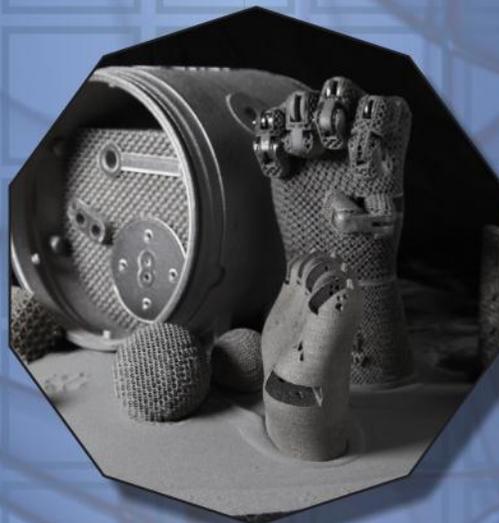
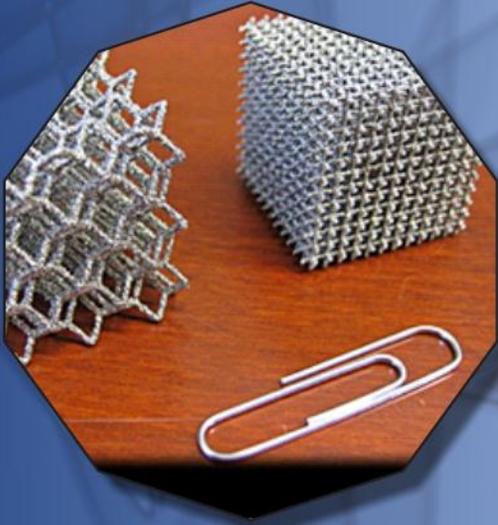


Measurement Science Roadmap for Metal-Based Additive Manufacturing



May 2013

Prepared by Energetics Incorporated
For the National Institute of Standards and Technology



PREFACE

The *Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing* was hosted by the National Institute of Standards and Technology (NIST) Intelligent Systems Division (ISD) within the Engineering Laboratory. Workshop planning and execution and preparation of this report were conducted under the direction of Kevin Jurrens, Deputy Division Chief for ISD. The information contained herein is based on the results of the workshop, which was attended by a diversity of stakeholders working in the field of additive manufacturing (AM). It represents the expert perspectives of participants, but is not intended to represent the views of the entire AM community.

Disclaimer

This report was prepared as an account of work cosponsored by NIST. The views and opinions expressed herein do not necessarily state or reflect those of NIST. Certain commercial entities, equipment, or materials may be identified in this document in order to illustrate a point or concept. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

Measurement Science Roadmap for Metal-Based Additive Manufacturing

WORKSHOP SUMMARY REPORT

May 2013

Prepared by

Energetics Incorporated, Columbia, Maryland
for the
National Institute of Standards and Technology,
U.S. Department of Commerce

ACKNOWLEDGMENTS

Many thanks to all those who participated in the *Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing* held December 4–5, 2012 at the NIST campus in Gaithersburg, Maryland. The presentations and discussions that took place at the workshop provided the foundation for this report. Special thanks are extended to the plenary speakers (listed below) and to the many expert participants (a complete list is provided in Appendix A).

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Gary Fleegle, *National Center for Defense Manufacturing and Machining*
Ed Herderick, *EWI*
John Hunter, *Carpenter Powder Products, Inc.*
Kevin Jurrens, *National Institute of Standards and Technology*
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Tom Kurfess, *Office of Science and Technology Policy, Executive Office of the President*
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Constance J.S. Philips, *National Center for Manufacturing Sciences*

Special thanks are due to the Energetics Incorporated team who provided support for workshop planning, facilitation, and preparation of the summary report. The workshop report and supporting documents can be found on the workshop website at <http://events.energetics.com/NIST-AdditiveMfgWorkshop/index.html>.

Further information about this report can be obtained by contacting Kevin Jurrens at kevin.jurrens@nist.gov.

Cover Photos

- ❖ Photos 1, 2, and 4, from top to bottom, NIST
- ❖ Photo 3, from top to bottom, Oak Ridge National Laboratory

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EXECUTIVE SUMMARY

BACKGROUND

The U.S. manufacturing sector has a significant impact on U.S. job growth, the country's overall economy, and national security. Additive manufacturing (AM), a process for fabricating parts layer-by-layer directly from a 3-D digital model, has tremendous potential for producing high-value, complex, individually customized parts. Companies are beginning to use AM as a tool for reducing time-to-market, improving product quality, and reducing the cost to manufacture products. Metal-based AM parts have emerged for use in applications such as automotive engines, aircraft assemblies, power tools, and manufacturing tools such as jigs, fixtures, and drill guides.

While the use of AM has been growing, a number of challenges continue to impede its more widespread adoption, particularly in the areas of measurement science and standardization. These challenges were explored in the *Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing* sponsored by the National Institute for Standards and Technology (NIST) and held on December 4–5, 2012 in Gaithersburg, Maryland. Workshop objectives included the following.

- Building on prior AM roadmaps and other efforts, gain expert input on:
 - Measurement science barriers, challenges, and gaps that prevent the broad use of metal-based AM
 - Research and development needed to address the priority measurement and standards challenges
 - Future measurement- and standards-related targets and goals for AM
 - Action plans to address identified barriers and gaps
- Provide input for strategic planning by the ASTM International standards organization F42¹ standards committee on Additive Manufacturing Technologies
- Influence and coordinate with the National Additive Manufacturing Innovation Institute on development of the national AM roadmap

Figure E-1. Workshop Breakout Topics

- AM Materials
- AM Processes and Equipment
- Qualification and Certification of Materials, Processes, and Products
- Modeling and Simulation of AM

White papers were created by workshop participants prior to the workshop to provide additional background and a starting point for discussions. The workshop opened with plenary presentations that provided context on AM challenges and use cases. About 75 expert participants then addressed the technical topics in Figure E-1 during breakout sessions.

This report is based on workshop results. The views presented are those developed by the experts that participated and do not necessarily represent the views of the entire AM community. In some

cases, ideas overlap among breakout groups illustrating the cross-cutting nature of some priorities and challenges.

This report provides useful information to public and private decision makers interested in furthering the capabilities of AM and accelerating its more widespread use. By focusing on metal-based AM, the workshop was able to thoroughly address one portion of the overall AM roadmap. It is hoped that the national research agenda for metal-based AM will incorporate the consensus-based needs and priorities established during this workshop and presented in this report.

¹ "Committee F42 on Additive Manufacturing Technologies," ASTM International, accessed June 5, 2013, <http://www.astm.org/COMMITTEE/F42.htm>.

