AU/AF FELLOWS/XXX/

AIR FORCE FELLOWS

AIR UNIVERSITY

TOWARDS CERTIFICATION OF ADDITIVELY MANUFACTURED SAFETY-CRITICAL PARTS FOR THE DEPARTMENT OF THE AIR FORCE

by

Jeremy D. Wimer, Lt Col, USAF

A Research Report Submitted to the Air Force Fellows
In Partial Fulfillment of the Graduation Requirements

Advisor:

Dr. Vincent Paquit
ORNL Senior R&D Staff, Data Analytics Lead

Maxwell Air Force Base, Alabama

April 2020

Disclaimer

The views expressed in this academic research paper are those of the author and do not reflect the official policy or position of the US government or the Department of Defense. In accordance with Air Force Instruction 51-303, Intellectual Property—Patents, Patent Related Matters, Trademarks and Copyrights, 1 September 1998, this research paper is not copyrighted but is the property of the United States government.

Contents

Illustrations

Acknowledgements

My sincere gratitude goes out to the people of Oak Ridge National Laboratory for sharing with me their profound love of science and resolute pursuit of national security solutions. Their steadfast dedication to our nation is inspiring. I would like to specifically thank Lonnie Love and Tom Kurfess at the Manufacturing Demonstration Facility for opening my eyes to the vastness of additive manufacturing technologies and letting me integrate with their teams of scientist to further the field. I would also like to thank Vincent Paquit and Andrzej Nycz for their time and for allowing me open access to their teams of researchers pursuing the science of additive manufacturing. Thanks also to J.D. Stauffer and the National Security Sciences Division for hosting the Air Force Fellows and opening my eyes to the wonderfully complex business of splitting atoms. Thank you to Dave Landguth for his fantastic hospitality and for passing on his 35 years of knowledge about the lab and advice on everything from the best parking spaces to the best place for a camping adventure in Tennessee. Most importantly, I'd like to thank my family for supporting me through this crazy 19-year Air Force career and for embracing our next adventure. Your resiliency amazes me and gives me motivation to continue on.

Abstract

Additive manufacturing (AM) is a disruptive technology that holds many benefits for the Department of Defense throughout product lifecycles including supporting the "digital century-series" concept of aircraft acquisition. The variability of parts created by AM is challenging, and the Department of the Air Force lags behind other departments in its adoption of AM. The main barrier to taking advantage of these benefits is the lack of confidence in certifying AM parts for safety-critical flight applications. The airworthiness process relies on process controls, testing, and analysis for risk mitigation and flight certification. The Air Force's current path towards certification has been to closely define and control AM process parameters, lock down that process, and conduct thorough non-destructive testing on individual parts. A better path to certification is to mitigate risks through informed awareness based on sufficient analysis of data created during each part's build process based on the part's criticality. This paper offers a Predict-Built-Test-Validate model as a means to create and analyze a "digital passport" allowing for certification of parts and informing airworthiness. In-situ data collection, closed-loop control of build process parameters, and machine learning algorithms for defect detection all offer promising methods of collecting data during a build, controlling the process, and ensuring enough information is known about the part to support certification.

This paper argues that the Department of the Air Force should not seek to certify individual AM processes or machines, but instead define technical data package requirements and certify processes of collecting and analyzing data whereby the properties of the AM part can be matched with the validated model ensuring it will meet designed performance requirements and be safe for flight.

Chapter 1: Introduction

Additive Manufacturing (AM), the process by which a part or structure is built layer-by-layer, is a fast-growing and potentially disruptive technology to both current and future warfare. AM, commonly referred to in the media as 3-dimensional (3D) printing, takes many different forms and differs from traditional manufacturing methods in which a large block of material is machined, stamped, or forged, and the final part is subtracted from the starting material.[1] Conceptually, AM is not new; the great pyramids were additively constructed block by block over 4000 years ago. Objects have been built layer by layer for centuries, but the recent advancements in computer processing, robotics, digital design, lasers, and sophisticated models have made building complex parts additively both achievable and economical. The aerospace industry along with medical and dental, oil and gas, heavy equipment, and even the construction industries are quickly adopting AM practices to reap the advantages. AM will not replace all traditional manufacturing methods, but it will prove a useful tool with a solid business case for many parts within the Department of Defense's (DoD) acquisition domain. The advantages which make it a disruptive technology in many aspects include reduced cost, higher "buy-to-fly" ratios of expensive materials such as titanium alloys, reduced lead time, and the ability to make complex parts that could not be fabricated by other means.[2] Also, AM allows the consolidation of multiple traditional parts with one complex assembly allowing significant weight savings. The annual Wohlers report estimates 3D printing to be a $35 billion a year industry by 2024 with no signs of slowing.[3] The DoD recognizes the importance of AM and has recently directed policy that it will "use AM to enable the transformation of maintenance operations and supply chains, increase logistics resiliency, and improve self-sustainment and readiness for DoD forces."[4] Previous Air Force Fellows at Oak Ridge National Laboratory (ORNL) have offered numerous advantages of AM including unlocking new design spaces, rapid prototyping, reduced tooling, reduced waste, and accessibility of digital designs.[5] These are distinct acquisition advantages that the DoD including the Department of the Air Force (DAF), and its newly created US Space Force, must pursue and seize.

AM takes many different forms, and new techniques are constantly evolving due to the amount of research being poured into the field. What began in the 1980s as a few expensive printers producing limited quantities of parts made from plastic or polymers has now widely proliferated into a multi-billion dollar industry with large-scale AM machines capable of rapidly printing millions of different parts, consumer-grade printers costing just a few hundred dollars, and large-scale metal AM systems capable of producing metal alloy parts consistent in quality with traditional forging and casting methods.

Industrial Advancements

Industry worldwide is moving at a rapid pace towards using AM in critical parts for commercial applications. During the past decade, technical advances in robotics and lasers has made the full-scale and full-strength AM of metal parts a reality. In 2017 Boeing subcontracted with Norsk Titanium to produce and obtain FAA certification for a handful of titanium parts. It now claims FAA process certification and the ability for widespread use of AM to shave millions of dollars off the production costs of its B787 Dreamliner.[6] General Electric has claimed its newest turboprop, the Advanced Turboprop, uses AM to replace 855 parts with just 12 and shave over 100 pounds off the design along with increased thrust and efficiency.[7] As part of its ongoing Transformational Challenge Reactor program, ORNL is attempting to print and certify a nuclear reactor core.[8] Trendsetting SpaceX as early as 2014 launched an additively manufactured main oxidizer valve in its Falcon 9 rocket and today widely uses AM titanium components in the SuperDraco thruster engines.[9] However, the use of AM is not without its risks. Following an explosion during a test firing in April 2019, SpaceX has initially claimed that a titanium part in the SuperDraco thruster may have failed causing the accident.[10]

AM Methods

The American Society for Testing and Materials (ASTM) defines seven different general methods of AM. Methods such as vat photopolymerization, material jetting, and material extrusion typically lend themselves to thermoplastic or resin applications.[11] This paper will focus on emerging techniques for creating metal parts, namely binder jetting, powder bed fusion (PBF) and direct energy deposition (DED).

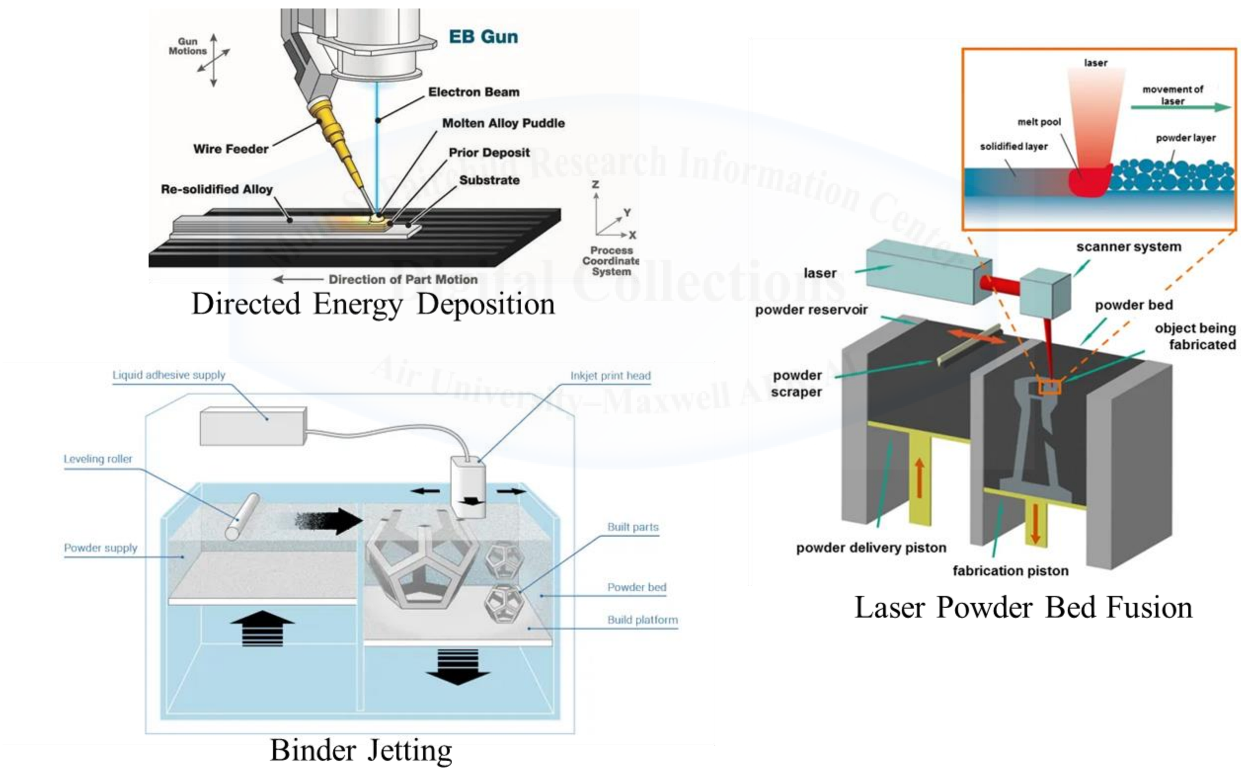

Figure 1: Three common AM techniques for metal part manufacturing[12]

Titanium alloys such as Ti-6Al-4V are popular in the aerospace industry and can be used to create AM parts via a variety of the above methods with baseline mechanical properties that match or exceed that of their traditionally made cast or wrought counterparts.[13] However, variability in the AM process can produce parts with non-desirable properties like surface roughness, residual stresses, voids, defects, and non-optimal microstructure which can be sources for crack initiation and failure.[14] Internal microstructure such as metal grain size and orientation is heavily influenced by the thermal history (maximum temperature and cooling rate) of a build. Mechanical properties often vary in the build height direction (when the build is not closely controlled) as heat conduction and convection varies due to the build base plate acting as a heat sink.

Disruptive Technology Potential

Dr. Will Roper, Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics has recently touted the "Digital Century Series" concept for fighter acquisition and stood up the Program Executive Office for Advanced Aircraft to develop future advanced warfighting aircraft. The office is responsible for using digital engineering, modular open systems architecture, and agile software development to field new aircraft in a timespan of a few years as opposed to decades that have characterized the current field of US Air Force (USAF) aircraft.[15] Digital engineering is critical to bringing this concept of a "digital twin" to reality. It requires a fully digital model to be created for the entire lifecycle of the aircraft.[16] Digital engineering enables rapid prototyping of designs that can be tested and modified early in the cycle to support rapid acquisition. AM is ideal to create many of the initial prototypes of these designs due to its shorter lead time and relatively low cost. It also opens new design spaces with its ability to produce complex parts that may not be possible with traditional manufacturing. AM is a key enabling technology that will support the "Digital Century Series" concept, and digital engineering is a key enabler of AM to produce quality structural parts that are certified for flight. In addition to enabling new aircraft designs, it is also predicted that AM will save the AF billions of dollars on the sustainment of aging aircraft fleets.[17] AM has the potential to produce new products quickly allowing the US to innovate faster than the enemy can copy and allowing them to stay ahead in a technological arms race. The use of AM across the DAF has begun, but lags behind other services. A 2019 DoD Inspector General report found that the DoD could make more use of AM to lower product lifecycle costs and increase readiness.[18] The main challenge of AM which is hindering the DAF from being able to take full advantage of this disruptive technology is the certification of safety-critical AM parts for flight. The DAF has yet to put trust in AM's ability to manufacture parts with properties equal to traditional manufacturing methods. That will soon change; this paper will propose a path and some accelerators down that path to reach the full potential and benefits of AM.

