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TUTORIAL

Development and qualification of additively manufactured parts for space

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Abstract. Additive manufacturing fabricates the desired final part by depositing and fusing layer upon layer of the source material and offers both benefits and disadvantages compared to traditional manufacturing. New engineering designs are possible in which a single optimized part with topology can replace several traditional parts. The complex physics of metal deposition leads to variations in quality and to new flaws and residual stresses not seen in traditional manufacturing. Additive manufacturing currently has gaps in knowledge. Mission assurance for the space industry will require: qualification and certification standards; sharing of data in handbooks; predictive models relating processing, microstructure and properties; and development of closed loop process control and nondestructive evaluation to reduce variability. A tailored qualification strategy for additive manufacturing accounts for the manufacturing readiness level, mission risk class, and the knowledge of material properties. Three case studies are presented on the development and qualification of AM for the space industry with the common goals of maturing the technology and improving its reliability.
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1 Introduction

Additive manufacturing (AM) fabricates the desired final part in a single step directly from the input digital computer-aided design (CAD) file by depositing and fusing layer upon layer of the source material with very little waste. An increasingly popular term for AM is "3-D printing." In contrast, for thousands of years, traditional machining (referred to as subtractive manufacturing) removes the material in several steps, which is often laborious and can generate large amounts of scrap chips and turnings. For the aerospace industry (which typically must rely upon costly exotic alloys), AM offers the key advantage of the "fly-to-buy ratio," which is the amount of raw material used to manufacture the desired finished part with the associated scrap. As a compelling example, each F-22 fighter plane started with 50 tons of expensive Ti-6Al-4V that were machined through conventional metal cutting to a net of 5 tons of final parts with 45 tons of waste chips,[1] giving a "fly-to-buy" ratio of 10%.

An important hallmark for AM is that it can make virtually any arbitrary shape or topology without the great cost, time, and penalty to make a complicated part by subtractive manufacturing. For AM, complexity is free because production cost is set primarily by the part's simple mass, which controls the production time much more strongly than the part's complexity. A complex part with intricate internal features may cost no more through AM than a simple part of similar mass. For AM, design engineering is liberated, and it becomes possible to design for build rather than design for manufacturing under the rule that "what you want is what you build" for AM, rather than "what you build is what you get" for traditional manufacturing.[2] AM, therefore, allows shapes and topologies not possible with traditional manufacturing.

AM is an example of a near net shape process in which the initially produced (gross) item is very close in dimensions to the final (net) shape. Other traditional near net shape processes (such as injection molding and die casting) lack the flexibility of AM and traditionally require machining a custom mold to make a specific one-of-kind part, whereas AM can make any arbitrary part unconstrained by any need for a pre-existing mold. Interestingly, one important application for AM is to actually make the intricate molds and dies for subsequent high-volume molding and casting because AM eliminates the great expense and long lead time of a highly skilled tool and die maker.[2]

2 Advantages of Additive Manufacturing

Traditional manufacturing specialized for high production rates (such as casting and molding) may always be more economical than AM. AM can be cheaper and faster for complex low volume parts that otherwise require intricate machining. AM may be particularly well suited for the space industry's low production volumes of satellites and launch vehicles. Elsewhere in the aerospace industry, General Electric is committed to implement AM for an annual production of 40,000 jet engine T-25 fuel nozzles because AM offers the potential for dramatic cost savings, which illustrates a cost-effective strategy at surprisingly high production rates.

It is currently common for design engineers to first use AM to make simple clones of existing parts. However, there is a revolutionary potential to replace several existing parts with a single optimal part with topology, which offers the prospect of cost savings in production and assembly. By reducing part count, there is a corollary revolutionary potential to eliminate the welds, bonds, and joints otherwise ordinarily needed with traditional manufacturing. In the case of the fuel nozzle, the cost savings are obtained by reducing the

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part count from 21 (for conventional manufacturing) to 1 (for AM) and eliminating the associated welding operations, along with the associated touch labor.[2,3]

As an added benefit, a law of failure analysis (known as Pelloux's law) states that "It always breaks where it's welded."[4] By eliminating welds and joints, it will become possible to eliminate an entire large class of failure mechanisms, which will improve reliability. Eliminating welds will also eliminate the expense of their specialized nondestructive evaluation (NDE).

3 AM for Metals: Key Concepts of the Production Process

The different AM production processes for metals are categorized according to (first) the material feed type and (second) the heat source used for fusion. Broadly, the two material feeds are either powder bed or beam deposition, and the three heat sources are either laser beam, electron beam, or (less commonly) plasma arc.

A traditional metal alloy with good weldability or good castability is a candidate for AM, and alloys that crack under high solidification rates are not good candidates.[2] Common AM metals include Ti alloys (such as Ti-6Al-4V), Al alloys (such as AlSi10Mg), Ni superalloys (such as Inconel 625 and Inconel 718), hot work tool steels (such as H13), stainless steels (such as 17-4 PH), and refractories (such as CoCr).[5]

3.1 *Key Concept of the Powder Bed Process*

In the powder bed technique, metal powder with a typical mean diameter of 50 μm is first spread to give a uniform layer with a typical thickness of 100 μm. Second, the heat source traces out and fuses the shape of the desired part in the layer. Figure 1 shows the details of the powder bed process. On the left-hand side, the piston in the powder supply is raised by the desired layer thickness (say, 100 μm). A roller or doctor blade then uniformly spreads the powder across the powder bed on the right-hand side. After the surface layer is fused to the solid part that is being formed beneath it, the piston in the powder bed lowers the part by the desired layer thickness. The process is then repeated from left to right by raising and lowering the two pistons in turn until the part is finished. In this way, a part height of 50 cm is built successively from thousands of individual layers.