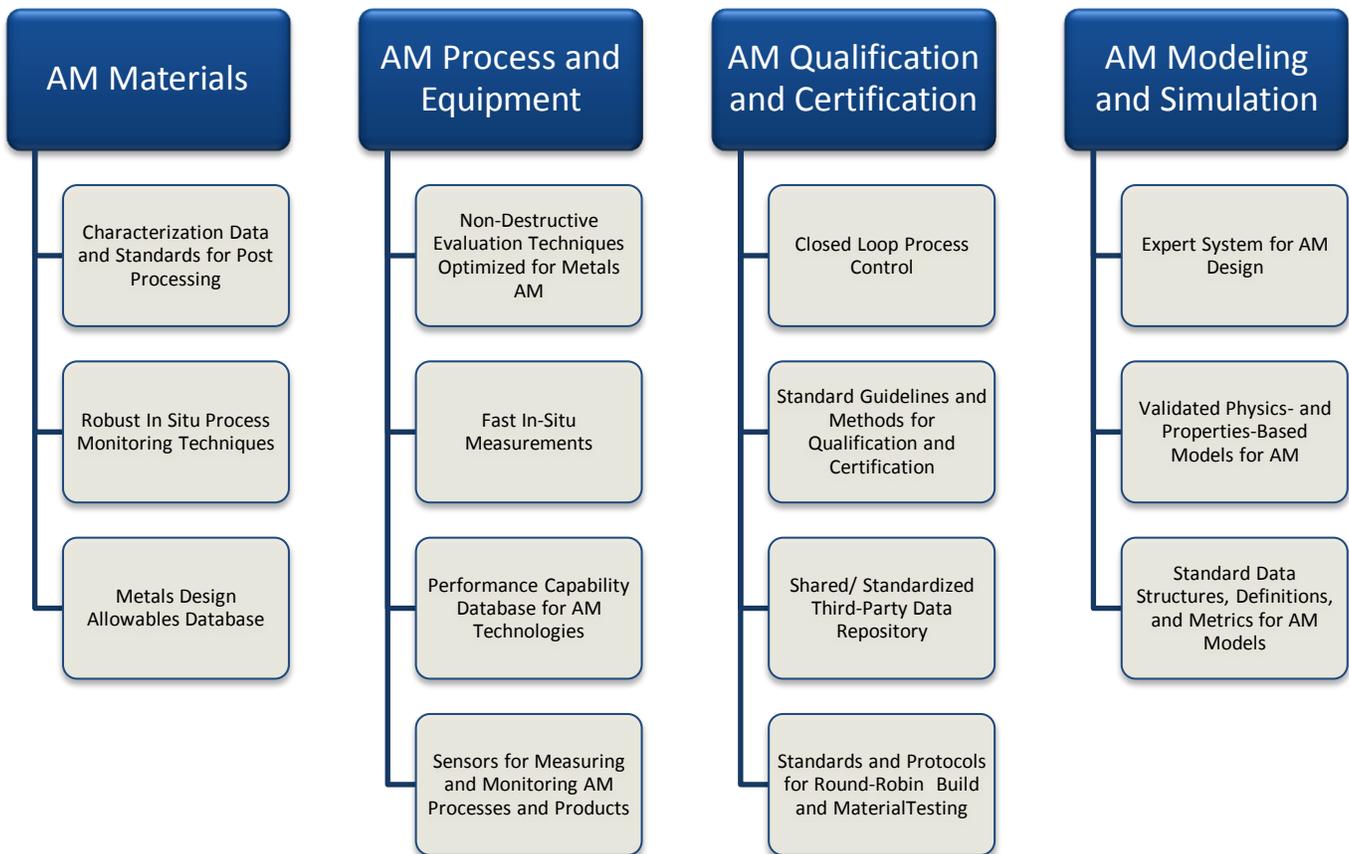


Figure E-2. Important Technology and Measurement Challenges for Additive Manufacturing

SUMMARY OF RESULTS

Each breakout group identified future desired capabilities and technologies for AM, and measurement barriers impeding advances. Several of the higher priority challenges were examined more closely to create a roadmap for R&D, standards development, and other future efforts for AM. The roadmap addresses the priority challenges for each topic area as illustrated in Figure E-2.

A number of the challenges shown in Figure E-2 have elements that cut across all aspects of additive manufacturing, from materials and modeling to design and manufacturing processes. Examples of some of these include:

- **Standards and protocols** for all aspects of AM, from materials design and use to part build and inspection
- **Measurement and monitoring techniques and data**, from material feedstock through final part inspection, including effective process controls and feedback
- **Fully characterized materials properties**, which are key to materials development, processing effectiveness and repeatability, qualification of parts, and modeling at many levels
- **Modeling systems that couple design and manufacturing**, which impacts the development of materials as well as new processing technologies
- **Closed loop control systems for AM**, which are vital for processing and equipment performance, assurance of part adherence to specifications, and the ability to qualify and certify parts and processes

CHAPTER 1: INTRODUCTION

OVERVIEW

Additive manufacturing (AM) is a high-priority technology growth area for U.S. manufacturers. Innovative AM processes that fabricate parts layer-by-layer directly from a 3-D digital model have great potential for producing high-value, complex, and individually customized parts. Companies are beginning to use AM as a tool for reducing time to market, improving product quality, and reducing the cost to manufacture products. Metal-based AM parts have emerged for use in a number of applications, such as automotive engines, aircraft assemblies, power tools, and manufacturing tools such as jigs, fixtures, and drill guides.

AM offers multiple advantages over traditional manufacturing techniques, including reduced material waste, lower energy intensity, reduced time to market, just-in-time production, and construction of structures not possible with traditional manufacturing processes. By adding precisely measured layers to create an object, wasted materials or by-products are greatly reduced when compared to traditional manufacturing techniques. In traditional aerospace manufacturing, for example, titanium parts are machined down to size from larger blocks of titanium, which produces up to 90% waste material that cannot be readily reused. AM could greatly reduce the waste from this process, reducing the energy used in production of raw materials and in the processing steps.

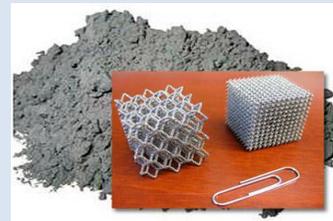
Historically, bringing a part from concept to production has required numerous prototyping iterations that include machine reconfigurations and expensive and time-consuming part tooling and prototype fabrication. Much of the prototyping with AM can be accomplished with computer models, thereby reducing the time to reach full production. In addition, the rapid reconfiguration of AM setups increases the economic feasibility of small batch production.

The unique AM process allows the creation of scaffolding-like structures, mimicking materials found in nature. These complex structures can reduce weight without compromising strength or increasing surface area. The potential applications for these structures are wide-ranging. AM can also be used for remanufacturing parts that have reached the end of their useful life, restoring them to like-new parts. Advanced techniques and surface treatment processes result in a part that potentially requires 2%–25% of the original energy and only a fraction of the material.²

A number of technical issues must be addressed to achieve widespread use of additive processes for direct part production, and to realize the potential economic benefits. Among the issues are gaps in measurement methods, performance metrics, and standards needed to evaluate

fundamental AM process characteristics, improve the performance of AM equipment, improve the accuracy of AM parts, and increase confidence in the mechanical properties of parts fabricated using these systems.

Materials Standards for AM



The adoption of parts made via AM processes into critical applications, such as aerospace engine components, is hampered by a lack of consensus properties for AM part materials (required for many procurement specifications). Industrial round-robin testing, which includes both the fabrication and mechanical property measurements of test specimens, is a required step for developing consensus properties and acceptance into authoritative material databases.

The National Institute of Standards and Technology (NIST) is currently assessing state-of-the-art testing methods for determining properties of bulk metal materials and raw metal powders, including mechanical testing, non-destructive techniques, and X-ray diffraction. Methods will then be evaluated and enhanced for use on AM parts and raw additive powder. Direct Metal Laser Sintering (DMLS) will be used to make parts and test the new methods. NIST will also coordinate an industry round-robin testing study of processed-part material properties for a selected AM material and AM process, a first step for acceptance of material into an authoritative database.

(<http://www.nist.gov/el/isd/sbm/matstanddmanu.cfm>)

² John Sutherland et al., “A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production,” *CIRP Annals—Manufacturing Technology* 57, no. 1 (2008): 5-8.

WORKSHOP SCOPE AND PROCESS

The National Institute of Standards and Technology (NIST) hosted the *Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing* at their Gaithersburg, MD campus on December 4–5, 2012. The workshop supported NIST programs in the area of smart manufacturing processes and equipment and addresses a high-priority technology growth area for U.S. manufacturers. The workshop brought together over 75 AM experts from industry, government, national laboratories, and academia to identify measurement science challenges and associated R&D needs for metal-based AM systems. This workshop aimed to accomplish the following.

- Build on prior AM roadmaps and other efforts that have identified technology challenges and R&D needs, by developing information on:
 - Measurement science barriers, challenges, and gaps preventing broad use of metal-based AM
 - Research and development (R&D) needed to address the priority measurement and standards challenges
 - Future measurement- and standards-related targets and goals for AM
 - Action plans to overcome the high priority barriers
- Provide input for strategic planning by the ASTM International standards organization F42³ standards committee on Additive Manufacturing Technologies
- Influence and coordinate with National Additive Manufacturing Innovation Institute (NAMII) on the development of a national AM roadmap

The workshop included a stage-setting plenary session, panel discussions, and extended breakout sessions as described below. The full workshop agenda is provided in Appendix B.

PLENARY SESSION

Presentations from leading industry experts were given to set the stage for the subsequent workshop discussions. The full presentations can be downloaded from the workshop website at <http://events.energetics.com/NIST-AdditiveMfgWorkshop/downloads.html>. The presentations included the following:

- **Workshop Scope and Objectives:** Kevin Jurrens, Deputy Chief, Intelligent Systems Division, NIST
This presentation discussed NIST's unique mission, measurement and standards outputs from NIST laboratories, and AM contributions from NIST's Engineering Laboratory, Materials Measurement Laboratory, and Manufacturing Extension Partnership. The workshop scope, process, and desired outcomes were also presented.
- **Roadmaps for Additive Manufacturing — Past, Present, and Future:** Dave Bourell, Temple Foundation Professor, University of Texas at Austin, Co-Chair 2009 Roadmap for Additive Manufacturing
A review and comparison of previous AM roadmap efforts was presented, including the 1998 National Center for Manufacturing Sciences Roadmap Study⁴, 2009 National Science Foundation/Office of Naval Research Roadmap Study⁵, and 2010 U.S. Naval Air Systems Command Direct Digital Manufacturing of Materials⁶.
- **Additive Manufacturing: Standards and Other International Trends:** Brent Stucker, Professor, University of Louisville, Chair of ASTM F42

³ ASTM F42: Committee F42 on Additive Manufacturing Technologies, <http://www.astm.org/COMMITTEE/F42.htm>

⁴ 1998 Industrial Roadmap for the Rapid Prototyping Industry", National Center for Manufacturing Sciences, Report 0199RE98

⁵ Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing, prepared by University of Texas at Austin, Missouri University of Science and Technology, and Georgia Institute of Technology, sponsored by the National Science Foundation and Office of Naval Research. 2009 <http://wohlersassociates.com/roadmap2009.html>

⁶ Direct Digital Manufacturing of Metallic Components: Affordable, Durable, and Structurally Efficient Airframes, NAVAIR, ONR, 2012.

