Digital Additive Manufacture:

Improved Product And Equipment Design For 3D Printing

By

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A thesis submitted to the faculty of graduate and postdoctoral affairs in partial
fulfillment of the requirements for the degree of

Master of Design

In

Industrial Design

Carleton University
Ottawa, Ontario

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I. Abstract

This thesis offers an understanding of the field of digital additive manufacture and introduces the role of design in advancing the technology and application of this novel commercial production capability. The field is distinguished from other additive techniques with the addition of “digital” to the additive manufacturing term. Methods of increasing process competitiveness for commercial applications are described with the use of low-cost open source equipment through two sets of case studies conducted by the author (design for extrusion-based digital additive manufacture and equipment design / operation). As a result, the author identified and improved eight areas of development: layer design; support design; profile design; mesostructure design; extrusion tooling; solidification control; printing surface and positioning system. These areas of development inform professional and hobbyist design for manufacture and future interdisciplinary research.

Keywords: Advanced manufacturing; Competitive advantage; Product design; Iterative design; Additive manufacturing; Fused Deposition Modeling; Computer Numerical Control

II. Acknowledgements

The author would like to thank his parents Jim and Louise Dewar for fostering curiosity and experimentation throughout his life.

Wim Gilles for starting the School of Industrial Design, in the Faculty of Engineering and Design, at Carleton University. For his pioneering work in the field of design for digital processes.

John Buschek, Brian Burns, Andrew Plumb, Steve Truttmann and Lois Frankel for helping in my research through conversations, electronics troubleshooting, operating testing equipment or creating a directed studies class.

Steve Macleod and Jim Dewar – no relation - for sharing practical CNC milling knowledge.

Alena Iouguina for inspiring greater exploration and interdisciplinarity over the years. Her assistance throughout my masters and thesis writing process and her partnership in Ecotonos as well as life.

Jeremy Laliberte and Bjarki Hallgrimsson for co-supervising this thesis and the many things of which that entails.

Thank you.

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1 Introduction

The wealth of nations

As Western nations attempt to revitalize their manufacturing industries, some – like the United States – are turning to research and development of robotics, with the goal of augmenting workers' productivity – White House robotics (Kalil & Thorpe, 2011) (Science Foundation, n.d.). This development falls into the category, defined by Adam Smith in *The Wealth of Nations*, as the creation of mechanical equipment that allows a single worker to do the work of several. The other two areas, which increase productivity, improve a worker's ability to complete a task by reducing and optimizing the number of steps needed thus saving time. These categories are not popular in modern western cultures as it makes people feel like gears in a machine and not like individuals producing valued goods (Dewar, 2013).

Wim Gilles and the School of Industrial Design at Carleton University

The school's founding director Wim Gilles researched and wrote on the topic of design for digital production (Gilles, 1991). One of the main points made in his book is the requirement for designers to develop tool paths that allow tolerance for bits and scallops. He also wrote on the topic of "Unwritten rules for efficient production" in his chapter on entrepreneurial design (Gilles, 1999) – expanded in Appendix A.

Process/history

The basis of current Additive Manufacture (AM), 3D printing and rapid prototyping technologies is the creation of two-dimensional profiles stacked upon one another to create a physical three-dimensional form. The material used, techniques of profiling, safety equipment, dimensionality, scale of production and overall processes requirements of building these parts change, but the simple idea of building up profiles, one on top of the other, stays the same. This process was first introduced in the 1980's as a prototyping technique that predominantly used waxes, later it evolved to use powdered materials in the 3DP and SLS processes, than to use acrylate photopolymers in systems based on jetting the liquid material and curing it with UV light (Gibson, Rosen, & Stucker, 2010). The most frequently used form of these technologies is extrusion based systems or fused deposition modeling (FDM) originally developed by Stratasys (Gibson et al., 2010). This technology is often what people think of in association with 3D printing because many consumer printers are based on the initial work of the RepRap project, created at Bath University following the expiration of FDM process patents (Hodgson, 2013).

Local, Niche and Democratic Production

As the economic, political, social and environmental worlds change, companies are reevaluating where they manufacture products. Some are beginning to shift production closer to the people that consume their goods – for example, Apple Computers are shifting some production lines to the United States (Rampell & Wingfield, 2012).

The types and quantities of manufactured goods are also changing along with the location of production, evident in Chris Anderson's observations initially pertaining to digital media (Anderson, 2006) and later to physical goods (Anderson, 2012). He observed a trend in which the goods people buy are shifting from blockbusters or popular culture items to unique items – this shift was defined as selling less of more. For design and manufacture this means producing more products for niche markets with fewer expected sales per item.

Much of the hype around digital manufacturing technology is that anyone is able to produce anything they need right in their homes. Many claim that when an object breaks you will no longer need to toss it in the trash and buy a new one, or pay for expensive parts, instead you can print a replacement. This is achieved without the use of expert knowledge in the field of product design and engineering through the use of vast databases or 3D scanners in which anyone can recreate designed artifacts. If a person happens to know a computer aided design (CAD) software package then they can design and produce their own products. Some points are debatable but before this pop culture prediction is possible, first small to medium professional firms – which make up the largest manufacturing sector in Canada (Industry Canada, 2013) - must be capable of producing commercial 3D printed products, before the masses are also capable of the same feat in their free time.

Rapid Prototyping Legacy and Design for Manufacture

Unlike mature manufacturing processes such as injection molding or woodworking techniques, designers have had little experience with 3D printing as a production tool. They are mostly familiar with the technology as a model making or prototyping tool predominantly utilized when designing for the injection molding process.

As many product development experts view the 3D printing process as a prototyping tool and not as a production tool, a major limiting factor of this technology being widely used in the production of commercial products, is the designers themselves (Hopkinson, Hague, & Dickens, 2005a). When a printed part is not designed for the process they often incur higher costs (Krottmaier, 1993). This association with higher costs has hindered widespread adoption for commercial end-use (Hopkinson, 2006).

A process-experienced designer can have a large influence on the cost of individual parts based on how well the part is designed for the specific process. By minimizing unnecessary features and developing design concepts for a known specific process, designers can reduce the cycle time to produce a part while reducing the amount of waste incurred in its production (Gilles, 1999). Designers have also had great influence over what production technologies and materials are accepted, for instance plastic parts were viewed as junk mimicking real products until design guidelines matured (Nyborg, 1993).

“The machine is here to stay... use this normal tool of civilization to best advantage instead of prostituting it as he has hitherto done in reproducing with murderous ubiquity forms born of other times and other conditions which it can only serve to destroy.”

Frank Lloyd Wright 1894

Unlike production molding techniques often used with plastics, extrusion-based 3D printing extrudes molten plastics into open air; presenting many formal possibilities. At the same time the absence of a mold provides technical and design challenges and limitations on how to support a molten polymer while it solidifies so that it does not collapse or distort due to its own weight. This design consideration and many other process specific considerations are not currently part of a designer's education. Since there are currently no widely used systematic design guidelines for additive manufacturing, product design teams who want to make better use of the technology must either rely on the experience of others or experiment with the technology before it can be used in their design process or part production. Such guidelines would therefore help designers make better use of these technologies for manufacturing ends, just as guidelines allowed for the proper design of injection molded plastic parts.

Digital Additive Manufacture Research

The current research presented in this thesis is the result of interdisciplinary research done by the author within the fields of Industrial Design and Mechanical/Aerospace Engineering. The research approach uses design and engineering method to improve the design and operation of 3D printed parts and equipment. To increase accessibility to manufacturing capable equipment, a low cost RepRap 3D printer kit is used for the research. This equipment is modified by the author with self-printed parts or locally sourced low cost components when

possible. This approach allows the research equipment and part design knowledge to evolve together, towards the goal of lowering printed part costs and increasing the competitiveness of the digital additive manufacturing process.

1.1 Research Scope and limitations

This thesis examines the process of digital additive manufacturing – the commercial use of 3D printing technology – as a modern technological process reliant on computer numerical control, materials processing, and product design. Current production limitations are investigated as a lack of process-specific design understanding instead of a technological shortcoming.

The interaction between design process and the manufacturing equipment is investigated with the goal of expanding process specific knowledge. This focus on the development of specialized design capabilities has the intent of informing future research into general use and design education, which are outside of the current research scope. Many legislative issues also exist around the research topic – prohibited manufacture, copyright violations, and product liability – however this is outside the author's area of expertise and not included in this work.

The equipment research uses available and low cost parts wherever possible. This allows design guidelines to be applicable to low-end machines that are easy to purchase and modify for professional purposes. This area of research is also limited to one extruder that reduces moving weight and cost, as well as removes the

capability for multiple nozzle sizes and multi-material structures. The experiments operate with PLA filament avoiding material selection as a variable and focusing research on part mesostructures. These two limitations on the research equipment focus research on design solutions rather than technological or material advances, leading to increased design complexity.

1.2 Research Questions

The research addresses the main question (Q1), by answering two sub questions (Q2 and Q3).

Q1: How can design increase the competitiveness of extrusion-based digital additive manufacturing?

Q2: What design considerations are required to produce cost effective and functional parts with digital additive manufacturing?

Q3: How can equipment design and operation be improved for lower-investment manufacturing?

1.3 Contributions to the field

The author proposes the addition of digital to the term additive manufacture as a key differentiator between the processes that employ digital control verses manual additive processes. Such manual processes are used in the aerospace industry to layup carbon fiber and in the addition on materials when prototyping a model, etc.

The author also highlights that digital additive manufacture is about more than just hitting the print button on a 3D printer. A thorough design understanding of the process and equipment is required to produce valued commercial objects – objects of high quality and high throughput. Further these commercial objects should be tested with engineering tools that are worked into the design process to ensure product reliability.

Also of importance is lowering the barriers to entry into this digital field of manufacture. Doing so enables design entrepreneurialism allowing for the creation of niche products to match fringe needs. This is accomplished through the modification of low cost equipment that allows for greater market agility due to less capital investment in equipment and the ability to customize the equipment to suite the companies needs.

The research contains many interdisciplinary elements due to a highly diverse nature of Digital Additive Manufacture that must draw knowledge from the fields of science, engineering, and design to truly succeed. As such the thesis will contribute differently to each discipline, and reader of the work (professional or hobbyist/ maker). The work is presented with the hope of cross pollinating several engineering qualitative methods such as ASTM testing or reliability testing with designs qualitative methods that allow for fast iteration such as paper prototyping.

Beyond this thesis the author has also contributed to the field with several publications, presentations, and provided case studies to other publications through work at Ecotonos design and manufacturing on the topic of designing for Digital Additive Manufacture.

- Additive Manufacturing Journal “Measurement of static tensile properties of 3D printed PLA using a custom designed “dog bone” coupon” J. Laliberte, A. Dewar, B. Rutkay, B. Hallgrimsson
- IDSA “Taking 3D Printing From Art To Science: Design For A Transformative Technology” B. Hallgrimsson, A. Dewar, J. Laliberte
- Fields Journal “Production Shifts: Specialized, Humanist, Niche, Local, And Open” A. Dewar
- Design Principles And Practices “Design For Digital Additive Manufacture: Design Guidelines For In-Use Printed Parts” A. Dewar, J. Laliberte, B. Hallgrimsson
- The Fermanian Business & Economic institute “Can 3D Printing Unlock Bioinspiration’s Full Potential?” Ecotonos case study
- Ottawa Magazine “The Next Dimension” Ecotonos interview
- Apartment 613 Talks“ 3D Printing: The Democratization of Production“ Ecotonos panel discussion
- Ottawa Mini Maker Faire (2013, 2014) Ecotonos booth on design for digital additive manufacture

2 Literature Review

The following sections present a literature review on increasing competitiveness as well as technical challenges of design for manufacture and equipment design.

2.1 Competitive factors

To become commercially competitive, printed parts need to overcome the current shortcomings of part aesthetics and mechanical behavior as well as reducing costs. These improvements are seen as the driving factor for 3D printing allowing it to evolve into a reliable manufacturing process. The authors proposed name for this process is Digital Additive Manufacture (DAM).

The general equation to calculate part cost is shown in Figure 1 (Gibson et al., 2010).

The purchasing cost value is the amortized cost for the company of purchasing the equipment required to produce a given part, designers will not have control over this value in the case that equipment is already owned. Operating cost refers to the cost associated with running the equipment such as electricity per unit time.

Material cost is the amount of material used for a part and its support material.

Labour costs cover the necessary operation and postproduction efforts required by employers to create finished parts.

$$\text{Cost} = P + O + M + L$$

Purchasing cost
Operating cost
Material cost
Labour cost

- Figure 1: General printed part costing

The competitiveness of the DAM process is application and part dependent, however reducing each of the above values in figure 1 will reduce costs, making the process more valuable to a manufacturer. The author investigates ways to reduce the overall cost through part and equipment design. The purchasing cost is reduced with less expensive customized open source equipment. Parts designed specifically for the process, which take advantage of mesostructures reduces operating costs along with equipment upgrades to create more capable/power efficient machine. Careful part and mesostructure design also reduce the material costs, increase the strength to weight ratio and reduce labor requirements for post processing. The reduction of these costs will help increase the processes competitiveness, eventually leading to a competitive advantage over other polymer manufacturing processes.

