NIST Advanced Manufacturing Series
NIST AMS 600-10

The Strategy for American Leadership in High-Consequence Additive Manufacturing

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Executive Summary

Over the past decade, the need for U.S. leadership in critical advanced manufacturing technologies has been a consistent theme in enhancing U.S. global competitiveness. Additive manufacturing (AM), also known as 3D Printing, is among those critical technologies. However, although major progress has been made in the last decade, a number of challenges remain, limiting adoption of AM, especially for high-consequence applications. High-consequence AM is additive manufacturing of a part where the application could impact personal and public safety in the event of a failure or result in profound economic impact. Performance attributes of AM materials – strength, fatigue, damage tolerance, *etc.* – are often different from, and potentially inferior to, their traditionally manufactured counterparts. Beyond materials concerns, limitations of relatively immature AM equipment, especially related to control, can make it difficult to build repeatable and predictable parts. Overcoming these challenges is critical to allow the U.S. to lead in this field.

Leadership in AM, especially high-consequence AM, is essential for the U.S. because of the outsized impact it can have on economic, energy, and national security. Overall, market growth for AM is expected to trend towards a 20-25% ($2-4 Billion) year-to-year increase in coming years, promising many technology-focused or technology-driven jobs for U.S. workers.

Recently, the National Science and Technology Council (NSTC) Subcommittee on Advanced Manufacturing (SAM) and Subcommittee on the Materials Genome Initiative (SMGI) jointly formed an interagency team to analyze the slow adoption of AM for high-consequence applications. The team identified opportunities for research and development (R&D) in six critical areas to improve the quality and reduce the costs of AM parts and processes in high-consequence applications. These are:

1. Well-defined requirements,
2. Validated performance modeling and analysis capabilities,
3. Well-characterized materials and materials designed for AM,
4. *In-situ* process monitoring and control with known measurement uncertainties,
5. Tailored post-processing and non-destructive evaluation (NDE), and
6. Secure, registered, interoperable data.

Risk is a critical concept in the consideration of adopting AM for high-consequence applications. The risk of use in any given context will drive the set of quality and performance requirements the AM part must meet. Existing regulations typically provide a set of requirements for a variety of material and manufacturing processes that reflect the application's criticality. The selection of focused R&D areas for establishing AM-specific methods of compliance should be driven by a comprehensive gap analysis of the regulatory requirements.

Further innovation and maturation in the state-of-the-art of AM material and part performance modeling and analysis is required. A current barrier to applying model-based assessment to high-consequence AM is the limited maturity and acceptance of such tools and methods in the context of AM qualification and certification, as well as limited predictive capabilities. Additionally, data available to validate the degree to which the models are able to predict the performance of AM materials is needed before the extent to which the current methods need revision or extension can be assessed. Furthermore, models can be used in conjunction with *in-situ* real-time

process data to enable feedback control as well as defect detection and correction to achieve specific performance requirements and improve material quality.

The current number of materials that have been successfully employed in AM is extremely small relative to the thousands of alloys produced using conventional manufacturing, and further expansion of the palette of available materials is critical to further adoption. Opportunities exist to craft custom materials and alloys that are optimized for AM suitability. Characterizing AM materials involves significant effort in demonstrating acceptable performance of the printed material for high-consequence applications by establishing trusted process/structure/property relationships. It is also vital for AM feedstocks to be properly characterized and controlled to ensure optimum and repeatable performance. While standards bodies are starting to develop common language to describe the re-use schemes and sampling plans, there is a dearth of technical knowledge around powder feedstock reuse.

The localized and serialized nature of AM processes provide opportunities for introducing advanced *in-situ* process monitoring methods that can lead to enhanced understanding and control of material properties. To realize these opportunities, innovation and new sensor development are required. Advanced sensing methods must be integrated with data analytics, simulation and process modeling, process control methods, and other tools to isolate signal from noise and increase understanding of the underlying physical mechanisms that affect part performance. Adaptive feedback control and *in-situ* defect detection are two areas of development where further R&D are needed to demonstrate their capability and reliability.

To achieve the high reliability required of structural AM parts in high-consequence applications, post-processing and non-destructive evaluation (NDE) need to be carefully tailored to meet the needs of individual parts for specific applications. A primary challenge is the integration, optimization, and sequencing of the post-processing operations. Additional consideration is warranted for potential inclusion of machining capability interleaved with the AM printing process, often referred to as “Hybrid AM”. Though many of the common NDE techniques are routinely used to detect and measure such internal and surface flaws, challenges remain. Focused R&D of measurement methods, establishing traceability and measurement uncertainty, is of primary interest ahead of determining the reliability of flaw detection in AM parts, the uncertainty in measuring small flaw sizes, and the quantification of the effects of process-induced flaws on the realized structural integrity of the AM part.

There exists a clear need for continued work in the area of data management, data curation and analysis, and data security pertaining to AM. Findable, accessible, interoperable, and reusable (FAIR) data and software would allow AM R&D practitioners to easily access the best codes, integrate available data into those codes, and use identified best practices to optimize their AM process. The AM community will need to collaborate with the cybersecurity community and the broader advanced manufacturing community to identify solutions to challenges with data security.

Focused and applied R&D in four of the critical areas listed above are likely to yield the short-term and long-term impacts needed to increase adoption of AM for high-consequence applications: (1) validated performance models and analysis capabilities, (2) well-characterized existing materials for AM and new materials tailored for AM, (3) *in-situ* process monitoring and control of AM processes, (4) and tailored post-processing and NDE. Complementary to these R&D topics there is a need for the methods of compliance with requirements governing AM materials and processes and their associated material and process data, to be fully and clearly defined to allow for compliance with regulations. The AM community also needs to leverage best practices of data experts in developing key manufacturing data to provide the necessary security and interoperability required of a data-intensive process.

Key R&D opportunities

Well-defined requirements:

- To inform AM-specific requirements relative to regulatory and formal certification requirements, customer or program requirements (including those of procurement agencies), or internal company requirements (including milestones, internal design, and quality assurance, *etc.*)
- To inform development of AM-specific methods of compliance

Validated performance modeling and analysis capabilities:

- Broad benchmarking activities to establish expected performance variability for defining material and process specifications, leading to databases of statistically significant, pedigreed, property data for AM materials
- Characterization techniques and characterization data for the types of defects unique to, or commonly found in, AM materials, and data on the effects of these defects on performance
- Extension and validation of existing material performance and response techniques to common AM features such as thin walls, overhangs, and rough surfaces
- Computationally efficient AM process models with enhanced insights into issues such as thermal history, residual stress, microstructural evolution, anisotropy, defect origination, *etc.*, that enable deposition strategies that significantly outperform current methods in reliability and performance
- Models that predict failure modes for AM specific materials and microstructures
- Methods for efficient verification and validation of AM process and performance models
- Expanding and tailoring well-established simulation capabilities to the information-rich and spatially inhomogeneous opportunities represented by AM and its associated *in-situ* data

Well-characterized material and materials designed for AM:

