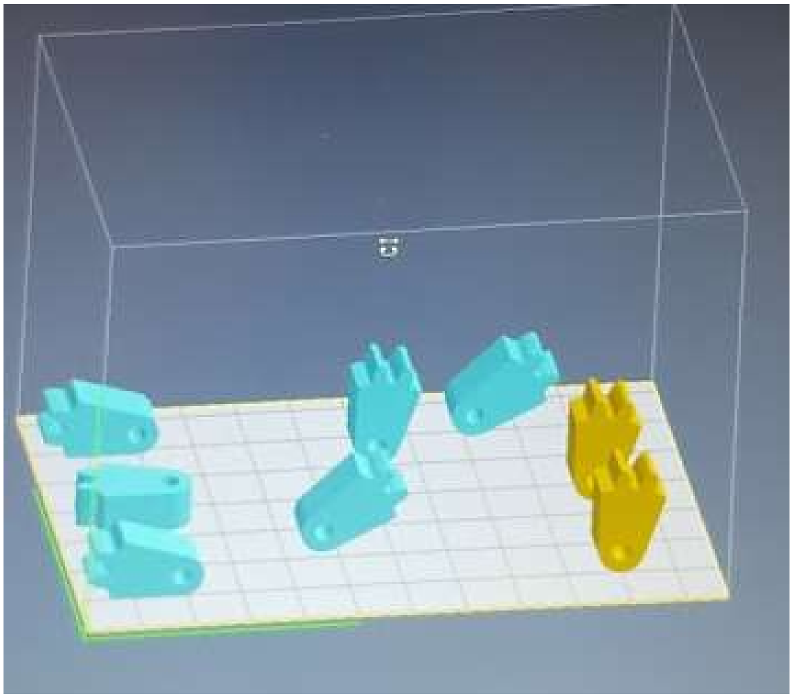


Figure 11: Layout of Gear Segments on Projet® 3500

The gear segments were printed on the Projet® 3500 first, in two total prints lasting a total of 33 hours and 36 minutes, averaging two hours and 15 minutes per segment. All the segments were printed using the strongest input material available—VisiJet M3 Black—and drew from a single input jug to ensure consistency.

Following the printing, the Projet® 3500 requires the printed parts to be placed in an oven at 70 degrees Celsius to melt off the support material surrounding the part, as seen in Figure 12. This support material, VisiJet S2300, is very similar to candle wax and simply melts away leaving only the completed part after about an hour (3D Systems, 2016).

Figure 12: ProJet 3500 Parts during Post-Processing

The second machine is the Lulzbot Taz 6 which does not have a different support material; rather, it uses the same material for the part to support the sections not attached to the build plate. These pillar-like support pieces must be removed by hand before the part is considered complete. Figure 13 shows a part printed on the Lulzbot with support material still attached. It is up to the operator to remove the extra supports without damaging the part itself.

Figure 13: Lulzbot Print with Support Material

Gear-Bending Test

Using the compression machine and the gear-bending fixture, thirty gear teeth were tested. The researchers decided to print pie-pieces of the gears to save on printer material. These pie-pieces included 36 degrees and two teeth of the original gear, which contains twenty total teeth. Modifying gears to complete single-bending tooth tests is common, and this particular technique was possible due to the nature of AM techniques (Handschuh, Krantz, Lerch, & Burke, 2008). Force from the upper arm of the compression machine was applied at .05 inches/second until the test tooth was cracked or broken off from the main gear section. This speed of testing coincides with ASTM standards for tensile properties of plastics (ASTM Norma, 2004).

Standard Strength Calculation for Comparison

In order to know if the AM gears were strong enough, a standard strength was calculated for a comparison. The basis for this calculated come from Equation (1), the Lewis Bending Stress Equation (Dornfeld, 2004).

Equation (1) $$\sigma_t = \frac{W_r P_d}{FY}$$

Where:

σ_t *is maximum bending stress* (MPa)

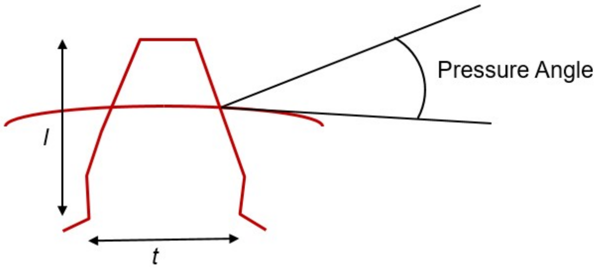
W_r *is the tangential load* (N)

P_d *is the diametral pitch* $(\frac{1}{mm})$

F *is the face width* (mm)

Y *is the Lewis form factor (no dimensions)*

Diametral pitch, face width, and the Lewis factor are known from the gear's design. The Lewis factor is a function of the number of teeth (20) and pressure angel (20 deg) and is .320 for the gear used in this research. Figure 14 depicts how a pressure angel is calculated and used to calculate the Lewis form factor.



$$Lewis\ Factor\ (Y) = \left(\frac{2}{3}\right) * Diametral\ Pitch * \frac{t^2}{4l}$$

Figure 14: Pressure Angle and Lewis Factor

Another equation must be used to calculate a strength starting point to compare to the test results. It is reasonable in the field of gears to estimate an allowable bending stress of a gear tooth as one third of the material's ultimate tensile strength (Dornfeld, 2004). The values to compare the results to were therefore calculated as follows:

Projet 3500's VisiJet M3 Black ultimate tensile strength = 35.2 MPa

(3D Systems, 2016)

Village Plastics ABS ultimate tensile strength = 40 MPa (MatWeb, 2015)

Equation (2) $$ProJet\ Load_r = \frac{\left(\frac{1}{3}\right) * 35.2MPa * 20\ mm * .32}{.2353(1/mm)} = 319.12\ N$$

Equation (3) $$Lulzbot\ Load_r = \frac{\left(\frac{1}{3}\right) * 40MPa * 20\ mm * .32}{.2353(1/mm)} = 362.66\ N$$

The values calculated in equations 2 and 3 will be used in Chapter IV to compare allowable stress levels against those seen from the tested gears.

Conclusion

This section provided a review of the equipment used for the thesis effort. It also covered the methodology for printing and testing the test gears. The next section reviews the results from the strength and compatibility tests. By following the AGMA standards, and carefully tracking the manufacturing and testing process, the researcher hoped to allow for further research teams to build on this effort. For this reason, repeatability was kept in mind throughout the development of the methodology.

IV. Analysis and Results

Chapter Overview

This chapter presents the results obtained from implementing the method discussed in the prior chapter. A review of the quality of prints is included first, followed by the results from the bending test. Pictures of the gears are shown including images of where and how the layers failed in each test. The data are paired with brief discussion points, including analysis on what the results mean as related to the overall thesis questions.

Quality of Additive Manufactured Gears

The quality of the gears manufactured was found to be noticeably different. This was due to the nature of the two printers used, including the input materials and manufacturing technique. The Projet 3500 was able to manufacture gear teeth at all the angles presented in the methodology section (On Surface, 0°, 45°, 90°, and 135°). However, the Lulzbot was unable to manufacture vertical gear teeth at the quality needed to complete the bending test. Figure 15 shows a 'failed print' from the Lulzbot while attempting to print a 45° tooth for testing. This pair of teeth was printed at an angle, with the tooth on the left above that on the right, and at 45° angle from the print bed—as can be seen from the layers running across the part. Although the non-test tooth looks to be of higher quality, and possible high enough to be tested for strength properties, when considering a full gear, it is not possible to 3D print all the teeth with the level of support material used by the 'bottom' tooth in this print. Therefore, the majority of gear teeth printed in the vertical plane will be closer to the quality of the tooth on the left. It was therefore decided to only manufacture gear teeth in the horizontal plane, which corresponded to the on-surface print on the Projet 3500.

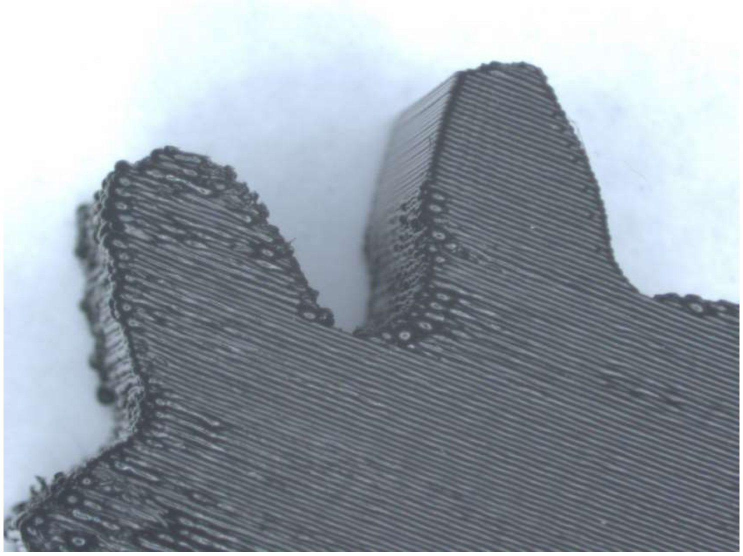


Figure 15: Low-Quality Print from Lulzbot (left tooth was proposed test tooth)

Even without vertical prints, the Lulzbot's gear teeth were of lower quality in terms of part detail. Figure 16 shows an on surface print from the Lulzbot while Figure 17 shows the same on surface print but made using the Projet 3500. Given the differences in the sizes of the orifices in the print heads between the Lulzbot and Projet 3500, coupled with the differences in input material and manufacturing process, a difference in quality is noticeable. That being said, the on-surface gears created with the Lulzbot are at a quality allowing a bending test to be completed, and also not of high enough quality to be included as a temporary part on a plastic robot. More discussion regarding the overall quality of the printed parts is included following this chapter.

