



**Additive Manufacturing in Army Aviation
Critical Applications, the Future or Now?**

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Abstract

The Department of Defense Additive Manufacturing Strategy (2021) and the Army Directive 2019-29 (2019) (Enabling readiness and modernization through advanced manufacturing) show that the military is working to integrate additive manufacturing into military systems. The purpose of this qualitative study is to explore advances in additive manufacturing technologies to assess the feasibility of additive manufactured part utilization in critical safety applications on Army rotary wing aircraft. This study provides an overview of the qualification process for critical safety items for Army aircraft, a review of DoD and Army policies for additive manufacturing, a detailed explanation of the Powder Bed Fusion and Directed Energy Deposition additive manufacturing processes, and review of a case study. Additive manufacturing technologies require tight material and process controls as well as significant qualification inspection and testing to support critical safety applications for Army aviation. However, additive manufacturing technology has matured to a point where the technology is ready now to produce high quality complex rotary wing parts for critical applications.

Introduction

In January 2021, the Joint Defense Manufacturing Council released a Department of Defense (DoD) Additive Manufacturing Strategy (2021) that describes the purpose, vision, and goals for integration of Additive Manufacturing (AM) technology into the Department of Defense mission. One of the goals discussed in the strategy document, “Goal 3: Advance and Promote Agile Use of AM” (Council, 2021, p.12), describes how AM can support the varied missions of the DoD including rapid prototyping, innovation, as well as sustainment. The definition of Additive Manufacturing (also known as 3-Dimensional printing) is a “process of joining materials to make parts from 3D model data, usually layer by layer” (ASTM International, 2021, p.1). AM is “a powerful tool to enable modernization of defense systems, support readiness and enhance warfighter readiness” (Council, 2021, p.4). This study will expand on the goals of the DoD strategy, looking specifically at utilization of AM to manufacture critical safety items for Army rotary-wing applications as well as explore the process of qualification.

Background

Army helicopters (also known as rotary-wing aircraft), exceptionally complex systems, contain parts called Critical Safety Items (CSI). The Department of the Army Pamphlet 95-9 (2006) indicates, “An item shall be identified as CSI when failure of that item could result in loss or substantial damage to the air vehicle or weapons system, or death or serious injury to personnel” (p.3). Due to their nature, these components are heavily regulated through design rigor, tight manufacturing process control as well as quality control. The pamphlet, “Establishes policy, procedures, and assigns responsibilities for the life-cycle management of replenishment items critical to aviation safety as required by and implements the Department of Defense (DoD) Critical Safety Item / Flight Safety Critical Aircraft Part (FSCAP) program” (Department of the Army, 2006, p.2). Manufacturers designing or fabricating parts for an Army helicopter that

meets the criteria from the pamphlet must follow the qualification and certification process prior to installation on an Army helicopter (Department of the Army, 2016).

Additive manufacturing technology has matured to the point where prototyped parts are common; however, production parts still pose significant challenges due to the repeatability of the process (AIA Additive Manufacturing Working Group, 2020). The prevalence of AM processes and parts appearing on commercial aircraft led to the creation of Army Policy 070-062 (2020) that “establishes the U.S. Army Aviation and Missile Command (AMCOM) policies regarding manufacture, use, and airworthiness qualification of AdvM [Advanced Manufacturing] aircraft repairs, parts, components, and support products” (p.2). For the purposes of this study, advanced manufacturing and additive manufacturing are synonymous. This study will explore recent advances in AM technologies to determine the feasibility of AM part usage in critical safety applications for Army helicopters. Throughout this paper the reader will learn about the CSI qualification process, state-of-the-art AM technologies, AM qualification processes, and examples of AM usage in aviation.

Problem Statement

Additive manufacturing of metal components is becoming more common in commercial aviation as well as military applications. In order to use AM parts in Army aircraft critical safety applications, the materials and manufacturing processes need to be well understood. In addition, post-processing and analysis methodology of AM parts need to be studied to verify part quality and repeatability to meet Army aviation critical safety standards and align with Army policy. Research into the application of CSI qualification processes and how they apply to the AM technologies will provide Army acquisition organizations and other researchers information to assist in decision making as well as conducting further research.

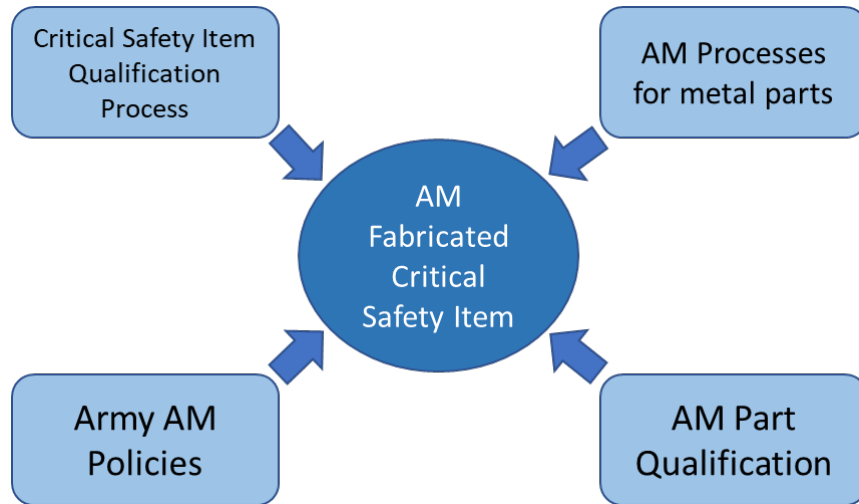
Statement of Purpose and Research Questions

The purpose of this qualitative study is to explore advances in additive manufacturing technologies to assess the feasibility of additive manufactured part utilization in critical safety applications on Army rotary wing aircraft.

1. What is the process for qualification of Army rotary wing critical safety items?
2. What are the Army policies on usage of additive manufacturing in rotary wing applications?
3. What are the processes for additive manufactured parts used in critical applications on rotary wing aircraft?
4. How are additive manufactured parts qualified for use on Army rotary wing aircraft?

Conceptual Framework

A conceptual framework of this study defines the objectives of the research process. First, this study will provide an overview of the Army aviation CSI qualification process. The study will briefly discuss Army and DoD policies related to AM and aviation to give context for the relevance of AM within Army aviation. The study will then provide research into the AM processes for fabrication of metal components applicable to critical applications for Army rotary wing aircraft. Finally, this study will conclude with a case study that provides an example of the qualification process for AM part usage on an Army rotary wing aircraft. Figure 1 shows a graphical representation of the conceptual framework for the research to produce an additively manufactured critical safety item.

Figure 1*Conceptual Framework for AM Fabricated CSI Parts***Significance of This Research**

By 2024, estimates show the AM industry will have grown by 485% over the levels from 2017 (Debnath et al., 2022). While these statistics represent all industries, AM as a disrupting technology significantly impacts the aviation industry and especially military aviation as evidenced by the numerous policies and guidance created by the Army governing the use of AM. As the AM industry grows and metal part manufacturing becomes more commonplace, CSI parts will eventually be impacted. This study will provide the Army Aviation and Missile Command (AMCOM) and the U.S. Army Combat Capabilities Development Command (DEVCOM) Aviation & Missile Center (AvMC) with critical insight into the AM processes for CSI parts.

Additionally, multiple potential benefits exist for producing CSI parts using AM. Rapid fabrication through AM could increase the speed of critical part procurement, enabling improvement to the schedule for returning an Army helicopter to service (Debnath et al., 2022). Also, AM could enable the development of a logistics center for repair part fabrication quickly

providing parts to the needed location improving supply chain performance. AM could also reduce the need for a large spares stockpile reducing weapon system sustainment costs.

Overview of the Research Methodology

This study utilizes a qualitative research methodology where the development of a purpose statement and research question helps to guide the reader through the logic of the research (Creswell & Guetterman, 2019). Following a literature review of the various articles, policies, processes, and AM technologies, an analysis of the research will be provided. This study will also include review of a case study. Research used multiple databases including ProQuest, EBSCOhost, Lawrence Technical University TechCat+, Google, Google Scholar, Defense Technical Information Center (DTIC), and Army publications. Due to the highly technical nature of the research, the author provides an overview of the Army airworthiness and critical safety item qualification process as a reference to provide context for the extensive qualification and inspection required to utilize AM parts on Army rotary wing aircraft.

Limitations of the Study

With limited time to conduct research as well as the broad topic of additive manufacturing, this study will be limited to metal part fabrication. Specifically, this study will focus on Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) additive manufacturing technologies. Within the PBF technology, the research is further restricted to the Selective Laser Melting (SLM) and Electron Beam Melting (EBM) methods. The PBF and DED AM technologies are the current leading fabrication techniques capable of making metal end items suitable for use in aviation applications (Gisario et al., 2019). Material selection also plays a significant role in the suitability of an AM part used in aviation applications; however, significant research has already been undertaken in this area. For a detailed review of materials used in AM and their application to Army aviation, see *An Exploration of the Additive*

Manufacturing Materials Roadmap for Army Aviation (2022) by Lisa Hirschler. As a result of Ms. Hirschler's thorough analysis, materials will not be reviewed as part of this study. Finally, this study will be limited to the AM processes and analysis for newly manufactured parts only. Stockpile reliability, conditioned-based maintenance, and the longevity of AM parts post manufacturing will not be considered.

Summary

As additive manufacturing advancements become more commonplace in aviation applications across the enterprise, the processes for creation and analysis of AM parts needs to be understood to utilize them in critical applications on Army rotary-wing aircraft. CSI parts require significant product and process control to verify the quality of the part and repeatability of the process. Two AM technologies lead the way for metal part manufacturing likely to be used in CSI applications. The next section presents a literature review of the current CSI qualification process, leading additive manufacturing technologies, AM certification, and a case study.

Literature Review

Introduction

This literature review provides an overview of the airworthiness process, a CSI overview, Army policies regarding AM, the leading AM technologies for metal part fabrication, the AM certification process, and a case study. The review of these topics through available research will set the framework for the follow-on analysis. A clear understanding of the requirements for CSI parts is required to complete an analysis of the AM processes and assess the applicability of AM parts usage in critical aviation applications.