---

[1] Froes, Francis, and Rodney Boyer. 2019. Additive Manufacturing for the Aerospace Industry. Elsevier Science.
[2] Ibid.
[3] McCue, T.J. 2019. "Significant 3D Printing Forecast Surges To $35.6 Billion." Forbes. March 27.
[4] Lord, Ellen M. 2019. "Directive-type Memorandum (DTM)-19-006." Interim Policy and Guidance for the Use of Additive Manufacturing (AM) in Support of Materiel Sustainment.
5 George, Major Benjamin E. 2014. 3D Printing in the Air Force - Dispelling the Myths of Additive Manufacturing. Maxwell AFB: Air University
[6] Scott, Alwyn. 2017. "Printed titanium parts expected to save millions in Boeing Dreamliner costs." Reuters.com. April 10.
[7] Kellner, Thomas. 2018. "Fired Up: GE Successfully Tested Its Advanced Turboprop Engine With 3D-Printed Parts." *GE.com.* January 2.
[8] Simpson, Joseph et al. 2019. *Considerations for Application of Additive Manufacturing to Nuclear Reactor Core Components.* ORNL/TM-2019/1190, Oak Ridge National Laboratory.
[9] 2014. "SpaceX Launches 3D-Printed Part to Space, Creates Printed Engine Chamber." *SpaceX.com.* July 31.
[10] 2019. "Update: In-Flight Abort Static Fire Test Anomaly Investigation." *SpaceX.com.* July 15.
[11] "7 Families of Additive Manufacturing." *Hybridmanutech.com.* Accessed Dec 30, 2019.
[12] 2017. "High Level Process - Directed Energy Deposition, Powder Bed Fusion, Binder Jetting." *Bits Into Atoms - 3D Printing and Design.* April 30.
[13] Seifi, Mohsen, Ayman Salem, Jack Beuth, Ola Harrysson & John J. Lewandowski. 2016. "Overview of Materials Qualification Needs for Metal Additive Manufacturing." *Journal of The Minerals, Metals & Materials Society* 66 (3): 747-764.
[14] Ibid.
[15] Brackens, Brian. 2019. "Air Force stands up new Advanced Aircraft PEO." *AF.mil.* October 3.
[16] Insinna, Valerie. 2019. "The US Air Force's radical plan for a future fighter could field a jet in 5 years." *DefenseNews.com.* September 16
[17] Roper, Will. 2019. "Stars and Stripes." *3D printing is about to save the military billions of dollars.* December 26.
[18] DoD Inspector General. 2019. "Audit of the DoD's Use of Additive Manufacturing for Sustainment Parts." Report No. DODIG-2020-003.

Chapter 2: The Challenges of AM

AM is a complex multi-physics process with numerous challenges that must be overcome in order to exploit the full advantages. An understanding of thermodynamics, electrodynamics, optics, and mechanics along with material science is necessary to understand the factors at play for many AM processes. Quality control and certification of AM parts, the security of the large cyber-physical attack surface, print speed and capacity limitations, and digital data rights along with the line between transparency and intellectual property are all challenges that must be addressed when considering AM for DoD applications.[19] This paper will focus on the first of these challenges, the certification of AM parts allowing widespread application.

Even traditionally manufactured part certification is difficult. The legacy FAA process has been documented to sometimes require over $130 million and take 15 years.[20] The largest barrier to widespread use of AM for safety-critical aerospace applications has been the variability of the build process and the challenge of quality control. Thus far AM has been plagued by a lack of quality and high variability in the produced part when it comes to things that are important for critical metallic components such as geometry, microstructure, defects, surface finish, and residual stress which all affect part performance.[21]

AM Variability

Thus far, AM has shown to be a highly variable process. Parts produced with slightly different parameters, on different machines, or even on the same machine but on a different day with slightly different environmental conditions have shown to produce drastically different results. A plethora of factors can introduce variability to part quality:[22]

- Material Feedstock: composition, powder size, and defect composition
- Process Parameters: beam power, velocity, melt-pool size, hatch spacing, layer thickness

- Geometry: heat transfer, grain size, and surface roughness due to build orientation
- Post-processing procedures: hot isostatic pressing, residual stress relief processes

The Figure 2 shows the complex interrelationship between input and process parameters and the product that results.

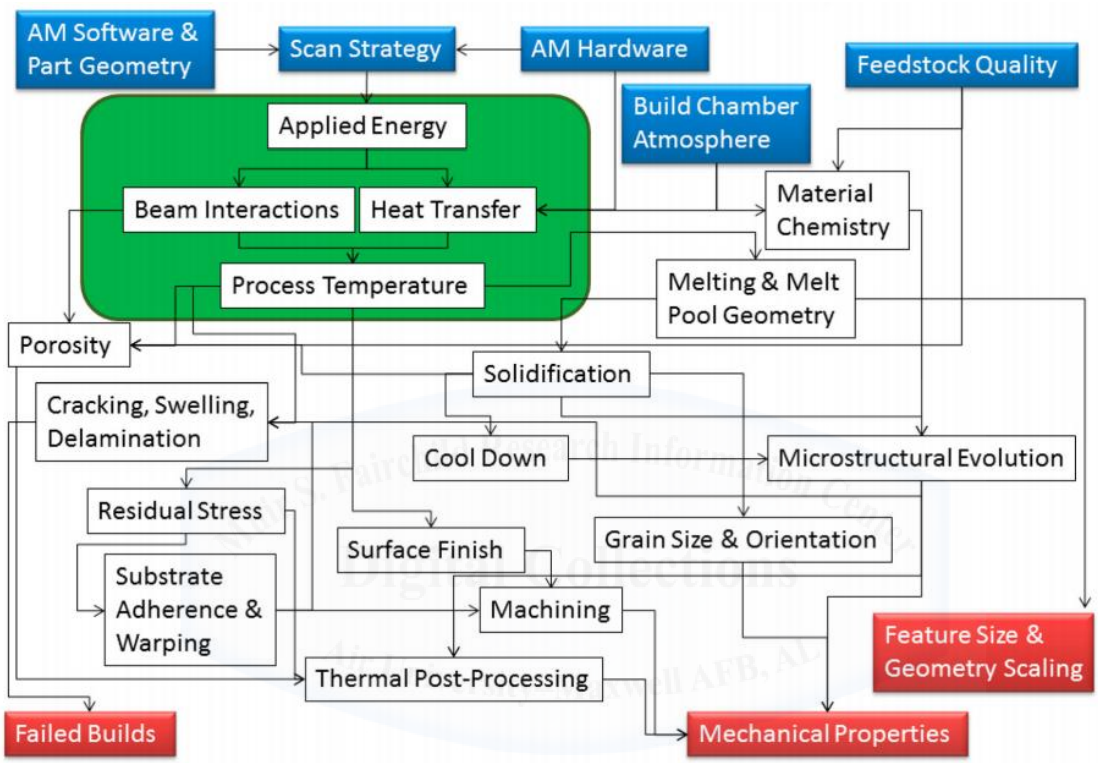

Figure 2: Process map showing complex relationship of AM parameters to outputs[23]

One key assumption in mechanical engineering allowing simplification in part analysis is often that the material is isotropic, or uniform in its properties, and thus behaves the same in any direction that stresses are put on it. Variability and the piecewise nature of AM results in parts that are generally anisotropic having different material properties and microstructure in different places. This causes difficulty in certification as it undermines the assumptions used in designing and analyzing a part. Controlling this variability and producing parts that are near isotropic or at least have known mechanical properties is key to certifying parts and unlocking the true potential and benefits of AM. While thus far many AM processes have been plagued by variable results, process controls seek to limit these variations and improve the quality and consistency of the product. Process control is the method by which the input and process variables are controlled to limit variability in the part. It is critical to the repeatability, reproducibility, and ultimately the certification of the part. The relationship between different process controls and their impact on the finished part properties is critical, but the AM industry is still developing this understanding.[24]

Most AM produced parts require at least some amount of post-processing before being ready for service. Examples include subtractive machining for achieving specific geometry and surface finish, or heat treatments designed to reduce residual stresses accumulated during the build and improve the microstructure's uniformity. Hot isostatic pressing (HIP) is a commonly used method where the part is heated in a high-pressure chamber to alleviate defects in the printed part like voids and internal cracks.[25] All post-production processes increase touch time and add to the cost and time for producing a part.

Certification Attempts

Certification at present for military applications is difficult, but not impossible. The Naval Air Systems Command (NAVAIR) demonstrated AM certification in 2016 with the flight of a relatively simple but critical titanium part in the engine nacelle of a CV-22 Osprey, but only after rigorous post-production component testing.[26] The first USAF use of AM for a certified metal aircraft structural part was for the replacement of an F-15 pylon rib and was produced via an early DED process in 2003.[27] However, DAF adoption of AM has not kept pace with industry. According to a 2017 report to Congress, most of the AM activity has focused on producing non-structural replacement parts and tooling for its ageing fleet.[28] Recently attempts to use AM for the sustainment of weapons systems have resulted thus far in only a handful of parts actually flying on aircraft, and these parts are all non-structural meaning they carry low risk of consequences such as loss of life or mission failure in the event of a part failure. While it appears that the DAF has done much groundwork and laid out a broad path towards certification, it has not committed to a definitive strategy and may be missing out on key accelerators down the path towards certification.

Another Challenge - Security

The digital nature of AM from part design to production and certification creates a large cyber-physical surface vulnerable to attack. Planning and considerations for cyber security must be baked into the design of the part as well as its production method because of the increased consequences of a cyber-attack or compromise of information. Armed with the stolen data of a "digital twin", an enemy or counterfeiter now has everything that they need to produce a similar product thus eliminating all the effort of reverse engineering a physical product. Similarly, the ability to covertly change an AM process could feasibly lead to parts produced that appear to be acceptable but include flaws that may lead to failure during use.

---

[19] George, Major Benjamin E. 2014. *3D Printing in the Air Force - Dispelling the Myths of Additive Manufacturing.* Maxwell AFB: Air University.
[20] Totin, Ashley, Eric MacDonald & Brett P. Conner. 2019. "Additive Manufacturing for Aerospace Maintenance and Sustainment." *DSIAC Journal* (DSIAC Journal) 6 (2): 4-11.
[21] Froes, Francis, and Rodney Boyer. 2019. *Additive Manufacturing for the Aerospace Industry.* Elsevier Science.
[22] Ibid.
[23] Sames, W. J. , F. A. List, S. Pannala, R. R. Dehoff & S. S. Babu. 2016. "The Metallurgy and Processing Science of Metal Additive Manufacturing." *International Materials* 61 (5): 315-360.
[24] Froes, Francis, and Rodney Boyer. 2019. *Additive Manufacturing for the Aerospace Industry.* Elsevier Science.
[25] Ibid.
[26] 2016. "NAVAIR Marks First Flight with 3-D printed, safety-critical parts." *Navy.mil.* Naval Air Systems Command Public Affairs. July 29.
[27] Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics. 2017. "FY 2017 Additive Manufacturing Report to Congress."
[28] Ibid.

