



**An Exploration of the Additive Manufacturing
Materials Roadmap for Army Aviation**

Lisa S. Hirschler

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Author: Lisa S. Hirschler

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Abstract

The Army's Advanced Manufacturing Campaign plan directs Army leaders to identify ways to use Additive Manufacturing to augment the supply chain, produce complex parts and improve performance of weapon systems (Department of Army, 2019). This research paper focuses on the Additive Manufacturing (AM) implementation roadmap for Army Aviation. Using AM in aviation is particularly challenging since, "parts installed on aircraft must be certified flightworthy as part of the overall certification of the aircraft. For engineers wanting to design additively manufactured flight parts, that's easier said than done. The reason is because there are no industry-standard design" (Stratasys, 2019, p. 5). In order to develop the roadmap, three areas of research are explored in this document. The first is the detailing of metal alloys currently used in aviation. The second is the aviation part families composed of each alloy. Finally, the current efforts among Department of Defense (DoD) services to obtain the Intellectual Property necessary to produce airworthy AM parts. This research culminates into recommendations for a roadmap prioritizing the order in which Army Aviation should move forward to pursue the required Intellectual Property. Once the Intellectual Property is obtained, it can be used to develop Additive Manufactured Data Sets (AMTDSs) of the metal alloys for airworthiness certification.

Chapter 1 - Introduction

Background

In 2015, then Army Chief of Staff, General Raymond Odierno and Secretary of the Army, the Honorable John McHugh put forth the Army Equipment Modernization Strategy stating that the Army shall “prioritize the development of technologies that reduce the logistics footprint and increase efficiency, providing tailorable and scalable combat enablers” (Department of Army, 2015, p. 4). With Army facing multiple enemies on multiple fronts, the supply chain must be agile (Department of Army, 2015). “To improve the Army’s ability to conduct expeditionary maneuver and sustain high tempo operations at the end of extended supply lines, the Army must increase logistical efficiencies and unit self-sufficiency” (Department of Army, 2015, p. 6). In addition, the 2019 Army Modernization Strategy end state:

is a modernized Army capable of conducting Multi-Domain Operations (MDO) as part of an integrated Joint Force in a single theater by 2028, and ready to conduct MDO across an array of scenarios in multiple theaters by 2035. To achieve this end state by 2035, the Army will modernize how we fight, what we fight with, and who we are” (Department of Army, 2019, p. 1).

One way the Army seeks to modernize in technology and supply chain is through Advanced Manufacturing. The Army Directive 2019-29 defines Advanced Manufacturing as new ways to produce current products or make new ones. Advanced Manufacturing can come through various innovative technologies such as robotics, AM and advanced diagnostics (Department of Army, 2019). However, for this study the focus will remain solely on Additive Manufacturing or three Dimensional “3D” printing. “Advanced Manufacturing will fundamentally change the way the Army designs, delivers, produces, and sustains materiel

capabilities. It will enable the Army to modernize systems while simultaneously enhancing readiness” (Department of Army, 2019, p. 1). Military leaders are highly interested in Additive Manufacturing’s capability to provide customized components with minimal raw material waste at the point of need, with quicker timeframes, and reduced costs, which will transform the supply chain (Collins, 2019). The Army’s Advanced Manufacturing Campaign plan directs Army leaders to look for ways to use Additive Manufacturing to augment the supply chain, produce complex parts and improve performance of weapon systems.

“It is important to note that the extent of qualification requirements and the supply chain footprint for additively manufactured hardware is not the same across applications. Requirements for the aviation community are particularly stringent to ensure the safety and airworthiness” (James, 2021, para 4). According to the Aerospace Industries Association, printing production parts for aviation with AM requires process that are yet to be developed (AIA Additive Manufacturing Working Group, 2020). As the Army Airworthiness Authority, Major General (MG) Todd Royar, Commander of the Aviation and Missile Command (AMCOM), is specifically interested in moving aviation forward with Additive Manufacturing to meet the Army’s objective to, “modernize and integrate aviation sustainment solutions that will improve Army Aviation’s support to the future battle field commander” (Royar, 2020, p. np). This paper will provide a discussion of metal alloys used in aviation and the order in which the Army should obtain the intellectual property necessary to produce additively manufactured parts, referred to in this research paper as Additive Manufactured Data Sets (AMTDSs), for material certification. The order of precedence will be based on the current stage of development for the metal alloys and the breadth of part families that can be impacted.

Statement of Purpose

The purpose of this study is to explore metal alloys used for Army Aviation parts and recommend the order of precedence Army Aviation should acquire the Additive Manufactured Data Sets (AMTDSs) needed for certification of specific alloys.

Research Questions

1. What are the Strategic goals/policies for our national defense, related to using AM for Army Aviation?
2. What metal alloys are most promising for Additive Manufacturing of aviation parts?
3. What current efforts are ongoing to develop metal alloy AMTDSs for Additive Manufacturing?
4. In what order of precedence should Army Aviation acquire AMTDSs for certification?

Conceptual Framework

With the purpose of developing a recommendation for an Army Aviation (AM) implementation roadmap, research must be completed. In order to bind the research within aviation and metal alloys, a conceptual framework was developed. This framework begins with focusing on the Army's requirement for AM in Aviation. It then moves on to current alloys used in aviation parts. Those alloys are then explored to determine the part families they are used to produce. The alloys and part families then culminate into a development list. The development list is researched to see what current efforts for certification are completed or in work. Finally, the research culminates into a recommended list/roadmap for AMTDSs development. Figure 1 is a visual representation of the conceptual framework.

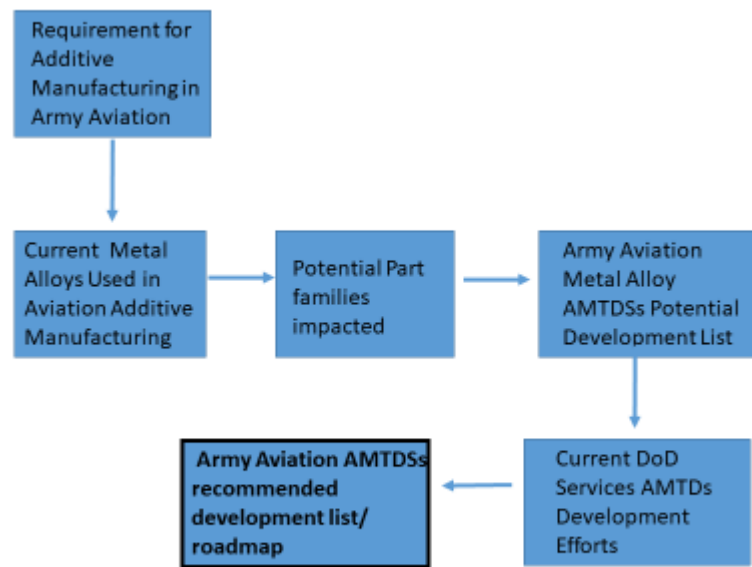


Figure 1- Conceptual Framework. This Figure depicts the conceptual framework used to develop this research paper.