- Advances in understanding of key characteristics for each AM feedstock type to drive improved characterization techniques, especially for powder feedstocks, and appropriate tolerances that ensure consistent performance in each associated AM technology
- Effective *in-situ* monitoring capabilities for ensuring feedstock quality during production, including appropriate models to capture monitoring activities / data into an effective feedstock control system
- Examination of how different re-use protocols affect feedstock characteristics and final part performance, leading to a scientific foundation to determine a priori an optimum powder reuse scheme for a specific AM process, feedstock material, or high-consequence application
- Development of feedstock-processing-structure-properties models, especially using high-throughput methods, to establish relevant processing conditions and reduce the amount of characterization and certification testing
- Development of AM-specific materials designed for AM processes, such that high cooling rates, tailored local processing histories, *in-situ* vaporization, and other AM-specific process conditions result in favorable, defect-free microstructures to create components that meet final part specifications with minimal post-processing requirements
- Physically informed models that relate: (a) AM processing parameters to local thermal history, local variations in composition, and the resulting spatial topology/microstructure, especially for modeling of heat transfer in complex AM parts; and (b) detailed microstructural information to component-level properties and performance
- Advanced data-driven and artificial intelligence and machine learning (AI/ML) tools that identify important data correlations and accelerate the analyst's ability to interpret large quantities of data and complement physics informed models to enhance abilities to design AM processable materials and optimize AM processes
- Validation of process and performance models using high-quality benchmark or use-case data

In-situ process monitoring and control with known measurement uncertainties:

- Development of more and novel sensing modalities with high frequency data capture rates that can be integrated into AM processes to capture critical data
- Multi-sensor spatial and temporal registration techniques
- Multi-sensor data fusion and data reduction, potentially aided by AI/ML approaches
- Integrated augmented reality / virtual reality (AR/VR) modeling of AM parts, particularly for space and medical applications
- Advanced deposition strategies and toolpaths that leverage process models in order to tailor thermal histories throughout a part, limiting defects and optimizing for material performance by design
- Adaptive feedback methods, potentially including AI/ML techniques, that can alter process parameters within a build to account for defects or other unexpected process conditions based on *in-situ* process monitoring
- Improved optical and physical manipulation systems and controls that can increase the fidelity of the power delivered to the material, either through focused high energy sources or coordinated arrays
- Deposition strategies for multi-material systems that optimize deposition based on the functions of the overall composite – for example, a long-fiber composite AM system needs to control both fiber orientation in the reinforcement material while simultaneously controlling porosity in the matrix material deposition as an integrated process

Tailored post-processing and non-destructive evaluation (NDE):

- Models for predicting thermal residual stresses induced by relieving processes, including the related effects on part geometry and microstructure
- Understanding the influence of support structure removal, including the effects on performance of critical, unimproved surfaces and potential geometric changes of related features
- Predictive models that enable the ability to eliminate or minimize the population of internal flaws such as pores and voids through hot isostatic pressing (HIP). This includes an understanding of the degree of material "healing" that may or may not occur during the HIP process and how void characteristics influence the effectiveness of HIP
- Understanding thermal processing effects on microstructure evolution (metallurgical outcomes: segregation, phases, grain size/orientation, texture, *etc.*), dimensional changes, and surface conditions (composition/contamination)
- Methods to tailor the integration, optimization, and sequencing of post-processing operations based on as-built material specification and characterization to obtain satisfactory performance outcomes, with a goal toward effective use of multi-stage post-processing
- Flaw classification including anomaly types, sizes and orientations, *etc*. and methods to construct relationships between the flaw characteristics and the source of process conditions for such flaw generation
- Methods to compare detected flaws and critical initial flaw size and flaw population related to different AM part structural demands or damage tolerance considerations
- Methods to quantify the spatial resolution and measurement uncertainty of NDE techniques in relation to flaw detection in metal AM parts, leading to understanding of the largest flaw that can be acceptably missed by an NDE technique as a function of technique, material, and part geometry
- Traceability of X-Ray computed tomography (CT) to the meter (the basic unit of dimension) to establish the process as a qualified NDE technique with quantified reliability of detection to improve upon the creation, understanding, and use of Reference Quality Indicators (RQIs) with well-defined artifacts used to quantify CT capability
- NDE modeling/simulation tools to simulate complex inspections on AM parts, reduce RQI dependence, and accelerate the physical reference development for NDE capability demonstration

Secure, registered, interoperable data:

- Identification and mitigation strategies for all security vulnerabilities unique to AM data streams
- Efforts to enable data registration and communication across modes of data such as computer aided design (CAD), simulation, and inspection

- Automated collection, registration, and fusion of component data across all aspects of part engineering and manufacturing such as design data (including modeling and simulation data that supports design), build data (including real-time sensor data and system control inputs), and inspection data
- Integrity validation of, and access controls for, data streams associated with the digital twins of critical parts
- Security, governance, and stewardship of data repositories appropriate for the storage and use of findable, accessible, interoperable, and reusable (FAIR) data

Keyword

Additive Manufacturing.

Acronym List:

Acronym	Definition
AI/ML	Artificial Intelligence and/or Machine Learning
AM	Additive Manufacturing
AR/VR	Augmented Reality and/or Virtual Reality
CALPHAD	Calculation of Phase Diagrams
CFR	Code for Regulations
CT	Computed Tomography
DoD	Department of Defense
FAIR	Findable, Accessible, Interoperable, Reusable
FDA	Food and Drug Administration
HIP	Hot Isostatic Pressing
ICME	Integrated Computation Materials Engineering
MGI	Materials Genome Initiative
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NIST	National Institute of Standards and Technology
NSTC	National Science and Technology Council
NSF	National Science Foundation
PCAST	President’s Council of Advisors on Science and Technology
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
RQI	Reference Quality Indicator
SAM	Subcommittee on Advanced Manufacturing
SMGI	Subcommittee on Materials Genome Initiative
TRL	Technology Readiness Level

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1. Introduction

Over the past decade, a consistent theme in enhancing U.S. global competitiveness has been the need for U.S. leadership in critical advanced manufacturing technologies. Additive manufacturing (AM), also known as 3D Printing, has been among those critical technologies. In July 2012, the President's Council of Advisors on Science and Technology (PCAST) published recommendations from the Advanced Manufacturing Partnership including AM among 11 top cross-cutting technologies.[1] It states that AM is a key technology holding the promise to produce highly customized and personalized products. Shortly thereafter, the National Additive Manufacturing Innovation Institute, America Makes, became the first public/private partnership in what is now known as the Manufacturing USA network. In 2018's "Strategy for American Leadership in Advanced Manufacturing," AM is identified once again as "beginning to realize its revolutionary potential" where "adoption of AM into manufacturing sectors depends on the ability to dependably set processing parameters that result in reliable and repeatable production…"[2]

Although major progress has been made in the ten years after the PCAST report, it is clear that AM has not become widely adopted, especially in high-consequence applications. There remains strategic focus on accelerating AM adoption as cited in the "Critical and Emerging Technologies List Update"[3] published by the National Science and Technology Council (NSTC) in February 2022.