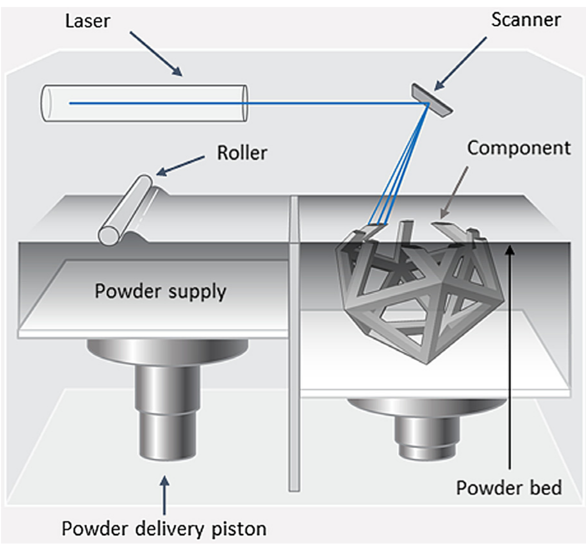

Fig. 1 Illustration of the powder bed process with the powder supply on the left-hand side and the powder bed on the right-hand side.

Europe leads in the powder bed process. Prominent examples of the powder bed with laser heating are EOS (Germany), Concept Laser (Germany) (Concept Laser was acquired by GE in 2016), Phenix (France) [Phenix was acquired by 3D Systems (South Carolina) in 2013], and Renishaw (Great Britain). The powder bed with electron beam heating is manufactured only by Arcam (Sweden) (Arcam was acquired by GE in 2017). The laser beam is typically steered by galvanometer mirror scanners and the electron beam by electromagnetic deflection coils. Scan speeds are very fast for the electromagnetic coils for the electron beam but are limited by the galvanometer's inertia for the laser beam. Representative scan speeds are 1000 m/s for electron beam heating[6] and 7 m/s for laser beam heating.[7] Consequently, deposition rates are faster for electron beam than for laser beam heating. As another difference, surface finish and feature resolution are generally worse for electron beam than for laser beam heating.[5] Because the electron beam is more efficient heating, its energy costs are lower than for laser beam heating.

3.2 *Key Concepts of the Beam Deposition Process*

In the competing beam deposition technique, the source metal is fed directly to the heat source in a single step, in contrast to the two separate steps of the powder bed technique. The source metal can be supplied as a powder though a nozzle or as a wire from a reel. America leads the beam deposition process. Optomec (New Mexico), RPM (South Dakota), and the POM division of DM3D (Michigan) use pressurized flow of an inert gas to deposit metal powder through multiple nozzles directly to the laser beam. Sciaky (Chicago, Illinois) feeds metal wire to the electron beam. Schematic illustrations of the various beam deposition processes can be found in the literature.[5]

The powder beam and beam deposition techniques have other differences. Powder bed has a single vertical build direction, whereas beam deposition can employ five-axis articulated wrists that can build the part free form in three-dimensional (3-D) space, thereby offering greater versatility and freedom to build complicated shapes. Beam deposition also provides faster build rates, namely 5 kg/h for the Sciaky process versus 0.1 to 0.2 kg/h for the powder bed. Beam deposition provides larger build volumes,[2] namely 1.2 m × 1.2 m × 5.8 m for the Sciaky process and 1.5 m × 1.5 m × 2.1 m for the RPM process versus 0.4 m × 0.5 m × 0.8 m for the Concept Laser process. As a limitation of beam deposition, processes with larger build volumes and faster build rates have worse accuracy and feature resolution.[2] An application for the nozzle fed beam deposition is the repair and refurbishment of worn metal parts for reuse; the most prominent example is the repair of the outer radial edge of Ni alloy turbine blades that naturally erodes during engine use. The Sciaky process also makes possible *in situ* repair.

3.3 *AM for Metals: Key Concepts of the Physics*

A heat source, such as an electron beam or laser beam, fuses the metal. For both forms of heating, the interaction of the electrons or photons with the metal surface is a complex physical phenomenon highly coupled to competing effects that act against the heating.

The fusion technique can be either solid state sintering or liquid melting. Sintering is driven thermodynamically by the reduction in surface area and the accompanying surface energy when (in the case of powder) loose particles are joined. Sintering is a diffusion process that occurs at temperatures between 0.5 and 1.0 of the homologous melting point. Liquid melting is driven by the mutual wetting and attraction between the molten metal, either powder or wire fed. Liquid melting naturally occurs at or above the melting point.

Fusion by sintering and liquid melting can occur simultaneously. In liquid melting, gradients in temperature can inadvertently allow unintended sintering of loose powder at the part's perimeter, which causes a porous sintered skin to grow around the fused part.[2] AM production machines for metals use liquid melting, including those that may retain the word sintering in their names from an earlier heritage process, such as selective laser sintering and direct metal laser sintering.[2]

For the electron beam approach, electrons are produced at an energized filament, accelerated by an anode to a high velocity (~0.5 the speed of light) and focused to a spot by electromagnetic coils acting as lenses.[8] The heated spot is commonly called the melt pool. At the surface of the metal that is to be fused, the electrons are absorbed, and their kinetic energy is converted to heat. Because the absorbed electrons must be conducted away, electron beam heating can only be used on conductors (such as metals) rather than insulators (such as polymers or ceramics). Because conduction of the electrons requires a finite time, there is competing build-up of net negative electric charge in the heated spot.[9] The built-up charge repels the incoming electrons, which diffuses and coarsens the electron beam and inadvertently increases the spot diameter, leading to poorer surface finish and feature resolution than for laser beam heating, which does not display these particular effects. The build-up of charge can also expel and eject particles from the powder bed, with the effect greater for finer particles, leading to unwanted defects in the fused layer.