Significance of This Research

This research will serve as an integral resource for the United States Army Aviation and Missile Command (AMCOM) commander to move forward with the Department of Defense Additive Manufacturing Strategy and the Army Directive 2019-29 (Enabling Readiness and Modernization Through Advanced Manufacturing) and prioritize the development of metal alloy AMTDSs for Army Aviation parts. This research will provide metal alloys currently used in aviation, part families potentially impacted by each metal alloy, and a path forward for the acquisition of AMTDSs. Additive Manufacturing will increase design capabilities and the speed at which innovation can occur as well as shortening the supply chain by combating obsolescence and providing on demand printing to soldiers in the field (U.S. Army Public Affairs, 2019).

Overview of the Research Methodology

To determine the overall requirement for Additive Manufacturing in Army Aviation, this research project will rely on current Army and DoD policies and regulations along with results from the following search engines: ProQuest, TechCat+, Google, Google Scholar, and Defense Technical Information Center (DTIC). In order to properly focus the metal alloy research internet search queries such as, “Aviation logistics in Additive Manufacturing”, “Metal Aviation Additive Manufacturing” and “Aviation supply chain Additive Manufacturing” were used. To research the question of current efforts, information was obtained from periodicals as well as information briefs and contract language from the Air Force Rapid Sustainability Office and the AMCOM Logistics Center.

Limitations of the Study

The limited amount of time available to complete this research narrowed the scope to the major current metal alloys used in both DoD and commercial aviation. More research could be done in the Science and Technology/Research and Development arenas to determine additional alloys and applications that may be available in the future. In addition, Additive Manufacturing is a rapidly developing technology with multiple efforts ongoing, the timelines and development stages identified for each material may have changed before this research is published. Finally, the elimination of personal interviews with Subject Matter Experts (SMEs), by the SSCF research guidelines, limits the most current developments in process by industry and information on future efforts.

Definitions

This paper uses terms that may not be familiar or may have a different connotation for the reader. The definitions are not all encompassing but represent the context in which each was used for this research paper. To clarify understanding for all readers, terms and definitions are provided below:

- **Advanced Manufacturing-** “Advanced manufacturing is new ways to produce current products or make new ones” (Department of Army, 2019, p. 1).
- **Additive Manufacturing-** “the manufacturing of solid objects by the deposition of layers of material in accordance with specifications that are stored and displayed in electronic form as a digital model” (Merriam-Webster.com, 2021, para 1).
- **Aluminum (Al) 7049-** aluminum based alloy containing 88.7% aluminum, 7.6% zinc, 2.5% magnesium, 1.5% Copper and, .15% Chromium. (Azo Materials, 2012).
- **Aluminum (Al) 7050-** aluminum based alloy containing 89% aluminum, 2.3% copper, 2.3% magnesium, 6.2% zinc and, .12% zirconium (Azo Materials, 2012).
- **Aluminum (Al) 7055-** a heat treatable aluminum wrought alloy consisting of 85.9-88.5% aluminum, 7.6-8.4% zinc, 1.8-2.3% magnesium, 2-2.6% copper, $\leq .15$ % iron, .08-.25 zirconium, $\leq .05$ % manganese, $\leq .04$ % chromium, $\leq .10$ % silicon, $\leq .06$ % titanium and traces of other elements (Azo Materials, 2013).
- **Aluminum (Al) 7075-** aluminum based alloy utilizing zinc for the chief alloying element (United Aluminum, n.d.).
- **Aluminum(Al) 7085-** high strength aluminum based alloy containing 7-8% zinc, 1.2-1.8 magnesium, 1.3-2% copper, .08% iron, .06% silicon, .15% zirconium. (Chakrabarti, Liu, Sawtell, & Venema, 2004).

- **Aluminum (Al) 7149-** a wrought alloy that is heat treatable containing, 85.9-89.5% aluminum, 7.2-8.2% zinc, 2-2.9% magnesium, 1.2-1.9% copper, $\leq .20$ % iron, $\leq .20$ % manganese, .10-.22 % chromium, $\leq .15$ % silicon, $\leq .10$ % titanium and, traces of other elements (Azo Materials, 2013).
- **Aluminum (Al) 7150-** a wrought alloy that is heat treatable containing, 85.9-89.5% aluminum, 7.2-8.2% zinc, 2-2.9% magnesium, 1.2-1.9% copper, $\leq .15$ % silicon, $\leq .10$ % titanium, $\leq .20$ % iron, .10-.22 chromium, $\leq .10$ % manganese and traces of other elements (Azo Materials, 2013).
- **Aluminum (Al) 7175-** aluminum based alloy containing, 90% aluminum, 5.6% zinc, 2.5% magnesium, 1.6% copper and .23% chromium (Azo Materials, 2013).
- **Aluminum (Al) 7249-** a wrought iron alloy that is heat treatable wrought alloy containing, 86.7-89.1% aluminum, 7.5-7.2% zinc, 2-2.4% magnesium, 1.3-1.9% copper, .12-.18% chromium, $\leq .12$ % iron, $\leq .10$ % manganese, $\leq .10$ % silicon, $\leq .06$ titanium and traces of other elements (Azo Materials, 2013).
- **Aluminum (Al) 7475-** aluminum based alloy containing 90.3% aluminum, 5.7% zinc, 2.3% magnesium, 1.5% silicon, .22% chromium (Azo materials, 2012).
- **Austenitic-** containing a high percentage of nickel and chromium (Corrosionpedia, 2016).
- **Cobalt-chromium alloy-** “Alloys of cobalt and chromium containing molybdenum alone or combined with tungsten plus trace elements” (The Free Dictionary, 2012, p. np).
- **Inconel 625-** “Alloy 625 is a nickel-chromium-molybdenum alloy that is used for its high strength, high toughness and excellent corrosion resistance. The strength of

alloy 625 is derived from the stiffening effect of molybdenum and niobium on its nickel-chromium” (Corrosion Materials, 2021, p. 1).

- **Inconel 718**- “Alloy 718 is a high strength, corrosion-resistant nickel chromium material used at -423° to 1300°F” (Special Metals, 2007, p. 1).
- **Material**- “the things used for typical daily duty, such as office supplies like paper, pens shipping boxes, paper towels, desks, chairs, lamps” (USAMMDA PA, 2020, p. np).
- **Materiel**- “supplies, equipment and weapons in military supply chain management, which are used by all of the Service branches. In most cases, materiel refers to the items needed by the force to execute a given mission” (USAMMDA PA, 2020, p. np).
- **Molybdenum**- “a metallic element that resembles chromium and tungsten in many properties, is used especially in strengthening and hardening steel, and is a trace element in plant and animal metabolism” (Merriam-Webster.com, 2021).
- **Niobium**- “a lustrous gray ductile metallic element that resembles tantalum chemically and is used in alloys” (Merriam-Webster.com, 2021).
- **Stainless steel 304**- is the most widely used and flexible austenitic form of stainless steel. It is resistant to corrosion and oxidation due to the 18% chromium and 8% nickel in its makeup (Corrosionpedia, 2016).
- **Stainless steel 321**- “Type 321 is a titanium stabilized chromium nickel austenitic stainless steel with corrosion resistance similar to 304/304L. This grade is typically used in the 800-1500°F temperature range” (Rolled Metal Products, 2021, p. np).