Information was provided on the role of the University of Louisville in AM, ASTM F42 scope and accomplishments, various AM processes (e.g., vat photo-polymerization, material jetting, powder bed fusion), the output and parameters of AM, current and future AM standards, and a strategic approach for AM standards development.

- **NAMII Priority Applied Research Needs:** Gary Fleegle, Vice President and Chief Operating Officer, National Center for Defense Manufacturing and Machining, NAMII Acting Deputy Director for Technology Development
This presentation illustrated how NAMII works toward goals by fostering strong public-private collaboration, using an integrated technology plan, and involving industry through open membership, project calls for key topics, and other initiatives.
- **Manufacturing – the Road to Success:** Tom Kurfess, Assistant Director for Advanced Manufacturing, Office of Science and Technology Policy, Executive Office of the President
This presentation stressed the importance of U.S. manufacturing to the economy. Conducting 70% of U.S. R&D and producing \$1.40 for every \$1.00 of manufacturing output, the U.S. manufacturing industry drives jobs throughout the economy. Advanced manufacturing initiatives, such as the National Robotics Initiative, the Materials Genome Initiative, and the White House’s initiatives encouraging science, technology, engineering, and mathematics (STEM) careers, were cited as greatly benefiting the AM industry.

INDUSTRY PANEL DISCUSSION

Following the opening presentations, a moderated panel session was held to discuss the current state and needs of the AM industry. The moderator and panelists are listed in Figure I-2. The key points that emerged are summarized below, and reflect the unique opinions of the panelists and their respective fields of endeavor. Many of the panel themes were echoed during the breakout sessions and further expanded upon.

Important overall goals for AM include:

- Reducing risk to stakeholders in the community and supply chain
- Transitioning AM into production applications
- Building the AM capabilities needed to successfully move forward and appropriately insert technology

Standards are important to moving AM forward. Some key standards-related issues include:

- Consistent machine calibration standards for prototyping or production beyond machine variability, this is especially important for the aerospace industry where standards are nonexistent
- Benchmarking studies to determine the frequency of machine calibration

Process monitoring is important for quality and production throughput. Key capabilities needed include:

- Real-time process monitoring techniques to increase knowledge base
- Data that will help develop feedback systems, predictive processing, and modeling capability
- Process sensing and control to improve the accuracy and repeatability of AM

Knowledge of AM raw materials is inadequate and requires work in these important areas:

- Output quality as a function of material input quality (e.g., composition, chemistry, morphology, and particle size distribution of the feedstock affects the final AM product)
- In depth understanding of raw materials (e.g., test for laser powder deposition conducted with virgin and recycled powder, the recycled performed better, why?)

Figure I-1. AM Panelists

Moderator, Ed Herderick, EWI, Chair of Additive Manufacturing Consortium (AMC)

- **Agnes Klucha**, Program Manager, Engineering Innovation Center, Pratt and Whitney
- **John Hunter**, Director of Marketing & Sales, Carpenter Powder Products, Inc.
- **Dean Robinson**, Manager, Model-Based Manufacturing Lab, GE Global Research Center
- **Hank Phelps**, Senior Engineer, Technology Development & Integration, Airframe Design, Lockheed Martin Aeronautics

- Chemistry of the powder and potential changes during AM processing (e.g., many powders are not designed specifically for AM processes)
- Clarify intended use and specifications for powder suppliers
- Openly accessible high-fidelity material property databases

Higher quality products require improvements to AM processes, including:

- Methods for improving as-built surface finish
- Predictive models for distortion correction such as process modeling, brute force methods, or reverse engineering (e.g., review work done for predictive modeling castings/forgings for heat treatment distortion); *Dante* software is commercially available and could have applicability for AM-produced metal parts
- Tools to exploit AM design capabilities, such as better geometrical design tools
- Incorporating lessons from historical development of parts or other manufacturing process

WORKSHOP PROCESS

The workshop was designed to include four breakout groups, each focusing on a different technical aspect of metal-based AM, as shown in Figure 1-2. White papers were created and submitted by workshop participants prior to the workshop to provide additional background and a starting point for discussions; these are provided in Appendix C. Within each breakout group, several key questions were posed to gain insights on the important challenges and pathways to address them, including:

- What are the ideal targets for technology, process, performance, or capability that we want to achieve for AM (in the breakout topic area)?
- What are the technology, measurement, and standards barriers that keep us from achieving the desired future end state why?
- Are there any additional barriers limiting the broad, more widespread use of additive manufacturing and why?

Figure 1-2. Workshop Breakout Topics

- AM Materials
- AM Processes and Equipment
- Qualification and Certification of Materials, Processes, and Products
- Modeling and Simulation of AM

The results of these discussions are summarized in the following report chapters, which are organized by breakout topic. Each breakout group used a simple voting scheme to indicate which challenges would potentially have the most impact if addressed and those most urgent to address to ensure progress. After prioritizing the challenges as high, medium, or low, several of the higher priority challenges were examined more closely to create a roadmap for R&D, standards development, and other future efforts for AM. The results of these in-depth examinations can be found in the *Roadmap for Priority R&D* section of each chapter. A variety of acronyms unique to this topic are noted throughout the report and listed with explanations in Appendix D.

Note that the ideas presented here are a reflection of the expert participants and not necessarily the entire metal-based AM industry. As such, they should be viewed as a snapshot of the important perspectives, but not all-inclusive. In some cases, ideas overlap among breakout groups, illustrating the cross-cutting nature of some priorities and challenges.

This report provides useful information to both public and private decision-makers interested in furthering the capabilities of AM and accelerating its more widespread use in the industrial sector. In addition, this report will be contributed for integration with the NAMRI national AM roadmap and will provide a foundation for development of the ASTM F42 Strategic Plan. By focusing on metal-based AM, the workshop was able to thoroughly address one portion of the overall AM roadmap. It is hoped that the national research agenda for metal-based AM will incorporate the consensus-based needs and priorities established during this workshop and presented in this report. The workshop report and supporting documents can be found on the workshop website at <http://events.energetics.com/NIST-AdditiveMfgWorkshop/index.html>.

CHAPTER 2: AM MATERIALS

OVERVIEW OF THE TOPIC AREA

Metal materials currently in use in additive manufacturing (AM) include steels (tool steel and stainless), pure titanium and titanium alloys, aluminum casting alloys, other alloys (nickel based and cobalt-chromium), gold, and silver. The range of metals available for use in AM continues to grow as new technologies and applications emerge.

AM materials have many implications for a wide range of applications in the areas of national security, energy, photonics, micro fluidics, and semiconductor manufacturing. To utilize the full potential of AM, the materials used will need further development. Although significant progress in new AM materials has been possible, a number of challenges remain. For example, AM parts must meet desired specifications for toughness, fatigue, strength, and other properties. Currently, such understanding is not available due to lack of sufficient testing, lack of shared knowledge and materials test results across the AM community, and lack of standardized test methods for AM materials.

FUTURE/DESIRED CAPABILITIES

In the future, AM materials will facilitate more direct part production and shorter lead times and production runs. Designers will find a greater variety of product capabilities to satisfy their form, fit, and function needs. Table 2-1 provides further details on the desired capabilities and technologies for AM materials. Many of the capabilities shown take advantage of additive manufacturing to provide new material functionalities or to utilize materials in unique ways.

Materials

Raw materials characteristics are critical to AM product quality. As a result, improvements to feedstock materials or development of new materials could have a direct impact on facilitating more widespread use of AM. A comprehensive understanding of the material properties that most affect micro-structure and those that can cause material deviation is essential to designing new materials to take full advantage of the AM process (e.g., faster solidification rates with new high-temperature alloys). Better understanding of AM materials properties, characteristics, and performance parameters is also desired to enable better utilization in applications. Greater knowledge in these areas would improve not only the ability to design new materials and products, but also enable better control of the AM process and the quality of the final products.

New materials could include multiple capabilities or smart technology (e.g., sensors built-in to material structures) that lead to new applications of AM. The ability to utilize multiple materials in the same part, or to change out single materials to provide unique characteristics, would open new opportunities for AM products.