Statement of Purpose and Research Questions

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Aviation Airworthiness: A Brief Summary

A detailed overview of the airworthiness process is beyond the scope of this paper, but some understanding of airworthiness is required to describe the similarities and differences between the qualification processes for critical safety items produced using AM. Review Army

Regulation (AR) 70-62 (2016) and Department of the Army (DA) Pamphlet (PAM) 95-9 (2006) for an in-depth explanation of the process.

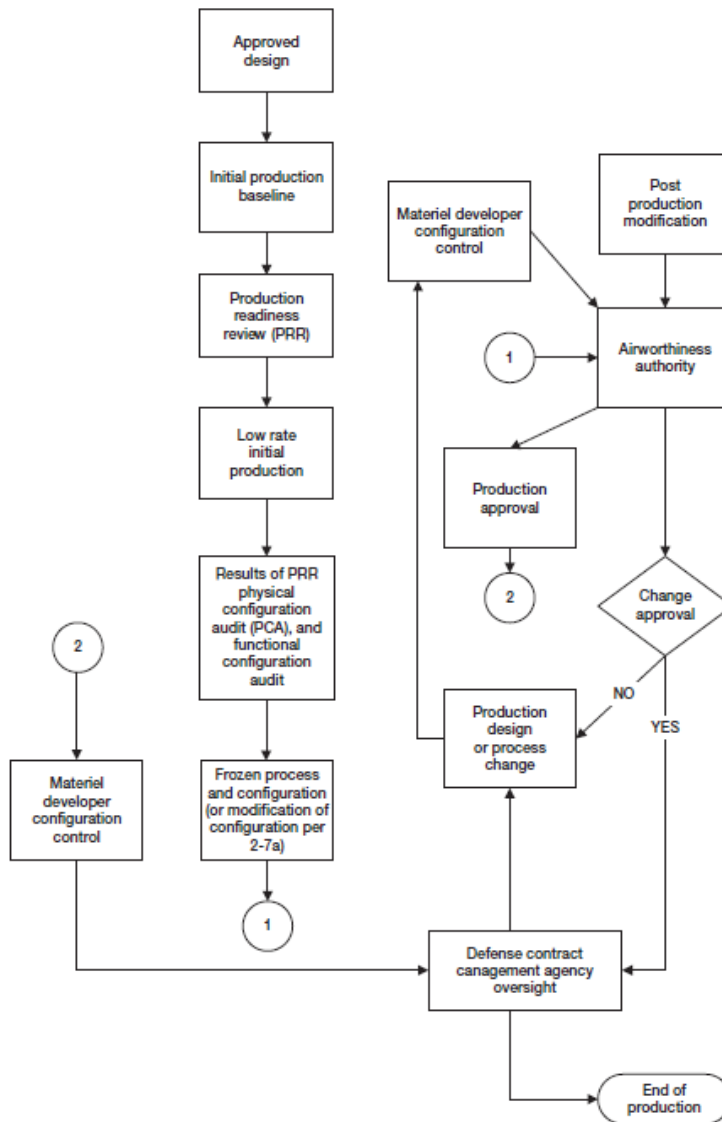
According to AR 70-62 (2016), airworthiness is defined as, “The property of an air system configuration to safely attain, sustain, and complete flight in accordance with approved usage limits” (p.19). In simple terms, a part is considered airworthy when an airworthiness authority completes a review of the part’s specifications, design, and test results and finds that the part will perform its intended function on a given aviation platform. The design of the part also includes all associated manufacturing, test and any post manufacturing processes. Testing completed throughout the qualification process establishes the limitations for the system or part under review. The limits vary widely and include structural limits, flight hours, rotation speeds, environmental limitations, etc. After successful completion of specification review, design, and test results, the airworthiness authority will provide an airworthiness release (AWR). The AWR serves as the official document authorizing the installation and usage of the part on one or more aviation platforms (Department of the Army, 2016).

Once a part has an approved design, approved manufacturing process, complete testing and qualifications, and receives an airworthiness release, manufacturing processes control takes on a significant role (Department of the Army, 2016). Figure 2 is a flowchart of the production airworthiness process. The figure shows how any design or process change flows through configuration control and back to the airworthiness authority. A frozen manufacturing process is especially important for a CSI part due to the consequences should a failure occur. In addition to a frozen process, the agency airworthiness authority must also qualify the manufacturer of the CSI part (Department of the Army, 2006). Oftentimes the prime contractor (e.g., Sikorsky) is the final assembly location of the aircraft but not the manufacturer of the CSI part. In this case, the

prime contractor’s vendor who manufactures the part must meet qualification standards and have their manufacturing process reviewed and approved. The next section will delve deeper into the details of the CSI part.

Figure 2

Production airworthiness process flowchart



Note: From Army Regulation 70-62, by United States Army, 2016

(https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/r70_62_FINAL.pdf).

Aviation Critical Safety Items: An Overview

According to the Department of the Army (DA) Pamphlet (PAM) 95-9 (2006), the CSI definition:

“A part, assembly, installation equipment, launch equipment, recovery equipment, or support equipment for an aircraft or aviation weapons system that contains a characteristic any failure, malfunction, or absence of which could cause a catastrophic or critical failure resulting in the loss or serious damage to the aircraft or weapons system, an unacceptable risk of personal injury or loss of life, or an uncommanded engine shutdown that jeopardizes safety.” (Enclosure 1, p.3).

The lengthy definition from the pamphlet is important to help understand the specialty nature of the CSI parts, as the most critical parts used in an aircraft design, and thus, the most heavily regulated. The CSI designation for a part is typically applied to repairable and consumable parts only (Joint Aeronautical Commanders' Group, 2011). As manufacturers assemble the airframe of an aircraft once, and regular repairs or overhauling occur rarely, the CSI label does not apply. Figure 3 is a CSI word cloud providing a visual representation of the complexity of CSI parts. A rotor blade hinge pin, the part holding the rotor blade to the main rotor assembly, comprises the center of the word cloud and provides a good example of a CSI part. There can be many CSI parts in an aircraft. Some examples include:

- propulsion, transmission, and power system items, such as high speed rotating components, bearings, propellers, etc.;
- landing and braking system components, such as nose wheel steering, wheels and hubs, brake pistons and assemblies, etc.;

- critical air vehicle subsystems, such as embedded, portable and engine fire suppression equipment, refueling equipment, armament/stores, etc.;
- flight control components, such as linkages, actuators, yokes, flight controls surfaces, etc.;
- support equipment, such as bomb loaders, engine hoists, external power units, etc.;
- aircraft launch and recovery systems, such as aircraft catapults, arresting gear, jet blast deflectors, holdback bars, etc.;
- escape systems and parts, such as ejection seats, parachutes, canopy release and fracturing systems, etc.;
- life support system equipment, such as oxygen delivery systems, acceleration protection systems, laser eye protection, etc.;
- survival and rescue gear, such as life vests and flotation devices, emergency radios and beacons, helmets, etc. (Joint Aeronautical Commanders' Group, 2011, p. 2-4)

During the process of designing a CSI part, identification of critical characteristics occurs (Department of the Army, 2006); while these vary depending upon the application, these can include surface finish, dimensions, resistance to bending, etc., and these characteristics allow the CSI part to perform its intended function. A supplier for a CSI part must gain approval to manufacture the part through a lengthy source approval process, including a review of the supplier's ability to repeatedly meet the critical characteristics of the parts.

depth understanding of the Airworthiness process, see *Airworthiness of Aircraft Systems* (AR 70-62) (2016). For an in-depth understanding of CSI parts and their qualification process, see *Management of Aviation Critical Safety Items* (DA PAM 95-9) (2006) and the *Aviation Critical Safety Item Management Handbook* released by the Joint Aeronautical Commanders' Group (2011).

Army Aviation Policies for Additive Manufacturing

The last section provided a brief overview covering the airworthiness process as well as the CSI qualification process. This section will review the policies that govern the usage of AM parts on aviation assets.

The DoD recognizes the “digital manufacturing revolution has far-reaching implications for the Department of Defense (DoD) and the defense industrial base” (Council, 2021, p. 4). In January 2021, the Joint Defense Manufacturing Council released a Department of Defense Additive Manufacturing Strategy. The strategy provides a vision to the usage of AM to modernize the military, increase readiness, and enhance innovation (Council, 2021). In addition, the strategy lays out goals for the services (e.g., Army) to meet the stated vision. The strategy makes a clear statement that the DoD will embrace AM taking advantage of the benefits where appropriate.

On 18 September 2019, the Secretary of the Army released Army Directive 2019-29 that “establishes policy and assigns responsibilities for the employment of advanced manufacturing methods and materials in all capability areas where the Army has an interest” (p. 1). “Advanced manufacturing includes, but is not limited to, additive manufacturing (also known as three-dimensional (3D) printing), artificial intelligence, robotics, and advanced composite materials” (Department of the Army, 2019, p. 1). The directive provides detailed policies where new development will incorporate advanced manufacturing early in the design process and fielded

systems will incorporate advanced manufacturing when appropriate and advantageous to the Government. An example of a potential benefit of AM and the new Army policies is an option to set up an alternate source of supply for aviation components with potential to quickly return a helicopter to service (Debnath et al., 2022). One drawback for the alternate source of supply, however, is that when the manufacturing method changes, the appropriate design agency is required to review and approve the new part (Department of the Army, 2019). Finally, the policy assigns responsibilities related to AM incorporation to the major commands who lead Army acquisition including Assistant Secretary of the Army (Acquisition, Logistics and Technology) (ASA(ALT)), Army Materiel Command (AMC), Army Futures Command (AFC), and U.S. Army Training and Doctrine Command (TRADOC).