Figure 16: Lulzbot On-Surface Gear Tooth Print

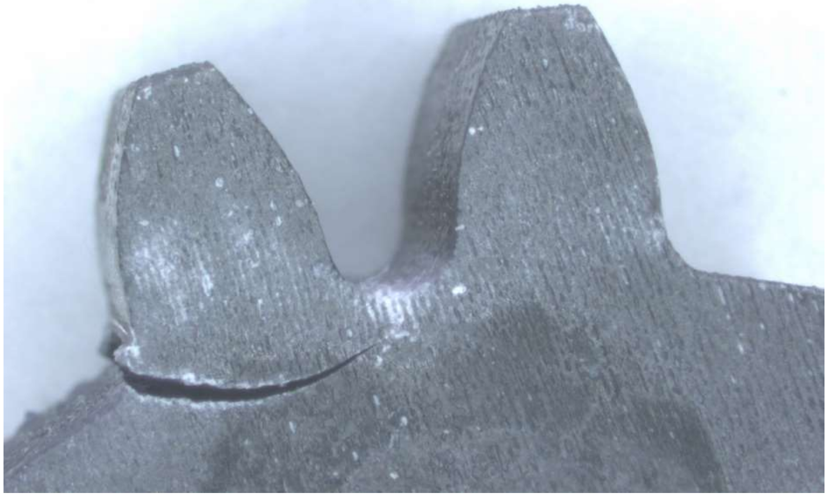


Figure 17: Projet 3500 On-Surface Gear Tooth Print (Post testing)

Strength of Additive Manufactured Gears

After the gear teeth were manufactured, the single tooth bending test was completed. A total of eighteen gear teeth were tested, fifteen of which were printed using the Projet 3500 and three of which were manufactured on the Lulzbot Taz 6. The bending stress was calculated from the maximum load using Equation 1 presented in the methodology chapter. The results, and how they compare to the allowable values calculated with Equations 2 and 3 are presented in Table 3.

Table 3: Average Bending Stress of Additive Manufactured Gears

Printer	Layer Alignment	Max Load (N)	Max Bending Stress (MPa)	Standard Deviation (MPa)	Calculated Stress (MPa)	% of Calculated Stress
Projet	0 Deg	3044.81	**111.94**	2.87	11.73	954%
Projet	45 Deg	2450.73	**90.10**	4.44	11.73	768%
Projet	90 Deg	2663.17	**97.91**	5.57	11.73	834%
Projet	135 Deg	2965.70	**109.04**	2.13	11.73	929%
Projet	On Surface	2828.88	**104.01**	5.51	11.73	886%
Lulzbot	On Surface	3858.80	**141.87**	4.89	13.33	1064%

As can be seen in Table 3, all of the gear teeth surpassed the allowable strength calculated using tensile strength divided by three. The Lulzbot's on-surface gear teeth reached the highest strength and the Projet's 45° print was the weakest. Figure 18 provides a visual for the compression test results, showing the loads vs time for each of the gear tooth orientations.

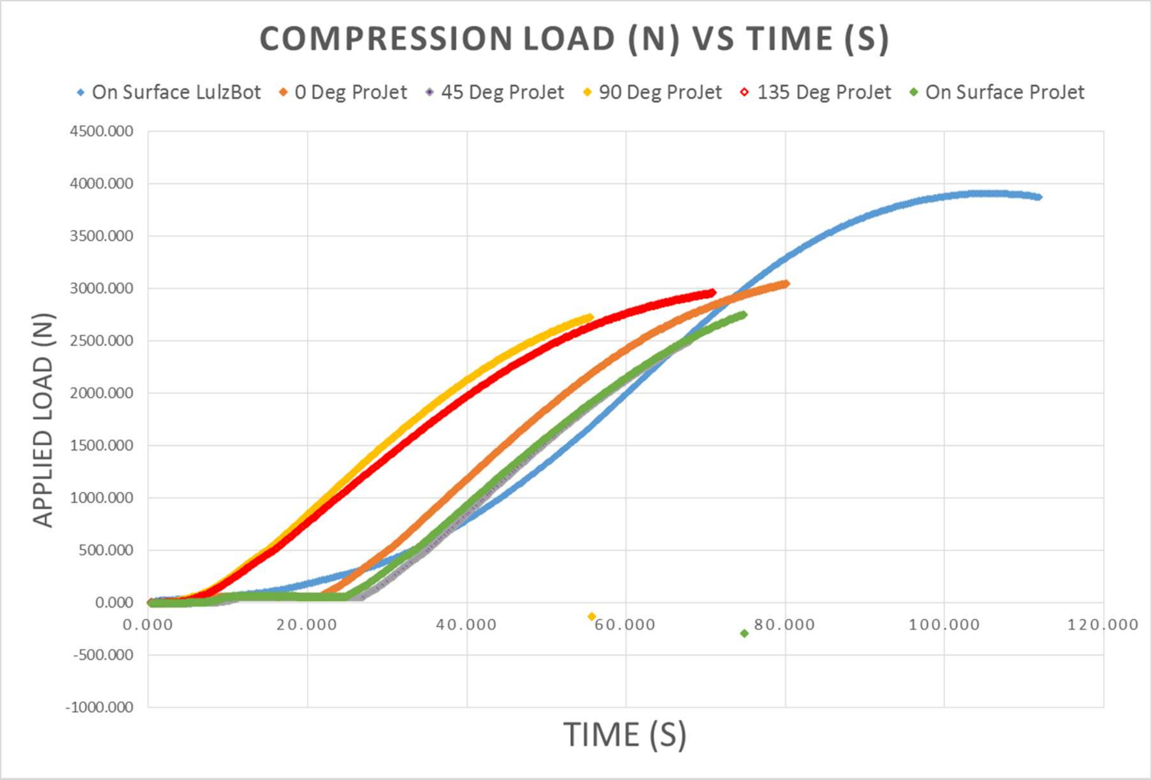


Figure 18: Compression Load vs. Time Plot

To provide a more in-depth comparison of the strength results JMP™ software was used to complete an analysis of variance (ANOVA) and non-parametric statistical analysis on the bending test results. Figure 19 is another visual display of the strength results. The dots represent individual test results (three for each orientation) and the horizontal bars show two standard deviations for each set of tests. The gray bar spanning the entire chart is the average of the full population, which does not provide any particular conclusions for this study.

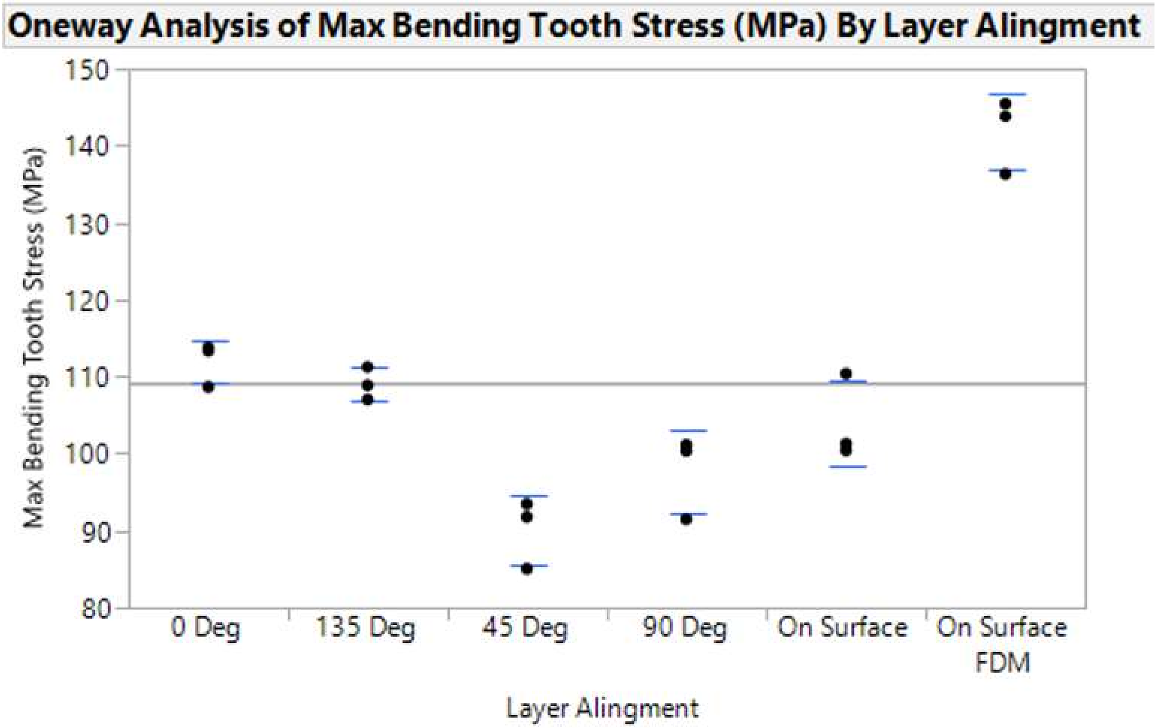


Figure 19: Single Tooth Bending Test Results in JMP™

In addition to the strength values, the manner in which the gear teeth failed also proved to be interesting. Figure 20 through Figure 25 show how each of the tested gear teeth failed. Only one gear tooth is shown from each category, as there was consistency in the way each category tooth failed. That is, all three test specimens given a specific orientation failed the same way. For completeness, the remainder of the pictures not shown in Figures 18 through 23 are included in Appendix A.