Materials Process Control

In-process material data acquisition would enable closed loop control, measurement of in-situ material properties, allow for property predictions, and provide micro-structural control. Improved understanding of in-process material performance would advance the ability to control residual stress distortion and in-process material consistency, issues that are both important to product quality.

Supply Chain Capabilities

Reliable, available, and consistent powders and wire are essential for quality AM products, reducing production risks, and gaining wider adoption of AM technology. Greater availability of materials is needed in general. Innovative methods for materials production, such as directly from ores, could be one approach for increasing materials availability. There is also a shortage of material recycling services and means for reusing AM materials.

Metallurgical / Powder Properties Knowledge

Greater understanding and characterization of AM materials is needed, such as powder size, shape, and chemistry. The ability to tie surface characteristics to effects on fatigue properties would enable design of materials with improved performance. Similarly, defect type, frequency, and size quantification could facilitate the understanding of property impacts on product quality and performance.

Standards Specification Database

Databases and standards or specifications for all aspects of AM materials were identified as an important foundational aspect. Databases would include alloy specifications, as well as information on AM material properties and micro-structural characteristics at all stages of processing and use. AM material properties should be housed in a publically accessible database that includes common alloy specifications, machine independent material properties for deposited metals, micro-structural characteristics, and images (for virgin and recycled feedstocks, in-situ processes, finished build, etc.).

Table 2-1. Desired Capabilities and Technologies for AM Materials

Materials by Design

- Materials designed for “build-ability,” chemistry, and physical form
- Materials engineered to take full advantage of AM functional materials, such as smart materials (e.g., sensor built-in to material structure where the material is the sensor) and new alloys (e.g., faster solidification rates with new high-temperature alloys)
- Multiple material capabilities (i.e., ability to print multiple powders in varying concentrations in a single build, ability to change out one part material)
- New materials (functionally-graded, metal/ceramics, metal matrix composites, new AM classes not derived from history or wrought, graded material properties within structures, location-specific materials and microstructures)
- Utilization of materials that cannot be converted into products via traditional processes (e.g., new materials enabled by AM processes)
- AM parts as “drop-in” replacements for conventional manufactured parts (e.g., castings or powder metal)

Material Process Control

- Advances in reducing/controlling residual stress distortion
- Knowledge of parameters (e.g., upper and lower limits) that can cause material deviation in a process
- Consistent material properties based on process control
- Understanding the parameters that most affect micro-structure
- Measurement of material properties in-process:
 - Real-time data from AM processes to enable property predictions (and process relationships) and micro-structural control
 - In-situ data acquisition, including temperature management, to enable closed loop control

Supply Chain Capabilities

- Reliable, available, consistent powders and wire for AM
- Ability to create feedstock for AM from ore elements
- Greater availability of materials
- Ability for recycling and reuse of AM materials

Metallurgical / Powder Properties Knowledge

- Quantification of defect types, frequency, size and impact on properties
- Established surface characteristics and effects on fatigue properties
- Better understanding and characterization of AM materials and input materials, including powder size, shape, and chemistry

Standards Specification Database

- Strong database of material properties
 - Public access to common alloy specifications for AM processes
 - Machine-independent material properties for deposited metals
 - Micro-structural database with images at each step, including (a) feed stocks, both virgin and recycled; (b) in-situ process; and (c) finished build

TECHNOLOGICAL & MEASUREMENT/STANDARDS CHALLENGES

A number of technical and measurement challenges to continued advances in AM materials were identified. A major issue is insufficient understanding of post-processing, which involves the removal of the part from the platform or the removal of support structures for the purpose of finishing the part. Another major issue is the inability to monitor and detect anomalies during the additive manufacturing process. This capability would allow the manufacturer to make appropriate adjustments to laser power, processing speed, or other parameters in real-time to improve the final product. A complete list of the challenges identified is provided in Table 2-2.

Table 2-2. Barriers and Challenges for AM Materials

(● = one vote)

Materials Processing	
<i>High Priority</i>	<ul style="list-style-type: none"> ● Limited understanding of post-processing issues for AM materials ●●●●● <ul style="list-style-type: none"> ○ Thermal post-processing behavior (not similar to wrought or forged materials) ○ Hot isostatic pressing (HIP), heat treatment, welding, etc. are not well-characterized
<i>Low Priority</i>	<ul style="list-style-type: none"> ● Lack of control over microstructure gradients in as-built parts ● Insufficient methods to manage AM process and technology risks ● Challenging materials data storage and retrieval solutions, image analysis, and modeling <ul style="list-style-type: none"> ○ Challenges in handling massive amounts of process data ○ Insufficient methods for process analysis and statistics
Measurement and Monitoring of Materials In-Process	
<i>High Priority</i>	<ul style="list-style-type: none"> ● Lack of robust in-situ monitoring and measurement for materials performance ●●●●● <ul style="list-style-type: none"> ○ Lack of capability for high-speed video and high-speed thermograph (e.g., for deposition of materials on windows) ○ Lack of real-time materials monitoring and measurements ○ Inability to perform in-situ detection of processing anomalies leading to discontinuities: thermal gradients, voids, and inclusions ○ Ineffective feedback control for material composition and microstructure; sensor integration is unattainable with current black box controllers
<i>Medium Priority</i>	<ul style="list-style-type: none"> ● Lack of external measuring, understanding, and ability to control residual stress ●●
<i>Low Priority</i>	<ul style="list-style-type: none"> ● Developing alternative in-situ instrumentation technologies (e.g., process monitors) ● Lack of robust, effective, affordable external non-destructive evaluation (NDE) methods ● Lack of validated characterization/selection criteria for powder or wire feedstock used in AM production
Materials Standards	
<i>Medium Priority</i>	<ul style="list-style-type: none"> ● Lack of microstructure standards to enable evaluative criteria/judgments ●●● ● Limited certified measurement methods/specifications for powder chemistry and size distribution ●●●
<i>Low Priority</i>	<ul style="list-style-type: none"> ● Incomplete understanding of how to characterize AM surface roughness ● ● Lack of AM materials standards to build customer confidence in AM ● ● Lack of standards for utilizing sensor technology/tools for open system in-process materials control ● ● Incomplete standards for collecting, mining, and combining data on materials ●
Materials Data	
<i>Medium Priority</i>	<ul style="list-style-type: none"> ● Lack of AM material data sharing across companies due to intellectual property (IP) restrictions, unique data types, and other factors ●●● ● Limited metallurgical/powder properties knowledge ●●●● <ul style="list-style-type: none"> ○ Variation of part properties when made on different machines ○ Limited availability of reference material/data ○ Lack of a fixed-source metals database (e.g., standard protocols and data for AM materials, x-y-z specimen preparation, etc.)
<i>Low Priority</i>	<ul style="list-style-type: none"> ● Compatibility of AM processes with regulatory certification requirements based on statistical process control (SPC)

ROADMAP FOR PRIORITY RESEARCH AND DEVELOPMENT

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 2-2. Roadmap action plans are outlined in more detail in Figures 2-1 through 2-3. The key barriers being addressed and the corresponding priority roadmap topics are summarized in Table 2-3.

Table 2-3. Key Barriers and Corresponding Priority Roadmap Topics for AM Materials

High-Priority Challenge/Barrier	Priority Roadmap Topic
<p>Understanding of post-processing issues for AM materials is currently limited, making it difficult to design AM hardware and effectively control materials properties.</p>	<p>Characterization Data and Standards for Post-Processing (Figure 2-1) Models, standards, and datasets are needed to improve post-processing control of material properties and ultimately the final product.</p>
<p>In-situ monitoring and measurement for materials performance is limited and lacks robustness (e.g., real-time measurements, deposition of materials, detection of anomalies, feedback control).</p>	<p>Robust In-Situ Process Monitoring Techniques (Figure 2-2) Robust, innovative inspection and control technologies are needed to enable effective in-situ monitoring of materials processing and allow for detection and/or mitigation of anomalies.</p>
<p>Metallurgical/powder properties knowledge and reference data is currently limited, particularly understanding how part properties vary by machine.</p>	<p>Metals Design Allowables Database (Figure 2-3) Open databases of material properties need to be developed to enable determination of product design and testing is needed to establish material design allowances.</p>

FIGURE 2-1. ROADMAP ACTION PLAN: CHARACTERIZATION DATA AND STANDARDS FOR POST PROCESSING

BARRIER: Thermal post processing requirements for AM components are different from thermal processing for wrought materials due to how the feedstock is manufactured and intrinsically due to the AM process itself. The effects of these factors on final product characteristics are poorly understood. Thermal post-processing behavior, HIP, and heat treatment of AM parts are not well-characterized.