The U.S. Army Aviation and Missile Command (AMCOM) is a subordinate command to AMC and is responsible for airworthiness certification for Army rotary wing aircraft (Department of the Army, 2016). Following the release of Army Directive 2019-29, AMCOM released policy memorandum 070-062. The policy exists to “manufacture, use, and airworthiness qualification of AdvM [Advanced Manufactured] aircraft repairs, parts, components, and support products” (Department of the Army, 2020, p. 2). While additive manufacturing is technically a subset of advanced manufacturing, for the purposes of this study and policy review, the terms can be used synonymously. The policy covers all U.S. Army manned and unmanned aircraft where AMCOM is the airworthiness authority.

Any part created using AM will be qualified using similar methods to traditional manufacturing with a couple of exceptions (Department of the Army, 2020). An AM part requires the submission of a “AdvM Technical Data Package [TDP]” containing the geometrical data necessary to fabricate the part using an additive layer-by-layer method. For example, the

technical data package for a part employing a metal casting fabrication process cannot be used to 3D print a similar part. The AdvM TDP must also include material qualification data for the intended application. Material, process, and design of an AM part share a close relationship. Improper material definition or lack of data can lead to performance or safety issues from product failures, and thus the policy provides roles and responsibilities for the Army organizations that support the Army aviation enterprise. For example, the AvMC must “establish and maintain processes for qualifying AdvM parts, components, and support products” (Department of the Army, 2020, p. 3). Finally, the policy details the data required for airworthiness qualification of various parts broken down by criticality category (Department of the Army, 2020). Items such as shop aids, fixtures and ground support equipment require less information and little to no development work for qualification. In contrast, a CSI part requires a significant amount of information and development work to become qualified. Table 1 shows the potential and required data requests that must be submitted for an airworthiness review for a CSI part. In the table, R represents items required for submission and P represents potentially required items at the discretion of the airworthiness authority. The number of Rs in the table provides an indication regarding the detailed material, design, manufacturing, and quality documentation required for a CSI part.

Table 1

Potential and Required Data Requests

Application:	Flight
Airworthiness Impact:	Safety
Annex:	I
	Cat 6
Qualification Item	
Material	
Material Identification	R
Material Specification documentation	R
Material Properties/Allowables (See Annex C)	R
Design	
Form, Fit, and Function Check	R
Safety Margin Analysis (Status, Fatigue, Fracture)	R
Validation Test (proof/static load, dynamic)	P
Manufacturing	
Process Specification documentation	R
Manufacturing Plan Review/Approval	R
On-sight Manufacturing Process/Audit	R
Part Quality	
First article verification	R
Acceptance inspection (dimensional, NDI, surface, functional)	R
In-situ test coupons (tensile, density, chemistry)	P

Note: Table referenced from Annex I of Department of the Army, 2020, *AMCOM Policy No. 070-062*, p. 41.

Metal Additive Manufacturing Processes

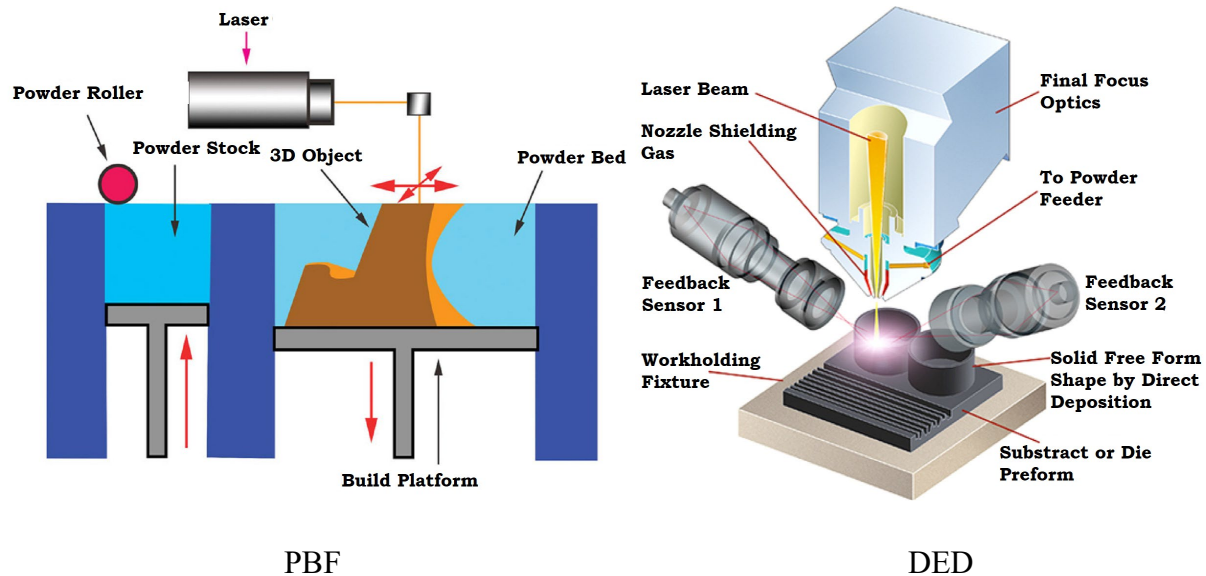
Inventor Chuck Hull patented the stereolithographic 3D printer in 1984, kicking off a manufacturing revolution where more complex designs can be prototyped faster than ever (Turney, 2022). Since that time, AM technology has advanced to include seven industry-recognized processes usable with various materials in a multitude of applications (ASTM International, 2021). Figure 4 shows the seven types of additive manufacturing processes recognized by the AM industry. For example, common desktop 3D printers available today

utilize an extrusion process where a thermoplastic fed through a heated nozzle prints a part layer-by-layer on a base plate (Turney, 2022). Although quite useful for toys and small prototype objects, this process cannot work for metal parts. For additive manufacturing of metal parts, Powder Bed Fusion (PBF) and Directed Energy Disposition (DED) lead the way in successful processes (Barroqueiro et al., 2019). PBF is defined as an “additive manufacturing process in which thermal energy selectively fuses regions of a powder bed” (ASTM International, 2021, p. 2). Directed Energy Disposition is defined as an “additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited” (ASTM International, 2021, p. 2). Figure 5 shows an overview of basic principle behind PBF and DED processes. The images show how PBF uses a roller to deposit a layer of powder before the laser provides energy, whereas in DED, the powder layers onto the part at the same time the laser energy applies (Barroqueiro et al., 2019). The next sections will provide an in-depth description of the PBF and DED processes.

Figure 4*Seven Industry Recognized Types of AM Processes*

Note: Image sourced from ASTM52900-15 by ASTM International, 2021

(<http://www.astm.org/cgi-bin/resolver.cgi?ISOASTM52900>).

Figure 5*Basic Principle of PBF and DED Processes*

Note: Images sourced from “Metal Additive Manufacturing Cycle in Aerospace Industry: A Comprehensive Review” by Barroqueiro, B., Andrade-Campos, A., Valente, R. A. F., & Neto, V., 2019, *Journal of Manufacturing and Materials Processing*, 3(3), p. 3 (doi:10.3390/jmmp3030052).

Powder Bed Fusion (PBF)

PBF is “the primary methodology for fabricating metallic parts for aircraft components” (Balaji et al., 2022, p. 7). The PBF process allows for fabrication of parts with complex internal structures otherwise impossible to fabricate using traditional manufacturing methods. The process utilizes a laser or electron beam focused on a specific area of a bed of powder to melt or sinter the powder grains (Barroqueiro et al., 2019). Following the laser melting the first layer, the build platform lowers slightly, allowing a roller to deposit another layer of powder. The laser or electron beam then melts the new layer of powder in a repeated process following the pattern loaded into the machine from the three-dimensional digital model of the part. The fact that the

fabrication time of the PBF process depends on the melted material volume rather than complexity of the part serves as an advantage (Gisario et al., 2019). However, a disadvantage of the process is a propensity to trap powder inside cavities of the part (Barroqueiro et al., 2019). The part design must include features to allow for the evacuation of excess powder. The PBF process includes the following additional subcategories for specific printing techniques: direct metal laser sintering (DMLS), selective heat sintering (SHS), selective laser sintering (SLS), electron beam melting (EBM), and selective laser melting (SLM). Table 2 provides a comparison of PBF processes showing the advantages and disadvantages of the various PBF processes. As noted in the table, the SLS and DMLS processes lack mechanical strength and are therefore less suitable for aviation applications (Barroqueiro et al., 2019). This study will focus on the SLM and EBM techniques due to their commonality for fabrication of aircraft parts (Gisario et al., 2019).

Table 2*PBF Process Comparison*

Technology	Advantages	Disadvantages
Shared specs	Cost Effective Geometrical complexity High resolution	Powder exit points Quality powder dependent
EBM	Minimal residual stress No thermal treatments Mechanical strength Malleability	Build rate Powder variety Vacuum atmosphere Surface finish Cost
SLM	Mechanical strength Surface finish	Build rate Residual Stress Stress relief / HIP Malleability Inert atmosphere
SLS	Build rate Footprint	Polymeric binder Thermal treatments Mechanical strength
DMLS	Build Rate	Mechanical Strength Low density

Note: Adapted from “Metal Additive Manufacturing Cycle in Aerospace Industry: A Comprehensive Review” by Barroqueiro, B., Andrade-Campos, A., Valente, R. A. F., & Neto, V., 2019, *Journal of Manufacturing and Materials Processing*, 3(3), p. 4 (<https://doi.org/10.3390/jmmp3030052>).

Selective Laser Melting (SLM)

SLM is a type of PBF that uses a laser and scanning mirror to focus the laser on a specific part of the powder bed as directed by the design (Gisario et al., 2019). The process can use different metallic powders; however, grain size should remain in the 45-63 micrometer range to achieve good surface quality of the finished part. The SLM machine uses a closed chamber filled with an inert gas to prevent oxidation of the particles. Once a layer has been printed, a piston lowers the base plate while another raises the powder. A roller then distributes the layer of powder evenly on top of the part. The laser melts the new layer according to the design, and the process repeats (Gisario et al., 2019). Steel and iron-based powders are the most often used with

SLM; although the process also works with titanium and other metals as well (Barroqueiro et al., 2019).

