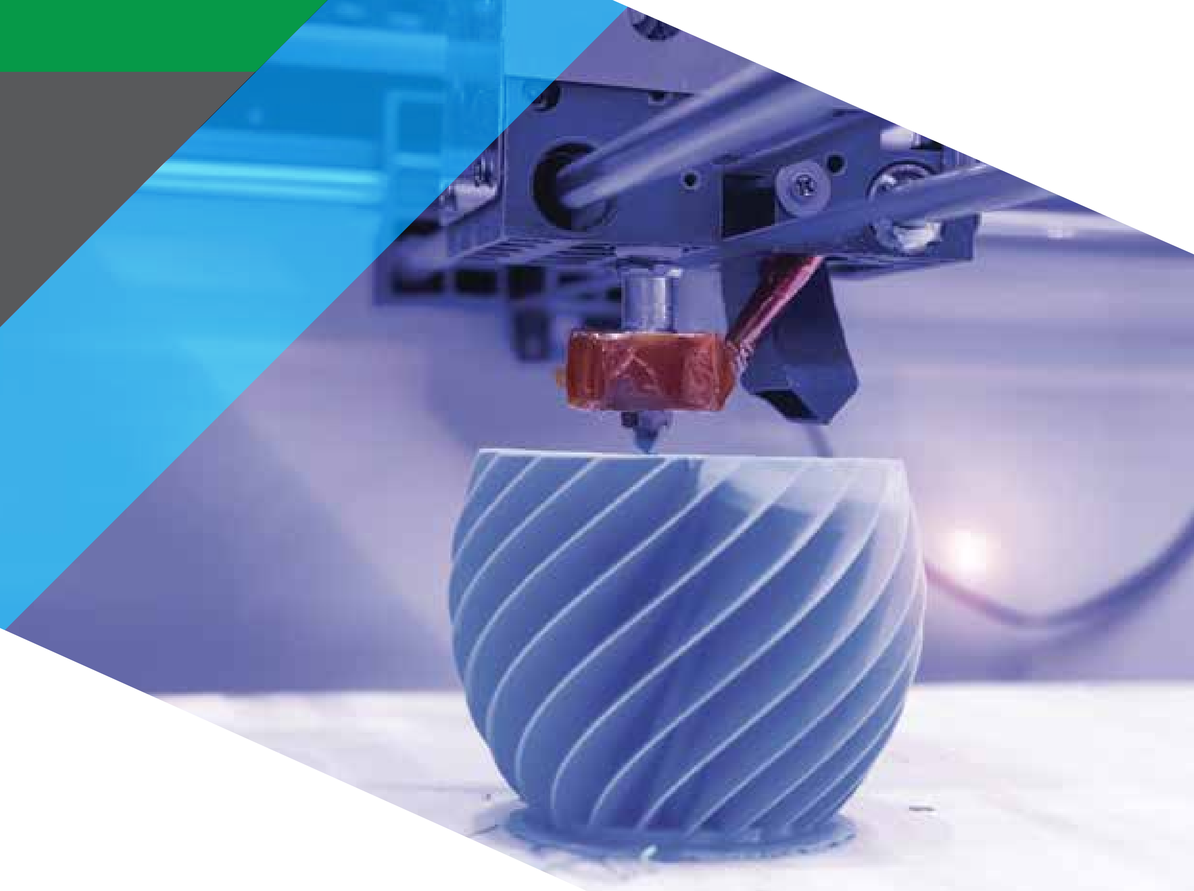
SOAR

STATE-OF-THE-ART REPORT (SOAR)
DECEMBER 2017



DSIAC-2018-0848

QUALIFYING ADDITIVE MANUFACTURING PARTS

Michael W. Mazurek, Doyle T. Motes III, Russel K. Austin

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State-of-the-Art Report

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14. ABSTRACT
This report is a summary of the state of the art for additive manufacturing (AM) certification. Because the development of AM certification is ongoing across multiple domains and disciplines, and due to the limits of this report, some areas may not be covered as thoroughly as some readers would like. In addition, given the expansiveness of the AM field, this report does not present the final answer to every AM issue. It can, however, serve as a gateway to facilitate discussions among experts and policy makers to bridge technical gaps and provide a baseline from which future research can begin.

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Quality Control, Additive Manufacturing, 3-D Printing (or 3D Printing), Nondestructive Inspection, Nondestructive Evaluation, Nondestructive Testing, Part Qualification, Part Certification, Process Control, Microstructural Analysis, Destructive Evaluation, Fitness for Service, Qualification Documentation, In-Service Monitoring

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SCOPE

Additive manufacturing (AM) has been prevalent throughout human history. In the construction of medieval castles, layers of bricks were stacked upon layers of bricks; this same philosophy has been carried over into modern times, only on slightly smaller scales and with materials ancient civilizations could only have dreamed about. As a strictly modern concept, AM is now at the forefront of rapid-prototyping technology to develop parts and structures used in our daily lives. As AM becomes more ubiquitous in everyday life, there are still lingering questions regarding how to qualify AM parts for fitness of service compared to their more traditional, subtractive manufactured or cast parts.

This report is a summary of the current state of AM certification. Because the development of AM certification is ongoing across multiple domains and disciplines, and due to the limits of this report, some areas may not be covered as thoroughly as some readers would like. In addition, given the expansiveness of the AM field, this report does not present the final answer to every AM issue. It can, however, serve as a gateway to facilitate discussions among experts and policy makers to bridge technical gaps and provide a baseline from which future research can begin.

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TABLES

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SECTION 01

AM: An Overview

The summer 2016 edition of the *DSIAC*[1] *Journal* discussed the concept of nondestructive inspection of AM aircraft components. The article provided a strong background on AM technology, which has been reproduced in this section as a primer on AM (1).

Recent advancements in AM have allowed the technology to move from simple prototyping using plastics to creating near fully formed metallic components that can be integrated into modern aerospace systems. AM presents a revolution in traditional manufacturing methods by removing the limitations of traditional casting and subtractive manufacturing processes. Using AM allows designers and engineers the freedom to create parts that not too long ago would have been considered either too costly or near impossible to machine. Consequently, the adoption and expansion of AM in the aerospace industry are leading to new structural concepts as well as reevaluation of established part design.

The 2014 *Wohlers Report* found that the AM market reached $3.07 billion in 2013, representing a 34.9% annual growth rate, the highest rate of growth in 17 years. Over the past 26 years, the average growth rate in worldwide revenue from AM was 27% (2). In 2013, the McKinsey Global Institute released a report discussing technologies most likely to transform the world; AM was included in that discussion (3). The economic numbers show that AM is fast becoming a strong segment of the global manufacturing economy, however, market penetration of AM products, specifically in aerospace markets, is limited by the lack of robust and mature inspection and quality assurance/quality control (QA/QC) technologies compared to traditional, subtractive manufacturing parts.

The National Aeronautics and Space Administration (NASA) has been promoting the development of AM as a tool for the next generation of space flight. In fact, astronauts aboard the International Space Station (ISS) have already begun printing parts such as threads, springs, clamps, buckles, and containers using a three-dimensional (3D) plastic printer (4). 3D printing in space overcomes a large logistics hurdle, minimizing the need to rely on launch facilities on Earth and the requisite launch window opportunities. In addition, the risks associated with supplying replacement parts to astronauts aboard the ISS can be avoided. But more than just replacing a broken screw, NASA wants to push for even more AM in space, which could remove size and weight restrictions placed on satellites and structures built on Earth.

The current process of launching material into space must consider the tremendous forces applied to the cargo, and since satellites and probes can cost millions of dollars, there is an onus on the engineer to overdesign these materials to ensure launch survival. But the overdesign comes at a cost of a higher launch weight, and

[1] *Defense Systems Information Analysis Center*

Figure 1-1. Titanium "tube in a tube" for a cryothermal switch on the ASTRO-H satellite. Traditional manufacturing would cost up to $20,000 and take 3 months to build. AM can drop the cost to $1,200 and the wait time to 2 weeks (5).

at the going rate of $10,000 per pound to launch an object into space, adding extra material can quickly increase costs. NASA believes that AM in space can circumvent this weight issue by transporting the bulk materials to build a structure that is optimized for the space environment, not for the launch environment. Unfortunately, the inability to certify AM parts and critical structures poses unknown risks that are unacceptable for manned spaceflight.

Figure 1-1 shows an example of the potential of AM. Manufacturing the cryothermal switch used in ASTRO-H using AM lowered the cost of the part by an order of magnitude and sped up production to a mere 2 weeks compared to the typical 3 months. Because the development of the AM cryothermal switch was still considered experimental, the AM part was listed as a flight spare instead of a primary part.

NASA's goal is to use AM and ensure that parts now considered only spare will soon be primary. NASA is leveraging its Nondestructive Working Group (NDWG) (4) to help coordinate interagency cooperation on developing standards for AM inspections, including new standards produced by the American Society of Testing and Materials (ASTM). The NDWG helps researchers target information and technology gaps and directs resources to bridge these gaps. The specific role of the NDWG regarding AM consists of the following:

- Establishing and ensuring compliance of AM with NASA Office of Safety and Mission Assurance (OSMA) strategies, policies, and standards.
- Improving nondestructive evaluation (NDE) methodologies as applied to AM for risk identification and assessment, and providing recommendations for risk mitigation and acceptance.
- Providing NDE analysis and AM-specific recommendations for critical NASA safety decisions.
- Sponsoring the innovation and rapid transfer of NDE methods applied to AM technologies, processes, and techniques to improve safety and reliability and to reduce the cost of mission success.

1.1 FACTORS FOR DETERMINING INSPECTIBILITY

1.1.1 Design Complexity

An understanding of current inspection technologies requires an awareness of the types of parts that can be produced through AM, the different AM techniques, and the defects seen in the AM process. These three factors guide the

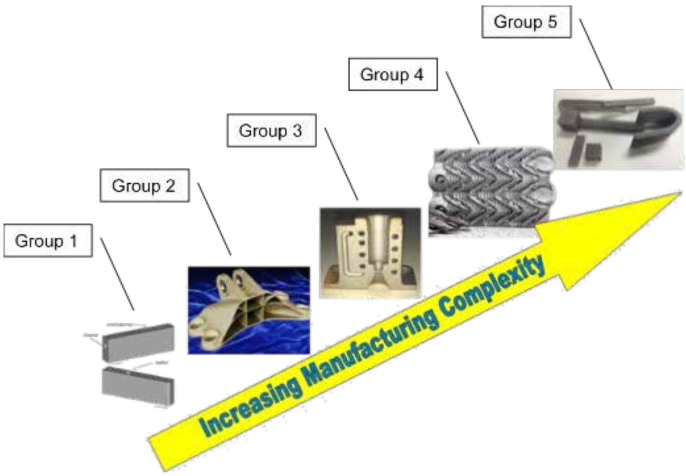

Figure 1-2. Examples of the increasing complexity in design that AM allows. Parts can range from simple subtractive manufacturing design, to optimized design and internal structures, and on to organic designs and structures that are impossible to build through traditional methods.

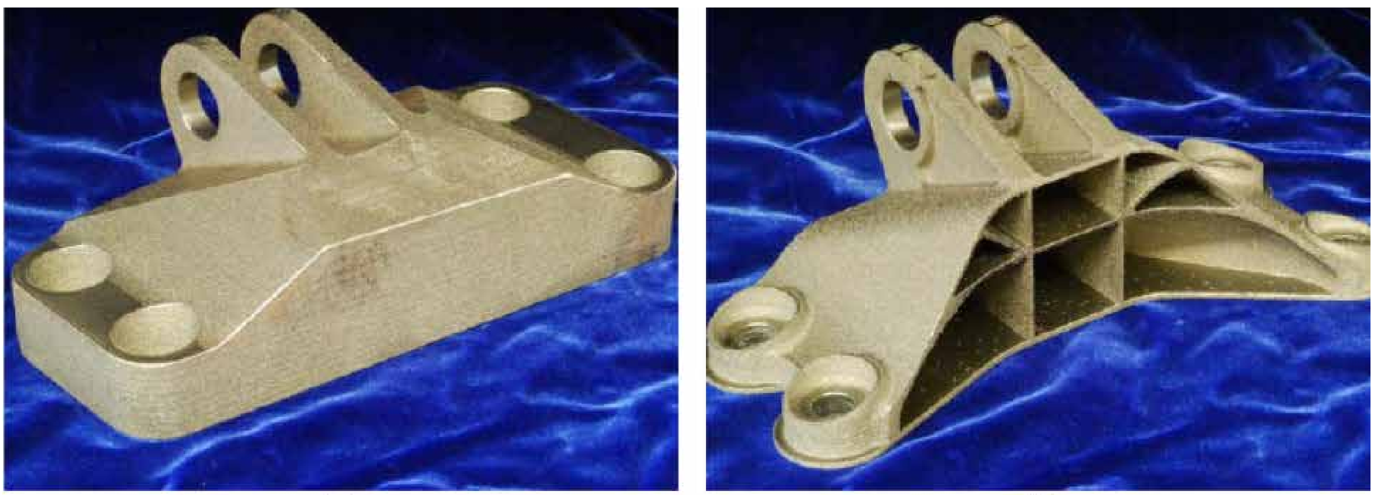

Figure 1-3. Comparison of a traditionally made engine mount (left) and the optimized design produced through AM (right) (7).

inspection selection process. In general, AM part design moves through a five-step group evolution that is based on the skill growth and increased technological comfort of the engineer designing a part (6). The design groups are shown in Figure 1-2.

Group 1. Group 1 includes relatively simple parts that can typically be fabricated using traditional machining. Parts produced in this group have surface features that can be easily accessed and served through traditional NDE technology. Parts in this group are often produced as proof-of-concepts or rapid prototypes, and because of the simplicity of the manufacturing techniques, are not seen as economically viable for AM production when compared to traditional, subtractive manufacturing parts for high-rate production.

Group 2. Group 2 parts reflect AM's ability to produce more complex shapes and designs than traditionally fabricated parts without the need for complicated tooling processes. The example shown in Figure 1-3 was produced through a 2013 GE Aviation crowd-sourced competition to find ways to reduce the weight of a standard, forged, titanium engine mount (7).

The original mount weighed 2.033 kg (4.48 lb), but the AM redesign reduced the weight by 84% while maintaining an equivalent performance in laboratory tests. Group 2 parts mark the start of cost savings as compared to subtractive manufacturing by reducing the need for excess materials and complex tooling. However, increased design complexity comes with the drawback of there being few available technologies to perform NDE on the part unless the technology is specifically made for the part. Generally, Groups 1 and 2 are not wholly dissimilar from subtractive manufactured parts in that they don't require any new or specialized inspection technologies from what is already available.

Group 3. Group 3 AM components are defined as parts that cannot be manufactured through traditional, subtractive manufacturing. These parts feature internal structures such as tubes or channels that previously would have necessitated the part being made through casting. In a traditional setting, these parts would have involved multiple, individual subcomponents being manufactured and then an assembly phase to produce the final component.

Figure 2-4 shows an injection molding tool representative of Group 3 AM parts. (Note the cooling channels moving through the component.) Group 3 parts represent the transition to embedded features within the build. The tight channels within the part increase the cooling efficiency of the tool, allowing for faster production rates. However, these embedded features represent a challenge to the inspectibility of the part and reduce the NDE technologies to those that can image the interior features.

Group 4. Group 4 demonstrates the transition to a focus on design optimization without necessarily considering the producibility of the part. The internal structure of these parts can be complicated and produced without the need for traditional "line of sight" in order to create the features. The ability to inspect these parts is reduced sharply due to the presence of highly detailed and embedded features. An example of a Group 4 part is shown in Figure 1-5.