APPROACH SUMMARY: Build on conventional metallurgical understanding of AM processes and materials, and develop requirements specific for AM processes.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1-2 years	<ul style="list-style-type: none"> Conduct industry survey of AM feedstock vendors to collect critical parameter information (e.g., chemistry, microstructures) Understand gaps in existing versus required process Begin to build repository of process parameters and existing controls, e.g., for non-destructive inspection (NDI) 	<ul style="list-style-type: none"> Consolidation of critical material and process parameters Published gaps in existing parameters and updated roadmap Established a database with key process parameters 	<ul style="list-style-type: none"> First-time, quality aerospace metal AM-built parts Validated and specified post process work for the first time on AM built parts
3-5 years	<ul style="list-style-type: none"> Define process standards and measurements Establish public access for AM microstructure database for aerospace alloys Integrate computational modeling of post AM material with database (e.g., for NDI) 	<ul style="list-style-type: none"> Published new/updated process and measurement standards Open access to alloy database Published model detail and preliminary comparison to micro-structural database 	
5+ years	<ul style="list-style-type: none"> Conduct demonstration to validate post AM process models and standards Update post process requirements and standards as required Develop NDI techniques and protocols 	<ul style="list-style-type: none"> Models and standards validated or revised Machine-independent properties for deposited metals Improved surface finish 	

STAKEHOLDERS & POTENTIAL ROLES

- Industry/AM Users:** Provide input on requirements, issues, needs
- Industry/AM Providers:** Provide solutions, tools, techniques
- Academia:** Develop model, frameworks, data and software
- Standards Committees:** Create guidance, standards, specifications, documents
- Government:** Provide infrastructure and test methods

RELATIVE IMPACTS

Low — HIGH

- ◆◆◆ **Accelerates innovation:** Engineers have valid information to design parts
- ◆◆◆ **Enhances industry competitiveness:** Industry becomes viable
- ◆◆◆ **Faster product development time:** Industry becomes viable
- ◆◆◆ **Improves product quality:** Improved part/quality and consistency
- ◆◆ **Reduces costs:** Reduces scrap and reduces redundant databases
- ◆◆ **Other:** Improves manufacturing methods

FIGURE 2-2. ROADMAP ACTION PLAN: ROBUST IN-SITU PROCESS MONITORING TECHNIQUES

BARRIER: In-situ process monitoring techniques for material and product defects are currently not robust and lack key capabilities (e.g., high-speed video and high-speed thermograph for deposition of materials, real-time measurement, and in-situ detection of processing anomalies leading to discontinuities, such as thermal gradients, voids, and inclusions). Feedback control for composition and microstructure, and sensor integration is not attainable with current black box controllers.

APPROACH SUMMARY: Identify, develop, and implement process monitoring, NDE, and in-process measurement techniques to enable maximum detection of material defects.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> Identify and implement existing process monitoring technologies, identify constraints and limits, and resolve measurement capabilities Collect and analyze critical data Correlate process monitoring data to NDE measurements 	<ul style="list-style-type: none"> Implementation of process monitors on existing AM platforms Identification of limits of existing sensor/process monitoring equipment Correlation of NDE and mechanical testing to determine if sensor resolution is adequate 	<ul style="list-style-type: none"> Maximized detection capabilities to qualify production with batch size of one
3–5 years	<ul style="list-style-type: none"> Correlate NDE data with destructive testing Identify existing, alternate, and in-process measurement techniques not being investigated that are capable of scaling with AM processes Identify and develop techniques for real-time and long-term collection, analysis, and storage of massive data sets 	<ul style="list-style-type: none"> Identification of alternatives that address the gaps of existing process monitoring technologies Implementation of these new technology detection limits Correlation to NDE and mechanical testing Demonstration of the ability to collect and store the pertinent data 	
5+ years	<ul style="list-style-type: none"> Use data to drive modeling efforts Correlate modeling with process measurement to enable robust process control (e.g., vision system identifies a defect/pore, process control system corrects and eliminates defects) 	<ul style="list-style-type: none"> Demonstration of direct correlation between process monitoring, control, and NDE 	

STAKEHOLDERS & POTENTIAL ROLES

- Industry/AM Users:** Aerospace, biomedical, oil and natural gas industry: Identify needed material and mechanical properties
- Industry/AM Providers:** Open up software and collaborate with researchers to implement and support these techniques
- Academia:** Conduct basic research and analysis
- Standards Committees:** Evolve standards along with the technology
- Government:** Support standards development; Coordinate and facilitate cooperation among NIST, Oak Ridge, NASA, DOE, DOC, NSF, NIH, DARPA; Resources (i.e., neutral source)

RELATIVE IMPACTS

LOW—HIGH

- ◆◆◆ **Improves product quality:** Eliminate defects; Have an intimate and unprecedented understanding of component quality
- ◆◆◆ **Reduces costs:** Scrap, raw materials; Reduce capital investments in forming/shaping
- ◆◆◆ **Accelerates innovation:** For example, making available the data needed to develop techniques for designing micro-structuring
- ◆◆◆ **Enhances industry competitiveness:** Lower lead times (e.g., batch size one production)
- ◆◆◆ **Faster product development time:** Eliminate need for tooling
- N/A **Other:** Needed for AM to be a manufacturing tool

FIGURE 2-3. ROADMAP ACTION PLAN: METALS DESIGN ALLOWABLES DATABASE

BARRIER: No public database exists to derive materials properties for design allowables for specific processes. Acquiring data is difficult due to the number of AM machine manufacturers, the evolution of machine control software/hardware versions, and the lack of standard protocols for AM materials (e.g., x-y-z specimen preparation).

APPROACH SUMMARY: Undertake collaborative effort to test specific materials and processes and establish databases. Three aspects of this activity are (1) Feedstock (e.g., powder, wire); (2) Manufacturing Platform (i.e., Electron Beam (ARCAM 5-12, A-1, A-2, A-2x, A-2xx) or Laser Beam (EOS – M270, M280; Concept laser – M2, M2ab; Renishaw – AM125, AM2510; ; Phoenix Systems - PXL, PXM, PXS, PXS & PXM dental; SLM Solution – SLM 280, SLM 250 Realizer) (3) Testing Protocol

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1-2 years	<ul style="list-style-type: none"> ◆ Feedstock <ul style="list-style-type: none"> ○ Identify alloy testing priorities ○ Develop material specification for each machine ◆ Manufacturing platforms <ul style="list-style-type: none"> ○ Prioritize processes/materials ○ Develop standards for initial machine metrics ○ Identify parameters that significantly affect material properties ○ Determine upper and lower limits for parameters that affect properties ◆ Testing Protocol <ul style="list-style-type: none"> ○ Design testing protocol (i.e., x, y, z build location); begin testing on high priority pairs (materials/processes) ○ Identify facilities where specimen building will occur ○ Qualify machines 	<ul style="list-style-type: none"> ◆ General <ul style="list-style-type: none"> ○ Documentation on data reporting ○ Initial database/repository established ◆ Feedstock <ul style="list-style-type: none"> ○ Materials/alloys identified ○ Alloys acquired ○ Material specification published ◆ Manufacturing Platforms <ul style="list-style-type: none"> ○ ASTM standard published for initial machine metrics ○ Process parameters identified for priority platforms ◆ Testing Protocol <ul style="list-style-type: none"> ○ Test specimens built and tested for top 2 alloy types 	<ul style="list-style-type: none"> ◆ Low cost, flexible database that can be updated as technology changes ◆ Industry acceptance of data ◆ Greater use of AM ◆ Feedstock <ul style="list-style-type: none"> ○ Standardized feedstock properties ◆ Manufacturing Platforms <ul style="list-style-type: none"> ○ Published standard for determining machine platforms suitable for processing materials
3-5 years	<ul style="list-style-type: none"> ◆ Testing Protocol <ul style="list-style-type: none"> ○ Produce test specimens ○ Test specimens and analyze results ○ Expand materials testing to cross process barriers ○ Compare results for models ○ Incorporate flexibility (database changes as more information becomes available from sensors) 	<ul style="list-style-type: none"> ◆ Feedstock <ul style="list-style-type: none"> ○ Alloys acquired ◆ Manufacturing Platforms <ul style="list-style-type: none"> ○ Machine standard to which machine manufacturer must comply ◆ Testing Protocol <ul style="list-style-type: none"> ○ Test specimens built and tested for top 10 alloy types 	<ul style="list-style-type: none"> ◆ Testing Protocols <ul style="list-style-type: none"> ○ Robust testing protocol that can accommodate the various technological differences

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide feedstock specifications for evaluation, data mining, and determining priorities; part production
- ◆ **Industry/AM Providers:** Identify parameters that significantly affect variability
- ◆ **Academia:** Determine upper and lower limits of parameters
- ◆ **Standards Committees:** Publish initial metrics, set material/machine standards
- ◆ **Government:** Support and facilitate cooperation

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** Improves part quality and consistency, understanding
- ◆◆◆ **Reduces costs:** Reduces scrap; Reduces redundant databases
- ◆◆◆ **Accelerates innovation:** Engineers have valid information to design parts, promotes use of AM
- ◆◆◆ **Enhances industry competitiveness:** Industry becomes viable
- ◆◆◆ **Faster product development time:** Industry becomes viable

CHAPTER 3: AM PROCESSES AND EQUIPMENT

OVERVIEW OF THE TOPIC AREA

Additive Manufacturing (AM) technologies use metal, polymer, or composite materials to develop a three-dimensional “print” of a given part. The two processes commonly employed for metal AM materials (the focus of this report) are powder bed fusion and directed energy deposition. Direct energy deposition potentially has the capability to use multiple materials (combination of two or more powders). Other metal-based processes in use, but not as common, include material jetting and ultrasonic bonding. Most AM systems melt the metal materials and produce parts with close to 100% density, with properties that can match or exceed those of a cast part.