SLM machines allow for a variable thickness per layer up to 100 micrometers, with an average of 30 micrometers (Gisario et al., 2019). Reducing the printed thickness per layer will improve the surface of the part but also slows down the fabrication process. Additionally, orientation of the part in the chamber is important due to a potential need to anchor the part to the base plate to avoid distortions and to avoid trapping powder in a cavity. Finally, during the SLM process, “the laser expands the material and then it shrinks after the laser has moved” (Gisario et al., 2019, p. 7). “This internal stress state promotes undesired localized deformation and premature failures, especially in over hanging geometries where distortion is severe” (Montero et al., 2020, p. 318). The thermal expansion and contraction lead to “high residual stress, with stress relief treatment being mandatory and HIP recommended” (Barroqueiro et al., 2019, p. 4). One of the popular post-fabrication processes is Hot Isostatic Pressing (HIP) where the part is subjected to high-temperature (1000-2000 °C) and high-pressure (200 MPa) to “eliminate the inherent defects and pores in the parts” that remain after printing (Peng et al., 2021, p. 2).

Electron Beam Melting (EBM)

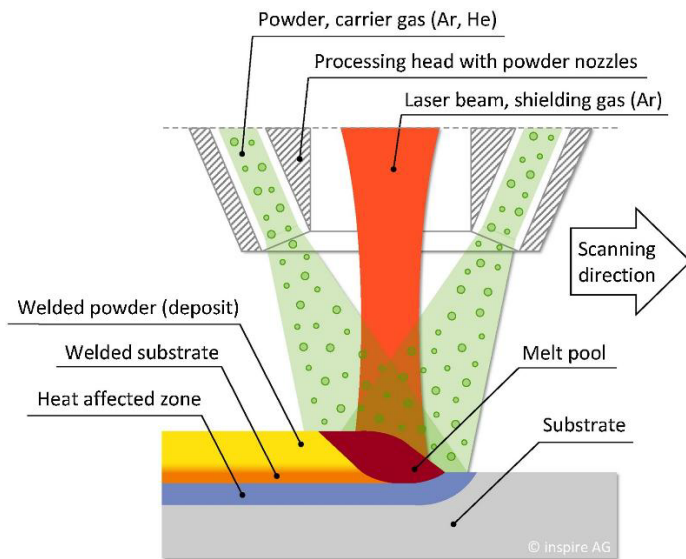
The EBM process is comparable to SLM with a few exceptions (Gisario et al., 2019). First, as the name suggests, the process uses an electron beam which penetrates the powder better allowing for faster scanning. The operation of the EBM machine chamber in a vacuum rather than using an inert gas provides a second difference from SLM, creating the advantage of near-perfect corrosion prevention. Finally, EBM machines keep the chamber temperature continually

high (above 700 °C) to optimize the process and minimize residual stresses on the part. HIP post-processing is optional due to the minimal residual stresses (Barroqueiro et al., 2019).

The faster scanning of the EBM process allows for double the performance of SLM at the expense of surface finish (Gisario et al., 2019). “The laser beam of SLM allows having a weld pool as narrow as 0.3mm compared to the 1mm minimum feature size achievable with the electron beam source” (Gisario et al., 2019, p. 8). If the design requires a specific surface finish, the need may arise for application of additional metal during fabrication, allowing for a post-machining operation to achieve the desired results (Balaji et al., 2022).

Directed Energy Deposition (DED)

Directed Energy Disposition is an AM “process in which focused thermal energy is used to fuse materials by melting as they are being deposited” (ASTM International, 2021, p. 2). As seen in Figure 5, DED uses a laser, electron beam, or plasma as a source of heat to melt powder or wire and deposit the melted material directly onto the part under fabrication (Barroqueiro et al., 2019). DED can produce parts much faster than PBF. PBF processes at about 0.1 Kg/h where DED is capable of 4 Kg/h (Gisario et al., 2019). Figure 6 shows a diagram of the DED AM process. The figure shows that, unlike PBF, the DED process feeds the powder at the same time the laser melts the powder and deposits it onto the previous layer. The process is akin to a traditional wire welding process using a laser instead of electricity as a heat source.

Figure 6*Schematic of DED Process*

Note: Image sourced from “Metal additive manufacturing in the commercial aviation industry: A Review” by Gisario, A., Kazarian, M., Martina, F., & Mehrpouya, M., 2019, *Journal of Manufacturing Systems*, 53, p. 10 (<https://doi.org/10.1016/j.jmsy.2019.08.005>).

Powder-fed DED systems can support a grain size ranging from 40-110 micrometers which is larger than PBF systems (Yang et al., 2021). In addition, powder-fed DED systems are capable of more complex geometries than the wire-fed systems; however, wire-fed systems are also useful for producing parts for aviation applications (Gisario et al., 2019). Furthermore, the electron beam and laser processes can produce more complex parts than the plasma process (Barroqueiro et al., 2019). Cost savings and speed of the plasma process makes it advantageous in certain applications.

Like PBF, DED needs a controlled atmosphere to prevent corrosion (Barroqueiro et al., 2019). Some machines use an inert gas (i.e., Argon), while others use a shielding gas flow as seen in Figure 6. Furthermore, in most DED processes, residual stress increases during fabrication requiring a post-fabrication stress relief process such as HIP, similar to PBF. The

DED process is capable of fabricating parts with comparable results to wrought or cast material (Gisario et al., 2019). The National Aeronautics and Space Administration (NASA) Langley research center developed a wire-fed system called Electron Beam Freeform Fabrication (EBF3) capable of fabricating ready to use parts with low residual stresses avoiding the need for additional post-processing (Barroqueiro et al., 2019). Additionally, since the process is wire-fed (powders cannot be used in zero gravity), EBF3 could be used in future space-based systems.

Post-Processing

While post-processing techniques were introduced briefly in previous sections when describing the various AM methods, this section will explore the importance of post-processing for AM parts as well as the different techniques and their purposes. AM parts commonly have low surface quality when compared to traditional subtractive manufacturing technologies (Peng et al., 2021). This rough surface finish results from the “staircase effect” caused by the layer-by-layer buildup utilized by AM processes. Furthermore, AM processes commonly undergo high residual internal stresses which necessitate attention to avoid negative effects on mechanical properties of the finished part (Gisario et al., 2019). Using SLM as an example, the complex interactions of the melt pool with the surrounding powder in addition to a high thermal gradient with the previous layer creates both internal stresses and a rough outer surface (Peng et al., 2021). “Internal defects such as balling, porosity, cracks, powder agglomeration, and thermal stress” (Peng et al., 2021, p. 2) between the layers can impact the mechanical attributes of the final part. Post-processing operations can improve the internal defects and surface quality. There are many post-processing techniques; however, the most common are “thermal post-processing, laser peening, laser polishing, machining, and abrasive finishing” (Peng et al., 2021, p. 2).

Achievement of the desired mechanical properties may require one or more post-processing techniques.

Thermal post-processing reduces internal defects and alleviates residual stresses (Peng et al., 2021). The most common type of thermal post-processing is hot isostatic pressing (HIP). HIP uses a high-pressure inert gas combined with high temperatures in a closed container to press evenly on all surfaces of the part simultaneously. The temperatures can reach 1000-2000 °C with pressures as high as 200 MPa. The HIP process can heal internal defects, reduce pores, eliminate cracks, and improve the uniformity of the internal structure of the part.

Laser peening is a process where a laser creates localized compression to the surface of a material, causing expansion in a lateral direction (Peng et al., 2021). A short, intense laser pulse creates plasma at the site, resulting in a pressure pulse slightly deforming the surface of the material. Also, usage of a water compactor increases the pressure making the process more effective. The process can improve the mechanical properties by improving the fatigue life, improving the surface quality, and reducing residual stresses in the part. Aviation turbine engine compressor blades and jet engine fans are commonly laser peened.

Laser polishing is a process where a laser improves the surface quality of an AM part (Peng et al., 2021). The laser scans the part and melts the peaks of the material, allowing the liquid material to flow into the valleys using gravity. Laser polishing can reduce the surface roughness by as much as 41% depending on variables such as the type of material, manufactured surface roughness, and number of passes (Gisario et al., 2019).

Post-process machining and abrasive finishing are traditional manufacturing processes applied after the AM process to improve the surface finish or increase the accuracy of a mechanical feature (Peng et al., 2021). Final machining of a part through Computer numerical

controlled (CNC) milling smooths the outer surface and creates precision mechanical features according to the design. Abrasive finishing covers several processes, including magnetic abrasive finishing, ultrasonic abrasive polishing, and a grinding process. Each process improves the surface finish and removes un-melted particles. The careful selection of process parameters prevents unwanted damage to the part.

Post-processing of AM parts is a crucial step in the manufacture of parts for aviation applications. The correction of internal defects, relief of internal stresses, and improvements in the surface finish can increase the fatigue life of the part as well as improve damage tolerance (Gisario et al., 2019). The AM industry widely uses “thermal post-processing, laser peening, laser polishing, machining, and abrasive finishing” (Peng et al., 2021, p. 2) together depending upon the design requirements for the part.

In summary, both PBF and DED processes can produce highly complex metal parts suitable for use in aviation applications. While PBF is only suitable to develop new parts, DED can also be used “for remanufacturing or repairing of damaged parts” (Pant et al., 2022, p. 3). Either process may require post-processing to meet the requirements of the part design. The next section will discuss qualification of AM parts for use on aviation assets.