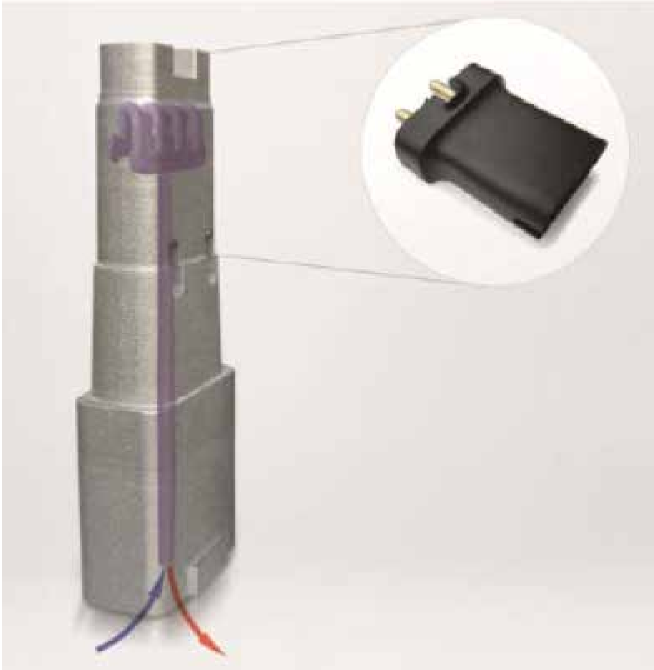

Figure 1-4. Tool insert and injection-molding component. Because of the internal conformal cooling channels, the manufacturing company was able to reduce cooling time from 14 seconds to 8 seconds (8).

Figure 1-5. Heat exchanger produced through Laser Powder Bed Fusion (L-PBF) is representative of Group 4 complexity (6).

Group 4 parts can be produced through traditional methods; however, the cost and skill required to produce the designs can make these designs economically unfeasible.

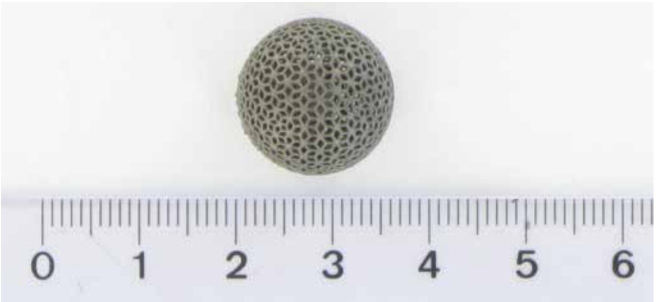

Figure 1-6. Group 5 complexity includes structures such as this titanium lattice ball, which cannot be produced through traditional means. The lattice ball has a hollow interior and a complex internal geometry (9).

Group 5. Group 5 parts are entirely produced through AM and consist of extremely fine features. Examples of these parts include metallic lattice structures, as seen in Figure 1-6. These lattice structures can be tailored to suit specific purposes and can include thousands of individual nodes in a relatively small space. The complexity of these structures requires a long fabrication time, but this is offset by the potential to reduce material costs while maintaining the strength-to-weight ratio of these structures' bulkier forbears. A by-product of the increased complexity of these parts is the lack of NDE technology that can reliably inspect the part for use in complex systems. Developing NDE technology for Group 5 parts would reduce the overall cost of the parts at a system level; that is, the cost of manufacturing the entire final deliverable part would be reduced even with the cost increase of fabricating the Group 5 part.

1.1.2 AM Processes

Selected Laser Melting (SLM) and Electron Beam Melting (EBM). Simple, inexpensive, in-home 3D printers tend to use spools of polymer wire that are melted and deposited in layers. The plastic parts formed in these machines are often the only experience the public has with AM. These parts, while certainly novel and exciting, are not very well suited for industrial or structural use. For industrial purposes, Powder Bed Fusion (PBF) systems are used for AM involving metals. The layers are joined either by SLM (also referred to in some cases as Laser Beam Melting (LBM)) or EBM. In both instances, layers of metal powder are deposited on the printing platform and then melted by either the laser or the electron beam. This process is repeated until the part is completed.

While the two processes are similar, the subtle differences between SLM and EBM can impact the final product. EBM has a higher energy density and scanning rate, which both give EBM a faster build rate. However, the trade-off is a poorer surface finish as compared to SLM. Because EBM also requires the printing tray to be preheated prior to use, the thermal gradient in the part is minimized resulting in a lower residual stress in the final product. However, EBM is limited to metal products, while SLM can be used with metals, ceramics, and polymers. Table 1-1 provides additional comparisons between the two systems.

Table 1-1. Comparison of EBM and SLM Traits (6)

Characteristic	EBM	SLM
Thermal Source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Energy Absorption	Conductivity limited	Absorptivity limited
Scan Speed	Very fast, magnetically driven	Limited by galvanometer inertia
Energy Costs	Moderate	High
Surface Finish	Poor to Moderate	Moderate to Excellent
Feature Resolution	Moderate	Excellent
Materials	Conductive metal	Polymers, metals, ceramics
Beam Size (μm)	100–500	100–150
Powder Size (μm)	45–100	20–50

1.1.3 Defects Found in AM Parts

PBF, whether laser-based or electron-beam based, is the most common form of AM manufacturing in the aerospace industry. In PBF-manufactured parts, there are typically four classes of defects that can occur: volumetric defects, cracking and delaminations, balling, and surface roughness. These defects are typically the result of poor process controls, process parameters, or even the geometry of the part to be produced. However, even the most stringent process controls can't prevent all defects in AM parts. As with traditional, subtractive manufacturing, these defects can be detrimental to the performance of the part. Therefore, the inspection process is vital in finding the defects before the part becomes compromised. Understanding the nature of the defect types is necessary in implementing the proper quality-monitoring process and inspection technique for the finished part.

1.1.3.1 Porosity and Lack of Fusion. The most common defects seen in AM parts are volumetric defects involving either porosity or a lack of fusion of the feedstock (Figure 1-7). Generally, porosity is spherical, whereas defects formed by a lack of fusion can be more irregularly shaped and may contain unmelted powder material within them. As Gong et al. (10) investigated, beam power and scanning speed are the main drivers of porosity and lack of fusion in AM parts. In their research, they discovered that at a given beam power level, a reduced scanning speed will produce porosity, while conversely, an excessive scanning speed will produce instances of lack of fusion in the material. Thus, to minimize the occurrence of volumetric defects in AM parts, operators must find the right scanning speed for a specific beam power for specific materials. Powder suppliers have extensively researched scanning speed and supply the necessary parameters to manufacturers to mitigate the risk of volumetric defects.

1.1.3.2 Cracks and Delaminations. Cracks and delaminations make up the second class of defects (Figure 1-8). These defects are similar to the traditional defects seen in subtractive manufacturing and result from internal thermal stress gradients produced through the additive process. As each layer of powder heats and cools, the thermal stresses can grow, leading to the AM part delaminating from the substrate or cracks growing between the layers. This type of defect is more readily seen in structures with low geometrical stiffness such as thin-walled tubes. Out of the two processes (SLM and EBM), delaminations and cracks are more often seen in SLM parts because EBM systems use a heated production tray to reduce the thermal gradient in the part as it is being constructed.

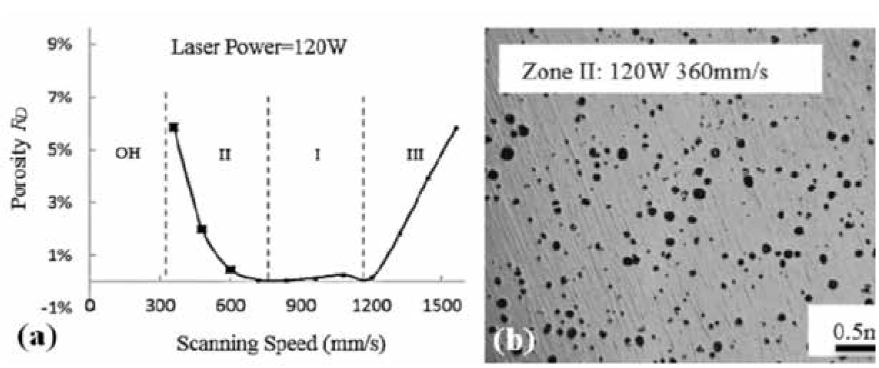

Figure 1-7. Porosity generated during SLS – (a) influence of laser scanning speed (and thus power) on the type of defect, (b) cross-section showing defects resulting from excessive energy input and (c) cross-section showing lack of fusion from insufficient energy input (6).

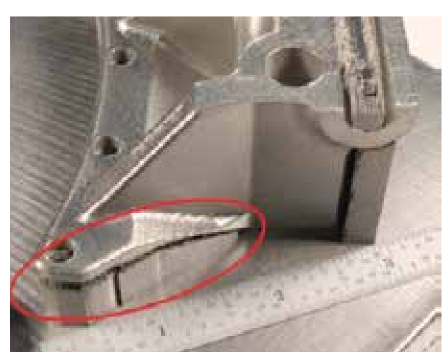

Figure 1-8. Cracking and delamination can result from residual stresses in the part during the build process (11).

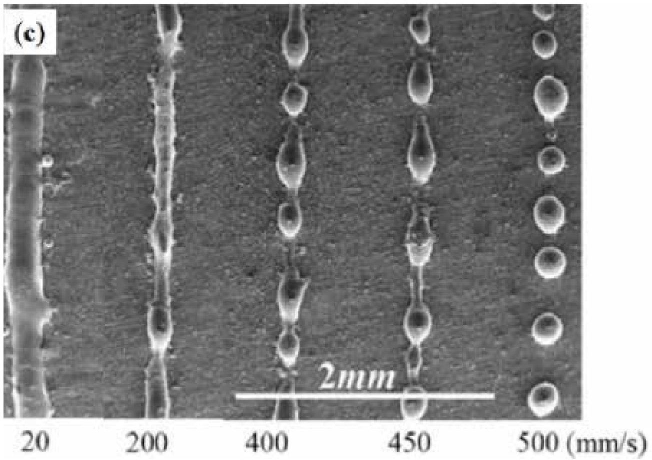

Figure 1-9. The formation of balling defects as the laser scanning speed is increased (6).

1.1.3.3 Balling. Balling is the third class of defect and occurs when instabilities cause the melt-pool to break into thin, spherical droplets (Figure 1-9). This occurrence is due to problems of the liquid metal wetting in its solid form (12). In these cases, the surface tension of the newly melted powder exceeds the wettability of the underlying layer, in much the same way that water beads up on a hydrophobic surface. As a result of this, increased scanning speed increases the change of the occurrence of balling defects. Because the molten powder resolidifies in the order of milliseconds, subsequent layers are built around the balling defects, leading to compounded defects as the part grows. Layers built around the balling can experience interlayer loss of adhesion due to the reduced surface contact, while the volume occupied by the sphere itself can grow into a volumetric defect.

1.1.3.4 Surface Roughness. Surface roughness is not considered an inherent defect in AM; however, it does have a bearing in the types of NDE that can be performed on finished parts. AM parts are built by slicing computer-aided design (CAD) models into consecutive layers that are translated into reality through the 3D printer. Due to this layering, any nonhorizontal or nonvertical face will be rough and have a step-like appearance. The junctures of the step features create sharp corners ideal for stress concentrations that can lead to part failure. Figure 1-10 compares SLM- and EBM-produced specimens to a traditional cast specimen.

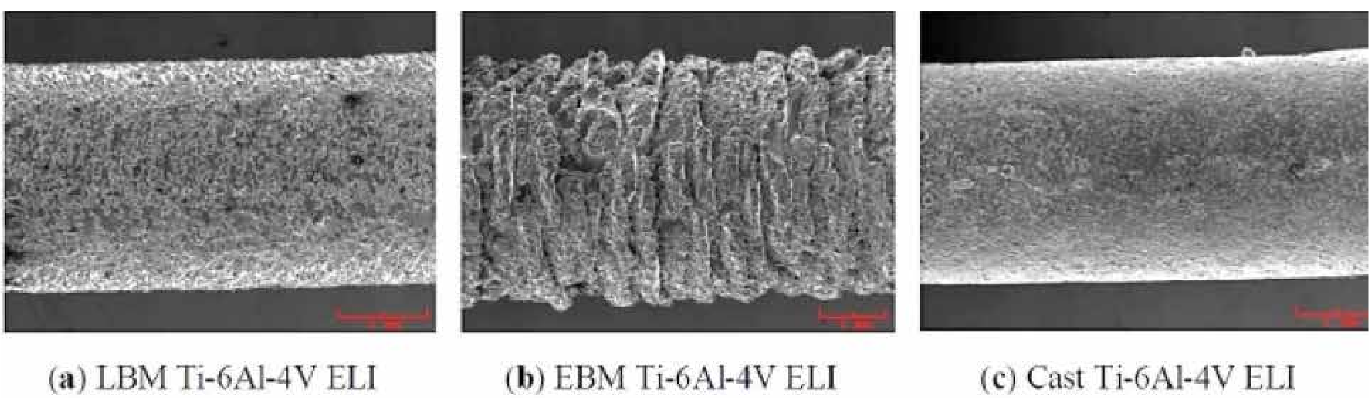

Figure 1-10. Surface roughness comparison between LBM (also known as SLM) (a), EBM (b), and cast Ti-6Al-4V extra-low interstitial (ELI), also known as Grade 23 Ti (c). Higher levels of surface roughness can produce stress concentrations resulting in crack formation (13).

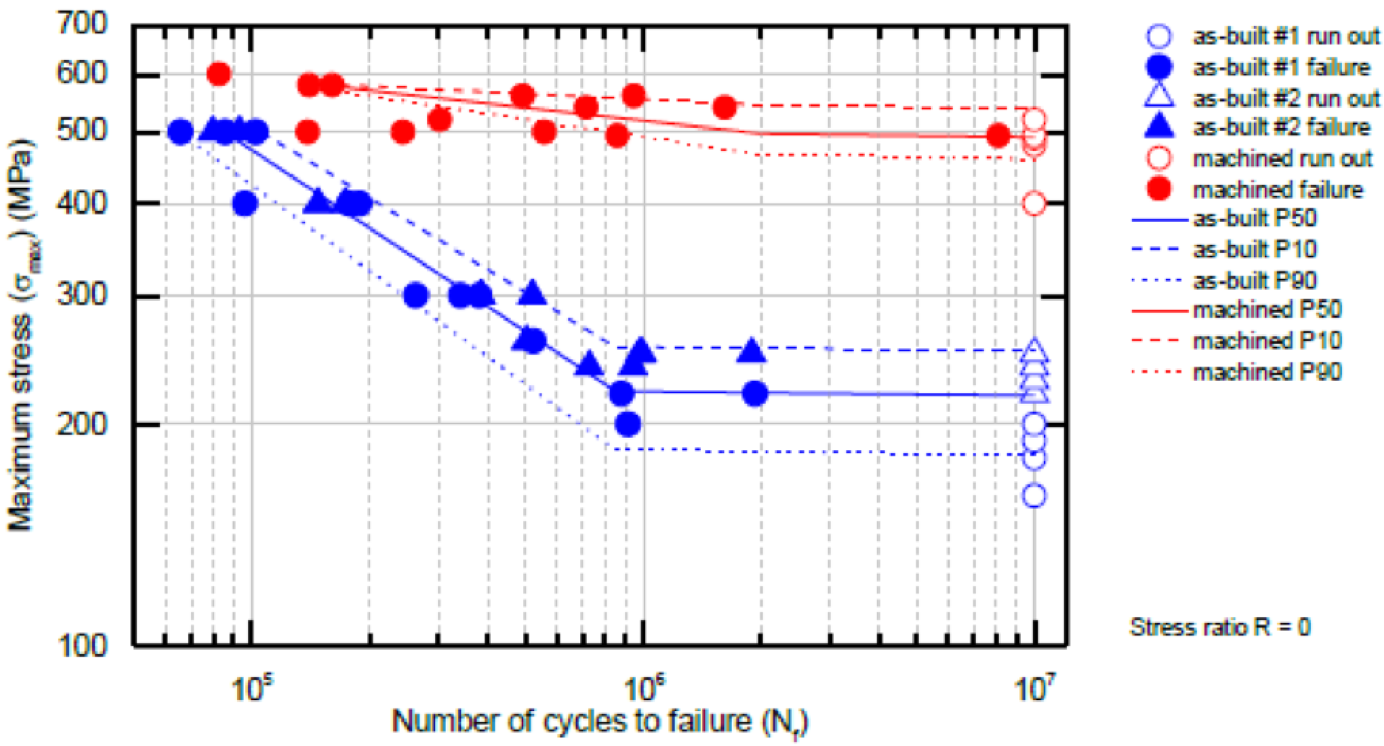

Figure 1-11. Strength vs. cycle number (S-N) curves (also known as Wöhler curves) for as-built AM parts (blue) compared to machined parts (red) (14).