- **Supply Chain** – “the series of processes involved in the production and supply of goods, from when they are first made, grown, etc. until they are bought or used” (Oxford English Dictionary, 2021, p. np).
- **Ti-3Al-2.5V**- a titanium alloy with 3% aluminum and 2.5% vanadium. Used for foil applications and tubing (Haynes International, 2021).
- **Ti-6Al-4V**- a titanium alloy containing 6% aluminum and 4% vanadium (FWMetals, 2021).
- **Ti-6Al-2Sn-4Zr-2Mo**- a near alpha alloy containing 6% aluminum, 2% tin, 4% zirconium, and 2% molybdenum (Azo Materials, 2013).
- **Ti-10V-2Fe-3Al**- a high-strength titanium-based alloy consisting of 10% vanadium, 3% aluminum, and 2% iron (American Elements, 2021).
- **Ti-15V-3Cr-3Al-3Sn**- a beta alloy containing 76% titanium, 15% Vanadium, 3% Aluminum, 3% Tin, and 3% Chromium (Azo Materials, 2013).
- **Vanadium (V)**- a chemical element alloyed iron and steel (Britannica, 2021).
- **Wrought**- beaten out or shaped by hammering (Oxford English Dictionary, 2021).

Summary

By referencing Advanced Manufacturing as a requirement to change the way the Army develops future methods and materials in the 2019 Army Modernization Strategy, the Secretary of the Army places value on Advanced Manufacturing, and in turn Additive Manufacturing, for the future Army. Due to the complexities and safety of flight concerns, Army Aviation must make efforts in concert with industry to move forward with cutting edge technologies to achieve the required end state of “A modernized Army capable of conducting Multi-Domain Operations

(MDO) as part of an integrated Joint Force in a single theater by 2028, and ready to conduct MDO across an array of scenarios in multiple theaters by 2035” (Department of Army, 2019, p. 2).

Chapter 2 – Literature Review

Introduction

This literature review focuses on three areas to define the framework and address the previously identified research questions. The first utilizes guidance set forth by DoD and United States Army in the form of Regulations, Policies and Strategies to solidify the requirement for Additive Manufacturing in the Army. The second looks at current Metal Alloy types used in DoD and commercial aviation. The third area focuses on current DoD aviation initiatives in progress for acquiring metal alloy Intellectual Property (IP). This literature review will provide the information necessary to explore the metal alloy types in development for AM that can be used for Army Aviation parts development. Lastly, the order of precedence in which the Army should develop the AMTDSs for certification will be addressed.

DoD and Army Guidance and Policies

The research below seeks to explore research question one: What are the Strategic goals/policies for our national defense, related to using AM for Army Aviation? The following DoD and Army guidance and policies were researched to determine if guidance exists for AM in Army Aviation.

National Defense Strategy Summary, 2018

In 2018, Secretary of Defense James Mattis published the unclassified synopsis of the National Defense Strategy (NDS). The strategy details the plans to “compete, deter and win in this environment. The reemergence of long-term strategic competition, rapid dispersion of technologies, and new concepts of warfare and competition that span the entire spectrum of conflict require a Joint Force structured to match this reality” (Department of Defense, 2018, p. 1). The Strategy specifies, the United States Army will face adversaries in a complex environment,

and forces must fight on many fronts: air, land, sea, space and cyberspace (Department of Defense, 2018).

The NDS states the following objectives:

Defending the homeland from attack; Sustaining Joint Force military advantages, both globally and in key regions; Deterring adversaries from aggression against our vital interests; Enabling U.S. interagency counterparts to advance U.S. influence and interests; Maintaining favorable regional balances of power in the Indo-Pacific, Europe, the Middle East, and the Western Hemisphere; Defending allies from military aggression and bolstering partners against coercion, and fairly sharing responsibilities for common defense; Dissuading, preventing, or deterring state adversaries and non-state actors from acquiring, proliferating, or using weapons of mass destruction; Preventing terrorists from directing or supporting external operations against the United States homeland and our citizens, allies, and partners overseas; Ensuring common domains remain open and free; Continuously delivering performance with affordability and speed as we change Departmental mindset, culture, and management systems; and Establishing an unmatched twenty-first century National Security Innovation Base that effectively supports Department operations and sustains security and solvency. (Department of Defense, 2018, p. 4)

The NDS emphasizes competition in industry, as well as partnering, while also defining three lines of effort listed below:

- First, rebuilding military readiness as we build a more lethal Joint Force;
- Second, strengthening alliances as we attract new partners; and
- Third, reforming the Department's business practices for greater performance and affordability (Department of Defense, 2018, p. 5).

In the area of building a more lethal force, the strategy details several key capabilities. Of note is the area of "Resilient and agile logistics. Investments will prioritize prepositioned forward stocks and munitions, strategic mobility assets, partner and allied support, as well as non-commercially dependent distributed logistics and maintenance to ensure logistics sustainment while under persistent multi-domain attack" (Department of Defense, 2018, p. 6).

Army Modernization Strategy, 2019

The Army Modernization Strategy (AMS), based on guidance given in the NDS, details the priorities for the future of the Army. In 2019 the Sergeant Major, Chief of Staff and Secretary of the Army published the Modernization Strategy, which detailed how we fight, what we fight with and who we are. The AMS details how it fits into other guidance by defining its end state as being:

nested with the 2018 Army Strategy, is a modernized Army capable of conducting Multi-Domain Operations (MDO) as part of an integrated Joint Force in a single theater by 2028, and ready to conduct MDO across an array of scenarios in multiple theaters by 2035 (Department of Army, 2019, p. 1).

Department of Defense Additive Manufacturing Strategy

The Department of Defense (DoD) Additive Manufacturing Strategy provides:

a shared set of guiding principles and a framework for AM technology development and transition to support modernization and Warfighter readiness within DoD, Military

Services, and Agencies. It supports the Office of the Secretary of Defense (OSD), Military Services, and relevant DoD Agencies to build on current or planned activities, reduce redundancy, align funding opportunities, and improve the effectiveness of AM implementation/campaign efforts (Department of Defense, 2021, p. 6).

To achieve the AM goals throughout the DoD, the strategy lays out five areas that are required for success:

(1) rapid and standardized approaches for qualification of materials and processes, and certification of AM parts, (2) new business models for contracting and acquisition of AM digital technical data, (3) logistics model for production of AM parts at forward operating locations, (4) standard AM technical data content, and (5) an interoperable secure AM digital thread for connectivity and data management. (Department of Defense, 2021, p. 6)

According to the Strategy's vision, AM will provide:

a more agile, adaptable and aligned defense supply base to outpace adversarial threats. AM will be a widely accepted manufacturing technology used across DoD and defense industrial base. It will be broadly applied for innovative designs, increasing lethality and reliability for weapons systems and the Warfighter. New technologies will transition more rapidly from research and development to fielded capabilities to support modernization and sustainment. (Department of Defense, 2021, p. 7)

The Strategy also lays out plans for the development of policies, stakeholder engagement, education and a digital thread. As detailed in the strategy, "AM creates the part and material at the same time. This improves production speed and flexibility, but requires careful control of the AM process" (Department of Defense, 2021, p. 4). AM can be used to craft tools and unique job aids;

create parts that cannot be developed in traditional methods; combine materials; create prototypes quickly; and combat obsolesce. Additive Manufacturing is a powerful tool to enable innovation and modernization of defense systems, support readiness and enhance warfighter readiness (Department of Defense, 2021).