For the laser beam approach, the absorption of photons heats the surface of the metal. However, absorption is accompanied by competing reflection and emittance of photons, which lessens the efficiency of laser beam heating. The rates of absorption, reflection, and emittance naturally change with time as the initially cold solid particles heat up, reduce their surface area and melt, all of which complicate the evolution of the temperature in the laser spot.

In addition, residual stress in the metal parts increases with the length and size of the heating spot as one end of the heating spot cools and freezes while another more distant end is heated and still molten. A common strategy to reduce residual stress is to heat the surface of the metal with small (say, 1 mm square) spots that are placed in a random checkerboard unaligned from one build layer to the next rather than to heat a single continuous long strip of metal. Each heating spot is quickly turned on and off in a transient mode rather than settling into a steady-state mode.

4 Variability of AM for Metals

Both the complex physics and the transient nature of heating lead to variations in fusion during the build, which are responsible for part variability. In addition, the leading powder bed production machines currently operate in simple open-loop control without a process sensor rather than closed-loop feedback control with a process sensor. Open-loop control of a transient process is naturally very difficult,[10] and poor control of the fusion process is ultimately responsible for part variability.[11] As a result, it is widely recognized that variability is displayed by a single production machine,[12] across similar production machines (such as two identical machines from the same manufacturer)[13] and across different types of production machines (such as laser beam-based and electron beam-based machines). Interestingly, two consecutive runs on the same production machine will display build-to-build variability.[14]

The research frontier for the field is the development of process sensors with feedback control to make AM repeatable and consistent. The sensors will measure the temperature, diameter, and temperature gradient of the melt pool. By controlling the melt pool directly, the fusion process can be controlled in turn. Optomec and POM actually pioneered closed-loop feedback control with a process sensor in the early 2000's for the beam deposition processes, and other manufacturers are now following for the powder bed processes. The development of feedback control for AM is an active area of research at original equipment manufacturers, contractors, universities, and national laboratories.

5 Mission Assurance Considerations for AM

AM is based upon complex physical phenomena that are currently poorly controlled by the common open-loop architecture of production machines, which leads to part variability. As a result, AM has new flaws that differ from traditional parts, such as:

(1) lack of fusion;
(2) interlayer lamination debonds that have the stress intensity of a sharp crack;
(3) gradients in consolidation;
(4) powder trapped in a part's interior;
(5) powder shorting in the powder bed;
(6) and voids and porosity that may be isolated or interconnected.

As with casting and welding, the melting and rapid cooling can lead to new residual stresses unseen in conventional machining of wrought stock. The residual stress can warp the part, and the tensile residual stress can inadvertently promote the part's failure during assembly or service. Furthermore, the porous sintered skin presents a risk of foreign object debris (FOD), and the rougher surface finish worsens the AM part's fatigue properties.[15] All of these factors (flaws, residual stress, and surface finish) are the sources of the variability observed in AM.

At this early stage in its development, AM has foundational knowledge gaps, such as:

(1) The effect of powder morphology (i.e., spherical versus blocky shape) and particle size distribution on

flow during powder bed lay down and subsequent densification during fusion;

(2) The characteristic defects of AM, and the NDE needed to find them, as well as the probability of detection for NDE of AM;

(3) The failure modes of AM have not yet been uncovered;

(4) The metal may not thermally process during heat treatment the same way as conventional wrought material;

(5) The debits on fatigue performance from the surface finish of AM parts;

(6) Closed-loop process control is lacking.

The inspection needs are not yet fully defined because the types of defects possible in the AM process are not fully understood and the possible failure modes during service are not known. A catalog of AM defects is needed for both inherent and rogue defect populations. Inspection standards, inspection capabilities, and acceptance criteria are not mature, although a draft ASTM standard is being developed.[16] The largest risks to mission assurance are the defects' impact on material behavior.

The powder bed process only makes sense economically if the source powder is recycled and reused. Part variability due to powder reuse is not known and requires further investigation before defining limits and specifications.[14] During reuse, the powder can inadvertently pick up unwanted oxygen or nitrogen or volatize alloying agents (such as the Al in Ti-6Al-4V), which will alter the alloy chemistry. For Ti-6Al-4V powder, the oxygen content increased from 0.08 to 0.17 wt. % and the Al content decreased from 6.47 to 6.36 wt. % after 11 reuses. In the printed Ti-6Al-4V samples, the Al content was 0.3 to 0.5 wt. % lower than the run's source powder because Al also volatizes during the high temperature fusion process.[17] The reused powder can also lose the small diameter fine particles and accumulate large diameter agglomerates.

The manufacturing instructions for the AM production machine, which is known as computer-aided manufacturing (CAM), are generated from the CAD model of the AM part, and the translation from CAD to CAM requires additional guidance. Historically, industry used two-dimensional print checkers, but no corresponding role exists for digital CAD files. An example of a printing error is incompatible surfaces constructed from the spline representation of CAD surfaces.

Identified risks for AM include:

(1) process sensitivity with unknown failure modes;

(2) lack of governing requirements and standards;

(3) AM is too easy and cheap, which makes it ubiquitous and nonrigorous;

(4) rapidly evolving pace of the technology, which makes it difficult to establish and lock a qualified process.[13]

Modern metallurgy is guided by the fundamental principle that processing controls microstructure, which in turn controls the metal's properties (whether mechanical, electrical, thermal, or magnetic). As an example, heat treating of metals offers very fine control of both microstructure and properties and was developed in practice thousands of years before any theory of atoms and microstructure.