As Stoffregen et al. (14) showed when comparing AM-produced test specimens of steel against those subtractively made, the rougher surface of AM parts is the site of initiation of fatigue cracks and the primary driver of failure in AM parts (Figure 1-11).

Stoffregen found that the mean deviation for surface roughness for AM parts in his study averaged R_a = 13.7 µm and that the maximum height of the roughness profile was R_z = 80 µm compared to machined parts having roughness parameters of R_a = 0.2 µm and R_z = 1.7 µm. At 107 cycles, the AM specimens had a maximum stress of 219 MPa, whereas the machined specimens had a maximum stress of 490 MPa. Surface roughness is a by-product of the build process, and Figure 1-11 illustrates how much the build process can affect the overall performance of the final part. It is essential to minimize the surface roughness of AM parts, whether through tight process controls and slow build times or by postproduction machining.

SECTION 02 Need for Qualification/ Certification to Allow Fielding of AM Parts

In traditional manufacturing, manufacturers often receive a statistically derived certification with bulk material, specifying that it meets the material specifications for the future parts and structures. The bulk material certifications, along with extensive destructive, nondestructive, and accelerated life testing, have given engineers and designers extremely in-depth, predictive knowledge of how materials will behave under expected life strains. Unfortunately, the process to qualify and certify AM parts and structures for flight has not reached the same level of maturity as those for traditionally made parts. As stated by Korbryn et al., "From a purely technical standpoint, AM cannot be considered for the manufacture of aircraft components unless the process is stable and controlled, and the resulting mechanical properties are well characterized and sufficiently invariable." (15)

NASA has been one of the agencies leading the drive to develop flight-certified AM parts as they view the ability to produce parts and structures remotely and ad hoc to be key to the future of human space flight. NASA has identified four key technical hurdles that must be addressed by the aerospace industry in the development of flight-certified AM parts (Table 2-1) (16). Understanding how to address these hurdles as the AM build complexity increases will drive the certification process as AM technology becomes more entwined with the manufacturing of aerospace components.

Table 2-1. NASA identified hurdles to development and certification of AM parts (17)

AM Technical Hurdle	Definition
Materials Characterization	Understanding the influence of AM build parameters, powder characteristics, thermal processing, and surface texture on the material properties of the end-use part
Standard Design Practices	Development of guidelines for mechanical design, testing specifications, and management of uncertainties associated with material properties and operational environments
Process Modeling, Monitoring, and Control	Physics-based modeling of transport phenomena in AM processes, in-situ defect detection, and prediction of material properties based on material characteristics and build parameters
Establishing Flight Certification Logic	Development of a part classification system using a risk-based approach, and understanding part failure modes, establishment of NDE and fracture-control requirements, and approaches to lot acceptance testing.

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SECTION 03

Design

3.1 MODELING AND SIMULATION

If AM parts are to be successfully integrated into aircraft and other vehicles, they must first be designed to meet or exceed the structural requirements of their traditionally made counterparts. Although AM parts are not currently being used in aircraft, the military is starting to implement AM machines and CAD software in forward bases to produce on-the-fly material solutions using plastic builds. These spare parts often serve a tactical or operational need that cannot be addressed quickly enough by normal procurement processes. The Marines have used AM to rapidly design plastic components that can be built overnight and then fielded in optimized battlefield operations.

While the ability to produce on-demand plastic parts can be a key logistics improvement, AM has much more potential. In typical structures, the loads are often carried by only a small section of the overall volume of material. Designers understand this aspect and try to reduce parasitic mass whenever possible; however, designers and engineers are limited by the ability of the manufacturing process to produce the actual parts. AM has the potential to remove many of these limitations.

Figure 3-1 illustrates how AM parts can be integrated into existing aircraft to optimize performance. By focusing on only the critical load pathways in the original part, engineers were able to produce a new generation of bracket that still met the performance requirements, but also produced an 87% volumetric reduction (Figure 3-2).

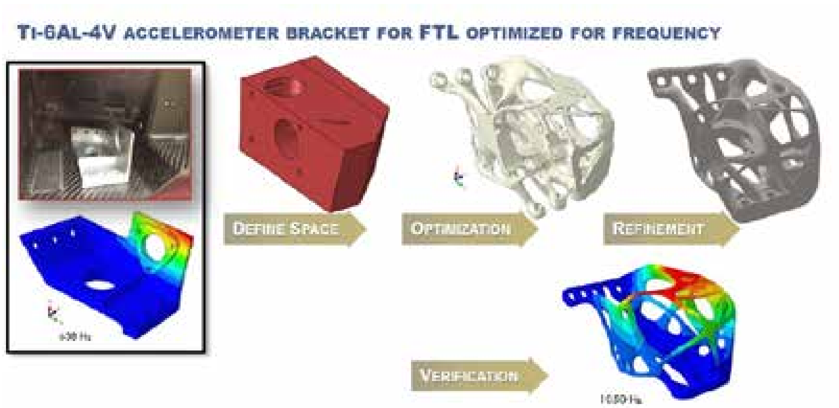

Figure 3-1. AM optimization of the natural frequency of an accelerometer bracket. The original bracket (left) is topologically optimized resulting in a new, more organic design with a higher natural frequency (18).

Figure 3-2. The finished bracket, as printed (18).

Currently, most AM parts that display the level of complexity of the one shown in Figure 3-2 are only used as proof-of-concept examples. Most AM parts still hew closely to their more traditionally made counterparts with simpler geometries. However, as the technology becomes more robust, part geometries will continue to grow more complex as designers become more comfortable designing in a much freer space. This increase in part complexity can challenge inspectors as the number of useable inspection tools decreases and the part geometry complexity increases. Surface roughness, possible voids, and internal delaminations may all be present in the structure, and if inspectors are unable to access those areas, the defects may go unnoticed and uncharacterized. This situation is part of an ongoing risk-management discussion about the bounds of acceptable risk in AM production lines.

3.2 FILE INTEGRITY AND SECURITY

3.2.1 Digital Thread for AM

Large-scale, qualified production of AM parts at an industrial level will require a series of complex, connected, and data-driven events, commonly referred to as the digital thread. The digital thread provides a single, seamless strand of data that stretches from the initial design concept to the finished part, constituting the information that enables the design, modeling, production, use, and monitoring of an individual manufactured part. This thread enables the flow of data throughout the manufacturing process, including design concept, modeling, build plan monitoring, quality assurance, the build process itself, and post-production monitoring and inspection (19).

The successful application of the digital thread for additive manufacturing (DTAM) allows the following:

- Ability to store and reference data for as long as needed.
- Capability to identify a design failure or a need for modification.
- Scalability to turn raw data gathered from the production of one part into applied process improvements for the next part.

Note that DTAM does not define the manufacturing process itself, but instead defines the connections and interactions between the manufacturing steps. The seamless interconnectivity provided by DTAM is the most important aspect of the concept. DTAM allows disparate printers, models, and data to exist in a single, coherent ecosystem.

3.2.2 Hacking of AM Machines

AM can be considered a revolutionary answer to the limitations of traditional logistics systems. Supply-chain management becomes easier if the only concerns are whether the raw material is on hand and the part file can be accessed. However, as cyber warfare becomes increasingly prevalent, the integrity of part files must be ensured. AM can open up new vectors of attack designed to compromise the integrity of the digital files and ultimately the physical part.

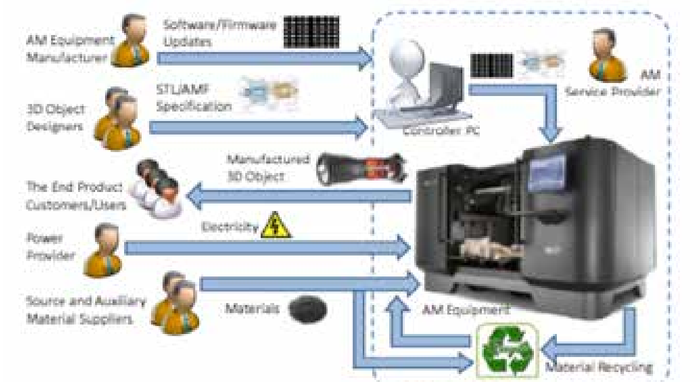

Figure 3-3. High-level AM workflow diagram (20).

As Figure 3-3 illustrates, there are many pathways to compromising an AM build. In fact, there have been many case studies demonstrating the ease of hacking an AM machine and even the computer that designed the parts to be printed (20). In the case study by Belikovetski et al., the researchers

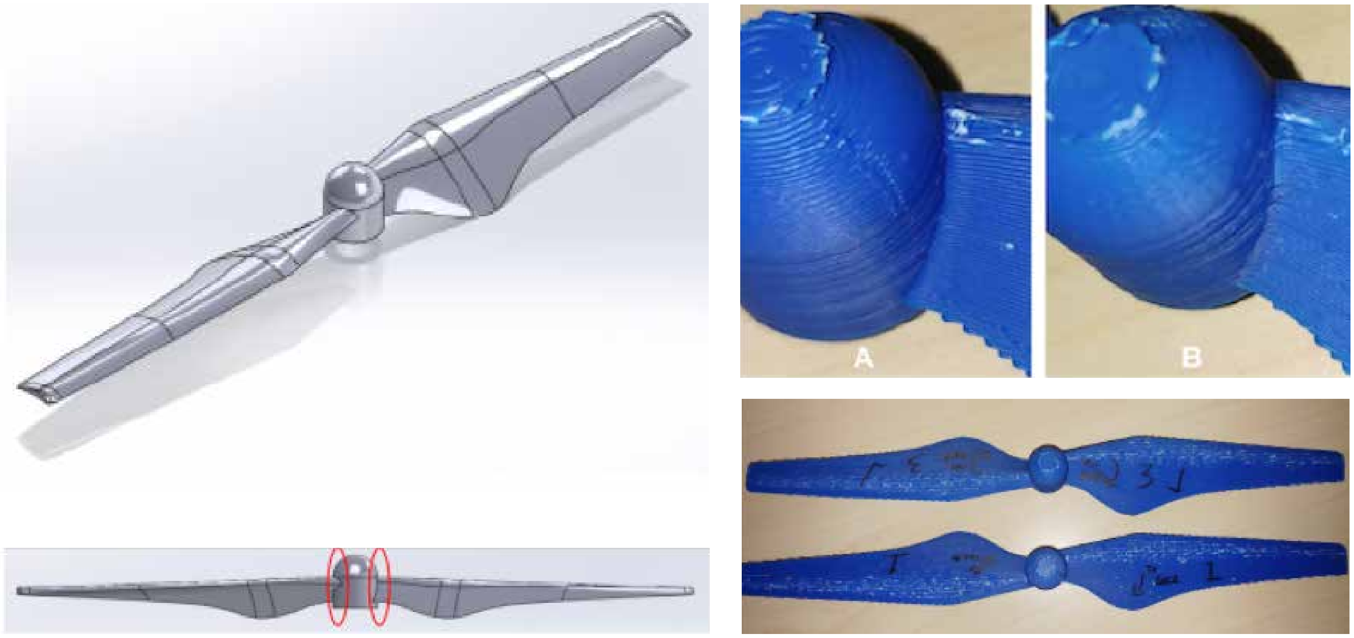

Figure 3-4. Top left: The original propeller design using SolidWorks. Bottom left: The red circles highlight the location selected for the defect. Top right: Two printed caps side by side. Cap A has been sabotaged and Cap B is benign. Bottom right: Two printed propellers side by side; the upper is benign and the lower has been sabotaged (20).

attempted to compromise a rotor blade for a small, commercial off-the-shelf unmanned aerial vehicle (UAV). They used a common phishing attack to access the computer that the .STL files were stored on and manipulated the CAD model to create an undetectable anomaly.

Figure 3-4 shows that AM parts can be sabotaged with no signs of tampering. To complete the attack, the sabotaged propeller was installed on the UAV, which was then test flown.

The properly printed propeller was rated to withstand over 15,000 revolutions per minute (RPMs) to support the flight of the UAV. The sabotaged propeller introduced a defect that caused it to break at 10,457 RPMs. Figure 3-5 shows the effects of the sabotage. The propeller broke in mid-flight, producing shrapnel and causing the drone to crash to the ground. The corruption of data files must be prevented to ensure AM part integrity.

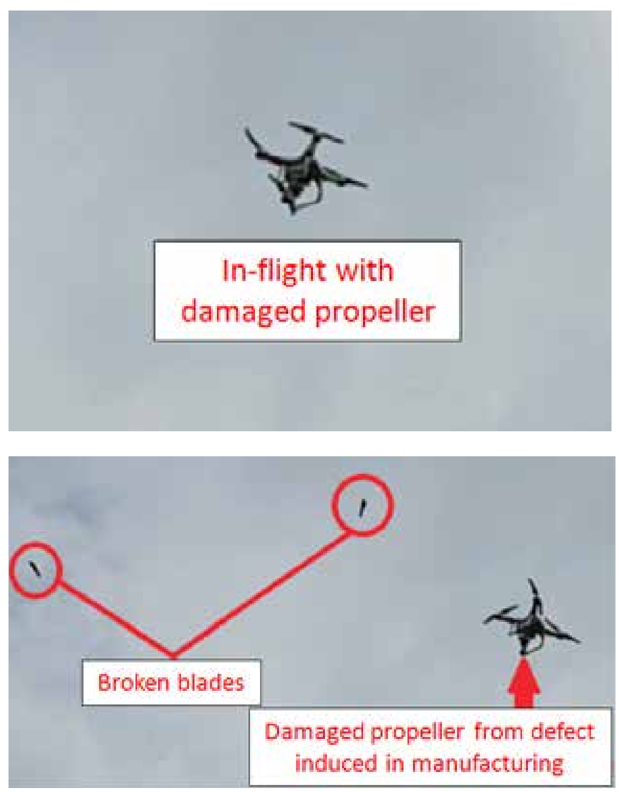

Figure 3-5. Top: The drone in flight with the sabotaged propeller. Bottom: The sabotaged propeller breaks in mid-flight (20).

3.2.3 Blockchain in AM

Blockchain provides a potential tool for securing AM files to prevent potential hacking as described in section 4.2.2. Appendix A provides an overview of the blockchain authentication protocol. Trouton et al. explain blockchain as follows:

> *Blockchain is a distributive ledger that provides a way for information to be recorded and shared by a community. In this community, each member maintains his or her own copy of the information and all members must collectively validate any updates. The information could represent transactions, contracts assets, identities, or anything else that can be described in digital form. Entries are permanent, transparent, and searchable, which makes it possible for community members to view transaction histories in their entirety.… Blockchain can exist as open source or in private, consortium, or other platforms. With blockchain, cryptology replaces third-party intermediaries as the keeper of trust with all blockchain participants running complex algorithms to certify the integrity of the whole (21).*

Implementing blockchain as a security protocol could be the first step in certifying AM parts. By providing a transparent and auditable chain of ownership through the life stages of AM parts, there can be assurances that the digital thread is uncompromised. Table 3-1 shows how the strengths of blockchain can be applied to secure AM. However, questions about file integrity would require engineering analysis on the receiving side, thereby limiting the number of people that can work with the files. This is potential drawback to the blockchain as it may negate some of the benefits of teleprinting parts.

Table 3-1. Blockchain characteristics and their relevance to AM (21)

Blockchain Characteristic	Relevance to AM
Distributed Data maintained within and among stakeholders.	Helps in management of the distributed supply-chain activity expected to be found in AM.
Near Real-Time Settlement and exchange are nearly instant.	Changes to a design are made instantly, which facilitates an efficient AM process.
Trustless Environment Cryptographic validation of transactions.	Designed to protect against risks of unauthorized data access.
Irreversibility The transaction history is append only.	Helps with cyber risk and IP protection as it is intended to provide an indelible and traceable record of changes.
Censorship-Resistant Modifying past transactions would be expensive and immediately detected.	

SECTION 04 Feedstock Quality Control and Standards

There are numerous standards designed to measure the properties of metal powders, but none apply specifically to AM. Current standards for AM titanium and nickel alloys (ASTM F2924, ASTM F3001, ASTM F3055) allow powders to be selected by the manufacturer as long as the powder meets compositional requirements (shown in Table 4-1) and the final product meets the specifications for tensile properties after heat treatment and any additional procurement requirements (22).