Army Directive 2019-29 (Enabling Readiness and Modernization through Advanced Manufacturing)

In September of 2019, the Acting Secretary of the Army, Ryan McCarthy, published Army Directive 2019-29 (Enabling Readiness and Modernization through Advanced Manufacturing). “This directive establishes policy and assigns responsibilities for the employment of advanced manufacturing methods and materials in all capability areas where the Army has interest” (Department of Army, 2019, p. 1).

This policy outlined that capability developers should account for increases in Advanced Manufacturing when designing for Additive Manufacturing, and leverage knowledge increases in robotics, digital networks, and sensors. The developers should leverage knowledge gained by connecting personnel, machinery, and the parts to improve quality, predictive maintenance, and supply requirements. In addition, the policy “requires that we consider and incorporate advanced manufacturing in all aspects of a system’s life cycle, from early design and development through sustainment” (Department of Army, 2019, p. 2). Organizations across the Army, including mission requirements, research and development, acquisition, sustainment, and contracting activities must continue to invest in and embrace advanced manufacturing (Department of Army, 2019).

The policy identifies activities and outcomes when incorporating advanced methods such as Additive Manufacturing to fielded systems:

- (1) Life-cycle managers must consider using advanced methods when shortfalls exist in the ability of the supply chain to support mission readiness. Valid needs must be

supported with analysis of materiel availability, backorder status, and order volume.

Advanced manufacturing will supplement—not supplant—the supply chain.

- (2) When changing the method of manufacture (for example, subtractive to AM method or additive to extrusion method) for a fielded system, subsystem, or part when the basic material properties could be altered, the Current Design Activity (CDA) must certify and qualify the system, subsystem, or part, and the life-cycle/configuration manager must approve the change.
- (3) Life-cycle/configuration managers will collaborate with U.S. Army Materiel Command (AMC) and U.S. Army Futures Command (AFC) to fund and expedite the test and evaluation, qualification, certification, inspection, and acceptance of advanced manufactured parts, materials, and equipment.
- (4) Systems, subsystems, and parts produced using advanced methods that were certified and qualified by the CDA and approved by the life-cycle/configuration manager are equivalent to original equipment manufacturer parts. (Department of Army, 2019, pp. 3-4)

All of the above strategies and policies from the President of the United States, DoD, Secretary of the Army, Army Materiel Command and finally to the AMCOM Commander identify the Army requirements for AM in production and supply chain augmentation.

Metal Alloys in Aviation

The research below seeks to explore research question two: What metal alloys are most promising for Additive Manufacturing of aviation parts? “Metal AM has been considered a new solution in the aim of weight, cost and time reductions for aircraft manufacturing industry”

(Zhang & Liang, 2019, p. 5). Currently, the most commonly used metals in the aerospace industry are alloys from titanium, nickel, stainless steel, and aluminum. (Barroqueiro, A. Andrade-Campos, & Neto, 2019). In addition, a fifth metal alloy, cobalt chrome was created for complex aircraft applications such as aircraft engines. (Haganas, 2021).

The current aviation applications for these alloys are summarized to inform the research for assessing where the Army should focus for Intellectual Property (IP) rights to develop AMTDS. The literature review below will concentrate on the metal alloy types in the following order: titanium, nickel, stainless steel, aluminum, and cobalt chrome.

Titanium

Titanium alloys are widely used in AM; the most recognized titanium alloy is the chemical element combination Ti6Al4V. The Ti6Al4v alloy occupies nearly 50 percent of the titanium products share with aerospace.

Traditional metals that are widely used in aircraft are aluminum alloys as well as titanium alloys, due to their relatively low density, high resistance to fatigue and corrosion and high strength. The most popular material for AM processes is titanium 6Al-4V alloy, which is already the most important titanium alloy in aviation industry. (Zhang & Liang, 2019, p. 1)

Titanium alloys are desirable for aircraft due to its light weight and strength. Table 1 (Inagaki, Shirai, Takechi, & Ariyasu, 2014) below gives examples of the various titanium alloys and their uses in airframes.

Table 1

Examples of Ti Applications (Inagaki, et al., 2014)

Material	Example of application
Ti-6Al-4V	Cockpit window frame, Wing box, Fastener
Ti-3Al-2.5V	Hydraulic pipe
Ti-10V-2Fe-3Al	Landing gear, Track beam
Ti-6Al-2Sn-4Zr-2Mo	Exhaust, Tail cone
Ti-15V-3Cr-3Sn-3Al	Duct

Ti-6Al-4V alloy is designed for a good balance of characteristics, including: strength, ductility, fracture toughness, high temperature strength, creep characteristics, weldability, workability, and thermal processability (higher strength is easily obtained by heat treatment). This alloy is therefore used for many airframe and engine parts. Furthermore, there are many actual applications of this alloy in aircraft where high reliability is required, and further, the availability of abundant data promotes its application. In airframes, it is used for general structural material, bolts, seat rails and the like. In engines, due to the relatively low allowable temperature of about 300°C, the alloy is used for fan blades, fan case and the like in the intake section where temperatures are relatively low. (Inagaki, et al., 2014, p. 23)

Ti-6Al-2Sn-4Zr-2Mo is oxidation resistant and has a maximum heat tolerance of 500°C. Due to these features it is utilized for Exhaust and Tail cones (Inagaki, et al., 2014).

The alloy, “Ti-10V-2Fe-3Al alloy has excellent hardenability, high strength, and high fatigue strength. It is mainly used for landing gear” (Inagaki, et al., 2014, p. 24)

Ti-15V-3Cr-3Sn-3Al is made in thin sheets. It is heat-treated. Because it is stronger than titanium and cold workability Ti-15V-3Cr-3Sn-3Al is primarily used for ducts (Inagaki, et al., 2014).

Excellent hardenability is a main characteristic of Ti-10V-2Fe-3Al. Main landing gear has been formed with Ti-10V-2Fe-3Al alloy due to its fatigue tolerance and extreme strength (Inagaki, et al., 2014).

Nickel

Nickel is also referred to as Inconel. There are two prominent Inconels used in aviation: Inconel 625 and Inconel 718.

Inconel alloy 625's high strength, resistance of corrosion and fabrication ability make it excellent for many Naval and Aviation applications. (Special Metals Corporation, 2013)

The properties of INCONEL alloy 625 that make it an excellent choice for seawater applications are freedom from local attack (pitting and crevice corrosion), high corrosion-fatigue strength, high tensile strength, and resistance to chloride-ion stress-corrosion cracking. It is used as wire rope for mooring cables, propeller blades for motor patrol gunboats, submarine auxiliary propulsion motors, submarine quick disconnect fittings, exhaust ducts for Navy utility boats, sheathing for undersea communication cables, submarine transducer controls, and steam-line bellows. Potential applications are springs, seals, bellows for submerged controls, electrical cable connectors, fasteners, flexure devices, and oceanographic instrument components. (Special Metals Corporation, 2013, np)

In addition to the features listed above, Inconel 625 has high tensile strength, fatigue strength and weldability. Inconel 625 is used to make, "aircraft ducting systems, engine exhaust systems, thrust-reverser systems, resistance welded honeycomb structures for housing engine

controls, fuel and hydraulic line tubing, spray bars, bellows, turbine shroud rings, and heat-exchanger tubing in environmental control systems” (Special Metals Corporation, 2013, p. 1).