Chapter 3: Paths Towards AM Certification

The DoD has recognized the benefits as well as the inherent risk of using new processes to build parts and has recently issued policy that, "AM parts or AM repair processes can be used in both critical and non-critical applications. For all applications, the appropriate level of qualification, certification, and risk/safety evaluation must be completed by the appropriate engineering support activity."[29] The USAF uses the airworthiness process to accomplish this risk evaluation for aircraft; satisfying this process is on the critical path towards widespread AM certification.

The USAF Airworthiness Process

In order to ensure safe flight operations, the USAF requires an airworthiness certification before flight of any new or modified air vehicle. The USAF airworthiness process is prescribed in Air Force Instruction (AFI) 62-601. Broadly this instruction describes airworthiness as "the verified and documented capability of an air system configuration to safely attain, sustain, and terminate flight in accordance with the approved aircraft usage and operating limits"[30] The AFI describes processes by which an independent authority, called a technical airworthiness authority (TAA), outside of the program execution chain, issues and maintains airworthiness for air vehicles. Ultimately the process comes down to the TAA, (a single human being) advised by a board of program managers and engineers, making a risk acceptance decision based on a combination of the severity of the consequences along with the likelihood of a failure of any of the systems required for flight. The TAA should ensure that every action has been done to mitigate risks to an acceptable level, and then accept those that cannot be mitigated. Risk mitigation then relies on reducing two things - the severity of the failure and the likelihood of its occurrence.

Classification Schema

Part of risk mitigation involves assessing the severity of the consequences of a failure. To do this, the AM part should be classified based on the function that it provides the aircraft and its criticality to flight. Classification is critical to consistently set appropriate levels of control and set risk mitigation policies and standards. The National Aeronautics and Space Administration (NASA) recognizes this and has developed a park classification schema for parts produced using laser-PBF based on the consequence of failure (catastrophic or not), the structural demands of the part (environment and engineering margin), and the "AM risk" (the geometry and how inspectable the part is).[31] Requirements for documentation, inspections, and non-destructive evaluation (NDE) of the part after manufacturing are based on the part's classification. A recent AFLCMC/EZ structures bulletin establishes requirements for Durability and Damage Tolerance of AM metal structural parts based on the Aircraft Structural Integrity Program (ASIP, MIL-STD-1530).[32] It sets requirements based on the classification of parts as fracture critical (FC), durability critical (DC) or normal controls (NC). These classifications are based on an assessment the relevance to safety-of-flight and engineering judgment.

Since the rigor of part analysis and process controls are defined by part classification, the DAF should design and define a consistent classification system that suits AM parts. This system should have a multitude of classifications (similar to NASA's schema) that allow the certification criteria to be a function of the consequences of part failure, the operating environment, the engineering design margins, the level of confidence in the AM process being used, and the availability and effectiveness of post-processing NDE. This would allow the appropriate amount of risk mitigation to be applied to each part classification resulting in less wasted time, money, and effort and increasing the likelihood of reaping the benefits of AM.

The DAF's Current Path

The DAF writ large recognizes the benefits of AM but has struggled with determining a path towards certification of AM parts. Thus far the USAF has taken a conservative approach in approving AM parts for flight that have a low consequence of failure (non-structural parts) which serves to mitigate risk to an acceptable level while the knowledge base of the AM industry builds and certified structural parts make it into mainstream air vehicles. One recently released publication from the acquisition community reflects a conservative and methodical path towards certification of AM parts.

The Air Force Life Cycle Management Center (AFLCMC) has been able to certify some parts with a rigorous and rigid design, production, and testing process. This type of part certification relies on controlling the AM process parameters for validation and locks down the process requiring much time and effort to re-certify if anything must be changed. This is problematic for a long-term strategy and kills the business case for using AM in the first place. Whenever a design changes or a machine becomes obsolete or even needs a simple software update, the entire certification process would need to be repeated. Aircraft supply chains routinely suffer from parts that must be redesigned or procured via a different process due to obsolescence, a factory closing, or as a result of a contractor completely exiting the market. It is overly burdensome to require a part manufacturer to maintain the same machine in the exact same configuration over the lifecycle of the aircraft, especially in a field like AM that is still rapidly developing.

In evaluating parts for ASIP, the previously mentioned structures bulletin points out that the most significant challenge is making an accurate assessment of structural performance (e.g. strength, rigidity, durability, and damage tolerance).[33] The bulletin describes a process reliant on NDE of samples (test coupons) produced via the same AM process to determine performance data. However, due to the complex nature of AM, there is no guarantee that a test coupon will have the same mechanical properties as the part, even if it was produced at the same time. Also, NDE is a complex, expensive, and time-consuming process. Any certification plan that relies too heavily on NDE risks spoiling the business case for using AM in the first place. NDE is also not suitable for some AM parts due to their complex geometries. X-Ray Computed Tomography (XCT), a type of NDE that uses X-rays to visualize porosity and defects in parts, produces good insight, but it not suitable for all applications.[34] Furthermore, the effect-of-defects is not well understood and no comprehensive accept/reject criteria are yet established.[35] For these reasons, the bulletin claims, "It is recommended the durability and damage tolerance (DADT) certification process for AM be expanded to FC parts only when sufficient data and experience are obtained from NC and DC parts by both the manufacturer and procuring agency."[36] This means that the DAF still has a large amount of knowledge and experience to gain about the AM process before it is comfortable with the certification standards for safety-of-flight critical parts.

This conservative approach effectively mitigates risk but will soon prove too slow to keep up with both industry and near peer competitors and will not support the vision for a "Digital Century Series" revolution in aircraft design and production.

Alternate Paths

Recognizing the need to confidently certify AM parts, several organizations have begun work on alternate paths and frameworks to guide AM development and achieve certification.

America Makes and the American National Standards Institute recently teamed up as the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) to release version 2.0 of the "Standardization Roadmap for Additive Manufacturing". The AMSC was established to, "coordinate and accelerate the development of industry-wide additive manufacturing standards and specifications consistent with stakeholder needs."[37] The AMSC asserts that standardization and production of parts with properties within the design allowables set forth in the Metallic Materials Properties Development and Standardization (MMPDS) Handbook is necessary for the certification of safety-critical parts for the entire AM industry. The MMPDS (formerly MIL-HDBK-5) is currently recognized by the FAA, DoD, and NASA for metallic material allowables. The problem at present is that there is a paucity of additively manufactured metallic alloy properties for the feedstock material or processing standards currently included in the MMPDS and a lack of data to arrive at a consensus on what those standards are.[38]

The AMSC highlights organizations that have led the way in attempts to develop certification schema. The American Welding Society (AWS) had drafted and recently published standards for PBF and DED systems where it uses three different classifications to set the qualification and inspection requirements. Likewise, NASA has published MSFC-SPEC-3716 and 3717 which lays out specifications for control of laser-PBF produced parts and qualification processes for use in its manned space programs. As part of an overall AM control plan (AMCP) it sets requirements for a Qualified Metallurgical Process (QMP) specific to each machine, a Part Development Plan (PDP) that sets the process for producing the AM part and a formal review leading to a locked-down Qualified Part Process (QPP). While encouraging that there is a documented path towards producing and flying AM parts, the NASA process is very burdensome and prescriptive, and it locks down a single process for one specific machine and part. There remains a large gap to realize the vision of AM rapidly producing certified and flyable prototypes of new aerospace vehicles.

The US Navy has recognized that the traditional path of qualifying a process to produce a certified part is not acceptable for AM.[39] Its long-term strategic approach to AM is to use Integrated Computed Material Engineering (ICME) to certify parts. According to Dr. William Frazier, the Navy's senior scientist for material engineering, "ICME links the AM process, part geometry, material microstructure, and properties together to understand these relationships for end-use."[40]

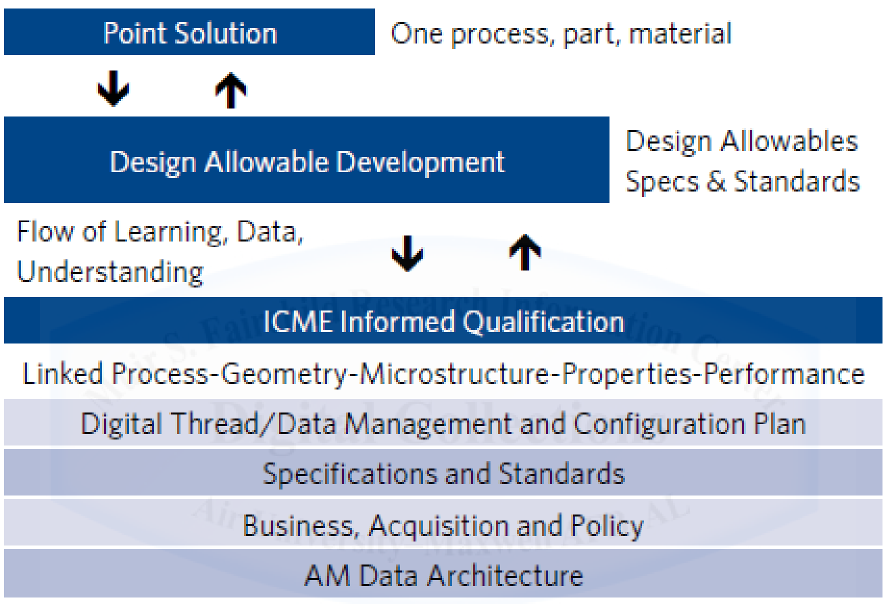

Figure 3: US Navy approach to qualification and certification[41]

Figure 3 depicts the basis of the Navy's approach which takes the traditional point solution and digitally develops a set of allowable parameters for each part. This digital model of a part then informs the choices of the right AM process, materials, and process controls that must be in place to ensure a quality part is made. The goal of this approach is to use data collected during the design and build phase to increase the confidence in the part, reduce the amount of post-processing inspection that must be accomplished, and drive down the risk to an acceptable level allowing certification. The traditional qualification paradigm of testing a statistically relevant number of parts produced during a controlled process and qualifying that process does not work for AM where a build requirement for a prototype air vehicle could theoretically be only one part. The Navy wants to replace that paradigm with an ICME informed approach.[42]

Sandia National Laboratory's "Born Qualified" grand challenge project was initiated with the long-term vision of being able to "…change the qualification paradigm for low volume, high value, high consequence, complex parts that are common in high-risk industries…"[43] It sees the opportunity to shift away from the current design-build-test qualification paradigm to one that uses probabilistic prediction of performance and data to optimally control the manufacturing process.[44] As shown in Figure 4, the framework used takes in requirements and design and outputs a qualified part. It uses models, in-situ diagnostics for process controls, and "properties alinstante" which is to say it quickly measures the mechanical properties of the part that is being produced while it is being built or immediately thereafter to gain information about the quality of the build and how it matches the model. Sandia researchers claim the computational and statistical methodologies exist for this framework to work, but integrating those methods with large data sets and at many different physical scales is what makes it challenging.[45] Modern instrumentation is able to acquire temporal and spatial data during a build that quickly exceeds storage limits for a typical desktop computer. Cloud data storage and computing are required for analysis. Sandia researchers point out the need for engaging the data science community for data reduction and analysis algorithms that can quickly process the gigabytes of data produced from a single part and determine the principle components and key data sets that are important for quality and certification.[46] They also point out the data structure, storage, and management issues that are present in the scientific community as being key enablers of this approach.