The heat treating practices for AM metals have not been established because the relationship between processing, microstructure, and properties is still being developed. AM metals may require new heat treating practices. One example is an Al-10Si-0.5Mg aluminum alloy used for AM that is based upon a traditional casting alloy. Although the heat treating practice for the very similar casting alloy has been published, the AM aluminum does not respond the same way to the standard T6 temper. Research is on-going to develop the modified heat treating practices for this AM aluminum.[18]

A leading approach to discover the relationship between processing, microstructure, and properties for AM metals is the process map (sometimes termed solidification map).[2] Physics-based finite element analysis of the AM fusion process can predict the temperatures and cooling rates of the melt pool for a set of process parameters (such as, laser power, scan speed, and scan spacing). The heat transfer analysis uses the nonlinear thermal properties of the metal (such as, thermal conductivity, diffusivity, specific heat, and heat of fusion) and the inert environment, which provides either a radiative (in the case of vacuum) or convective boundary condition (in the case of inert gas). The process map approach is potentially faster and more productive than the trial-and-error approach otherwise used to select the process parameters.

The microstructural development and evolution during solidification can be calculated by using independently characterized metallurgical thermodynamics and kinetics. The process map allows the selection of process parameters that yield a desired microstructure, such as columnar, equiaxed, or even single crystal, and also allows tailoring of the grain size. In addition, the physics-based analysis can predict the residual stress upon cool down and offer processing strategies to reduce or eliminate the residual stress.[11]

6 AM Part Design

The part should be designed to take advantage of AM, which should not be used if the design is easy to manufacture conventionally. The AM part should offer cost and/or schedule savings compared to conventional manufacturing for the production run. For powder bed AM, print time is slow. For beam deposition AM, dimensional tolerance is coarse. For all AM, surface finishing is expensive. The part must fit in the production machine's build volume. Material properties are needed for relevant environments, including static, dynamic, acoustic, and fatigue loading, which is an added expense and need for schedule.

Good AM candidate designs have weight reduction holes and pockets that otherwise require machining in a conventional part. In addition, they have reduced part count, weld count, and touch labor, or are not possible with other conventional fabrication methods. A complex part may not be attractive if it requires the same number of setups to machine critical features as a conventional part. An excellent candidate for AM requires less machining.

The AM design controls the part and includes:

(1) geometry definitions via drawings;

(2) identifying dimensional requirements and critical dimensions;
(3) material and process specifications and controls;
(4) witness sampling requirements and acceptance criteria for the process;
(5) accounting for the effects of build orientation, build platform material, and layout;
(6) requirements for inspection and flaw detection by NDE;
(7) requirements for cleanliness and FOD removal;
(8) required controls for handling, storage, and environmental protection;
(9) first article evaluation and resampling period, design qualification testing, and part acceptance testing;
(10) and assessments of part performance, both analytical and experimental.

For the space industry, the requirements for AM can be tailored based upon risk and desired reliability. Primary load bearing structure for which failure is catastrophic to mission or human life would receive the most stringent requirements and would require the highest structural margins. Redundant structure whose failure can be tolerated or secondary structure would have lower requirements and margins. In addition, the nature of the AM part can be judged to be high or low risk depending upon its intrinsic characteristics, such as build complexity and access for inspectability after build, both of which are potentially very different from traditionally manufactured parts.

7 Tailored Approach to Qualify AM for the Space Industry

Figure 2 is a proposed top-level flow diagram for the development of AM for nonmanned space programs.[19] Preliminary part design starts after the flow-down and derivation of design requirements, which arise from the program's mission risk class (A, B, C, or D). Mission risk class A is an extremely critical mission with minimally practical risk and an operational payload. Mission risk class B is a critical mission with low risk and an operational or demonstrator payload. Mission risk C is not critical and accepts moderate risk with an exploratory or experimental payload. Mission risk class D is not critical and accepts higher risk with an experimental payload.

The mission risk class and the AM process' manufacturing readiness level (MRL) and rigor of the material properties together lead to the classification of the part as AM category I, II, III, or IV in block 1 of the flow diagram. AM is ranked from most mature, category 1, to least mature, category 4. Table 1 shows how the mission risk class, MRL, and rigor of material properties define the AM categories. MRL 4-6 is the capability to produce a prototype in a laboratory or production environment. MRL 7-8 is the capability to produce a system in a production or pilot line environment. MRL 9-10 is the capability to begin or demonstrate full rate production. Material properties with high rigor satisfy the requirements of the metallic materials properties development and standardization[20] (MMPDS) and are based upon extensive testing of the full suite of material properties with a sound statistical basis. Material properties with low rigor do not satisfy the MMPDS approach.

In Table 1, the loss of a mission critical part leads to direct loss of the primary mission because the part is a single point failure. The loss of a nonmission critical part does not lead to loss of the mission, either because the part has redundancy or represents a secondary function. Proof testing is the mitigation for low manufacturing maturity and to demonstrate that design allowables are met for material properties with low rigor. Once an AM part category is defined, an assessment should be performed to quantify the risk of AM part use in the mission.