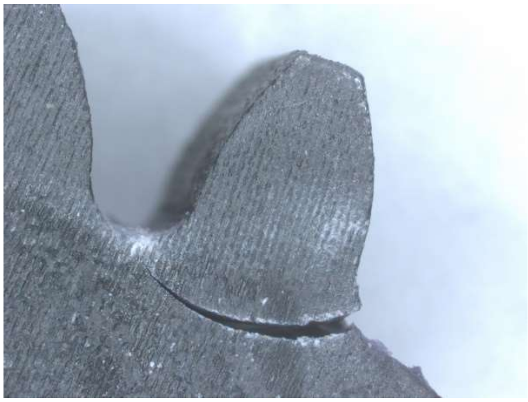


Figure 20: ProJet 0 Deg Post Test

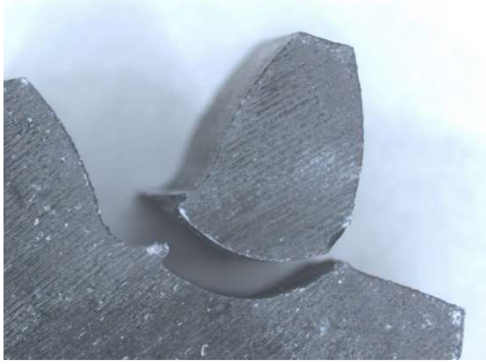


Figure 23: ProJet 45 Deg Post Test

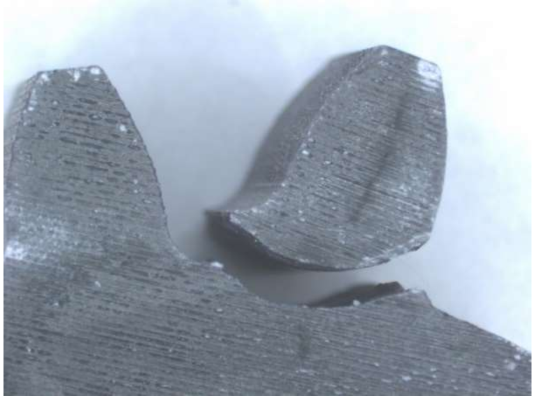


Figure 21: ProJet 90 Deg Post Test

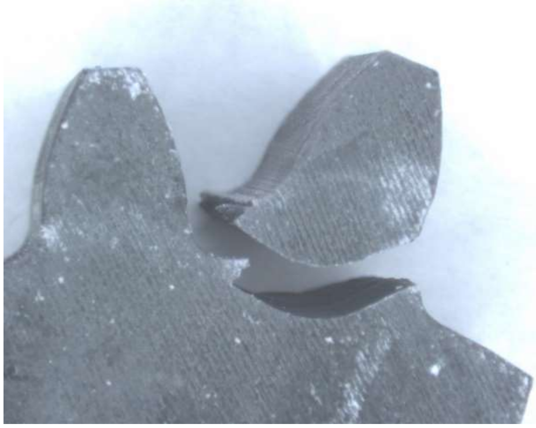


Figure 24: ProJet 135 Deg Post Test

Figure 22: ProJet On Surface Post Test

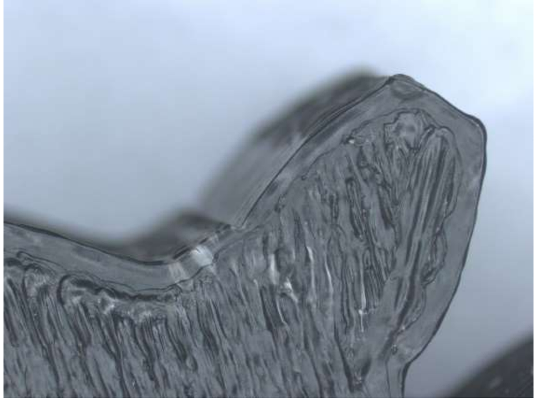


Figure 25: LulzBot On Surface Post Test

The ABS used to manufacture the LulzBot gear teeth showed more bending when compared to the VisiJet M3 Black used by the ProJet 3500. Although this bending did not take place until after the strength had surpassed all of the ProJet's gear teeth. The layer-alignment of the ProJet's gear teeth did play a part in how the gear failed. However, all of the tests proved to surpass the required stress levels using their materials tensile strength. This leads the researcher to believe that in terms of gear tooth strength, the layering process of AM does not overly affect the strength of AM gears to a point where they cannot be trusted to perform correctly.

Conclusion

Results of a single tooth bending tests on additive manufactured gears had not been available prior to this research. These results provide an initial look at what the layering process of additive manufacturing has on the strength of gear teeth. The results also provide evidence that additive manufactured gears meet and surpass the stress required when their input material's strength properties are considered. The impact of these results, as well as further research opportunities, are discussed in the next and final chapter.

V. Conclusions and Recommendations

Chapter Overview

This final chapter includes a review the answers to the research questions. This is followed by a review of the impact of this research, and concludes with a look at future research opportunities.

Research Questions Answered

1) *To what extent is additive manufactured gears' strength affected by the layering technique used during their manufacturing?*

The results that best answer this first research question come from the Projet 3500, as this printer was able to print quality prints at all five orientations. Of these five layer orientations, the gear tooth printed in the vertical direction, with the layers running at a 0 degree angel was the strongest. As seen in the results, the order went as follows after that: 135 degrees, on surface, 90 degrees, and 45 degrees. The range totaled approximately 20% of the highest strength.

The layering technique did prove to have an effect on the Projet's gear teeth. If a gear was printed vertically, the gear teeth at 45 degrees would be expected to fail first if bending strength was the reason for failure. Other failure mechanisms were not explored as part of this research question. Pitting and other wear may lead to a different result, and this will be discussed in the future research section of this chapter.

2) *Would either or both of the AM machines provide quality parts for the Micro Tactical Ground Robot (MTGR)?*

This research question was only partially answered during this research effort. As the researchers were not able to obtain access to a MTGR due to contractual and logistical delays, the gears were not able to be designed and fit directly for the MTGR. What the researchers were able to determine was the part-quality from two 3D printers on the relative ends of the price and size spectrum of the market.

The Projet 3500 was able to manufacture gears at a high level of visual quality and strength. This printer would be able to manufacture a number of parts for the MTGR that should be at a quality high enough to use as a temporary fix for a broken piece. The Lulzbot was not able to print as high of quality pieces, especially when printed in the vertical direction. Simple and large gears, like those used in this study, would not be an issue for the Lulzbot, as they can be printed flat on the bedplate. However, more complicated parts such as smaller gears or components with intricate designs may require a more 3D manufacturing effort may not be at the quality needed.

Research Impact

To the leaders of the EOD field, additive manufacturing is a technology with much potential for increasing the field's flexibility and resiliency. This research follows multiple years of additive manufacturing research focused on impact within the EOD field. This combined effort of research has provided strong evidence for the use of AM machines for a number of applications.

For those outside the field of EOD but interested in the impact of AM's layering process on the strength of parts, this research is a starting point. As the rapidly developing field of AM continues to move forward, quality controls are a necessity for safety and reliability of manufactured parts. By completing strength tests similar to this research, the gaps in knowledge concerning strength and reliability of AM parts will begin to be filled.

Limitations

By only using two of many 3D printers, this research was not able to provide an in-depth understanding of the quality differences between different types of AM techniques. Each printing technique provides its own nuances when it comes to making parts, and each printer brings even more uncertainty to the process. More research is needed to fill in the gaps by using more printers that use more AM techniques.

The single tooth bending test was also completed with some known limitations. The equations used to calculate required-stress assume the force is applied at the very tip of the test tooth. The test completed in this study was close but not exactly applied to the tooth-tip, which may have affected the stress results.