Recently, the NSTC Subcommittee on Advanced Manufacturing (SAM) and Subcommittee on the Materials Genome Initiative (SMGI) jointly formed an interagency team to analyze this challenge. The initial charge to this team was to recommend an inter-agency strategic plan and to guide research efforts that will ultimately result in a high degree of confidence in the use of AM parts in sensitive, high-reliability, and safety-critical applications with a predictable service life. The broad question posed to the team: What is needed to advance U.S. leadership in this area?

Instead of preparing an interagency strategic plan, the interagency team was re-tasked to identify opportunities for research and development (R&D) to improve the quality and reduce the cost of AM parts and processes in high-consequence applications. The fact that "high-consequence AM" does not have one standard regulatory definition is important because the benefits of AM are widespread across government in various application areas. High-consequence AM connotes highly impactful applications where predictability and reliability have outsized importance. This encompasses safety-critical applications as well as applications that could be highly impactful on the U.S. economy.

High-consequence AM: additive manufacturing of a part where the application could impact personal and public safety in the event of a failure or result in profound economic impact.

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[1] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_27_2012.pdf
[2] https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/10/Advanced-Manufacturing-Strategic-Plan-2018.pdf
[3] https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf

The interagency team developed this report to define the problems limiting implementation of AM, with a focus on identifying the specific issues limiting wider adoption of AM for high-consequence parts, and the R&D gaps that need to be addressed to reduce the risk and cost of adoption of AM by increasing confidence in AM processes and parts used in high-consequence applications. The sections that follow define the specific issues holding back AM technology and provide the context of the problem. This leads to recommendations to guide future efforts in technology development to ensure increased adoption of high-consequence AM and U.S. leadership in the field.

2. The Strategic Importance of American Leadership in High-Consequence Additive Manufacturing

Originally developed as "rapid prototyping" in the early 1980s, AM has evolved and demonstrated the potential to be a disruptive technology in the manufacturing sector. AM is the quintessential advanced manufacturing technology: agile, inherently digital, and knowledge intensive. The lack of need for extensive tooling allows for highly customized and cost-effective small-lot-size parts and the potential for distributed (or forward-deployed) manufacturing, revolutionizing supply chains and shortening design-to-product cycle times. The layer-by-layer nature of AM makes the processes amenable to creating geometrically complex parts with tailored material properties, as well as in-process monitoring based on significant data generation and utilization. Potential applications are wide in scope, from large (vehicle hulls and chassis) to small (synthetic aperture radar antennas); from newly designed parts, to replacement parts that lack original data, tooling, or product specifications, to maintenance and repair of existing and legacy parts and systems.

In the recent 26th annual *Wohlers Report*[4], the industry-leading annual report on AM and 3D printing, Wohler's and Associates documented industry expansion of 7.5% to nearly $12.8 billion in 2020. This growth was down considerably (compared to an average annual growth of 27.4% over the previous 10 years) due to the challenging business environment caused by COVID-19. Most established manufacturers of AM systems saw a decline in equipment sales in 2020, but some less-established companies grew. An increase in business by AM service providers supported industry-wide growth. The report documented 7.1% growth from independent service providers worldwide, resulting in nearly $5.3 billion of revenue from the AM service providers group. Market growth is expected to trend towards a 20-25% ($2-4 Billion) year-to-year increase as the business community adapts to and overcomes the challenges presented by the pandemic and regional conflicts in Europe.

Important progress and recent successes of AM technology can be observed in aerospace, medical, defense, energy, and other applications. Recently, Department of Energy's Oak Ridge National Laboratory researchers refined their design of a 3D-printed nuclear reactor core through the Transformational Challenge Reactor[5] demonstration program. With the maturing of the technical field, approaches toward standardizing AM material and process qualification are emerging. National Aeronautics and Space Administration (NASA), for example, has published

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[4] *Wohlers Report 2021* ISBN 978-0-9913332-7-1
[5] https://doi.org/10.1080/00295639.2021.1996196

several standards to guide production of AM parts intended for applications in space flight: MSFC-STD-3716, "Standard for Additively Manufactured SpaceFlight Hardware by Laser Powder Bed Fusion in Metals,"[6] MSFC-STD-3717, "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes,"[7] and NASA-STD-6030 "Additive Manufacturing Requirement for Spaceflight Systems."[8] The Food and Drug Administration (FDA) published a guidance document for incorporating AM parts into medical devices: FDA-2016-D-1210, "Technical Considerations for Additive Manufactured Medical Devices."[9] Department of Defense (DoD) published its AM strategy[10] and provided guidance on implementation of AM within the DoD[11].

Some of the early promise of AM was more fairly classified as hype, as implementations were shown to be considerably more nuanced and challenging than anticipated. For example, the "complexity is free" idea that geometrically complex parts can be printed directly, without the slow and costly need for assembly from sub-components or post-printing operations, has failed to emerge. This is due to challenges in distortion and residual stress development, post-process measurement, and the associated complexities of part qualification. Furthermore, attempts to utilize materials that are already in use for parts made using traditional manufacturing processes have generally not resulted in faster or cheaper[12] qualification of AM materials and parts. Performance and geometric attributes of AM materials – strength, fatigue, damage tolerance, *etc.* – are often different from, and potentially inferior to, their traditionally manufactured counterparts. This contributes to the lack of confidence in AM. Beyond materials, shortcomings of AM equipment, especially related to control, can make it difficult to build repeatable and predictable parts.

Overcoming these challenges is critical to widespread use of AM for high-consequence applications. Doing so will allow the U.S. to lead in the field, creating many technology-focused or technology-driven jobs for U.S. workers in the growing field, and securing supply chains needed for these applications.

3. Contextualizing the term High-Consequence

AM is seeing increased use as a preferred manufacturing method due to its potential to deliver parts that are prohibitively complex or challenging to procure via the current (non-AM) manufacturing supply chain. For any manufacturer or end user of parts produced by a relatively new process, a key decision must always be made: given the stringent requirements for high-consequence applications, are the risk and cost commensurate with expected application benefits? There are three key components to this question:

1. Identifying the requirements for the part, which are driven by assessment of the risk of using an AM part in a given application, and any consequences of part failure.
2. Determining what data are needed to demonstrate that requirements are met.

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[6] https://standards.nasa.gov/standard/msfc/msfc-std-3716
[7] https://standards.nasa.gov/standard/msfc/msfc-spec-3717
[8] https://standards.nasa.gov/standard/nasa/nasa-std-6030
[9] https://www.fda.gov/regulatory-information/search-fda-guidance-documents/technical-considerations-additive-manufactured-medical-devices
[10] https://www.cto.mil/dod-additive-manufacturing-strategy/
[11] https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500093p.PDF?ver=t9U2MxdIBhofxnEOhrcx6A%3d%3d
[12] https://doi.org/10.1016/j.addma.2020.101070

3. Determining if the resources (time/funding/personnel) required to generate sufficient data are available, and whether those resources are justified by the benefits of the intended application.