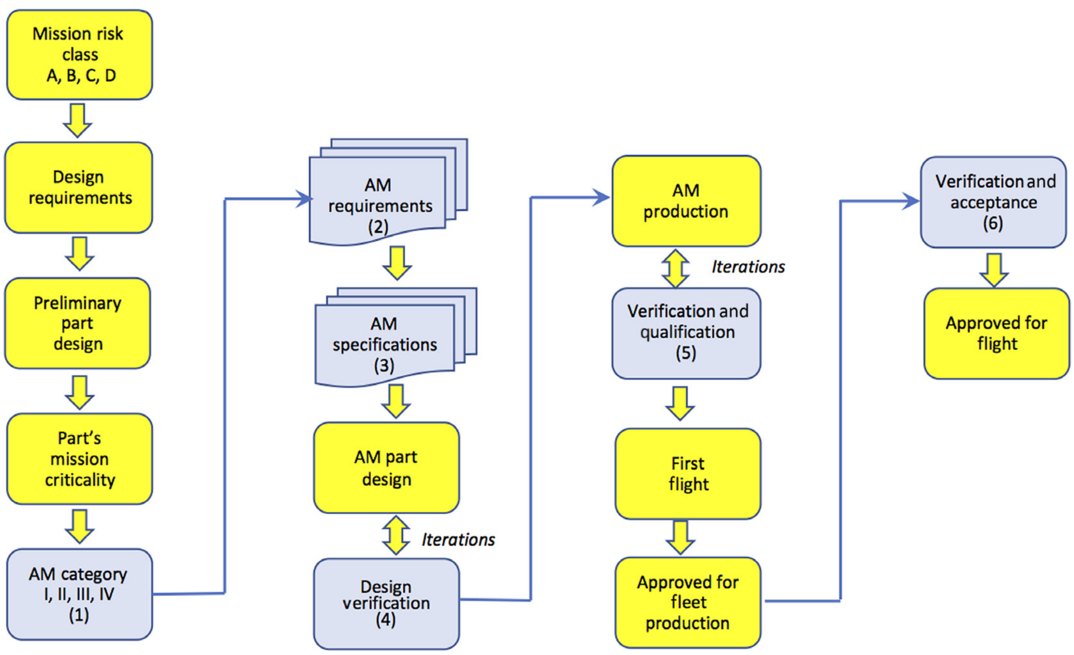

Fig. 2 AM part development program. Boxes filled in blue and numbered 1 to 6 indicate areas with specific requirements and specifications flowing down from the part's classification as AM categories I, II, III, or IV.

Table 1 Definition and usage guidance for AM categories I, II, III, and IV.

Manufacturing maturity level	Material properties rigorously characterized under MMPDS	Material properties not rigorously characterized under MMPDS
High maturity (MRL 9-10)	Category I: Acceptable on all mission risk classes (A–D) for both mission critical and nonmission critical parts	Category II: Requires proof testing on mission risk classes A and B for mission critical parts
		Acceptable as-is on mission risk classes A and B for nonmission critical parts
		Acceptable as-is on mission risk classes C and D for all parts
Medium maturity (MRL 7-8)	Category III: Requires proof testing on mission risk classes A and B for mission critical parts	
	Acceptable as-is on mission risk classes A and B for nonmission critical parts	
	Acceptable as-is on mission risk classes C and D for all parts	
Low maturity (MRL 4-6)	Category IV: Not acceptable on mission risk classes A, B, or C for mission critical parts	
	Requires proof testing on mission risk class A or B for nonmission critical parts	
	Acceptable as-is on mission risk class C for nonmission critical parts	
	Not acceptable on mission risk class D for safety critical parts	
	Acceptable as-is on mission risk class D for nonsafety critical parts	

Blocks 2 to 6 of the flow diagram define, use, and verify the associated AM requirements. The part's AM category carries with it the corresponding AM requirements (block 2) and specifications (block 3). The requirements and specifications are tailored to satisfy specific program requirements, and compliance is tracked. Table 2 lists the structural requirements for National Security Space (NSS) missions by mission risk class.[21]

The detailed design of the AM part is ready to proceed under the complete set of tailored design requirements. Block 4 of Fig. 2 is an analysis to verify that the design satisfies specified requirements and the part can perform its designated functions. Structural and stress analyses are part of this process, using both interim and final geometric configurations, as well as the AM requirements and material properties. When necessary, allowance should be made for any expected variability in the AM material properties and manufacturing procedures. The verification analysis may impact the final AM part design and, as a result, this step is likely to be an iterative process.

The manufacturing of the AM part is the next step in this development process. Because AM manufacturing technology is still developing, careful monitoring of the process and definition of the material properties should be considered necessary. Block 5 of Fig. 2 is the verification of the AM parts, followed by the qualification process that entails analyses, testing, and inspections, as well as programmatic reviews and authorizations to proceed to this phase of the program. This is potentially another iterative step where adjustments to the manufacturing process, material properties verification, etc., might be necessary to complete part qualification.

In the space industry, and especially for the development of launch vehicles, it is common to require a first flight as final demonstration of system performance and functionality before the fleet production is undertaken. Spacecraft systems are typically acquired in small blocks or as single units, and the "first flight" item may take the form of an engineering model that is subjected to various flight environments in the laboratory to verify performance requirements.

Once the fleet production is approved, flight units are manufactured. However, flight approval requires that flight units be verified and subjected to acceptance screening according to program requirements. This step is shown in block 6. Acceptance screening may require extensive proof testing of AM hardware in addition to ongoing monitoring of the manufacturing process and tracking of material properties until the AM process matures.

8 Case Studies to Develop and Qualify AM for the Space Industry

Three case studies are presented on the development and qualification of AM for the space industry. All three examples (NASA Marshall Space Flight Center, USAF Space and Missile Center, and the Defense Production Act Title III Program) share the common goals of reducing variability for AM, making AM repeatable and reliable, and maturing the AM process.