Inconel 718 is a commonly used alloy for metal AM in aerospace engines. Its vast availability due to large supplier base, high temperature tolerance, as well its ability to withstand corrosion make it a common choice for aircraft engine manufacturers (Kroger, 2021).

Nickel was a game changer in the aerospace industry because it allowed much higher fuel efficiencies and engine power compared to one or two decades before their introduction. To this day, Ni 718 is one of the most-used materials for the hot sections of both aircraft engines and rocket engines, comprising around 50% of the weight of advanced aircraft engines. (Kroger, 2021)

Inconel 718 is the “main component for discs, blades and casing of the high pressure section of the compressor and discs as well as some blades of the turbine section” (Farinia Group, 2014, p. np).

Stainless steel

Like other metals used in the aviation industry, the reliability, strength, and corrosion resistance of stainless steel makes it a good choice for aviation applications (Clinton Aluminum Innovative Alloys, 2019). Although stainless steel is often desirable, costs and weight can come in to play causing other metals to be selected over stainless. When stainless is chosen, there are two frequently utilized in aviation: 304 and 321. Stainless 304 is commonly used in tubing and wiring because of its weldability and machinability as well as its corrosion resistance. “304 grade stainless steel is known to be the most widely used and flexible austenitic form of stainless steel. It contains 8% nickel and 18% chromium, making it ultra-resistant to corrosion and oxidation” (Corrosionpedia, 2017). Due to its corrosion resistance brought forth since it is alloyed with titanium and its ability to maintain its characteristics in high temperature ranges from 800-1500°F

(Clinton Aluminium Innovative Alloys, 2019), stainless 321 is used in high temperature areas such as, “jet engines, exhaust ducts, flanges, piston engine exhaust manifolds, afterburners, flash boilers, and more” (Clinton Aluminium Innovative Alloys, 2019, p. 2).

Aluminum

Aluminum Alloys are a key material for aviation structures.

As the main part of high-strength and high-toughness aluminum alloy, Al 7XXX alloys have high specific strength, high specific stiffness, high toughness, excellent processing, and welding performance. They are widely applied in the manufacture of aircraft frame, spars, and stringers as load-bearing components (Liu & Zhang, 2021, p. 718).

Aluminum alloys are prevalent and host many uses in aviation. Liu and Zhang provide Table 2 which details the main features and applications of the various aluminum alloys for aviation. It is evident there are many alloys and applications for aluminum in aviation, of particular note is the number of aviation applications for each alloy.

Table 2

Features and Applications of AI 7XXX (Liu & Zhang, 2021)

Alloy	Main Features	Main Products and Status	Main Applications
7075	High strength at low temperature, poor weldability, poor SCC resistance	T6 T73 T76 sheet plate, T651 T7651 T7351 thick plate, T6 T73 T7352 casting, T6511 T3511 extrusion	Upper and lower wings skins, stringers, frames
7049	Instead of 7079, high strength, good SCC resistance	T3511 T76511 extrusion, T73 T7352 forgings, T73 sheet and thick plate	Main landing gear
7149	Good strength, good SCC resistance, better fracture toughness than 7049	T73 T74 T7452 forgings, T7351 T76511 extrusion	Main landing gear
7249	Better comprehensive properties than 7149	T73 T74 T7452 forgings, T7351 T76511 extrusion	Main landing gear
7175	High strength, good corrosion resistance, High strength, high fracture toughness, good fatigue resistance, good corrosion resistance	T66 T74 T7452 forgings, T74 T6511 extrusion	Spars, main landing gear
7475	High strength, good fracture toughness, good SCC resistance, good EXCO resistance, poor hardening sensitivity	T61 T761 sheet plate, T651 T7351 sheet and thick plate	Fuselage skins, wing skins, central wing structures, spars, bulkheads
7050	High strength, good fracture toughness, good SCC resistance, good EXCO resistance, poor hardening sensitivity	T651 T7451 thick plate, T3511 T76511 T73511 T74511 extrusion, T7452 T76 T7652 T74 forgings, T73 wire, T76 sheet plate	Fuselage frame, wing skins, bulkheads, stringers, stiffener
7150	High strength, good corrosion resistance, good fatigue resistance	T651 T7751 thick plate, T6511 T77511 extrusion, T77 forgings	Upper wing structures, fixed leading edge, upper wing stringers, fuselage reinforcement, skeletons, seat tracks
7055	Higher compressive strength and tensile strength than 7150, similar fracture toughness and corrosion resistance to 7150	T7751 thick plate, T77511 extrusion, T77 forgings	Upper wing skins, stringers, horizontal stabilizer, skeletons, seat tracks, cargo tracks
7085	Good comprehensive properties, high hardening, high strength, high fracture toughness, good SCC and EXCO resistance	T7651 thick plate, T7452 forgings	Wing spars and stringers for A380

Cobalt chrome

Alloy L605, also referred to as cobalt chrome, is a cobalt-chromium-tungsten-nickel alloy. It demonstrates a high strength tolerance in heat up to 1500°F. “It is the strongest of the cobalt alloys, and is characterized by being able to withstand a wide range of conditions” (Vestedmetals, n.d., p. np). In addition, it has shown oxidation resistance in corrosion conditions with moderate overall strength. These features make cobalt chrome an excellent material for parts in gas turbine and jet engines as well as aircraft engine combustor liners (Vestedmetals, n.d.).

Current Efforts

As this research is being done, efforts are being conducted to acquire necessary IP rights to move forward in metal aviation print capability for the Army. This section explores current

efforts to obtain aviation application alloy IP rights for DoD uses by the United States Air Force and the United States Army Aviation and Missile Command.

Air Force Efforts

The Air Force's Rapid Sustainability Office (RSO), Propulsion Directorate has partnered with General Electric (GE) Additive to develop AMTDSs (material quality standards and process control limits for additively printed metal parts). Phase 1a is the printing of the metal sump cover for the F110 engine shown in Figure 2. The sump cover utilizes cobalt chrome (CoCr). "It is the first engine component designed for and produced with metal 3D printing technology to be qualified by any US Department of Defence organization" (Davies, 2021, p. 1).



Figure 2: The F110 Additively Manufactured cobalt-chrome sump cover (Davies, 2021).

Phase 1B will be for the sump cover of TF34 engine which is no longer in production. Phase 1B will utilize the metal alloy Inconel 718. The contract vehicle used to develop the AMTDSs for the Air Force is Pacer Edge Program and the Army Additive Material Property Evaluation and Demonstration (AAMPED) (United States Army, 2021).