Future Research Opportunities

With the limitation of not receiving the MTGR, the main future research opportunity is testing an AM part on the robot itself. It is near impossible to know if the quality of a part is high enough to perform correctly without testing it on the asset itself. Once the MTGR is acquired, a wheel similar to the gears in this study can be designed to fit and be tested in the field for performance ability.

For a more accurate comparison of AM gear strength and traditional gears, a similar bending test could be completed on injection molded gears. By testing matching gears printed on AM machines and manufactured by traditional injection molded processes, a better understanding of the effects of the layering process may be discovered. Digital image correlation could also be used on future bending tests. This process uses slow motion cameras to capture where and how the materials fail initially during a test. Results from these images may help expand the understanding of exactly how these gear teeth are failing.

In the more general field of AM research, other gears and other printers can be tested. The testing fixture designed for this research will remain at Wright Patterson AFB and made available for any future researchers interested in strength tests of gears. It should also be noted that the fixture was designed to be flexible in nature—the bottom piece will fit in an compression while the gear-specific pieces can be removed and replaced with any other design.

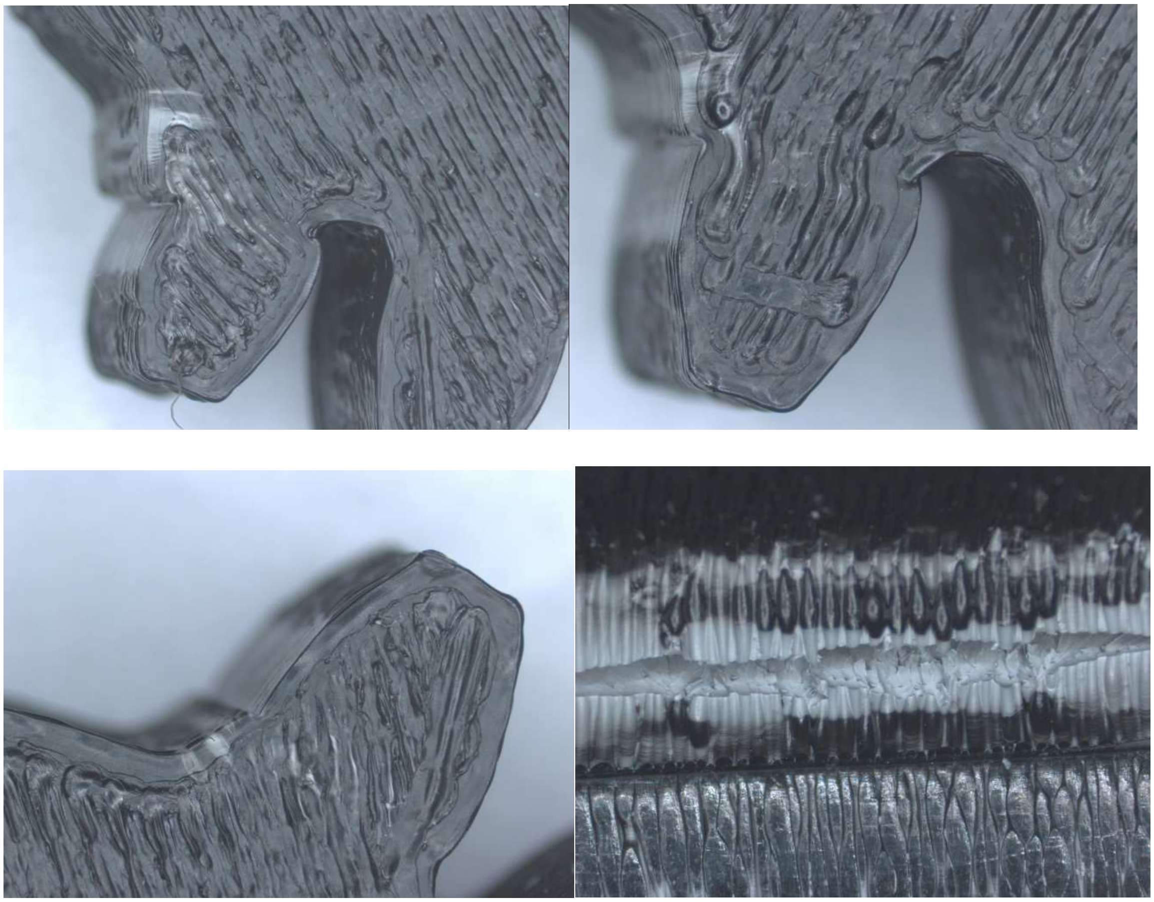
Final Thoughts

The two 3D printers used for this study were able to manufacture gears that performed well above the required stress for their input material's tensile strength. By completing a number of single-tooth bending tests, the researchers were able to prove the layering process of AM does not overly diminish the strength of the manufactured gear teeth. This thesis also showed the difference between the quality of a part 3D printed on a high cost material-jetting printer vs. a low cost material-extrusion printer. It is up to the user to decide what is to be valued in 3D printing between printer size, cost, and part quality.

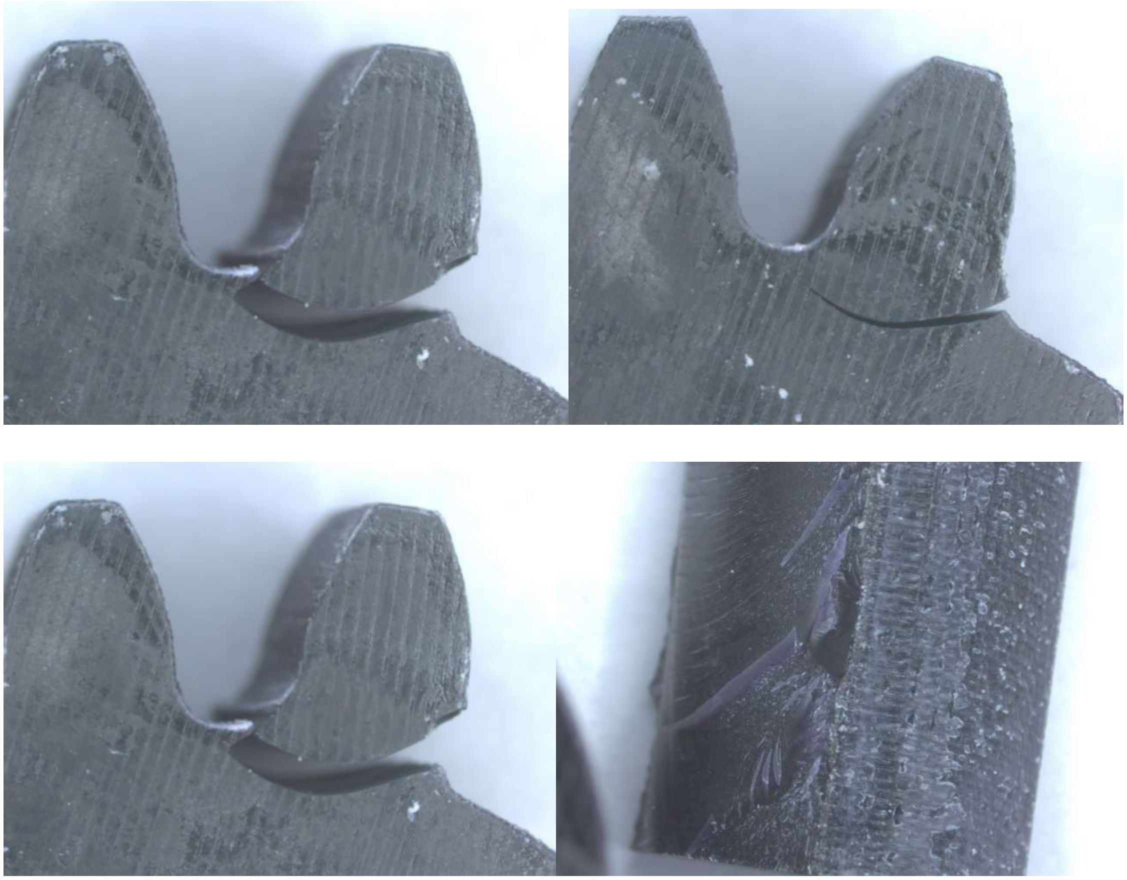
One topic not discussed in this research, but important to consider, is the moral and legal implications of AM replacement parts. If this research stream continues to develop and EOD units are in fact able to manufacture their own replacement parts at a high quality, will the original manufactures allow it? There is potential for the AM field to have a major impact on how intellectual property is tracked and handled, and only time will tell how humans will legally and morally classify the copy methods used in many AM efforts.