8.1 *NASA Standards for AM*

NASA's Marshall Space Flight Center (MSFC) has published two standards for the laser powder bed production of metals by AM.[22,23] The standards are specialized for human space flight, for which reliability and risk reduction are paramount. The standards establish controls for the metallurgical fusion process, part process, equipment process, and vendor process.

The metallurgical process control is composed of:

(1) Feed stock controls on metal chemistry, powder morphology, particle size distribution, particle shape, and

Table 2 Manufacturing, process, quality assurance, and testing requirements by mission risk class.

Requirement	Mission risk class A	Mission risk class B	Mission risk class C	Mission risk class D
Eng. develop. units	Common, widespread, and expected	Common but limited	Unusual	No
Manufacturing process	Contractor best practices	Contractor best practices	Contractor best practices	Contractor best practices
Parts screening	Part level	Part level	System level	System level
Material	Heritage or test qualification	Heritage or test qualification	Heritage or test/analysis qualification	PMP Control Board approval
Material approval	Formal	Formal	Informal	Informal
Reliability life testing	Qualification margins to life req.	Protoflight margins to life req.	Acceptance margins to life req.	Recommended for unknown qualification margins on new hardware
Reliability testing	Subassembly-/part-level qualification and assembly-level ESS on volume units	Subassembly-/part-level qualification and assembly-level ESS on volume units	Selected part level based upon critical mission reliability. Reduced ESS on volume units. Use of data more acceptable, as well as reduced margins	Qualification limited to safety-critical items only
Environmental stress screening (ESS)	Required for NSS programs. Recommended for volume units	Required for NSS programs. Recommended for volume units	Recommended for volume units. Reduced screening may be used	Not required
Process verification and capability	Quality assurance (QA) shall certify the qualification of machines, equipment, and procedures used in complex, critical operation. Validation prior to production shall include measurements on first article. For new processes, conduct process FMEAs. Customer may be included in verification process	Same as mission risk class A	Same as mission risk class A, minus customer involvement, and process FMEAs normally not performed	N/A

powder production method. The latter is important because the popular gas atomization method produces particles with hollow centers, which cannot be removed by subsequent heat treating or hot isostatic pressing (HIP).

(2) Fusion process controls for machine type, fusion parameters (such as laser power, electron beam power, rastering speed, layer thickness, and hatching width), and chamber atmosphere. These process parameters are specified for an individual production machine identified by serial number because variations are observed in consecutive runs on the same machine, as well as from machine-to-machine and also across machine types.

(3) Thermal process controls, which govern the microstructural evolution, the as-built recrystallization, and the final densification. The thermal process should not yield cracks between layers that are healed by subsequent HIP. Further, no remnant weld microstructure is allowed. HIP is always required to remove residual porosity.

After a metallurgical process is qualified, it is locked down and finalized, and changes are not allowed.

The part process control governs all operations needed to produce a given part. The process control plan specifies the build layout; witness specimens and testing; and powder and platform removal after build. Inadvertent remnant powder in the part's interior represents a risk for FOD. Witness samples may provide an avenue to monitor the part process control. The witness coupons can be used to measure the distribution of material properties for the controlled process. The measured distribution reflects not the design values but, rather, the actual observed mean and variability in properties associated with the controlled AM process. The ongoing running history of witness coupons will start to establish a trend if it is sampled finely enough. Material properties can be monitored and controlled by applying statistical process control (SPC).

To set the equipment process controls, the equipment calibration and certification must be determined for the mechanical, electronic, optical, and software components of the AM production machines. It is not known, for example, how fast the laser heating source will degrade. SPC on a build-to-build basis may provide long-term monitoring of the equipment's health. Possible convenient SPC metrics for tracking may include mechanical strength, dimensional accuracy, and surface finish. Drifts and instability in the

SPC trends can forecast that the manufacturing is out of control and incapable.

The vendor of the part is required to implement quality assurance. The CAD model for the AM part must be checked and requires file controls. The stereolithography (STL) file that provides instructions for the AM production machine must also be checked. The vendor is necessarily responsible for implementing and managing the production machine's quality control program, and a quality system must be in place, such as AS9100. An auditing agency such as NADCAP can provide the audit and accreditation of the vendor that include both the digital inputs (such as the CAD and STL files) and the production process.

8.2 *USAF Space and Missile Center's Strategic Plan for AM*

The Space and Missile Center (SMC) has developed a strategic plan to advance AM to Technology Readiness Level (TRL) 9 in three phases.[24,25] The application is first identified and married with the development of the technology because SMC does not want to develop technology without a real-world use. The overall goals are to demonstrate cost and schedule savings and to demonstrate that the production process is reliable and repeatable. Table 3 summarizes the three phases to mature AM.[26]

In the first phase, the contractor prioritizes the list of candidate parts for AM production and develops an integration plan to insert the parts with the highest prospects for success and lowest risk. Laboratory testing is conducted to measure the database of properties needed for the initial design of the AM part. Phase 1 ends at TRL 5 with an initial proof-of-concept part that meets the design intent.

The second phase develops the production process. The design, production controls, NDE, and testing are iterated to establish the best practices for production. Phase 2 ends at TRL 6 with a prototype that satisfies lab testing relevant for its application and demonstrates readiness for mass production.

The third phase produces and integrates the part for flight. The first article production part is qualified through SMC's mission assurance practices. Parts at TRL 9 are produced for launch vehicles and satellites. As mentioned above, cost and schedule savings and production process reliability and repeatability are all demonstrated.