Army Aviation Efforts

In order to continue the development of AMTDSs, the United States Army has contracted GE Additive to develop the AMTDS for Ti-6Al-4V. This contract is for a 12 month period. At the end of the contract period, GE Additive will, “grant certain rights and licenses to the United States Government for use of Technical Data and know-how and to enable the United States Government to eventually produce airworthy parts in support of its sustainment operations” (United States Army, 202, np).

Summary

This literature review has resulted in the successful collection of information on Army requirements for AM; metal alloys used in aviation and; current efforts to develop AMTDS for Army Aviation. This information provides the basis for the analysis which will be provided in Chapter 4 and finally the recommendations which will be provided in Chapter 5 of this research paper.

Chapter 3 – Research Methodology

Introduction

This chapter details the research methodology applied to examine the purpose of the study and explore the data related to the research questions. Given the continual advancement of metal AM manufacturing in Aviation, the research of relevant documentation is limited to 2014 to the present.

Statement of Purpose

The purpose of this study is to explore metal alloys used for aviation parts and the order of precedence Army Aviation should acquire the Additive Manufactured Data Sets (AMTDSs) needed for certification of the alloys.

Research Questions

1. What are the Strategic goals/policies for our national defense, related to using AM for Army Aviation?
2. What metal alloys are most promising for Additive Manufacturing of aviation parts?
3. What current efforts are ongoing to develop metal alloy AMTDSs for Additive Manufacturing?
4. In what order of precedence should Army Aviation acquire AMTDSs for certification?

Research Methodology

This research paper is qualitative in nature. Qualitative research explores a problem by stating a purpose of the research and focusing the research through open-ended research questions (Creswell & Guetterman, 2019). This paper focuses on a literature review to answer the research questions.

The research methodology for this paper was organized into three distinct categories. The first category focused on Department of Defense and Army guidance. An extensive review of Department of Defense strategies as well as United States Army regulations, policies and publications was performed. These DoD strategies and Army regulations and policies document the Army's requirement to incorporate Additive Manufacturing in aviation design and current sustainment efforts. Personal interviews were not part of the research methodology; therefore, any current information that could be gleaned from recent AM efforts were not included. Army leadership perspectives not available in print media were also not considered.

The second category concentrates on metal alloys currently used in Additive Manufacturing for aviation parts. Applying a qualitative research methodology, Google Scholar, ProQuest, and Google search engines were used. Searches included "Additive Manufacturing in Aviation", "Additive Metals in Aviation" and, "Additive Metal Aviation Parts". While some relevant information was obtained in the form of Journal Articles, the evolving uses of metal advanced manufacturing led to the use of white papers and industry articles to provide some of the most recent information in the strides being made.

The third and final category looks at efforts within the Department of Defense to obtain aviation metal AMTDS. This research led to articles and contracts for current efforts to detail the types of metal alloys where IP rights for aviation AMTDS have been contracted.

Using the information gathered in Chapter 2, alloys were categorized by the underlying predominant metal. Alloys were then analyzed for priority by the number of part families impacted.

Summary

This chapter detailed the research methodology to include the various search engines and types of documents utilized to explore the research questions and purpose of the document. Due to the limited amount of time and fast pace at which Additive Manufacturing in Aviation is moving, this research could be extraneous by the time of publication. To avoid duplicate efforts, continual research and monitoring of efforts will be needed to continue with the Army Aviation Roadmap development.

Chapter 4 – Findings

Introduction

This chapter will detail the findings based on the literature review conducted in Chapter 2 of this document. The findings put forth in this chapter will serve as the basis for the recommendations present in Chapter 5.

Statement of Purpose

The purpose of this study is to explore metal alloys used for Army Aviation parts and the order of precedence Army Aviation should acquire the Additive Manufactured Data Sets (AMTDSs) needed for certification of the alloys.

Research Questions

1. What are the Strategic goals/policies for our national defense, related to using AM for Army Aviation?
2. What metal alloys are most promising for Additive Manufacturing of aviation parts?
3. What current efforts are ongoing to develop metal alloy AMTDSs for Additive Manufacturing?
4. In what order of precedence should Army Aviation acquire AMTDSs for certification?

This chapter analyzes the information gathered during the literature review which is located in Chapter 2. The research findings will move toward answering the research questions posed for this analysis. In order to easily detail the findings the researcher has developed a table providing essential information on the metal alloys, their features, as well as their main applications.

Metal Alloys for Additive Manufacturing in Aviation

The metal alloy section in the literature review in Chapter 2 culminated into 20 metal alloy AM candidates currently used in aviation. While this is an extensive list it is not all inclusive. The following tables group the alloys by the underlying element.

The titanium based alloys that are most promising for AM aviation applications are depicted in Table 3. There is not a one-size-fits-all alloy as the applications require significantly different material properties.

Table 3

Titanium Alloys Features and Aviation Applications

Underlying Element	Alloy	Main Features	Main Applications
Titanium	Ti-6Al-4v	Good balance of strength, ductility, fracture toughness, high temperature strength, creep characteristics, weldability, work ability and thermal processability. Low allowable temperature of 300 degrees Celsius	Airframe (cockpit window frame, wing box, general structural material, bolts, seat rails, etc.) and Engine parts (fan blades, fan case and intake sections where temperatures are relatively low)
	Ti-3Al-2.5V	High corrosion resistance, ability to be cold rolled	Hydraulic pipe
	Ti-10V-2F3-3Al	Excellent hardenability, extreme strength and fatigue strength	Landing gear and Track beam
	Ti-6Al-2Sn-4Zr-2Mo	Oxidation resistance and heat tolerance of 500 Degrees Celsius	Exhaust and Tail cones
	Ti-15V-3Cr-3Sn-3Al	Cold workability stronger than titanium	Ducts
(Inagaki, Shirai, Takechi, & Arivasu, 2014, p.23)			

The Ti-6Al-4v provides a plethora of part families and is the most commonly used titanium for aviation applications. While the remaining four titanium alloys listed also have excellent features the applications are for significantly less part families than Ti-Al-4v.

Nickel has two prominent alloys used in aviation, Inconel 625 and Inconel 718. Like the titanium alloys, each nickel alloy has different features that make it a good fit for various applications. Table 4 describes the features and various applications for each of the nickel alloys.

Table 4

Nickel Based Alloys Features and Aviation Applications

Underlying Element	Alloy	Main Features	Main Applications
Nickel	Inconel 625	High strength, corrosion resistance fabrication ability, high tensile strength	aircraft ducting systems, engine exhaust systems, thrust-reverser systems, resistance welded honeycomb structures for housing engine controls, fuel and hydraulic line tubing, spray bars, bellows, turbine shroud rings, and heat- exchanger tubing in environmental control systems
(Special Metals Corporation, 2013)			
	Inconel 718	Considered as a refractory super-alloy since it can be used permanently above 600°C. Associates good creep and rupture strength with a high resistance to fatigue. It possesses long time strength and toughness at higher temperature along with confinement of corrosion resistance up to high temperature.	Accounts for almost 50% of aircraft turbojet engines, Main components for discs, blades and casing of the high pressure section of the compressor and discs as well as some blades of the turbine engines.
(Farina Group, 2014)			

While Inconel 625 and 718 provide different features, both alloys provide many applications for aviation. Each should be of high priority for Army AMTDS development.