The risk of use in any given context will drive the set of quality and performance requirements for an AM part. Higher impacts and consequences from inadequate part performance drive higher requirements. The first issue, requirements identification, is critical in defining the high priority areas that require significant national attention. Stringent requirements are typically set for applications that are deemed high risk. While what is considered high risk is very context-dependent, most of the recommendations in this report will consider the risk and cost of using AM parts in systems that could potentially impact personal and public safety, or have profound national security or economic impact in the event of a failure. Examples of these high-consequence AM parts that are already being used or considered include flight-critical parts for aerospace systems, components for nuclear reactors, and medical implants and orthotics.

Determining the type and quantity of data needed to demonstrate compliance with requirements is also a critical activity, and this activity is linked to the question of resources. Confidence is a function of data. The more data (experience) we have, the more confident we are that the part can meet the requirement. However, resource limitations will impact how much data can be generated. Additionally, the methods of quantifying AM product performance and quality are still maturing. If there is significant variability and uncertainty in the data, increased data generation and analysis will likely be required for high-consequence applications. For these reasons, risk of not meeting the design requirements will usually remain. For “advanced manufacturing” or “new materials,” the resource justification sometimes extends beyond the specific part or program. For example, a strategic decision may be made to implement thermoplastics, despite a higher cost and negative business case, because of the overall technical advantages and associated impacts on future programs. Further, the high levels of automation and digital integration inherent in AM allows further mitigation of risks by using modeling, advanced process science, and data analytics, coupled with *in-situ* data and feedback, to rapidly and affordably assess AM product performance and quality.

4. Technical Challenges and Research Opportunities for AM

The additive, serial nature of AM processes requires that material and energy are delivered precisely to a physically small location repeatedly over very long timeframes (*e.g.*, days of printing over miles of linear “weld” lines). This localization of manufacturing requires AM machines to maintain deposition within a processing window that is orders of magnitude faster and smaller than those typically seen in bulk materials processing. Furthermore, unlike conventional processing of metal alloys (*e.g.*, involving casting, metalworking, heat treatment, *etc.*) that rely on well-known bulk material properties (or well-known process/structure/property relationships), conditions within the AM process window affect fundamental material structure and properties in ways that may significantly affect part performance, including porosity, residual stresses, or problematic microstructures. These factors contribute significantly more to different material properties, life-cycle behaviors, and overall part performance of AM components compared to those that the industrial base has come to rely on in conventional manufacturing processes. Although post-build heat treatment or machining may overcome some of these differences, these extra processing steps ultimately add costs that negatively impact the business case and thus might further hinder adoption of AM. As such, these differences must be well understood and characterized.

Through a broad ranging process of discussion with relevant experts and literature research, the interagency team has identified six major categories of research challenges that are slowing or inhibiting the implementation of AM for high-consequence applications. The following sections seek to contextualize the challenges and provide a few concrete examples that, if overcome, could accelerate AM adoption in high-consequence applications, and provide strategic and sustained benefit for the nation.

4.1. Well-defined requirements

Broadly speaking, requirements represent a formal definition of the problem that someone is trying to solve, in this case through the potential use of AM. The context for defining requirements for both conventional and emerging technologies spans a wide range of concepts. These include technology development and maturation (*e.g.*, as reflected in technology readiness level (TRL) or manufacturing readiness level (MRL) criteria), qualification and certification (especially for regulated industries), procurement and supply chain management, design and engineering, among others.

Requirements can be broadly categorized into:

- Regulatory and formal certification requirements,
- Customer or program requirements (including those of procurement agencies), and
- Internal company requirements (including milestones, internal design, quality assurance (QA), *etc.*).

While there are many common elements among the above categories, there are also several important distinctions. For instance, regulatory or certification requirements are primarily focused on ensuring product safety. Customer or program requirements, in addition to safety considerations, may include product-specific attributes that are tailored to a particular application or program objectives. Internal company requirements (often proprietary) may reflect a number of company-specific best practices, internal processes, and competitive considerations. These often stem from internal expertise, or prior “lessons learned”.

Regardless of the requirements categorization, introduction of new technologies typically prompts the review of existing requirements and associated processes and criteria. This review, however, does not always necessitate changes. In fact, it is often more likely that technology-specific changes are needed not for the requirements themselves, but for the methods, procedures, and approaches used to meet these requirements (sometimes referred to as “methods of compliance” in the regulatory environment).

The other distinction worth noting in the regulatory context is the difference between prescriptive vs. performance-based requirements or regulations. Examples of the former include a number of DoD[13] and NASA requirements. Examples of the latter include FDA regulations, the recently revised Title 14 Code of Federal Regulations (14 CFR) part 23 FAA rules (for

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[13] MIL-HDBK-516 and JSSG 2xxx series

General Aviation), or the Navy Sea Systems Command requirements for additive manufacturing.[14] The Navy specifications are very closely related to welding specifications for critical applications. With performance-based regulations, there is a more significant reliance on corresponding guidance materials and best practices, including consensus-based public standards. By and large, higher-level requirements such as CFR rules are written in more generic terms and are typically agnostic to specific materials or manufacturing methods. Therefore, they are less likely to be influenced by the introduction of new technologies such as AM. For this reason, the corresponding methods of compliance (including public standards or regulatory guidance) are more likely to be adjusted to account for technology-specific considerations and attributes.

As stated earlier, the main focus of this document is on “high-consequence” AM applications. While not a formal regulatory definition in most cases, this term typically implies applications where there is potential impact on personal and public safety or a profound economic impact in the event of a failure. This is seen more commonly in aircraft, spacecraft, medical, or nuclear applications. Such applications correspond to the high end of the requirements spectrum. Existing regulations typically provide a set of requirements for a variety of material and manufacturing processes that reflect the application’s criticality. Recently, efforts have been made to establish a graduated set of requirements specifically for AM parts that scale directly with the criticality level of the application. Examples include Classes A / B / C per NASA-STD-6030. AM parts classification has also been developed recently by the ASTM F42.07.01 sub-committee on Aviation Applications of AM.

The complete list of requirements categories for a material or manufacturing system such as AM is hard to compile. Some of the common requirement categories that have been used for a variety of structural applications, and are now being applied to AM include:

- Process stability (ensured by process qualification and machine qualification);
- Acceptable material properties (at both feedstock and printed component level);
- Part-level properties (post-built / fully finished, after all the applicable post-processing steps);
- Development of material allowables and design values;
- Requirements associated with design practices and criteria (regulatory / customer / company-internal) such as
  - Static analysis,
  - Dynamic analysis,
  - Damage tolerance,
  - QA / quality control (QC) and inspection requirements, and
  - Other requirements (flammability, outgassing, operational environment challenges, *etc.*); and
- Other considerations (use of safety factors, part zoning, *etc.*).