8.3 *Defense Production Act Title III Research Program for AM*

Under the Defense Production Act Title III, a partnership of Aerojet Rocketdyne (AR), Oak Ridge National Laboratory (ORNL), and Atlantic Precision, Inc (API) is developing and qualifying metal AM parts for a wide range of first and second stage rocket engines, such as the AR1, RS-25E, and RL10C.[27] Inconel IN718 Ni super alloy, AlSi10Mg, and Cu-Cr alloy are being developed for laser beam powder bed production. The total budget is $11,750,000 with equal cost sharing by the government and the industry consortium. A capital investment of one quarter of the total budget has purchased two Concept Laser X-Line 1000R's (at AR and ONRL) and one EOS M400 (at API).

The goals are to scale up and qualify the AM of large parts from diverse alloys and to demonstrate AM's cost savings. Complex components will be produced, including: Inconel ducts, housings, and baffles; Al structural housings for turbomachinery pumps and gear boxes; and the Cu-Cr high temperature thrust chamber assembly (TCA). The research has the potential to sharply reduce part count and internal/external welds for parts and to dramatically shorten schedules, all of which offer the prospect of cost savings estimated in the range of 30% to 40%. Historically, the RL10C Al gearbox housing has been very difficult to make by casting, and AM has cut the production time by 90%. The AM RL10C Cu TCA has eliminated hundreds of cooling tubes traditionally brazed by hand, and the switch away from manufacturing by skilled craftsmen offers a steep reduction in nonconformances and rework accompanied by additional cost savings. The Inconel AM RL10C injector has reduced the part count by combining a complex, joined assembly into a single part and has eliminated the traditional manual alignment and welding of injector posts. In addition, the AM injector has increased the engine's specific impulse because the as-built AM surface is in new fluid dynamics and heat transfer regimes.

The consortium has conducted extensive experiments to develop and validate optimized process parameters. Design of experiments (DOE) has been employed to define the relationship between processing, microstructure, and properties for the three alloys. For the Cu-Cr alloy, density close to the theoretical limit has been attained in the as-built state. For the AlSi10Mg alloy, the strain to failure has been doubled

Table 3 Summary of USAF SMC's strategic plan to develop and mature AM.

Phase 1: Understanding AM technology: application and design (ending in TRL 5)	Phase 2: Development of the production process (ending in TRL 6)	Phase 3: Part production and integration (ending in TRL 9)
(1) Contractor prioritizes list of candidate components	(1) Design, process control, NDT, and testing are iterated to establish best practices	(1) First article production part is qualified through SMC's mission assurance processes
(2) Integration plan to insert part with highest success and lowest risk	(2) Prototype satisfies relevant lab testing for application	(2) Parts are produced for launch vehicle or satellite
(3) Database of properties needed for initial design	(3) Demonstrated readiness for mass production	(3) Demonstrated cost and schedule savings
(4) Proof-of-concept part meets intent		(4) Production process is reliable and repeatable

compared to the standard AM process for the production machine.

9 Discussion

AM of metals is at an early stage in maturity and will naturally improve as the technology rapidly develops. With development, the part variability currently observed should naturally be reduced. Until that reduction is seen in practice, it may be sensible in the near future to use AM for secondary or redundant structures rather than for primary load bearing structure whose failure may lead to loss of mission. As a related point, an early failure may unnecessarily throttle the field. While AM makes possible topologies, a sound AM design at this stage of maturity should recognize the needs to inspect and proof test the part. "Design for AM" should consciously include "design for inspection and proof testing" until the field develops further.

Two advancements for the field are anticipated in the coming years. First, closed-loop feedback control should reduce the part variability. Second, AM's layer-by-layer build inherently allows access to the part's interior during fabrication, and real-time *in situ* inspection of flaws will be possible during the build, rather than after. Further, the inspection of the layer-by-layer build will conceivably allow a repair of the flaw by going back to fuse the flaw again before resuming the lay down of the next layer. This anticipated advancement should naturally reduce variability, as well as the burden placed upon conventional NDE methods traditionally used after production.

The AM field lacks a database of material properties similar to the MMPDS published for conventionally produced metal. In addition, the field does not know how the AM process parameters control microstructure and properties. Sharing of data and processes across industry, national laboratories, and universities may be the path to advance the field as quickly and cheaply as possible. The database will allow a new vendor to qualify its production by showing statistically that its production is in-family with accepted properties from accepted processes.

The aerospace industry is in the early stages of developing and publishing the qualification and certification standards for AM, which will be the consensus of industry, government, and the governing bodies for standards. The broad acceptance of the best practices for qualification will mature the field more rapidly and will help the space industry by improving quality and reducing the expense of qualification. As an ultimate goal, qualifying AM as a process should reduce the need for extensive qualification part by part, which would otherwise be expensive, duplicative, and time consuming.

10 Conclusion

AM (commonly called "3D printing") fabricates the desired final part directly from the input CAD file by depositing and fusing layer upon layer of the source material with very little waste. AM offers the revolutionary potential to eliminate welds and joints and, as a result, an entire class of associated failure mechanisms. New engineering designs are possible in which a single optimized part with topology can replace several traditional parts. For the AM of metals, the complex physics of metal deposition leads to variations in quality and to new flaws and residual stresses not seen in traditional manufacturing, which makes mission assurance challenging. The field also has knowledge gaps in material properties, NDE, and process control. Mission assurance will require: qualification and certification standards; sharing of data in handbooks; predictive models relating processing, microstructure and properties; and development of closed-loop process control and *in situ* NDE to reduce variability. Mission assurance can be tailored to account for mission risk class, MRL, and rigor of material properties. Proof testing of the AM part can be the mitigation for a low maturity process. AM parts for the National Security Space programs illustrate the potential for part count, cost, and schedule savings and the challenges to mature the technology. Three case studies for space programs share the common goals of improving the reliability and reducing the variability of AM, which can be achieved through DOE to optimize the process and SPC to monitor the process and properties. The fields need a breakthrough, which is a new process combining both high build rates and high accuracy and resolution.