Additive Manufacturing Qualification

Qualification for a part for usage in an Army aviation application involves more than just approving the design of the part. The Aerospace Industries Association (AIA) Additive Manufacturing Working Group created guidance for certification of AM components. While the working group focuses on commercial aviation, the recommended guidance can apply to Army aviation. The AIA working group (2020) states,

while current powder bed fusion and directed energy deposition machines are highly capable for prototyping, there is a need to establish material and process controls if part

certification is to be considered. Whether by public domain standards or proprietary standards, these controls are reliant on end-user protocols that assure part-to-part repeatability, in terms of material properties and part function. While currently used aerospace product development methodologies still apply (e.g., risk assessments, qualification test planning, etc.), AM-specific process controls need to be developed. (p. 5)

The statements from the AIA working group align with the AMCOM policy document (2020) that explains, “AdvM parts, components, and support products shall be qualified using the same general approach and standards that are used to qualify parts produced using traditional methods of manufacturing” (p. 4). In addition, CSI part airworthiness qualification must have documented “manufacturing processes, methods, controls, manufacturing locations, or manufacturing facilities” (Department of the Army, 2006, p. 6). The next sections will discuss AM process control documentation, process performance qualification, material approval, design qualification, and inspection.

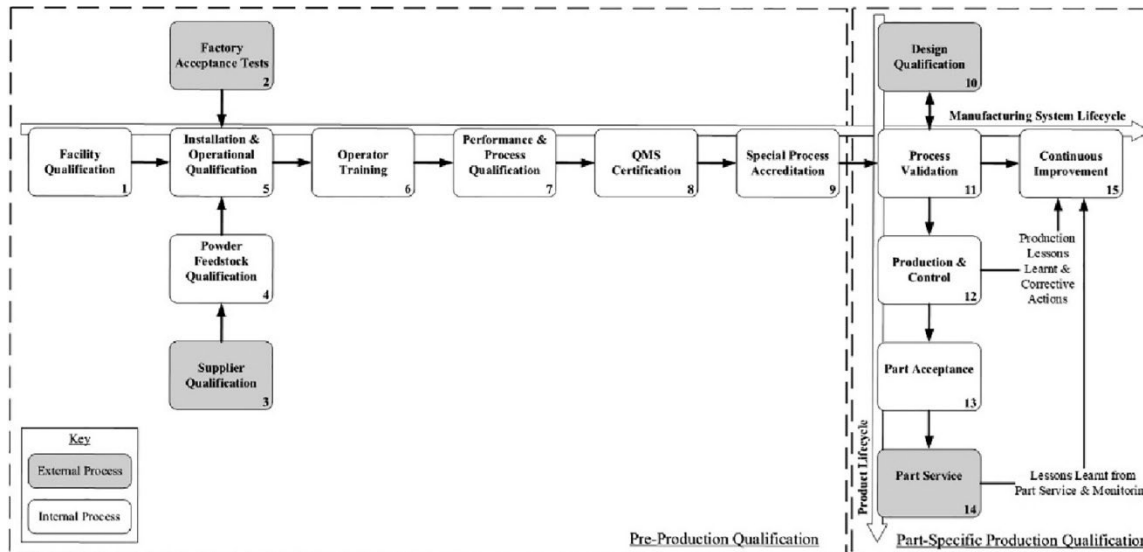
Process control documentation

Process control documents are a collection of plans that provide a detailed breakdown of all the processes that need to be controlled to maintain part quality and mechanical characteristics (Balaji et al., 2022) According to Pant et al. (2022), “controlling all the process parameters is a challenging task and there are about a hundred process variables that influence quality and product performance” (p. 6). Process control documents fit into five categories: Infrastructure, Machine Qualification Plans, Feedstock Control Plan, Part Production Plans, and Post-Process Plans (AIA Additive Manufacturing Working Group, 2020). Infrastructure plans define the facilities, work instructions and training for the operators. Machine qualification plans

describe the configuration, maintenance, calibration, and key process variables of the AM machine itself. Feedstock control plans define the raw materials used in the process, including certificates of conformance, lot control, and materials handling and reuse. Part production plans cover the engineering requirements, quality control, the design model, and fabrication in-process monitoring, including necessary steps for process interruption. Post-process plans include removal of excess powder, stress relief plans, surface treatments, etc.

Process performance qualification

Process performance qualification is the demonstration of the process control documentation. Qualification is complete after the machines have been qualified, the processes sufficiently documented, and first article parts inspected over multiple runs (AIA Additive Manufacturing Working Group, 2020). Qualification is required because no AM industry-wide standards for qualification and certification exist due to the combination of variables from machines, materials, and processes (Liu et al., 2017). Once qualification completes, the processes are updated; any deviations require requalification (AIA Additive Manufacturing Working Group, 2020). Figure 7 shows the flow of internal and external processes required to qualify a PBF part. The figure shows that there are several steps required to qualify the process before fabrication of the part begins. Furthermore, external process qualifications such as powder supplier, factory acceptance testing, and design qualification must occur in addition to the internal process qualification.

Figure 7*PBF Part Qualification Flow*

Note: Figure sourced from “Mapping the path to certification of metal laser powder bed fusion for aerospace applications” by Gibbons, D. W., Serfontein, J. L., & André Francois van, d. M., 2021, *Rapid Prototyping Journal*, 27(2), p. 358 (<https://doi.org/10.1108/RPJ-07-2020-0154>).

Material approval

Material properties are a critical factor in the process of fabricating parts using AM (Gisario et al., 2019). Designers utilizing traditional manufacturing processes can leverage the Metallic Materials Properties Development and Standardization (MMPDS) Handbook, recognized by the DoD, and containing metallic material property information (Russell et al., 2019). Traditional manufacturing methods use materials with decades of historical information. The handbook does not currently contain material properties for AM metals. Material properties correspond with design values for the part and have a direct impact on the part’s static strength, fatigue life, damage tolerance, and potential for defects from the fabrication process (AIA Additive Manufacturing Working Group, 2020). Due to the lack of industry-wide information

and the impact the material properties can have on AM processes, the AM raw materials must be approved alongside the processes.

The method for approval is two-fold. First, to generate the material properties, samples are either specifically built for testing or taken from the buildup of a final part (e.g., support structure) (AIA Additive Manufacturing Working Group, 2020). The samples are then inspected using nondestructive evaluation methods or tested to failure to verify material and process conformance to the design specifications (Russell et al., 2019). Second, the supplier must provide certificates of conformance with raw materials such as the metal powder used in PBF processes (Gibbons et al., 2021). The certificate of conformance provides a guarantee by the supplier that the material meets the specifications of the order.

Design qualification

Before release for manufacturing, the design for a part must be qualified (AIA Additive Manufacturing Working Group, 2020). The part requirements, intended use, basic geometry, material, failure modes, and predicted performance are all components of the engineering approach to design qualification. CSI parts require a detailed fatigue analysis and damage tolerance analysis as part of the design qualification (Gibbons et. al, 2021). Establishment of worst-case stress conditions typically occurs through finite element analysis or testing (AIA Additive Manufacturing Working Group, 2020). Other aspects of the AM process such as build direction, temperature, and grain expansion not included in the finite element model need to be included in the part-specific design. “Design qualification is complete when all requirements have been shown to meet the associated design value” (AIA Additive Manufacturing Working Group, 2020, p. 30).

Qualification is a critical part of approval of an AM part for aviation use. Few standard qualification and certification documents exist for the AM industry; therefore, many companies must develop their own (Balaji et al., 2022). Qualification requires approval of the design, materials, processes, and process controls.

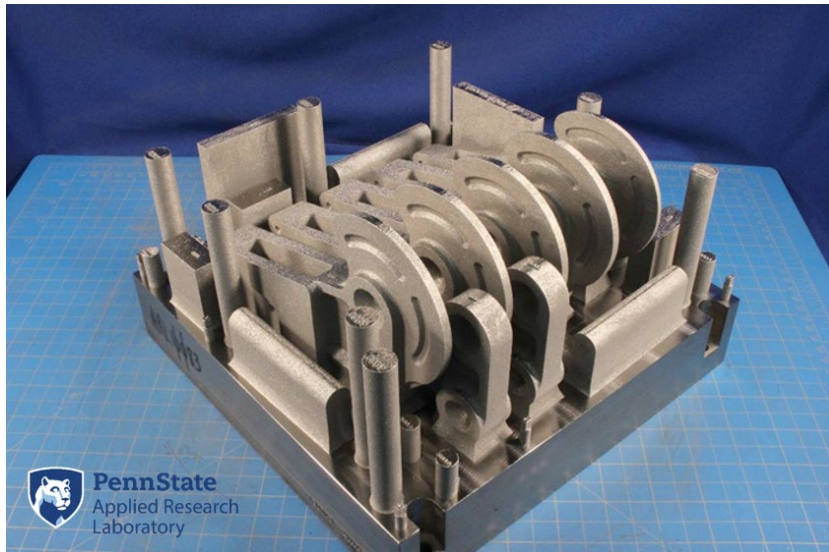
Army Aviation AM Parts case study: Utility Helicopter (UH)-60M Black Hawk bellcrank

AvMC and the Utility Helicopters Project Office (the office that manages the UH-60M Black Hawk platform) selected a UH-60M bellcrank component to prove the qualification and certification process for replacement of a traditionally built aviation component with one built using AM processes (Keist et al., 2019). The bellcrank is a component of the flight control mixer assembly which is a CSI part of a UH-60M. The bellcrank, shown in Figure 8, was selected because of its long lead time for procurement, the fact that it is not CSI, the Government owns the design data, and the part design has a high factor of safety for mechanical stress (Minor, 2019). Utilizing support from AvMC and the Applied Research Laboratory (ARL) at the University of Pennsylvania, the team defined the fabrication process, post-processing requirements, design changes unique for AM, and the qualification testing (Keist et al., 2019). The process for qualification of the part went through a powder characterization for the titanium alloy selected, a PBF build process, build characterization, inspections, and mechanical testing. Due to the sensitive nature of the part covered in this case study, actual numerical values and dimensional data have been removed throughout this section. The powder characterization first involved the procurement and certification inspection of the raw material (Keist et al., 2019). Next, the team built three components using the powder; two used virgin powder, and the third used reuse powder left over from building the first two samples. Samples were taken from all three and used to evaluate powder chemistry, particle size distribution, and flow characterization.