2.1.1 Design With Manufacture

The topic of “design freedom” within additive manufacturing began with research institutes and equipment vendors comparing the new rapid manufacturing ability to injection molding. Therefore, the initial research focused on how parts no longer need a constant wall thickness, how multiple parts could be consolidated into a single part saving assembly time, how the process could easily produce undercuts,

and general geometric freedoms allowed by the process (R Hague, Campbell, & Dickens, 2003). Even though this comparison helps to define how the process differs it does not provide an independent look at the process' strengths and weaknesses in producing digital additive manufactured products but rather in producing injection molded parts.

To fully utilize this process, a design's complexity must increase to match the level of digital control this process allows over many manufacturing factors. Decision based design (Pandey, 2013) is utilized to inform this greater complexity. The field of industrial design alone cannot inform every decision and requires greater interdisciplinary skills and collaborations. These collaborations can come from other engineering and/or scientific fields such as aerospace engineering and biology.

Collaborative development

The modern product design process focuses on the communication of ideas and production methods. This is the case as our current means of manufacture takes place around the world with design, manufacturing and assembly taking place separately (Gilles, 1999). Before the current separation of the production process, designers and manufacturing experts or laborers used to work together in the same complex, allowing for iterative development and constant improvements. To create better working conditions and easier-to-produce products pioneering techniques such as time and motion studies created a greater understanding of human labor

and machine capabilities, leading to great efficiency gains (Taylor, 1923). The Gilbreths' motion studies involved designing new processes and tools to minimize waste motion and fatigue (Gilbreth, 1911). This study method can also be applied to newer digital labour to better understand its capabilities and design better motions or apparatus for its weaknesses. In this case the typical role of labourer is replaced with the digital control system, and tooling replaced with the equipment's extruder, solidification controllers, printing surface, and positioning system. To improve efficiency either the set of instructions for the laborer/digital control can be modified based on observation, the tooling modified for the specific task or the design can be slightly changed to match the production capabilities.

A design is not fully optimized for a manufacturing process when manufacturing development is separated from design development (Krottmaier, 1993). This separation leads to design specifications that are not optimal for the implemented manufacturing process and require more effort to produce. By simultaneously optimizing the product and manufacturing process, rejects and rework costs can be reduced (Krottmaier, 1993). The design and manufacture method known, as "over the wall" has this separation between engineering and design. Lockheed Martin's Skunk Works is a famous example of what can happen when the "over the wall" approach was replaced. In this system designers, engineers, and factory workers worked together to quickly develop America's first jet fighter in 143 days (Lockheed Martin, 2014).

A new approach has been proposed for digital manufacture that is similar to the over the wall approach, including the handoff between mechanical design and aesthetic design (Richard Hague, Tuck, & Raymond, n.d.). This proposed method uses finite element analysis (FEA) to develop an initial design that is handed off to a designer. Once the designer adds aesthetic modifications they pass the design off for an assurance test with further FEA. The issue with this scenario is that mechanical engineering is given priority over industrial design (ex. usability and manufacturability). This method does not include an iterative back and forth process between the two areas of expertise minimizing its effectiveness to optimize both design and manufacturing.

Prototyping

The purpose of a prototype is to quickly test individual sections of a design. Early prototypes can be made quickly with easily workable and available/found materials to provide design insights (Hallgrimsson, 2012). These quick early prototypes are important to further speed up the development cycle and save materials when using digital additive manufacture. Beyond this stage, material and process substitutes are not as advantageous as the technology allows for manufactured and prototype models to be produced in the same amount of time, using the same materials. This integration allows for production part testing of earlier concepts. Engineering test methods such as Highly Accelerated Life Test (HALT) help reduce design time, increase reliability, and decrease cost by subjecting parts to accelerated conditions to find the weakest link which can be removed through iteration (Hobbs, 2000).

Carleton University's School of Industrial Design's founding director Wim Gilles wrote about the possibility of expanding beta testing with rapid prototyping technology, allowing a greater number of people to be involved in the design process, because of the lower investment required to produce plastic parts (Gilles, 1999). The use of beta testing can be expanded beyond Wim Gilles' idea as modern consumers are not only willing participants in beta testing but pay money to be a part of the process. This is the case with popular products funded on crowd funding sites such as Kickstarter, which allow consumers to play an active role in funding products and provide design feedback.

2.1.2 Materials and Technology

The amount of individual technologies related to the process – used for manufacture or rapid prototyping - is staggering with massive list of acronyms defining ever minuscule differences between how shapes are created. To help organize these technologies different stakeholders categorize them into lists based on varied shared properties amongst the technologies. Some of these focus on material inputs – powder, resin, filament – while others focus on the equipment or process. The classification used in this thesis is based on how the material is processed – curing, fusing, and extrusion. Curing based systems initiate a chemical shift in the raw often liquid material via a light source – laser or projector. A fusion based system bonds raw material often in the form of a powder with directed heat or a binding agent. Extrusion systems, which are the focus of this thesis, liquefy the raw material and extrude it through a nozzle.

Just as design for injection molding and blow molding, require different designs, but also have similarities like draft for mold release, designing for each form of digital additive manufacture also has similarities and differences in design requirements per unique process variation. Each technology category has its strengths and weaknesses with varied industrial uses. Curing systems have been used to produce optical lenses (Form Labs, 2014) to show off their high resolution capabilities, fusing systems are being used to produce metal parts for rocket engines (Kraft, McMahan, & Henry, 2013), and extrusion systems are creating biological parts for the medical industry (Seol, Kang, Lee, Atala, & Yoo, 2014). Beyond these exotic examples the technology most used around the world is extrusion based systems (Gibson et al., 2010).

Equipment in the extrusion category often has an advantage in operation as they use common thermoplastics, and use non-specialty tools for post-processing – picks and pliers. The plastics used in extrusion systems can release VOC's and nanoparticles during processing, while plastics such as PLA (poly lactic acid) are gaining popularity and should minimize possible health hazards. PLA nano-particles are used in drug delivery by pharmaceuticals and are deemed safe as PLA breaks down into lactic acid in the body which is then converted into glucose (Mahapatro & Singh, 2011). Scrap parts produced via extrusion can be recycled into new filament via shredding and extrusion. The extrusion process has been used for one-off models,

small manufacturing runs (Hopkinson et al., 2005a) and for the production of manufacture and assembly tooling (Stratasys, 2014).

2.2 Technical Considerations

In order to develop these competitive capabilities many technical factors must be considered and tested.

2.2.1 Design for Extrusion-based Digital Additive Manufacture

Much research into part design related to additive manufacturing is presented as a comparison to how the part would be designed and manufactured with other – often injection molding – techniques. Two key areas of research are on the design freedom these new digital processes allow for manufacturing and research conducted into understanding the limitations of rapid prototyping technology.

Anatomy of a 3D printed part

In order to understand the unique design freedom and opportunity that 3D printing affords, it helps to understand the typical 3D printed part anatomy. A designed part is created with several key structures – shell, core, and external support – that are made up of controlled material extrusion. These extrusions have a controlled height and width; the speed at which they are created is also controlled. Adding design intent to these structures through designing the extrusions allows for greater control of structural properties and material use (Basic Energy Sciences Advisory Committee, 2012). The structures unlike those found in injection molding can vary based on how these extrusions are used to deliberately design the internal structure

of the part. It could for example have an internal honeycomb structure. These intermediate design structures are described as mesostructures. The equipment's extrusion tooling and positioning system must work together to create controlled extrusions based on the design's CAD file and CAM profile that make up these key mesostructures.

Figure 2: 3D printed part anatomy

By designing mesostructures a designed part can use fewer resources to create - material and time - by understanding design decisions effect on structure and drawing inspiration from nature. For instance a part can draw inspiration from a bones structure by applying a strong shell with decreasing density towards the core, allowing for a lightweight and strong part. With further knowledge of the process and part requirements each individual extrusion could be designed to counteract applied forces with the minimal amount of possible material for the application, while maintaining the same macrostructure that interfaces with other parts or with people.

Design Constraints

While research into “design freedom” creates excitement around the process and allows designers and the general public to imagine a new way of making the manufactured world, many constraints still exist on its wide spread application. These restraints are often viewed as technological issues that must be overcome with better technology. However, as history has shown with the development of plastics and injection molding (Nyborg, 1993), apparent technological issues may require a better understanding of how to design specifically for the process.

Research into designing for the process thus starts with an understanding of some of the known considerations inherent with the DAM processes. A staircase effect will appear on curved surfaces producing an aesthetic flaw (Hallgrimsson, 2012). The support material must be removable which limits possible geometries. Part orientation / number of layers affects the print time of a part (Gibson et al., 2010). Mechanically parts are anisotropic (Rodríguez, Thomas, & Renaud, 2003), with around 80% the strength of injection molded parts. However they can have thicker hollow walls similar to laminated plates or cardboard drastically increasing their strength (Dieter, 1991).

2.2.2 Equipment Design and Operation for Extrusion-based Digital Additive Manufacture

Equipment design, operation and maintenance are often seen as key areas of development for the technology, which according to the authors (Hopkinson et al., 2005a) should enable absolute freedom in design. This thesis takes a contrary view,

with the approach of better understanding the current technology and process behind this new manufacturing method, to enable design research and equipment developments based on use. Literature on basic engineering principles behind core equipment functions such as motion and temperature control are used as the bases for iterative design research and reliability testing, since methods to create better equipment are generally trade secrets or unorganized and sometimes contradicting posts on online open source hardware forums.

Equipment Overview

The research equipment's original design started with an open source RepRap 3D printer model based on designs by Printbot - Figure 3. The equipment is broken down into three main components the extruder, print surface and positioning system - Figure 4. Each component is powered and controlled by the systems electronics and power supply. The printer's extruder is further broken down into the cold-end that controls the material feed rate, and hot-end that liquefies the material. The equipment researched is a 0D system meaning it processes a single point at a time – 1D systems process a line and 2D systems process an entire layer at once (Hopkinson, Hague, & Dickens, 2005b). This type of positioning system - 0D - relies on a positioning system to move the extrusion tooling or print surface between X,Y,Z points in a Cartesian grid. This positioning ability is combined with the capability of loading material into a liquefier that forces it through a die. Once extruded the material binds with previous laid extrusion - part or support material - and solidifies in a controlled manner (Gibson et al., 2010).

Figure 3: Printrbot (Gordon Wrigley, 2010)

Figure 4: Research Equipment

Stepper Motors

An understanding of stepper motor function is necessary in the design and operation of DAM equipment. These motors are used in both extrusion tooling and positioning systems in most RepRap/ low cost machines. What sets stepper motors

apart from other motor types is they do not freely turn when power is applied but step to the next position and wait for another signal to make the next step. A combination of these steps and the other mechanical linkage of an axis determine the minimum distance of travel – its resolution – which directly influences what layer heights are reachable without causing inaccuracies (Prusa, 2014). To control these steps an extra electronic board is needed which turns pulses from a microcontroller into current to the motors coils (Platt, 2012). Stepper motors are often used in what is referred to as an open-loop system. Unlike a closed-loop system – one that uses servos or encoders – an open loop system has no feedback. Accordingly the system does not know if it missed a step or overstepped, and thus there is no correction resulting in possible accuracy losses.

As stepper motors move faster the torque they can produce is lessened (Condit & JONES, 2004). This affects the design of faster machines, as they must use larger motors or reduce the forces acting on the motors. These forces are from mass inertia and friction for positioning motors and backpressure forces for the extruder motor. Stepper motors also have a limitation when moving at lower rates of motion as micro-stepping dead zones exist – caused by low holding torque and static friction – which cause inaccuracies (Condit & JONES, 2004).

PID Temperature Control

PID control stands for Proportional Integral Derivative control and is used to accurately control system variables through feedback signals from a sensor. This is

used to control the temperature of the heated print surface and extrusion tooling. Each proportional, integral and derivative value – K_P K_I K_D – is dependent on the machine's design and is defined in the printer's firmware. When tuning the controller a higher K_P value increases the response to temperature variations. The K_D value is used to dampen the response and the K_I value is used to correct for offsets when at a steady state (Johnson & H.Moradi, 2005). The firmware used during testing can auto generate these three values through a test process on each component controlled.

Errors arise with the use of large thermal masses as a printing surface (e.g. borosilicate glass surfaces). These materials provide a buffer between the surface temperature and sensed temperature or between a PID control signal and feedback – depending on sensor placement.