Much progress has been made in the development of AM processes and equipment, but some significant challenges must be addressed to move AM more into the mainstream. Improving product quality, increasing the efficiency of production, gaining the ability to rapidly produce larger and more diverse parts, and lowering production costs are a few of the important challenges that are directly impacted by processing techniques. Overcoming these barriers in many cases requires approaches that are unique to the type of processes and equipment employed, and account for the materials being used.

FUTURE/DESIRED CAPABILITIES

In the future, new capabilities are needed to improve equipment efficiency, enable more rapid production at larger scales, and ensure repeatable product quality. The capabilities identified to achieve this are described briefly below and listed in Table 3-1.

AM Process Technology

Improved equipment efficiencies and finishing processes are needed. Ideally, overall equipment efficiencies (OEE) of greater than 70% are desired (i.e., world-class automotive production has OEE of roughly 85%). The AM community would benefit from technology that effectively utilizes multiple material types to create products with increased functionality. This includes, for example, the ability to facilitate composite fabrication (i.e., non-metal and metal composites) to produce multi-functional composite materials. More efficient powder distribution systems (i.e., cleaner, targeted, and recycle control) can lessen the waste of powder inputs. In addition, better control and capabilities to build microscale features (i.e., less than 200 microns) are needed, along with commercially viable equipment that can be used across industry platforms.

Production Speed and Scale

High-speed production equipment is needed for high-volume manufacturing, potentially at a lower cost. Achieving a level of affordable, small-lot production could provide a range of users (i.e., supply chain companies and end-use consumers) with access to designer materials and a network of AM part producers. Continuous processing and distributed manufacturing would also allow for more rapid and customized production of parts.

Product Quality

Producing higher quality parts is a key capability identified by experts and stakeholders in the AM community. Minimal post-AM processing can help achieve defect-free parts that meet technical requirements at cost-competitive rates of production. Issues with product quality have emphasized the need for stress-relieved, geometry- and composition-correct, homogeneous deposited materials that will enable production of higher quality parts. Broad deployment of machines and processes capable of producing parts at the level of quality seen in the aerospace industry, for example, would greatly benefit the growing AM industry.

Standards and Protocols

Development of standards and protocols for metal-based AM parts can help improve the quality and repeatability of results from AM processes. Developing standards will require determining what factors need to be controlled to ensure part consistency. The objective is to develop standard methods for qualification and certification that will increase the numbers of certified AM parts in service in the U.S. economy. Computer-Aided Design (CAD) approaches and best practices must be developed that take advantage of unique AM capabilities. This highlights the need for an improved common file format for use in AM equipment and processes. The goal is transforming CAD into a computer-aided manufacturing tool for AM technologies. New AM file formats would need to be standardized through the ASTM F42 committee.

The large amounts of data being generated and made available to the AM community continue to grow, driving the need for data analysis tools and definition of part properties to enable appropriate archiving. Techniques and standards are also needed to characterize multi-material parts.

Process Measurement, Monitoring, and Control

Improved sensors and controls used in AM equipment and processes can enhance monitoring and control capabilities to provide real-time visibility and control of the build environment. Optimal systems for process monitoring and control will help AM systems limit the risk of cross-contamination of metal powders. Real-time inspection and material property determination during the deposition process can improve production of qualified parts directly from the AM machine. Process monitors and controls should be fully integrated with the AM process. This would enable a number of improvements to monitoring and control capability, such as the ability to monitor part geometry layer-by-layer for real-time part qualification, and the ability to control or mitigate distortions and residual stress in parts. In the future, machines that are self-monitoring and self-calibrating could self-correct and control important equipment performance parameters.

Measurement methods and tools are critical to monitoring and control on many levels. Benchmarking of experience is needed to improve various aspects of AM equipment and processes. This would include, for example, benchmarks related to the design of AM parts, part geometry, and measurements and accuracies of AM processes. Environmental conditions and impacts are also important, including time, temperature, humidity, dew point, re-use of materials or parts, recyclability, virgin material and re-use ratios, thermal cycling, and oxidation. Non-destructive evaluation (NDE) techniques are needed to enable validation of process performance. Measurement methods before, during, and after the production process should include feedstock “qualification” in the process loop (i.e., before building the part) as well as the ability to quickly and easily validate achievement of desired output, including part microstructures, geometry, and quality.

Process Models

Accessible, user-friendly, high-fidelity modeling tools would benefit all aspects of the metal-based AM community. Modeling and simulation of AM processes can help in assessing the costs and design of parts, thereby improving the final products. Deterministic modeling of the inputs (materials), the transformation process, and final outputs can be used to better predict processing results. Integration of the design function—also known as design for additive manufacturing (DFAM)—with optimization software would lead to more predictable processes and higher quality products.

Knowledge and Data

A greater understanding of properties of materials and AM parts, process parameters, performance, and relationships is needed to improve the predictability of both models and results. A life-cycle knowledge base that captures the evolution of AM technology is an essential component of building this understanding. AM machines vary greatly and have unique life-cycles, from the generation of feedstocks to the end of the process. Capturing data on process performance and parameters to feed life-cycle analysis will require collaboration between the equipment industry and end users.

Table 3-1. Desired Capabilities and Technologies for AM Processes and Equipment

AM Technology

- Open atmosphere processing
- Overall equipment efficiencies (OEE) of greater than 70% (world class automotive production has an OEE of roughly 85%, typical OEE is about 30%)
- Automated, non-geometry-specific finishing processes (tumbling, shot peening, machining, etc.)
- Production of net-shape parts that are ready-to-use
- Technology to enable use of multiple materials in the same part
 - Multi-functional composite materials
 - Facilitation of composite fabrication (non-metal and metal composites)
- Process to produce isotropic material properties
- More efficient powder distribution system (i.e., cleaner, targeted, with recycle control)
- Machine self-validation of maintenance status/build readiness
- Better control and ability to build micro-scale features (i.e., less than 200 microns), including large scale parts (e.g., good properties and surface)

Production Speed and Scale

- Distributed manufacturing (i.e., Kinko's-type AM, iTunes download files)
- Affordable, small-lot production
- Continuous processes for AM
- High-speed AM production equipment for high volume/mass production, faster manufacturing of lower cost parts
- Big working envelope
- Series production, not rapid prototyping or rapid manufacturing; fast cycles and minimized post-processing

Product Quality

- Aerospace production-quality-capable machines and processes
- Scrap rate of less than 1,000 parts per million
- Defect-free parts that meet technical requirements at cost-competitive rates in production
- First-part correctness with minimal post-AM processing (as good as wrought metal)
- Stress-relieved, geometry-correct, composition-correct, homogeneous deposited materials that meet high reliability standards
- Application of statistical process control (SPC): Process capability, Six Sigma (values and distribution) for quality control

Standards and Protocols

- Certified parts in service
- File format commonality (CAD leading to computer-aided manufacturing) synchronized with the ASTM format
- Knowledge of factors that need to be controlled to ensure part consistency
- Standards to ensure repeatability of results

Process Measurement, Monitoring, and Control

- In-process, real-time sensing/monitoring, measurement, and control:
 - Integrated with AM process
 - Intelligent and calibrated decisions and control
 - Contamination-free monitoring capabilities
 - Optimized sensors for process monitoring and control for high-volume production
 - Monitoring geometry of the part layer-by-layer for real-time part qualification
 - Closed-loop process control specifically for metals AM
 - Control/mitigation and measurement of distortion and residual stress in parts
- Self-monitoring, self-diagnostic, self-calibrating machines
- Smart systems with integrated sensors, systems, and software
- Benchmarking of design, part geometry, measurements, accuracies, and number of tests can aid in validating models
- Knowledge of environmental impacts (time, temperature, humidity, dew point, reuse, recycle, and virgin and reuse ratios, thermal cycling, oxidation, etc.)
- Process validation through NDE techniques
- Technician-friendly control part that quickly and easily validates achievement of desired output
- Rapid feedstock “qualification” in the loop just before building the part