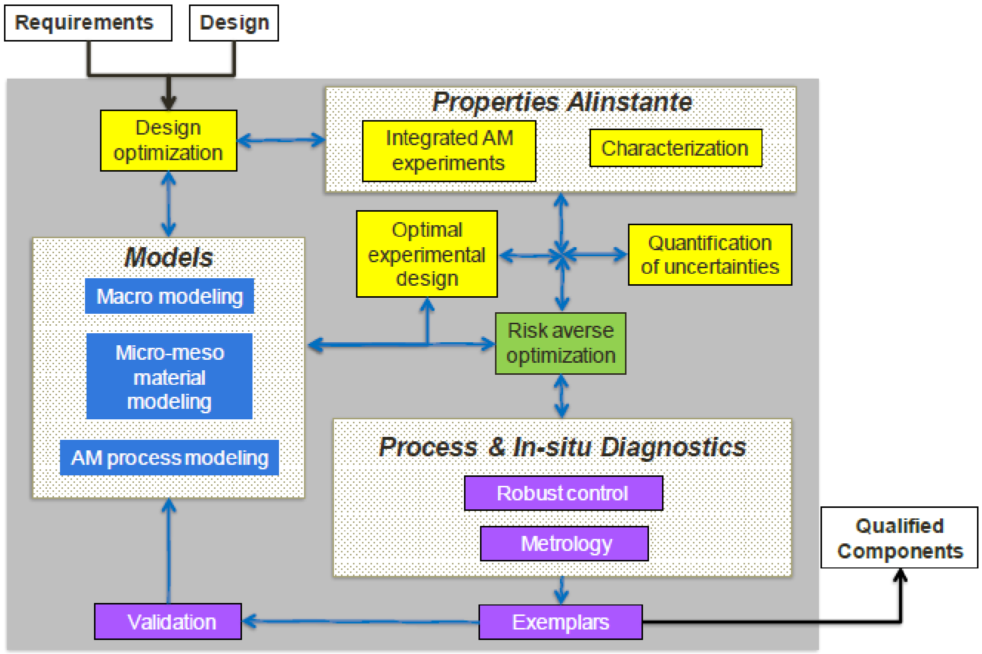

Figure 4: Sandia's Born Qualified Framework[47]

An Ideal Path – Creating a Digital Passport for AM Parts

A traditional statistical-based certification process using massive up-front and post-process mechanical testing costing millions of dollars and consuming multiple years is not conducive to the low-volume builds or repairs that make AM attractive.[48] Broadly defined AMCPs and general quality assurance standards are important for building a solid AM process that is repeatable, but reliance on strict process control could prove counter-productive. Future certification paths must focus on the use of digital engineering for the creation of a digital model for each part allowing model validation through data collection and analysis, process development, monitoring, and testing. This type of digital model is sometimes referred to as a "digital twin" meaning a replica of a physical part that exists in the digital domain. It consists of the digital design of the part including its desired properties and performance as well as the data collected during its creation. These data can then be analyzed to provide information about the part necessary for certification and use. Many researchers at ORNL's Manufacturing

Demonstration Facility (MDF) prefer the term "digital passport" of an AM part to describe the concept of capturing and consolidating all of the data about a part useful in proving its provenance.[49] A traditional individual passport provides a means of identification, proof that a person is a citizen of a country, and open travel within an international system. Similarly, a digital passport of an AM part provides a means of identifying an individual part, the data providing proof that it was manufactured correctly and possesses acceptable properties, and certification for its use within a logistics chain. The digital passport concept is ideally suited for creating a path for widespread use of AM parts in the DAF's supply chain. Its utility would not end when the part was created or installed. Instead, data can be continuously added to the digital passport throughout the part's lifecycle creating an extremely valuable tool for calculating lifecycle costs, evaluating actual performance, and providing traceability for analysis in the event of a mishap.

In contrast to AFLCMC's current path of point designing each AM part and build process and then locking down that process, the DAF should focus on creating a process whereby sufficient data are collected to support a digital passport for individual parts. The analysis of these data would then allow the as-built part to be compared to its model and give enough information about its properties to probabilistically predict performance and risk thereby building confidence sufficient for certification.

---

[29] Lord, Ellen M. 2019. "Directive-type Memorandum (DTM)-19-006." *Interim Policy and Guidance for the Use of Additive Manufacturing (AM) in Support of Materiel Sustainment.* Under Secretary of Defense for Acquisition and Sustainment, March 21.
[30] Air Force Instruction (AFI) 62-601. 11 June 2010. *USAF Airworthiness.*
[31] NASA Marshall Space Flight Center. 2017. "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals." *MSFC-STD-3716.* October 18.
[32] AFLCMC/EZ Structures Bulletin. 2019. "Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts." *EZ-SB-19-01.* June 10.
[33] Ibid.
[34] Ibid.
[35] Froes, Francis, and Rodney Boyer. 2019. *Additive Manufacturing for the Aerospace Industry.* Elsevier Science.

[36] AFLCMC/EZ Structures Bulletin. 2019. "Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts." *EZ-SB-19-01.* June 10.
[37] America Makes & ANSI Additive Manufacturing. 2018. "Standardization Roadmap for Additive Manufacturing, Version 2.0." June.
[38] Ibid.
[39] Frazier, William E., Elizabeth L. McMichael, Jennifer Wolk, Caroline Scheck. 2016. "Ensuring a Safe Technological Revolution." *Defence Acquisition Technology and Logistics* 14-16.
[40] Ibid.
[41] Ibid.
[42] Frazier, William E. 2016. "An ICME Informed Approach to Qualification for Additive Manufacturing." *MRS Bulletin* (Materials Research Society) 41: 737-739.
[43] Roach, R Allen et al. 2018. *Born Qualified Grand Challenge LDRD Final Report.* SAND2018-11276, Sandia National Laboratories.
[44] Ibid.
[45] Swiler, Laura P. et al. 2018. *Data Analysis for the Born Qualified LDRD Project.* SAND2018-11244, Sandia National Laboratories.
[46] Ibid.
[47] Roach, R Allen et al. 2018. *Born Qualified Grand Challenge LDRD Final Report.* SAND2018-11276, Sandia National Laboratories.
[48] Seifi, Mohsen, Ayman Salem, Jack Beuth, Ola Harrysson & John J. Lewandowski. 2016. "Overview of Materials Qualification Needs for Metal Additive Manufacturing." *Journal of The Minerals, Metals & Materials Society* 66 (3): 747-764.
[49] Kurfess, Dr. Tom, interview by the author. 2020. *Chief Manufacturing Officer - ORNL Manufacturing Demonstration Facility* (January 22).

Chapter 4: Certification Path Accelerators

The above certification paths all rely on a build-up approach and comparison to existing models and processes to achieve certification. A build-up approach is certainly prudent for certification of safety-critical parts, but the rate of build-up must be accelerated if the DAF is to take advantage of AM for both air and space applications and stay ahead of our competitors.

Exploiting Models

We rely on models for many aspects of our daily lives. Weather models inform what to wear for the day and what activities we will be able to do, traffic models predict how long our trip to work will take, and aircraft performance models predict the fuel required for a given mission and the optimal altitude to travel for the maximum efficiency. While accurate predictions in general are very difficult, validated models can be extremely valuable when it comes to predicting performance and reducing risk in decision making. The unfortunate aspect about models lies in the common aphorism, "all models are wrong, some models are useful." Even the most sophisticated model cannot accurately predict our infinitely complex world, but models remain our best tool to gain knowledge about a complex process and garner useful information. To increase accuracy, models must be updated based on test data in order to validate the model and make it useful. Predict-Test-Validate is a common method to successfully validating models in the flight test profession, and so too this can be applied to AM where the Predict-Build-Test-Validate model can provide a path towards certification of critical parts.

A 2016 DoD report laid out an AM roadmap that recognized the need for a model-based approach to accelerating AM materials qualification and certification. It called for the development of advanced computational methods and empirical physics-based models to simulate different AM processes and materials and predict performance.[50] The backbone of this approach is effective data management allowing a digital thread to be established.

Exploiting data and models will prove to accelerate the DAF's journey to wide-scale certification and use of AM. At its core, AM is a digital process; data are ubiquitous throughout a build. Requirements inform the digital engineering of a computer-aided design (CAD) part which is engineered and optimized by techniques like finite element analysis and then digitally sliced up into layers for loading into an AM machine that digitally controls robotics, power, and optics to melt and deposit the material and form the part. Mountains of time-series data about the AM machine and the parameters of the build (log files) are available to collect and store for analysis. In-situ data (i.e. data generated on-site during the build) can be collected based on the types of sensors installed in the machine. Then, post-processing and inspection generates more data which can be attributed to individual voxels (3D microscopic pixels) in the part creating a post-built digital representation of the part. It is often said that the AM process can be data rich, but information poor.[51] Data analysis methods are required to transform data into information that can support a decision. All these data, when properly analyzed, give us insight about the part and allow for comparison to the model in order to gain useful knowledge, mitigate risk, and make certification decisions.

PSPP Model

Researchers at Northwestern University have applied the Processing-Structure-Properties-Performance (PSPP) model to metal AM. Their depiction of the relationship is shown in Figure 5. The model shows how the AM build process determines the structure of the part, which then determines the mechanical properties and ultimately the part's performance.

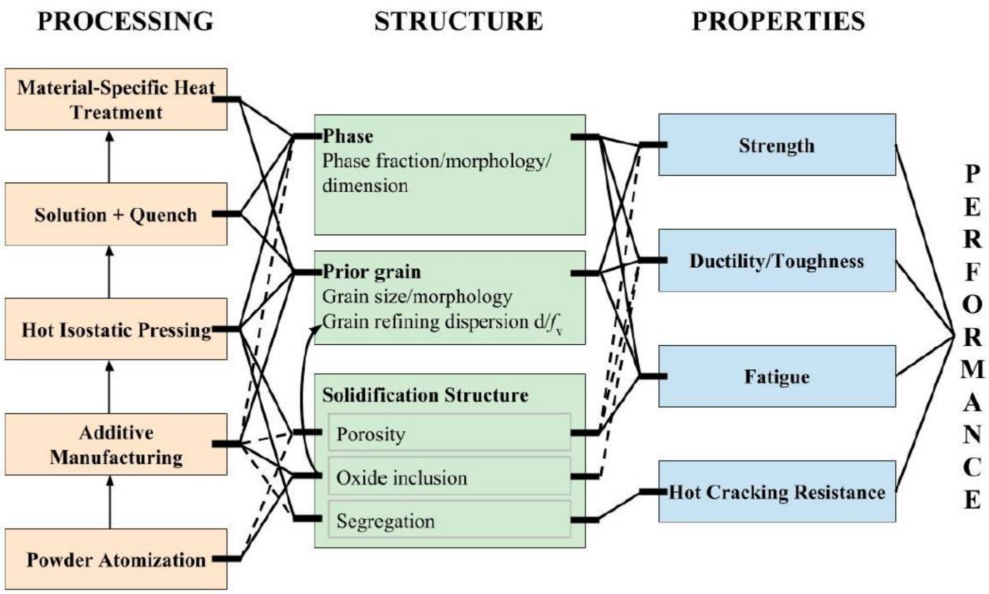

Figure 5: PSPP model for metal AM [52]

Confidence in the performance of the part is ultimately what certification is about. Following the PSPP model, if the process is sufficiently controlled and monitored, then the data generated from that process should give insight to the part's structure, its properties, and then ultimately allow for certification. Thus, a robust data collection and analysis strategy during the build process will allow for insight into the part's performance and enable certification.

A Digital Thread for AM

In search of competitive advantages, large companies are increasingly digitizing their supply chains and manufacturing processes to find efficiencies. This technology is often called a "digital thread" as it creates a digital representation of a process from concept all the way to finished product. This representation, or model, can be manipulated to optimize the design throughout its lifecycle. AM is uniquely suited to this technology as the entire process is based on digital data. A successful digital thread will require structure for data capture, storage, data availability, security and protection of intellectual property, and tools for data mining and analysis.[53] This data structure will then allow informatics, the science of processing data, to exploit the data and reveal information about the AM part supporting certification. A robust manufacturing digital thread allows the creation of a digital passport supporting critical part certification.