In defining AM-specific elements of the above requirements categories and the corresponding methods of compliance, it is important to consider the relevance of “Lessons Learned” for other

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[14] NAVSEA Technical Publication S9074-A4-GIB-010/AM-WIRE DED “Requirements for Metal Directed Energy Deposition Additive Manufacturing” and NAVSEA Technical Publication S9074-A2-GIB-010/AM-PBF “Requirements for Metal Powder Bed Fusion Additive Manufacturing”

material systems (*e.g.*, how existing requirements were applied and/or adopted to novel material and manufacturing technologies in the past).

Focused R&D programs can play an important role in defining AM-specific requirements relative to any one of the three broad categories discussed at the beginning of this section. The selection of such R&D focus areas should be driven by a comprehensive gap analysis of the regulatory requirements and corresponding methods of compliance. The key objectives of such R&D efforts should be:

- To inform AM-specific requirements, and
- To inform development of AM-specific methods of compliance.

The ultimate goal is to make sure that the U.S. industry has means available to meet the AM-specific regulatory requirements for high-consequence applications and remain the global technology leader.

4.2. Validated performance modeling and analysis capabilities

For AM to be trusted and adopted for use in high-consequence applications, further innovation and maturation in the state-of-the-art of performance modeling and analysis is required. The design of safe and effective products suitable for AM production must incorporate modeling[15] and analysis. As of yet, however, the necessary tools and workflows have not been developed adequately or validated for use in AM production applications. Standards exist[16,17] that set forth conventional processes for the validation of models and analysis techniques, but slow progress has been made in implementing these standards to support more rapid design and use of AM techniques.

4.2.1. Validation of existing performance and analysis capabilities

Some approaches to analysis of high-consequence part performance rely on well-established modeling techniques, such as finite element analysis or fracture mechanics, which are not expected to vary significantly due to the manufacturing method. Other analysis methods commonly in use rely on the conservative application of established principles of statistical analysis to provide bounds on performance capability. Current barriers to applying these statistical approaches to AM include the complex nature (*e.g.*, multi-scale, multi-physics) of the predictive models to be validated and the limited data available for validating that AM materials perform as predicted. Nascent efforts such as the AM Benchmark Test Series[18] at the National Institute of Standards and Technology (NIST) are providing benchmark measurements for additive manufacturing, and more are needed.

Key research needs in this area are:

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[15] https://www.nap.edu/catalog/12199/integrated-computational-materials-engineering-a-transformational-discipline-for-improved-competitiveness

[16] https://www.asme.org/codes-standards/find-codes-standards/v-v-10-standard-verification-validation-computational-solid-mechanics

[17] https://www.asme.org/codes-standards/find-codes-standards/v-v-40-assessing-credibility-computational-modeling-verification-validation-application-medical-devices

[18] https://www.nist.gov/ambench

- Broad benchmarking activities to establish expected performance variability for defining material and process specifications, leading to databases of statistically significant, pedigreed, property data for AM materials;
- Characterization techniques and characterization data for the types of defects unique to, or commonly found in, AM materials, and data on the effects of these defects on performance; and
- Extension and validation of existing material performance and response techniques to common AM features, such as thin walls, overhangs, and rough surfaces.

4.2.2. Development and maturation of AM-specific performance modeling tools

While some existing techniques can aid in the design of high-consequence parts to be produced via AM, more efficient and trustworthy techniques are still needed to embrace the complexity that AM offers. Many subtle variations in process parameters used in the manufacture of AM parts, can have significant impact on expected part performance. There are often countless variables that are critical to part quality and performance that need to be controlled precisely within an AM process to achieve the desired outcomes. Because AM is a highly automated process, consistent results can be expected once a process is fully specified for a given part. It is not uncommon, however, to undertake many attempts to build a part via AM to achieve that fully specified state. This is inefficient, slow, and costly. It could be alleviated by better AM process and properties models.

Key research needs in this area are:

- Computationally efficient AM process models with enhanced insights into issues such as thermal history, residual stress, microstructural evolution, anisotropy, defect origination, *etc.*, that enable deposition strategies that significantly outperform current methods in reliability and performance;
- Models that predict failure modes for AM specific materials and microstructures;
- Methods for efficient verification and validation of AM process and performance models;
- Expanding and tailoring well-established simulation capabilities to the information-rich and spatially inhomogeneous opportunities represented by AM and associated *in-situ* data; and
- Models that accept *in-situ* real-time process data to allow feedback control as well as defect detection and correction to achieve specific performance requirements.

4.3. Well-characterized materials and materials designed for AM

Fundamentally, high-consequence applications call for high-performance materials, high reliability materials, or both. Traditionally manufactured metals use public specifications, but other types of materials such as composites rely historically on proprietary company specifications. This lack of standardization is a huge cost factor for composites because they are not a commodity. For this reason, AM would likely benefit from the development of public specifications, or definition of performance-based attributes, for printed materials that cover all critical performance parameters. It is often challenging and costly to obtain and characterize such materials, and increased research and development focused on the materials themselves will provide long-term benefits.

4.3.1. Characterization of existing materials

It is vital for AM feedstock (*e.g.*, powder, pellet, wire, or resin) to be properly controlled to ensure optimum and repeatable performance of final AM parts. Improvements in feedstock characterization would reduce need for re-validation with material lot changes and reduce variability in AM part performance. Further, while *in-situ* monitoring is being adopted in AM processes to allow for real-time observation, and in some cases correction, of the manufacturing process (see section 4.4), this approach could be applied to the entire supply chain of the AM process. Improvements in modeling, *in-situ* monitoring, and control could be applied to feedstock processing and production to improve consistency of feedstock and ultimately AM parts.

To reduce waste and feedstock cost, powder bed fusion and binder jetting processes often reuse powder that is assumed to be not modified or degraded by the building process. The high costs of metal powders (compared to wrought counterparts) often make this a necessary aspect of the process for economic viability. While standards bodies are starting to develop common language to describe the re-use scheme and sampling plans, there is a dearth of technical knowledge around powder reuse.

To understand the effects of these powder properties, the feedstock must be properly and fully characterized and related to defect formation in the part, and to final part performance. While this effort has been underway, there are still gaps in understanding how to fully characterize a feedstock to ensure uniform performance within and across material lots. Possible techniques include: X-ray computed tomography to explore particle structure and porosity; image analysis to evaluate particle size and shape distribution; and metallography to characterize internal structure, composition fluctuations, and related properties. These techniques are far too slow and expensive for use in a production environment, regardless of the criticality of the application. Additionally they have accuracy and detectability limits due to the often complex nature of the AM geometries being evaluated. While this challenge may be most apparent in powder feedstock, it impacts the use and reuse of all feedstocks (*e.g.*, wire, liquid resin, *etc.*).