Figure 8*UH-60M Bellcrank*

Note: Image sourced from “Bellcrank: Demonstration of Qualification and Certification for AM Army Aviation Components TM 19-021” by Keist, J. S., Brennan, M. C., Jones, G., & Mitchell, W., 2019, Penn State Applied Research Laboratory, p. 1.

The next step in the qualification process was to evaluate the AM build process. Each build fabricated four bellcrank parts as well as multiple witness and test coupons (Keist et al., 2019). In addition, the team created an extensive set of build documentation including “[build] file origination, machine properties, shielding gas properties, substrate properties, recoater blade condition, powder usage, laser processing parameters, machine setup values, environmental conditions, machine calibration status, laser power measurements, and important events that occurred during the build process” (Keist et al, 2019, p. 9). Figure 9 shows the bellcrank parts with witness and test coupons after the fabrication process. The image shows the sample parts in the center surrounded by test coupons of different shapes and sizes. Following the fabrication process, a test coupon and witness coupon were removed from the base plate. The rest of the parts still attached to the base plate were post-processed using hot isostatic pressing (HIP). Prior to HIP, removal of the coupons made them available for comparative analysis (Keist et al., 2019).

Figure 9*Bellcrank with Witness & Test Coupons Post Fabrication*

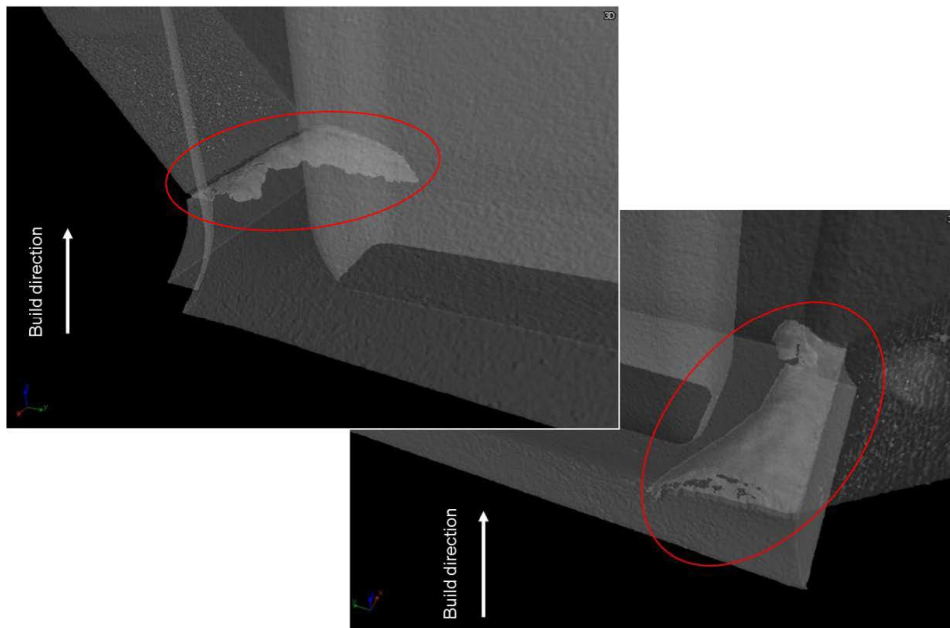
Note: Image sourced from “Bellcrank: Demonstration of Qualification and Certification for AM Army Aviation Components TM 19-021” by Keist, J. S., Brennan, M. C., Jones, G., & Mitchell, W., 2019, Penn State Applied Research Laboratory, p. 11.

Following the build process, the team needed to characterize the quality of the build as part of the process certification. To characterize the build, the team took samples from various locations on the part to facilitate a microstructural characterization (Keist et al, 2019). Using optical microscopy, the samples were compared to one another and compared to existing data from a similar build process. The results show a consistent metallic microstructure among the parts. Next, the team tested the hardness of the samples using a standard Rockwell hardness test method as well as microhardness measurements using a Vickers hardness method. The team evaluated residual stresses in the parts after HIP with the expectation that residual stresses remaining from the fabrication process would relax after HIP. Residual stresses from all three samples tested reflected low values (Keist et al., 2019).

Finally, the team completed the qualification of the process through inspection and testing. Inspection of the parts used X-ray computed tomography (CT) scanning prior to mechanical testing (Keist et al, 2019). The CT scan showed no defects in all the parts inspected except for one for which the scan detected a crack not visible to the naked eye. Figure 10 shows a magnified view of the CT scan showing the internal crack circled in red.

Figure 10

CT Scan of Bellcrank



Note: Image sourced from “Bellcrank: Demonstration of Qualification and Certification for AM Army Aviation Components TM 19-021” by Keist, J. S., Brennan, M. C., Jones, G., & Mitchell, W., 2019, Penn State Applied Research Laboratory, p. 28.

Samples were machined from tensile/fatigue coupons as well as specimens from select bellcranks to perform tensile strength testing (Keist et al., 2019). The American Society for Testing and Material (ASTM) E8-16a (2020) standard provides the requirements for sample sizes and test parameters. Comparison of the test results from the coupons and samples showed a

favorable correlation. This correlation leads to a high confidence level that the coupons match the bellcrank parts. The team completed further mechanical testing for fatigue life and fatigue fracture surface analysis. Fatigue life testing results were favorable and aligned with predicted data. The fatigue fracture surface analysis showed minor crack initiation near the surface of the test coupons. While some cracks initiated from the interior of the coupon, no defects significant enough to degrade fatigue performance appeared.

Following the mechanical testing completed by the ARL at Penn State University, samples were provided to the Redstone Test Center (RTC) component test and analysis division for additional component testing. The RTC team developed a test plan that included fluorescent penetrant inspection, radiography, metrology, proof testing, and finally overload testing (Minor, 2019). RTC received six bellcrank parts for their testing and analysis. The team performed the final machining of all six sample parts in accordance with their design before the inspection and component testing (Minor, 2019). In addition, RTC machined another sample bellcrank from a solid Grade 5 titanium block to represent a traditional manufactured part and serve as a baseline.

After final machining the samples, the RTC team performed fluorescent penetrant inspection (a method using fluorescent dye to reveal microfractures invisible to the naked eye) and radiographic (i.e., X-ray) inspection (Minor, 2019). According to Minor (2019), “no relevant indications were observed” for the fluorescent penetrant inspection and “no rejectable indications were observed” (p. 3) for the radiographic inspections. The samples were then sent to the metrology team who inspected each part for dimensional accuracy. Although minor non-conformances were noted, five of the six parts passed inspection with one rejection (Minor, 2019). The rejected part showed a non-conforming dimension that could affect the part’s performance.

The bellcrank samples assembled with bearings and bushings prepared them for the proof load and overload testing (Minor, 2019). All seven (six AM samples plus one machined sample) parts passed 120% proof load testing without any deformation. The proof test utilizes maximum operating load data provided by Sikorsky (the original equipment manufacturer) and tests the parts to 120% of that maximum operating load. Following the successful proof testing, the RTC team continued their test plan by executing an overload test which tests to failure two of the bellcrank samples in tension and two in compression. The machined sample was also tested to failure for comparison. The results of the overload tests showed that the AM bellcranks were “compositionally, microstructurally, and mechanically similar to a Grade 5 titanium block” of the same alloy (Minor, 2019, p. 17). Furthermore, the bellcrank samples failed at loads 12 to 16 times higher than the maximum flight loads. Overall, the AM bellcranks passed the RTC test plan (Minor, 2019).

This case study of the UH-60M bellcrank provides an example of the complex process to qualify and certify an AM component for an Army aviation application. This case study covered the powder characterization, the build process, build characterization, inspections, and mechanical testing required to prove the AM process can successfully produce a part that both meets the design requirements and is proven airworthy.

Army Aviation AM CSI Part Future: Improved Turbine Engine Program

The Army’s Improved Turbine Engine Program (ITEP) is developing a new engine for planned use on the H-60 Black Hawk helicopter, AH-64 Apache helicopter, and the Future Vertical Lift (FVL) Future Attack Reconnaissance Aircraft (FARA) Competitive Prototype Program (Smith James, 2021). The program replaces the legacy model T700 engine with the new General Electric (GE) T901. One of the ways GE can meet the Army’s requirement for 50%

increased power and 25% reduced fuel consumption is through usage of AM parts in the design. According to Smith James (2021), “GE combined more than 50 separate parts that make up the T700 lubrication system B-sump into one component for T901” (para. 3). GE builds the B-sump assembly using a process similar to SLM to fabricate the part. The innovative design allows GE not only to make the assembly lighter weight, but also to improve performance at a reduced cost. GE is investing heavily in AM applications for their aviation engine designs for both commercial and military applications. For example, GE has flown over 716 million flight hours on their Leading Edge Aviation Propulsion (LEAP), GE9X and GEnx engines that use AM parts (Smith James, 2021). The ITEP program is still in development, and therefore little technical data exists in open-source format due to the sensitivity of the program. As a result, the author was unable to provide an in-depth case study of the AM parts that are integral to the T901 design.

Summary

The literature review for this study provides information collected covering Army aviation CSI requirements, Army policies for CSI and AM, the AM processes of PBF and DED, and the qualification of AM processes. The review also covers a case study of an Army UH-60M bellcrank part built using AM processes. The information reviewed in this chapter provides the foundation for further analysis in a later section of this paper. The next section will provide the detailed research methodology supporting this study.

Research Methodology

This section will provide a detailed description of the research methodology utilized to conduct this study. This section will cover how the data collection was performed followed by how the study was performed. This study utilizes a qualitative research methodology in which the development of a purpose statement and research question helps to guide the reader through the logic of the research (Creswell & Guetterman, 2019). Following an introduction to the study topic, readers will find a detailed literature review of the research completed followed by a description of the research methodology. Next, a summary of the findings resulting from the literature review is provided followed by a conclusion, recommendations, and areas for further research.

Statement of Purpose and Research Questions

The purpose of this qualitative study is to explore advances in additive manufacturing technologies to assess the feasibility of additive manufactured part utilization in critical safety applications on Army rotary wing aircraft. The following research questions form the basis of this study.