Sufficient data about a part establishes part provenance and enables parts to be reproduced in the same manner. Research has shown that when two different manufacturers were supplied with the geometry and material of a test artifact, they created drastically different parts due to their different AM processes and build parameters. However, when given a complete data package including the part geometry, processing plan, testing plan, and design requirements, they were each able to reproduce the parts with very close similarity.[54]

ICME approaches

An ICME approach to AM would focus on the predictive nature of models to improve quality and allow for certification. The development of accurate and validated modeling and simulation tools for AM will enable a process that can produce parts with known geometry, microstructure, and defects such that part performance can be predicted allowing for certification without extensive post-build inspection.[55] Accurate models would also inform the process parameters and in-situ data collection requirements required to validate each build. An ICME approach allows for sampling and analysis of pre-process, in-process, and post-process data to compare to the model and inform quality and certification decisions.[56] The Defense Advanced Research Projects Agency's Open Manufacturing program is focused on an ICME approach. Some of its stated goals include developing probabilistic performance models to guarantee that an AM product's performance lies within the design requirements and a rapid qualification process for statistical methods and simulation to predict product performance and inform decisions.[57]

In-Situ Data Collection and Closed-loop Control

Data collection during the AM build process and feedback of those data to control the build process is absolutely critical to control the quality of AM builds and provide data for analysis and certification. Metal AM shares much of the same physical phenomenon as welding. An experienced human welder senses a plethora of data about a weld via sight, sound, and feel as the weld is being made. He continuously adjusts process parameters such as wire speed, power, and toolpath to control the weld. This feedback loop increases the quality of the weld. Likewise, an aircraft pilot or autopilot system closes the loop around altitude or airspeed to obtain a desired flight condition. Much like the human or aircraft feedback loops, an AM machine feedback loop will increase the quality of a build and allow for the control of the physical properties as long as the correct data are collected, analyzed, and fed back to the machine in a timely manner for process parameter control. This same data that are used for control can also be collected layer by layer during the build and can then be compared to the 3D model and used for part performance prediction and certification as part of the digital passport concept.

Dr. Brian Gibson at ORNL led a study to enable closed-loop control on a laser-wire DED machine using Ti-6Al-4V wire to produce improved quality titanium alloy structures.[58] The team found that a consistent melt pool size was an important aspect of ensuring uniform deposition and geometric properties of the build. A commonly available thermal camera was used to image the melt pool in-situ and digitally quantify the size of the melt pool in pixels as the wire traveled along the build surface. This melt pool size was then measured while changing primary process parameters such as the laser power, wire feed rate, and the print speed.[59] After determining the effects on melt pool size, the parameters can be fed back to the machine controller allowing it to adjust process parameters in real-time and create a consistent melt pool and part geometry, greatly increasing part quality and consistency. By varying process parameters, this closed-loop control was also demonstrated to be able to create geometries that were outside of the actual tool path of the laser resulting in increased part control.[60] This capability could be adapted to imprint anti-counterfeit artifacts such as QR codes into metal parts.

Figure 6: Oak Leaf image in titanium wall build resulting from melt pool size control[61]

Another team of researchers at ORNL are developing the Metal Big Area Additive Manufacturing (MBAAM) system using gas-metal arc welding to additively manufacture large metal parts and tooling. This open-air system uses existing wire-arc welding technology to additively manufacture large-scale parts such as excavator arms. Due to the large build volume, lower capital costs, and established supply chain (commonly available metal wire and welders)

MBAAM is currently seen as the most economical method to build large metal parts.[62] A high level of closed-loop process control is necessary to turn a messy process like welding into a part that meets the net shape of the original design. To accomplish this, the MBAAM system uses a proprietary feedback loop and algorithm to measure the current build height and then adjusts the vertical location of the printing head and the deposition rate (speed and wire feed rate) to control the amount of deposited material resulting in flat depositions that meet the near net shape requirements.[63] Through proper planning and closed-loop control, the MBAAM system was able to achieve stable and nearly isotropic properties in a thin wall build.[64] Other research on a powder bed electron beam system has even shown that location specific microstructure control, although difficult and tedious, is possible by varying process parameters.[65] The researchers believe that soon microstructure control will be common and open up another design space in the field of topology optimization where different microstructures can be designed into the part allowing optimized geometries, increases in strength, and reduction in weight. These microstructures can then be printed through sophisticated scan strategies and closed-loop control.[66]

Machine Learning for Defect Detection

Machine learning (ML) algorithms have become a useful tool for researchers in understanding the massive data generated by AM. In the quality control process, when ML is properly implemented it can quickly analyze large amounts of data and generate information about the build to either detect anomalies and disqualify the part or support certification.

ORNL researchers recently studied the characterization of laser melt pool defects using a machine learning algorithm on a laser-PBF machine.[67] A visible-light high-speed camera was used to collect images of the laser melt pool layer by layer in-situ, and then supervised ML was able to classify melt pools and identify the types of pools that tended to generate material flaws. ML proved critical in either detecting and registering flaws in builds or identifying potential anomalies that can focus a human interpreter on areas of the part that may have flaws.

In metal powder bed machines, the uniform spreading of metal powder at each layer is critical to the build process and anomalies like incomplete spreading, hopping, streaking, and debris in the powder lead to failed builds or defects in specific sections of the part. These anomalies can often be observed with the human eye in a digital image each layer, but with thousands of layers and builds taking multiple days, human monitoring is problematic. Modern ML techniques like Convolution Neural Networks (CNN) are valuable tools for analyzing thousands of images to detect and classify anomalies. Dr. Luke Scime, an ORNL researcher, has shown that a multi-scale CNN can be trained to detect spreading anomalies in digital images of the laser PBF process. As shown in Figure 7, the layer-wise anomaly detection and classification can be combined into a model representation of the build volume that has shown to accurately portray defects in the actual part.[68]

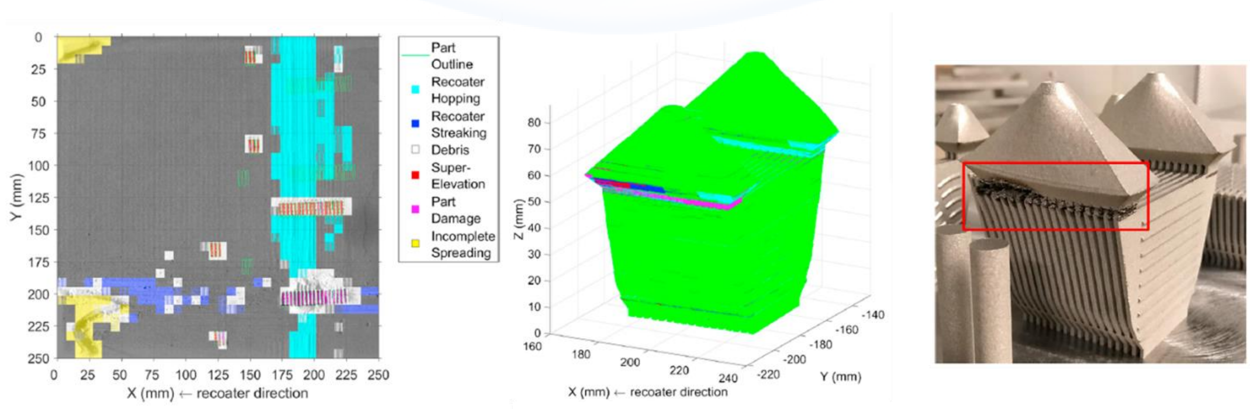

Figure 7: (left to right) An anomaly detection algorithm output of a single spreading layer, a composite model of anomalies in the build volume, and the as-built part with defects visible[69]

One current advanced data analytics project at the MDF is on a comprehensive ML software application called Peregrine. This application is being designed to autonomously track layer-wise image data collected in-situ along with part metadata and produce advanced visualizations allowing anomaly detection or supporting part certification. It uses a deep learning method called Dynamic Segmentation Convolutional Neural Network to classify each pixel of each layer as powder, a fused part, or some type of anomaly. The application is being developed to be AM machine agnostic meaning it has the potential to be implemented on a wide variety of AM machines.[70]

The advantages gained by instrumenting AM machines and adapting sensors, instruments, and advanced analysis methods greatly increases the knowledge that is gained about a part as it is produced. Some experienced researchers at ORNL believe that we will soon know so much about an AM part and its properties and performance that we will look at other traditional manufacturing methods like casting and forging with suspicion because they cannot provide us with the layer-by-layer or voxel level of data that AM can.[71]

Standards Development

A key barrier to certification and realization of the benefits of AM for the DAF and the aerospace industry is the development of accepted material, process, and inspection standards. Due to the new and developing nature of AM, the standards development organizations (SDOs) like ISO, SAE, and ASTM have not yet been able to nail down accepted standards for use throughout the community. In 2018 the AMSC roadmap identified 93 open gaps with 65 areas requiring additional research and development towards producing adequate AM standards for the community. Among the high priorities for standards development, the AMSC identified the need for a common Technical Data Package (TDP) format and content for AM, dimensioning tolerancing requirements, material precursor standards and storage requirements, AM machine calibration and maintenance, minimum mechanical properties of given designs and build methods, design allowables, part classification systems, a guide for NDE techniques, data fusion of NDE results, and acceptable flaw criteria for fracture-critical parts.[72] It acknowledged that no standards even exist for the terminology difference between "qualification" and "certification" and the two are often used interchangeably in the industry resulting in confusion.[73] Perhaps the best definitions of these two and the ones used in this paper are provided by the US Navy: "…qualification refers to the manufacturing process used to produce a material and the means by which reproducible, reliable, minimum design material allowable properties are ensured. Certification refers to a specific part and whether it is fit for use in its intended operational environment."[74] In short, a process is "qualified", and a part or product is "certified".

The DoD does not write these standards but must play a large and active part in their development since they are a significant barrier to AM part certification. The achievement of certification thus far has only been by large companies like Boeing convincing authorities like the FAA that their in-house standards and testing processes are adequate as a means of compliance with the CFRs. Common standards will level the playing field and open the market for small-sized companies to participate.[75] A broader market base is beneficial to the DoD as it gives more acquisition options, reduces costs, and allows replacement parts to be manufactured when needed even if the original equipment manufacturer is no longer in business or has divested that production process.

---

[50] 2016. *Department of Defense Additive Manufacturing Roadmap.* Final Report, DoD, America Makes

[51] Paquit, Dr. Vincent, interview by the author. 2019. *Senior R&D staff – Imaging, Signals, and Machine Learning group and Data Analytics Lead* (December 4).

[52] Yan, Fuyao, Wei Xiong and Eric J. Faierson. 2017. "Grain Structure Control of Additively Manufactured." *Materials* 10 (11): 1260.