Environmental control

Several environmental factors can affect the material being loaded into the extruder, most notably dust and humidity. A buildup of dust or other particles can lead to clogging of the extrusion nozzle, while excess water absorbed by the filament from humidity changes its dimensions leading to inconsistent extrusion rates along with pot marks from the water rapidly expanding due to the heat applied to create viscous flow for the extrusion process. These environmental factors not only affect the extrusion system but also the positioning system – as particle buildup on the rails causes excess friction – therefore it is best to limit the sources of dust and

humidity in the environment the machine will operate rather than attempting to filter out the environmental contaminate at the locations it will do harm. This method aligns with ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards for removing air contaminants which states that the most effective way of reducing indoor air contaminants is source control, followed by dilution with ventilation, and lastly filtration (ASHRAE, 2001).

2.3 Design Challenges

Currently manufacturing positions in Canada account for 15.35% of the total labour force. Statistics shows that the majority is employed in a small to medium enterprises accounting for 84.40% of total manufacturing jobs. With 18.75% of Canadian manufacturing positions being offered by companies that employ 1-19 people (Industry Canada, 2013). These small firms can augment their production abilities with the assistance of robotic or other advanced manufacturing technology increasing productivity and competitiveness.

The use of digital additive manufacture can enable the rapid design and manufacture of bespoke items, small manufacturing runs and production tooling, allowing a firm to be more competitive. As digital additive manufacturing allows for digital controlled production, these systems can be integrated with other computer systems – such as modern e-commerce networks. The integration of computers and manufacturing in this way is called Computer integrated manufacturing (Gilles, 1999) and can allow for a leaner manufacturing system that autonomously

produces goods on demand. If the country's manufacturing future relies on small to medium enterprises, then a great number of small firms could produce the expanding variety of niche products the market is beginning to demand.

To obtain this goal accessible equipment must be understood through motion studies. These studies will allow part design and machine design to be developed around the technology's "natural" abilities and motions. By doing so the equipment and design process will become more reliable and repeatable leading to more accessible consumer products.

3 Research Objectives And Methodology

To discover ways in which design can improve the competitiveness of digital additive manufacture two questions are asked:

Q2: What design considerations are required to produce cost effective and functional parts with digital additive manufacturing?

Q3: How can equipment design and operation be improved for lower-investment manufacturing?

These questions investigate how design can influence improvements in the physical artifacts produced and how the process of manufacturing can be improved through analysis and redesign. These two areas of interest are framed in Figure 5 showing the area of research as a combination of material processing, computer numerical control, and product design. The two intersecting areas of research are defined as *Equipment Design And Operation* and *Design For Digital Additive Manufacture*, with the ultimate goal of creating better equipment and defining to a greater depth design guidelines for the extrusion-based digital additive manufacturing process.

Figure 5: Conceptual Framework

These areas of intersection were researched through various methods and approaches. In some cases parts were built to investigate and extend the limits of part design as currently possible with 3D printing. Some of these parts push the equipment's limits and are investigated as opportunities to further improve the process. As an example the issue of material utilization, was researched through design, by printing parts where support material and infill was reduced or eliminated. Additionally techniques such as printing parts with metal inserts provide an opportunity to adapt low cost RepRap parts and designs for reliable and accessible manufacturing. Additional technical studies on the limits of extrusion

width and height were complemented by research through design of a guitar pick and earrings (parts that normally would break easily when 3D printed). Standard engineering ASTM tests were also employed to investigate the functionality and variation of mesostructure control.

3.1 Research framework

The research questions examine how the extrusion-based DAM process can be better understood to improve the design of parts produced by this manufacturing process and how the equipment can be bettered through analysis and redesign. In order to accomplish this, the areas of intersection shown in Figure 5, are systematically investigated through various methods and approaches. An iterative experimental procedure is required to assess and evaluate the various variables involved in the design and manufacturing of parts utilizing the extrusion-based DAM process. This procedure is shown in Figure 7.

3.1.1 Objectives

As stated the two main objectives of the research areas are to create a better understanding of the design process required and to develop low cost equipment for manufacture from 3D printer components.

Design for extrusion based digital additive manufacture

- Increase accuracy and speed through design for manufacture
- Investigate layering
- Reduce support / part material use

- Investigate profile design
- Investigate mesostructures

Equipment design and operation

- Increase accuracy and speed through equipment design
- Create reliable and capable extrusion tooling
- Minimize solidification errors
- Create reliable printing surface
- Create low cost, scalable positioning system

3.1.2 Test Methods

One or multiple test methods are used during the research procedure (Figure 7) per test. These test methods are introduced in the current section, with their application discussed further in Section 3.2, Section 3.3 and Section 3.4.

Research through design

The use of iterative design, including recorded observations and experiments is considered the act of conducting research through design (Martin & Hanington, 2012). The process and output of design is used as a means of research and test method for both part and equipment design. This ensures the results stay relevant to the field of industrial design as the design process is guiding the research. These designs attempt discover possible issues in the process to be improved upon. The

issues are observable during the production stage or are shown during reliability testing.

Direct Observation

Observations of the process, part and equipment are made by directly observing the process, with further data collection via timers, video recordings and the analysis of the parts G-code (which acts as an experiment procedure log). These methods allow for the analysis of possible errors by providing information on the motions and timing of the tooling. This information is used to better understand the digital control systems “natural” abilities allowing for the creation of better CAM profiles (sets of instructions for the digital laborer). These observations and understandings also inform part and equipment design.

Reliability testing

Reliability testing is used to determine how a process variable - Figure 8 - or mesostructures - Figure 9 - affect a part or system. Failures are found by stress testing and using the HALT methodology (Hobbs, 2000). Once analyzed and iterated upon parts are retested to help determine design guidelines.

ASTM method

Tensile testing is used to determine the effect of a part’s mesostructures on its tensile properties. A test coupon is designed and tested in a load frame to the ASTM D638-10 standard (ASTM International, 2013) with internal grip modifications to

allow successful low density testing. The results from these tests are analyzed and provide valuable quantitative data for the mesostructure design process.

Figure 6: ASTM tensile coupon in testing equipment

3.1.3 Procedure

The research procedure displayed in Figure 7 allows for an expansion of the literature with many quick studies that focus on a small development issue or opportunities. The development issues are also generated from observed issues during product development studies and during studies of features or equipment, allowing the design and manufacturing processes to guild the research.

The procedure starts with opportunities from the literature and initial use observation that are tested using one or multiple of the test methods (Section 3.1.2). If the test study works then it is added as a solution towards the thesis questions. If not the procedure moves into the *Problem Definition* section, which draws in information from previous studies and literature to develop possible solutions. The list of possible solutions are tested in the *Solution Testing* section of the procedure with complex design problems being tested at the component level and then the

part or assembly level. Once a possible solution passes these tests it becomes part of the appropriate thesis section and leftover possible solutions are added to the opportunities list. Of the many test cases this procedure produces, some have little influence on the final results and are not discussed in Chapter 4; these cases are shown grayed out in Table 1 and Table 2.

3.2 Manufacturing competitiveness through interdisciplinary research and design

The interdisciplinary research conducted allows for on demand design and manufacture along with iterative design and testing of both products and production equipment.

3.2.1 On Demand Design and Manufacture

New designs and the equipment itself can be tested for failure by subjecting manufactured prototypes to excessive forces. Such as strumming a table with guitar picks, running a printers axis at 4x its normal max operating speed – Figure 8 – or stressing a mount in a c-clamp - Figure 9 - to reveal design flaws.

Figure 8: Failed electrical connection while stress testing a pulley at high speeds

Figure 9: Reliability testing a 20% infill mount as part of the iterative design process

New products can go from the concept to low scale-manufactured state within an afternoon, as done with the Canada Day earrings displayed in Figure 10. These designs can then be tested in the market and production scaled up on the same machine as needed. The earrings without any more iteration or extra equipment could be scaled up to produce 630 pairs a month to meet demand (assuming 6 hours of production a day for 21 days, with 10.42 minutes print time and 1.58 minutes downtime between prints).

Figure 10: 12 pairs of earrings designed and manufactured on Canada day

3.2.2 Iterative Equipment

By utilizing open hardware a designer gains the ability to iteratively modify their manufacturing equipment to match their unique needs at a given time. By starting

with inexpensive equipment and an understanding of each of its components' functions these designers are also able to scale up production with little extra investment.

Figure 11: Cooling fan added during print operation

Upgrades are designed and tested rapidly with the use of simple and quick design techniques such as paper prototyping. These materials can be combined with basic printed parts when needed to further iterate the upgrades. Each iteration can be put into use on the machine such as the blower design in Figure 12 with components upgraded or modified based on in use observations.

Figure 12: Paper functional and looks like prototype (top), steel blower (bottom)

3.3 Design for digital additive manufacture studies

Research into design for digital additive manufacture is driven predominantly by the research through design methodology. These designs are meant to understand the limits of the technology and the best methods of design based on these limitations. Some of these limits are investigated further as equipment design and operating limits in section 3.4. Direct observations and reliability testing are used to test each experimental case with ASTM tensile testing informing mesostructure design. Design for digital additive manufacturing's main objectives are:

- Increase accuracy and speed through design for manufacture
- Investigate layering
- Reduce support / part material use

- Investigate profile design
- Investigate mesostructures

Table 1: Design for manufacture development studies / opportunities list

Study Name	Study Type	Conceptual Framework		
		Equipment	Tool-path	Part design
Layer Design				
Layering calculator	Numeric Modeling			X
Guitar Pick	Design	X	X	X
Gang Head Study	Feature	X	X	
Metal Inserts	Feature		X	X
Slicer layering study	Test		X	X
Bike Generator	Design		X	X
Circuit board snap fit	Feature		X	X
Scaled Furniture	Design			X
Card reader	Design		X	X
Support Design				
ASTM Surface	Feature			X
Go-Pro Mount	Design			X
Self-supporting perimeter	Numeric Modeling			X
Ripple earrings Bio-support structure	Design		X	X
Bag Man keychain	Design			X
Bike Pedal Cap	Design			X
Profile Design				
First layer speed modifier	Feature	X	X	
Extrusion Ratio Tests	Feature	X	X	
Bio earrings	Design		X	
Ripple earrings	Design		X	X
Z-axis frame mount	Feature	X	X	
Bearing C clamps	Feature	X	X	X
Cornering test cubes	Feature	X	X	
Radii Acceleration	Numeric Modeling		X	
Canada day earring	Design			X
Cookie cutter	Design		X	X
Mesostructure Design				
Half Cubes Parameter Test	Feature		X	
ASTM CAD/CAM Strips	Feature	X	X	X
Cold-end tensioner	Feature	X	X	X
ASTM Internal Study	Feature	X	X	X
ASTM Dimension Test	Feature		X	X
Extrusion width test	Test	X	X	
Slicer layering study - dimensional	Test		X	X
Furniture Hardware	Design			X
Dew claw protector	Design			X
Ikea shelf hooks	Design			X

3.3.1 Layer design

To investigate the layering process' effect on design many small experimental parts are designed and created. As with many of the studies throughout this thesis, formula are devised and a calculator created from them to assist in the design process and experimentation. This calculator is used in the design of many parts including a hollow guitar pick, created to research thin parts – with layers of 10-50 micrometers (0.01-0.05mm) thick.

Figure 13: 0.9mm thick Guitar pick with 10 to 50 micron layers

Through accelerated reliability testing – strumming the guitar pick against a table - and research through design the design evolved through several iterations to create a reliable printed guitar pick – eight major reliability iteration. These tests are followed by another round of iterations to lower the print time – six major commercial iterations. During these iterations key variables that created a reliable mesostructure included a honeycomb infill, the direction of the infill, extrusion height and width experimentation for the shell and core of the part and experimental manipulation of the top and bottom solid layer thickness. Beyond part

redesign to lower print time a study is conducted on the use of packs – many of the identical item printed at once- and analytical research conducted on the use of gang heads – multiple print heads working simultaneously on a single machine.

Two more studies are conducted into layer design accuracy to help inform the design process. A metal nut insert is investigated as a means to accurately integrate non-printed features into part design, opening opportunities for low cost mechanical fasteners and embedding electronics inside parts. The creation of layered radii is also observed throughout many experiments and defines how these part features are designed for.

3.3.2 Support Design

With the goal of reducing support material use and print time direct observations are made from multiple experiments and several experiments are design and run specifically for support design. The ASTM test specimens – created for mesostructure design - are analyzed to determine the effectiveness of infill and solid layers as support structures. A GoPro mount is experimentally iterated to investigate the use of perimeters as self-supporting structures, resulting in equations and a calculator to assist in the design process. Lastly external support design is investigated with a fragile earring design – ripple effect earring – and an experiment is run to determine a form of biologically informed external supports.

3.3.3 Profile Design

Profile design is investigated through extrusion ratio tests, first layer speed modifiers and observations of printed objects to determine the design of first layer profiles. Also investigated is the creation of thin features through several product design experiments. Several studies are conducted on how the use of radii affects a parts accuracy and speed.