Table 3-1. Desired Capabilities and Technologies for AM Processes and Equipment

Process Models

- Integrated modeling and simulation platform with atomistic informed meso-scale capability
- Integration of the design function (i.e., design for additive manufacturing - DFAM) with process optimization software
- Design allowable guidelines integrated with design modeling and simulation tools
- Physics- and chemistry-based cost estimation models
- Deterministic models and predictive capabilities for input transformation and outputs

Knowledge/Data

- Life-cycle knowledge base (i.e., expert systems, artificial intelligence)
- Understanding of properties, process parameters, performance, and relationships to improve predictability
- Recording of material transformation physics data in real time, creating a part history database as the part is being built
- Understanding capabilities (design, materials, cost, and properties) via knowledge a database to identify the best process/application match
- Knowledge of parts where AM could improve the cost-effectiveness of production
- Open architecture for hardware and software
- User friendly hardware, software, maintenance/repair, training, and segue to education

TECHNOLOGICAL & MEASUREMENT /STANDARDS CHALLENGES

The barriers and challenges currently impeding large-scale deployment of AM processes and equipment are presented in Table 3-2 and are categorized by common themes. In each category, specific barriers or challenges are prioritized based on expert and stakeholder input.

The challenges identified revolve primarily around the development of advanced technology; the ability to better monitor and control processes and outputs; the standardization of all aspects of AM, from materials inputs through products; and the enhancement of the knowledge base to support process improvements. The lack of real-time sensors in all the areas critical to process monitoring and control was identified as a major challenge. Closely related to this is the absence of non-destructive evaluation techniques that could be utilized in-situ to monitor and calibrate performance.

The lack of standards was identified as a challenge in a number of areas, since standards are particularly critical to ensure machine-to-machine consistency and provide guidelines for test parts and sensors. Standards development is necessary to overcome the lack of accurate, achievable material datasets for design allowable and control samples. Converting high-fidelity, academic modeling tools into easy-to-use tools for engineers with desktop machines was also noted as a major challenge. While such models exist, they are not comprehensive, readily available, or usable by the AM community at large.

Table 3-2. Barriers and Challenges for AM Processes and Equipment

(• = one vote)

Technology Challenges	
High Priority	<ul style="list-style-type: none"> Limited availability of design tools optimized for AM ●●●●●
Low Priority	<ul style="list-style-type: none"> Powder process technologies that yield reproducible feedstocks ● Achieving a desired surface finish on the internal geometry of complex shapes ● High machine cost, metals are high (~\$750,000) compared with plastics Machine control software that inhibits real-time parameter changes using sensor-derived inputs High-resolution, high-speed, affordable, high-power computed tomography or alternative technology for complex geometry Limited availability of mature technologies
Process Measurement, Monitoring, and Control	
High Priority	<ul style="list-style-type: none"> Lack of sensors for monitoring and in-situ control ●●●●●●●● <ul style="list-style-type: none"> Development of real-time sensors and measurement methods for: <ul style="list-style-type: none"> Dimension, including geometry, roughness, and low-cost residual stress measurements Microstructure and mesostructure Surface finish Defects, porosity, and flaws Feedstock tolerance Energy source, including laser beam and electron beam High-speed imaging and non-imaging Complete process and system sensor schemes (real-time, continuous), knowing what to measure and how to measure it Low cost, high-resolution thermal sensing <ul style="list-style-type: none"> Sensors for melt pool, total part, large areas in harsh environments By type of AM process/scenario Temperature range/accuracy Calibration (bench and installed) Errors and uncertainty Input/output, display, archives, and controls Lack of measurement methods for in-situ process control ●●●●●●●● <ul style="list-style-type: none"> In-situ distortion monitoring (including inside the powder bed) Active process measurement and control Optimizing NDE techniques for metals AM ●●●●●●●●●● <ul style="list-style-type: none"> Combining NDE techniques to better assess quality via an integrated approach Adapting existing NDE techniques to AM, especially parts, and characterizing defects Lack of affordable quality inspection tools for direct metal parts
Medium Priority	<ul style="list-style-type: none"> Lack of applied statistical process control ●●●
Low Priority	<ul style="list-style-type: none"> Lack of predictive feed-forward models and descriptive process control and sensing measurements ● Understanding how to measure complex internal/lattice structures (dimension, roughness) ● Laser/electron beam quality and spot location monitoring <ul style="list-style-type: none"> Spot, shape, and size Z-shift (process control parameter) Mode Power and scatter Beam diagnostics (real-time) Spot location monitoring, both lateral (x-y plane) and vertical Laser/energy beam standards for quality and characterization Understanding/measuring differences in machines Sensors that integrate AM system and material standards Developing high-speed feedback control for Direct Metal Laser Sintering, Selective Laser Melting, and Electron Beam Melting Lack of low-cost solutions for dynamically controlling laser beam diameter, power location, and shape

Table 3-2. Barriers and Challenges for AM Processes and Equipment

(• = one vote)

Standards	
High Priority	<ul style="list-style-type: none"> • Lack of metrics and standards for measuring and characterizing AM processes and artifacts ●●●●●● <ul style="list-style-type: none"> ○ Lack of standards for geometric accuracy, material properties (spatial), defects, surface characteristics, and variation in these characteristics ○ Establishing standards for “boundary conditions” ○ Lack of standards for microstructure quantification • Lack of standards for ●●●●●● <ul style="list-style-type: none"> ○ Machine-to-machine consistency ○ Measurement test pieces ○ Sensors
Medium Priority	<ul style="list-style-type: none"> • Lack of techniques/standards to characterize multi-material parts (characterize before qualify) ●●● • Lack of calibration parameters for processes and ASTM F42 equipment (existing and future) ●●● • Lack of standards for creating, reporting, and storing AM test data ●●● • Complexity of standards needed to characterize process and system capabilities ●●
Low Priority	<ul style="list-style-type: none"> • Developing standardized calibration/qualification protocol for machines and equipment <ul style="list-style-type: none"> ○ Standards for prototyping, production-quality-parts-capable machines ○ Requirements (features and properties) ○ Calibration frequency • Lack of measurement standard for total energy input and loss • Determining when a process/product standard is needed (given the dozens of technologies) ● • High cost associated with development of measurement standards (too many processes and metals) • Leveraging the harmonization of International Organization for Standardization (ISO) and ASTM standards <ul style="list-style-type: none"> ○ Reaching out to small and medium-sized enterprises (SMEs) and new AM entrants • Lack of a timely and adaptable standards process to keep up with rapidly shifting or new AM technologies • Developing “lot-based” testing standards • Lack of standards for presenting/reporting data and findings, no credible methods (e.g., fatigue plot)/database for comparisons • No standards for disciplined technology delivery (key parameters, traceability, and documentation)
Knowledge/Data	
High Priority	<ul style="list-style-type: none"> • Lack of accurate, achievable material dataset (design allowable and control samples) ●●●●●●●●●● • Lack of standards and protocols for datasets and data transfer ●●●●●●
Medium Priority	<ul style="list-style-type: none"> • Incomplete knowledge capture, organization, and codification for life-cycle; challenges in changing paradigm from experimental base to smart machine/smart production; open architecture is not available (i.e., proprietary) ●●●
Low Priority	<ul style="list-style-type: none"> • Understanding the relationship between raw material, build process parameters, and post-processing • Understanding the interplay between multiple disciplines (e.g., design, manufacturing, materials, thermodynamics, mechatronics, etc.) • Storing and scrubbing huge quantities of data
Models	
High Priority	<ul style="list-style-type: none"> • Converting high-fidelity, academic modeling tools into easy-to-use tools for engineers with desktop machines (or on machine control computer for process/control) ●●●●●●●●
Low Priority	<ul style="list-style-type: none"> • Lack of model integration throughout the digital thread ● • Insufficient as-built material properties, based on type of process • Lack of predictive distortion models in real-time and inability to measure residual stress • Incompleteness of physics and chemistry models, atomistic mesoscale simulations are lacking • Lack of integration of models and process knowledge to enable qualification of processes that are inherently transient with many control variables

ROADMAP FOR PRIORITY RESEARCH AND DEVELOPMENT

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 3-2. Roadmap action plans are outlined in more detail in Figures 3-1 through 3-5. The key barriers being addressed and the corresponding priority roadmap topics are summarized in Table 3-3.