The AM build process, including the selection of process parameters, has a significant effect on material properties. Characterizing AM materials involves significant effort in demonstrating acceptable performance of the printed material for high-consequence applications by establishing trusted process/structure/property relationships. Most materials currently used in AM were developed in traditional product forms for use in traditional manufacturing processes. The unique conditions present in many AM processes, such as the non-equilibrium conditions resulting from extremely high heating and cooling rates, can generate porosity, residual stresses, and deleterious microstructures in the final parts. In cases where the best achievable build parameters have already been established for a given feedstock, there is currently no effective and reliable way to transfer this information across different AM platforms in which the feedstock could be used. Beyond AM build parameters, thermal post processing parameters can be used to improve AM part performance by reducing defects and achieving more beneficial microstructures. This is at the expense of added time and cost. Labeling feedstock for either optimum AM build/post-processing conditions, or providing multiple recipes to produce known mechanical responses, would reduce re-validation time and streamline material lot changes.

Key research needs in this area are:

- Advances in understanding the key characteristics for each type of AM feedstock to facilitate improved characterization techniques, especially for powder feedstocks, and appropriate tolerances for key characteristics that will ensure consistent performance in each associated AM technology;
- Effective *in-situ* monitoring capabilities for ensuring feedstock quality during production, including appropriate models to capture monitoring activities and data into an effective feedstock control system; and
- Examination of how different re-use protocols affect feedstock characteristics and final part performance, leading to a scientific foundation to determine a priori an optimum powder reuse scheme for a specific AM process, feedstock material, or high-consequence application.

4.3.2. Tools for developing new materials

Use of computational tools for designing materials for AM processes and applications has been limited to date, but represents an important avenue of research to optimize material performance and cost. The current number of materials that have been successfully employed in AM is extremely small relative to the thousands of alloys produced using conventional manufacturing. Further expansion of the palette of available materials is critical to further adoption. Opportunities exist to craft custom materials and alloys that are optimized for AM suitability or that are so challenging to conventionally process that they may only be realistically manufactured by AM. Application and expansion of non-equilibrium and thermodynamic modeling tools and approaches (*e.g.*, CALPHAD coupled with AI/ML) is an important area of research that will enable the design of new alloys that are specific to AM.

Physics informed process modeling is an important step for AM process maturation and adoption. It can allow designers to predict the nominal material properties they can expect in a part through established process/structure/properties knowledge. Complex AM part design through, for example, the incorporation of lattice structure or topology optimization, leads to different regions of a part having very different local processing histories (*e.g.*, different cooling rates). These local variations, in turn, can lead to heterogeneity in mechanical performance that can potentially make specific regions or design elements more susceptible to failure. This makes advanced process models, as referenced in section 4.2.2, to predict accurately the location-specific process history throughout an AM part important in process design and properties prediction.

Current material models are not capable of predicting fully the final material properties based on AM processing parameters. This deficiency makes determination of optimum process parameters for a specific application an arduous experimental exercise. As these models are further developed for existing materials, they can be potentially leveraged to enable design of new materials.

For example, one can envision gigabytes to terabytes of critical data (*e.g.*, the laser power, velocity, scan direction, thermal imaging, *etc.*) produced during the additive manufacture of a component. These data would represent a “processing signature” for the component. After manufacture, the component is further characterized in terms of strength, creep resistance, etc. These additional data represent a "performance signature". Physics-based models can be coupled with AI/ML in determining correlations between certain attributes of the processing signature and performance signature. The data from both the processing signature and the performance signature could be integrated with a so-called "digital twin,"[19] a computational representation of the fabricated part, allowing for virtual testing in a variety of potential environments.

Key research needs in this area are:

- Development of feedstock-processing-structure-properties models, especially using high-throughput methods, to establish relevant processing conditions and reduce the amount of characterization and certification testing;
- Development of AM-specific materials designed for AM processes, such that high cooling rates, tailored local processing histories, in-situ vaporization, and other AM-specific process conditions result in favorable, defect-free microstructures to create components that meet final part specifications with minimal post-processing requirements;
- Physically informed models that relate: (a) AM processing parameters to local thermal history, local variations in composition, and the resulting spatial topology/microstructure, especially for modeling of heat transfer in complex AM parts; and (b) detailed microstructural information to component-level properties and performance;
- Advanced data-driven (*e.g.*, AI/ML) tools that identify important data correlations and accelerate the analyst's ability to interpret large quantities of data and complement physics informed models to enhance abilities to design AM processable materials and optimize AM processes;
- Validation of process and performance models using high-quality benchmark or use-case data; and
- Development of materials design workflows that enable the concurrent design and optimization of local alloy chemistry, part topology, and AM processing parameters to create optimized microstructures and material properties for a given high-consequence application.

4.4. *In-situ* process monitoring and control with known measurement uncertainties

AM processes introduce opportunities for enhanced understanding and control of material properties in ways that are not possible (or prohibitively difficult) in other manufacturing processes. Because the AM processing window is small and localized and the parts are printed layer-by-layer, there is an opportunity to examine the process through its entire deposition, thus yielding precise and location-specific information. *In-situ*, or real-time, process monitoring and controls, therefore, may enable the use of AM parts in critical applications. Opportunities for R&D to improve the quality and performance of AM parts and processes in order to accelerate adoption into high-risk applications are discussed below.

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[19] ISO 23247-1:2021
Automation systems and integration — Digital twin framework for manufacturing — Part 1: Overview and general principles, https://www.iso.org/standard/75066.html

4.4.1. *In-situ* sensing

While the serial, localized deposition of material in AM creates opportunities to understand the quality of a part as it is being printed, there are numerous challenges to implementing process monitoring approaches that can lead directly to improved reliability and decreased uncertainty in AM parts. The deposition environment – especially with fusion processes – is extraordinarily complex and dynamic, and different sensor modes may be suited to detecting only specific types of features. To support the high reliability needed for high-consequence AM applications, advanced sensing methods must be integrated with data analytics, simulation and process modeling, process control methods, and other tools in order to isolate signal from noise. This will increase our understanding of the underlying physical mechanisms that lead to part performance and/or ultimate failure.

While several promising *in-situ* sensing techniques, such as optical imaging, are well developed and becoming available on commercial platforms, these advances by themselves are not sufficient to remove or reduce uncertainty for critical applications. Multiple different types of sensors may be required to validate certain properties, and redundant measurements from similar sensors may also be necessary to decrease uncertainty in the measurements. Therefore, innovation and new sensor development is required, especially for critical applications.

As more sensors are needed to validate part quality and performance capability, there is also a need to transform all available data into a common language to register data sources into a three-dimensional framework such that multiple data sources can be accurately analyzed for each location in the part. Registering data between stationary and coaxial sensing data, for instance, represents a challenge that will only grow with the available sensing modes. Furthermore, as additional energy sources are added to AM systems to accommodate higher throughput or larger part volumes, data collected simultaneously from different locations in the part will need to be merged both spatially and temporally. With such a tremendous amount of integrated and registered data, augmented reality / virtual reality (AR/VR) will be valuable in visualizing how the data fit together, especially when combined with modeling of AM parts.