1. What is the process for qualification of Army rotary wing critical safety items?
2. What are the Army policies on usage of additive manufacturing in rotary wing applications?
3. What are the processes for additive manufactured parts used in critical applications on rotary wing aircraft?
4. How are additive manufactured parts qualified for use on Army rotary wing aircraft?

Research Methodology

The research for this study was broken down into three areas framed by the research questions. These three areas are the critical safety item qualification process, Army policies for additive manufacturing, and AM processes used for aviation parts. In addition, a case study was used to provide an example.

To provide an overview of the critical safety item qualification process, an extensive review of Army regulations and guidance was completed. Due to the highly technical nature of the topic, additional research was completed to analyze the airworthiness process because critical safety items are a special category of the overall airworthiness process (Department of the Army, 2016). This study included an overview of the Army airworthiness qualification process. The additional requirements for CSI parts were also reviewed with the reader guided to DA PAM 95-9 (2006) that governs the critical safety item process for a more in-depth understanding.

The second area covered in the literature review was the Army policies for additive manufacturing. Because AM utilization in aviation is a new usage of the technology, the policies and guidance update regularly. As a result, the higher-level Department of Defense guidance is more recent than the Army policy guidance. This study limited the policy review to the most current versions available at the time of writing. The Army regulations and pamphlets can be viewed on the Army publications website; however, one AMCOM policy memo is not available to the public. The author acquired the memo through the AvMC systems readiness directorate who provides airworthiness engineering support to AMCOM.

The third area covered by the research was the AM processes used for fabrication of aviation parts. This area covered the bulk of the research using numerous databases and resources to gather the information. The research was limited to metal components and the latest technologies as these had the most relevance to critical safety applications for Army rotary wing

aircraft. Limited time for research prevented an in-depth analysis of all available AM technologies. The detailed research in this area provided a greater understanding of the AM processes for fabrication of metal parts suitable for use on rotary wing aircraft. The research also went into depth on the importance of post-processing and inspection for AM parts.

This study was limited to metal part AM processes as these are most applicable to Army rotary wing critical safety items. The study specifically focuses on the PBF and DED processes because these currently lead technologies capable of making a metal end item suitable for use in aviation applications (Gisario et al., 2019). Within the PBF process, the research is further restricted to the Selective Laser Melting (SLM) and Electron Beam Melting (EBM) methods as these both can make highly complex metal parts with good mechanical strength. While material selection plays a significant role in AM process, this study only includes material properties as relevant to explaining the AM process itself. For a detailed review of materials used in AM and their application to Army aviation, see *An Exploration of the Additive Manufacturing Materials Roadmap for Army Aviation* by Lisa Hirschler (2022). Furthermore, this study covers the AM processes and analysis for newly manufactured parts only. This study does not consider stockpile reliability, conditioned-based maintenance, and the longevity of AM parts post manufacturing.

The author used multiple databases including ProQuest, EBSCOhost, Lawrence Technical University TechCat+, Google, Google Scholar, DTIC, and the Army publications website to complete the research. Search terms included “additive manufacturing for aviation,” “additive manufacturing technologies for aerospace,” “metal additive manufacturing for aircraft,” and “additive manufacturing qualification.” Filtering reduced the substantial number of results to only those results with peer-reviewed articles and full text availability. Furthermore, the author reviewed numerous articles, books, and excerpts, further limiting the research to the

most relevant information related to AM technologies, aviation applications and analysis of AM parts.

A subject matter expert from the material science and technology division of AvMC provided case study documentation. The documents provide an example of an AM fabricated part approved for flight on an Army rotary-wing aircraft. The references section of this study cites the technical reports used for the case study. The reports are Controlled Unclassified Information (CUI) and not publicly available; therefore, the case study intentionally excludes technical details to allow this study the widest dissemination possible.

Summary

In summary, the qualitative research methodology focused on three principal areas of research to complete this study. Those areas are critical safety item qualification process, Army policies for additive manufacturing, and AM processes used for aviation parts. The review of a case study provides an example. Numerous databases and different search terms generated a considerable number of sources that were then reduced to the most relevant information to answer the research questions.

Findings

Introduction

This section provides the findings based on the literature reviewed for this study. The research questions restated below serve as a foundation for the analysis in this section. The findings will then serve as a basis for the conclusions and recommendations discussed in the next section.

Statement of Purpose and Research Questions

The purpose of this qualitative study is to explore advances in additive manufacturing technologies to assess the feasibility of additive manufactured part utilization in critical safety applications on Army rotary wing aircraft. The following research questions form the basis of this study.

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4. How are additive manufactured parts qualified for use on Army rotary wing aircraft?

Results of Army Policy Research

The literature review of the Army airworthiness process and the subcategory of the CSI process revealed that the Army has robust policies and procedures in place for the management and approval of rotary wing parts. DA PAM 95-9 provides policies, procedures, and part management requirements for CSI (Department of the Army, 2006). The nature of CSI parts and

the impact on personnel safety drives the need for a high degree of analysis and testing before using an AM part in a CSI application.

The manufacturing of CSI parts for Army aviation platforms requires design, manufacturing process, and vendor approval before part installation and use in flying an aircraft (Department of the Army, 2006). The approval process includes a detailed review by the Army organization designated as the air-worthiness review authority for Army Aviation, AvMC. Prior to fabrication of a part, the AvMC team will review the design, safety margin analysis, design validation testing, process specifications, manufacturing plan, first article verification data, inspection data, and qualification test plan (Department of the Army, 2020). After fabrication of a first article, the team will review the results of the dimensional verification, non-destructive inspection, and qualification testing. Once all the data is reviewed, and assuming no issues are found, the AvMC team will produce an Air Worthiness Release (AWR) formally allowing the installation and usage of the part on one or more aircraft.

The DoD developed guidance to promote innovation in the AM field focusing on the clear advantages of AM. The DoD Additive Manufacturing Strategy states, “AM can be used to: build parts that cannot be made any other way; uniquely combine materials; produce obsolete parts; rapidly prototype; create tools and specialized job aids” (Council, 2021, p. 4). Through this strategy, the DoD provides support to the armed services to embrace the advantages of AM. The Army also embraces AM technologies as seen in Army Directive 2019-29 in which the Secretary of the Army provides guidance for the Army to leverage AM where practical to take advantage of AM’s benefits (Department of the Army, 2019). Following the high-level Army directive, AMCOM released policy 070-062 in 2020 providing specific guidance to ensure AM’s integration into aviation in a controlled and safe manner. The policy clearly states the roles and

responsibilities of the various Government organizations supporting the Army aviation enterprise as well as provides guidance to contractors who produce repair parts, new designs, and support products for Army aircraft (Department of the Army, 2020).

Results of AM Process and Analysis Research

PBF is the most common AM process used to create metal parts for aviation applications (Balaji et al, 2022). The DED process, however, has the advantage of faster processing time, producing parts much more quickly (Gisario et al, 2019). Both processes require inert gases to shield the fabrication process from corrosion or other contaminants. The PBF and DED processes have advantages and disadvantages depending upon the design and application of the part. Both processes can produce high quality metal parts usable in a variety of aviation applications. The properties of the raw powder material, especially the grain size have a substantial impact on the quality of the final product (Gisario et al, 2019). As a result, quality control of the material supply is a critical aspect of AM technology.

PBF has two subcategories, SLM and EBM that are the most common PBF processes used for aviation parts (Gisario et al., 2019). The primary difference between SLM and EBM is the usage of a laser as the heat source for SLM instead of an electron beam for EBM. The electron beam used in EBM processes provides better powder penetration, allowing for faster processing. Additionally, the EBM machines use a vacuum chamber instead of flooding the chamber with inert gas. This has both the advantage of increased protection from corrosion and a reduction in the amount of inert gas used throughout the process. The laser used in the SLM process focuses much tighter than the electron beam used in EBM which comes at the expense of scanning speed. Thus, EBM can double the performance of SLM at the expense of surface finish (Gisario et al., 2019).

The DED process can utilize a powder or wire-fed process (Gisario et al., 2019). In addition, the process supports using an electron beam, laser, or plasma for the heat source (Barroqueiro et al., 2019). Plasma has the advantage of faster processing times at a reduced cost. Furthermore, DED has the unique advantage of being able to repair damaged parts (Pant et al., 2022). In contrast, PBF can only produce new parts. Overall, PBF and DED are both capable of producing high quality and complex metal parts; however, residual internal stresses and issues with surface finish require post-processing to produce a final component (Gisario et al., 2019).

Post-processing of AM fabricated parts is extremely important for elimination of internal defects, improving surface finish, and reduction of internal stresses. Post-processing techniques like HIP can remedy internal defects such as minor cracks, porosity, and powder particles not fully melting during the printing process (Peng et al., 2021). Additionally, HIP can also relieve internal stresses that build up due to the heat generated in the layer-by-layer process. HIP uses high pressure inert gas combined with high temperatures to press evenly on all surfaces of the part which can heal internal defects, reduce porosity, and improve the uniformity of the part's internal structure. HIP can reach temperatures up to two thousand degrees centigrade and pressures as high as two hundred megapascals. Surface finish is an issue with both PBF and DED. While reducing the layer thickness can improve the surface finish, oftentimes post-fabrication machining is required to achieve surface finish requirements. Table 3 provides a summary of the results with the advantages and disadvantages of PBF and DED as well as the post-processing required for each AM method.

Table 3

Summary of Results

AM Method	Advantages	Disadvantages	Post-Processing
Powder Bed Fusion	<ul style="list-style-type: none"> • Heat Source: Laser or Electron Beam • Produces high quality complex parts 	<ul style="list-style-type: none"> • New parts only • Surface Finish • Residual Internal Stress 	<ul style="list-style-type: none"> • Hot Isostatic Pressing • Final machining
Directed Energy Deposition	<ul style="list-style-type: none"> • Heat Source: Electron Beam, Laser, or Plasma • Plasma processes faster at reduced cost • Powder or wire-fed • Repair of damaged parts • Produces high quality complex parts 	<ul style="list-style-type: none"> • Surface Finish • Residual Internal Stress 	<ul style="list-style-type: none"> • Hot Isostatic Pressing • Final machining

Results of Case Study Research

The UH-60M Black Hawk bellcrank case study provided an example where an AM-produced part is now qualified for flight after the completion of extensive inspection, analysis, and testing. If the bellcrank had been a CSI item, the engineers at AvMC would have required a detailed manufacturing plan approval prior to the start of the manufacturing process (Department of the Army, 2020). In addition, the team would have required an on-site manufacturing process audit for which a team would travel to the supplier’s facility and audit their processes. There was no audit completed for the bellcrank because the part was not CSI.