Table 4-1. Applicable standards for characterizing the density, flow rate, and size distribution of metallic powder particles based on National Institute of Standards and Technology (NIST) evaluation of applicable ASTM standards (23)

Characteristic	Applicable Standards
Density	ASTM B212 Density of Free-Flowing Powders Using Hall Flowmeter Funnel ASTM B329 Density Using Scott Volumeter ASTM B527 Tap Density ASTM B703 Density Using Arnold Meter ASTM B923 Skeletal Density by Helium Or Nitrogen Pycnometry
Flow Rate	ASTM B213 Flow Rate of Metal Powders Using Hall Flowmeter Funnel ASTM B855 Volumetric Flow Rate by Arnold Meter, Hall Flowmeter Funnel ASTM B964 Flow Rate Using Carney Funnel
Particle Size	ASTM B214 Sieve Analysis for Particles Over 45 Microns ASTM B822 Particle Size Distribution by Light Scattering
Sampling	ASTM B215 Sampling Metal Powders

Ambiguity in the standardization of powders is likely to continue, as each system being produced by different manufacturers has varying requirements, especially regarding the powder-size distribution, which is a consequence of the recoater blade systems, which vary in size and form (22). ASTM F3049 ("Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes") does provide some guidance on the types of measurements and applicable standards that may be appropriate, but does not provide guidance on such items as appropriate particle-size distribution or shape. Ultimately, the goal of this standard is to "point readers to existing metal powder standards that may be appropriate for additive manufacturing powders. It will provide one-stop shopping for someone who may want to measure the properties of AM powders but doesn't necessarily know what standard methods exist" (24). A companion standard to cover the mechanical properties of metal parts, WK43112, "Guide for Evaluating Mechanical Properties of Materials Made via Additive Manufacturing Processes," is also in development.

For the assessment of powder specifically, there are a number of parameters (key process variables [KPVs]) that must be examined. A list of KPVs that have been determined to impact part density, dimensional accuracy, surface finish, build rate, and mechanical properties, as well as the means with which to perform variable assessments, is presented in Table 4-2.

Table 4-2. Powder KPVs and Techniques Suitable for their Measurement (25)

Powder Property	Assessment Technique
Particle shape (morphology)	Scanning electron microscopy (SEM) Optical microscopy
Particle size and particle-size distribution	Sieve Laser diffraction Optical microscopy
Particle porosity	Particle polishing and optical microscopy
Apparent density	Hall flow Freeman FT4
Tap density	Tapped density tester
Flowability	Hall flow Dynamic flow testing (e.g., revolution, Freeman FT4) Shear cell Angle of response
Cohesiveness	Freeman FT4
Surface area	Brunauer-Emmett-Teller (BET) surface area analysis
Chemical composition	Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) X-ray Diffraction (XRD) Inert gas fusion Combustion infrared

SECTION 05 Process Control

5.1 BUILD CONTROL PARAMETERS

Process control is key to the qualification and certification of AM parts. Variables from beam power output to track speed can result in partial melts and delamination if not properly controlled. Table 5-1 lists the NASA-defined build-control parameters. No one parameter can be considered a separate parameter to control because the build optimization relies on the interplay of all four parameters to produce a quality part. These parameters must be controlled in all builds to guarantee that the parts can meet the specifications. In Figure 5-1, Reider et al. (26) provide an example of the effects of nonoptimized beam power during a build.

Table 5-1. NASA-defined build-control parameters for AM. The collective parameters must be optimized holistically rather than as distinct, individual parameters (27)

Build-Control Parameter	Definition
Build layer thickness	The depth of powder consolidated as each layer is produced.
Beam power	Power delivered to melt powder layer.
Beam scan hatch width	Overlap between beam passes within a layer.
Beam scan speed	Speed at which the beam moves along the layer.

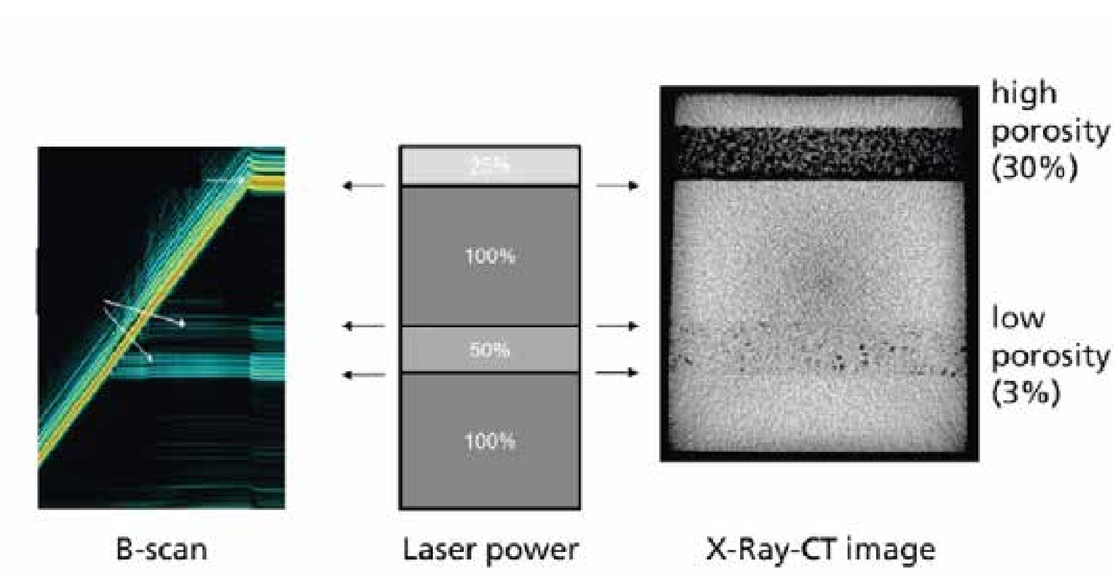

Figure 5-1. The B-scan (left) clearly shows a drop in laser power during the build time (center), with the resulting porosity verified through a postbuild CT scan (right) (27).

Table 5-2. Design of NASA experiment (28)

Factor	Level 1	Level 2	Level 3
Power (W)	180	256	332
Scan speed (mm/s)	500	13,030	1,560
Hatch spacing (mm)	0.0675	0.105	0.1425

Table 5-3. NASA study sample blocks (28)

Block set	Deposition pattern	Heat treatment
A	Continuous	No
B	Continuous	Yes
C	Chess	No
D	Chess	Yes

During the build, the researchers monitored the process using in-situ ultrasound and varied the beam power, as shown in Figure 5-1. Postproduction X-ray computer tomography (CT) scans verified the in-situ monitoring, presenting a clear correlation between the beam power and the resulting porosity of the finished part. While the purpose of the experiment was to validate in-situ ultrasonic monitoring, it also serves as a strong reminder of the need for stringent process controls to produce quality parts.

NASA examined controllable machine parameters and their effects on the AM build. NASA examined the effects of beam power, scan speed, and hatch spacing on the relative density of simple AM blocks. Table 5-2 lists the parameters for the experiment, which was a 27-sample, full factorial (three factors at each level) (28).

The tests also studied the effects of deposition pattern and heat treatment with the sample blocks listed in Table 5-3. Four block sets were produced (27 in each set) for a total of 108 specimens.

NASA analyzed the blocks for four different density measurements:

- **Gravimetric Density.** Uses the dry mass of the specimen and the volume calculated directly from the measurement of the length between specimen faces.
- **Open Porosity.** Percentage of the volume enclosed by the specimen that is made up of voids that open to or are capable of interacting with the specimen surface and may facilitate crack growth.
- **Bulk Density.** Uses the open porosity data to calculate a volume.
- **Apparent Density.** Volume used in the calculation does not include open porosity (but internal porosity is reflected in this value). Apparent density is a closer representation of the material that composes the specimen.

The resulting density values are shown in Table 5-4.

In general, NASA found that larger hatch spacing resulted in a lower-density material. For the material in this study, Inconel 718, it was determined that hatch spacing was the leading cause of porosity, and therefore should be held at the smallest reasonable value to ensure sufficient material consolidation (28). The results of this study suggest that as production rates move from low volumes to higher volumes, one process parameter

Table 5-4. Impact of deposition pattern and heat treatment on density across all parameter sets approaching high-rate mass production applications (28)

Density Value	A	B	C	D
Open porosity (%)	0.7	0.9	0.4	0.7
Apparent density (g/cc)	8.158	8.239	8.155	8.245
Bulk density (g/cc)	8.104	8.166	8.119	8.191
Gravimetric density (g/cc)	8.074 (98.2%)	8.134 (98.9%)	8.086 (98.4%)	8.171 (99.4%)

should be held at the default (lowest) value. Additional studies are needed to determine how varying the process parameters affect the build beyond just density values.

5.2 IN-SITU MONITORING

5.2.1 Near-Infrared (NIR) Cameras

One method of qualifying the build process is in-situ monitoring, using either infrared or optical monitoring. The most widely used in-situ system uses NIR cameras to capture the temperature gradients between two melt layers. The cameras can detect "cold" spots indicative of areas where the beam energy was not sufficient for properly melting the material. These cold spots can produce defects in the finished part. NIR camera systems can be improved to include multiple cameras and real-time tracking, and feedback algorithms can help improve the weld consistency in AM, which has been seen in the manufacturing of stainless steel straight wall samples (4).

5.2.2 Optical Image Analysis

Recently, researchers at The Pennsylvania State University have examined the use of optical image analysis to perform layerwise in-situ monitoring of AM (11). The research team focused on using the layerwise monitoring to correlate the anomalies seen in postproduction 3D X-ray CT scans to features seen in the images between layer melts.

Figure 5-2 shows how the individual layer images can be stacked to produce a 3D CAD model that maps the locations of defects. This type of in-situ monitoring is useful in improving the process controls by identifying where in the build the defects were generated. Then, the source of the defects can be eliminated before they can affect the build process.

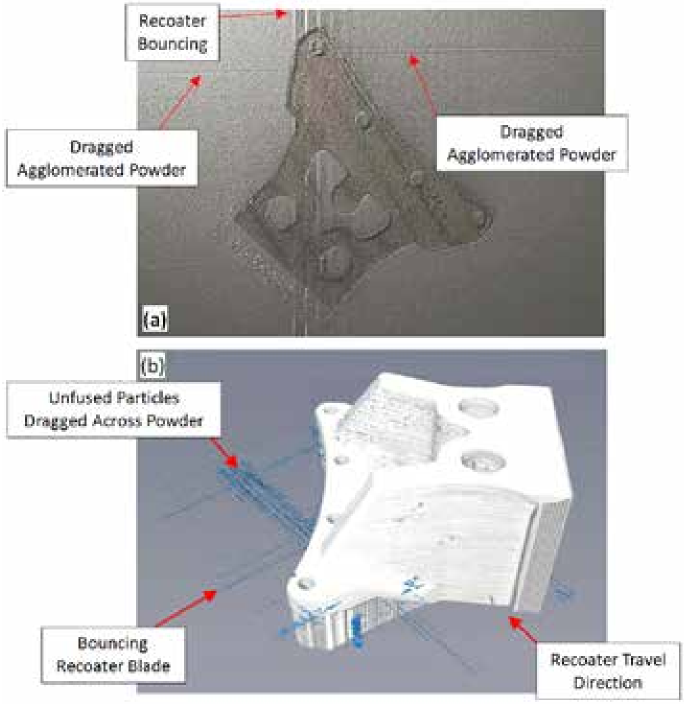

Figure 5-2. As individual images are collected of each layer of the build (a), a 3D model can be generated and correlated with CT scans (b) (11).

5.2.3 Ultrasonic (UT) Monitoring

One of the more promising techniques being developed is in-situ UT monitoring of the build process. In-situ UT monitoring can be used to analyze the laser power in SLM machines with the A-scans[2] allowing inspectors to infer conclusions about the quality of the SLM process. Reider et al. (26) describe the process of using in-situ UT monitoring when producing Inconel 718, a nickel alloy used for aero engine components (26). The UT monitoring system used a four-channel transmitter and receiver system with a bandwidth ranging from 400 kHz up to 30 MHz and a sampling rate of 250 MHz and 14-bit resolution. It could perform 1,000 A-scans every second and had a temporal resolution of 4 ns. The SLM process was monitored layerwise with simultaneous visualization of the RF signals. Because in-situ UT monitoring is still a relatively recent development, the parts

[2] *A-scans represent the basic ultrasonic signal response, typically signal amplitude vs. time for a single, discrete point along the scan axis. B-scans allow the integration of a series of A-scans through the part to produce an amplitude vs. depth plot.*

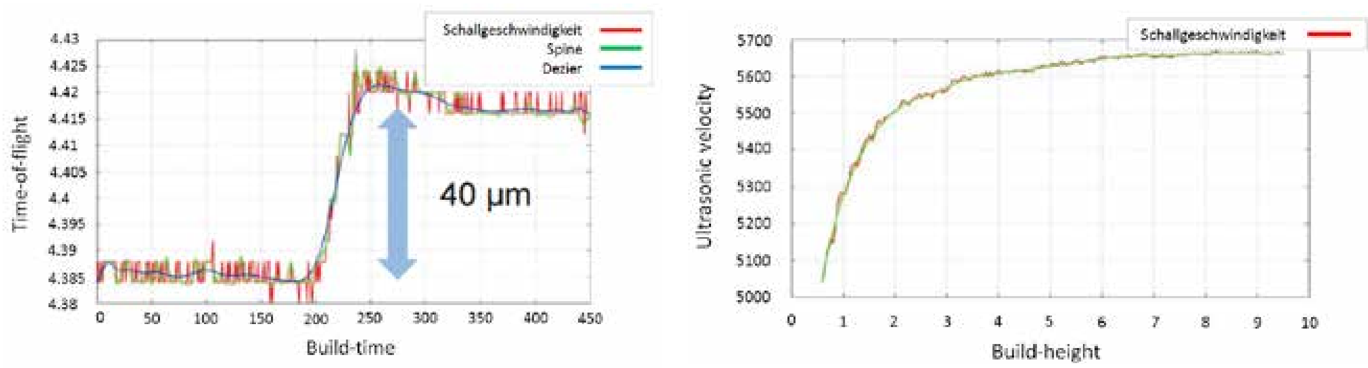

Figure 5-3. (Left) A single-layer measurement of the ultrasonic signal showing a direct correlation with the welding process, allowing the ultrasonic velocity changes to be determined as a function of build height (right) (27).

manufactured for testing were simple test cylinders having intentional defects of spherical and half-spherical voids made of nonmelted powder added to the build. During the build, the voids were clearly seen in the scans, thus indicating that the SLM process can be used to fabricate calibration blocks.

In-situ UT monitoring can also be used to analyze the single-layer fusion process by comparing the time of flight of the ultrasonic signal and the build time. This technique uses the ability of AM to produce nominally consistent layer thicknesses during the build time. In the graphs shown in Figure 5-3, the average layer thickness was 40 µm, meaning that for a part with a total thickness of 20 mm, the build time is approximately 90 minutes.

5.2.4 Laser Ultrasonics (LUT)

LUT is a maturing technology that has the potential to be used for in-situ monitoring. LUT uses a pulsed laser beam to generate ultrasonic waves in the solidified layer. The waves then interrogate the layer for defects and arrive at the point of detection. The resulting surface displacement is then detected with a separate, laser-based receiver. As the beams scan along the layer during production, the signal detected at each position is acquired, and the signals are combined to form a B-scan image that can be interpreted with advanced, automated signal and image processing algorithms to determine the integrity of each layer (29).

Figure 5-4 shows a defect and the corresponding signal used to create the defect profile. When a threshold level is applied, as shown by the yellow line in the right image, the detection of defects can be an autonomous process. LUT in-line monitoring is still in development, but if the technology matures, it could ensure that all finished AM parts will be qualified without the need for further inspections.

In-situ monitoring is still in the development phase, with most systems applied only in laboratory settings. More research is needed to further develop the various technologies so they can be integrated with AM machines.