[53] Mies, Deborah, Will Marsden and Stephen Warde. 2016. "Overview of Additive Manufacturing Informatics: 'A Digital Thread'." *Integrating Materials and Manufacturing Innovation* 5 (6): 1-29.
[54] Kim, D., P. Witherell, Y. Lu, and S. Feng. 2017. "Toward a Digital Thread and Data Package for Metals-Additive Manufacturing." *Smart and Sustainable Manufacturing Systems* 1 (1): 75-99.
[55] Seifi, Mohsen, Ayman Salem, Jack Beuth, Ola Harrysson & John J. Lewandowski. 2016. "Overview of Materials Qualification Needs for Metal Additive Manufacturing." *JOM* 66 (3): 747-764.
[56] Ibid.
[57] Vandenbrande, Jan. n.d. "Open Manufacturing Program Information." *DARPA.mil.* Accessed Dec 8, 2019.
[58] Gibson, Brian et al. 2019. "Melt Pool Monitoring for Control and Data Analytics in Large-Scale Metal Additive Manufacturing." *International Solid Freeform Fabrication Symposium.*
[59] Ibid.
[60] Gibson, Brian T et al. 2019. "Beyond the Toolpath: Site-Specific Melt Pool Size Control Enables Printing of Extra-Toolpath Geometry in Laser Wire-Based Directed Energy Deposition." *Applied Sciences* 9: 4355.
[61] Ibid.
[62] Hu, Xiaohua, Andrzej Nycz, Yousub Lee, Benjamin Shassere, and Srdjan Simunovic. 2019. "Towards an Integrated Experimental and Computational Framework for Large-scale Metal Additive Manufacturing." *Materials Science and Engineering: A.*
[63] Ibid.
[64] Shassere, Benjamin, Andrzej Nycz, Mark W. Noakes, Christopher Masuo and. 2019. "Correlation of Microstructure and Mechanical Properties of Metal Big Area Additive Manufacturing." *Journal of Applied Sciences* 9 (4): 787.
[65] Dehoff, R. R., M. M. Kirka, W. J. Sames, H. Bilheux, A. S. Tremsin, L. E. 2014. "Site Specific Control of Crystallographic Grain Orientation through Electron Beam Additive Manufacturing." *Materials Science and Technology* 931-938.
[66] Dehoff, Dr. Ryan, interview by the author. 2020. Group Leader - ORNL Deposition Science and Technology (January 21).
[67] Scime, Luke, Jack Beuth. 2019. "Using Machine Learning to Identify In-situ Melt Pool Signatures Indicative of Flaw Formation in a Laser Powder Bed Fusion Additive Manufacturing Process." *Additive Manufacturing* 25: 151-165.
[68] Scime, Luke, Jack Beuth. 2018. "A Multi-scale Convolutional Neural Network for Autonomous Anomaly Detection and Classification in a Laser Powder Bed Fusion Additive Manufacturing Process." *Additive Manufacturing* 24: 273-286.
[69] Ibid.
[70] Scime, Dr. Luke, interview by the author. 2019. *R&D Associate Staff Scientist, Imaging, Signals, and Machine Learning Group* (December 20).
[71] Love, Dr. Lonnie, interview by the author. 2020. Group Leader - ORNL Manufacturing Systems Research (February 14).
[72] America Makes & ANSI Additive Manufacturing. 2018. "Standardization Roadmap for Additive Manufacturing, Version 2.0." June.
[73] Ibid.
[74] Frazier, William E. 2016. "An ICME Informed Approach to Qualification for Additive Manufacutring." *MRS Bulletin* (Materials Research Society) 41: 737-739.
[75] Seifi, Mohsen, et al. 2017. "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification." *JOM* 69 (3).

Chapter 5: From Data to Certification

The massive amounts of data generated in the design of AM parts, simulation of AM processes, and collected during AM builds makes the use of big data techniques essential to understanding the process and informing decisions about certification. The key to certifying safety-critical parts and unlocking the true potential of AM will be to manage and exploit these data to gain knowledge and inform certification decisions.

A Model for AM Part Certification

The predict-test-validate model commonly used in flight test to validate aircraft or subsystem performance and proclaim it ready for the warfighter can be expanded and applied to the certification of AM parts. A predict-build-test-validate model is offered here as a method for manufacturing and certifying parts. The predict phase allows us to design the part, determine what performance is needed, and determine the material and process controls necessary to achieve that performance. Parts can be over-designed to allow for some variability and level of defects which are common in AM. In the build phase, both data from overall setup and process parameters as well as in-situ data from machine instrumentation are collected. The test phase is then tailored based on the confidence in the model and the process by which is was built. Results from the test phase, which may include both ground and flight tests, are fed back to update and improve the model. In the validation phase, the finished part is compared to its digital thread and the predictions of its performance. Data from every phase of this process are accumulated in a digital passport, then analyzed and exploited to gain information and knowledge supporting a certification decision. A visual depiction and details of this model are shown in Figure 8 below.

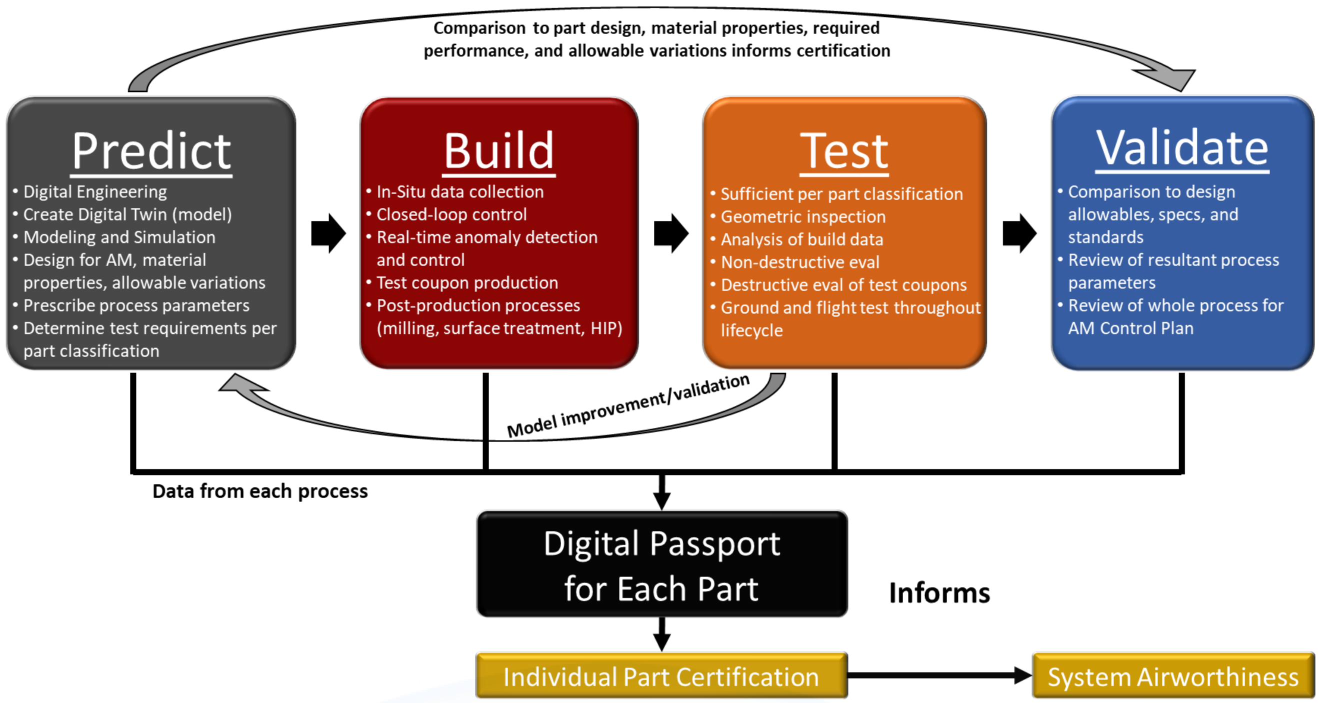

Figure 8: Proposed AM part certification model

Armed with voxel-level data from each phase in the above model, a manufacturer can sufficiently analyze the data to confidently show that the created part matches its model or is within the design allowables and will perform suitably in its intended application thus mitigating risk and allowing certification.

Two key capabilities gaps which are barriers to implementing the above model are the existence of a standard TDP that allows data to be collected, stored, and analyzed in a consistent manner, and the overall lack of data science professionals that are capable of analyzing these data, creating analysis tools and algorithms, and transforming it all into actionable information for senior leaders to make certification decisions. The DAF must make research and personnel investments in these areas if it is to realize wide-spread AM use.

A small demonstration was conducted on a Computer Numerical Control (CNC) milling machine to demonstrate the Predict-Build-Test-Validate model on a part depicting the USAF symbol. Details are in the next chapter.

Part, Process, or Machine Certification?

This paper has shown that certifying and locking down a singular process or machine is time consuming and inflexible. While this method may be the quickest path in the short term to get a handful of parts certified and flying, it does not allow us to infer knowledge about the processes' ability to create other parts reliably. Likewise, certifying individual parts through rigorous post-production testing is cost and time intensive.

In the long run, the DAF should seek to certify a part that matches a validated model and is produced with a machine capable of collecting and analyzing data that can provide assurance that the part satisfactorily matches that model. This type of data collection and analysis allows the creation of a digital passport for each part. This passport allows the certification authority, armed with knowledge about the part's provenance and its final structure, to have confidence in its properties and performance throughout its lifecycle. The DAF should only acquire AM systems for sustainment and contract with manufacturers that are able to provide an adequate amount of in-situ data to validate that the part matches the model and its performance requirements. It should not certify a specific AM process, but a production process of data collection and analysis which matches a part to its model and creates a digital passport for the supply chain.

Chapter 6: A Machine Data Collection and Analysis Example

The original plan for this research paper was to design, print, and test a small part while collecting data at every step of the process to demonstrate the concept of a digital passport in a simple example. The COVID-19 pandemic altered those plans slightly as the MDF machines were not available or were engaged in creating face mask molds for healthcare professionals to support mass production for the fight against the disease. However, a small demonstration was still accomplished to showcase in-situ data collection and analysis principles using a subtractive CNC machine. While this machine was subtractive only, for our purposes a CNC is actually a suitable surrogate for an AM machine since the process parameters used will determine the resulting properties of the part in terms of geometry and finish according to the PSPP model described earlier.

Kyle Saleeby, an ORNL researcher, is designing and implementing a digital data collection architecture for the entire MDF. The goal is to demonstrate the power of collecting multitudes of diverse data from each machine in a factory for real-time display and monitoring, control, trend analysis, and production line optimization. For this project, the basic architecture and some methods of his data collection scheme were used allowing a determination of part quality to support certification. Two sample parts were machined, the second with an intentional error in the code causing a geometry offset defect. In practice, this type of error even in a tightly controlled and qualified process could be introduced in a number of ways such as operator error, cyber attack, or worn CNC mechanical components. The goal was to identify the resulting defective part using in-situ data and without any post-build measurements or testing.

Setup and Data Collection

A CAD model of a surface with a raised Air Force symbol was used as a simple representation of a part requiring a very specific and precise geometry. The PocketNC V1, a table-top 5-axis CNC with a 10,000-rpm spindle for machining small metal, wood, and polymer parts, was used to mill the two parts out of wood.[76] It was fitted with a ¼ inch diameter ball end mill. Autodesk Fusion 360 was used for part design and generating the G-code for the toolpath.[77] It created an adaptive toolpath (keeping load on the cutting tool approximately constant) to clear the bulk material, and then a final contouring toolpath to create the final outline of the part. The software generated toolpaths and the physical setup is shown in Figure 9.