Appendix A – Complete Picture Set of Gear Teeth Post Testing

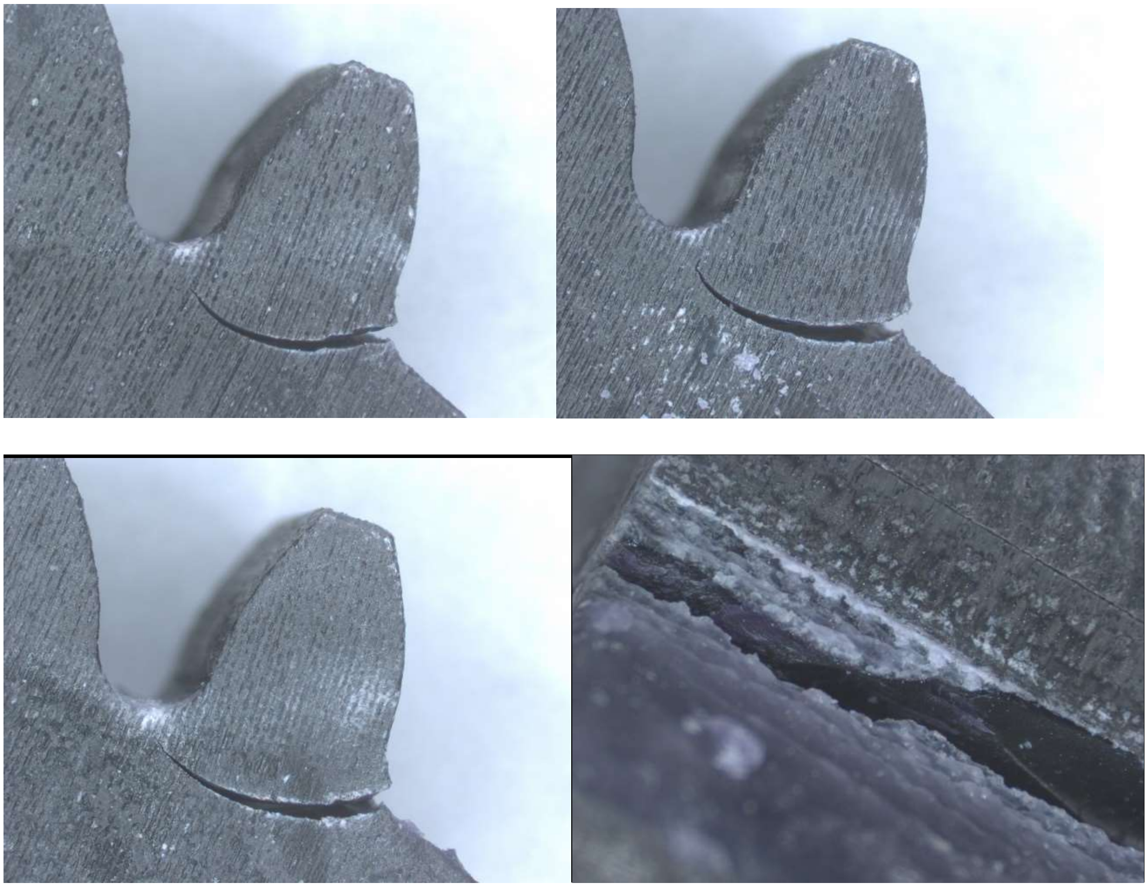
Lulzbot Taz 6 On Surface



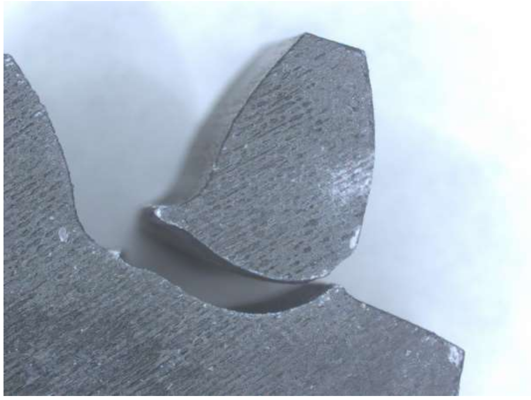
ProJet 3500 On Surface

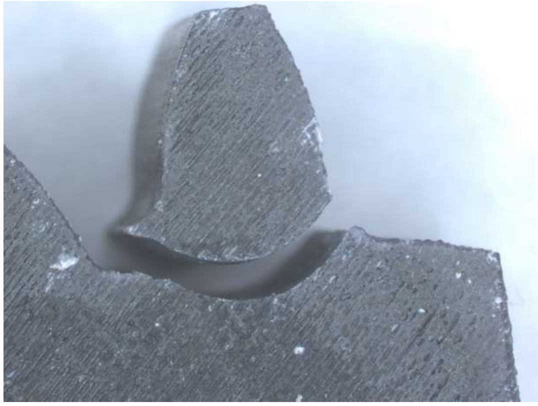


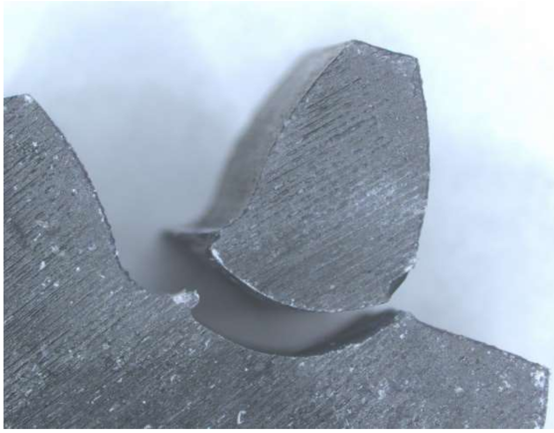
ProJet 3500 0 Degrees



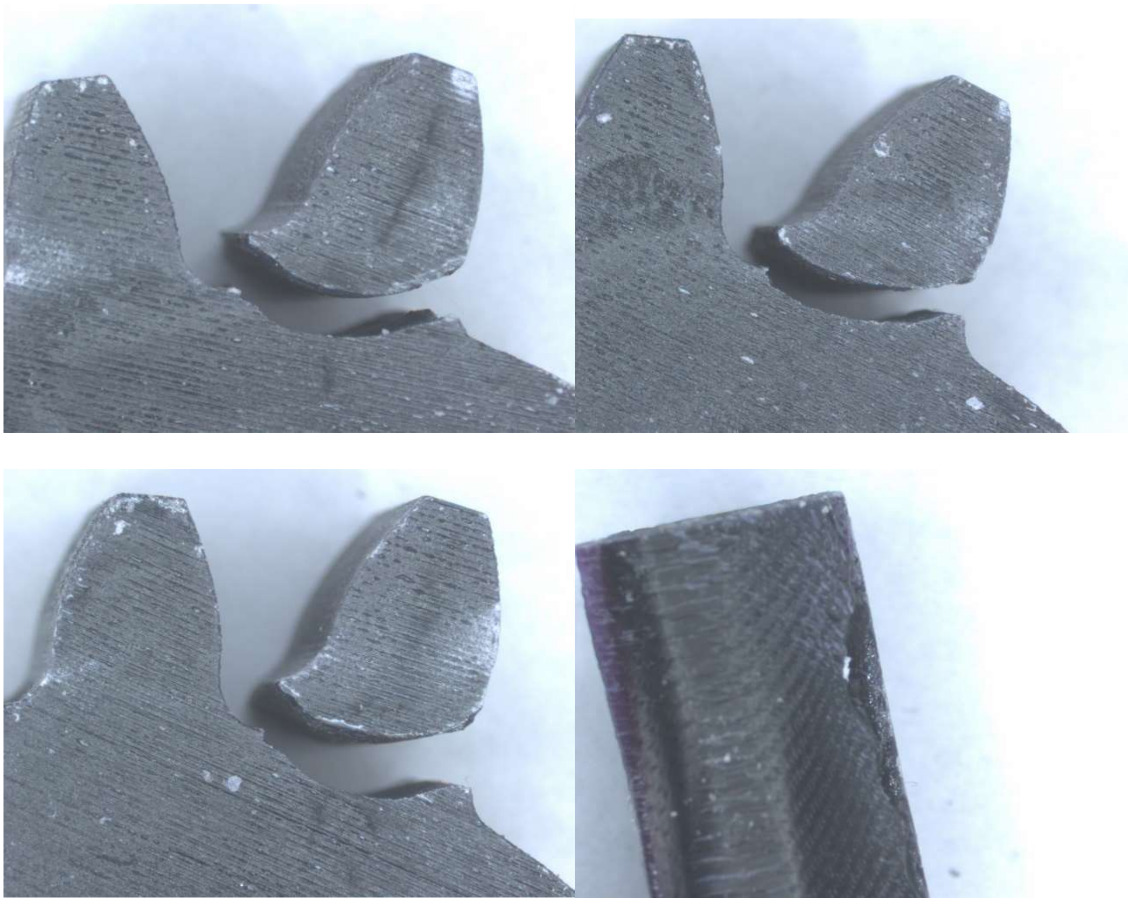
ProJet 3500 45 Degrees



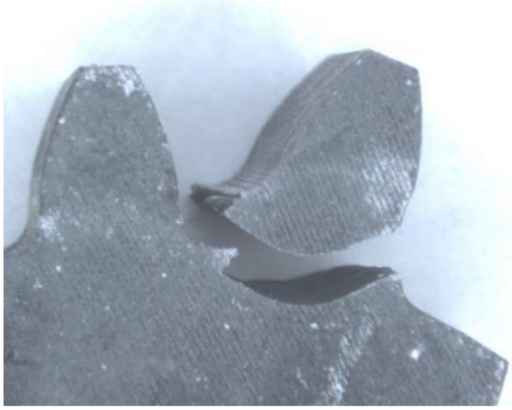


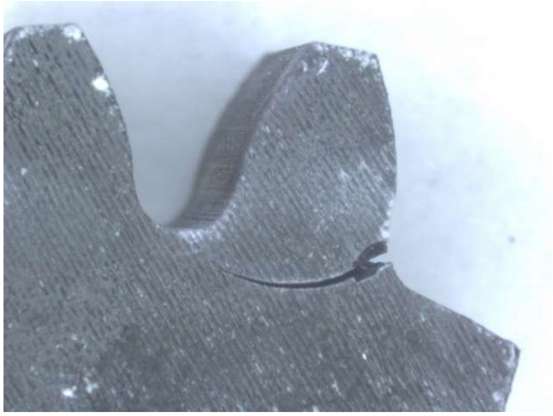


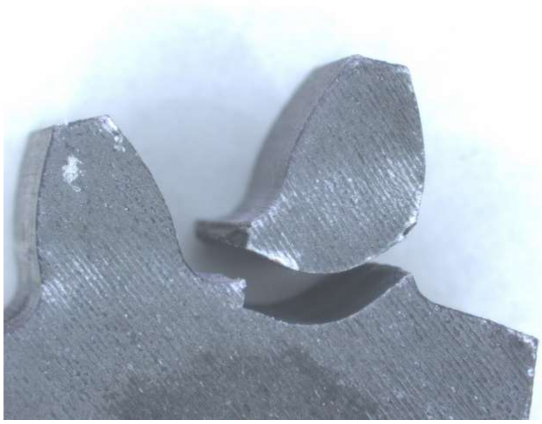
ProJet 3500 90 Degrees



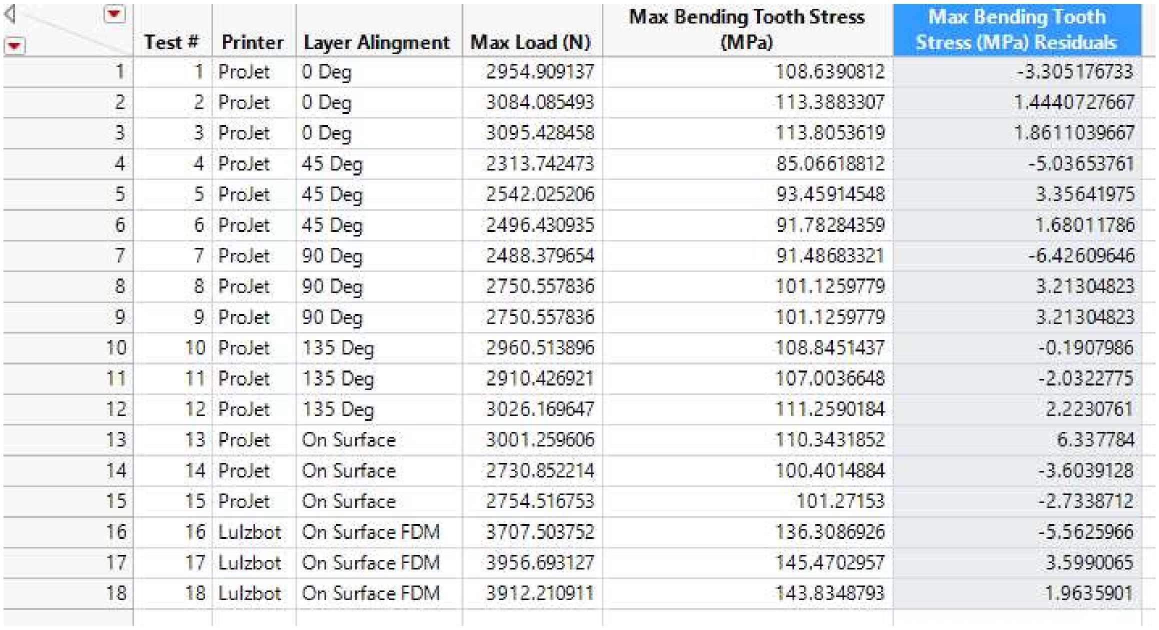
ProJet 3500 135 Degrees



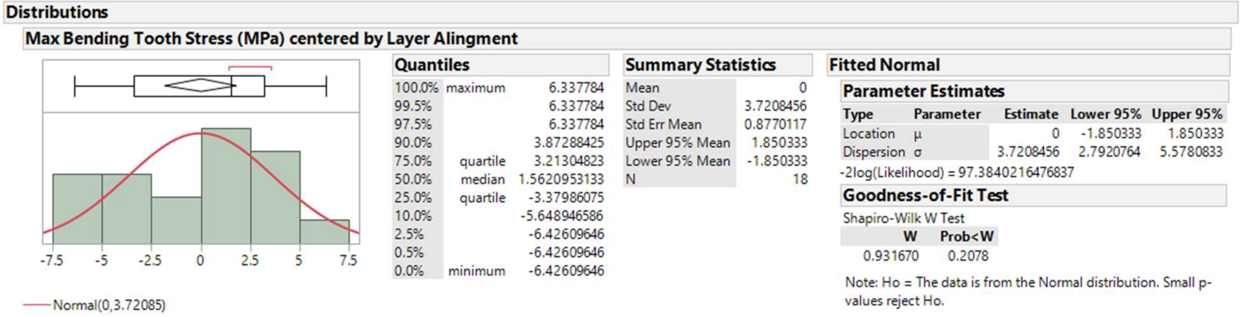




Appendix B – JMP® Statistical Analysis



	Test #	Printer	Layer Alingment	Max Load (N)	Max Bending Tooth Stress (MPa)	Max Bending Tooth Stress (MPa) Residuals
1	1	ProJet	0 Deg	2954.909137	108.6390812	-3.305176733
2	2	ProJet	0 Deg	3084.085493	113.3883307	1.4440727667
3	3	ProJet	0 Deg	3095.428458	113.8053619	1.8611039667
4	4	ProJet	45 Deg	2313.742473	85.06618812	-5.03653761
5	5	ProJet	45 Deg	2542.025206	93.45914548	3.35641975
6	6	ProJet	45 Deg	2496.430935	91.78284359	1.68011786
7	7	ProJet	90 Deg	2488.379654	91.48683321	-6.42609646
8	8	ProJet	90 Deg	2750.557836	101.1259779	3.21304823
9	9	ProJet	90 Deg	2750.557836	101.1259779	3.21304823