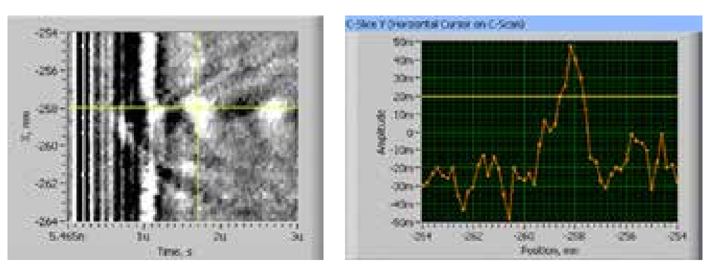

Figure 5-4. B-scan of a sample specimen (left) with a defect located at position -258 mm. A defect profile can be generated from the returned laser ultrasound signal (right) (29).

SECTION 06 Postprocessing

6.1 CLEANING

A necessary step in the manufacturing of AM parts is cleaning the part once the build is complete. However, the introduction of complex internal structures also creates a demand for special cleaning techniques to ensure that particulates left over from the build are not impeding the functionality of the part. Of particular concern is powder removal, where engineers have one opportunity to remove the powder from build internals. If the loose powder is not sufficiently removed, the Hot Isostatic Pressing (HIP) processor heating for stress relief of the part can cause the powder to bind in place (30). Initially, there was little concern about powder removal when AM parts were designed. This lack of concern led to designs such as the one shown in Figure 6-1.

Loose powder is built up through the layers and may be used to support the build of more solid structures. However, if the powder is not accounted for, AM parts could end up like the one shown in Figure 6-1 where powder is trapped inside. Trapped powder can act as an abrasive causing surface scratches and potentially creating stress nucleation sites that generate cracks earlier than anticipated. Even in parts where the powder is bound that undergo postprocessing, the powder may travel through the structure and cause issues far from where they would be expected. Improperly cleaned AM parts are at risk for premature failure, and presumably could not be certified for flight in such a state. Currently, there is very little study being devoted to the best practices for designing and cleaning AM parts postbuild.

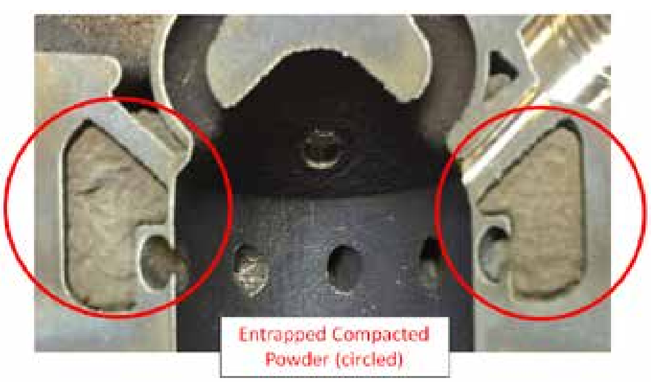

Figure 6-1. A cutaway of an AM part with trapped impacted powder (circled in red) that would be impossible to remove postbuild (30).

6.2 FINAL MACHINING AND FINISHING

It is very rare to encounter a metal part in use consisting of just the base alloy. Usually, traditionally made parts are tempered or heat-treated to tailor the metal to meet certain material strengths. AM parts, while being able to be produced at net or near-net shape, still must undergo postprocessing treatments to meet design needs. Because the build process creates thermal gradients along the part, residual stresses within the build are common and must be relieved before the parts can undergo HIP.

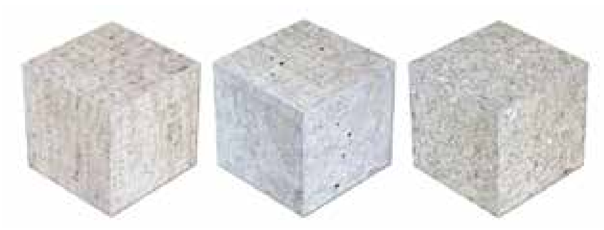

Figure 6-2. (Left) An as-built cube of material; (middle) the same cube after undergoing stress relief; (right) the same cube after undergoing HIP and final machining (31).

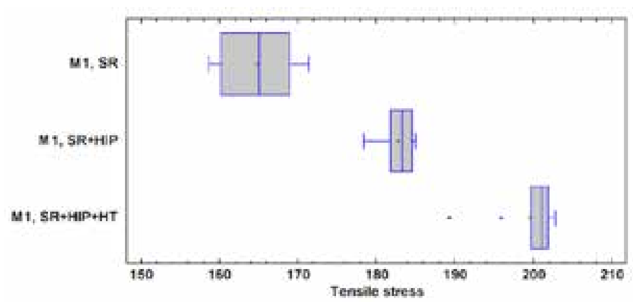

Figure 6-3. Box and whisker plot comparing the ultimate tensile strength stress data (KSI) for Inconel 718 subject to combinations of stress relief (SR), HIP, and heat treatment (HT) postbuild (17).

Figure 6-2 shows the evolution of a sample material. The first cube shows clear striations indicative of the layerwise build process. In the second cube, after undergoing stress relief, the striations are gone; however, the voids, shown as dark spots, are clearly visible. The third cube has undergone HIP and the voids are gone.

The effects of postbuild treatments can be seen clearly in Figure 6-3, which shows that applying traditional postbuild treatments can generate significant increases in the ultimate tensile strength of the material. There is little literature to provide guidance on qualifying the effectiveness of these treatments for various metals and alloys and warrants further study for AM parts. However, the intelligent employment of witness specimens and NDE techniques may be enough to verify the treatment process.

The goal of AM technology is the ability to produce fully as-built parts ready to be integrated into larger systems. However, the technology has not matured to that level. Finishing operations are still required that often include producing a surface finish more comparable to that of traditionally manufactured parts. While depot-level production facilities may have the tooling to produce a smooth surface finish, in forward areas with limited capabilities or in time-sensitive builds, a method is needed for certifying a rougher-than-normal surface.

Rougher surface finishes create stress concentration areas that can act as nucleation points for the development of cracks in the material. If AM certification is going to be developed according to risk based analytics, it is important to understand how as-built surface roughness shortens the life cycle of AM parts. An example of the effect of surface roughness on high cycle fatigue life is illustrated in a NASA study of Inconel 718, as shown in Figures 6-4 and 6-5. The results from these ASTM E466 tests with a stress ratio of r=0.1 (in which all the SLM components utilize Z-oriented specimens) show that the low stress ground specimen possesses the best fatigue life characteristics, with notably poorer performance from the "As-built," "Tumbled & Electropolished", and the "Tumbled & Chem Milled" specimens. Of these last three, and as expected, the "As-built" material yields the poorest fatigue life results.

A rough surface can dramatically lower the life cycle of an AM part. While simple AM parts can be machined to create adequate surface finishes, as the complexity of AM parts increases, it may not be possible to remove surface roughness from all areas of the part. This situation may change the calculus for designing AM parts for aircraft, especially if the goal is to reduce parasitic weight and volume. If the rough surface produces stress concentrations that increase the potential for crack growth at lower stress levels and cycles, it may be necessary to either add bulk to the part in high stress areas or reduce the life cycle schedule of the part and replace it sooner than traditional parts would be. This is an area that requires more study to determine the acceptable surface finish levels.

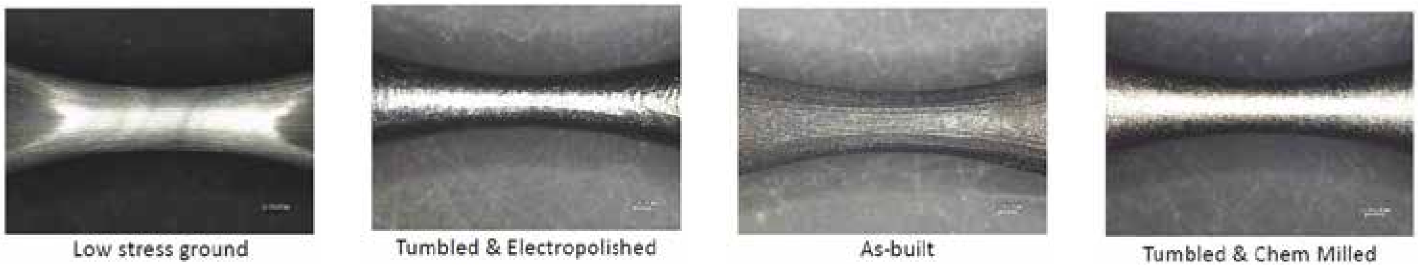

Figure 6-4. Four surface finishes used by NASA to investigate the effect that surface finish has on material fatigue life — the as-built surface finish is notably rougher than the other three (32).

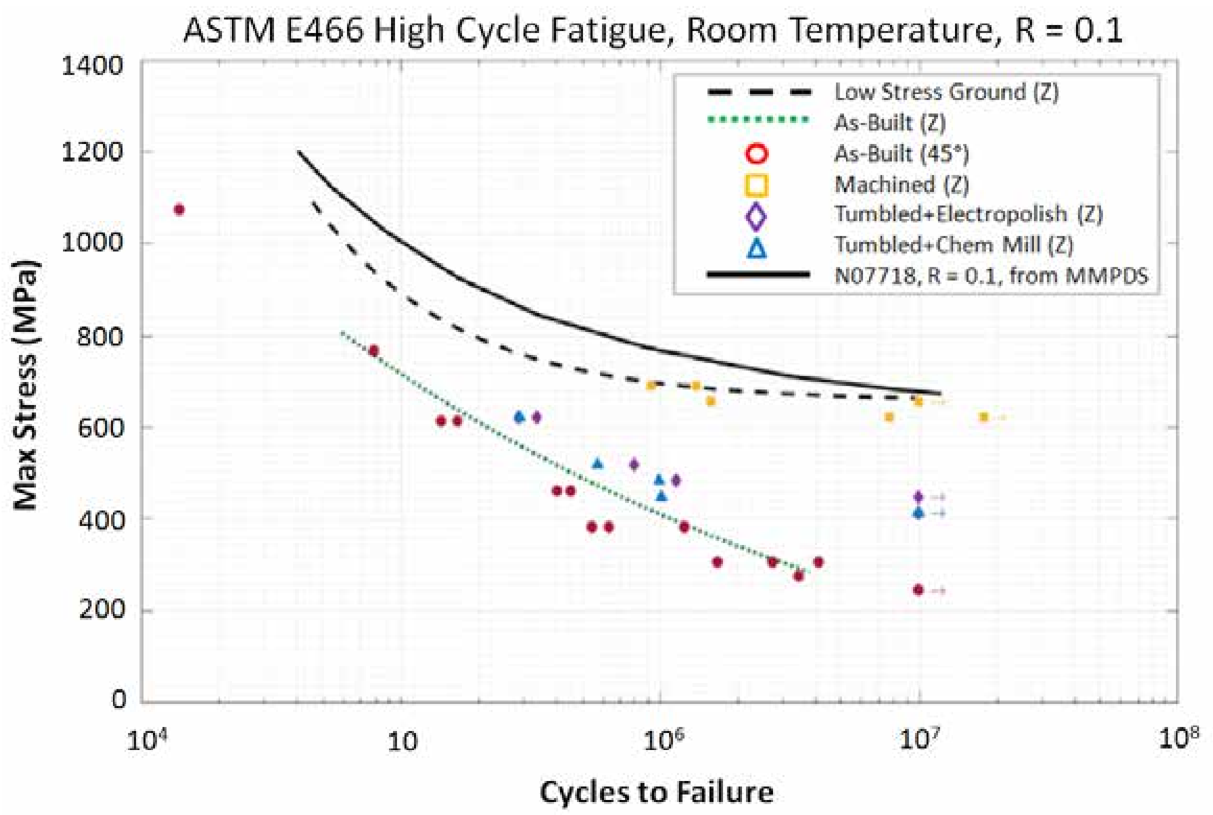

Figure 6-5. High cycle fatigue loading of the specimens seen in Figure 6-4. The as-built parts show considerably lower maximum stress levels, indicative of the rougher surface finish (AM components described here are Z-oriented) (32).

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SECTION 07 Quality Assurance/ Quality Control (QA/QC)

It cannot be assumed that parts made in a computer-controlled environment, such as AM parts, will meet the specifications and tolerances defined in the original CAD file. As mentioned in section 6, the build process can induce residual stresses in the AM part. The residual stresses in some instances can be enough to cause warping in the part; therefore, the part must undergo quality checks to make sure it still meets the engineering specifications.

The results of a study on the effects of surface deformation in Inconel 718, seen in Figure 7-1, demonstrated the warping ability of residual stresses from the build. The initial surface profile measurement of the specimen while still attached to the build plate showed very little surface curvature along its longitudinal direction. However, once the specimen was separated from the build plate, there was significant warping along its longitudinal direction, with 0.15-mm uplifts near the edges of the 20 mm long specimens. While that is a relatively small uplift, with high-precision aerospace tolerances, this small uplift might be enough to ruin the build. Postbuild quality checks are crucial in determining if a part should move forward through the process to being installed in a final form. By understanding how the residual stresses affect the build, designers and engineers can predict the stress behavior in future builds, and if the behavior can be predicted, it can be mitigated. Additional research in stress behavior prediction is definitely needed for further understanding.

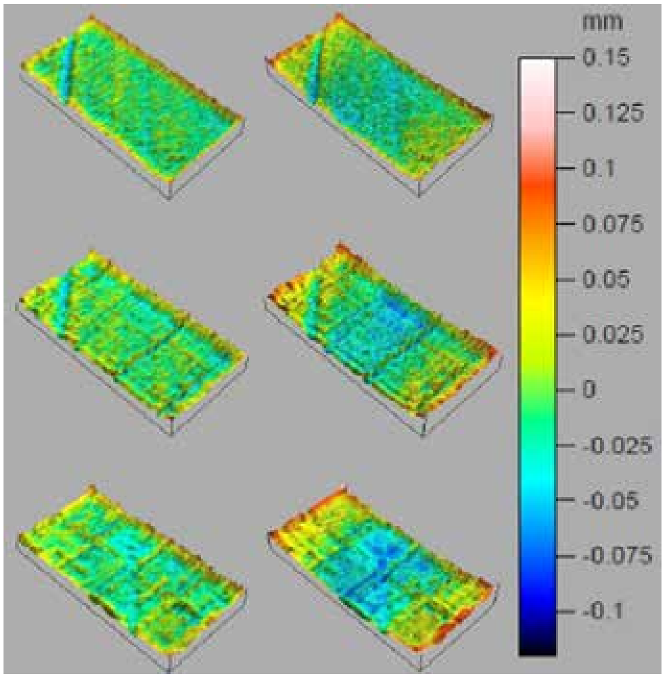

Figure 7-1. A series of Inconel 718 specimen builds showing the surface profile while still attached to the base plate (left) and then separated from the base plate (right) (33).

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SECTION 08 Microstructural Analysis

8.1 MICROSTRUCTURE EVOLUTION DURING AM AND MECHANICAL PROPERTIES

The microstructural evolution within AM materials is complex. A single component with a constant cross-section, which for a conventional manufacturing process will usually possess a consistent microstructure, may no longer have a uniform microstructure when fabricated using AM, this is illustrated in the example shown in Figure 8-1. The result, for this particular example, is an effect of the cooling rate. The section of the specimen near the top of the component experiences heat losses both as a result of convection (heat being rejected into the build atmosphere) and conduction in the direction of the build plate. In Ti-6Al-4V, the higher cooling rate after the material has been heated past the β-transus temperature results in thinner lamella in the microstructure. The material closer to the build plate experiences lower convective losses, and acts as a heat path for energy being conducted from the top of the component down to the build plate, resulting in a lower cooling rate, and thicker lamella within the microstructure.