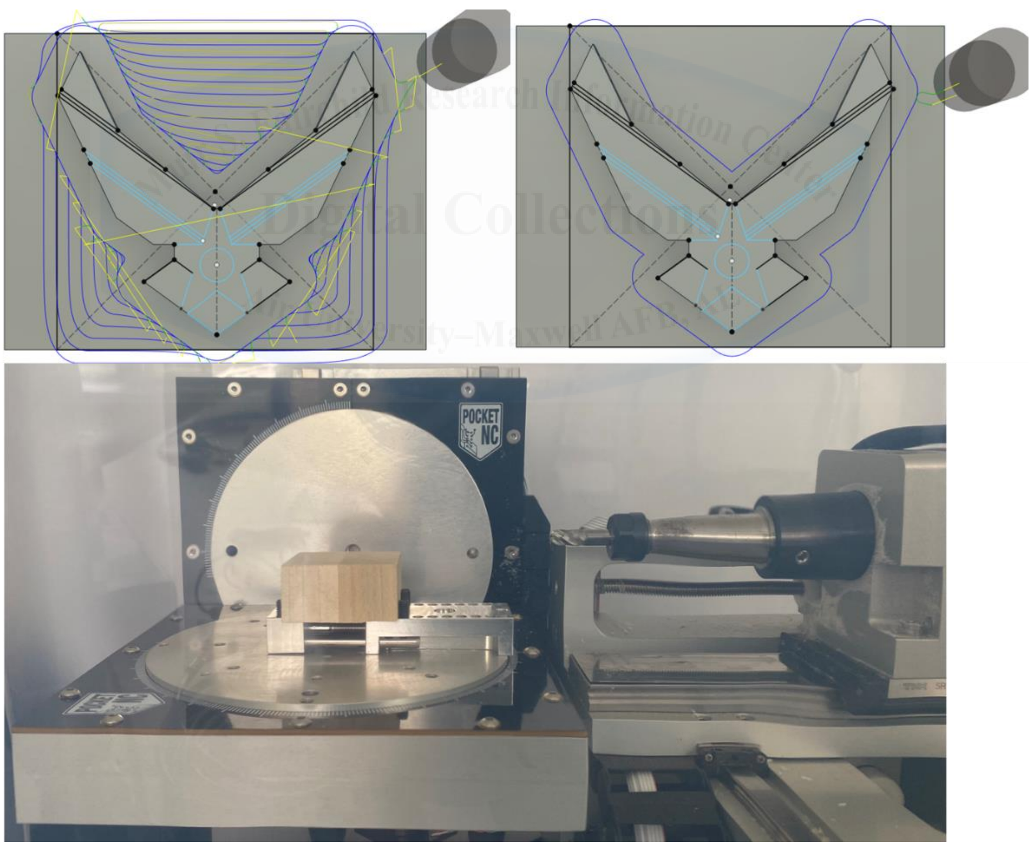

Figure 9: Planned adaptive and contouring toolpath (top) and PocketNC setup (bottom)

The PocketNC was instrumented to report its linear and angular positional data as it cut the part. To record these data, the MTConnect standard (ANSI/MTC1.4-2018) was used as it provides an open source and standardized vocabulary for a multitude of different machine types to communicate data.[78] The PocketNC machine included a previously developed MTConnect adapter to output machine data in JavaScript Object Notation (JSON) format at a rate of 5 Hertz. The JSON data were then read and streamed to a Message Queuing Telemetry Transport (MQTT) broker using Node-RED, an open-source programming tool made for wiring together many processes.[79] Node-RED is capable of being run with very low computing resources making it ideal for a Raspberry Pi or other inexpensive products. This data stream was then stored in a Structured Query Language (SQL) database as a JSON string. After the build, Node-RED was again used to query the database and feed a custom Python script for analysis and visualization.[80] The Node-RED visual flow is depicted in Figure 10.

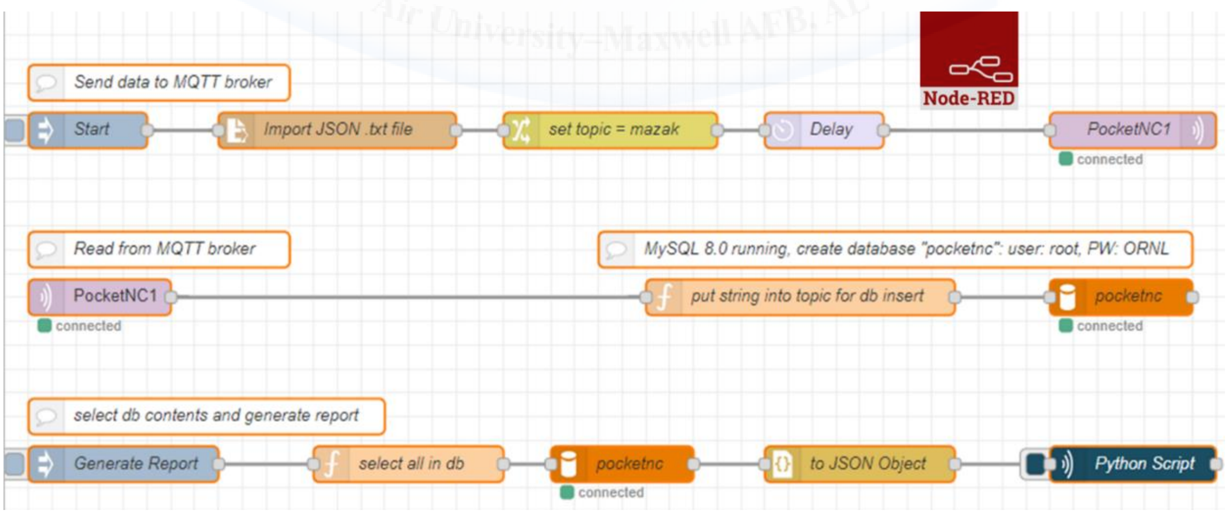

Figure 10: Example Node-RED flow to collect machine data and send for analysis

While this data analysis flow is admittedly overly complex for this simple demonstration, the architecture can be easily scaled and automated such that many different machines and machine types can stream data into a database for storage and future analysis. There are no physical wires between layers of the flow, meaning that once the machine data is collected, it can be stored and analyzed via cloud or edge computing resources located anywhere.

The final contour of the AF symbol geometry was considered to be the critical parameter to certify or reject the part. A simulated tolerance of .01 inches was chosen to represent the allowable tolerance meaning the toolpath needed to be within .01 inches of the design or the part would be rejected. Two parts were machined out of blocks of wood and the data were analyzed to determine which could be accepted and which should be rejected.

Data Analysis

The XY-plane plot of the final contouring toolpath used to create the part is shown in Figure 11. Visual examination of this toolpath plot shows that the first part created was within positional tolerances and can be accepted, while the second is clearly out of tolerance and should be rejected. Physically the two parts look the same and the human observer would be unable to visually tell the difference, but a quick examination of the data gives the builder useful information about the part.

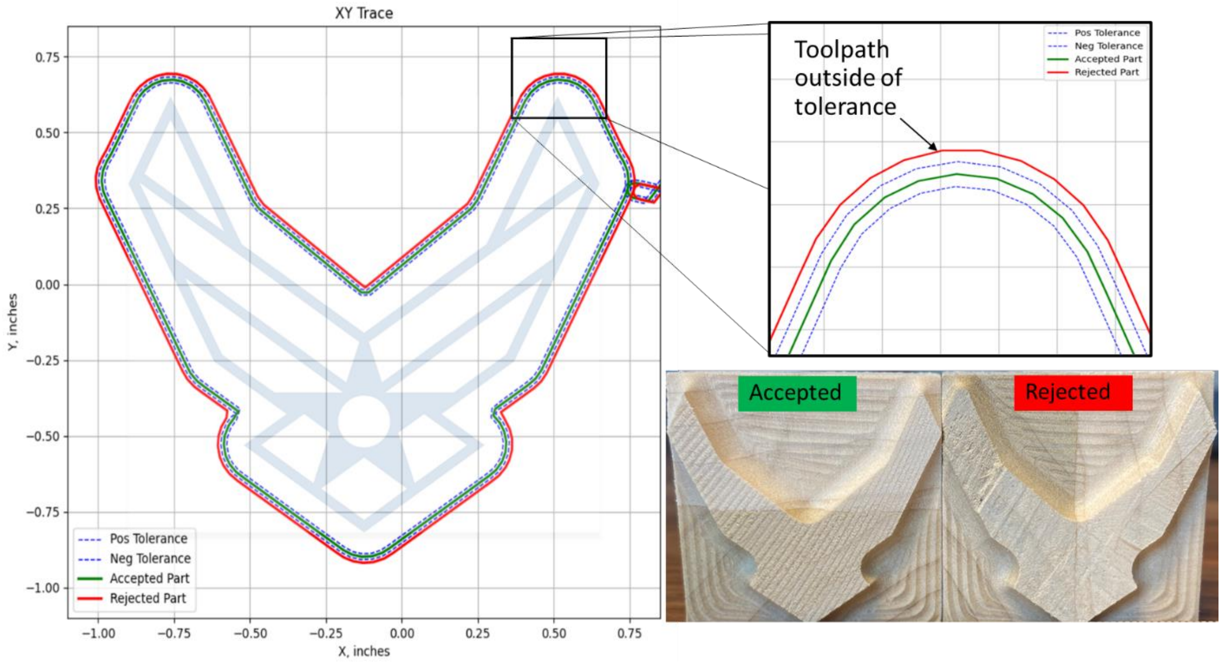

Figure 11: Resulting XY-plane trace and analysis of final contour toolpath

Demonstration Results

This demonstration showed how in-situ data can be collected, stored, and analyzed to support part certification or rejection. While it only focused on the toolpath and resulting geometry, a true digital passport would include many more parameters that would have an impact on the structure of the part thus dictating its properties and performance and necessary to reduce risk for certification. Each parameter would need its own collection and analysis strategy. Applying the AM part certification model offered in the previous chapter, the steps that were demonstrated to accept or reject a part were:

Predict – Precise geometry requirements, CAD model, and toolpath tolerances (.01 inches)

Build – In-situ collection, streaming, and database storage of machine data

Test – Python script to plot recorded toolpath versus the allowable tolerances

Validate – Report generated to accept or reject the part based on comparison to model

Without the in-situ data collection in this demonstration, the only way to assure part geometry would be through an expensive and time-consuming metrology process using a separate coordinate-measuring machine (CMM). Also, the type of data collection and analysis employed in this demonstration is extremely low cost. MTConnect is an open source standard, NodeRED is open source and community developed, and the free Python libraries include a plethora of open source data analysis tools. This architecture could realistically be achieved by a very small machine shop with minimal computing resources. Given a well-defined and standard technical data package as a requirement for certification, there is opportunity for small and medium-sized shops to compete with larger traditional manufacturers. This would increase the overall manufacturing base for the Air Force, lower manufacturing costs, and give innovative start-up businesses an opportunity to prototype safety-critical flight parts.

---

[76] *Pocket NC.* Accessed May 4, 2020. https://pocketnc.com/
[77] *Autodesk Fusion 360.* Accessed May 4, 2020. https://www.autodesk.com/products/fusion-360/overview
[78] *MTConnect Institute.* Accessed May 4, 2020. https://www.mtconnect.org/about
[79] *Node-RED.* Accessed May 4, 2020. https://nodered.org/about/
[80] *Python 3.0.* Accessed May 4, 2020. https://www.python.org/downloads/

Chapter 7: Conclusions and Recommendations

To certify the airworthiness of AM parts and seize the full advantages that AM offers, the DAF needs to mitigate risks through informed awareness about the parts using the correct level of oversight and scrutiny. It should follow the offered Predict-Build-Test-Validate model to collect and analyze enough data to create a digital passport for each part and support certification.

Following this model, the DAF can accelerate down the path towards safety-critical part certification by taking several steps:

- Develop a consistent digital data package format and content for AM part design, engineering, build, and inspection that can be written into contract language – A digital passport.
- Do not certify individual AM processes or machines; instead seek to certify processes of collecting data and data analysis methods whereby the properties of the AM part can be determined and matched with the validated model ensuring it will meet designed performance metrics.
- Develop a robust classification schema for AM parts which appropriately classifies parts by function and consequence of failure based on the operating environment, the engineering design margins, the level of confidence in the AM process being used, and the availability and effectiveness of post-processing NDE. This will ensure the right amount of rigor is applied to each part.
- Partner with other certifying organizations (e.g. FAA and USN) to develop consistent standards and methods for certifications.

- Use AM for safety-critical components in a build-up fashion (non-fracture critical components, fracture critical component of small UAV, Large UAV, manned aircraft with redundancies etc.) - Use these cases to validate the certification method and allow scaling up to safety-critical parts on manned aircraft.
- Plan and use AM in a new aircraft platform yet to undergo “iron bird” type testing where AM parts can be rigorously ground- and flight-tested in order to exercise AM and develop the digital passport concept.
- Invest in research needed for optimizing what to sense, how to sense it, and how to process the volumes of data generated.
- Participate in industry-wide standards development efforts of the SDOs to ensure that the standards meet DAF requirements and are not too stringent nor too lenient.
- Invest in human capital and AM education programs that will increase the overall knowledge base especially in the data science field in order to collect, analyze, and interpret the vast amount of data generated by the AM process and understand contractor processes that claim to collect and analyze these data.
- Apply the AFWERX innovation paradigm to AM (think big, start small, scale fast)[81]; do not be afraid to fail fast on a low-consequence AM application.