Another aspect that challenges the development of in situ sensing in regard to enabling high-consequence AM parts is the distinction between the direct detection of defects familiar in the common implementation of NDE versus the detection of process conditions that may, or may not, lead to a defect in the AM material as is the case with most in situ sensor systems. This distinction adds a layer of complexity to the interpretation of in situ data streams and makes quantification of defect detection based on these streams particularly challenging.

As the number and variety of sensors increase, there is strong need for real-time computational approaches that can combine multiple data streams with logic and data truncation techniques in order to separate important signals from much more prevalent noise. Data generation will increase dramatically with increased sensor resolution, number of sensors, number of energy sources, and higher sampling frequencies that are likely required to enable critical part production.

Key research needs in this area are:

- Development of more and novel sensing modalities with high frequency data capture rates that can be integrated into AM processes to capture critical data;
- Multi-sensor spatial and temporal registration techniques;
- Multi-sensor data fusion and data reduction, potentially aided by artificial intelligence and machine learning approaches; and
- Integrated AR/VR modeling of AM parts, particularly for space and medical applications.

4.4.2. Advanced process control

As compared to conventional manufacturing processes, AM machines rely on very precise, well controlled energy sources to directly fabricate near-net-shaped components. However, the degree to which today's AM machines can reliably deposit material with consistently reliable material properties is limited by many factors. Physical constraints limit sizes of parts and consistency of the motion and optics systems limit achievable tolerances. Software constraints limit available toolpaths and deposition strategies on existing commercial machines. Toolpath strategies optimized for ease of deposition and control, rather than material properties, are not currently available. Adaptive feedback control and *in-situ* defect detection are developing capabilities but are only in their infancy.

Process control options exist for AM that are challenging to implement or simply not practical in many conventional manufacturing processes. For example, a proven strategy for high performance manufacturing is to compensate for variation in the chemistry and structure of feedstock by on-the-fly variation in processing. The automation and fine-scale deposition control of AM offers a means to do this in ways that are very difficult to achieve with conventional (bulk) processing.

Key research needs in this area are:

- Advanced deposition strategies and toolpaths that leverage process models in order to tailor thermal histories throughout a part, limiting defects and optimizing for material performance by design;
- Adaptive feedback methods, potentially including AI/ML techniques, that can alter process parameters within a build in order to account for defects or other unexpected process conditions based on *in-situ* process monitoring;
- Improved optical and physical manipulation systems and controls that can increase the accuracy and fidelity of the power delivered to the material, either through focused high energy sources or coordinated arrays; and
- Deposition strategies for multi-material systems that optimize deposition based on the functions of the overall composite – for example, a long-fiber composite AM system needs to control both fiber orientation in the reinforcement material while simultaneously controlling porosity in the matrix material deposition as an integrated process.

4.5. Tailored post-processing and non-destructive evaluation (NDE)

For most AM parts, post-processing (operations subsequent to the AM part print completion) is currently essential. Additionally, inspection of the part is often required to satisfy the quality control process and to use the part in its intended application with full confidence.

4.5.1. Tailored post-processing

To achieve the best mechanical performance and part quality with current materials and AM processes, thermal treatments or other post-process refinements are usually required. One example of this is a treatment to homogenize the microstructure of the as-built material, to reduce residual stresses, or to potentially reduce the inherent flaw sizes and population induced during the layered AM operation.

In addition to removing or separating parts from the build plate, post-processing for AM parts includes, but is not limited to, stress relief, removal of support structures, thermal processing (*e.g.*, hot isostatic pressing (HIP), solution treatment, aging, *etc.*), machining, and finishing and/or surface treatments (such as shot peening, abrasive honing, polishing, *etc.*). In addition to the principal goals of modifying the near-surface and bulk microstructures (or other metallurgical features) and minimizing internal defects, post-processing of AM parts also aids in eliminating or alleviating residual stresses, improving surface conditions for performance or cosmetic purposes, and achieving the final part geometry to meet design specifications.

Given the broad variety of materials, geometries, process conditions, and component performance requirements of AM parts, there is no single approach to the post-processing of AM parts. To achieve the high reliability required of AM parts in critical applications, post-processing needs to be tailored carefully to meet the needs of individual parts for specific applications. A primary challenge in designing a tailored post-processing approach for an AM part includes the integration, optimization, and sequencing of the post-processing operations, as well as consideration of potential inclusion of machining capability interleaved with the AM printing process, often referred to as “Hybrid AM”. This approach requires an understanding of each individual operation, its effect on the AM part, and how that process may influence subsequent operations.

Key research needs in this area are:

- Models for predicting thermal residual stresses induced by relieving processes, including the related effects on part geometry and microstructure;
- Understanding the influence of support structure removal, including the effects on performance of critical, unimproved surfaces and potential geometric changes of related features;
- Predictive models that enable the ability to eliminate or minimize the population of internal flaws such as pores and voids through HIP – including an understanding of the degree of material “healing” that may or may not occur during the HIP process and how void characteristics influence the effectiveness of HIP;

- Understanding thermal processing effects on microstructure evolution (metallurgical outcomes: segregation, phases, grain size/orientation, texture, *etc.*), dimensional changes, and surface conditions (composition/contamination); and
- Methods to tailor the integration, optimization, and sequencing of post-processing operations based on as-built material specification and characterization to obtain satisfactory performance outcomes, with a goal toward effective use of multi-stage post-processing.

4.5.2. Nondestructive evaluation (NDE)

The field of nondestructive evaluation (NDE) includes a wide-ranging variety of techniques and methods for the inspection of part quality without altering the part itself, thus having no effect on part performance. Some of the most common NDE methods include forms of X-ray radiography (traditional film, digital, or computed tomography (CT)), eddy current, fluorescent penetrant, and ultrasound. The primary purpose of NDE is to reliably detect flaws (especially internal flaws) in AM parts that may impact structural integrity and functional part performance (*e.g.*, fatigue strength or wear rate).

For metal AM parts, internal defects such as pores, delaminations, and lack of fusion zones, are detrimental to surface and component structural integrity. Though many of the common NDE techniques are used routinely to detect and measure such internal flaws, challenges remain, including determining the reliability of flaw detection in AM parts. These include the uncertainty in measuring small flaw sizes and the measurement of surface finish, along with their correlation to AM part performance.

Key research needs in this area are:

- Flaw classification including anomaly types, sizes and orientations, *etc.*, and methods to construct relationships between the flaw characteristics and the source of process conditions for such flaw generation;
- Methods to compare detected flaws and critical initial flaw size and flaw population related to different AM part structural demands or damage tolerance considerations;
- Methods to quantify the spatial resolution and measurement uncertainty of NDE techniques in relation to flaw detection in metal AM parts, leading to understanding of the largest flaw that can be acceptably missed by an NDE technique as a function of technique, material, and part geometry;
- Traceability of X-Ray CT to the meter (the basic unit of dimension) to establish the process as a qualified NDE technique with quantified reliability of detection to improve upon the creation, understanding, and use of Reference Quality Indicators (RQIs) with well-defined artifacts used to quantify CT capability; and
- NDE modeling and simulation tools to simulate complex inspections on AM parts, reduce RQI dependence, and accelerate the physical reference development for NDE capability demonstration.