3.3.4 Mesostructure design

Basic mesostructures are investigated with half printed cubes that have varied infill densities, extrusion widths and height, along with perimeter count. These parts determine the basic effect these parameters have on a printed objects shell and core. This knowledge is expanded with the design of tensile specimens and tensile experiment following the ASTM D638-10 standard. These specimen are tested in an engineering load frame with results and fail characteristics analyzed to determine how different mesostructures affect a parts mechanical performance. This data is combined with recorded data on material use and time spent per test specimen and compared against a standard 30% test specimen to provide a deeper insight into mesostructure design. Data on the mesostructure of the standard specimen is in Appendix C.

3.4 Equipment design and operation studies

Equipment design and operation research is predominantly driven from direct observations during design for manufacture studies. The studies arise from noticed errors when producing parts that appear to be coming from the equipment or that

can be alleviated with equipment modifications. Possible solutions are designed and tested in use and under accelerated conditions to ensure reliability and further the equipment's design through failure. Equipment design and operations main objectives are:

- Increase accuracy and speed through equipment design
- Create reliable and capable extrusion tooling
- Minimize solidification errors
- Create reliable printing surface
- Create low cost, scalable positioning system

Table 2: Equipment development studies / opportunities list

Study Name	Study Type	Conceptual Framework		
		Equipment	Tool-path	Part design
Extrusion tooling				
Filament spool hub	Feature	X		X
Filament drive	Feature	X		
Cold-end tensioner	Feature	X	X	X
E-motor cooling	Feature	X		
Hot End Design	Feature	X		
Extrusion model	Numeric Modeling	X	X	
Extruder test	Test	X	X	
Fan controller	Feature	X		
Solidification Control				
Part Cooler	Feature	X	X	X
Heated aluminum surface	Feature	X		
Bed insulation	Feature	X		
Electronics Cooling	Feature	X		
Printing Surface				
Z end stop	Feature	X		X
Locked setscrews	Feature	X		
Automation G-code	Feature	X	X	
Surface Texture	Test	X		
Expansion coefficient release	Feature	X		
Extrusion ratio calculator	Numeric Modeling	X	X	
Cat earrings	Design	X	X	X
Positioning System				
End-stop Mounts	Feature	X		X
Cold-end mass alignment	Feature	X		
Frame Mounts	Feature	X	X	

Axes lubrication	Feature	X		
Steel Frame	Feature	X		
Axis stress Test	Test	X	X	
Locked T5 Pulleys	Feature	X		X
Z coupler shield	Feature	X		X
Bearing C clamps	Feature	X	X	X
Cable drive	Numeric Modeling	X		
Printed Bushing	Feature	X		X

3.4.1 Extrusion tooling

Extrusion tooling is investigated with the goal of increasing reliability and the tooling capabilities. To accomplish this the tooling is broken down into four main functional components, material loading, cold-end, hot-end, and fan control. A long-term study is conducted on reducing the backpressure applied by the unreeling action of the material from the spool with a *filament spool hub* created to alleviate pulsation in the feed material. To maximize the forward force applied by the cold-end the drive gear is redesigned, along with the cold-ends tensioner, which applies force against the filament pushing it into the drive gear. Both these components are tested with the extrusion calculator developed for the purpose of tuning the extrusion steppers current and the pressure applied by the tensioner. To increase the hot-ends reliability – reduce the number of thermal plugs – three thermal design concepts are tested – insulated, low conductivity and varied conductivity – with the insulated design being commonly used at the beginning of research in the field.

3.4.2 Solidification control

To minimize solidification errors design experimentation and reliability testing are conducted on print cooling and print heating. The design of print coolers is investigated to increase print accuracy of newly printed layers. Part heating is

investigated to reduce thermal stresses in a part, which cause poor surface adhesion and warping, along with the reduction in power consumption with the use of an aluminum print surface and insulation. As the solidification control systems requires the highest switched current of any sub-system the cooling for the associated electronics is investigated through design.

3.4.3 Print surface

The print surface is investigated with the goal of creating a reliable adhesion surface. The surfaces leveling equipment – Z end stops and setscrew – are investigated along with the leveling process. The surface texture is investigated through use during design for manufacture experiments and through microscopic observations to determine effective and low wearing surface textures.

3.4.4 Positioning system

The positioning system is iteratively designed through in use testing and accelerated axes stress testing to determine which components require a redesign. Any upgrade work tries to use printable components or commonly available materials such as angle iron over aluminum extrusions. The two areas of research are, increasing structural rigidity and reducing the position forces. The use of a steel frame, with printed frame mounts is investigated along with locked T5 pulleys, all to increase the positioning systems rigidity. Forces are reduced through lubrication experiments, the design of Z coupler shielding, end stop mounts and an extrusion tooling redesign to better balance the moving mass.

3.4.5 Maximum print speed

A calculator is developed as a combination of knowledge in extrusion tooling and positioning which allows for the design of maximum print speed tests. These tests are conducted to determine the machines maximum stable operating parameters. These tests are also designed to stress test the equipment's components to guide further iterative equipment development

3.5 Variation in Research Methodology

Changes arise in the research methodology as not all variables are controlled. This is due to the environment and equipment of the study changing between design studies as the machine is being evolved along with design considerations and seasons changes – temperature and humidity. Another source of variation between studies is the use of newer slicing software that fixes bugs in previous versions but also changes feature sets and how objects are processed into G-code commands. Other small sources of variance are caused by material consumption from the spool and material irregularities.

Controlling these variables would be too difficult with the available resources or would focus iterative development on software glitches or details that have been solved through software updates. The research results would also be limited to optimal conditions with a perfect full role of material and an even temperature room, which is not always the case when using the technology.

4 Results and Discussion

The following chapter presents results and discusses the resulting design considerations for the correct use of digital additive manufacture as resulting from directed and exploratory research. From design details to create stronger parts in less time to equipment design and operation for reliability and greater capabilities.

4.1 Design for Extrusion-based Digital Additive Manufacture

This section presents results from research into the product design process for additive manufactured parts, showing that low-resolution equipment can produce highly accurate parts in less time, that printed parts can have a consistent surface, support material is often not needed, machines can profile faster, and structural properties can be tuned all through designing for the process specific properties.

Basic mesostructure variables

To determine how parameters which designers have control over affect the process half cubes - 10mm cubes printed with no top half as to see internal structures - were created with varying infill density, layer height, extrusion width, and perimeter count. Infill, layer height, and perimeters modify the profile as expected. The application of a thinner extrusion width also creates more infill extrusions. This is the case, as halving the extrusion width requires two times the infill extrusions to match the same infill density. The use of smaller layers or increased infill both increases print time. The addition of another perimeter reduces the infill area. These

variables are discussed in Appendix D and further explained throughout the chapter.

4.1.1 Layered Design

Extrusion heights, design features and mesostructures must be designed as multiples of the selected layer height to insure accuracy – as layer heights must be a multiple of the equipment’s resolution to avoid inaccuracies caused by unreachable destinations. Doing so requires intent on the designer’s part as to which machine properties will be used while manufacturing their design. Alternatively their design could be modified at the manufacturing level by a modern equivalent of a mold designer. When features align with a machine’s layer height they are processed quicker during the slicing stage and can be printed in less time as dimensional accuracy can be achieved without the use of high resolution – thin layers – leading to cheaper and more accurately produced parts.

Figure 14: Two designed dimensions being shifted to match the closest layer

As CAM software automatically shifts a designed surface towards the nearest layer an inaccuracy of up to half a layer height can occur at the G-code generation stage before reaching the manufacturing equipment. This can be solved by reducing the layer height – raising the resolution – to reduce the error caused by misalignment or in extreme cases raise resolution to a point that layer heights are smaller than any

desired increment; however this leads to expensive equipment and longer print times. As an alternative the Z-axis dimensional accuracy can be improved by a designer aligning each feature with the nearest layer multiple, reducing inaccuracies while using a lower resolution machine, producing parts with fewer layers and reducing print time. This also reduces CAM processing time as the software has fewer calculations to make in approximating the design.

The tool shown in Figure 15 is developed from layer design research to help align design features with layers and layers with machine capabilities. It also takes into account the simple mesostructure property of solid layer thickness for the layered shells of parts and suggests the closest alternative dimensions to the designer's intent. For example, a 1.90mm feature height would produce an inaccuracy of 0.05mm so the alternatives of 1.80mm and 1.95mm are suggested based on an extrusion height of 0.15mm. The calculations that this tool is built on could be built into CAD software such as Solidworks to accelerate the design process.

Layering Calculator V1 (2014May8)						
Step Length	EH	Solid Layer	Feature	Infill		
1.25 mm/Rotation	0.15 mm	0.25 mm	1.90 mm			
200 Steps/Rotation	0.1500 mm	0.30 mm	low 1.80 mm	8 layers	1.20 mm	67%
0.00625 mm/Step	24 Steps	2 layers	high 1.95 mm	9 layers	1.35 mm	69%
16 Microsteps/Step						
0.00039 mm/Microstep	384 microsteps					

Figure 15: Layering calculator

Thin-layers

The above tool helps reduce the number of required layers for a design by increasing the layer height to the maximum a design will allow. The tool also has an important use when designing parts that require thin layers to meet project

requirements – high tolerances, mechanical, etc. The importance of layers being multiples of the machine's resolution increases as the chosen resolution approaches the machines limit – as possible Z-axis errors can account for a larger percentage of desired movement.

Most of the research in thin layers in this thesis comes from experiments related to the guitar pick project. During this project it was found that multiple thin layers perform better than larger layers. These results align with composite literature into thin layers. When iterating a design's layer height it is important to modify the number of solid layers the CAM profile uses for the top and bottom of the part as four layers are required at 0.1 mm layer height to equal two layers at 0.2 mm layer height – this effect increases drastically as layer height lower into the tens of micrometer range.

As discussed in detail Section 4.2.2, the process will lower print speed to allow enough time for each layer to cool and solidify before the next is printed. This increases print time particularly on parts created from a larger number of layers. As a greater number of layers produce a more reliable guitar pick, packs of 9 picks can be printed at once allowing the process to operate at full speed and allow enough time for each layer to solidify. These packs take a greater amount of time to print (~37 min) than an individual pick (5 min). Printing in packs allows for a timesaving's per pick of ~1 min or ~9 min time savings over printing each pick individually.

Figure 16: Printing in packs for faster feed rate

Longer print times can also be reduced in manufacturing with the use of multiple print heads on a single machine – gang heads – which reduce individual part costs for production by creating multiple identical parts at once – parallel production. By adding a second print head and surface, the same pack of guitar picks can be printed in ~2minutes per unit, a third head allows for ~1.3minutes per unit, and so on. The benefit of adding more heads on unit cost is diminishing, making a large number of gang extrusion heads viable for longer prints or to increase production scale.

Figure 17: Diminishing returns of added gang heads

Integrating non-printed features

As the DAM process can build intricate internal features into parts - with minimal additional cost incurred by the added complexity – an opportunity arises to insert non-printed objects, partway through prints for added functionality. These added parts can allow for a stronger assembly by adding objects like bolts, or allow for added interaction by adding electronic parts such as LEDs or temperature sensors.

Again the use of layer multiples allows for easy integration of inserts as parts offset from layers can produce a cavity that is too small for the insert and create a collision between the part and hot-end during production, or it will produce a cavity which is too large, not holding the part securely.

Figure 18: Inserts and Layers

The process of inserting non-printed parts consists of modifying the G-code to pause the print at the top of the designed cavity, retract the filament – as to avoid oozing of molten plastic onto the part - and move out of the way. At this point the insert can be manually placed or an automated tool can be used to pick and place the inserts. The tool must then be moved back into place, the filament pushed back into the hot-end and the printing process continued (Figure 19).

Figure 19: Insert Process (top), paused print with inserted nut (left), finished print with captive nut (right)

Layered Radii

The process creates all radii in the Z-axis by offsetting consecutive layers - Figure 20. Designed features must take this into account to reduce the staircase effect by creating larger radii - that are larger than a single layer. Smaller radii are created with the use and design for thinner layer height, however this will increase the production costs.

Figure 20: Layered Radii

This is an area of rapid advancement, as older version of slic3r – from 2 years ago (2012) - would create a hole and a partial part failure. However the newer versions fill in the area below the radii with a solid layer and ignore smaller radii. This is an example of when design suggestions to avoid failure can be automated into software tools. Beyond changing the dimensions of layers or radii splines can be used to produce curved surfaces that balance design intent and process capabilities. This is discussed in greater detail in the next section.

4.1.2 Support Design

Key to designing support material is an understanding of how the process is going to build your part and which areas will potentially fail. A printed parts surface is either internally supported with infill, self-supported with solid layers or perimeters, externally supported with removable material, or a combination of. Understanding these methods and iterating with prototypes allows for smoother and stronger surfaces while reducing production costs.