10	10	ProJet	135 Deg	2960.513896	108.8451437	-0.1907986
11	11	ProJet	135 Deg	2910.426921	107.0036648	-2.0322775
12	12	ProJet	135 Deg	3026.169647	111.2590184	2.2230761
13	13	ProJet	On Surface	3001.259606	110.3431852	6.337784
14	14	ProJet	On Surface	2730.852214	100.4014884	-3.6039128
15	15	ProJet	On Surface	2754.516753	101.27153	-2.7338712
16	16	Lulzbot	On Surface FDM	3707.503752	136.3086926	-5.5625966
17	17	Lulzbot	On Surface FDM	3956.693127	145.4702957	3.5990065
18	18	Lulzbot	On Surface FDM	3912.210911	143.8348793	1.9635901



Distributions

Max Bending Tooth Stress (MPa) centered by Layer Alingment

Quantiles

100.0%	maximum	6.337784
99.5%		6.337784
97.5%		6.337784
90.0%		3.87288425
75.0%	quartile	3.21304823
50.0%	median	1.5620953133
25.0%	quartile	-3.37986075
10.0%		-5.648946586
2.5%		-6.42609646
0.5%		-6.42609646
0.0%	minimum	-6.42609646

Summary Statistics

Mean	0
Std Dev	3.7208456
Std Err Mean	0.8770117
Upper 95% Mean	1.850333
Lower 95% Mean	-1.850333
N	18

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	0	-1.850333	1.850333
Dispersion	σ	3.7208456	2.7920764	5.5780833

-2log(Likelihood) = 97.3840216476837

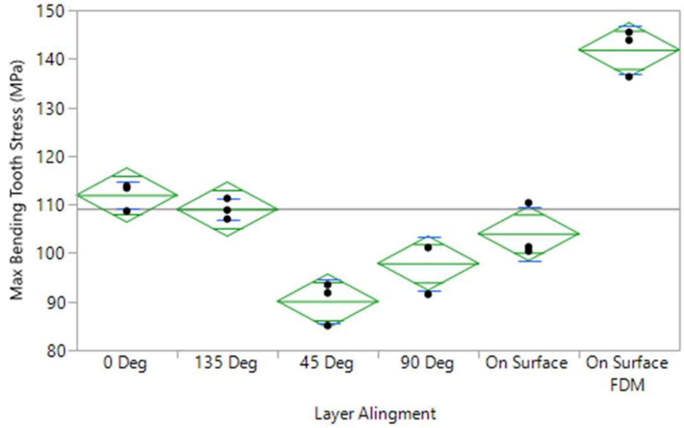
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.931670	0.2078