The best attitude and philosophy towards AM found while researching this topic came from the US Navy who is arguably the most aggressive in their pursuit of using AM to this point. According to Dr. Frazier, “If we want to use AM, we need to start using AM.”[82]

[81] "AFWERX Innovation Handbook v 1.0." *afwerx.af.mil.*
[82] Frazier, William E. 2016. "An ICME Informed Approach to Qualification for Additive Manufacturing." *MRS Bulletin* (Materials Research Society) 41: 737-739.

Bibliography

2019. "7 Families of Additive Manufacturing." *Hybridmanutech.com.* Accessed Dec 30, 2019. www.hybridmanutech.com/resources.html.

AFLCMC/EZ Structures Bulletin. 2019. "Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts." *EZ-SB-19-01*. June 10.

n.d. "AFWERX Innovation Handbook v 1.0." *afwerx.af.mil.* Accessed January 6, 2020. www.afwerx.af.mil/resources/Innovation%20Handbook.pdf.

Air Force Instruction (AFI) 62-601. 11 June 2010. *USAF Airworthiness.*

America Makes & ANSI Additive Manufacturing. 2018. "Standardization Roadmap for Additive Manufacturing, Version 2.0." June. www.ansi.org/news_publications/news_story?menuid=7&articleid=fc19f3c2-de56-4d96-9d42-cc0c7a0c8c37.

n.d. *Autodesk Fusion 360.* Accessed May 4, 2020. https://www.autodesk.com/products/fusion-360/overview.

Brackens, Brian. 2019. "Air Force stands up new Advanced Aircraft PEO." *AF.mil.* October 3. www.af.mil/News/Article-Display/Article/1979065/air-force-stands-up-new-advanced-aircraft-peo/.

Dehoff, Dr. Ryan, interview by the author. 2020. *Group Leader - ORNL Deposition Science and Technology* (January 21).

Dehoff, R. R., M. M. Kirka, W. J. Sames, H. Bilheux, A. S. Tremsin, L. E. 2014. "Site Specific Control of Crystallographic Grain Orientation through Electron Beam Additive Manufacturing." *Materials Science and Technology* 931-938. doi:10.1179/1743284714Y.0000000734.

2016. *Department of Defense Additive Manufacturing Roadmap.* Final Report, DoD, America Makes. www.americamakes.us/wp-content/uploads/sites/2/2017/05/Final-Report-DoDRoadmapping-FINAL120216.pdf.

DoD Inspector General. 2019. "Audit of the DoD's Use of Additive Manufacturing for Sustainment Parts." Report No. DODIG-2020-003.

Frazier, William E. 2016. "An ICME Informed Approach to Qualification for Additive Manufacturing." *MRS Bulletin* (Materials Research Society) 41: 737-739. doi:10.1557/mrs.2016.217.

Frazier, William E., Elizabeth L. McMichael, Jennifer Wolk, Caroline Scheck. 2016. "Ensuring a Safe Technological Revolution." *Defence Acquisition Technology and Logistics* 14-16. www.dau.edu/library/defense-atl/DATLFiles/Nov-Dec2016/DATL%20Nov_Dec2016.pdf.

Froes, Francis, and Rodney Boyer. 2019. *Additive Manufacturing for the Aerospace Industry.* Elsevier Science. doi:10.1016/C2017-0-00712-7.

George, Major Benjamin E. 2014. *3D Printing in the Air Force - Dispelling the Myths of Additive Manufacturing.* Maxwell AFB: Air University.

Gibson, Brian T. Bradley S. Richardson, Tayler W. Sundermann, and Lonnie J. Love. 2019. "Beyond the Toolpath: Site-Specific Melt Pool Size Control Enables Printing of Extra-Toolpath Geometry in Laser Wire-Based Directed Energy Deposition." *Applied Sciences* 9: 4355. doi:10.3390/app9204355.

Gibson, Brian, Bandari, Yashwanth Kumar, Richardson, Brad, Roschli, Alex, Post, Brian, Borish, Michael, Thornton, Aaron S., Henry, William C., Lamsey, Matthew D., and Love, Lonnie.

2019. "Melt Pool Monitoring for Control and Data Analytics in Large-Scale Metal Additive Manufacturing." *International Solid Freeform Fabrication Symposium.* OSTI. www.osti.gov/servlets/purl/156163.

2017. "High Level Process - Directed Energy Deposition, Powder Bed Fusion, Binder Jetting." *Bits Into Atoms - 3D Printing and Design.* April 30. www.bintoa.com/.

Hu, Xiaohua, Andrzej Nycz, Yousub Lee, Benjamin Shassere, and Srdjan Simunovic. 2019. "Towards an Integrated Experimental and Computational Framework for Large-scale Metal Additive Manufacturing." *Materials Science and Engineering: A.* doi:10.1016/j.msea.2019.138057.

Insinna, Valerie. 2019. "The US Air Force's radical plan for a future fighter could field a jet in 5 years." *DefenseNews.com.* September 16. www.defensenews.com/digital-show-dailies/2019/09/16/the-us-air-forces-radical-plan-for-a-future-fighter-could-field-a-jet-in-5-years/.

Kellner, Thomas. 2018. "Fired Up: GE Successfully Tested Its Advanced Turboprop Engine With 3D-Printed Parts." *GE.com.* January 2. www.ge.com/reports/ge-fired-its-3d-printed-advanced-turboprop-engine/.

Kim, D., P. Witherell, Y. Lu, and S. Feng. 2017. "Toward a Digital Thread and Data Package for Metals-Additive Manufacturing." *Smart and Sustainable Manufacturing Systems* 1 (1): 75-99. doi:10.1520/SSMS20160003.

Kurfess, Dr. Tom, interview by the author. 2020. *Chief Manufacturing Officer - ORNL Manufacturing Demonstration Facility* (January 22).

Lord, Ellen M. 2019. "Directive-type Memorandum (DTM)-19-006." *Interim Policy and Guidance for the Use of Additive Manufacturing (AM) in Support of Materiel Sustainment.* Under Secretary of Defense for Acquisition and Sustainment, March 21.

Love, Dr. Lonnie, interview by the author. 2020. *Group Leader - ORNL Manufacturing Systems Research* (February 14).

McCue, T.J. 2019. "Significant 3D Printing Forecast Surges To $35.6 Billion." *Forbes.* March 27. www.forbes.com/sites/tjmccue/2019/03/27/wohlers-report-2019-forecasts-35-6-billion-in-3d-printing-industry-growth-by-2024/#2764f7127d8a.

Mies, Deborah, Will Marsden and Stephen Warde. 2016. "Overview of Additive Manufacturing Informatics: 'A Digital Thread'." *Integrating Materials and Manufacturing Innovation* 5 (6): 1-29. doi:10.1186/s40192-016-0050-7.

n.d. *MTConnect Institute.* Accessed May 4, 2020. https://www.mtconnect.org/about.

NASA Marshall Space Flight Center. 2017. "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals." *MSFC-STD-3716.* October 18. https://standards.nasa.gov/standard/msfc/msfc-std-3716.

2016. "NAVAIR Marks First Flight with 3-D printed, safety-critical parts." *Navy.mil.* Naval Air Systems Command Public Affairs. July 29. www.navy.mil/submit/display.asp?story_id=95948.

n.d. *Node-RED.* Accessed May 4, 2020. https://nodered.org/about/.

Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics. 2017. "FY 2017 Additive Manufacturing Report to Congress."

Paquit, Dr. Vincent, interview by the author. 2019. *Senior R&D staff – Imaging, Signals, and Machine Learning group and Data Analytics Lead* (December 4).

n.d. *Pocket NC.* Accessed May 4, 2020. https://pocketnc.com/.

n.d. *Python 3.0.* Accessed May 4, 2020. https://www.python.org/downloads/.

Roach, R Allen et al. 2018. *Born Qualified Grand Challenge LDRD Final Report.* SAND2018-11276, Sandia National Laboratories. doi:10.2172/1481619.
Roper, Will. 2019. "Stars and Stripes." *3D printing is about to save the military billions of dollars.* December 26. www.stripes.com/opinion/3d-printing-is-about-to-save-the-military-billions-of-dollars-1.612681.
Sames, W. J. , F. A. List, S. Pannala, R. R. Dehoff & S. S. Babu. 2016. "The Metallurgy and Processing Science of Metal Additive Manufacturing." *International Materials* 61 (5): 315-360. doi:10.1080/09506608.2015.1116649.
Scime, Dr. Luke, interview by the author. 2019. *R&D Associate Staff Scientist, Imaging, Signals, and Machine Learning Group* (December 20).
Scime, Luke, Jack Beuth. 2018. "A Multi-scale Convolutional Neural Network for Autonomous Anomaly Detection and Classification in a Laser Powder Bed Fusion Additive Manufacturing Process." *Additive Manufacturing* 24: 273-286. doi:10.1016/j.addma.2018.09.034.
Scime, Luke, Jack Beuth. 2019. "Using Machine Learning to Identify In-situ Melt Pool Signatures Indicative of Flaw Formation in a Laser Powder Bed Fusion Additive Manufacturing Process." *Additive Manufacturing* 25: 151-165. doi:10.1016/j.addma.2018.11.010.
Scott, Alwyn. 2017. "Printed titanium parts expected to save millions in Boeing Dreamliner costs." *Reuters.com.* April 10. https://www.reuters.com/article/us-norsk-boeing-idUSKBN17C264.
Seifi, Mohsen, Ayman Salem, Jack Beuth, Ola Harrysson & John J. Lewandowski. 2016. "Overview of Materials Qualification Needs for Metal Additive Manufacturing." *JOM* 66 (3): 747-764. doi:10.1007/s11837-015-1810-0.
Seifi, Mohsen, Michael Gorelik, Jess Waller, Nik Hrabe, Nima Shamsaei, Steve Daniewicz, and John Lewandowski. 2017. "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification." *JOM* 69 (3). doi:10.1007/s11837-017-2265-2.
Shassere, Benjamin, Andrzej Nycz, Mark W. Noakes, Christopher Masuo and. 2019. "Correlation of Microstructure and Mechanical Properties of Metal Big Area Additive Manufacturing." *Journal of Applied Sciences* 9 (4): 787. doi:10.3390/app9040787.
Simpson, Joseph et al. 2019. *Considerations for Application of Additive Manufacturing to Nuclear Reactor Core Components.* ORNL/TM-2019/1190, Oak Ridge National Laboratory.
2014. "SpaceX Launches 3D-Printed Part to Space, Creates Printed Engine Chamber." *SpaceX.com.* July 31. www.spacex.com/news/2014/07/31/spacex-launches-3d-printed-part-space-creates-printed-engine-chamber-crewed.
Swiler, Laura P. et al. 2018. *Data Analysis for the Born Qualified LDRD Project.* SAND2018-11244, Sandia National Laboratories. doi:10.2172/1481602.
Totin, Ashley, Eric MacDonald, & Brett P. Conner. 2019. "Additive Manufacturing for Aerospace Maintenance and Sustainment." *DSIAC Journal* (DSIAC Journal) 6 (2): 4-11. www.dsiac.org/sites/default/files/journals/dsiac-spring-2019-vol-6-no-2_0.pdf.
2019. "Update: In-Flight Abort Static Fire Test Anomaly Investigation." *SpaceX.com.* July 15. www.spacex.com/news/2019/07/15/update-flight-abort-static-fire-anomaly-investigation.
Vandenbrande, Jan. n.d. "Open Manufacturing Program Information." *DARPA.mil.* Accessed Dec 8, 2019. www.darpa.mil/program/open-manufacturing.
Yan, Fuyao, Wei Xiong and Eric J. Faierson. 2017. "Grain Structure Control of Additively Manufactured Metallic Materials." *Materials* 10 (11): 1260. doi:10.3390/ma10111260.