The ITEP engine currently in development provides an example where the Army is investigating AM part utilization in aviation CSI applications. The GE T901 engine uses a PBF-printed B-sump single part that was more than fifty separate parts in the legacy T700 engine (Smith James, 2021). The addition of AM parts in the T901 design is helping GE meet the ITEP

requirements to increase power and reduce fuel consumption as compared to the legacy T700 engine.

Summary of Findings

The research for this study provides an overview of the Army CSI qualification process for aviation parts, Army policies for additive manufacturing, a review of the most common AM processes used for aviation, and a case study example. The findings from this research provide answers to the research questions as well as areas for additional research. The next section will provide the conclusions gained from this study, recommendations, and several areas for additional research.

Conclusions and Recommendations

Introduction

The research completed in support of this study has revealed several conclusions. This section will discuss the conclusions, recommendations, and areas for future research. Due to the rapid progression of the AM technologies, the assumptions made in this study as well as conclusions may change significantly as time progresses.

Conclusions

The primary conclusion of this study is that additive manufacturing technologies have advanced to a point of feasibility to fabricate Army rotary wing critical safety items. The senior leadership of the military support AM technology integration to increase readiness and innovation. Furthermore, the Army not only supports the integration of AM technology into new development and fielded weapon systems but also has put a policy in place to guide the technology integration. AMCOM has put a specific policy in place for AM integration into Army aviation; therefore, all needed policies are already in place to support AM critical safety items.

Airworthiness approval for CSI parts on Army rotary wing aircraft is achieved through a robust process designed to maximize safety and maintain quality and consistency. While AM uses new manufacturing techniques, the qualification process changes little from traditional manufacturing techniques. Regardless of the AM process used, extensive first article inspections and likely testing will be required for each fabrication run.

AM materials and techniques have advanced to the point at which these can create equivalent, if not superior, high-performance parts when compared to those fabricated using traditional manufacturing methods. The two AM processes researched for this study, PBF and DED, are both capable of producing high quality parts for use in critical applications on Army rotary wing aircraft. However, the AM processes alone are insufficient to produce final parts

ready for installation. Post fabrication processes such as HIP and other techniques are critical to produce a final CSI component. The examples of the UH-60 bellcrank and the ITEP B-sump show where Army programs are beginning to look at ways to incorporate AM into legacy designs as well as future development.

Recommendations

Recommendation #1: AM technologies and post-processing techniques continue to progress rapidly. As a result, the Army needs to closely monitor these advances and update policies accordingly. Suppliers developing the AM processes and using AM to create parts for the Army need the Army policies to be aware of Army senior leader guidance as well as the requirements for AM part qualification. In addition, the Army needs to continue to monitor industry and other Government agencies for new developments in AM technologies, non-destructive inspection methods, and post-processing advancements.

Recommendation #2: The Army needs to develop standards for AM raw material properties such as the Metallic Materials Properties Development and Standardization Handbook (MMPDS). Currently, raw material properties and AM process parameters differ depending upon the supplier. The AM industry would benefit from consistent standards by which raw material properties (i.e., grain size and chemistry) and AM process parameters would produce known outcomes. The standards would eliminate the need for material approval in addition to design and process approval for AM parts.

Recommendation #3: The Army should develop facilities to rapidly fabricate repair or replacement parts for aircraft leveraging the flexibility of AM technology. The facilities could be forward deployed alongside the aircraft to increase operational readiness. Those facilities would also need to include post-processing (i.e., HIP) and non-destructive inspection capabilities in addition to the AM machines due to the criticality of post-processing to create final parts.

Recommendation #4: Army aviation programs should incorporate AM into the initial design phase. ITEP is a good example with GE looking at areas for which AM technology can provide advantages to reduce weight and manufacturing complexity. AM incorporated into the initial design of the system would take advantage of benefits such as rapid production, complexity, and reduced weight. In addition, adopting the technology early would avoid future redesign and requalification necessary to change from a traditionally manufactured part to an AM part for repair or spares.

Areas for Future Research

The following are areas for future research that would advance AM integration into Army rotary wing aircraft for critical applications.

1. Conduct additional research into the repeatability of AM processes once a design and first article are qualified.
2. Explore advanced material alloys and multi-material AM parts.
3. Explore AM processes beyond PBF and DED for applicability for Army aviation.
4. Continue to research and monitor advances in AM technology and post-processing techniques.
5. Conduct additional research on the shelf life of AM parts. Corrosion occurring during the manufacturing process could have a significant negative affect on the performance of the part after long term storage.
6. Explore the feasibility of forward deployed AM machines capable of quickly fabricating repair parts for deployed aviation assets.

Summary

The purpose of this qualitative study was to explore advances in additive manufacturing technologies to assess the feasibility of additive manufactured part utilization in critical safety

applications on Army rotary wing aircraft. This study provided an overview of the qualification process for critical safety items for Army aircraft, a review of DoD and Army policies for AM, a detailed explanation of the PBF and DED AM processes, and review of a case study. AM technology has matured to a point where the technology is ready now to produce high quality complex rotary wing parts in critical applications. Suppliers of AM parts need to understand and closely follow the qualification process for airworthiness paying close attention to part quality and safety requirements. The Army needs to develop a standard containing material properties achieved through a set of AM process parameters for future design and qualification efforts. Furthermore, the Army needs to incorporate AM technology during the initial design phase of new programs. This study supports the guidelines set forth in the Department of Defense Additive Manufacturing Strategy as well as Army Directive 2019-29 (Enabling readiness and modernization through advanced manufacturing). The ability to manufacture CSI parts using AM methods can improve the speed of returning a helicopter to service, allow for forward deployed logistics facilities capable of manufacturing parts, and reduce the cost of maintaining large spare stockpiles, all of which ultimately save taxpayer funds and increase operational readiness.

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Appendix A – Glossary of Acronyms

AdvM	Advanced Manufacturing
AFC	Army Futures Command
AIA	Aerospace Industries Association
AM	Additive Manufacturing
AMC	Army Materiel Command
AMCOM	U.S Army Aviation and Missile Command
AR	Army Regulation
ARL	Applied Research Laboratory
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics, and Technology
ASTM	American Society for Testing and Materials
AvMC	Aviation & Missile Center
AWR	Airworthiness Release
CAD	Computer-Aided Design
CNC	Computer Numerical Controlled
CSI	Critical Safety Item
CT	Computed Tomography
CUI	Controlled Unclassified Information
DA	Department of the Army
DCMA	Defense Contract Management Agency
DED	Directed Energy Deposition
DEVCOM	U.S. Army Combat Capabilities Development Command
DMLS	Direct Metal Laser Sintering
DoD	Department of Defense
DTIC	Defense Technical Information Center
EBF3	Electron Beam Freeform Fabrication
EBM	Electron Beam Melting
FARA	Future Attack Reconnaissance Aircraft
FSCAP	Flight Safety Critical Aircraft Part
FVL	Future Vertical Lift
GE	General Electric

HIPHot Isostatic Pressing
ITEPImproved Turbine Engine Program
LEAP.....Leading Edge Aviation Propulsion
MMPDSMetallic Materials Properties Development and Standardization
PAM.....Pamphlet
PBFPowder Bed Infusion
PCA.....Physical Configuration Audit
PRR.....Production Readiness Review
QMS.....Quality Management System
RTC.....Redstone Test Center
SHSSelective Heat Sintering
SLMSelective Laser Melting
SLS.....Selective Laser Sintering
TDPTechnical Data Package
TRADOCU.S Army Training and Doctrine Command

Appendix B – Author Biography

Mr. Welch assumed his current duties as the Army Hypersonic Project Office Integration Deputy Project Manager in March 2019. Since that time, he was responsible for development and fielding of the launcher and command and control system for the Nation's first hypersonic capability. Prior to his current assignment, he served as the Multi-Mission Launcher Deputy Program Director and Tech Chief from November 2017 to March 2019. Mr. Welch spent a number of years leading various programs in support of the Prototype Integration Facility including spare parts critical shortages for the Defense Logistics Agency, led the platform development of the ACAT-II Kiowa Warrior Cockpit and Sensor Upgrade Program developing the OH-58F aircraft, as well as multiple other programs supporting fielded systems within Army aviation. Mr. Welch began his career as a design engineer at the Naval Surface Warfare Center, Crane Division in Indiana shortly before transitioning to the Army at Redstone in support of then newly formed Prototype Integration Facility under the U.S. Army Combat Capabilities and Development Command Aviation & Missile Center.



Mr. Welch attended the University of Kentucky graduating in 1999 with a Bachelor of Science degree in Electrical and Electronics Engineering. In 2004, Mr. Welch completed the necessary training and began service as a Contracting Officer's Representative on a number of developmental contracts in support of the Prototype Integration Facility. Mr. Welch is a practitioner in the Engineering and Technical Management career field. In 2019, Mr. Welch achieved the advanced level in the civilian education system. In addition, he has served as an

Agreements Officer Representative on multiple Other Transaction Authority Agreements in addition to source selection boards.

Mr. Welch received the Commander's Award for Civilian Service in 2013 for support to the Kiowa Warrior program, Superior Civilian Service Award in 2016 for support to the Multi-Mission Launcher Program, and a Civilian Service Commendation Medal in 2022 for his support to the Army Hypersonic Project Office.

In his spare time, Mr. Welch enjoys playing golf, reading, watching movies, playing video games, and traveling with his family.