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Oneway Analysis of Max Bending Tooth Stress (MPa) By Layer Alignment



Oneway Anova

Summary of Fit

Rsquare	0.953092
Adj Rsquare	0.933547
Root Mean Square Error	4.428692
Mean of Response	109.1454
Observations (or Sum Wgts)	18

Analysis of Variance

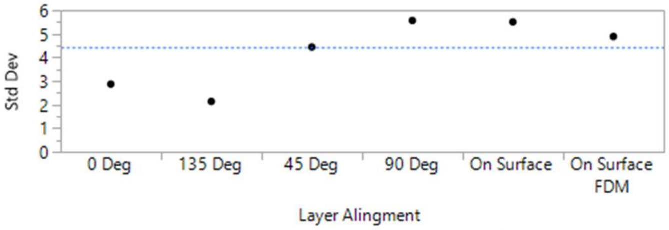
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Layer Alingment	5	4782.1225	956.424	48.7640	<.0001*
Error	12	235.3598	19.613		
C. Total	17	5017.4823			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0 Deg	3	111.944	2.5569	106.37	117.52
135 Deg	3	109.036	2.5569	103.46	114.61
45 Deg	3	90.103	2.5569	84.53	95.67
90 Deg	3	97.913	2.5569	92.34	103.48
On Surface	3	104.005	2.5569	98.43	109.58
On Surface FDM	3	141.871	2.5569	136.30	147.44

Std Error uses a pooled estimate of error variance

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
0 Deg	3	2.869952	2.203451	1.722094
135 Deg	3	2.134083	1.482051	1.418451
45 Deg	3	4.441568	3.357692	2.797652
90 Deg	3	5.565163	4.284064	3.213048
On Surface	3	5.505894	4.225189	3.313899
On Surface FDM	3	4.886257	3.708398	3.053868

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.4505	5	12	0.8052
Brown-Forsythe	0.1284	5	12	0.9830
Levene	1.5229	5	12	0.2545
Bartlett	0.4129	5	.	0.8401

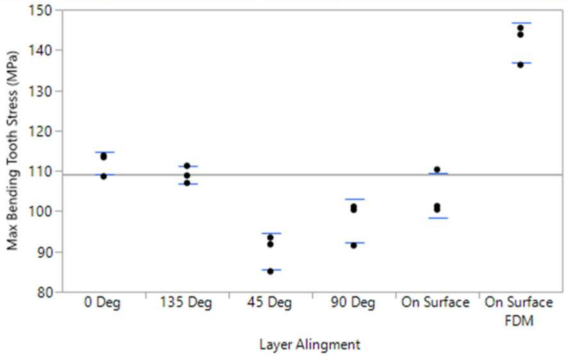
Warning: Small sample sizes. Use Caution.

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
27.8301	5	5.4531	0.0007*

Oneway Analysis of Max Bending Tooth Stress (MPa) By Layer Alingment



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

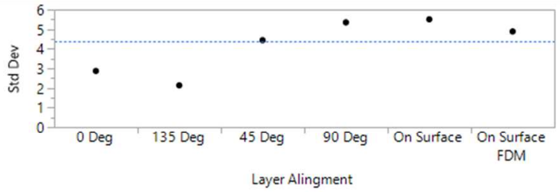
Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
0 Deg	3	39.000	28.500	13.0000	1.185
135 Deg	3	33.000	28.500	11.0000	0.474
45 Deg	3	8.000	28.500	2.6667	-2.369
90 Deg	3	14.000	28.500	4.6667	-1.659
On Surface	3	26.000	28.500	8.6667	-0.237
On Surface FDM	3	51.000	28.500	17.0000	2.606

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
14.8947	5	0.0108*

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
0 Deg	3	2.869952	2.203451	1.722094
135 Deg	3	2.134083	1.482051	1.418451
45 Deg	3	4.441568	3.357692	2.797652
90 Deg	3	5.349679	4.106712	3.213048
On Surface	3	5.505894	4.225189	3.313899
On Surface FDM	3	4.886257	3.708398	3.053868

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.4358	5	12	0.8153
Brown-Forsythe	0.1390	5	12	0.9798
Levene	1.4506	5	12	0.2760
Bartlett	0.3988	5	.	0.8500

Warning: Small sample sizes. Use Caution.

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
28.0658	5	5.4559	0.0007*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

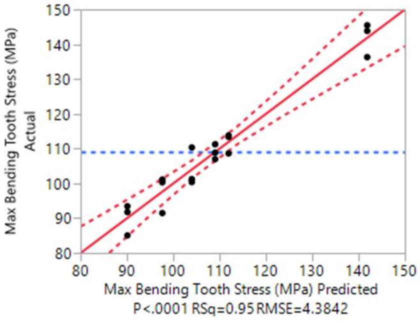
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
On Surface	45 Deg	2.66667	1.527525	1.74574	0.0809	15.3353	.	.
On Surface FDM	0 Deg	2.66667	1.527525	1.74574	0.0809	30.4465	.	.
On Surface FDM	135 Deg	2.66667	1.527525	1.74574	0.0809	34.2113	.	.
On Surface FDM	45 Deg	2.66667	1.527525	1.74574	0.0809	52.0112	.	.
On Surface FDM	90 Deg	2.66667	1.527525	1.74574	0.0809	44.3443	.	.
On Surface FDM	On Surface	2.66667	1.527525	1.74574	0.0809	35.9072	.	.
On Surface	90 Deg	2.00000	1.527525	1.30931	0.1904	8.9147	.	.
90 Deg	45 Deg	1.33333	1.527525	0.87287	0.3827	7.6668	.	.
135 Deg	0 Deg	-1.33333	1.527525	-0.87287	0.3827	-2.5463	.	.
On Surface	135 Deg	-1.33333	1.527525	-0.87287	0.3827	-6.6022	.	.
On Surface	0 Deg	-2.00000	1.527525	-1.30931	0.1904	-8.2376	.	.
45 Deg	0 Deg	-2.66667	1.527525	-1.74574	0.0809	-21.6055	.	.
45 Deg	135 Deg	-2.66667	1.527525	-1.74574	0.0809	-17.7999	.	.
90 Deg	0 Deg	-2.66667	1.527525	-1.74574	0.0809	-13.0604	.	.
90 Deg	135 Deg	-2.66667	1.527525	-1.74574	0.0809	-10.1330	.	.

Response Max Bending Tooth Stress (MPa)

Whole Model

Actual by Predicted Plot



Summary of Fit

RSquare	0.954152
RSquare Adj	0.935049
Root Mean Square Error	4.384212
Mean of Response	109.1011
Observations (or Sum Wgts)	18

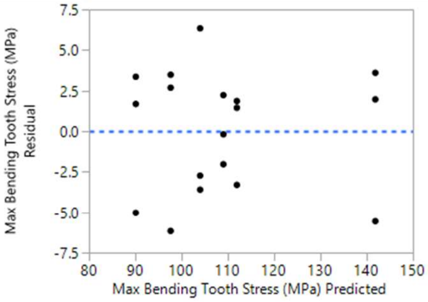
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	4800.2284	960.046	49.9469
Error	12	230.6558	19.221	Prob > F
C. Total	17	5030.8842		<.0001*

Effect Tests

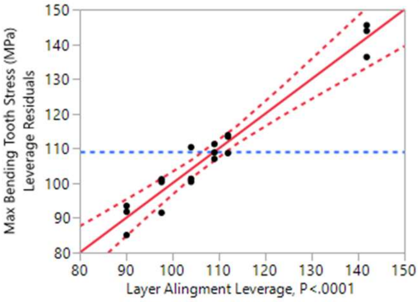
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Layer Alingment	5	5	4800.2284	49.9469	<.0001*

Residual by Predicted Plot



Layer Alingment

Leverage Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
0 Deg	111.94426	2.5312263	111.944
135 Deg	109.03594	2.5312263	109.036
45 Deg	90.10273	2.5312263	90.103
90 Deg	97.64690	2.5312263	97.647
On Surface	104.00540	2.5312263	104.005
On Surface FDM	141.87129	2.5312263	141.871

LSMeans Differences Tukey HSD

α= 0.050 Q= 3.35886

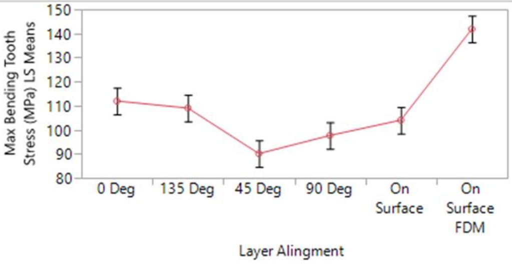
LSMean[j]