4.6. Secure, registered, interoperable data

AM is a process driven by the creation, management, and processing of numerous data streams. This results in a number of challenges and opportunities for advancement. For essentially all modern manufacturing systems, the generated data is “born digital.” That is, it is output by a device as a digital signal and is processed by a computer. Thus, a well-designed manufacturing process would capture all data, and associated metadata, generated at each stage of the AM process chain, from design of the part, through fabrication, additional processing steps, and any pre- and in-service performance assessments. This capture of information would be invaluable, as it would lead to enhanced quality assurance capabilities and, via feedback loop, to optimization of AM processes and improved ultimate performance of the manufactured part.

Additionally, software plays a crucial role in AM and manifests many of the same issues, challenges, and opportunities as those associated with data. For example, process modeling and simulation codes are digital objects (like data) and have versions, other metadata, and, ideally, interoperate to enable a pipeline of models from, possibly, the atomic scale, to a fabricated part. There are also codes that control AM fabrication systems, and potentially software-driven AI systems that can optimize the AM process to achieve targeted properties and performance. Synthesizing validated codes and data allow the construction of a digital twin. Additionally, a sophisticated version of that twin would allow practitioners to “re-run” the fabrication process under different processing conditions, allowing for virtual experiments yielding optimized performance. This level of sophistication is dependent on experimental techniques that can provide information about the fabrication process at each point in the part (to some level of precision). That is, information about the state (*e.g.*, temperature, energy input, local composition, *etc.*) of the part at each point must be measured to obtain a digital twin that can provide insights into the formation of defects in the part and subsequent failures in service.

This merging of the digital thread from manufacturing into the information flows emanating from materials R&D is one of the central themes of the U.S. Materials Genome Initiative[20] (MGI). Thus, AM provides a proving ground for many of the capabilities that have been and continue to be developed within the context of the MGI, and advances from both communities promise to mutually accelerate progress.

In the past few years, the data management community has distilled many of the best practices into the acronym “FAIR,” meaning findable, accessible, interoperable, and reusable.[21] FAIR data and software would allow AM R&D practitioners to easily access the best codes, integrate available data into those codes, and use identified best practices to optimize their AM process. Truly FAIR data and software would be of enormous value to the AM enterprise, allowing for seamless interoperation of manufacturing equipment, materials models, and characterization and evaluation systems, and yielding improved performance at lower cost. Discussion has begun to identify barriers and identify a strategic path forward for FAIR AM data, with socialization of FAIR principles among the AM community as a critical first step.[22]

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[20] https://www.mgi.gov/sites/default/files/documents/MGI-2021-Strategic-Plan.pdf

[21] Wilkinson, M., Dumontier, M., Aalbersberg, I. et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data* 3, 160018 (2016). https://doi.org/10.1038/sdata.2016.18, https://www.nature.com/articles/sdata201618#citeas

[22] W. Frazier, Y. Lu, P. Witherell, R. Fryan, A. Kitt, “Unleashing the potential of additive manufacturing: FAIR AM data management principles,” Advanced Materials and Processes, July/August 2021, 179(5), 12-19.

Of course, with any discussion of FAIR data, there are justifiable concerns about data security. These issues are complex and cover a variety of challenges. It is important to note that the desire for FAIR data does not override corporate interests in maintaining control of their intellectual property, or, in the case of classified or otherwise export-controlled technologies, preventing the dissemination of such information to unauthorized recipients. In general, one can imagine FAIR data infrastructures that operate inside secure information technology ecosystems. This would allow for rapid discovery, access and interoperation of AM software and data along a corporate supply chain or any other cohort of authorized users. Another issue in data security is around the integrity of the data and ensuring that no entities have tampered with the information. Finally, the data provenance must be documented fully and assured. The AM community will collaborate with the cybersecurity community and the broader advanced manufacturing community to identify solutions to these challenges, because they generally lie outside the domain expertise of AM practitioners.

There exists a clear need for continued work in the area of data management, data curation and analysis, and data security pertaining to AM. A challenge is that these needs are rarely met by research projects in and of themselves. Funded data centric efforts are often adjuncts to AM programs. It is likely that an increased emphasis on dedicated data science and management projects for AM would accelerate the rate of development in this critical area.

Key research needs in this area are:

- Identification and mitigation strategies for all security vulnerabilities unique to AM data streams;
- Efforts to enable data registration and communication across modes of data such as computer aided design (CAD), simulation, and inspection;
- Automated collection, registration, and fusion of component data into a package across all aspects of part engineering and manufacturing such as design data (including modeling and simulation data that supports design), build data (including real-time sensor data and system control inputs), maintenance, and inspection data;
- Integrity validation of, and access controls for, data streams associated with the digital twins of critical parts; and
- Security, governance, and stewardship of data repositories appropriate for the storage and use of findable, accessible, interoperable, and reusable (FAIR) data.

5. Recommendations

A desired end state for AM is a set of clear requirements that allow quantifiable decisions on when AM is an appropriate choice of manufacturing technology over other traditional and advanced manufacturing processes. Robust and validated models of AM processes are needed that incorporate changes in the AM processes and accurately predict AM process/structure/property relationships in complex geometries. There is also a need for materials that are tailored to the end-use application and designed specifically for the physics of AM processes. The ability to acquire data at all phases of the manufacturing lifecycle presents additional opportunities for integrating the data in a way that analytics allow critical decisions to be made on the fly. While this end state is many years away, several barriers can be more immediately overcome that will allow phased introduction of AM into increasingly more critical applications.

As discussed in this report, high-consequence applications require understanding and acceptance of the risks of using a part for an application. This effectively translates in practical terms into the risk acceptance culture of the organizations assuming the risk. Disruptive process changes and large leaps from a current body of knowledge are not likely to be accepted by regulatory agencies or oversight authorities. Therefore, when pursuing improvements in high-consequence applications, measured and conventional approaches to technology adoption should accompany more fast-paced or revolutionary research focused approaches. R&D related to validated performance models and analysis capabilities, new and well-characterized existing materials for AM, *in-situ* process monitoring and control of AM processes, and tailored post-processing and NDE are poised to yield both near-term and longer-term impacts needed to increase adoption of AM for high-consequence applications. Accompanying this R&D is the need for the requirements of AM materials and processes, with associated material and process data, to be fully and clearly defined to allow for compliance with regulations. The AM community needs to leverage the best practices of data experts in developing key manufacturing data to provide the necessary security and interoperability required of a data-intensive process.

Recommendation:

Conduct targeted research and development to create:

1. *Well-defined requirements,*
2. *Validated performance modeling and analysis capabilities,*
3. *Well-characterized materials and materials designed for AM,*
4. *In-situ process monitoring and control with known measurement uncertainties,*
5. *Tailored post-processing and non-destructive evaluation (NDE), and*
6. *Secure, registered, interoperable data*

for high-consequence AM applications.