All fusion-based metal AM processes lead to a unique combination of thermal gradients and liquid/solid interface velocities during processing. These combinations directly and most influentially affect the material microstructures. The same rules apply to AM materials as to annealed, forged, or extruded materials. The microstructural grain shapes/features (columnar, dendritic, cellular, etc.) and sizes have significant effects on the bulk material properties (tensile strength, fatigue/creep resistance, fracture toughness, etc.). As layers are deposited, remelting of underlying layers occurs, and the root of the weld deposit may penetrate through one or more previous layers, depending on the level of heat input. An example of melt-pools being distinguished

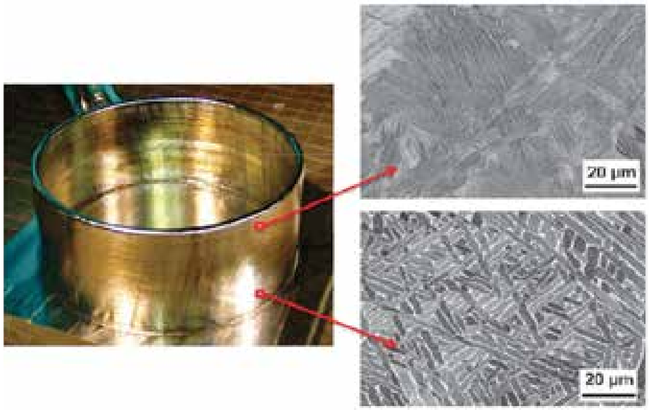


Figure 8-1. Microstructures from a Ti-6Al-4V cylinder printed onto a build plate. The bottom image shows a large, lamellar microstructure, indicative of slower cooling; the top image shows a thinner lamellar, "basket-weave" or Widmanstatten microstructure indicative of rapid cooling (34).

within the penetration depth is shown in Figure 8-2 (35). Here, the melt-pools are obvious, and the surface contour paths at the part edges are distinct from those of the fill pattern. In addition, columnar grains are observed within the build direction in the mesostructure, as is common for all AM parts.

8.2 QUALIFICATION

If melt-pool solidification and alloy feed parameters are controlled sufficiently, AM can provide the capability to tailor the microstructure, alloy, and even material gradients to component property requirements. Examples of such requirements are shown in Figure 8-3, which shows the microstructures of as-built Ni 718 and post processed (stress relieved and hipped) Ni 718. Here, columnar grains are visible as well as instances of the melt-pools at different locations are present in the as-built material and a homogenized microstructure is present in the post-processed Ni 718. This control leads to the goal for AM qualification, which is the capability to monitor applicable melting and structural solidification parameters continuously, with predictive, closed-loop feed-back control in real-time to prevent potential defects in the product.

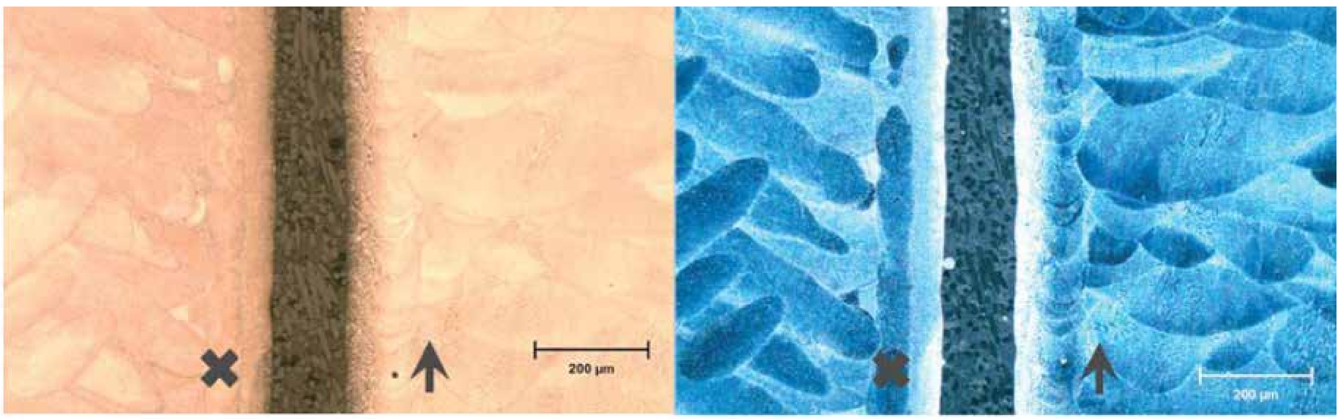
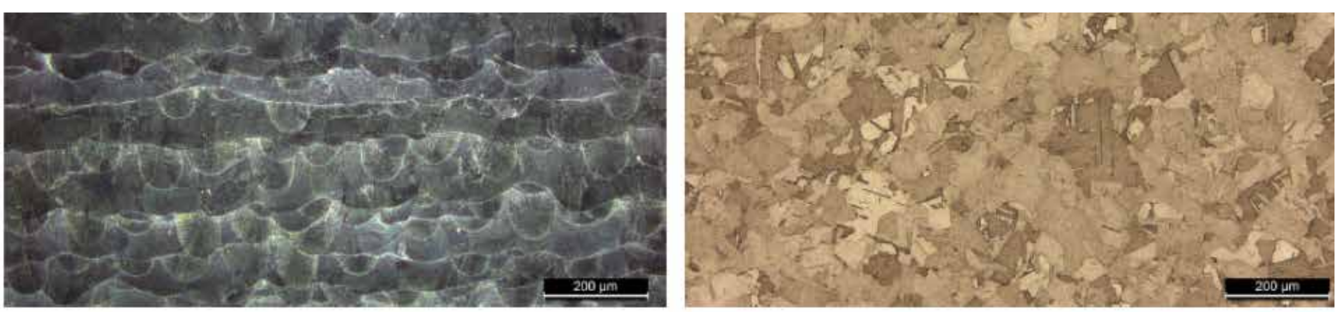


Figure 8-2. Bright- (left) and dark-field (right) optical micrographs comparing build directions in as-deposited Direct Metal Laser Sintering (DMLS) material. The build orientation is indicated with an arrow, while the X denotes samples viewed within the build plane (35).



Example acceptance criteria - as-built state:

- Weld penetration depth and shape
- Grain nucleation patterns
- Porosity
- Lack of fusion / Cracks

Example acceptance criteria - final state:

- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks

Figure 8-3. Examples of acceptance criteria. The goal of qualification is to be able to confirm that the parameters used for the build resulted in material with the required properties for its final application (36).

The performance of an AM part is directly affected by its microstructure, which is a permanent record of the processing pedigree (37). To take full advantage of the unique benefits offered by AM (complex parts with integral structures or extending part life with novel repair methods offered by direct-deposition techniques), users need to verify that the part meets the design requirements. Since AM is suitable for complex geometries and therefore often used for such applications, it poses a particular challenge for conventional NDE techniques such as ultrasonic, eddy current, and radiographic.

Although geometric complexity is a lesser concern for surface-sensitive techniques like penetrant and magnetic particle inspection, accessibility is not necessarily guaranteed for complex parts. CT is used for examining complex geometries, but has limitations including detectability, sensitivity, and ease of use. In particular, the qualification of microstructures has long been performed exclusively by optical means (metallographic sectioning, polishing, and etching) or using SEM. Although both methods are destructive, they are the only widely accepted methods capable of unambiguously producing information on the grain size, grain size distribution, grain shapes, and texturing. This situation has led to such practices as the fabrication of "witness" specimens that become a part of each build, which are destructively analyzed to confirm that the machine is performing properly (see section 9.2). However, these specimens are still only representative of the part being fabricated and may not accurately predict actual part behavior. This is especially true for parts with highly complex geometries in which large thermal gradients may be experienced compared to what takes place in a witness sample.

Process mapping studies conducted for Ti-6Al-4V appear to be successful in mapping coarse microstructural features occurring during solidification (e.g., such as β-grain size). It is likely that microstructural qualification will need to be focused on thermal modeling and examinations of the process parameters recorded by the machine for each build after completion. Further work is needed on solid-state phase transformations that occur during subsequent cooling to room temperature as well as any thermal transients that occur during the build. The flexibility associated with producing complicated geometries using AM will require the ability to change location-specific processing parameters to optimize powder melting and solidification rates to produce parts free of defects and with the desired microstructural features over a range of size and length scales (37). Microstructural heterogeneity (morphology, crystallography, and alignment with the build direction) is expected and may be desired in some cases. Finally, microstructural features and characteristics will need to be linked to probabilistic approaches for fracture, fatigue, and life predictions.

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SECTION 09 Destructive Testing

9.1 UNDERSTANDING BUILD QUALITY

As mentioned in section 3.2.2, internal defects in AM builds remain undetected during a cursory, visual inspection. Certainly not all internal defects are the result of malicious cyber activity; rather, most result from poor melt during the build. However, given the expense of AM parts, it doesn't make economic sense to dispose of a defective build. In many instances, the application of postproduction techniques, such as HIP and heat treating, will eliminate the negative impacts of the defects.

Figure 9-1 shows the stress-strain curves from SLM Inconel 718 components produced by NASA after it had been stress relieved, undergone HIP, solution-treated, and aged, with the material exhibiting typical yield and ultimate stress and strains for a properly manufactured SLM material. As Table 9-1 shows, the material properties are comparable to the values produced through traditional manufacturing.

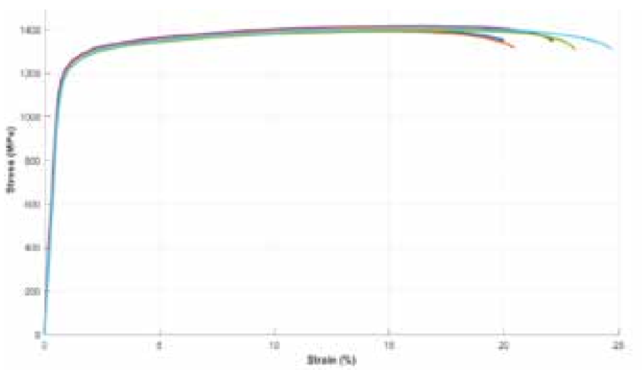

Figure 9-1. Stress-strain curve for SLM Inconel 718 produced by NASA (32).

Table 9-1. Material Properties of AM Inconel 718 compared to nominal values provided by Aerospace Specification Metals[3]

Material Properties	Nominal Values	AM Values
Ultimate Tensile Strength (MPa)	1,375	1,380
Yield Strength (MPa)	1,100	1,170

[3] *http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=NINC34*

However, it should not be assumed that large-scale facilities will necessarily be conducting the postproduction work on AM parts. As AM technology is pushed further into field environments and away from large-scale facilities, it may not be feasible to run the gamut of postproduction work on a part so that it meets traditional material property values. In those instances, the risk of internal defects must be considered when developing an AM part for use.

NASA has also shown that internal defects can significantly affect the life of AM parts. Figure 9-2 shows there is a marked decrease in the strength of AM parts if defects are not removed. If production facilities cannot provide a proper postprocessing treatment for the part, understanding the risks and consequences of potential defects is crucial. If the goal of AM is to produce as-built parts with minimal postprocessing, engineers and designers must understand and accept build defects.

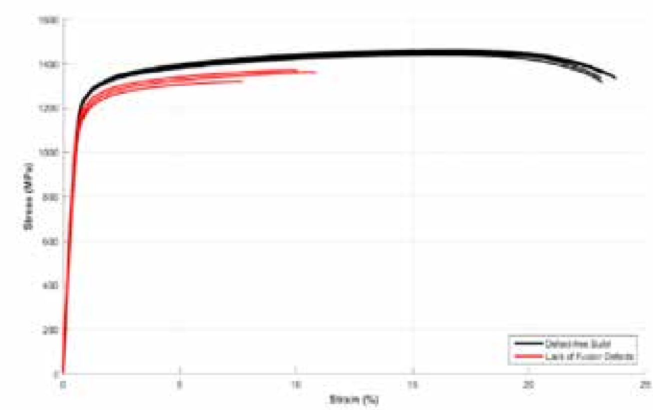

Figure 9-2. Comparison of defect-free build of Inconel 718 with as-built Inconel 718 (32).

9.2 WITNESS SPECIMENS

Discussions about AM part certification are frequently focused on the production of witness specimens alongside the build that can be used as benchmarks to judge the properties of the built AM part. There are four main types of AM build witness specimens (31):

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties (as needed)

Used properly, witness specimens can provide direct evidence of the systemic health of the AM process during the build; however, witness specimens can only provide an indirect indication of the AM part build quality through inference. Witness specimens are meant to be a statistical process control where the build acceptance is measured against the 99%/95% tolerance interval,[4] or at the very least acceptable minimums. Witness specimen testing, along with NDE and accelerated life testing (ALT), allow designers to buffer the uncertainty of the build process with reasonable engineering assurance that the parts fall within the statistical allowances.

NASA, as part of their effort to create guidelines for the use of AM parts, has suggested that in each build there should be six tensile and two fatigue witness samples. The implication of the use of witness specimens as a means of statistical control of the build process is that there needs to be a statistical foundation for each machine and material used in the build process. Time and effort must be devoted to developing these foundations before widespread use of witness specimens can be accepted.

[4] A 99%/95% tolerance interval means that 99% of the population meets the standards with a 95% confidence.

SECTION 10 NDE

10.1 PENETRANT DYE TESTING (PT)

While most of the postbuild inspection of AM parts is identical to the inspection processes of subtractive manufacturing, the method of inspection is often found to be a greater function of the complexity of the AM part. For instance, PT is often used to find surface cracks in traditionally made parts. However, because AM relies on the stepwise layer slice build-up of the part, the surface roughness is often greater than with subtractive manufacturing. PT is based on capillary action, which draws the dye into the crack. Then, the excess dye is removed from the surface and an ultraviolet light is shone on the part to illuminate any dye that has become trapped in the cracks. The surface roughness of the AM part presents multiple opportunities for small cracks to form between the layers as the part is built up, as seen in Figure 10-1. Due to the many small cracks common in AM as-built parts, using PT is an almost insurmountable task, at least without first performing a postprocessing machining and polishing.

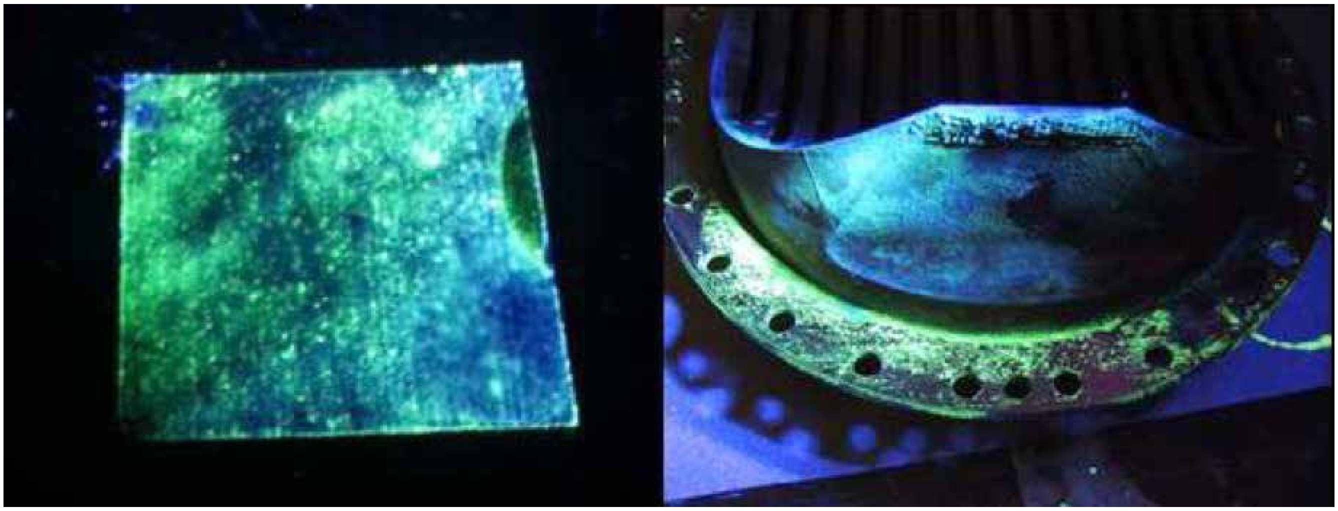

Figure 10-1. Penetrant dye testing of Ti-6Al-4V for a liquid rocket gaseous hydrogen/liquid oxygen injector (left) and a pogo Z-baffle (right) showing high levels of noise due to the surface roughness of the parts (4).