Infill

A parts' infill is an internal support structure for solid layers above it and provides strength to the part. A denser infill provides greater support for solid layers while lower densities such as less than 10% infill do not provide adequate bridging support. These parts must rely on the machine's ability to bridge gaps – discussed in section 4.2.2- and on the self-supporting nature of multiple solid layers.

Solid Layer

Solid layers are capable of bridging wide gaps with little to no support – Figure 22. Each successive layer adding support to the next increases the surface quality from an unacceptable level to a smooth finish. To better communicate this style of support a construction metaphor is used. When a floor is built, floor joists, which are equivalent to the 1st layer type – Figure 21 - are used which are spaced apart and span large distances while providing support for a floorboard. The floorboards or 2nd layer type placed above in turn provide support for a decorative 3rd layer.

Figure 21: Layer support classification

Just as floor joists are not considered a desirable ceiling feature in housing an exposed under side of a 1st layer type is often inconsistent and should be avoided on parts or limited to non-aesthetic sections of a part (as done in Figure 22). A designer can increase the surface quality by increasing the layers support by other means

such as greater infill - for non-overhanging surfaces -, self-supporting perimeters or external supports.

Figure 22: Surface defects from extended bridging

Self-Supporting Perimeters

When a surface is not located above its internal structure but rather overhanging, support strategies such as solid layers or infill are not practical or possible. The next design consideration for creating supported surfaces is in using the perimeter as an integral support structure. Similar to bridging gaps, the limit on self-supporting perimeters is dependent on a machine's ability to rapidly cool molten extrusions. A greater cooling ability allows for a higher surface quality at a larger step over - a smaller overlap with the previous layer. Greater step over abilities can produce curves that are closer to the horizontal plane as shown in Figure 23.

Figure 23: Varied curves and resulting overlap percentages

Figure 24: Failed step-over rate (e) and one solution (f) to obtain a similar curve

The limit of 0% overlap can be overcome with self-supporting perimeters by modifying the parts intended extrusion height and width. Shown in Figure 24 the same angle can be produced with a greater overlap between layers by using a smaller extrusion height. The same effect is achieved by extending the extrusion width within the capabilities of the machine. These options can be explored by using the calculator and supporting material shown in Figure 25 which is based on the equations $[Tan \theta = (Extrusion \ Width \times (\%Overlap/100)) / Extrusion \ Height]$ and $[\%Stepover = (1 - (\%Overlap/100)) \times 100]$ developed during this thesis.

Figure 25: Self-supporting perimeters calculator

A redesign using both solid layers and perimeters can create an exposed 1st layer type – Figure 21 – that is consistent. This has been done on the hot mount shown in Figure 26. In which the self-supporting perimeter was used to reduce the distance of unsupported extrusions.

Figure 26: GoPro video camera printed mount version 1 (top), iterative design process from version 1 on the left to the self-supporting surface on version 3 (bottom)

External

The use of external support should be minimized through the already described methods above as its use increases the amount of material used, print time, and post-processing labor. The design of external support material is a complex task that involves designing many temporary parts. Limited design intent can be given to

automatically generated support material in the CAM phase or designed for with the part in the CAD phase of design.

The support structures created must not be stronger than the features it supports as this increases part damage during removal. Each of these temporary parts ideally must not fuse with the intended part but provide support for it. Creating supports that have undesirable part properties such as thin extrusion widths, low density, few solid layers, and little inter layer adhesion can do this. If the support material is made to weak via the mentioned methods it will provide inadequate support.

Figure 27: Biologically informed support material, version 1 (left), version 2 (right)

Applying knowledge of support design to manually written G-code can produce novel support structures that mimic nature. Shown in Figure 27 are two prototype support structures that mimic a spider's dragline that reduces both print time and material required to support the design. These biologically informed support structures are created with the help of the tool shown in Figure 28 that calculates extrusion rates. As this support material is not automatically designed or coded the use of this support style is limited due to the greater design and coding time/skills required in its creation.

EH	EW	E Length	Material Needed (mm ³)	Fillament D (mm)	Extrusion Length Needed (mm)
0.2	0.6	19	2.28	1.7018	1.00237
		84	X1		
		0	Y1		
		103	X2		
		0	Y2		

Figure 28: Extrusion Calculator for Biologically informed support

4.1.3 Profile Design

Like when building a house the foundation or first layer profile is important to the print's success. To succeed the profile must adhere to the print surface and allow for removal of the part once complete. The extrusion ratio, print speed, and surface area of the first layer profile all influence adhesion and part removal. The effect of surface features on adhesion is discussed in section 4.2.3.

If greater adhesion is required and the equipment/design allows for it, a shorter and or wider extrusion can be used. Extreme extrusion widths also affect inter layer bounding as thin extrusions have a weaker bond and can make a part flexible, thicker extrusions have a stronger bond but at an extreme cause collisions and nozzle wear from the excess material oozing upwards.

Figure 29: Extrusion Ratio

These ratios also apply to part design as a short wide part has a greater surface area in contact with the bed, creating a stronger bond. A sort part also reduced the torque applied to the bond between the part and bed – $\text{torque} = \text{length} * \text{force}$ – reducing print failure when the extruder bumps the part, while making the part harder to remove when complete. A part can be made artificially wider with the use of a brim that adds extra material around the first layers profile to increase its surface area. The use of brims should be avoided as they add extra material, print time, and add a step in post processing.

Parts with thin sections like the earring displayed in Figure 30 are difficult to remove without causing fractures in the thinner profile sections. Such parts should be modified to have an even surface adhesion. This can be done by cutting out the center of each solid section for the first layer, creating a hollow void under the raised section of the earrings.

Figure 30: Algae inspired earrings

More important than the extrusion width or extrusion ratio is the speed at which the layer is placed. If too slow, time is wasted, but if too quick the nozzle collides with previous laid extrusions causing defects. Increased rigidity in the positioning

system, can allow for faster first layer movements. Faster movements can also be made through G-code modifications made manually to the acceleration (M204 S5000) and travel move feed rates (F6000) for all first layer moves. This is required to reduce travel moves to the speed of extrusion moves, as a fast travel rate on the first layer causes previously laid extrusions to become dislodged from the surface.

Thin features

Every feature's profile is made up of a perimeter section with a core of infill at varied densities. The width of the perimeter section is dependent on the extrusion width multiplied by the number of perimeters used, while the infill fills the remaining area to the selected density - 0% to 100% - using the selected pattern - rectilinear, honeycomb, etc. - these two simple structures are what create the profile of every printed object.

When creating thin profiles at the limit of two times the extrusion width - Figure 27 - errors occur in both processing the design and creating it. Through design and CAM iteration a part can be created thinner with the use of only perimeters or the use of smaller extrusion widths. A design that uses two perimeters without an infill allow for the narrowest sections but are susceptible to delamination under minimal force. If the machine is capable of producing thinner extrusions the infill and/or perimeter can be made thinner than the other allowing for the creation of both structures. A narrower perimeter increases strength but narrower areas remain weak, as the infill does not fit. A narrow infill illuminates this problem but results in

excessive infill print time for thicker parts of a profile. In practice these options should be avoided by redesigning the part to allow for thicker sections or closer widths that can use a smaller nozzle/extrusion width effectively.

Mandatory radii for part accuracy

To accurately design for printed parts each edge that is to be profiled must have a radius equal to or greater than the extrusion width. This is the lower limit that edges can be created at due to the nozzles shape Figure 31.

Figure 31: Profile radii

The inner edge of a designed sharp corner also becomes rounded and requires post processing or a design modification to allow assembly with sharp cornered parts – such as angle iron. This can be done by adding a circle cut along the inside edge and filleting the resulting corners – Figure 32 and Figure 33.

Figure 32: Exaggerated sharp inner corner correction

Figure 33: Failed part on left and successful compensation on right

Radii for increased profiling speed

Much as the design of a road influences how quick a car can maneuver its corners the design of parts and their tool paths also depicts how fast a printer head can move, along with the forces it will experience when doing so. Just like when driving if you come to a sharp corner like one at an intersection, you must first nearly stop in the direction you are traveling before you can start traveling in another. If the road has a ramp than your car – or extruder – can move along at a higher speed with minimal deceleration, in the optimal case for both situations the curve is such that no deceleration is required and just a change in direction can be achieved.

Figure 34: Corner action while profiling

This smoothing out of acceleration and deceleration allows the addition of radii to have a large effect on profiling time by reducing the amount of material required – as radii get larger – and by superimposing one axis’s deceleration with another axis’s acceleration. The profiling speed increase via the addition of radii is limited by the equipment’s maximum print speed and by the cooling time per layer - which are discussed in section 4.2.5 and section 4.2.2 – both limits can be reduced through equipment design to allow faster printing.

Figure 35: Radii speed test

When the corners of a four-sided hollow part - Figure 35 - (10mm x 10mm x 4.95mm) are given a radius of 0.5mm a timesaving is realized. Larger radii reduce the time further to a maximum timesaving of 12 seconds - 12.6% reduction at 5mm radii – by also lowering the amount of material used. When numerically analyzed

based on machine capabilities the addition of radii has a larger effect on average speed when the acceleration rate is lower - 9% average speed difference at 3000mm/s² acceleration, 90mm/s max speed – or when the maximum speed is higher – 8% at 9000mm/s² and 150mm/s – this is compared to a normal speed change of 3% - at 9000mm/s² and 90mm/s. these results show that the addition of radii is beneficial to both lower accelerating machines and to sturdier machines that are capable of high speeds and acceleration, as radii increase the amount of time spent at the desired speed.

4.1.4 Mesostructure Design

The observations from the testing of seven different parameters has generated a greater understanding of structural and commercial changes caused by mesostructure design decisions. The collected data is compared against the standard 30% test specimen – Appendix C - and other infill data collected during an engineering directed study on the effect of infill on tensile properties of materials. The study is conducted using the ASTM D638-10 standard with a single specimen per case. Each specimen design is a modification of the 30% infill specimen's mesostructures. The following modifications were made to each case:

- **Infill every 2 layers:** The infill for this specimen is printed every second layer creating a core made up of 0.3mm layers and a perimeter of 0.15mm.
- **Infill +45 Degrees:** The infill pattern was rotated 45 degrees switching its +45/-45 layup to a 0/90 layup with the applied force.
- **TB 0.45:** An extra solid layer – 0.15mm - was added to both the top and bottom of this specimen. 2x 0.3mm solid thickness to 2x 0.45mm solid thickness.

- **2 perimeter:** An extra perimeter has been added to this specimen
- **EW0.3 EWP0.5:** The perimeters extrusion width is kept at 0.5mm, while all other extrusion widths are modified to 0.3mm.
- **Honeycomb:** This specimen's infill style has been modified from a -45/45 layup to a honeycomb pattern.
- **Side:** This specimen's orientation has been rotated 90 degrees so that it is printed along its long side.

A large variation in material properties is capable via mesostructure design modifications as shown in Table 3. The extended data and observations are discussed further in the rest of this section.

Table 3: Material property range via mesostructure variation

	Min	Max	Units
Yield			
Elongation	0.95	1.35	%
Strength	7.19	23.40	Mpa
Specific strength (MassVolume+AirVolume)	12.51	20.35	Kn*m/kg
Break			
Elongation	2.83	8.31	%
Strength	2.19	27.58	Mpa
Specific strength (MassVolume+AirVolume)	2.53	23.98	Kn*m/kg
Other			
Material used	2.62	7.14	Cm^3
Tensile modulus	536.43	2415.40	Mpa

As a major part of commercial design, how much material and how long a process takes, influence the cost of production and the products success or failure. A typical pricing structure is shown in Figure 1 and each mesostructures influence on operational and material costs are ranked in Table 4.

Table 4: Mesostructure resource comparison (percentage change)

	Resources		Comparison	
	Time	Material	% Sum	Rank
0% Infill	-39%	-42%	81.0%	1
10% Infill	-21%	-21%	42.0%	2
infill every 2 layers	-18%	0%	18.2%	3
Infill +45 Deg	-4%	-2%	6.0%	4
30% Infill	0%	0%	0.0%	5
TB 0.45	5%	6%	-10.6%	6
2 Perimeter	9%	9%	-17.1%	7
EW0.3 EWP0.5	29%	-2%	-27.9%	8
Honeycomb	24%	6%	-29.4%	9
60% Infill	28%	29%	-57.3%	10
90% Infill	55%	58%	-113.1%	11
Side	93%	22%	-114.6%	12

As the data in Table 4 shows the most extreme variation in resources occurs when a part is printed on its side - as shown in Figure 36. This change in orientation requires 22% more material and takes 93% more time then the reference specimen. This time increase makes print orientation the largest factor for costing. Comparing this to printing an infill for every two perimeters – 0% change in material, 18% less time – shows that design decisions related to how the part is created (its mesostructures) can raise or lower the amount of time required printing the same amount of material.

Figure 36: Print orientation has a greater effect on structure and time than any other mesostructure

Part orientation also effects the creation of radii – profiled vs. layered - and need for support, both discussed earlier in this chapter. As such a balance must be found between factors affecting the mesostructures design, layer design, support design, and profile design. This balance should be considered from the beginning of the design phase as to minimize the number of layers, which reduces costs and maximize desired part qualities such as surface quality and strength.

Figure 37: Correct orientation allows plastic parts to cheaply connect steel structures

Table 5 adds yield data to the comparison of resources and are ranked based on an equal weighting of each of the five variables shown. In practice this weighting would not be equal but rather vary based on project goals. Again print orientation is least

desirable, as its structural performance does not make up for the extra resources it takes to create.

Table 5: Equally weighted comparison of mesostructures (percentage change)

	Resources		Yield			Comparison	
	Time	Material	Strength	Elongation	Specific S	% Sum	Rank
0% Infill	-39%	-42%	-35%	28%	15%	89.5%	1
90% Infill	55%	58%	112%	-8%	35%	26.3%	2
TB 0.45	5%	6%	16%	3%	12%	20.2%	3
Infill 45 Deg	-4%	-2%	5%	-3%	11%	19.4%	4
10% Infill	-21%	-21%	-24%	-5%	-4%	9.1%	5
2 Perimeter	9%	9%	14%	3%	9%	8.7%	6
infill every 2 layers	-18%	0%	-8%	-1%	-5%	5.0%	7
30% Infill	0%	0%	0%	0%	0%	0.0%	8
Honeycomb	24%	6%	16%	1%	12%	-0.6%	9
EW0.3 EWP0.5	29%	-2%	-8%	0%	-4%	-39.6%	10
60% Infill	28%	29%	28%	-10%	-1%	-39.8%	11
Side	93%	22%	-2%	-3%	-17%	-137.0%	12

Shell design

Adding an extra top and bottom layer and/or adding another perimeter can strengthen a part by increasing the thickness of its shell. Both options add similar strength to the test specimen with modest additions to time and material consumption. Due to solid layers taking less time and delamination issues with multiple perimeters it is recommended to add solid layers to your design.

The use of extra solid layers more evenly balances the shells thickness (0.5mm walls and 0.3mm top/bottom to 0.45mm top/bottom) then the addition of an extra perimeter that increases the wall thickness to 1mm. This balancing should help more evenly distribute the forces placed on the part and could be the reason for the higher yield specific strength.

Adding another perimeter to the shell mostly increases strength when parallel to the applied force. When force is applied on other angles delamination can occur between the two perimeters. This failure most likely starts as small inter-perimeter fusing errors, as shown in Figure 38. Even though an additional perimeter adds 54.29% to the break strength of a tensile specimen the extra layer causes a small part such as a printed c-clamp to fail much easier than one printed with a single perimeter. Each extrusion in the bellow pictures is 0.6mm wide.

Figure 38: Inter perimeter bonds between 0.6mm extrusion widths (4X and 10X magnification)

Core Design

If the force acting on a part is simple the infill can be orientated to match. Aligned infill with the applied force produces 5.3% higher yield strength and requires less time and material to print. Aligning the infill with loads in complex parts is often difficult or impossible and a +45/-45 layup approach produces a stronger part – particularly in small features under tensile load (e.g. Figure 37).

A weaker core is created with the use of thinner extrusion widths, reduced number of inter-layer bonds and reduced core density. Each test case that represents these

weakening factors exhibited a bending or warping of the specimen under load. This bending is responsible for the failure of the infill every 2 layers specimen outside of the desired zone and most likely effected the other bent specimens negatively. Also observed is a correlation between bowed specimens and consistency between the top and bottom layers break profile – higher strength cores have an even and straight break profile. This points towards an error in the shell that causes early failure when the core is weaker. Reliability testing of printed guitar picks that showed that increasing the layer height – reducing the number of inter-layer bonds – caused the picks to fail under less force. This is similar to a part printed with infill every 2 layers of perimeter. In this case the forces between layers are applied to a single joint rather than 3 joints.

Speed and acceleration

Thinner extrusion sections exist in lower infill parts that act as a stress concentrator. This concentration of force may cause lower density parts to fail prematurely and can be reduced by using lower printing speeds or higher rates of extrusion acceleration.

Figure 39: tested specimen failure (left), 70mm/s and 5000mm/s² bridging trial (right)

Figure 40: 50mm/s trial (left), 70mm/s and 10,000mm/s² trial (right)

4.2 Equipment Design and Operation for Extrusion-based Digital Additive Manufacture

This section presents results from research into equipment design and operation, showing that low-cost equipment can produce highly accurate parts in less time. With an understanding of each parts function and effect on the process, observations can be made and equipment weaknesses upgraded through an iterative design process.

4.2.1 Extrusion Tooling

The extrusion tooling has the job of accurately feeding material through a controlled heater, followed by extruding the material to be fused with other layers. Many design and operational issues arise that require a designer's or operator's attention.

Material Loading

To minimize pulsations in the extrusion tooling the material spool must be mounted with a centered rotation. As shown in Figure 41 an off-center rotation reduces the radius value of the torque equation leading to a higher required force to overcome rotational resistance. In practice this difference is multiplied, as the rotational resistance is much higher in the left case as friction is produced between a threaded steel rod and smooth plastic reel – friction in the right case is between two dissimilar smooth plastics. Without taking the resistive forces into account the applied force by the cold end would need to be 1.5 times larger when off centered vs. centered design. This extra force adds to the system's backpressure and energy requirements reducing the amount of and consistency of material extruded by the tooling.

Figure 41: Rotation alignment and material loading forces

As parts are printed, the spool's effective diameter is reduced, lowering the applied torque by the cold-end. When reduced to half the original diameter the torque is also half its original requiring twice the force to unspool the filament. In practice it has also been found that filament is not wound as consistently near the center of the spool, which leads to increased resistance.

Figure 42: Material depletion effect on loading forces

To overcome fluctuations in the force required to unspool filament the feeding system can be redesigned to put the extra force on the X-axis rather than on the cold end. This can cause some inaccuracies in X positioning (errors were noticeable only in extreme situations). An alternative solution is to re-spool the material before loading or add an additional motor dedicated to unspooling filament.

Figure 43: Left relies on extruder force, right uses X-axis force to unwind material
Cold-End

Three areas of improvement for cold end design are in the areas of stepper heat buildup; drive gear design and tensioner design/operation. As stepper motors produce less torque at elevated temperatures, active cooling is needed when printing in warmer environments ($>\sim 30^{\circ}\text{C}$), along with correct tuning of the extrusion tooling – higher current produces greater heat leading to greater torque loss.

To transfer the torque into filament linear motion the drive gear has to have an even toothed surface (non-ovoid profile) and dulled teeth – sharp ones lead to sheared filament inside the cold end – particularly when over-tensioned. Attention must also

be paid to the alignment of the drive gear to the input and output of the cold end as misalignment causes loss of traction and filament damage.

As cold ends are often printed it is important to correctly design and manufacture the tensioner in order to provide a constant force on the filament and drive gear. The correct orientation allows for the tensioner to be printed at a lower density while eliminating flex and eventual failure of the component – Figure 22.

Many factors can cause excessive backpressure in the extrusion tooling and lead to failure, thus it is important to tune for reduced damage during failure. The ideal failure situation for the cold end is a misstep by the stepper motor that reduces accuracy over the slipping of the drive gear on the filament that causes a failure of the tooling. For this reason the tensioner is slightly over tightened and the stepper motor provided slightly less current than optimal. If this balance is toward stronger tension – excessive gripping force – higher pressure is put on the stepper motor, which leads to greater inaccuracies. When towards a stronger motor – excessive torque - the filament is damaged by the drive gear slipping over the filament. The tool shown in Figure 44 helps this tuning process by providing extrusion test rates that are equivalent to desired printing profiles. This concept is further discussed in Section 4.2.5 when used to determine a machine's maximum speed.

Cad driven V3						
Material variables	EH	EW	E Length	Material Needed (mm ³)	Fillament D (mm)	Extrusion Length Needed (mm)
	0.15	0.5	50	3.75	1.7018	1.648634363
Time Variables	Speed		Acceleration (mm/s ²)	Time Based on XY with Accel	Material Flow (mm ³ /sec)	
	18000 mm/min		3000	0.26666667	14.0625	
	300 mm/s					
Testing Variables	E Feedrate				Material flow limits	
	6.18237886 mm/s				15.16	edge of capability
	370.942732 mm/min				27.74	Beyond capability

Figure 44: Cold-End Tuning

Hot-End

A hot end must have dual temperature zones to allow for minimal backpressure and reliable operation. This is possible as the second cooled zone allows for a quicker transition between solid filament and molten filament, which does not happen on an insulated or non-conductive design – insulated to keep heat in or hot end material does not allow heat to transfer up towards the cold end. When a hot end jams it not only ruins the print but also ruins the hot end part as removing the solid material causes damage to the internal surface, which encourages another jam.

Other issues with the insulated design are a large dimensional variance in hot end length according to temperature – making it hard to tune the distance to the printing surface. A low thermal conductivity design is difficult to machine and when used with a higher conductivity material like PLA, causes a large thermal plug as it does not cool the filament.

The dual temperature design must however have a balance between cooling the filament to prevent jams and allowing for quick heating of the material during processing. A variable resistor is used to find this balance based on the system's performance during tests. However a better option is to add a second thermistor to the hot end, allowing digital control of both zones' temperatures – one with heating and one with cooling.

In operation it is important to retract the filament from the melt zone after each job. When the material is not removed from the melt zone it experiences a fast heating – upon initial entry into the melt zone - then a slow cool down between jobs, followed by a slow heating – when the next job is started. This affects the material's ability to be extruded again leading to a jam in the melt zone or excessive leaking from the nozzle.

The tooling's nozzle occasionally leaks and gets a buildup of material on its outer surface, which causes print artifacts and failed first layers, thus regular cleaning must take place. This is best done with the same type of plastic, which presents an opportunity for failed parts or a piece of filament to be used in the cleaning process. For basic cleaning the edge of the adhesion surface – section 4.2.3 – can be cut to create a wiper that removes material at the beginning of each print. Possible disassembly of the hot end or nozzle replacement may be required if the extrusion comes out on an angle when extruded into the air. This is a sign that material has

built up in the nozzle and could possibly be eliminated by advancing new material into the hot end and pulling it out to advance another new section.

Extrusion Tooling Fan Control

As multiple parts of the extrusion tooling and control electronics require active cooling, an expansion board is designed that provides digital control through transistors. Key cooling controls that avoid damage allow the hot end to cool below the filament's glass transition point before being turned off (to avoid the creation of a thermal plug) and cooling of the power mosfets and stepper drivers whenever the motors or heaters are active (to avoid thermal damage to the electronics – Figure 46.

4.2.2 Solidification Control

Each part of the solidification control must allow for the extruded material to evenly cool. This system prevents parts from warming due to a heat buildup or difference within the part and helps material adhere to the print surface.

Print Cooling

Properly designed and operating part cooling insures part stability and printing speed, as each layer must first be cooled before printing the next. The minimum cooling time is set when designing a machine, based on the minimum time it takes for a layer to cool and not cause warping on any overhangs or on the next layer. If a layer completion time is lower than this set value, the machine will automatically

slow the profiling speed to insure the minimum cooling time is met. This time can be adjusted for varied cross sections or by adding additional cooling to the equipment.

Since current software does not take into account the amount of material in a profile or the size of an extrusion, a designer can develop multiple profiles that take into account taller, wider, and higher density extrusions, which take longer to cool. When these profiles are applied accordingly they allow the designer to reduce part print time while retaining quality.

A machine can also be modified to use a larger CFM fan or a redesigned cooling system that more effectively cools a part. These modifications not only allow for quicker printing but can enable a burst of cooling that allows for larger bridging of unsupported design features. Excessive or sporadic cooling has a negative effect on the printer and part performance as the extrusion tooling is cooled at a rate it cannot recover from quickly, increasing backpressure and causing extrusion errors. This negative effect can be reduced by insulating the hot end, using a pulse width modulation control for the cooling fan instead of an on/off control, allowing for more gradual changes in temperature which the hot end can recover from quicker, and by designing the cooling system to reduce its effect on the extrusion tooling.

Many of the problems stated above are caused by the attachment of a fan to the extrusion tooling directed at the nozzle. This 'direct method' also produces a blind spot behind the extrusion tooling that is not adequately cooled leading to part

warping in that area. Ducted cooling gets around this blind spot by creating a pathway for cool air to selectively flow to areas that need cooling. These are not only difficult to design but also require heat shielding/resistance as they are usually printed and require close proximity to the printer's hot-end. These designs also do not transfer well between printer designs or iterations as each setup has a different desired flow rate and angle, along with mounting and clearance considerations. These discovered issues are overcome by designing a stationary duct as shown in section 3.2.2 - Figure 12. The large stationary duct allows for even cooling at a greater flow rate over the entire part, faster printing speeds due to reduced weight and cooling time, and allows for integration into a wide range of machine designs.

Print Heating

Temperatures between 30 to 50°C help the first layer of a PLA part adhere to the print surface, and are required to stop part from warping due to uneven cooling on a higher density PLA part or any ABS part. Substituting the common borosilicate glass printing surface for an aluminum one and adding an insulated backing made out of cork allow for quicker initial heat up times, faster and accurate heater responses and less energy consumption.

Figure 45: Loss of heated surface caused this high density part to warp

The heated surface is the highest consumer of energy on the printer (11amps at 12 volts), thus the standard ramps board must be modified to allow for reliable switching of the high current. If an additional conductor is not added between the mosfet and screw connector, damage is caused by the trace overheating – shown in Figure 46 – and results in the loss or instability of heating control.

Figure 46: Burnt component and board from bad connection and component

Uneven surface heating – due to thermal transfer design issues - and lack of tolerance for thermal expansion causes an aluminum-printing surface to warp. This warped aluminum causes similar effects to an unlevelled bed – discussed in section 4.2.3- and a brim must be used to provide extra surface adhesion. Although the

addition of a brim will allow a part to be successfully created it will have unintended changes to its mesostructure due to the irregular shape of the printing surface.

Figure 47: Extrusions on an uneven surface

Figure 48: Thermal bridge between heater and print plate allows for an even print surface

4.2.3 Printing Surface

The surface texture and even nature of a printing surface allows the build material to adhere and a part formed on the equipment.

Leveling

A constant distance between the extrusion tooling and printing surface is key to equipment operation and longevity, particularly during the creation of the first layer. By locking the adjustment hardware – with lock nuts or hot glue inserted into the threads – and securing the nuts to the axis surface, the distance remains stable

in operation allowing for constant production without shutdown for re-tuning and maintenance.

Figure 49: Locked hardware (left), Z end stop (right)

The correct distance between the tooling and surface is required for correct adhesion and extrusion sizing of the first layer. If the distance is too small the extrusion tooling's backpressure will rise and the print surface will experience excessive wear – extreme error will cause damage to the nozzle and bed. If the distance is too large, material will build up on the nozzle, as it does not adhere to the surface. If gaps between extrusions are observed on the first layer too large of a distance is likely. The distance between the tooling and bed is likely to small, if a part is very difficult to remove, light colored filament color shifts towards the bed color, or an adhered extrusion is pulled up or off the bed by the extruder.

Figure 50: Extrusion Distances

Parts may exhibit signs of the extrusion distance being both too small and too large. This is caused when the bed is not leveled and requires tuning. To obtain the correct

distance between the print surface and tooling each corner must be tuned to the right distance and then checked once again both at working temperature – hot ends expand when heated to varied amounts based on their design. A G-code file can be used to speed up this process by traveling to each point and waiting for the user to adjust each corners setscrew directly modifying the distance.

Surface texture

PLA filament best adheres to a three dimensional fibrous surface as shown in Figure 53, over a smooth – Figure 51 – or pitted surface. The structure is created by agitating the fibers of painter’s tape as shown in Figure 52 with coarse sandpaper as discovered during operation with simple surface adhesion experiments. This structure becomes worn out when the nozzle to surface distance is too small, or during normal use – by flattening/removing fibers and filling gaps with plastic. This effect is reversed via a light sanding between prints as necessary to extend the surface life. This technique is similar to lightly sanding a painted surface between coats and has been used to print over 20 parts in the same location on a single surface without replacement or first layer defects.

Figure 51: Green painter's tape at 10X magnification

Figure 52: Blue painter's tape at 10X magnification

Figure 53: Sanded blue painter's tape at 10x magnification (focused on raised 3D fibers)

4.2.4 Positioning System

The positioning system must reliably and accurately move the tooling into the correct location at a rapid rate. To achieve this two important features have emerged from reliability testing and are designed for, rigidity and reduced forces.

Rigidity

A rigid positioning system allows for faster tooling movement and reduces layer banding. Two key areas to secure are the linear bearings used on the X and Y-axis along with the ground rod of the Z-axis. Threaded rod used for the Z-axis positioning should not be restricted in movement as doing so causes any bends in the rod to shift the X-axis causing layer banding.

Figure 54: Printed bracket (left) and shield (right) on Z axis

The addition of a tab to the axis pulleys creates a more accurate connection between the axis motors and belting system. This also reduces failures - in low-density printed pulleys - and increases possible printing speeds/moving weight by shifting axis forces off the setscrew. Along with this design change the system's firmware should keep all axes active during a print to ensure micro stepping accuracy.

Figure 55: Failed pulley left, supported pulley right

Reduced Positioning Force

Frictional forces, wear, and excess noise can be reduced with the use of appropriate lubricants. If source control practices are used to reduce airborne particles, common oils and grease can be used without an enclosure. A light oil is best used to lubricate a machine's linear bearings – white mineral oil (Wahl, 2013). Heavy grease used on a Z-axis threaded rod would cause bald spots on the ball bearings. Any friction caused by interference of components should be removed via correct tuning – Figure 56 - or the creation of guards – Figure 54 - that prevent small forces from interfering with micro steps.

Figure 56: Belt friction with the idlers sides' causes inaccuracy in the positioning system

When large masses are in motion it is important they are balanced around the positioning force to minimize unwanted motion during printing. This is important for the print surface in this design and of greater importance for the heavy direct drive extrusion tooling. An unbalanced extruder not only causes unwanted motion but also vibrations that lead to equipment damage. Repositioning the cold ends center of mass inline with the X-axis belting minimizes these forces allowing for quicker positioning and greater part accuracy.

4.2.5 Maximum Print Speed

Once the equipment is designed and tuned, a maximum print speed test can be done. This test can also determine if the extrusion tooling or positioning system is the slowest stable part of the machine for future equipment iterations. By inputting the design's intended extrusion height and width, filament diameter and the mm/min results from a cold-end calibration test into the calculator - Figure 57 - an expected XY rate is calculated.

Steady state max required XY speed based on extrusion rate limit (calculated with extruder calibration tool)								
Extrusion Rate	500.00	mm/min	Filament D	1.7018	mm	EH	0.20	mm
	8.33	mm/s	F area	2.27	mm^2	EW	0.60	mm
XY Rate	9477.54	mm/min				E area	0.12	mm^2
	157.96	mm/s	F/E Ratio	18.96				

Figure 57: Positioning speed based on extrusion rate calculator

The use of a wider and taller extrusion reduces the maximum print speed, as more material needs to be extruded at a time. This does not necessarily affect the print time negatively as taller extrusions require fewer stacked profiles to build a part. This is similar to CNC milling as creating a layer that is twice the thickness just needs to move over half the feed rate to save time.

Figure 58: Max print speed test (70mm/s left to 380mm/s right)

The calculated rate of 157mm/s is a conservative maximum speed as shown in Figure 58 where print speeds topped at 380mm/s. This test has shown that higher speeds are possible without extrusion errors. The tools underestimation comes from errors in the testing procedure for the extrusion tooling's maximum feed rate. These errors arise from temperature instabilities when extruding large quantities of material and from backpressure when the extruded material is pushed back towards the extruder, both of which do not occur during normal operation.

To correctly test the maximum extrusion rate around 2mm of filament should be extruded – this equals 37.9mm of extrusion at 0.2mm height and 0.6mm width. This length is longer than most print surfaces and represents a maximum continuous flow for the equipment. Testing a longer length such as 100mm is equal to an extrusion 1895mm long that is well beyond normal operation. The hot-end cannot keep up with the amount of material in a short time, which causes temperature fluctuations leading to extrusion tooling failure at a lower test speed. Feeding less material during a test also eliminates backpressure caused by the extrusion tooling

needing to push the already extruded material out of the way. This excess backpressure does not occur in operation as the positioning system moves the printed material out of the way allowing for a higher extrusion rate.

The research and iterative development done during this thesis has brought a machine that once struggled to print at 20mm/s to the point of printing at 380mm/s successfully. More testing and equipment iteration is required moving forward to discover the maximum accurate print speed possible with modified open source equipment.

5 Conclusion

The author conducted two sets of studies in which he addressed the question of how can design increase the competitiveness of extrusion-based digital additive manufacturing. The main question was broken down into two sub-questions:

Q2: What design considerations are required to produce cost effective and functional parts with digital additive manufacturing?

Q3: How can equipment design and operation be improved for lower-investment manufacturing?

The first sub-question addressed the challenge of increasing competitiveness of product design using digital additive manufacture and the second sub-question answered how these products can be manufactured on accessible low-cost equipment. The studies demonstrated reductions in all four contributions to final part cost, including equipment purchase, operations, materials and labour. It was discovered that such reduction in cost is possible due to greater involvement of the designer in the manufacturing process. This allows for an efficient iteration process as it results in continuous design and equipment modifications and ultimately mesostructure and processing improvements. Thus, cost savings with the integrated prototyping and production capabilities of the digital additive manufacturing

process allow a designer to introduce competitive products to niche markets on demand.

5.1 Design for extrusion-based digital additive manufacture

When designing a part for extrusion-based digital additive manufacture it's important to understand that what one is designing will be sliced into many layers and individual profiles created for each layer. Beyond considering how a part's layers and profiles will be produced other mesostructures must also be considered to take full advantage of the process. When properly designed for, the surface texture is viewed as a finish, such as glossy or satin, instead of a process error.

Form follows process

The design scale must shift down from parts to mesostructures and extrusions to take advantage of the complex digital control the technology offers, which designers are not currently accustomed to. Designing in such a way allows for greater dimensional accuracy to the point that metal inserts are used and allows for lighter hollow structures to be designed and built. The following are design considerations that a designer should be aware of when developing a part for the digital additive manufacture process.

- **Layer design:** When all features are aligned with the part's intended layers in the design phase, parts are more accurate and a lower resolution can be used. A part designed to use larger extrusions not only takes less time to

print but also allows a large number of printers to produce the designed product around the world.

- **Support design:** The addition of design intent to support material is key to the reduction of part cost. These designed structures can be informed by nature, allowing for minimal material use. The part can also be redesigned to allow for self-supporting features by understanding the material and machine limitations.
- **Profile design:** The design of the first layer to allow correct adhesion and easy part removal is crucial to the production of a successful part. The reduction of density and addition of radii to corners allow for a significant reduction in print time.
- **Mesostructure design:** Modifications to a part's mesostructures allow for great control over the resources used in its production. Material properties are also tailored through mesostructure design allowing seemingly identical parts to perform very differently in use.

5.2 Equipment design and operation for low-investment manufacturing

Knowledge in equipment design and operation allows designers greater access to manufacturing by utilizing low-investment open hardware, but also creates several

functional and reliability problems that need to be solved. The following are key components whose optimization allows for the creation and operation of highly capable digital additive manufacturing equipment.

- **Functional minimalism:** Each component of the machine should be minimized to its key features. Expensive or rare components and materials can be switched out for locally sourced ones, allowing for a wider use of the technology. Creating a capable machine with little waste allowing for more sustainable options like solar power.
- **Extrusion tooling:** Tooling is made reliable through proper equipment design and through tuning for the material and parts it will be creating. A balanced mass allows extruders to be positioned faster without reducing weight or increasing print errors.
- **Solidification control:** Proper design and operation of the solidification control components allows for the faster creation of profiles without warping. The equipment's function is better understood when classifying the part cooler and printing surface heater in this separate category. This allows designers to better tune the solidification process for each design they produce.

- **Printing surface:** A stable surface allows for reliable extrusion adhesion through correct leveling with locking features and minimal surface maintenance. As a result, the printing surface's added texture does not need to be frequently replaced, nor does the surface need to be leveled between jobs.
- **Positioning system:** A positioning system should be easily tunable for maintenance, ridged to reduce inaccuracies, and have minimal forces acting on it to reach higher speeds. The use of commonly available materials for the positioning system allows for the wider spread of the technology, as electronics are cheaper to ship than a steel or aluminum frame.
- **Maximum print speed:** Running tests on the machine's maximum obtainable print speed not only inform how quickly a designed part can be created, but also informs the equipment's design and operation. By pushing a machine beyond its limits the weakest components or processes are revealed. This allows for subsequent upgrading and tuning, ultimately resulting in a higher performance machine.

5.3 Recommendations for Further Research

The author plans on conducting further research from the foundational research presented in this thesis through interdisciplinary collaborations and commercial application through Ecotonos design and manufacture. The usage of both

quantitative and qualitative research methods from multiple disciplines should be used to develop a deeper understanding of the area of digital additive manufacturing beyond this thesis.

Equipment design should be furthered by developing the use of common materials, such as angle iron, as an alternative to aluminum extrusions to allow greater access to the technology. The operational speeds of equipment could be sped up with the use of thinner filament and the development of positioning systems with accelerometer data to minimize unwanted forces. To further design for digital additive manufacture the topics discussed should be researched on other technology classes such as curing and fusing systems. The design understanding of mesostructures should also be furthered with more in-depth and broader engineering testing of printed specimens. Ultimately through interdisciplinary collaboration, digital additive manufacture can be improved to control finer scales with greater design intent given to an ever smaller scale of material. Possibly, all the way down to the atomic level.