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References

1. S. Seong et al., *Titanium Industrial Base, Price Trends, and Technology Initiatives*, pp. 1–2, RAND Corporation, Santa Monica, California (2009).
2. I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed., pp. 9, 110–111, 113, 114, 125, 274, 334–335, 437–479, 470, Springer, New York (2015).
3. General Electric Additive, "New manufacturing milestone: 30,000 additive fuel nozzles," https://www.ge.com/additive/blog/new-manufacturing-milestone-30000-additive-fuel-nozzles (4 October 2018).
4. K. Russell, "The case of the wayward weld," *Design News*, https://www.designnews.com/materials-assembly/case-wayward-weld/42663527027815 (22 September 2003).
5. W. Frazier, "Metal additive manufacturing: a review," *J. Mater. Eng. Perform.* **23**(6), 1917–1928 (2014).
6. Arcam, "Arcam 2: setting the standards for additive manufacturing," http://www.arcam.com/wp-content/uploads/Arcam-A2.pdf (10 May 2010).
7. Concept Laser, "M2 cusing multilaser metal laser melting system," https://www.concept-laser.de/fileadmin/user_upload/PDFs/1510_M2_cusing_Multilaser_EN.pdf (19 October 2015).
8. J. Hiemenz, "Electron beam melting," in *Advanced Materials and Processes*, pp. 45–46, ASM International, Materials Park, Ohio (2007).
9. R. M. Taylor, J. Manzo, and L. Flansburg, "Certification strategy for additively manufactured structural fittings," in *Proc. 27th Annu. Int. Solid Freeform Fabr. Symp.*, Austin, Texas, pp. 1985–2000 (2016).
10. P. Aggarangsi, J. L. Beuth, and D. D. Gill, "Transient changes in melt pool size in laser additive manufacturing processes," in *Solid Freeform Fabr. Proc.*, Austin, Texas, pp. 163–174 (2004).
11. M. Mani et al., "Measurement science needs for real-time control of additive manufacturing powder bed fusion processes," NISTIR 8036, Department of Commerce, Washington, D.C. (2015).
12. NIST, "Measurement science roadmap for metal-based additive manufacturing," p. 26, Department of Commerce, Washington, D.C. (2013).
13. Comptroller General of the United States, "3D printing opportunities, challenges, and policy implications of additive manufacturing," GAO-15-505SP, p. 25, Government Accountability Office, Washington, D.C. (2015).
14. J. A. Slotwinski and E. J. Garboczi, "Metrology needs for metal additive manufacturing powders," *JOM* **67**(3), 538–543 (2015).
15. D. B. Witkin, T. V. Albright, and D. N. Patel, "Empirical approach to understanding the fatigue behavior if metals made using additive manufacturing," *Metall. Mater. Trans. A* **47**(A), 3823–3836 (2016).
16. ASTM International, "ASTM WK47031: new guide for nondestructive testing of additive manufactured metal parts used in aerospace

applications," ASTM WK47031, ASTM International West Conshohocken, Pennsylvania (draft).
17. H. P. Tang, "Effect of powder reuse times on additive manufacturing of Ti-6Al-4V by selective electron beam melting," *JOM* **67**(3), 555–563, (2015).
18. N. Aboulkhair et al., "On the precipitation hardening of selective laser melted AlSi10Mg," *Metall and Mater. Trans. A* **46**(A), 3337–3341 (2015).
19. M. J. O'Brien and A. M. Kabe, "TOR-2017-02432: part evaluation for additive manufacturing," TOR-2017-02432, Aerospace Corporation, El Segundo, California (2018).
20. Battelle Memorial Institute, Metallic materials properties development and standardization, MMPDS-09, Battelle Memorial Institute, Columbus, Ohio (2014).
21. G. A. Johnson-Roth, "TOR-2011(8591)-21: mission assurance considerations for A-D mission risk classes," TOR-2011(8591)-21, Aerospace Corporation, El Segundo, California (2011).
22. NASA Marshall Space Flight Center, "MSFC-STD-3716: standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals," MSFC-STD-3716, NASA Marshall Space Flight Center, Huntsville, Alabama (2017).
23. NASA Marshall Space Flight Center, "MSFC-STD-3717: specification for control and qualification of laser powder bed fusion metallurgical processes," MSFC-STD-3717, NASA Marshall Space Flight Center, Huntsville, Alabama (2017).
24. G. Meholic, B. Lucky, and J. Fjeld, "TOR-2015-00736: Air Force Space and Missile Center strategic master plan for the application of additive manufacturing technology to spacelift systems," TOR-2015-00736, Aerospace Corporation, El Segundo, California (2015).
25. M. J. O'Brien and D. Davis, "Mission assurance for AM of metal parts," in *Proc. 29th Aerosp. Test. Seminar*, Vol. 4, pp. 138–155 (2015).
26. M. J. O'Brien, "Mission assurance for AM of metal parts," in *29th Aerospace Testing Seminar*, Los Angeles, California (2015).
27. "Space industrial base working group additive manufacturing for liquid rocket engines," Department of Defense, 2017, http://www.dpatitle3.com/dpa_db/project.php?id=216.

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