10.2 PROCESS-COMPENSATED RESONANCE TESTING (PCRT)

AM parts can also be inspected using PCRT, which is used in the automotive, aerospace, and power-generation industries. It also has been employed in evaluating in-service engine blades. In PCRT, the AM part is excited at its resonance frequency, and the frequency shift is analyzed to determine whether the part is acceptable. If the mass and the stiffness of the part are known, the process is fast and reliable. However, PCRT is considered a global test and does not provide the location of any defects, thus making it a good gatekeeper test to identify the parts that have no defects or the parts that needed additional inspections.

10.3 X-RAY CT

Due to the need for fast, first-look testing, the most widely used inspection method is X ray CT. The industrial use of CT inspection began in 1972 and has proven its effectiveness by allowing inspectors to detect the exact position of the defect within the body of the part. In a CT scan, a radiation source transmits X-rays through the part to a collector, where the images are compiled and reconstructed by a computer to create a 3D image. CT scans can be a powerful tool, able to reach further into a part than other NDE methods, regardless of the complexity.

The resolution of the CT scan is dependent on the power of the scanner. As the power of the beam increases, the depth of the beam penetration increases, which means that a more powerful beam can scan a denser part. However, low-powered scanners are also useful in the inspection process. Less-dense parts can be inspected with a low-powered scanner with a radiation source having a small emitter size and achieve resolutions down to the submicron scale (6). For AM parts produced through powder beam methods, defects are expected to be on a smaller scale, and therefore submicron detection is a powerful asset.

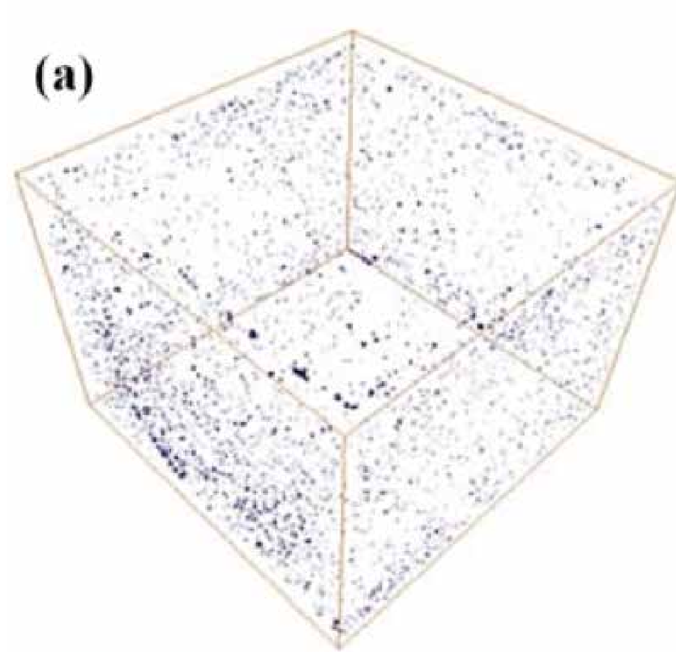

Figure 10-2. 3D view generated by a CT scan of the porosity in a Ti-6Al-4V cube produced by electron beam melting (6).

Figure 10-2 illustrates the power of CT scans. Inspectors can detect and locate all instances of porosity in the test cube. The CT scan is considered the best postproduction inspection method for AM parts up to Group 4 complexities. If microfocused CT scans are employed, even Group 5 complexity parts can be inspected by this method. However, CT scanning equipment is expensive and needs a radiation source to power the beam. CT scans also produce high volumes of data and therefore need intense computing power to return results efficiently. A CT scan of a Group 2 part might take 10 minutes to process a few gigabytes of data using dual, multicore processors, but as the parts become more complex and the number of welds increases, the scan analysis can take hours to perform. If the use of complex AM parts is to become more prevalent, the ability to inspect the parts quickly and accurately is going to be the limiting factor.

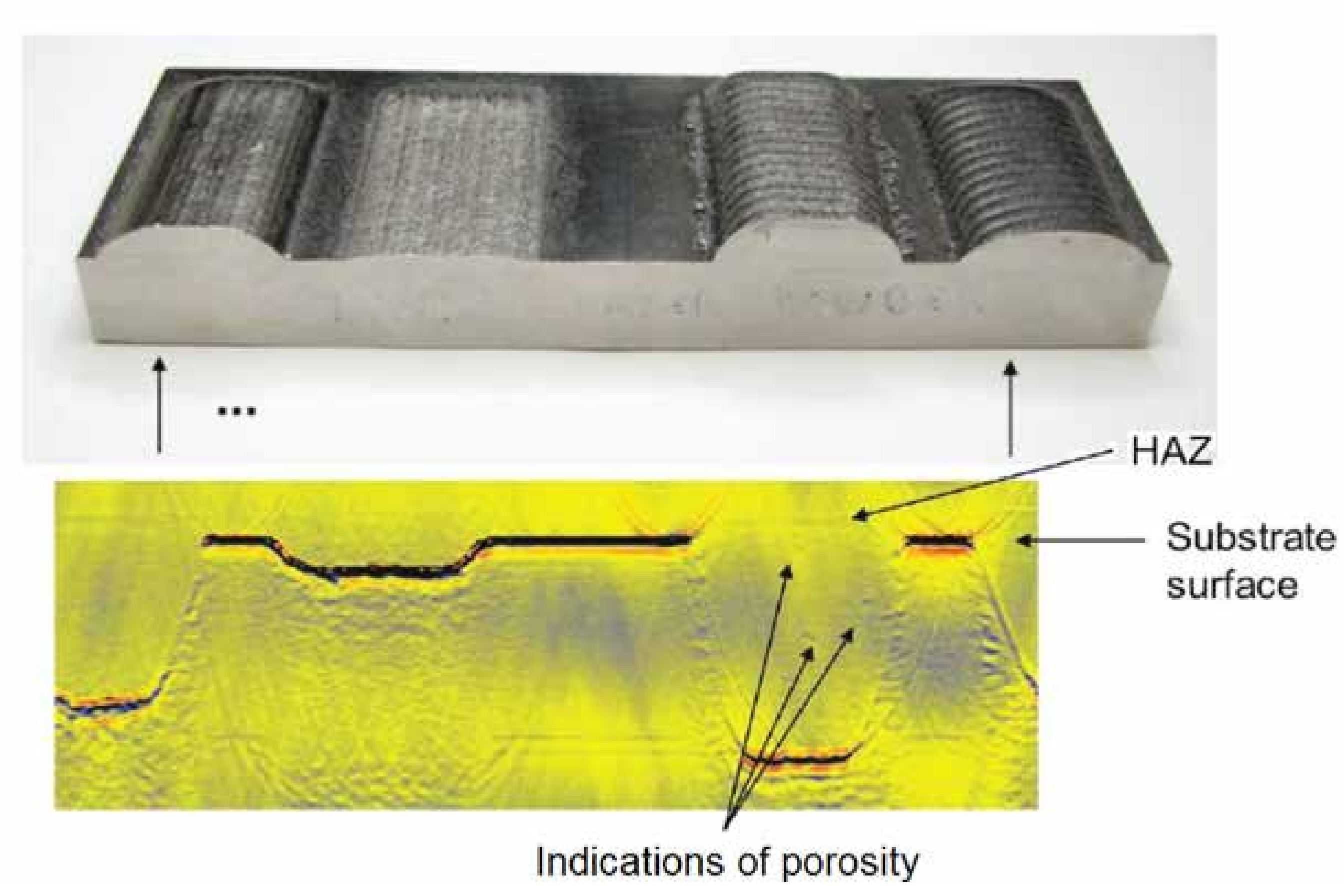

Figure 10-3. Laser ultrasound B-scan of an Inconel 718 coupon showing indications in the build (38).

10.4 LUT

As with its use in-situ monitoring, LUT is also showing promise in postproduction inspections. The benefits of the LUT as opposed to CT devices are the lack of a need for a radiation source and the subsequent infrastructure needed to support it. These benefits make the LUT systems less expensive and therefore more available to manufacturers.

Figure 10-3 shows the work performed by Levesque et al. in applying LUT to postproduction inspection of AM parts. The Inconel piece was scanned from the substrate underside in the span marked by the arrows in (a) of the figure. The scans detected a slight Heat Affected Zone (HAZ) as well as indications of possible discrete porosities in the thicker areas of the part as shown in (b) of the figure. LUT is still being developed but has the potential to work in conjunction with in-situ processes and other postproduction inspection methods to decrease the time needed to inspect complicated AM parts.

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SECTION 11

In-Service Monitoring

A standard practice in most aerospace systems is the incorporation of health and usage monitoring systems (HUMS) to track stresses seen on structures during operations. Given the observed lower fatigue life and yield strength of representative samplings of AM parts, the use of HUMS technology is prudent. While AM parts that undergo extensive post-processing show material properties that are closer to those of traditionally made parts, as more AM parts are installed closer to as-built conditionals, there will be a greater need for in-use monitoring, such as vibration monitoring or strain monitoring, to better understand the life cycle of AM parts. There is no evidence to suggest that AM parts would require different means of in-service monitoring compared to parts already in service, though literature review on this subject yielded no results of any case studies comparing the two. More research in this area is needed before any conclusions can be drawn.

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SECTION 12 Fitness for Service

12.1 ALT

As AM parts are included in aircraft manufacturing, it is necessary to understand how the parts perform during their lifetime of in-use service. Witness specimens may help establish upper bounds on the material property, but in-service monitoring provides a real-time assessment of the part health. However, without an understanding of how stress response of parts changes over the course of a service life, engineers who use in-service monitoring would have no metrics on which to gauge part health. The use of ALT provides this understanding. ALT, unlike single-instance tensile tests, subjects specimens to cyclic stress loading designed to mimic the stresses and loads experienced by the part, including thermal loads. Applying ALT to parts helps engineers and designers better understand any potential failure modes of the part. AM parts provide a new avenue of ALT study.

Figure 12-1 shows that for comparable strain amplitudes, the fatigue lives of the wrought Inconel were two to three times that of the AM counterparts. And while fatigue analysis is a good place to start for understanding the life cycle of AM parts, more research is needed on full ALT of specific AM parts to completely understand their life spans.

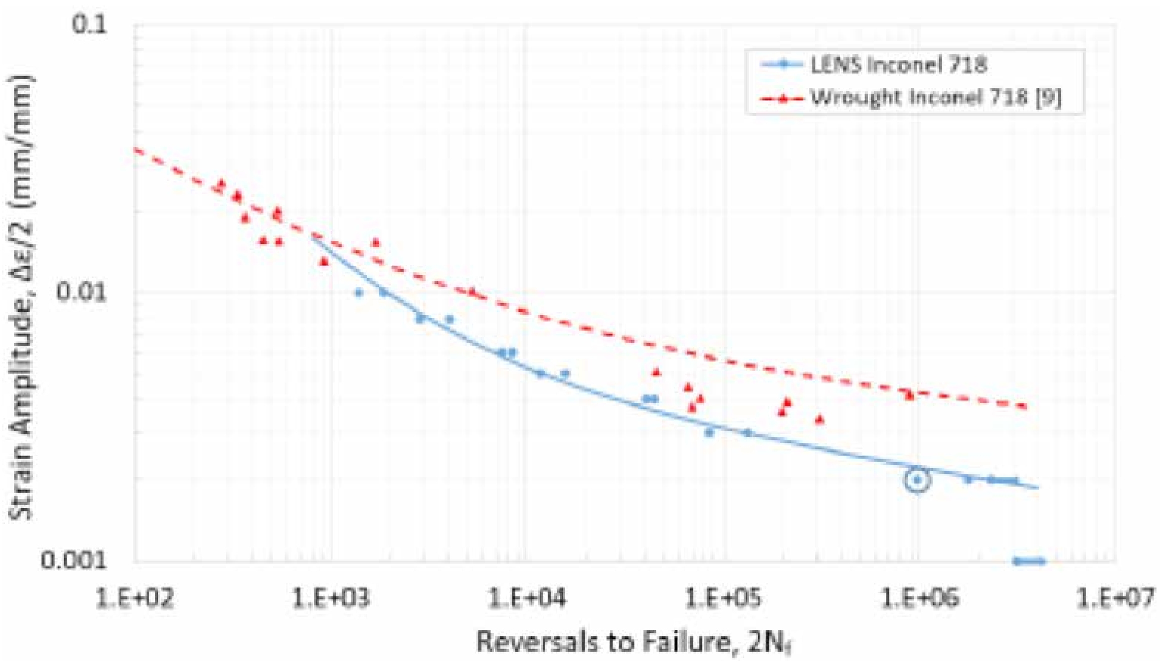

Figure 12-1. Comparison of wrought Inconel 718 and laser-sintered Inconel 718 (39).

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SECTION 13

Certification/Qualification Documentation, Pathways, and Process Standardization

In typical manufacturing scenarios, there is documentation at every step to provide a record of certification. From the supplier's bulk material certifications to the manufacturing certifications, and through the inspector records, parts are supplied with a pedigree that ensures the end user that the part satisfies all requirements. AM parts require a structured documentation process that provides the pedigreed assurances expected by end users, but which allows for ad hoc design changes without requiring a complete recertification process.

NASA created an AM production pathway that allows for certification documentation of AM parts at all stages of the build process, starting in the initial design phase (Figure 13-1). To navigate the process, NASA developed a stepwise plan to provide a pedigree to the part at each critical point in the build process. This plan is discussed in sections 13.1 through 13.5.

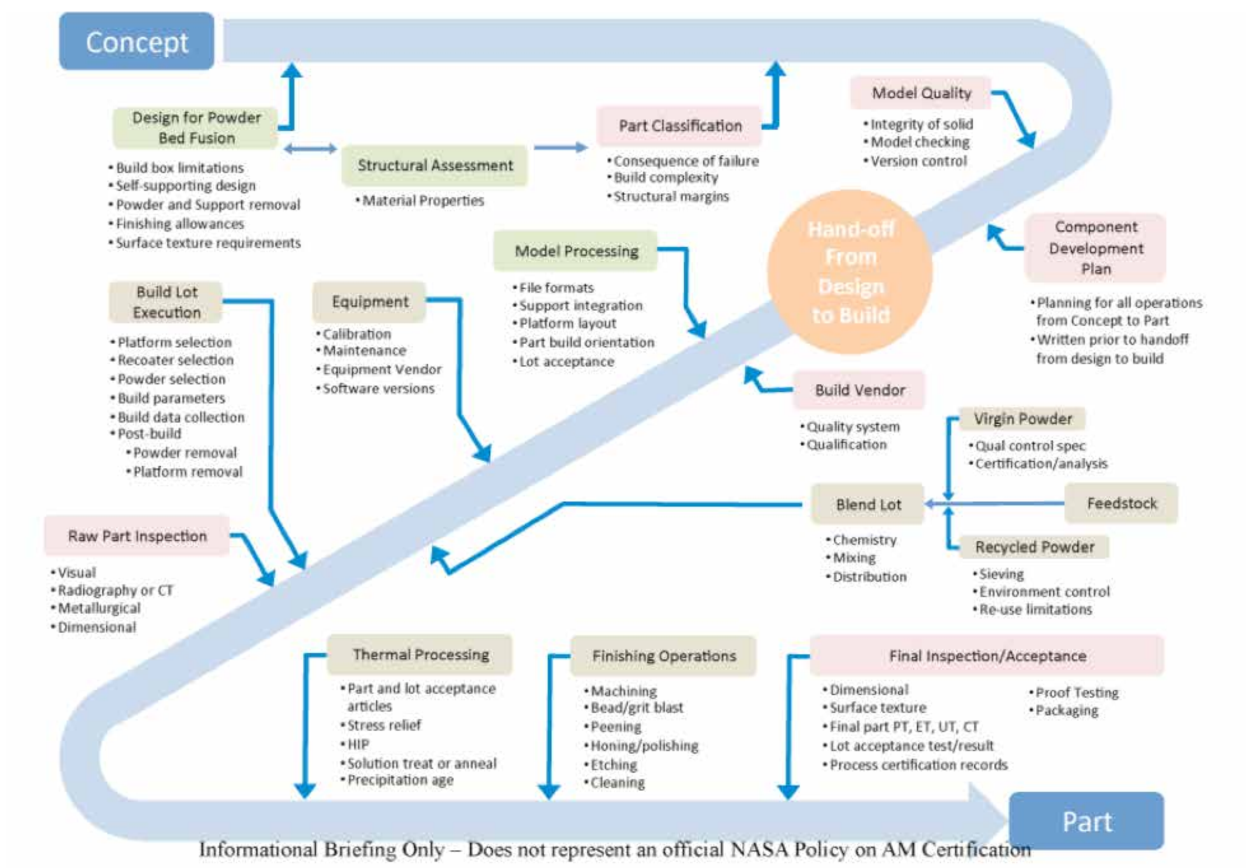

Figure 13-1. The NASA AM Path: From concept to part (40).

13.1 TAILORING

The tailoring step, which starts in the initial design phase, consists of succinct, high-level requirement statements. Inflexible, overly detailed requirements are avoided. This is a higher-level process that is focused on the holistic requirements of the AM parts. As such, a high level of commentary should be included in the documentation, which can help facilitate tailoring the part for individual intent along the pathway.

13.2 CLASSIFICATION

NASA places all AM parts into a risk-based part classification schedule to help customize the requirements according to the certification risk schedule. This risk schedule, presented in Figure 13-2, shows the decision paths to determine the correct risk group for AM parts. The risk groups are divided into three levels:

- Consequence of failure: High/Low (Catastrophic or not)
- Structural margin: High/Low (strength, high cyclic failure, low cyclic failure, fracture)
- AM risk: High/Low (build complexity, access, inspectability)

The part classification schedule then identifies the part risk and provides another documentation point for the ultimate certification document.

13.3 PROCESS DEVELOPMENT PLANS (PDP)

PDPs rely on the tailoring and the classification documentation to document the implementation and interpretation of the requirements for the AM parts. PDPs serve as a companion to the drawing file, provide the configuration controls for the build, and serve as a supplement to any requirements not found within the drawing notes. An example of the content found in the PDP would be the following:

- Part classification and the rationale.
- Witness sampling requirements and the acceptance criteria.
- Test article evaluations and resampling periods.
- Build orientation, platform material, and layout.
- Any special cleaning requirements.
- Repair allowances, inspection requirements, and critical dimensions.

The PDP then becomes the driving document of the build in that all further documentation must meet the standards defined within the PDP.

13.4 PROCESS CONTROLS

There are four defined process control parameters, each requiring its own qualification or certification. These parameters are discussed in sections 13.4.1 through 13.4.4.

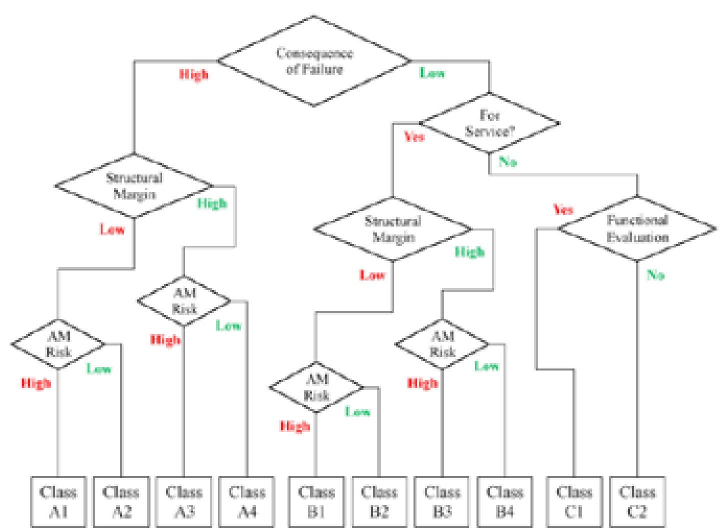

Figure 13-2. The AM certification risk schedule helps sort the parts into risks groups to guide the customization process (40).

13.4.1 Metallurgical Process Control

The Metallurgical Process Control consists of the parameters shown in Table 13-1. When these parameters are finalized, they establish a Qualified Metallurgical Process (QMP), which is then referenced in the part processes.

13.4.2 Part Process Control

The Part Process governs all the operations needed to produce an AM part. It is documented mainly through the drawing and the PDP. The Part Process contains every step of the part production including the QMP, build layout, witness specimens and testing, powder removal, platform removal, thermal processing, final machining operations, surface improvement, inspections, and part acceptance requirements. Once the process is established and approved, it is then considered a Qualified Part Process (QPP).

13.4.3 Equipment Process Control

The Equipment Process Control is being developed. The Equipment Process is designed to provide certification for the AM machines by documenting the calibration and maintenance schedule. However, the scope of the certification is to be determined. More work is needed to account for allowing updates to improve machine performance and keeping the same level of machine control.

Table 13-1. Metallurgical process control parameters

Process Control	Parameters
Feedstock	Chemistry Powder morphology (shape, atomization methods)
Fusion	Machine type Parameters (beam power, speed, layer thickness, hatch width) Chamber atmosphere
Thermal Processing	Microstructure evolution As-built through crystallization Final densification

13.4.4 Vendor Process Control

The Vendor Process may be the easiest process control to implement. Because there are established quality system requirements such as AS9100, there is already a structure in place to assess the quality control of vendors in the market. Vendors must be able to provide their own internal documentation for part designs and any necessary training and skill certifications, as well as be open to auditing and approval systems.

13.4.5 Material Properties Monitoring

Traditionally, designers and engineers have taken an up-front approach to account for all process variability. However, material properties monitoring involves thorough, intelligent witness sampling of each build to create a statistical process control that is combined with the QMP to create a Process Control Reference Distribution (PCRD) of material properties. The PCRD reflects not only the design values but the actual mean and variability in the AM process. The PCRD is continuously updated through witness sampling, and the value distribution of the PCRD is used to determine the acceptance of the AM build. Using the statistics-based PCRD allows for the adoption of new processes without necessarily invalidating previous designs that assume a certain set of material property variability.

The NASA certification pathway guides the development of a comprehensive certification regimen. There are still areas that need further investment, such as unknown failure modes, part cleaning, and NDE of complex AM parts. The Department of Defense has not indicated whether they will adopt the same certification plan or if they will develop their own. However, by setting requirements to allow for innovation while managing risk, the NASA pathway provides a way forward that balances AM opportunities and risks.

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SECTION 14

Conclusions

AM is a dynamic field of study in which new discoveries and new insights are made every day. As AM grows, so does the need for structure. In fact, the biggest hindrance to more widespread adoption of AM parts is the lack of part certifications. NASA has been making strides in developing this process and has created the most comprehensive plan to date for AM part certification. Whether that pathway is valid for the defense industry is unknown at this time, and warrants further discussion. AM part certification still needs studies to identify and close knowledge gaps and discuss acceptable risk allowances. Much like AM, the process for granting part certification will continue to build on itself to produce a final product born of imagination and ingeniousness.

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APPENDIX A

Blockchain

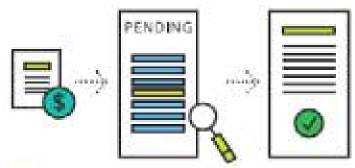
BLOCKCHAIN: HOW IT WORKS (21)

Blockchain allows for the secure management of a shared ledger, where transactions are verified and stored on a network without a governing central authority. Blockchains can come in different configurations, ranging from public, open-source networks to private blockchains that require explicit permission to read or write. Computer science and advanced mathematics (in the form of cryptographic hash functions) are what make blockchains tick, not just enabling transactions but also protecting a blockchain's integrity and anonymity.

1

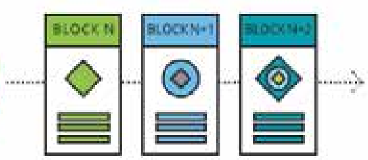
TRANSACTION Two parties exchange data; this could represent money, contracts, deeds, medical records, customer details, or any other asset that can be described in digital form.

2



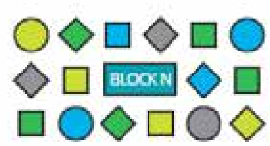
VERIFICATION Depending on the network's parameters, the transaction is either verified instantly or transcribed into a secured record and placed in a queue of pending transactions. In this case, nodes—the computers or servers in the network—determine if the transactions are valid based on a set of rules the network has agreed on.

3



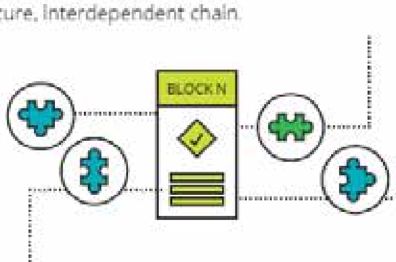
STRUCTURE Each block is identified by a hash, a 256-bit number, created using an algorithm agreed upon by the network. A block contains a header, a reference to the previous block's hash, and a group of transactions. The sequence of linked hashes creates a secure, interdependent chain.

4



VALIDATION Blocks must first be validated to be added to the blockchain. The most accepted form of validation for open-source blockchains is proof of work—the solution to a mathematical puzzle derived from the block's header.

5

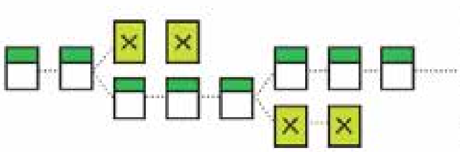


BLOCKCHAIN MINING Miners try to "solve" the block by making incremental changes to one variable until the solution satisfies a network-wide target. This is called "proof of work" because correct answers cannot be falsified; potential solutions must prove that the appropriate level of computing power was drained in solving.

6

THE CHAIN When a block is validated, the miners that solved the puzzle are rewarded and the block is distributed through the network. Each node adds the block to the majority chain, the network's immutable and auditable blockchain.

7



BUILT-IN DEFENSE If a malicious miner tries to submit an altered block to the chain, the hash function of that block, and all following blocks, would change. The other nodes would detect these changes and reject the block from the majority chain, preventing corruption.

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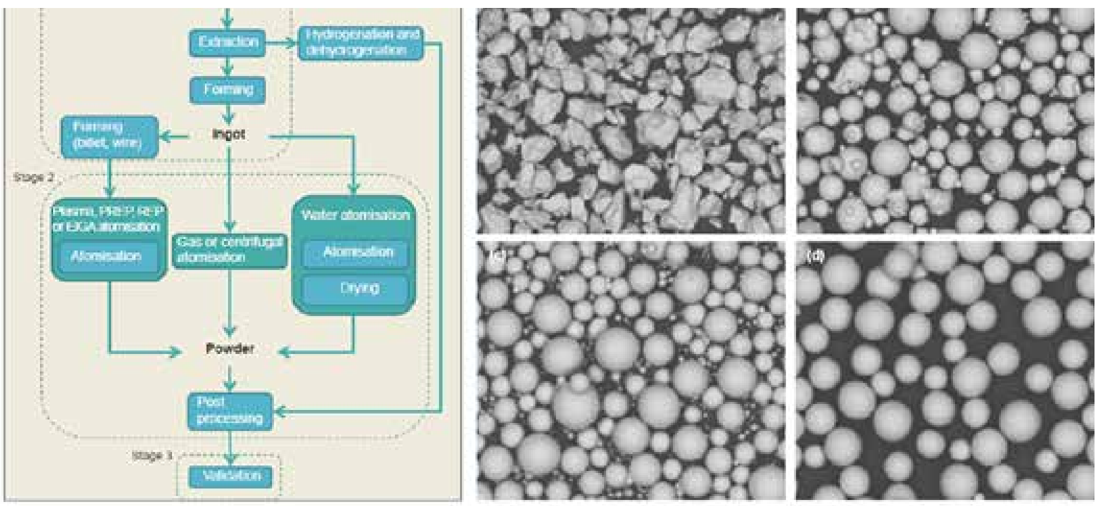
APPENDIX B Processes in Metal Powder Production

Metal powder production first involves mining and extracting the ore to form a pure or alloyed metal product. The second stage is powder production, and the final stage is classification and validation (Figure B-1). Because no powder production route results in a 100% powder yield in the required size fractions, postprocessing is necessary to obtain the well-defined particle size distributions suitable for SLM (~ 15–45 µm) and EBM (~ 45–106 µm) (25).



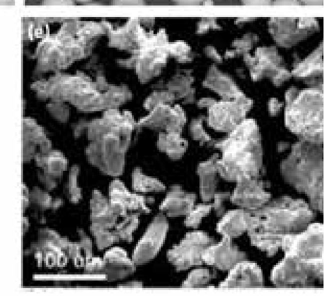


Figure B-1. Process diagram showing AM metal powder production steps (left) and SEM images (right) for Ti-6Al-4V typical particle morphologies obtained using a) the hydrate-dehydrate process, b) gas atomization, c) plasma atomization, and d) the plasma rotating electrode process (25), and e) water atomization (shown here using H13 tool steel) (41)

The metal powder processing methods for AM include the following:

1. Hydride-Dehydride Process
2. Water Atomization
3. Gas Atomization
4. Plasma Atomization (Variations are the Plasma Rotating Electrode Process and Centrifugal Atomization).

Each of these processes is discussed in sections B.1 through B.4, respectively. Images of the particle morphologies characteristic of some of these processes are shown in Figure B-1.

B.1 HYDRIDE-DEHYDRIDE PROCESS

This method does not involve melting the feedstock. Instead, crushing, milling, and screening are used to resize larger pieces of metal feedstock into finer particle sizes. This method relies on the brittle nature of certain metals, such as titanium, when exposed to hydrogen. After the metal is ground, the hydrogen is removed prior to use.

B.2 WATER ATOMIZATION

The water atomization process begins by melting the feedstock alloy, usually in a furnace prior to its transfer to a crucible to regulate the flow rate of the melt into the atomizer. The melt enters the atomizer from above and free falls through the chamber. Water jets symmetrically positioned around the stream atomize and solidify the particles, which then collect at the bottom of the chamber. Additional processing is required to dry the powder, which has an irregular morphology. This method is typically used for iron and steel powders and is a source for press-and-sinter industries rather than specialized AM.

B.3 GAS ATOMIZATION

Gas atomization mimics water atomization, but uses gas instead of water. Air can be used, but an inert gas is preferred to reduce the risk of oxidization. This method is often used for aerospace industry material, resulting in the use of vacuum induction melting (VIM) furnaces to control interstitial elements during preparation of the raw material. The process to fabricate the powder is the same as that for water atomization. However, when the high-pressure jets are used to cool the melt, the lower heat capacity of the gas causes the powder to have an increased solidification time, resulting in powder that is more spherical. This method is commonly used when processing reactive material such as Ti-6Al-4V.

B.4 PLASMA ATOMIZATION

Plasma atomization produces highly spherical particles. The process is also similar to water and gas atomization, but the atomization is produced by simultaneously melting the raw material and atomizing it using plasma torches and gas jets. Variations on this method include a plasma rotating electrode process and centrifugal atomization.

A summary of the particle sizes, advantages, disadvantages, and most common uses for the metal powder manufacturing methods is shown in Table B-1.

Table B-1. Summary of Metal Powder Characteristics Categorized by Manufacturing Process as Described by Dawes et al. (25)

Manufacturing Process	Particle size (µm)	Advantages	Disadvantages	Common uses
Water Atomization	0–500	High throughput, range of particle sizes, and only requires feedstock in ingot form	Postprocessing required to remove water, irregular particle morphology, satellites present, wide particle size distribution (PSD), low powder yield between 20–150 µm	Nonreactive metals
Gas Atomization (including Electrode Induction Gas Melting (EIGA))	0–500	Wide range of alloys available, suitable for reactive alloys, only requires feedstock in ingot form, high throughput, large range of particle sizes, use of EIGA allows for reactive powders to be processed, spherical particles produced	Satellites present, wide PSD, l ow powder yield between 20–150 µm	Nickel, cobalt, iron, titanium (EIGA), aluminum
Plasma Atomization	0–200	Extremely spherical particles	Requires feedstock to either be in wire or powder form, high cost	Titanium (Ti-6Al-4V most common)
Plasma Rotating Electrode Process	0–100	High-purity powders and highly spherical powder	Low productivity and high cost	Titanium exotics
Centrifugal Atomization	0–600	Wide range of particle sizes with very narrow PSD	Difficult to make extremely fine powder unless very high speed can be achieved	Solder pastes, zinc of alkaline batteries, titanium and steel shot
Hydride–Dehydride Process	45–500	Low-cost option	Irregular particle morphology, high interstitial content (hydrogen, oxygen)	Ti-6Al-4V Limited to brittle metals

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