Table 3-3. Key Barriers and Corresponding Priority Roadmap Topics for AM Processes and Equipment

High-Priority Challenge/Barrier	Priority Roadmap Topic
<p>Current NDE techniques are not optimized for metals AM and adaptation of existing technology can be challenging.</p>	<p>NDE Techniques Optimized for Metals AM (Figure 3-1) New and improved imaging and processing NDE techniques are needed to enable optimization of in-situ non-destructive inspection (NDI) and post-process part inspection.</p>
<p>In-situ measurement methods are currently lacking to enable monitoring and control of critical process and material parameters, such as microstructure and mesostructure, surface finish, defects, porosity, online convection, powder bed distortion, and numerous others.</p>	<p>Fast In-Situ Measurements (Figure 3-2) In-situ measurement methods are needed that can be utilized in production environments to assess key parameters and optimize part-to-part reproducibility.</p>
<p>Metrics and standards for measuring and characterizing AM processes and artifacts are lacking (e.g., geometric accuracy, material properties (spatial), defects, surface characteristics, microstructure, and machine-to-machine consistency). Standards and protocols for datasets and data transfer are also lacking.</p>	<p>Performance Capability Database for AM Technologies (Figure 3-3) Protocols, standards, and procedures are needed to collect AM process and equipment capability data and establish a performance database.</p>
<p>Sensors are currently lacking for process monitoring and in-situ control, including real time sensors and measurement methods, integrated process and system sensor schemes (real-time and continuous), and low-cost, high-resolution thermal sensing technology. Easy-to-use modeling tools for engineers with desktop machines or machine control computer for process/control are also lacking or too complex.</p>	<p>Sensors for Measuring and Monitoring AM Processes and Products (Figure 3-4) Standardized, repeatable, and reliable sensor technology and validated models are needed that can be applied across multiple AM platforms.</p>

FIGURE 3-1. ROADMAP ACTION PLAN: NDE TECHNIQUES OPTIMIZED FOR METALS AM

BARRIER: Existing NDE techniques are not optimized for AM processes, materials, or parts. Techniques are lacking for in-situ, NDI, and post-process AM part inspection.

APPROACH SUMMARY: Evaluate existing AM processes and adapt or develop, as appropriate, for AM processing or parts. Develop new techniques and address both in-situ and post-process applications.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> Identify in-situ imaging techniques and image processing approaches; evaluate the best technologies Evaluate existing post-process NDE techniques and identify approaches for AM Identify opportunities to develop new techniques for in-situ and post-process NDE; plan for research and development (R&D) 	<ul style="list-style-type: none"> Identification of techniques that apply to AM Identification of a few candidate techniques Plan for development of new techniques 	<ul style="list-style-type: none"> Build confidence in AM processes Find defects and processing issues early in the process Develop more efficient and effective inspection schemes Understand processes enough to reduce inspection requirements Use in-situ techniques for closed-loop diagnostics
3–5 years	<ul style="list-style-type: none"> Develop selected imaging and processing techniques for in-situ AM processes Develop and adapt existing NDE techniques for AM Conduct R&D for new NDE in-situ and post-process techniques 	<ul style="list-style-type: none"> Proven techniques Plan for implementation List of potential techniques for further development 	
5+ years	<ul style="list-style-type: none"> Plan for and accomplish implementation of successful new techniques Transition technologies, commercialize as appropriate Evaluate and plan for the next round of development 	<ul style="list-style-type: none"> Development of available techniques Techniques incorporated into AM machines Ability to collect supporting data for inspection reports and traceability 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Collect a history of data, track process capabilities, participate in NDE development efforts, use new techniques and provide feedback, and investment
- ◆ **Industry/AM Providers:** Implement NDE techniques, enhance equipment, and provide capability and access
- ◆ **Academia:** Help with software and technology development and algorithms for image processing
- ◆ **Standards Committees:** Document standard inspection processes and define NDE attributes and limits
- ◆ **Government:** Define programs to develop NDE to meet government (military) requirements

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** Enables needed inspection techniques and ensures product quality
- ◆◆ **Reduces costs:** Minimizes inspection requirements, reduces destructive testing requirements, allows earlier detection of problems
- ◆◆ **Accelerates innovation:** Shorter time to market
- ◆◆◆ **Enhances industry competitiveness:** Enhances traceability and ensures product quality
- ◆ **Faster product development time:** N/A

FIGURE 3-2. ROADMAP ACTION PLAN: FAST IN SITU MEASUREMENTS

BARRIER: Systems are lacking to measure parameters that are key to part quality and reproducibility, including online convection, density of powder bed, distortion/residual stress, composition, absorbed power, cracking, and porosity. The relationship between part quality and in-situ thermal management is poorly understood.

APPROACH SUMMARY: Develop pilot system to measure and control key parameters.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> Measure and analyze the role of thermal sensing on part quality Survey and evaluate existing in-situ measurement techniques for distortion, surface roughness, cracking, and porosity 	<ul style="list-style-type: none"> Demonstration of in-situ detection of cracking Improved measurement of heat flow 	<ul style="list-style-type: none"> Improved confidence level of model input Part-to-part reproducibility using in-situ sensing Optimized throughput Improved distortion control Improved surface finish Identification of porosity and cracking
3–5 years	<ul style="list-style-type: none"> Fundamentally understand the relationship of part quality to spatially absorbed power, temperature distribution, fluid flows, and composition Develop control methods and systems for production environments 	<ul style="list-style-type: none"> Demonstration of viable control methods 	
5+ years	<ul style="list-style-type: none"> Transition to production of control and in-situ measurement techniques Develop techniques for in-situ measurement of composition and microstructure 	<ul style="list-style-type: none"> Demonstration of phase and composition detection 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Input on priorities
- ◆ **Industry/AM Providers:** Implementation and collaboration
- ◆ **Academia:** Innovation in sensing and modeling
- ◆ **Standards Committees:** Standards for in-situ measurement
- ◆ **Government:** Infrastructure support and consensus building

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** Improved process control
- ◆◆ **Reduces costs:** Tradeoff between capital cost and part repeatability
- ◆◆◆ **Accelerates innovation:** Improved understanding of process dynamics opens new possibilities
- ◆◆◆ **Enhances industry competitiveness:** Reduces lead time
- ◆◆◆ **Faster product development time:** Reduces cycle and qualification time
- ◆◆◆ **Other:** Removes operator variability

FIGURE 3-3. ROADMAP ACTION PLAN: PERFORMANCE CAPABILITY DATABASE FOR AM TECHNOLOGIES

BARRIER: There is currently a lack of process performance capability data relevant to AM. Standards and protocols to support such characterization (e.g., dimensional and mechanical) are also lacking.

APPROACH SUMMARY: Create protocols, standards, and procedures for establishing a performance database and involve ASTM F42 and ISO committees in activities.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1-2 years	<ul style="list-style-type: none"> ◆ Determine direction for ASTM F42/ISO/ASTM ◆ Complete current round-robin and initial mechanical property programs ◆ Pick materials, processes, and tests ◆ Identify and substantiate key input/output characteristics ◆ Set-up national repository ◆ Start specification writing 	<ul style="list-style-type: none"> ◆ Industry standards developed for process capability ◆ Established protocols ◆ Identification of key process characteristics ◆ Creation of national repository 	<ul style="list-style-type: none"> ◆ Established procedures for characterizing process and outputs, including reporting, sharing, and accessing ◆ Viable, robust database accessible to the public ◆ Correlation to predictive process modeling, sensor feedback and control, and process outputs, and process outputs, ◆ Enabled rapid qualification
3-5 years	<ul style="list-style-type: none"> ◆ Expand round-robins to additional sites, processes, and materials ◆ Expand input/output parameters and parameter ranges ◆ Publish a database on metallic materials properties development and standardization ◆ Begin including life-cycle data 	<ul style="list-style-type: none"> ◆ Development of a broader, more robust database 	
5+ years	<ul style="list-style-type: none"> ◆ Establish a relationship between modeling, process monitoring and control, and rapid qualification ◆ Substantiate/develop relationships between inputs and outputs 	<ul style="list-style-type: none"> ◆ Established relationships and tie-in to modeling, control, and rapid qualification ◆ Rapid qualification capability 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide guidance and feedback for establishing priorities in terms of processes and requirements
- ◆ **Industry/AM Providers:** Process knowledge and sharing
- ◆ **Academia:** Process understanding and R&D advancements
- ◆ **Standards Committees:** Establish procedures, standards, and engagement
- ◆ **Government:** Provide oversight and resources and serve as a repository

RELATIVE IMPACTS

Low — High

- ◆◆ **Improves product quality:** Establishes baseline, leading consistency, and understanding
- ◆◆◆ **Reduces costs:** Reduces testing costs for individual stakeholders
- ◆◆◆ **Accelerates innovation:** Establishes a knowledge baseline to leverage R&D, rapid qualification, and feedback controls
- ◆◆◆ **Enhances industry competitiveness:** