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REPEATABILITY AND COUNTERPROLIFERATION OF METAL ADDITIVE MANUFACTURING TECHNOLOGIES IN AEROSPACE APPLICATIONS

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ABSTRACT

Additive manufacturing ("3D printing") is emerging as a promising and disruptive technology for high-performance military aerospace applications. The ability to additively print rather than subtractively machine critical components presents opportunities to lower cost, weight, production time, part count, and material waste while improving performance and functionality. However, reliance on additive manufacturing also involves storing increasingly large amounts of sensitive information and intellectual property in digital media. As the additive manufacturing industry continues to rapidly develop, the factors affecting its accessibility and repeatability from digital information are subject to constant change. This thesis examines the current and future accessibility of additive manufacturing and the cybersecurity risks of its associated digital information. It then synthesizes this to analyze potential interdiction points in the proliferation of high-performance additive manufacturing.

This thesis concludes by experimentally testing the current repeatability of high-performance additive manufacturing under one counterproliferation leverage point: the use of recycled titanium 6-4 powder to simulate interdiction of a consumables supply chain. The study concludes that direct metal laser sintering of the tensile specimens resulted in critical surface inconsistencies, including biases based on part orientation and some out-of-tolerance geometry. However, the specimens exhibited no significant variation in performance-critical mechanical properties (modulus of elasticity and yield strength).

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Chapter 1

Background of Additive Manufacturing

Additive manufacturing ("3D printing") enables skilled engineers and practitioners to redefine how products are designed and produced. Satellite brackets once welded together from eight different parts can be printed as a single unit while expending less time and material. Many printing processes are faster, weight-saving, and simpler for the operator. These devices are a major step in the evolution of manufacturing overall, and in minimizing the need for skilled machining and post-processing. At the same time, additive manufacturing (AM) machine code also includes far more intellectual property than conventional design (CAD) files. In a field in which wrenches can be printed in outer space, it is not yet clear what outside actors can achieve using proprietary machine code.

One of the main challenges with assessing these proliferation risks is that "additive manufacturing" is a deceptively simple term that in fact includes a wide variety of disparate technologies. These technologies range from desktop plastic printers to room-sized electron-beam melting chambers. Calling a part "additively manufactured" is approximately as elucidating as calling something "subtractively manufactured": the latter could be milled, turned, drilled, bored, laser cut, or produced by a combination of several techniques. This thesis provides an overview of the technical processes and practical accessibilities of both consumer-level plastic and high-performance metal 3D printing. This is important because while the proliferation of plastic consumer-grade AM poses far fewer risks to industrial and governmental applications, the plastic printing industry is more mature than its metal counterpart. As such, understanding the history and growth of plastic AM technologies can provide some insight into the future trajectories of metal AM.

Nowhere are the risks of metal AM proliferation more salient than in the sector of national defense. Both military and civilian governmental agencies have already begun incorporating high-performance AM metal parts into national security missions. While most of these components are non-critical for the time being, research-and-development efforts are rapidly moving towards the inclusion of structural components and critical and complex replacement parts. These advancements mean that more intellectual property is being stored as AM digital media, and associated cybersecurity risks are already under investigation [E. Brown, 2015; Daly, 2014; National Defense Industrial Association, 2014]. However, the question remains as to whether a data breach could allow potentially belligerent entities to “just press print” and make their own spy satellite or fighter jet components.

There are several questions embedded within the “just press print” security risk and quality control question. The first is how much intellectual property is actually stored in AM data files. The second is whether and how that information is extractable and usable from the compromised data. The third question is what can actually be done with the extracted data, including if and how AM processes can be interdicted or monitored. Finally, the question remains as to how repeatable AM printing is between and even within batches, printers, operators, and environments.

This thesis examines the “just press print” question in terms of technical insight, policy development, and experimental testing in several ways. Chapter 2 begins with an outline of AM technologies and then assesses the current and future accessibility of the printers themselves. Chapter 3 begins the cybersecurity discussion by overviewing the major aerospace components currently being printed by U.S. industry, civilian government, and military organizations as well as by allied and non-allied nations. Chapter 4 examines AM digital information, including the intellectual property, vulnerability, and extractability inherent in different current and potential file formats. It also considers the future of AM digital media and begins with the discussion of repeatability. Chapter 5 synthesizes this information to assess physical and intellectual interdiction points to the proliferation of high-performance metal AM capabilities. Chapter 6 presents an experimental case study in repeatability testing for one of these points, namely the use of recycled powder when the supply chain for feedstock is interdicted. Chapter 7 summarizes and presents the conclusions of this thesis.

Chapter 2

Metal and Plastic AM Technologies and Accessibility

Additive manufacturing (AM) offers a number of fundamental differences from conventional manufacturing methods such as machining, welding, and molding. These conventional or “subtractive” technologies are limited by the locations from and processes by which material can be removed. For instance, the creation of internal cavities require chemical processes or seams between parts. In addition, weight optimization requires more material removal, sometimes in very complex patterns. Each of these processes equates to more time, higher costs, and greater material waste. Most importantly, that complexity is directly proportional to the required hours of skilled labor. In contrast, AM technologies use automation to deposit small particles, drops, or pieces of material exactly where desired. This means that complexity in AM is not proportional to the need for operator talent or training. While skilled technicians must prepare print jobs and maintain equipment, this is largely a platform-level investment independent of component design. This makes advancements in design freedom accessible at lower labor costs and potentially to less technically skilled competitors. Potential advancements include increasing geometric and alloy complexity while reducing lead-times, part counts, assembly work, material waste, and weight.

Of course, there are limitations to the “add material anywhere” opportunities of AM. Different technologies require different support structures, and different additive techniques create different material properties. In addition, while AM began as “rapid prototyping” for a reason, it cannot yet compete with traditional manufacturing for volume production. Most importantly, as with all emerging fields, the future of AM is not yet clear. Design and implementation best practices are still under development; long-term outcomes, impacts, and quality assurances are unclear.

Herein the word “printer” is used as a proxy for any specific model of an AM system, whereas “technology” refers to the more general method of manufacturing. (For instance, an HP LaserJet Pro is a printer, whereas dry electrophotographic laser printing is a technology.)

Plastic Printing Systems

Stereolithographic Printing. Stereolithography was the first-developed viable AM process, though it is currently used almost exclusively for prototyping. The process uses a vat of liquid plastic that is cured layer by layer via a guided UV laser. Once one layer is cured, the bottom platform drops a specified distance to expose a new layer of liquid plastic. Post-processing involves rinsing with a solvent and baking in an ultraviolet oven.

SLS Printing. Selective laser sintering (SLS) is very similar to stereolithography, except that it replaces the liquid vat with a metal or plastic powder bed. A roller or blade spreads a thin layer of powder across the platform, after which that layer’s shape is sintered by a high powdered laser. The platform is then dropped by a layer thickness and more powder is rolled or scraped onto the platform. SLS thus differs from stereolithography because it does not require support structures—the powder bed always supports the part 3D geometry. SLS typically refers to indirect sintering (compare to DMLS below), in which the sintered powders are mixed or coated with polymers. SLS actually involves melting these polymers, which act as binders. These are later burnt off, and the part (which is thus not fully dense) is infiltrated with a main material of sufficiently low melting point [Calignano et al., 2013].

FDM Printing. Fused deposition modeling (FDM) is a similar technology to SLS except that instead of a liquid or powder bed and laser, it uses a guided nozzle depositing molten plastic onto an in-air platform. Each thin layer of molten plastic cools and hardens on the last before the bottom platform lowers the specified distance. Post-processing involves the removal of support structures either by manual breaking or submersion in detergent solutions.

Laminated Object Manufacturing. LOM can be used for both plastic and metal laminates. It involves cutting successive layers to shape with a knife or laser cutter. After each layer is cut, the platform is lowered and a new sheet is rolled over the top and adhered to the part. This is a low-cost process, and laminate sheets are some of the most readily available feed materials. It also requires minimal post-processing, though dimensional accuracy is slightly lower.

Metal Printing Systems

SLM and DMLS. Selective laser melting (SLM) is comparable to SLS powder bed technology, except that, as the name implies, SLM fully melts the powder. This changes the crystalline structure, porosity, and other characteristics of the final part. Direct metal laser sintering (DMLS) is similar to SLM, and the line between them is not universally accepted. The terms may be used interchangeably, or DMLS may apply to more fully-dense parts made with thinner layers, smaller powder diameters, and no binding agents. Post-processing generally involves standard surface finishing techniques such as abrasive blasting, electroplating, CNC and micro-machining, and polishing [Agarwala et al., 1995; S. Kumar, 2003]. DMLS parts are also often heat-treated to relieve stresses and age harden. Binder jetting is another related technology that deposits glue along what would be the laser sintering geometry. It is relatively less expensive, but is uncommon in high-performance applications due to its density and the need to infuse bronze.

LENS Printing. Direct metal deposition or laser powder forming, which is typically known by the proprietary term laser engineered net shaping (LENS), is similar in concept to FDM. It uses a laser beam guided through a coaxial deposition head. The deposition head delivers metal powder to the melt pool via either gravity or a pressurized inert gas. The gas also serves to shield the melt pool from oxidation. (The LENS chamber is also atmospherically controlled.) Rather than moving the nozzle and laser, the platform with the attached part moves in both the *x* and *y* direction in addition to the *z* direction. Variations include using metal wire instead of powder or an electron beam instead of a laser. A type of the latter technology is also known as electron beam melting (EBM). Electron beam free-form fabrication uses a setup similar to EBM printing, but the metal feed is via an off-axis metal wire.

LENS systems have the advantage of being able to alter alloy composition throughout a single build process. LENS printing, as the name implies, creates near-net shapes that usually require conventional finishing. It also requires support structures where necessary, and these may need to be substantial given the ability to print large and heavy parts. However, LENS parts do have the distinct advantage of being fully dense with similar or better metallurgical properties than the raw stock. LENS also allows for some of the largest prints, up to several feet for some printers—which also necessitates large, expensive machines and consumables.

Accessibility of AM Technologies

Plastic Printing. The accessibility of AM for public, industrial, and foreign use varies widely based on the printing technology. In terms of plastic printing, both stereolithography and FDM are available as desktop consumer printers. The former is used primarily for prototyping, while FDM can also produce small batches of final parts. Even professional models of these systems are readily available, both in terms of printers and consumables. In contrast, SLS plastic printers are more common in manufacturing facilities, as the lasers required must be of higher power.

U.S.-based companies are dominant across the plastic printing marketplace, although one of the leading consumer brands (Ultimaker) is from The Netherlands. A leading industrial brand, Objet, is headquartered in Israel, though it is now owned by the Minnesota-based Stratasys Corporation. China also produces its own consumer and industrial plastic printers. Printer use is apparently popular in consumer and industry markets, but the scale and quality of domestic sale is not well known. Chinese corporations are setting records in the field however, including unveiling the world’s largest 3D printer at a 2014 World Exhibition in Qingdao. It is designed to build entire houses from glass-reinforced plastic [*3Ders News* 2014b]. Another firm revealed a five-story apartment building printed from recycled construction materials [Davison, 2015; Stampler, 2015]. With regard to U.S. export, the International Traffic in Arms Regulations (ITAR) and Directorate of Defense Trade Controls focus on arms-related printing designs rather than on printers themselves [Masero, 2014; Osborn, 2014]. Specifically, the U.S. Department of State required that printing instructions for the first all-plastic 3D printed gun (a Category I pistol) be removed from internet sites. This situation is now a pending lawsuit concerning ITAR as of May 2015, but the Department of Homeland Security warns practically that “limiting access may be impossible" [Bilton, 2014; Greenberg, 2013]. Similar accessibility issues are also being examined from an intellectual property and legal standpoint [Hornick and Roland, 2013; Depoorter, 2015; Kurfess and Cass, 2014; Bradshaw, Bowyer, and Haufe, 2010].

Metal Printing. Current metal 3D printers are far more expensive and complex than their plastic counterparts. Metal printers also tend to be larger on average, and desktop models are currently uncommon [Morris, 2015]. The only potentially consumer grade model is open-source from Michigan Technological University (MTU) [Goodrich, 2013]. This type of open-source project can progress quickly and without major public attention, but the underlying technology of the MTU printer relies on a commercial MIG welder. This inherently limits effectiveness compared to more controlled and specialized technologies, and MTU's resolution is bounded by MIG wire diameter (approximately 0.6mm) [Anzalone et al., 2013]. There is no current project that attempts to bring high-performance metal AM into the consumer market.

High-performance metal AM printers are all contained within universities, government research facilities, major corporations, and specialized service companies that are ITAR certified. For comparison to plastic pistol, the first AM metal pistol consists of thirty-three DMLS titanium and Inconel parts. In fact, the 3D printed M1911 uses seven fewer parts than the factory version and withstands 20,000 psi per shot—exceeding the factory version's rating by 3,000 psi. On the other hand, Solid Concepts only made 100 and sold each for $11,900. Table 1 compares the first metal and plastic pistols as an exemplar of the main tradeoffs between the two technologies.

Consumables are an additional accessibility limitation for metal printers. Most notably, feedstock is more expensive and specialized, as powder quality is based on grain size and uniformity, fluidity, and packing density. In addition, current technologies rely on highly controlled inert gas or vacuum environments, usually by way of consumable shielding gas. Both the standard powders and inert gas are openly available, and their costs will likely drop as metal technologies develop and disperse.

However, the need for trained operators and the complexity of proper consumable use is likely to still limit diffusion throughout the market vis-à-vis plastic printing. Use will remain concentrated within the realms research and manufacturing for the foreseeable future. This is an international domain however, including several records set by China in specialized aerospace applications. These and other current applications are described in Chapter 3.

Table 1 Comparison of first publically known plastic and metal AM pistols to the metal version's conventional counterpart. The highlighted factors represent the tradeoffs between plastic and metal printing technologies and conventional manufacturing. *Conventional unit price is the sale price to the U.S. Army in 2013 dollars. Conventional service life is for the modern MEU(SOC) model. There are many variations of the military standard issue M1911, which itself changed over time. [Colt's Manufacturing, 2003; Slowik, 2012; National Rifle Association, n.d.; Dodson, 2013; Mearian, 2013; Gibbs, 2013].**Error! Bookmark not defined.**

	AM Plastic "Liberator" Pistol	**AM Metal M1911 Pistol**	**Conventional M1911 Pistol**
Provider	Defense Distributed (publisher)	Solid Concepts (manufacturer)	Colt's Manufacturing Company
Release date	May 2013	November 2013	1911
# Produced	Unlimited from public domain plans	100	2.7 million
Technology	Multiple from ABS or other plastic	DMLS from stainless steel & Inconel	Varied (including CNC) from steel
Part count	16 (15 printed)	33 (all printed)	approx. 50
Unit price	$25	$11,900	approx. $350*
Printer price	approx. $2,000	approx. $700,000	N/A
Cartridge	.380 ACP (single shot)	.45 ACP (7 rounds)	.45 ACP (7 rounds)
Service life	≥9 rounds	≥5000 rounds	≥150000 rounds*
Accessibility	Pending lawsuit; plans uncontrollable in public domain	Sold in accordance with ITAR and Federal Firearms Licensing	Standard issue 1911-1986; still available

Chapter 3

Metal AM Aerospace Applications

AM began as a method of rapidly prototyping new parts and complex geometries. This is still the most common application for virtually all AM technologies, but there is also a slow development towards employing components as final use parts. This chapter provides key examples of AM parts in industry and government in the U.S. and abroad, with emphasis on the industrial astronautics and the U.S. Air Force.

It is important to note two of the main factors that separate aerospace AM from other AM applications. The first is the performance requirements and operating conditions of aerospace components, and specifically the high standards and certifying requirements that accompany them. Aerospace represents an extreme use of AM in terms of low defect rates, high performance, and low component weights. However, it also leverages AM's main advantage: the ability to increase complexity at little to no additional manufacturing cost. The second issue relates to the production volumes and throughput rates achievable with AM. Though AM speeds are increasing, they will not reach the efficiencies of die-casting and other high-volume methods in the foreseeable future. However, aerospace and particularly astronautics require inherently lower part quantities than other industries. For instance, automotive manufacturing also includes high safety standards, but General Motors alone sold 9.9 million cars in 2014, whereas had only been 6039 space launches *total* as of 2009 [Rhodan, 2015; Noland, 2009]. In combination, the high performance requirements and lower part quantities mean that astronautics is among the best-suited industries for AM at this time.

Industrial Aeronautics

Virtually all of the publicly accessible early progress in defense-applicable AM research has been conducted within industry, much of it without DOD contracts. Most notably, Aerojet Rocketdyne successfully hot-fire tested a completely 3D printed, three-part rocket engine in 2014 [Aerojet Rocketdyne, 2015]. Airbus is replacing 1,000 parts on its flagship A350 XWB aircraft with FDM printed components [Krassenstein, 2015]. That same airframe is also adding titanium DMLS printed parts [Jordan, 2014]. General Electric has invested in producing AM jet engine fuel nozzles at a current output of 1,000 per year in 2014 but with plans to reach 40,000 per year by 2020 [Norris, 2014]. The most advanced avenue of AM production though is still in plastic, primarily SLS printed plastic. As of 2015, Boeing has approximately 20,000 plastic AM parts on aircraft across 10 different production programs [Krassenstein, 2015]. In 2014, its Dreamliner set the industry record of 30 3D printed parts [Walsh, 2014].

Industrial Astronautics

Airbus has developed titanium DMLS brackets for mounting carbon fiber reflectors to satellite bodies. The new design has reduced cost, production time, and weight by approximately 20% each while maintaining thermal resistance and mechanical load capacity [*3Ders News* 2014a]. Airbus U.K. has also developed aluminum brackets that are 35% lighter and 40% stiffer for the Eurostar satellite. These brackets are the first flight qualified part to be printed in additive layer manufacturing, a technology related to EBM printing [Airbus, 2015]. As of 2014, Boeing is also 3D printing brackets for spacecraft, though it declines to comment on the details [Tadjdeh, 2014].

Lockheed Martin is likely the current public leader in AM astronautics, though most of its work in contracted from NASA. Most notably, they already have a dozen titanium EBM brackets aboard NASA's Juno spacecraft. As of 2014, Lockheed Martin is also prototyping one of the largest AM spacecraft parts, a 7-foot forward bay door for NASA's Orion Multi-Purpose Crew Vehicle [Tadjdeh, 2014]. Lockheed Martin is also testing a satellite bus, the A2100, of which more than half is 3D printed. For subsystems, this process has reduced part counts by 60%. Production time and manual finishing operations for parts ranging from brackets to antenna reflectors to fuel tanks have been cut from months to weeks or days to hours [Svitak, 2014].

U.S. Air Force

The U.S. military started publically researching and funding AM research only a few years ago, but AM parts are already being used as tools for construction of the F-35 and as prototypes for operational aircraft repairs [Krassenstein, 2015]. For instance, the 309th Maintenance Wing began using a powerful FDM printer in 2014 to make and test reverse engineered repair parts for their airframes. Northrop Grumman uses AM air ducts on its X-47B stealth drone. In addition, 900 components on the F-35 have been identified as suitable for AM [*The Economist Technology Quarterly* 2013]. For instance, Phillips Service Industries is pursing EBM printing flaperon spars are that estimated to save the USAF $100 million for each plane over its lifetime according to Lockheed Martin [Kaelin, 2013c]. 3D Systems demonstrated to the Air Force Research Lab (AFRL) in 2012 that it could use SLS printing to transition a number of F-35 components from qualification into production. It also has another contract to examine DMLS printing of an aircraft heat exchanger. The weight reduction provided by these integrated

AM parts will enhance fuel efficiency and maneuverability while reducing cost and assembly time. The conformal structures still provide high impact durability and thermal resistance [Naramore, 2012]. However, flight readiness is contingent on adequate non-destructing testing procedures [*The Economist Technology Quarterly* 2013; Waller et al., 2014]. Non-destructive testing is discussed in Chapter 5 as an interdiction point in the proliferation of advanced AM components. To date, the only operational fighter jet to fly with metal AM parts is the U.K. Royal Air Force Tornado (see below).

U.S. National Aeronautics and Space Administration

NASA is developing technologies both for printing spacecraft parts on Earth and for 3D printing in space. In 2014 and 2015, astronauts aboard the International Space Station 3D printed 25 parts using a microgravity-adapted FDM printer [Millsaps, 2015; Dunn, 2011]. This illustrates how AM's onsite manufacturing capabilities are of benefit in resource-constrained environments where storage and transportation are limited. A printer and feedstock take up far less room than pre-made spare parts, whether on the International Space Station or a forward air base in Afghanistan.

Though in-space manufacturing is still in its infancy, Earth-based AM is mature for a number of minor aerospace parts. Flown parts include Lockheed Martin's EBM brackets aboard Juno and plastic battery case aboard a sounding rocket [Committee on Space-Based Additive Manufacturing, 2014; Keesey, 2014]. NASA Langley is also the facility that developed EBF3 printing [Keesey, 2014], and Goddard is working on DMLS for instrument structures and radiation spot shielding [Waller et al., 2014]. The Human-Supporting Rover intended for use on

Mars also includes FDM parts, and NASA has hot-tested DMLS rocket fuel injectors [Stratasys, 2013; Hutchinson, 2013]. In 2015, it also SLM printed the first full-scale rocket engine part make of copper, an uncommon material in AM [McMahan, 2015].

Aeronautics in the U.S. Navy and Army

In 2013, a typical U.S. Navy F/A-18 fighter jet had approximately 90 AM parts onboard [*The Economist Technology Quarterly* 2013; U.S. Navy, 2009]. The Navy has also installed its first 3D printer shipboard, on an amphibious assault warship, though it is still years away from printing repair parts for ships, aircraft, or unmanned aerial vehicles [Weisgerber, 2014]. The Army is equally if not more invested in AM, including forward deploying printers to Afghanistan and developing AM repair procedures for air and ground vehicles [*Defense Systems* 2012; Breeden, 2013].

Aerospace in Allied Countries

Other countries, including those that are and are not major U.S. allies, have also invested in aerospace AM development. Most notably, the U.K. Royal Air Force flew the first metal AM parts on a fighter jet in 2014. The RAF Tornado flew with an AM stainless-steel camera bracket as well as number of plastic AM components including protective guards and support struts [BAE Systems, 2014; “3D Printing Bringing Opportunities Across the Board” 2014]. Also in 2014, the U.K.’s Advanced Manufacturing Research Center FDM printed a fixed wing UAV [Advanced Manufacturing Research Center, 2014]. A U.K. contractor for Rolls-Royce has printed and intends to fly the largest AM structure ever flown: a titanium engine structure 1.5

meters in diameter and 0.5 meters thick [Molitch-Hou, 2015]. In 2013, Cranfield University and BAE Systems in the U.K. printed a 1.2-meter spar section via a unique printing method related to EBF3 [BAE Systems, 2014; J. Chen, 2012]. In 2015, an Australian university working for a French company made the first AM gas turbine jet engine via SLM [Milman, 2015].

Aerospace in Other-Than-Allied Countries

China the only government actively engaged in AM for aerospace that is neither a NATO nor major non-NATO ally. Much of the information on these activities is not independently reviewable or confirmable, though some objects have been publically displayed. In 2013, a government-funded company publically displayed at an international expo what is apparently the world's largest titanium AM part. Presenters at China's International High-tech Expo claim that it is a critical component of the military's J-20 or J-31 fifth-generation stealth fighter [Grevatt, 2014]. (The J-31 bears a "striking resemblance" to the U.S.'s fifth-generation fighter, the F-35 [Wendell Minnick, 2015].) The People's Liberation Army also claims that the J-20's advantages over the U.S.'s F-22 are due largely to the stealth and lighter weight afforded by AM parts in the fuselage [Krassenstein, 2014]. The J-20's parts have not been publically displayed.

Additional Chinese claims purport to use AM for training flight repairs to the new J-15 aircraft-carrier based fighter [Goehrke, 2015]. Separately, the chief architect of the J-15 revealed that 3D printing was used in designing and producing the air defense fighter [*3Ders News* 2013a]. (This is a different claim, as design and production can refer to AM tools and prototype parts.) Outside of the military, a Chinese government-controlled university printed and internationally displayed a 5-meter AM titanium wing spar for a Comac commercial airliner—

four months before BAE Systems U.K. revealed their 1.2-meter spar [*3Ders News* 2013a]. The China National Space Administration also reportedly uses AM seats for astronauts during space launches [Kaelin, 2013b].

Future Trajectories of AM in the U.S. Government

The U.S. military has fully embraced researching 3D printing for various current and future applications. The Air Force Research Laboratory supports research for additively manufactured spacecraft, particularly for modifying commercial off-the-shelf parts, for instance with printing radiation shielding on commercial parts [Kaelin, 2013a]. Lockheed Martin wants to cut the production time for complex military satellites in half with AM, from 8 years to under 5 [Leone, 2015]. NASA is investigating options for printing materials mined from asteroids, and Air Force officials anticipate AM will “bend the cost curve” and free up additional manpower [Siceloff, 2013; Clark, 2014].

The Army, for its part, is moving AM to the frontlines in ways that are also of interest for Air Force forward air bases and U.S. Navy ships. AM can shorten supply chains, particularly for interim replacement parts. Currently a single broken bracket at a forward-deployed post can take weeks to replace [Calloway, 2013]. Army researchers are also investigating printing food in isolated locations as a way to drastically reduce waste and transport requirements.

Many AM research areas are less about the frontline than the cutting edge. U.S.-based Army researchers are working to print sensors on equipment, munitions, and clothing. In particular, the potential for directly printing electronics onto parts could reduce cost, time, and hazardous chemical use for critical materiel. The eventual goal of this research is to reduce production infrastructure so far that an entire weapon system can be produced within a single manufacturing station [Calloway, 2013]. The Army is also funding investigation of 4-D printed materials, or those that can adapt to their environments in terms of water, light, or temperature [Fedele, 2013].

Chapter 4

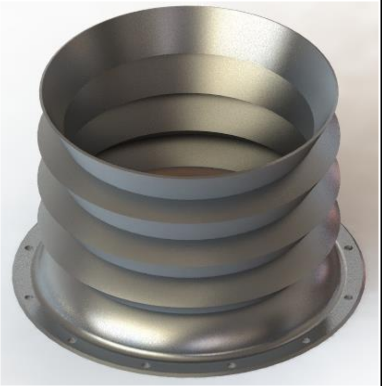
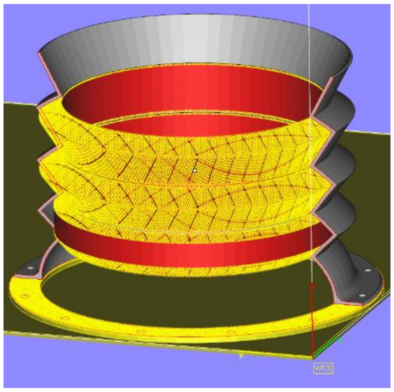
Storage and Repeatability of Digital AM Information

Additive manufacturing enables skilled engineers and practitioners to redefine how products are designed and produced. For example, satellite brackets once welded together from eight different parts can be printed as a single unit with less time, material, and labor. The complex geometry of a stray light baffle or a remotely piloted vehicle airfoil can be printed directly, minimizing the need for manual machining. Skilled operators are still needed to setup and monitor printers and to supervise post-processing, but printing itself is largely autonomous. Much of the information required for that autonomy is stored in and deployed from digital file formats. This has the potential to open more intellectual property to the risks of cyberattack, including espionage and sabotage. Moreover, current efforts in industry and academia involve both automatically generating machine code from models and reserve-deriving full designs from machine code.

Digital Files in AM Processes

The process of designing and building an AM component involves a number of different digital file formats, each of which contain different information and present different risks in the event of a cybersecurity incident. In general, the amount of manufacturing specificity in a file is inversely proportional to its ease of interpretability. For instance, CAD files do not include any AM-specific parameters, but will model and label specific features as “Fillet1” or even (if named by the user) “baffle baseplate fillet”. In contrast, machine code provides all print settings but is specific to a given machine make/model and specifies only programming objects such as tool paths (or the equivalent for a different printing technology). The specific files are discussed below and displayed in Table 2.

Table 2 Types of AM files by level of intellectual property and ease of adaptability. The images reflect the process of printing an astronautical stray light baffle. The AM build file was created by CIMP-3D at the Pennsylvania State University. The baffle was printed on an EOS M280, pictured above, whose code is proprietary [EOS, n.d.].

		
CAD Design Files Geometric Features History and Parameters Units and Tolerances Annotation and Labels Material Properties	**AM Build Files** Part Orientation & Subdivision Support Structures *Future Possibilities:* Materials, Units, Tolerances, Buildability	**Printer Machine Code** Laser/Tool Paths Laser/Tool Specifications Feed Specifications Printer Parameters Layer Divisions

Specificity and Exposure of Intellectual Property

Ease of Interpretability and Adaptability

Design (CAD) Files. Design or computer-aided drafting (CAD) file formats are proprietary, but virtually all of them can be read easily, often with free software. (Editing legally is more expensive.) CAD files include the part geometry itself and signals of its design intent by way of the order and type of digital features (cuts, extrudes, fillets, etc.) used to create it. They can also include tolerance and material information. CAD assembly files include the constraints between part surfaces but do not include the parts themselves.

Conversion Files. CAD files cannot be read into AM processes directly. The current translation file format is called STL, named for stereolithographic printing. STL files describe only the final surface geometry by way of three-dimensional Cartesian triangles. Files include no design intent information or intermediate drafting steps. In fact, they include no scale, material, or unit system information, though the designer can set its resolution and a few other parameters. Most conversion errors can be corrected automatically by software packages, though some very complex parts may require manual intervention [Gibson, Rosen, and Stucker, 2010]. Conversion failures can severely affect prints. This is the file type with the least intellectual property.

Build Files. Build files are currently the same file format as STL conversions files; the difference is functional rather than technical. Once an STL design is sent to a printer operator, the operator may have to modify it slightly. This is usually done on-site, and many printers include integrated software for this purpose. Different technologies and even different vendors have different build software, but if the data are again returned to a universal file format before building, that format is typically STL. Such a file would include part reorientation, modified or generated support structures, small scale change to compensate part shrinkage and coatings, and parts combinations or divisions for printing in a single build session.

Alternatives to STL Files. STL is currently the de facto standard in the AM community, but there is some competition, particularly from STEP (ISO 10303), which is already the international standard for trading CAD files. STEP files still do not include digital design tools, but they can include intermediate sketches and bodies, simulation results, and annotations, among other features. They also have the basic information about scale and units that is omitted from current STL files. A third alternative is XML (ASTM F2915). XML uses the same basic triangular mesh approach as STL files, but can also describe curved triangles. (In STL files, the resolution for planar triangles is typically just set higher than the resolution of the printer, but these files are larger than their XML counterparts.) For the purposes of this thesis, the most notable differences between STL and XML is that XML files are self-describing, human readable, and can include multiple material specifications.

Future Trajectories in AM Digital Information

Most of the current developments in AM file types are in the space between STL and G-code information. ASTM International is supporting the development and implementation of the XML file format known as AMF (Additive Manufacturing File). There has also been some additional work into non-proprietary methods of slicing files into printable layers [Nassar and Reutzel, 2013; Topçu, Taşcıoğlu, and Ünver, 2011]. Other efforts involve pursuing layerless alternatives and generic tool path software [Y. Chen, Zhou, and Lao, 2011; Liu, Fan, and Lu, 2014]. STL files will almost certainly be replaced eventually, though the time horizon is unclear. For future planning though, there is a reasonable expectation that the ubiquitous and universally traded file format will include information similar to that which is being considered for the AMF file type. In other words, it is likely to include at least units, materials, and tolerances if not also buildability verification.

It is critical to understand the potential evolution to more uniform and/or comprehensive of file types, as this will intensify another issue of AM cybersecurity. Though each file type on the process diagram (Figure 1) contains increasingly more specific intellectual property, there have been some efforts already to reserve engineer between file types. For instance, accurate reserve engineering would allow a cyberespionage agent to covert stolen machine code from one machine make and model to another. It would essentially remove the barriers to use of machine code by deciphering a full CAD design with all the necessary AM build structures and the machine parameters, all in a language that the user could comprehend and put to new use. While this is currently impractical, it is unclear who might develop the capability or when.

Future Trajectories of AM Cybersecurity

There are a number of cybersecurity risks to AM files including data exfiltration, denial, and sabotage. Data exfiltration is of particular concern to AM, as it may allow unintended users to “just press print” and manufacture sensitive equipment. The readability and employability of AM files by unintended actors is likely to change as the field develops and is not easily predictable. However, one way to examine the industry’s future trajectory is by analogy to previous technologies. Most usefully, AM is not the first highly automated manufacturing process in industry or government. Computer Numerical Control (CNC) machining is the subtractive equivalent of AM, and uses machine code to specify parameters such as tools paths and material feed rates. In fact, CNC and AM use similar files and processes for computer-aided drafting (CAD) design and generating machine code. As such, digital files used for CNCing pose similar cybersecurity risks to those for AM. In addition, the more than half-century existence of CNC technology provides some insight into the evolution of digital information processing. Over the years, CNC engineering professionals have developed methods of optimizing machine code in order to determine how best to physically manufacture a part [S. P. L. Kumar, Jerald, and Kumanan, 2014; Balic, Kovacic, and Vaupotic, 2006; Klancnik et al., 2012]. These programming processes are far more advanced than current AM software’s ability with some

CAD models to orient and add support structures [Sheen and You, 2006; Bao, 2013; Zhang, Nassehi, and Newman, 2014].

Some CNC programming advances also include sophisticated feature recognition, and researchers have already applied this to extrapolating (reverse engineering) part models from machine code [Sheen and You, 2006; Bao, 2013; Zhang, Nassehi, and Newman, 2014]. It is possible that a physical part could even be scanned and reverse engineered into AM code, which is already possible with some CAD programs [Stackpole, 2014; SolidWorks, n.d.]. This sort of feature recognition, whether from a machine code or physical part, is the main risk for AM. In fact, within digital media the risk to AM is relatively larger because more information is contained in digital files. For instance, CNC reverse engineering only works properly if the engineer also knows the raw material and the geometry of each tool. This information is not contained in the machine code. In contrast, AM reserve engineering only requires the machine code (from which one can determine the printer involved) and the material alloy. And for machines that mix their own alloys, that type of information is also included in the code. Intellectual tools to accurately reverse engineer complex AM parts do not yet exist publically. However, given the competition in AM and the early attempts at sharing even sensitive information (e.g. plastic firearms), it is likely that AM reserve engineering will follow a path similar to that of CNC. This is thus an important cybersecurity issue as more intellectual property is converted into digital AM information.

Repeatability of AM from Digital Information

Despite the “just press print” impression of 3D printing, many factors can contribute to the production of widely disparate parts from the same digital data. First, a significant level of intellectual property goes into converting CAD design files into printable code. While there are some widely known best practices with regard to part orientation and support structures for different AM technologies, professional shops can reasonably develop very different print models for even moderately complex parts. This can result from different trade-offs in terms of geometric fidelity or material characteristics. Even when these are specified however, there are also variations due to in-house techniques, prices, materials, and technologies. In addition, these difficulties are compounded by the lack of new inspection procedures that directly address AM’s potential failure modes in terms of physical geometry and material properties. These issues are discussed as intellectual interdiction points in Chapter 5. The chief experimental focus of this thesis, however, is the issue of physical repeatability in AM: namely the potential for the same machine code on the same machine to generate significant but unknown variations between batches of parts.

Chapter 5

Interdiction Points in Additive Manufacturing

The physical supply chains and information dissemination processes of AM are complex and still rapidly developing. Leverage points for controlling these routes also differ based on the type of aforementioned AM technology, most notably for consumer-grade versus aerospace-grade production. This chapter synthesizes the previous discussion of AM technology, current and future applications, and digital information storage to evaluate potential physical and intellectual interdiction points for controlling access to high-performance aerospace AM capabilities. Topics include printers and their physical environment, printer consumables, post-processing and inspection, and design for AM. Traditional protocols regarding the protection of intellectual property, trade secrets, and national security would also apply within their given purviews.

Printers and Work Environment

Currently, all printers that produce advanced AM parts (e.g., for aerospace) require well-trained operators working in controlled and supportive environments. Foreign object damage (FOD) can affect both feedstock and printer components, including print beds [Chianrabutra, Mellor, and Yang, 2014]. In addition, high-performance metal feedstock reacts to chemicals and humidity and requires care in storage, dispensing, and excess capture for recycling. This is in contrast to current desktop plastic printers, which can be more forgiving about user error: even if a part fails, the printer itself requires less expertise to avoid irreparable breakage.

Installing a metal printer is also a significant undertaking in and of itself. Major machines can be the size of a small room, and even lower-capacity printers require professional care. Most printers are installed in controlled manufacturing or research settings, and vendors offer installation, service, and featuring licensing agreements to use and maintain them properly [Moylan, Jurrens, and Cooke, 2013; Carnegie Mellon University, 2012]. This becomes a possible interdiction point in itself, as almost all major multinational companies involved in metal AM unit manufacturing and maintenance are based on the U.S. or allied nations. However, China makes its own AM technologies, principally for domestic use as described in Chapter 3. This demonstrates that wholesale monopolization of even high-performance the technology is not feasible, and counterproliferation will have to rely on a wider spectrum of tactics.

Future Trajectory: Outside of the U.S. military, there is minimal public push for metal printers able to operate in austere (minimally controlled) environments. However, there is some movement towards printer models for non-research/industrial use. This does not mean that high-performance metal printers will be on the average consumer or even prosumer’s desktop within the foreseeable future of technical development. Rather, it is likely that the industry will follow the general path of technologies like CNC machining and plastic printing: prices drop to the point where smaller businesses can invest in the infrastructure. This is likely to create a push for open-source designs, as it did in its plastic AM counterpart.

Outside of efforts by the U.S. Army, there is no public push towards commercially available printers for austere environments. Nonetheless, some advancements in usability and failure point reduction could make austere use more viable for high-performance printers. For instance, current trajectories indicate that design for installation and maintenance will improve and more best practices will be quickly developed. In addition, logistical simplifications in terms of changing feedstock will reduce the risk of FOD by making the systems more self-contained and error tolerant. Industrial printer models already vary some in the logistics consumables like feedstock: some are highly self-contained, while others can easily result in powder lingering in the air and on the floor. As the ease of using industrial printers improves, it will also become easier to maintain suitable printing environments outside of industry and academia.

Consumable Accesses and Parameter Settings

AM feed material is carefully developed to produce the best results for specific technologies. This includes certifications and standards, such as AS 9100 and AS 9120 for aerospace applications, but these are far from comprehensive [SolidConcepts, 2013; Uriondo, Esperon-Miguez, and Perinpanayagam, 2015]. In terms of interdiction, individual applications should be tested directly to determine the performance drop-off between specialized/proprietary powders and uncertified or “knock-off” variants. Some studies have begun powder characterizations, but not to the extent needed for specific policy setting [Strondl et al., 2015; Slotwinski, 2013; Clayton, Millington-Smith, and Armstrong, 2015]. There is also some work into experimental replacement powders [Sun et al., 2015; Tong et al., 2015]. Without testing third-party substitutes in an operational setting, feedstock cannot be considered a full-stop interdiction point.

Another concern with AM powder is the original raw material. High performance AM powders such as titanium 6-4 and Inconel 718 are more complex and generally more expensive than counterpart forms suck as bar stock. For instance, powder characteristics also affect the printers themselves, for instance whether or not nozzles clog or deteriorate [Reutzel et al., 2012;

Quan et al., 2015]. Printer lifetime could thus be compromised by incorrect recycling powder, potentially to the point of damaging nozzles. Even if an operator avoids immediate or catastrophic failure, the lifetime of printer mechanisms is likely to decrease. However, they still rely on the availability of titanium, nickel, and chromium, and other elements found is highest abundance internationally. As Table 3 shows, the locations of these large natural deposits mean that feedstock supply chains cannot by fully controlled domestically.

Table 3 Top five countries for the production of different aerospace metals as of 2014. Rankings are by gross weight of mine production; NATO and major non-NATO allies are highlighted in green [U.S. Geological Survey, 2015; Papp, 2012].

Titanium	**Nickel**	**Chromium**	**Molybdenum**
China	Philippines	South Africa	China
Russia	Russia	Kazakhstan	USA
Japan	Indonesia	India	Chile
Kazakhstan	Canada	Turkey	Peru
Ukraine	Australia	(unlisted, Russia as of 2012)	Mexico

Recycling powders is one way to minimize the need for foreign raw stock as well as reduce material waste and production cost. This is a unique advantage of AM, specifically that powder that is not used in one print (e.g. is on the printer bed but not contacted by the laser) can be reused for subsequent parts. However, effective recycling requires specialized quality control to maintain proper alloying ratios as well as grain and thermal characteristics [Cooke and Slotwinski, 2012; Hunter, 2014; Tang et al., 2015].

AM technologies also use other consumables, but most pose fewer complexities and risks than the feedstock. For instance, many metal printers use a shielding gas such as argon or nitrogen to prevent oxidation. Use parameters depend on the build process, and part failure is likely with no gas or with improper settings. However, many machines help minimize user error by monitoring oxygen content, and it is common to test the printing until the environment is correct [EOS, n.d.; Optomec, n.d.].

As has been alluded, many performance variations center on the machine operator’s skill with the printer and consumables rather on the quality of the materials themselves. This is important, as AM’s use of skilled labor differs from that of conventional manufacturing. On one level, AM requires less of such labor, as technician time is flat per printing batch rather than dependent on component complexity. Similar transitions into automation have previously challenged U.S. competitive advantages, as with the Japanese automotive industry’s embrace of automation in the mid-1900s [Cusumano, 1988; Daito, 2000].

Despite the advancements of automation, there are some noteworthy intellectual interdiction points in current AM technologies. Setting up a new high-performance metal print job with its feedstock or supporting consumables and their respective parameters can be a full day or multi-day task for today’s trained operators. This involves the correct selection of laser or tool parameters, proper use of shielding gas, and adjustment for different feedstocks. For instance, while printer may be capable of handling feedstock A or feedstock B, changing between them currently requires great care and sometimes as much art as science. One professional described the question of “what can an untrained operator do incorrectly?” as “how many ways can a non-pilot crash an airplane?”

Future Trajectory. Vendors are already trying to streamline material handling and refilling feedstock. This work is likely to progress quickly as design foci begin to shift away from breaking technical barriers to producing useable and less user-intensive machines. There are no major technical barriers to making standard filling processes more straightforward and self-contained, and the current marketplace already has some variation across these metrics. It is also possible that more effort will be put towards standardizing recycling procedures. In-house recycling is already common at service shops, but there is a dearth of industry standards for different materials and different part uses and quality levels.

On the other hand, there is continued advancement in terms of specialized metal powders and alloys. This development extends beyond differences in conventional alloying (e.g. creating titanium 6-4 or Inconel 718 bar stock) and thus has AM-specific characteristics. For instance, research includes using AM to create alloy gradients and developing specialized control of grain characteristics [Hofmann et al., 2014; LPW Press Office, 2015; QuesTek, n.d.; Sun et al., 2015]. This is likely to remain a major research area for AM. As such, specialized feeds with unique quality characteristics may remain controllable into the future. Prices are also likely to remain high, as the commodities themselves (titanium, Inconel) are expensive. This may serve as a leverage point for controlling distribution, but high cost is still a limiting factor in overall use.

Post-Processing and Inspection

Though AM techniques can reduce part count, cost, and production time, most components cannot currently be printed in their final form. Even simple parts require traditional machining to improve surface finish, and some applications need heat treatment to change mechanical properties. Different printing technologies also require their own specific post-processing techniques. For instance, some SLS/SLM parts are infiltrated after printing to improve density and mechanical properties [Zarringhalam and Hopkinson, 2003; Khaing, Fuh, and Lu, 2001]. LENS printing can make fully dense parts, but requires subtractive machining to meet the final geometric tolerances [Mazumder et al., 2000]. These processes can be labor intensive and complex, and supplies and skillsets may be open to interdiction as with AM techniques above. However, the popularity of commonly needed post-processing equipment (for surface finishing, annealing, etc.) and the variation in application-specific requirements limit this as an avenue for broad counterproliferation.

The more promising avenue of post-printing control is with nondestructive inspection (NDI). Quality assurance is as critical with any high-performance component, but AM poses unique challenges that are not yet well understood [Berumen et al., 2010; Schmid and Levy, 2012; Cooper and Wachter, 2014; Mahesh et al., 2015]. Both industry and governmental organizations are attempting to address these challenges [ASTM International, 2014; Lang, 2015]. NASA identifies the top challenges as AM-specific properties, differences in defect causes, and lack of standardized monitoring and procedures [Waller et al., 2014]. In particular, AM allows for complex internal channels, lattice structures, and thin walls. The additive techniques also create complicated and variable grain structures, porosity, and surface characteristics. These grain and geometrical issues both cause different types of defects whose critical characteristics, sizes, and shapes are not yet well understood [Todorov et al., 2014].

Future Trajectory. AM post-processing techniques are still under development, but current procedures offer limited interdiction potential. Most AM techniques are similar to their conventionally-manufactured counterparts, such as subtractive machining, blasting, coating, and electroplating. While these machines can be expensive, they are widely available for conventional manufacturing. Proprietary and complex procedures may be controlled as other similar intellectual property, particularly given the infancy of the industry.

The mechanical and physical effects of AM are currently not well characterized, and the field has limited studies on defect and probabilities of detection. This means there are few AM inspection procedures, reference standards, and during-print monitoring techniques. Although current processes use conventional equipment, the uniqueness of AM grain and geometric structures are likely to lead to AM-specific inspection and monitoring requirements. For instance, current research is focused on in-process monitoring of printing quality [Bi, Sun, and Gasser, 2013; Groom, 2014; Dunskey, 2014; Tapia and Elwany, 2014; Rao et al., 2015; Jahns, 2015]. Depending on the determined defect rates and risks, these specialized processes and skills may become a unique and controllable part of high-performance AM production chains.

Part Orientation and Support Structure Design

Selecting the correct part orientation is a critical and highly technology-dependent challenge in AM. Orientation changes affect surface and build times for almost all AM technologies, albeit in different ways. On a general level, orientation is a tradeoff with time, as height in *z* (the printer's build direction) corresponds to build time. Downward-facing surfaces will almost always have poorer surface finishes than upward-facing ones due to gravitational forces (for parts printed on or near Earth) [Gibson, Rosen, and Stucker, 2010]. For complex parts, it can be a judgment call of which features are the most important to preserve.

In technologies that require support structures, orientation changes also require different supports that may have varied effectiveness, material use, build time, and removal requirements. Removed supports also affect the finish of the surfaces against which they were built. (However, most surface finish issues already are or can be addressed in post-processing.)

Part orientation also matters when the printer in use is not the one for which the part was designed. Different printers have different maximum bounds in each Cartesian direction.

Therefore, for instance, a 100-mm cylinder intended to be oriented vertically must be printed horizontally on a printer whose maximum *z* is less than 100-mm. This changes support requirements and build time (though in this case it would be shorter) and ultimately will likely result in different geometry. A separate alternative to changing orientation for oversized parts is to subdivide them. Redesigns of this type often include specific interlocking features or adhesive surfaces to facilitate reattachment, though this is complicated if the component must handle significant and/or varied load conditions as with other conventional assemblies.

As one of the most basic issues in AM, part orientation is receiving a great deal of studious attention. As such, it is one of the aspects farthest along the transition from art into automation. The more common technologies—which, granted, are also the simpler ones—already have well publicized best practices for part orientation and support structures. Many printer software packages will even automatically generate support structures for a given part orientation [*3Ders News* 2013b]. These can be edited by the user and at this time are suboptimal for sufficiently complex and uncommon parts. While analysis and performance prediction features are not as popular in such programs, as printed material properties become better understood, there is little to stop the automation of these decisions as well.

Future Trajectory. Once a given AM technology is sufficiently popular (among a public that is willing to share its findings), it is unrealistic to consider part orientation as an interdiction point on anything but the most complex components. As desktop plastic printers have demonstrated, the knowledge base on orientation tradeoffs and support structure design is likely to grow and spread quickly via the internet. Higher performance and metal printers also typically allow higher manufacturing tolerances, which make assembly design more straightforward.

Unless engineers deliberately develop design principals that make these tradeoffs complex or deceptively difficult, part orientation and support is not a reliable control point.

Redesign of parts for different printers has the potential to be far more challenging, particularly if the components are subject to complex mechanical or thermal loads. The actual redesign requires operating knowledge of both the equipment and the source files. However, if someone is capable of altering files, simple part divisions and interlocking features may evolve to the point of not only being commonly understood, but even automated. Both this automation and the automation of orientation and support structures will be much further simplified by any “smart” programming for AM that might mimic the advancements in CNC machine code generation part [S. P. L. Kumar, Jerald, and Kumanan, 2014; Balic, Kovacic, and Vaupotic, 2006; Klancnik et al., 2012].

Though it is not a concentration of this thesis, one of the main benefits with AM in general is the ability to conduct high-level redesign of parts. This goes beyond the issues of support structure, orientation, and code optimization. Current advancements involve significant weight savings, part number reductions, and value-added feature changes. These advancements are currently the cutting edge of AM design. For the purposes of this thesis though, these improvements are considered part of the at-risk digital information as these changes are reflected in CAD design files. Nonetheless, it is important to point out that as a field, AM will always include significant intellectual “art”. On the other hand, as a relatively new industry, it will also continue to develop and generate more well-defined, publicized, and even automated best practices.

Chapter 6

Experimental Testing of AM Repeatability

The case study in this thesis is of a reflective stray light baffle, the type used on imaging lenses for space satellites. The titanium 6-4 baffle and five subsize tensile specimens were DMLS printed in a single batch on an EOS M280. The surface dimensions and density of the five tensile specimens and stray light baffle were subsequently tested. In addition, the tensile specimens were tested to failure and indention hardness was measured on multiple locations of each part.

AM Stray Light Baffle Design

Stray light baffles (Figure 1) are used on many orbital satellites as critical components of aerospace imaging technologies [Seiferlin et al., 2007; Greenbaum et al., 2013; Perinati et al., 2008; Irons, Dwyer, and Barsi, 2012; Mei et al., 2011]. The baffle is aligned in front of an imaging lens in order to isolate it by reflecting away all light that enters at an angle (i.e. not from the object under study). This baffle was chosen specifically because its geometric complexity makes it ideal yet challenging for AM. It is composed of three vanes with a diameter of 100 mm, height of 75 mm, and wall thickness of 1 mm. These vanes are formed from a series of nested hyperbolas and concentric ellipses with shared foci, as shown in Figure 1a. This geometry intersects to create seven successive vane edges, each requiring a print angle between approximately 60° to approximately 45° off horizontal. This is a significant issue in DMLS printing, because angles approaching 45° (extending horizontally more than vertically) are not inherently self-supporting and thus require additional structures. The difficulty of support structures in baffles of this type is that the zig-zagging cross-section and enclosed cylindrical shape make removing support structures post-printing difficult. One of the three service shops contacted could not print it properly at the designed wall thickness. For final performance as a stray light baffle, the surface would need to be highly finished and typically coated or plated. However, all testing in this thesis was conducted on the as-printed parts, with the exception of some sanding in order to get accurate hardness measurements.

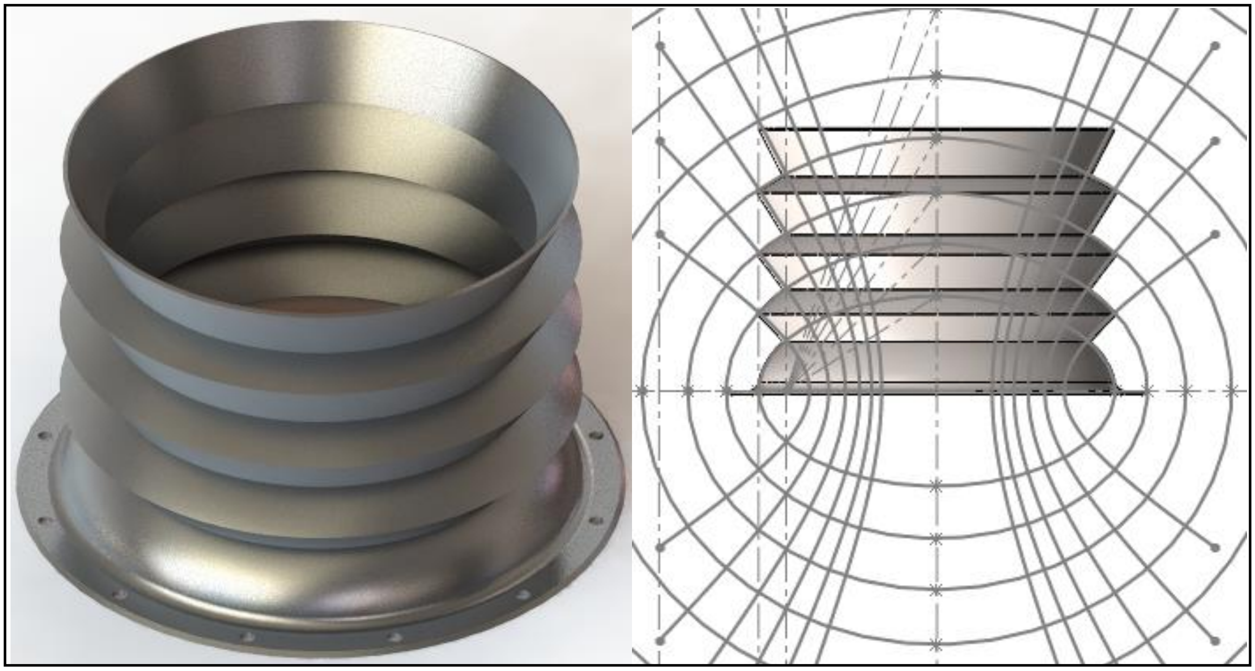


Figure 1 Stray light baffle design for AM printing. The left-hand image shows a SolidWorks rendering, while the right displays the ellipses and hyperbolas used to construct the baffle geometry.

The stray light baffle and five tensile specimens were all printed in a single batch on a M280 printer. The M280 was chosen because it is an industry standard for the characteristics and tolerances required. This DMLS printer model is designed to create fully-dense 0.38-mm features to 0.05-mm tolerances by using a 200-watt, 0.2-mm diameter laser to sinter 20-micron layers of titanium in an argon rich environment [GPI Prototype & Manufacturing Services, n.d.].

The feedstock was titanium 6-4 (Ti6-4), which is 6% aluminum, 4% vanadium, a maximum of 0.2% oxygen and 0.25% iron. Ti6-4 is the standard material for many high-performance aerospace applications, including baffles [Beck et al., 2011; Molitch-Hou, 2015; Tadjdeh, 2014; Gibson, Rosen, and Stucker, 2010; Nassar and Reutzel, 2013]. In order to simulate challenges with supply chains due to interdiction efforts, this batch was printed with greater than 60% recycled powder. The exact ratio cannot be known due to the specialized processes of refining the recycled material based on grain characteristics [Gibson, Rosen, and Stucker, 2010; Slotwinski, 2013; C. Brown et al., 2015; Jelis et al., 2015]. Though the EOS printing process meets ASTM F1472 for impurity limits [GPI Prototype & Manufacturing Services, n.d.], this study is intended to examine the variation between specimens (the tensile coupons) printed in a single batch.

Tensile Specimens and AM Repeatability

The tensile specimens in this experiment are subsize ASTM E8 coupons measuring 4in long with a gauge area of $0.0625in^2$ [ASTM International, 2010]. All five fivewere printed flat alongside the stray light baffle in order to examine the repeatability of their printed material characteristics. Some past studies have characterized titanium DMLS components, though most concentrate on medical rather than aerospace applications [Ramosoeu et al., 2010; Mangano et al., 2014; Jardini et al., 2011]. Several characterization studies have examined the differences between part orientation, printing parameters, and post-processing, though this work is more common for ferrous materials than with titanium [Khaing, Fuh, and Lu, 2001; Wang, Bergström, and Burman, 2006; Jelis et al., 2015; Delgado, Ciurana, and Rodríguez, 2012]. In addition, few studies directly examine repeatability issues with the same parameters [Jelis et al., 2015; Wang, Bergström, and Burman, 2006]. One such study found that DMLS printing of 4340 steel produced specimens whose mechanical characteristics and variability were comparable to those of wrought 4340 [Jelis et al., 2015]. Another found that alloying a new Fe-Ni-Cu-P DMLS material resulted in component heterogeneity with a multiple microstructural phases, but the research did not test mechanical properties [Wang, Bergström, and Burman, 2006].

Visual Examination Results

The baffle and five tensile specimens were visually examined as-printed with no post-processing. Density was determined using Archimedes' principle, and all parts measured within the experimental error of both their expected mass and volume (and thus density). All dimensions are correct within the specified printing tolerance (0.05 mm), except as noted once below.

The components do exhibit observable differences in surface roughness, both within and between specimens. The baffle exhibits clear printing marks (similar visually to tool marks) running vertically along all inner and outer surfaces of the part at approximately 6 mm intervals. This is in addition to curved striations, surface pitting, and areas of discoloration, all of which favor one side of the baffle versus the other. Figure 2 shows the baffle as printed, with the smoother side shown in 2a and the more impure side in 2b. Finally, the baffle base plate also exhibits disproportionate discoloration, though no striations (print markings cannot exist perpendicular to the build direction). In addition, the base plate contains the only out-of-tolerance dimensions, with some short arc lengths even being visibly out of round. This exceeds the tolerance specification of 0.13 mm for the first 25 mm of build height (the tolerance drops to 0.05 mm thereafter) [GPI Prototype & Manufacturing Services, n.d.].

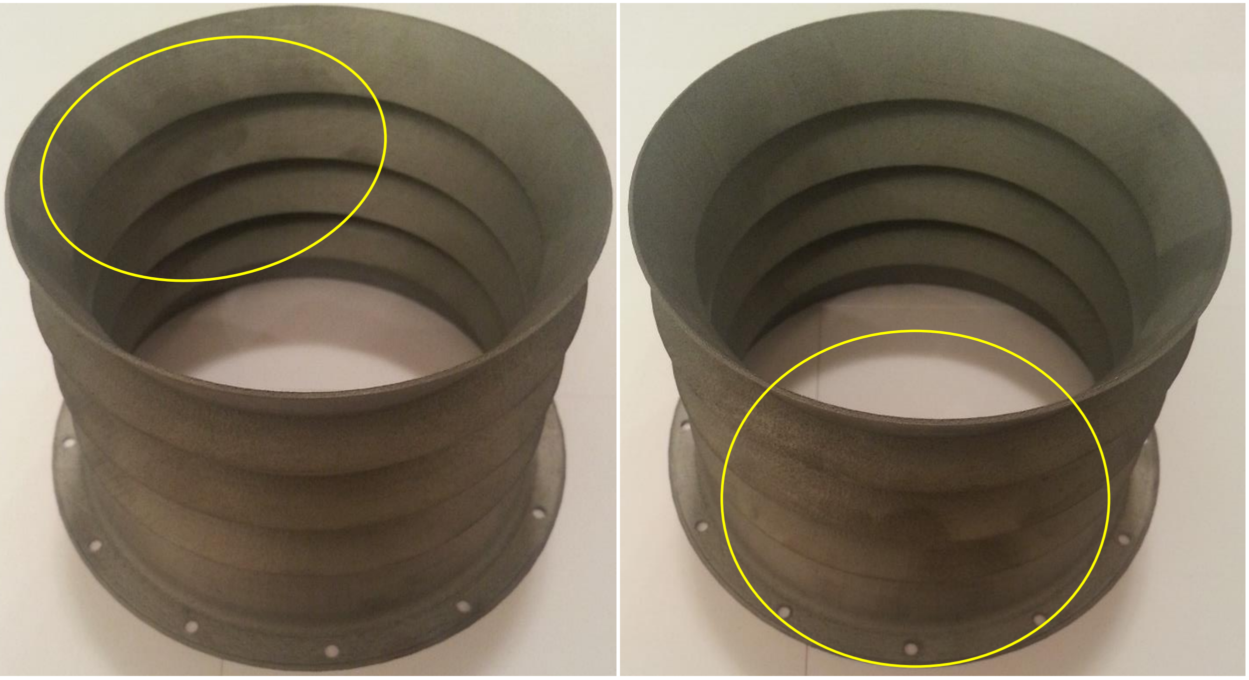


Figure 2 AM stray light baffle as printed. The directionality of printing imperfections is clear visually (particularly within the yellow circles), with the more pitted and discolored outer surface shown on the right. The inner surface on the left exhibits similar defects.

The tensile specimens also exhibit some print markings, though their shorter height renders this less recognizable than on the baffle. More notable are the occasional pitting and defects and the clear directionality of the specimens. Each one is visibly unique, and each was numbered such that the top is the flatter end. Figure 3 shows all 5 specimens standing on end (on their top surfaces in 3a and on their bottom surfaces in 3b), which clearly illustrates the geometric imperfections of the pieces.

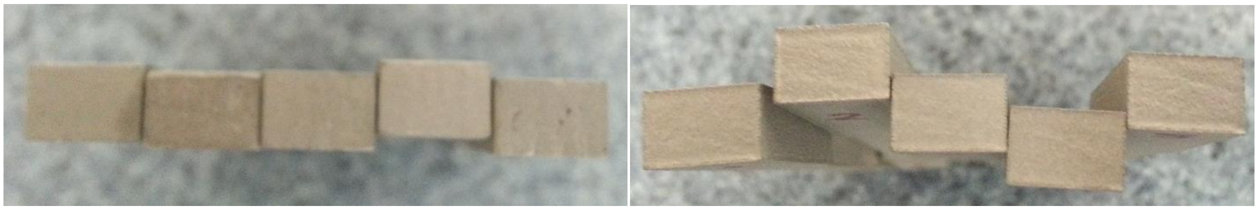


Figure 3 AM tensile specimens as printed standing on end. The photograph on the right highlights the geometric imperfections in one set of end surfaces. Specimen 1 is on the left in both images.

Tensile Testing Results

The tensile specimens were tested on an MTS Criterion 45 at room temperature using an Instron 2630-106 extensometer for strain measurement. The extensometer was removed when loads began to fluctuate and decrease (a sign that necking is likely) in order to prevent damage to the strain gauges. The final cross-section areas of the fracture surface were measured and used to calculate fracture stress. The first 4 broken coupons are shown in Figure 4 alongside the fifth for comparison. The results of the tensile testing are plotted in Figure 5.

Figure 4 Tensile specimens after fracture. This photograph shows the first 4 failed specimens alongside Specimen 5 before its tensile testing.

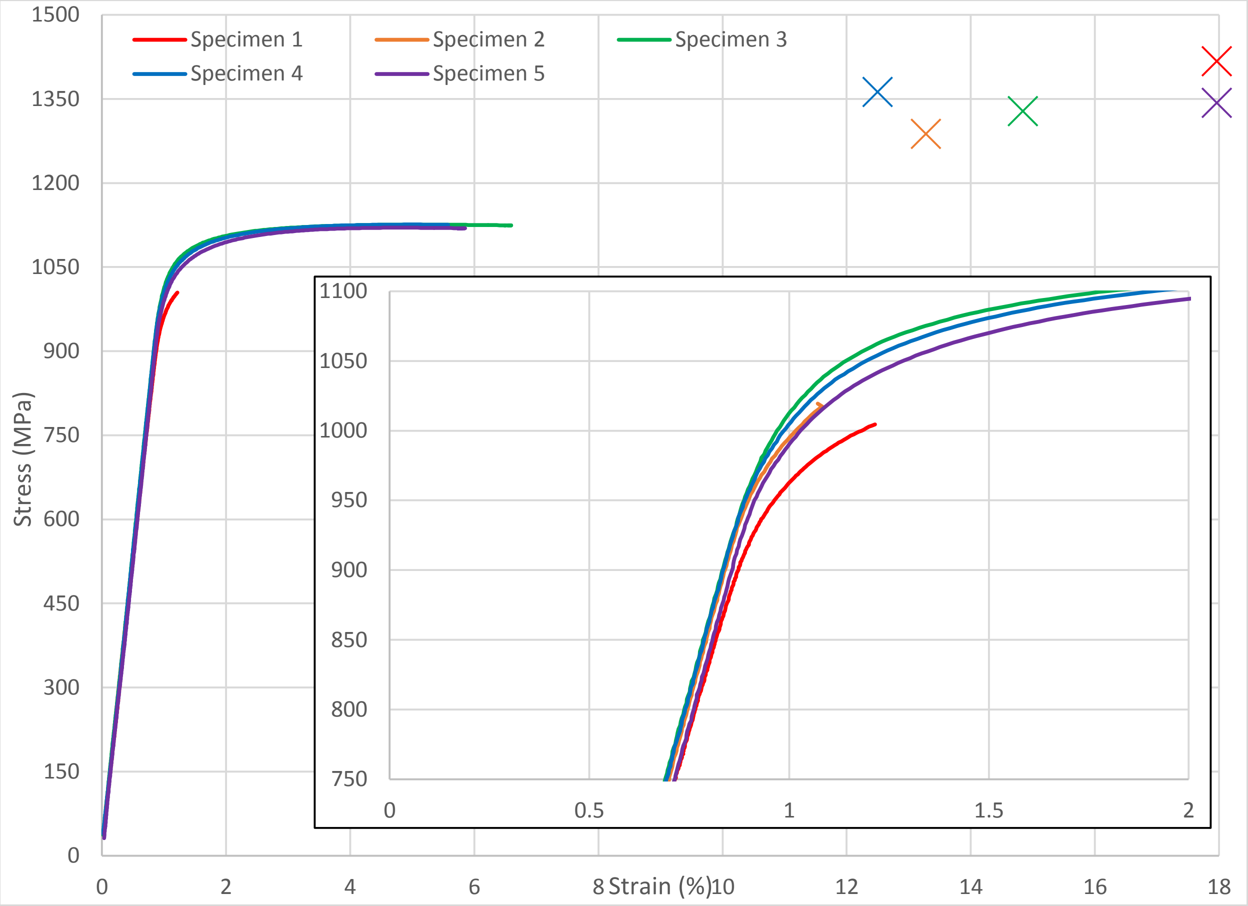


Figure 5 True strain-strain curves for the 5 tensile test specimens. The insert shows the yield region based on extensometer data; the fracture stress is determined from the final cross-section area.

As shown in Figure 5, the only outlier for yield characteristics is Specimen 5, which is still within 100 MPa of the norm. Specimen 1 began to neck earlier than the others (the strain gauge malfunctioned on Specimen 2 and was removed early), but experienced the largest strain at fracture. The strain at fracture, and less so the stress at fracture, is the most notable difference between the specimens. Percent strain at fracture has a standard deviation of 2.56%; true stress at fracture has a standard deviation of 47.6 MPa.

The fracture surfaces of each specimen are similar and exhibit semi-ductile characteristics expected in Ti6-4. Fracture surface characterization did not reveal any indicative crack initiation or propagation features, and all surfaces exhibited similar discoloration and cupcone topographies. It is therefore unlikely that fracture in any specimen was initiated by a major defect or FOD, though a scanning electron microscope examination would be needed to reveal this more clearly.

Hardness Testing Results

Vickers hardness testing was conducted on an MHT 200 indenter with an MA50 objective lens and under 1 kgf load. 45 indentations were made and measured on the front and back faces, left and right sides, and front and back of the necking regions on each specimen. Figure 6 presents some photographs of indentations, and Figure 7 presents the hardness data with standard error bars.

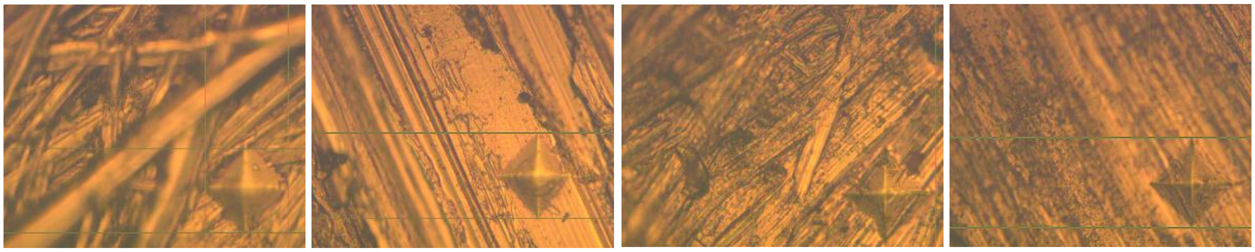


Figure 6 Vickers hardness indentation photographs with 40× magnification. These photographs show the surface roughness of the AM titanium even after polishing for hardness testing.

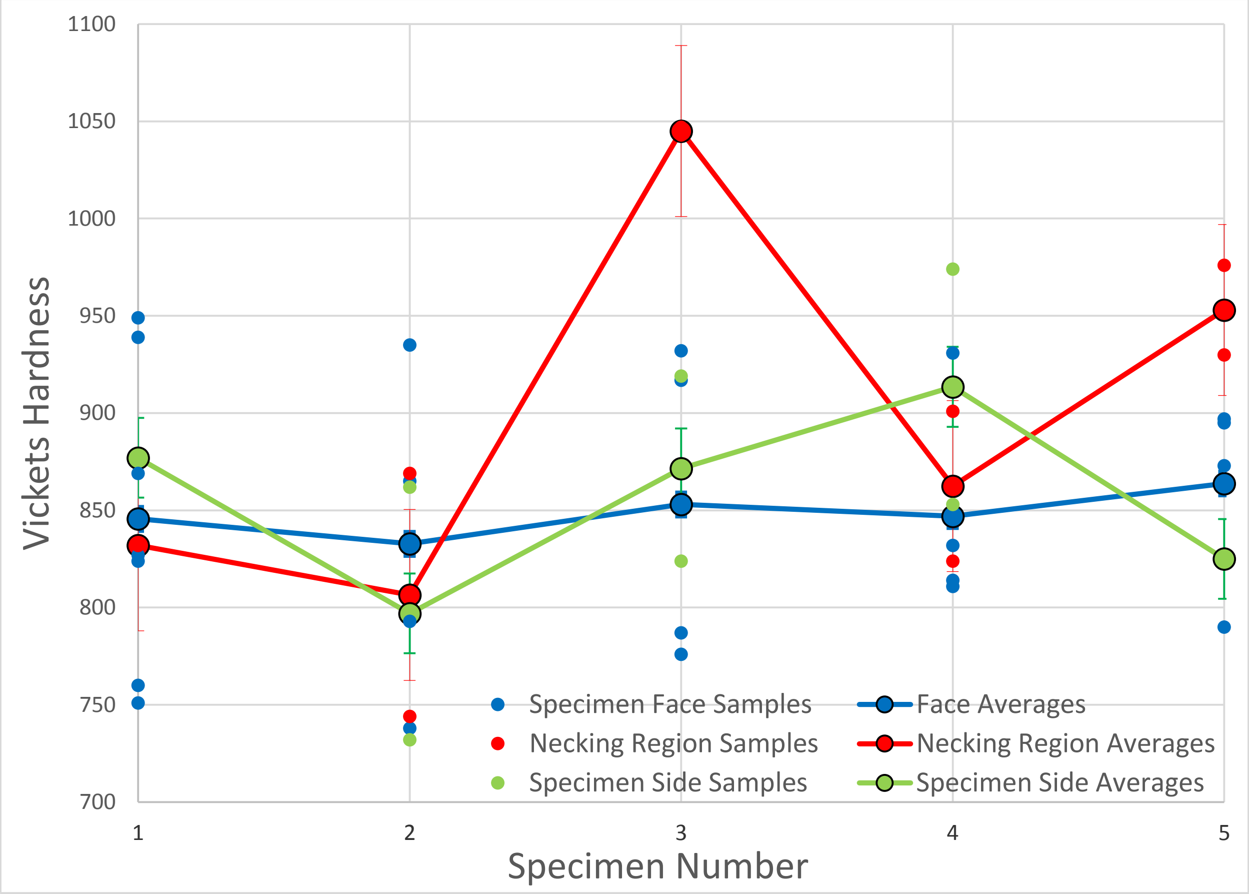


Figure 7 Vickers hardness test data for the difference surfaces of each specimen. The data shows potential variation between specimens despite considerable noise.