The literature review in Chapter 2 led to the identification of two stainless steel alloys, 304 and 321. Again, as detailed in Table 5, the features are varied between the alloys providing for different application.

Table 5

Stainless Steel Based Alloys Features and Aviation Applications

Underlying Element	Alloy	Main Features	Main Applications
Stainless Steel	304	Weldable, formable, and machinable with good corrosion resistance	tubing, wiring and sheet metal
	321	Because it is alloyed with titanium, this grade is especially resistant to intergranular corrosion. This alloy can withstand temperatures in the 800 to 1500°F range and still maintain its stability.	jet engines, exhaust ducts, flanges, piston manifolds, afterburners and flash boilers
(Clinton, Aluminum Innovative Alloys, 2019, n.p)			

Both stainless steel 304 and 321 provide excellent features. Stainless steel 321 provides more applications than 304. To widen the number applications available with AM, the stainless steel 321 alloy should be considered for AMTDS development before 304.

The literature review illuminated that aluminum currently provides the most alloys used in aviation. Once again, the alloys have unique features which dictate the applications for which they are best suited. Table 6 provides detail of each alloy's features and main applications.

Table 6

Aluminum Based Alloys Features and Aviation Applications

Underlying Element	Alloy	Main Features	Main Applications
Aluminum	Al 7075	High strength at low temperatures, poor weldability, poor SCC resistance	Upper and lower wings skins, stringers, frames
	Al 7049	High strength, good SCC resistance	Main landing gear
	Al 7149	Good strength, good SCC resistance, better fracture toughness than 7049	Main landing gear
	Al 7249	Better comprehensive properties than 7149	Main landing gear
	Al 7175	High strength, good fatigue resistance, good corrosion resistance	Spars, main landing gear
	Al 7475	High strength, high fracture toughness, good fatigue resistance, good corrosion resistance	Fuselage skins, wing skins, central wing structures, spars, bulkheads
	Al 7050	High strength, good fracture toughness, good SCC resistance, good EXCO resistance, poor	Fuselage frame, wing skins, bulkheads, stringers, stiffener
	Al 7150	High strength, good corrosion resistance, good fatigue resistance	Upper wing structures, fixed leading edge, upper wing stringers, fuselage reinforcement, skeletons, seat tracks
	Al 7055	Higher compressive strength and tensile strength than 7150, similar toughness and corrosion resistance to 7150	Upper wing skins, stringers, horizontal stabilizer, skeletons, seat tracks, cargo tracks
	Al 7085	Good comprehensive properties, high hardening, high strength, high fracture toughness, good SCC and EXCO resistance	Wing spars and stringers for A380
(Liu & Zhang, 2021)			

While the number of aluminum alloys is large compared to other metal alloys, many of the aluminum alloys currently have one or two applications making them a lower priority for AMTDS development. However, there are two alloys, Al 7150 and Al 7055 that have a large number of applications and would warrant consideration as a top priority for AMTDS development.

The literature review of cobalt chromium resulted in only one alloy, L605. Alloy L605 features and applications are detailed in Table 7.

Table 7

Cobalt Chrome Based Alloys Features and Aviation Applications

Underlying Element	Alloy	Main Features	Main Applications
Cobalt Chromium	L605	High strength up to 1500°, good sulfidation resistance, moderate strength, good oxidation resistance to hot corrosive atmospheres.	Aircraft engine combustor liners, jet engine components, industrial furnace liners, springs, gas turbine engines
(Vestedemetals, nd)			

As shown in Table 7, the alloy L605 boasts many features making it useful for many aviation applications. This wide variety of applications make L605 a top candidate for AMTDS development.

Current Efforts

The Air Force has contracted with GE Additive to develop the Intellectual Property necessary for AMTDSs for the metal alloys cobalt chrome and Inconel 718 (United States Air Force, 2019). Meanwhile the U.S. Army is contracting with GE Additive to develop the AMTDS for Ti-6Al-4V (Department of the Army, 2021). Each of the AMTDSs developed under the Air Force and Army contracts will be available upon contract completion.

Priorities

In this research paper, the need for Army Aviation Metal Additive Manufacturing has been established based on DOD/Army Strategic guidance; the promising metal alloys currently available have been identified; and current development efforts have been noted. The question of the priority in which the Army should pursue AMTDs remains.

Summary of Findings

This research provides an overview of the metal alloys for AMTDS development consideration in aviation AM as well as the ongoing efforts for developing AMTDSs. The results of this research analysis provide answers to the research questions of which metal alloys are most promising and what efforts are currently on going. The results from the literature review in chapter 2 provided 20 alloys, three of which are under current development. The results provide a basis for categorical rank of the seventeen alloys identified. While a 1-17 rank order could not be definitively found in the research, Chapter 5 contains a categorical prioritization, based solely on aviation parts related to the alloys identified.

Chapter 5 – Conclusions and Recommendations

Introduction

The purpose of this chapter is to provide conclusions and recommendations of the research performed through the literature review and the analysis developed in the research methodology. In addition to conclusions and recommendations this chapter provides a section of additional areas of research for consideration.

Conclusion

The literature review resulted in the identification of 20 metal alloys promising for all DOD aviation Additive Manufacturing. The literature review provided information that three of the alloys have current efforts ongoing with the Air Force and the Army to develop AMDTs. In this chapter the remaining 17 alloys are grouped in tables by the number of part families they affected. While this literature review did not result in a 1 to N list of the order in which the AMTDS should be developed, it did result in areas of focus for the Army to do further research.

Recommendations

The following tables detail the recommendations priority of AMTDS development for the remaining alloys. It should be noted that the alloys are grouped by priority but further research by an independent organization (e.g. government laboratory) should be conducted to determine the exact order in which the Army should pursue each AMTDS. The alloys are placed in three priority groups based on the number of part families each alloy impacts. The highest priority alloys, listed in Table 8 are the alloys with largest number of aviation part family applications (six or more).

Table 8

Alloys with six or more aviation part family applications

Metal	Alloy	Main Applications
Nickel	Inconel 625	aircraft ducting systems, engine exhaust systems, thrust-reverser systems, resistance welded honeycomb structures for housing engine controls, fuel and hydraulic line tubing, spray bars, bellows, turbine shroud rings, and heat-exchanger tubing in environmental control systems (Special Metals Corporation, 2013)
Stainless Steel	321	jet engines, exhaust ducts, flanges, piston manifolds, afterburners and flash boilers (Clinton, 2019)
Aluminum	Al 7150	Upper wing structures, fixed leading edge, upper wing stringers, fuselage reinforcement, skeletons, seat tracks (Liu & Zhang, 2021)
Aluminum	Al 7055	Upper wing skins, stringers, horizontal stabilizer, skeletons, seat tracks, cargo tracks (Liu & Zhang, 2021)

Each of the alloys above have multiple applications. The sheer number of part families affected by these four metal alloys could provide the largest impact to Army aviation.

Table 9 delineates the alloys with four to six part family applications. Of note is that all of the elements in this list derive from aluminum.