“The beauty of a living thing is not the atoms that go into it,
but the way those atoms are put together.” Carl Sagan

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Glossary of Terms

Beta testing – The use of a pre-commercial product for the purposes of testing before commercialization.

CAD – stands for computer aided design. CAD software is used to create the macro structure components of a design.

CAM – Stands for Computer aided manufacture. CAM software plans tool paths for digital machines based on CAM profiles and exports G-code. This software is used to design mesostructures in this thesis.

Slic3r – Is an open source CAM software suite that is specialized for 3D printing applications.

Tool paths – are created by CAM software such as Slic3r or created manually through written G-code.

G-code – Is a machine language that consists of instructions that tell equipment how to produce a design. G-code is produced by CAM software or manually written.

Design Terms

Self-printed part – a part made to fix or upgrade the machine it is printed on. For example, a printed bracket to upgrade a printers positioning system.

Filament – Is the semi-processed material input for most extrusion-based printers, which is bought on roles and feed into the printer's extrusion tooling for processing.

Extrusion – The individual strands of material placed by the equipment's tooling to create structures. The process has control over both an extrusions width and height.

Extrusion width – A design controllable parameter that determines the width of created extrusions.

Extrusion height – also known, as layer height is the thickness of each extrusion in the Z-plane. The extrusion height is designer controllable and is often considered the machines resolution.

Step over – A step over is the distance or percentage offset a perimeter is created vs. the previous created layer. The designer has indirect control over step-over through part design. A large step over is often referred to as a staircase effect.

Staircase effect – is a surface feature resulting from the layering process. The effect is most noticeable when step over rates or extrusion heights are large.

Macrostructure – A macrostructure is typically designed for as parts which have a consistent material property.

Mesostructure – Sub part properties, which have a great influence on a printed part's structural properties and the resources (time and material) a part requires in construction. These structures are typically not designed for, as most processes do not have control over their construction.

Support material – Is an external structure that supports printed parts against gravity until solidification. These structures are removed upon part completion and thrown out or recycled.

Shell - A parts shell is the external surfaces, which a user interacts with and is controlled via mesostructure design.

Core – A parts core is the internal features made up of infill or other designed mesostructures.

Equipment Terms

Curing-based process - Curing based systems initiate a chemical reaction in the raw often liquid material via a light source – laser or projector

Fusing-based process - A fusion based system bonds raw material often in the form of a powder with directed heat or a binding agent.

Extrusion-based process – Extrusion systems, which are the focus of this thesis, liquefy the raw material and extrude it through a nozzle using extrusion tooling.

Extrusion Tooling – Allows for the controlled extrusion of material through a nozzle. The equipment used in this thesis consists of a material loading system, cold-end and hot-end.

Cold-end – Is the section of the extrusion tooling responsible for the highly controlled movements of the filament into the hot-end. The cold-end consists of a stepper motor, filament drive and tensioner.

Tensioner – A cold-ends tensioner applied a controlled amount of pressure onto the filament securing it against the filament drive.

Filament Drive - The filament drive transfers a stepper motors force into the filament via its textured or toothed surface.

Hot-end – A hot-end applies controlled heating to the filament, liquefying the material allowing for extrusion from the nozzle.

Nozzle – A part of the hot-end that reduces the filaments diameter to the intended size. A 0.4mm nozzle is used during this thesis however they come in many larger and smaller sizes.

Thermal plug – A thermal plug happens when a heat build causes filament to swell to the point of causing an impassable material buildup in the hot-end.

Print surface – Is the part of the printer that a part is built on. The surface must have a maintained distance to the extrusion tooling and allow for the adhesion of extrusions.

Positioning system – The positioning system moves the extrusion tooling and or print surface in an XYZ coordinate system.

Layer banding – Layer banding is a visible zigzag offset of printed layers on what should be a smooth vertical surface.

Appendix A: Wim Gilles “Unwritten Rules” Applied To

Digital Additive Manufacture

Wim Gilles Unwritten Rules for Efficient Production (Gilles, 1999) in the context of Digital Additive Manufacture

Rule #1: Storage

The supply kept of material stock, supplied parts, and semi-finished products should be kept to a minimum to reduce the companies day to day costs. End products should be designed to occupy little space by allowing stacking, or flat packing.

Minimal Feed Material

By employing the emerging material design principle of manipulating the built structure of a material to alter its properties, a single material can take the place of many in the manufacturing process.

Common Supplied Parts

Design for commonly available parts and/or parts that are being used in your production already. By using the same part of multiple products you reduce the variety of supplied parts needing storage and handling while increasing the quantity used reducing the component cost with economies of scale.

Digital Storage of Molds

By using a digital pattern to produce parts the storage of “molds” for every part of many complex products can be done in the area many times smaller than any of the products, virtually.

Just in Time Manufacture

By producing all possible parts only when needed on digital additive equipment the need of design for storage during production is reduced along with the cost of storing parts.

Rule #2: Creating two parts costs twice as much as one

Rather than producing many Lego blocks that are later assembled, parts should be combined into a larger unit and produced. Doing so reduces the cost of production and more importantly the cost of handling the part, as size does not affect cost as much as number of units handled.

The cost of handling a part dominates over the production cost, thus many smaller parts that can be produced as a single large part should not be produced as handling costs are similar for both sizes.

Digital Era Design for Assembly

As digital production methods particularly additive ones can produce vastly more complex parts without adding to the cost of production, larger parts that encompass

what used to be many smaller individual parts can be produced with ease; the downside to such a practice is increases support material required and more importantly structural properties due to the layered nature of the production process.

Rule #3: Part Complexity

Making simple parts is much less expensive than making complex ones. Complex parts require more expensive molds and often require longer cycle times, to produce. A solution is to combine the majority of a product's complexity into one part to drastically reduce the complexity of all other parts.

Geometric freedom

With the production pattern being digitized no longer does part complexity change the cost of producing a mold, more complex parts do take longer to process on a computer but this does not add significantly to the cost of production. Cycle times do however still increase with part complexity as the positioning system must slow down and accelerate around added features.

Rule #4: Material Use and Waste

Preventing the production of waste over the collection for reuse. This has existed before environmental concerns and was a rule of good manufacturer's housekeeping.

Support material

Much like in the past a design could be changed to produce less waste, creating a more viable product; Modern printed objects can be designed in a way that reduces or eliminates the need for support material that are later removed and recycled.

Infill

Unlike subtractive methods or many molding methods of production, layered methods have the ability to vary the amount of material used within a part's wall or other features. By doing so material savings can be realized, lighter weight parts produced, along with parts with designed material structures for increased situational performance.

Appendix B: Mesostructure Variables

- **Extrusion Height:** This variable controls how tall each layer is that makes up a part, which has a large effect on print time, structural qualities and aesthetic qualities. Typical values for this research are between 50micrometers (0.05mm) to 150 micrometers (0.15mm). Testing extremes where 0.01mm and 0.3mm with the lower drastically increasing speed and hitting an extrusion control limit, the higher reducing part quality.
- **Extrusion Width:** Has multiple variables in current software that can control the extrusion width of multiple mesostructures. Values between 0.2mm to 0.6mm have been tested, with 0.3mm to 0.5mm producing the best results on a 0.4mm nozzle.

Shell

- **Perimeter Count:** Controls the number of perimeters used in a profile that when multiplied by the extrusion width produces the shells thickness in the XY plane. The research has shown that using a single perimeter is optimal in most situations as it reduces resources used and can have a positive effect of a parts structure when in use.
- **Top/Bottom Solid Layer Count:** Is usually set to the same value but can be individually set per top and bottom surface which is useful when minimal infill is used – additional top solid layers can be added to better support the top surface. The shells thickness in the Z axis is a multiple of this variable/s multiplied by the extrusion height.

Core

- **Infill %:** Allows for core densities from hollow (0%) to solid (100%). Throughout the case studies most used an infill from 20% to 30%.
- **Infill Style:** Selectable methods to infill the core of a part with rectilinear and honeycomb being used most often in this research.
- **Infill Angle:** This variable defines what angle the infill is printed at in the XY plane. The research used 0, 45, and 90 degree angles for this as current software does not allow each layers orientation to be controlled – each layer is 90 degrees to the last. Such control would allow for greater research into composite layup methods – as used in aerospace engineering.
- **Infill Every n Layers:** Allows for the infill to be printed every second – or more layers up to the nozzle width – which reduces print time, but as shown in section 4.1.4 also reduces tensile strength.

Appendix C: Mesostructure Study

Standard 30% Specimen:

- Layer height - 0.15mm
- Extrusion width - 0.5mm
- Perimeters - 1
- Top solid layers - 2
- Bottom solid layers - 2
- Infill - 30%
- Infill pattern – rectilinear
- Infill angle – 45 degrees

Print Time	
Side	192.82%
90% Infill	155.49%
EW0.3 EWP0.5	129.48%
60% infill	128.32%
Honeycomb	123.53%
2 Perimeter	108.51%
TB 0.45	104.71%
30% infill	100.00%
Infill 45 Deg	96.20%
Infill Every 2 Layers	82.08%
10% infill	78.53%
0% infill	61.19%

Table 6: Print time

Material Usage	
90% Infill	157.56%
60% infill	128.98%
Side	121.82%
2 Perimeter	108.57%
TB 0.45	105.89%
Honeycomb	105.84%
30% infill	100.00%
Infill Every 2 Layers	99.69%
EW0.3 EWP0.5	98.41%
Infill 45 Deg	97.77%
10% infill	79.45%
0% infill	57.82%

Table 7: Material Used

Yield Strength	
90% Infill	212.10%
60% infill	128.13%
TB 0.45	115.89%
Honeycomb	115.87%
2 Perimeter	114.46%
Infill 45 Deg	105.30%
30% infill	100.00%
Side	98.01%
EW0.3 EWP0.5	92.40%
Infill Every 2 Layers	92.03%
10% infill	75.73%
0% infill	65.22%

Table 8: Yield Strength

Yield Elongation	
0% infill	128.09%
TB 0.45	103.12%
2 Perimeter	102.51%
Honeycomb	101.04%
30% infill	100.00%
EW0.3 EWP0.5	99.68%
Infill Every 2 Layers	99.29%
Infill 45 Deg	97.30%
Side	96.61%
10% infill	95.47%
90% Infill	92.30%
60% infill	90.27%

Table 9: Yield Elongation

Yield Specific Strength	MV+AV
90% Infill	134.96%
0% infill	115.24%
Honeycomb	111.89%
TB 0.45	111.77%
Infill 45 Deg	110.79%
2 Perimeter	108.79%
30% infill	100.00%
60% infill	99.12%
EW0.3 EWP0.5	96.19%
10% infill	95.90%
Infill Every 2 Layers	95.48%
Side	82.97%

Table 10: Yield Specific Strength (material + air volume)

Ultimate Strength	
90% Infill	237.60%
60% infill	143.50%
2 Perimeter	130.46%
TB 0.45	128.43%
Honeycomb	124.91%
Side	116.73%
Infill 45 Deg	110.07%
EW0.3 EWP0.5	108.60%
Infill Every 2 Layers	102.33%
30% infill	100.00%
10% infill	73.77%
0% infill	54.91%

Table 11: Ultimate Strength

Break Strength	
90% Infill	316.60%
TB 0.45	177.19%
Honeycomb	162.07%
2 Perimeter	154.29%
Infill 45 Deg	130.84%
EW0.3 EWP0.5	127.94%
60% infill	103.10%
30% infill	100.00%
10% infill	74.52%
0% infill	54.98%
Side	25.14%
Infill Every 2 Layers	N/A

Table 12: Break Strength

Break Elongation	
Side	146.65%
90% Infill	105.38%
30% infill	100.00%
0% infill	95.27%
TB 0.45	92.63%
EW0.3 EWP0.5	88.91%
2 Perimeter	85.54%
60% infill	82.64%
10% infill	74.44%
Honeycomb	63.73%
Infill 45 Deg	49.96%
Infill Every 2 Layers	N/A

Table 13:Break Elongation

Break Specific Strength	MV+AV
90% Infill	201.45%
TB 0.45	170.89%
Honeycomb	156.50%
2 Perimeter	146.63%
Infill 45 Deg	137.65%
EW0.3 EWP0.5	133.20%
30% infill	100.00%
0% infill	97.15%
10% infill	94.36%
60% infill	79.76%
Side	21.29%
Infill Every 2 Layers	N/A

Table 14: Break Specific Strength

Figure 59: Tested 10% infill specimen with stress concentration

Figure 60: Tested 30% specimen with stress concentration

Figure 61: 60% infill specimen with stress concentration

Figure 62: 90% infill specimen with uniform extrusions

Appendix D: Author information

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