The standard deviation of 5 indentations taken in the same area of one surface of one specimen is 49 HV. This is higher than is typical for such tests, which is likely attributable to one of two related causes. The as-printed surface roughness of the tensile specimens was too inconsistent to obtain accurate hardness measurements. The test surfaces were thus polished in order to obtain visible indentations, though not to the extent typically used in hardness testing. This was done in order to best preserve the printed conditions. However, that process introduces more scatter in the data in addition to adding another unrelated variable in terms of how polishing affects the surface conditions. As such, the level of scatter is not unexpected and heavily limits the usefulness of the dataset.

There is no statistical significance in the difference hardness values between the back and front of the specimens, i.e. the face in contact with the printer build plate versus the last layer printed. The same is true of the left versus right sides of the specimens. Thus, front and back values are displayed identically in Figure 7 (as “faces”), as are left and right values (as “sides”). Between specimens, the variation in face values is not appreciable: the averages vary between 832.75 HV and 863.75 HV for a range of 31 HV. However, the side values vary from 797 HV to 913.5 HV for a range of 116.5 HV. The spread in this data is too large to conclusive however, as data points for the same specimen can differ by similar margins. The scatter of the necking region data is much lower for three of the five samples (1, 3 and 5). Those results differ significantly from each other (at 832 HV, 1045 HV, and 953 HV) and from the non-necking region average of 848.4 HV. This may relate to the differences in strain-at-fracture, which were 17.9%, 14.8%, and 17.9% of those specimens respectively. Together these results could indicate material inconsistencies at the fracture zones, but more testing would be necessary to further investigate the variations.

Experimental Conclusions

The overall conclusion of this repeatability study is that, though there are visible surface inconsistencies in DMLS parts including apparent biases based on part orientation, there is no demonstrated effect on the critical mechanical properties. While specimens exhibited different necking and fracture behavior, they share similar yield characteristics, and failure revealed no major fracture surface defects. However, more testing is necessary to examine whether Specimen 5 is a slight outlier in the yield testing or signifies an AM-specific yielding issue. Hardness results within the operating range (i.e. not in the necking region) of the printed material are highly consistent between specimens, though they may vary by orientation of the specimen surface. This is an issue to consider in part design and orientation, and thus warrants closer attention using scanning electron microscopes and CT scanners for both surface and internal characterizations.

Chapter 7

Conclusion and Future Trajectories

Metal AM is growing into a useful and promising field for high-performance aerospace applications. Though the future trajectories and risks of the industry cannot be known definitively, examining the development of plastic AM and CNC machining provides some insight into expectations for technical and user-facing advancements. Most notable among them are the potential for the proliferation into smaller businesses and the risk that this diffusion will open critical cybersecurity vulnerabilities such threats of data exfiltration on proprietary or classified components and manipulation of the manufacturing files among other items. In addition, the history of CNC indicates a likely concentration on feature recognition and reverse engineering of AM machine code, which would expose more digital media to data exploitation and potential sabotage. As such, this thesis advises reviewing cybersecurity skills, policies, and processes to address specific vulnerabilities of AM digital media, particularly from reserve engineering machine code.

Interdiction Guidance

In addition, since AM is likely to become a significant technology in non-allied nations threatening the US manufacturing advantage, this thesis identifies a number of potential counterproliferation strategies with differing feasibilities and utilities. Given the trajectory of more and increasingly critical AM components in military and astronautical applications, it is advisable to prepare counterproliferation plans before more design data is generated or used. This means beginning to examine specific paths for consumables monitoring, skillset monopolization, and non-destructive inspection (NDI) immediately, before technical advancements and market demand increase access and mitigate current control points. Many of these topics, such as NDI, are already important areas of development for government and industry. The perspective of a counterproliferation leverage point need only be added as an avenue of innovation.

Repeatability testing will be one of the most useful tools in the analysis of potential interdiction points. Testing the variation within and between AM processes is the only way to directly examine how different counterproliferation strategies actually affect the performance of specific critical AM components. These conclusions will change rapidly with the technologies, and the studies are best served by being forward-looking.

Counterproliferation Guidance

Three main issues that arise with AM when considering aerospace counterproliferation specifically. First, AM technologies require the storage of more intellectual property in digital media. The cybersecurity challenges here are numerous, but cyber operators should specifically consider the AM-specific risks of advancements in file types and “smart” reverse engineering. In particular, some developments may allow unintended users to fill in information gaps in decrypted files. Second, the raw materials for high performance feedstock are likely still require elements most commonly found internationally (particularly Russia with titanium and nickel). As such, even significant advances in feedstock quality will not put the supply chains under full domestic control. Third, AM erodes the advantage gained from the U.S. workforce of skilled technicians because complexity is no longer proportional to skilled labor.

To counteract these three AM-specific challenges, the AM competitive advantage efforts should shift towards intellectual property and advanced manufacturing techniques. This means that engineers must understand the critical and difficult-to-duplicate features of their designs, and preferably make these one in the same while balancing performance and resource use considerations. Continuous development and control of specialized printing processes and NDI will help maintain a domestic technical advantage, but only if designers take specific advantage of these value additions. Handling that tradeoff requires specific knowledge of the repeatability limitations in AM with respect to both industrial quality control and proliferation vulnerabilities. However, this prioritization of security on an engineering level as well as the policy and cybersecurity levels will help prevent critical AM aerospace components from ever being “just press print” outside of their designated facilities.

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Credits: 248.5 **Graduation: August 2015** **Contact: skm5107@psu.edu**

PROFESSIONAL EXPERIENCE

TA & EDITOR – Humanitarian Engineering Program (Pennsylvania State University) 2012-Present

- Revise, redirect, and edit 70+ articles; guide undergraduate authors through publishing process.
- Assisted teaching honors/graduate seminar and undergraduate social entrepreneurship course.
- Created course website and developed content for full social entrepreneurship course curriculum.
- ★ Nominated for the LaMarr L. Kopp International Achievement Award (2013-2014).

TEACHING ASSISTANT – Mechanical Engineering Dept. (Pennsylvania State University) Spring 2014

- Proctored exams and held office hours and reviews for 300-level experimental analysis class.
- Setup labs, prepared quizzes and graded assignments for 300-level engineering design course.
- Prepared solutions, graded exams, created/reviewed texts, and handled emails and clerical tasks.
- ★ Tutored 200 students on experimental analysis and coached 6 teams through design projects.

CHANGEAGENT – Humanitarian Engineering Program (Nyeri, Kenya) 2011-2013

- Led design, adaptation, and construction of successfully-adopted solar food dryer in Kenya.
- Coordinated and deliberated further venture development with local partners and officials.
- Conducted research for now-published study on international youths' conceptions of innovation.
- ★ Synthesized work into refereed article as first author and presented at annual NCIIA conference.

FIRST ROBOTICS – Volunteer Teacher/Mentor (Exton, PA and Countrywide) 2009-2015

- Guide students through high-pressure international competitions, directing repairs and strategy.
- Facilitate and enhance efficiency, professionalism, and teamwork on diverse, all-volunteer team.
- Lead and teach engineering systems design, mechanics, and machining to high school students.
- ★ Coached student drivers and engineers in World Championship semis (2013) and finals (2014).

HONORS & AWARDS

- Undergraduate Nominee, W. LaMarr Kopp International Achievement Award (2013-2014)
- Mechanical Engineering Honors Scholar, Schreyer Honors Scholar, Paterno Fellow
- Coach, World Semifinalist (2013) and Finalist FIRST® Robotics Team (2014)
- ★ Member, Phi Beta Kappa (Liberal Arts) & Tau Beta Pi (Engineering) Honor Societies

Academic Vita

Siri K. Maley
Schreyer Honors College
The Pennsylvania State University

PROFESSIONAL PUBLICATIONS

- Maley, S., Perez, A., Mehta, K. (2013). “The Significance of Implementation Strategy for Scaling-Up Base of Pyramid Ventures.” Open 2013: NCIIA’s 17th Annual Conference.
- Lissenden, J., Maley, S., Mehta, K. (2013). “An Era of Appropriate Technology: Evolutions, Oversights and Opportunities.” Journal of Humanitarian Engineering. (3)1: 24-35.
- Patel, S., Maley, S., Mehta, K. (2013). “Appropriate Technologies in the Globalized World: Frequently Asked Questions.” IEEE Technology & Society. 33(1): 19-26.
- Henry, M., Maley, S., Mehta, K. (2013). “Designing a Low-Cost Ceramic Water Filter Press.” International Journal for Service Learning in Engineering. 8(1): 62-77.
- ★ Mehta, K., ed. (2015). Solving Problems That Matter (And Getting Paid for It). CreateSpace eBook. In Press.

STUDY & WORK ABROAD SUMMARY

NYERI, KENYA: Pennsylvania State University’s Humanitarian Engineering Summers 2011 & 2012

- Coordinated in-country prototyping and design adaptation of affordable solar food dehydrator.
- ★ Guided new Penn State students through working, prototyping, living in and around Nyeri.

SINGAPORE, SINGAPORE: National University of Singapore Summer 2010

- Led design and prototyping, cited as best project with attention from international philanthropy.
- ★ Tutored and led engineering design process on multinational, multi-age, interdisciplinary team.

PARIS, FRANCE: American University of Paris Summer 2012

- Achieved 4.0 / 4.0 GPA in polemology and international politics under Dr. Hall Gardner.

AMMAN, JORDAN: CIEE at Princess Sumaya University for Technology Summer 2014

- Learned Modern Standard (final proficiency 51/75, Intermediate II) & Jordanian Arabic (basic).

CARIO, EGYPT: Ambergh Education at Arabeya Language School Winter 2014-2015

- Studied intensive Modern Standard Arabic (Intermediate I/II) in downtown Cairo.

ADDITIONAL SKILLS & SCORES

- Languages: English (native), Spanish (previously conversant), Modern Standard Arabic (intermediate II), Colloquial Jordanian Arabic (beginner I), Colloquial Egyptian Arabic (basic)
- Engineering Software: SolidWorks (Certified Professional – Core), CATIA (basic proficiency), Inventor (basic proficiency), MATLAB (basic proficiency), LabVIEW (basic understanding)
- Air Force Officer Qualifying Test Scores: 97/99 Academic, 98/99 Verbal, 88/99 Quantitative
- ★ GRE Scores: 169/170 Verbal, 162/170 Quantitative, 5.5/6.0 Writing