Table 9

Alloys with between four and six aviation part family applications

Metal	Alloy	Main Applications
Aluminum	Al 7075	Upper and lower wings skins, stringers, frames (Liu & Zhang, 2021)
Aluminum	Al 7475	Fuselage skins, wing skins, central wing structures, spars, bulkheads (Liu & Zhang, 2021)
Aluminum	Al 7050	Fuselage frame, wing skins, bulkheads, stringers, stiffener (Liu & Zhang, 2021)

There are three alloys with four and six part family applications. It should be noted that although they are different alloys, they affect many of the same part families.

Table 10 provides the third level of impact to the Army based on number of part family applications. There are a total of ten alloys in this table, four titanium, one stainless steel and five aluminum. These ten alloys consist of those with less than four aviation part family applications.

Table 10

Alloys with less than four aviation part family application

Metal	Alloy	Main Applications
Titanium	Ti-3Al-2.5V	Hydraulic pipe (Inagaki, Shirai, Takechi, & Ariyasu, 2014)
Titanium	Ti-10V-2F3-3Al	Landing gear and Track beam (Inagaki, Shirai, Takechi, & Ariyasu, 2014)
Titanium	Ti-6Al-2Sn-4Zr-2Mo	Exhaust and Tail cones (Inagaki, Shirai, Takechi, & Ariyasu, 2014)
Titanium	Ti-15V-3Cr-3Sn-3Al	Ducts (Inagaki, Shirai, Takechi, & Ariyasu, 2014)
Stainless Steel	304	tubing, wiring and sheet metal (Clinton, 2019)
Aluminum	Al 7149	Main landing gear (Liu & Zhang, 2021)
Aluminum	Al 7249	Main landing gear (Liu & Zhang, 2021)
Aluminum	Al 7175	Spars, main landing gear (Liu & Zhang, 2021)
Aluminum	Al 7085	Wing spars and stringers for A380 (Liu & Zhang, 2021)
Aluminum	Al 7049	Main landing gear (Liu & Zhang, 2021)

The 10 alloys listed in Table 10 affect less than three aviation part families. Due to the limited number of part families affected, these alloys are placed in the third priority group for the Army to pursue AMTDS development.

In addition to the order of priority listed in Tables 8-10 the following are additional recommendations culminating from this research:

1. The Army should continue to collaborate and monitor activities by other Government Agencies/ Services, Industry, Universities, and Allies to determine additional efforts that may be ongoing which could alter the list of potential metal aviation alloys.
2. When evaluating the top alloys to develop an AMTD, it would appear that Inconel 625 should be the highest priority since it has the largest number of parts listed. However,

- further research should be done to determine if Inconel 625 would be the most prudent for the Army to pursue first, as other circumstances such as obsolescence or supply issues could cause other alloys to be a higher priority.
3. When looking at the second priority group, due to the lower number of part families impacted, it is recommended that these alloys be pursued at a later date. A relook of the list would be judicious as other applications may have been identified for these alloys which could affect the order of AMTDS development.
 4. It is recommended that the Army perform a cost/benefit analysis to determine the 1 to N list for developing AMTDS, by developing a set of comprehensive criteria for prioritizing AMTDs
 5. Leverage Air Force, and other Contract Vehicles for the development of AMTDs, to promote efficiencies.
 6. Consider which Army aviation assets could leverage the Air Force F110 Engine Cover success

Areas for Future Research

The following are additional areas of research which could prove beneficial to the Army's pursuit of AM.

1. Perform a gap analysis on current efforts to ensure all necessary data is being obtained.
2. Conduct a bias assessment based on the performance specifications and applications given by industry.
3. Explore materials that could replace metal for aviation applications.

4. Compare the metal alloy applications identified in this paper against the AMCOM Aviation top ten readiness drivers to see if any alloy should be moved to a higher priority based on impact.

Summary

The research conducted provided a basis for the requirement of Army Aviation to pursue Advanced Manufacturing in aviation. It also provided detailed features and information on the current metal alloys used in aviation. The research provided details as to the aviation part families manufactured by each metal alloy. The culmination of this research resulted in grouping of alloys based on the number of part families each alloy impacted. It is recommended that the U.S. Army take two actions: the first is to continue to collaborate and monitor activities by other Government Agencies that might provide Intellectual Property on additional alloys. The second recommendation is that a government laboratory perform additional analysis beginning with the alloys in Table 8 to determine the exact order in which the United States Army should pursue Intellectual Property/AMTDS. These findings provide Army Aviation with a path forward necessary to meet the objectives of the Army Directive 2019-29 (Enabling Readiness and Modernization through Advanced Manufacturing).

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Appendix A – Glossary of Acronyms

3D	Three Dimensional
AM	Additive Manufacturing
AMTDS	Additive Manufactured Data Sets
AdvM	Advanced Manufacturing
AAMPED	Army Material Property Evaluation and Demonstration
AFC	Army Futures Command
Al	Aluminum
AM	Additive Manufacturing
AMC	Army Materiel Command
AMCOM	Aviation and Missile Command
AMS	Army Modernization Strategy
CoCr	Cobalt Chrome
CDA	Current Design Activity
DTIC	Defense Technical Information Center
DoD	Department of Defense
GE	General Electric
IP	Intellectual Property
MDO	Multi-Domain Operations
NDS	National Defense Strategy
OSD	Office of the Secretary of Defense
RSO	Rapid Sustainability Office
S&T	Science and Technology
SME	Subject Matter Expert
Ti	Titanium
U.S.	United States
V	Vandium

Appendix B – Author Biography

Ms. Lisa Hirschler is the U.S. Army Aviation and Missile Command (AMCOM) Advanced Manufacturing (AdvM) Lead for the Army's Advanced Manufacturing Campaign. In this position she directs efforts to institutionalize the Aviation and Missile Enterprise AdvM parts development and qualification process. Her efforts have led to the development of AdvM Policy. This AMCOM Command policy establishes manufacturing, use, and airworthiness qualification policies for AdvM aircraft and missile parts. In addition, Ms. Hirschler serves as the AMCOM Logistics Center (ALC) Program Management Support Division Chief. In this role, she manages the Army Working Capital Fund (AWCF) Investment Program Logistics team as well Subject Matter Experts (SME) and senior logisticians providing maintenance analysis, depot assessment, and sustainment planning support across 18 programs for both Aviation and Missile.

Prior to being assigned her current position, Ms. Hirschler served as the Army's Aircraft Survivability Equipment Associate Program Manager (APM) for the Common Missile Warning System (CMWS) and Future Missile Warning System (FMWS). In this role, she successfully developed, monitored, and managed programs valued in excess of \$300M ensuring required Missile Warning Systems were fielded and sustained to maintain threat overmatch.

Ms. Hirschler has over 25 years of leadership, logistics, and finance experience in both the US Army and industry. During her career, she has personally provided acquisition analysis and sustainment strategies for over twenty programs in both Aviation and Missile as well as Special Operations and the Missile Defense Agency.

Ms. Hirschler holds a Bachelor of Science degree in Management Information Systems from the University of Alabama in Huntsville (UAH); a Master of Science in Logistics from

Florida Institute of Technology and holds graduate certifications in Supply Chain from UAH and Additive Manufacturing from Purdue University. She is graduate of the Advanced Civilian Education System and Defense Acquisition University Level III certified in Lifecycle Logistics. She currently resides in North AL with her husband and two sons.