LSMean[i]	Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	0 Deg	135 Deg	45 Deg	90 Deg	On Surface	On Surface FDM
0 Deg		0	2.90832	21.8415	14.2974	7.93886	-29.927
		0	3.57969	3.57969	3.57969	3.57969	3.57969
		0	-9.1154	9.81783	2.27365	-4.0849	-41.951
		0	14.932	33.8652	26.3211	19.9626	-17.903
135 Deg		-2.9083	0	18.9332	11.389	5.03054	-32.835
		3.57969	0	3.57969	3.57969	3.57969	3.57969
		-14.932	0	6.90951	-0.6347	-6.9932	-44.859
		9.11539	0	30.9569	23.4127	17.0542	-20.812
45 Deg		-21.842	-18.933	0	-7.5442	-13.903	-51.769
		3.57969	3.57969	0	3.57969	3.57969	3.57969
		-33.865	-30.957	0	-19.568	-25.926	-63.792
		-9.8178	-6.9095	0	4.47953	-1.879	-39.745
90 Deg		-14.297	-11.389	7.54418	0	-6.3585	-44.224
		3.57969	3.57969	3.57969	0	3.57969	3.57969
		-26.321	-23.413	-4.4795	0	-18.382	-56.248
		-2.2736	0.63467	19.5679	0	5.66521	-32.201
On Surface		-7.9389	-5.0305	13.9027	6.3585	0	-37.866
		3.57969	3.57969	3.57969	3.57969	0	3.57969
		-19.963	-17.054	1.87897	-5.6652	0	-49.89
		4.08485	6.99317	25.9264	18.3822	0	-25.842
On Surface FDM		29.927	32.8353	51.7686	44.2244	37.8659	0
		3.57969	3.57969	3.57969	3.57969	3.57969	0
		17.9033	20.8116	39.7449	32.2007	25.8422	0
		41.9507	44.8591	63.7923	56.2481	49.8896	0

Level					Least Sq Mean
On Surface FDM	A				141.87129
0 Deg		B			111.94426
135 Deg		B	C		109.03594
On Surface		B	C		104.00540
90 Deg			C	D	97.64690
45 Deg				D	90.10273

Levels not connected by same letter are significantly different.

LS Means Plot



References

3D Systems. (2016). ProJet® 3500 HDMax | 3D Systems. Retrieved May 10, 2016, from http://www.3dsystems.com/3d-printers/professional/projet-3500-hdmax

Airforce.com. (2016). U.S. Air Force—Explosive Ordnance Disposal (EOD). Retrieved May 9, 2016, from https://www.airforce.com/careers/detail/explosive-ordnance-disposal-eod.

Aleph Objects. (2017). LulzBot TAZ 6. Retrieved January 1, 2017, from https://www.lulzbot.com/store/printers/lulzbot-taz-6

Alwabel, A. S., Greiner, N., Murphy, S., Page, W., Veitenheimer, S., & Valencia, V. V. (2017). *Additive Manufacturing Handbook: Product Design for the Defense Industry Ch. 43*. Taylor & Francis/CRC Press.

Army, U. S. (2016). Rapid Equipping Force. Retrieved from https://bitcoin.org/en/faq#how-does-one-acquire-bitcoins

ASTM Norma. (2004). Standard Test Method for Tensile Properties of Plastics. *Annual Book of ASTM Standards*, 1–15. http://doi.org/10.1520/D0638-14.1

Baker, B. (2014). Bomb Disposal Robots: Evolution and Revolution. army-technology.com. Retrieved from http://www.army-technology.com/features/featurebomb-disposal-robots-evolution-and-revolution.

Dornfeld, W. H. (2004). Gear Tooth Strength Analysis. Retrieved May 23, 2016, from http://www.faculty.fairfield.edu/wdornfeld/ME312/ToothLoads04.pdf

Gibson, I., Rosen, D. W., & Stucker, B. (2009). *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Springer Science & Business

Media. Retrieved from https://books.google.com/books/about/Additive_Manufacturing_Technologies.html?id=jcFs0VVi9OAC&pgis=1.

Graham, T., Dijkstra, M., Krause, A., Masri, L., McCambridge, G., Ng, J., … Zheng, Y. (2014). U . S . National Strategy for Additive Manufacturing, 1–25.

Grunewald, S. J. (2015). Using 3D Printing to Help Rid the World of Landmines, 1–13. Retrieved from https://3dprint.com/97417/rid-world-of-landmines/

Handschuh, B. R. F., Krantz, T. L., Lerch, B. A., & Burke, C. S. (2008). Low-Cycle Bending Fatigue of AISI 9310 Steel Spur Gears. *Gear Solutions*, (January), 19–25.

Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2014). Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. *Journal of Manufacturing Science and Engineering*, *137*(February), 1–10. http://doi.org/10.1115/1.4028725.

Insinna, V. (2014). Military Scientists Developing New 3-D Printing Applications. *National Defense*, *98*(727), 22–23. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=96262135&lang=pt-br&site=ehost-live

Magnuson, S. (2016). Navy Presses On With Long-Delayed Bomb Disposal Robot Program. *National Defense Magazine*, 1–4. Retrieved from http://www.nationaldefensemagazine.org/archive/2016/March/Pages/NavyPressesOnWithLongDelayedBombDisposalRobotProgram.aspx

MatWeb. (2015). Tensile Property Testing of Plastics Typical Tensile Strength , Elongation , and Tensile Modulus of Polymers. Retrieved from http://www.matweb.com/reference/tensilestrength.aspx

Obama, B. H. (2013). President in the State of the Union Address | whitehouse.gov. The White House. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/remarks-president-state-union-address

Poulsen, S. N. (2015). A DELPHI STUDY OF ADDITIVE MANUFACTURING APPLICABILITY FOR UNITED STATES AIR FORCE CIVIL ENGINEER CONTINGENCY OPERATIONS THESIS MARCH 2015.

Ravai Nagy, S., & Lobontiu, M. (2015). Gear Teeth Bending Test Upon the Gear with Asymmetric Teeth. *Academic Journal of Manufacturing Engineering*, *13*(1), 63–68.

Ray, J. T. (2013). The 3D Printed Supply Chain. *Defense Transportation Journal*, *October*.

Roboteam. (2016). MTGR. Retrieved May 9, 2016, from http://www.robo-team.com/products/systems/mtgr

Shields, B. L. (2016). *United States Air Force Civil Engineering Additive Manufacturing Application : Tools and Jigs*. Air Force Insitutie of Technology.

Shigley, J. E., Mischke, C. R., & Budynas, R. G. (2004). *Mechanical Engineering Design* (7th ed.).

Tadjdeh, Y. (2014a). 3D Printing Promises to Revolutionize Defense, Aerospace Industries. *National Defense Magazine*, 20–24.

Tadjdeh, Y. (2014b). Navy Beefs Up 3D Printing Efforts With New “Print the Fleet” Program. *National Defense*, *99*(731), 24–26. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=98611965&lang=pt-br&site=ehost-live

Wohler, T.-I. (2014). *Additive Manufacturing and 3D Printing - State of the Industry Annual Wourldwide Progress Report, Wohler's Associates*. Fort Collins, CO: Wohlers Associates, Inc.

Yeh, C.-C. (2014). Trend Analysis for the Market and Application Development of 3D Printing. *International Journal of Automation and Smart Technology*, *4*(1), 1–3. http://doi.org/10.5875/ausmt.v4i1.597

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to an penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)* 23-03-2017	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From – To)* September 2015 – March 2017

TITLE AND SUBTITLE Strength Test and Analysis of Additive Manufactured Gears and Their Applicability for Explosive Ordnance Disposal Robots	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Murphy, Sean T., Captain, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENY) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENV-MS-17-M-204
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Joint EOD Technology Division, Air Force Civil Engineer Center STEPHEN P. EMBORSKI, Major, USAF 2008 Stump Neck Road, Indian Head, MD 20640 301-744-5955 (DSN 312-354-5955) stephen.emborski@navy.mil	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFCEC/CXE **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

Recent advancements in additive manufacturing have led to a number of fields within the Department of Defense employing this technology. This research determines if additive manufacturing can assist the field of explosive ordnance disposal by manufacturing replacement gears for the micro tactical ground robot. This is accomplished by completing a single-tooth bending test on a number of gear teeth manufactured using two different 3D printers. The ProJet 3500, a $90,000 material-jetting printer, produced gear teeth that proved to be of high strength and quality. The Lulzbot Taz 6, a $2,500 material-extrusion printer, also produced strong gear teeth, but lacked quality dependent on build orientation. The research shows the orientation of layers affected the strength of the gear teeth, but not to a point where the tooth failed before reaching a pre-calculated, required stress. This work provides a starting point for understanding the effect of layering on additive manufactured gears while providing strong evidence toward the efficacy of additive manufacturing within the field of explosive ordnance disposal.

15. SUBJECT TERMS

Additive Manufacturing, Single Tooth Bending Test, 3D Printing, Explosive Ordnance Disposal Robots

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Vhance V. Valencia, AFIT/ENV
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	72	**19b. TELEPHONE NUMBER** *(Include area code)* 937) 255-6565, ext 4826 (Vhance.valencia@afit.edu)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18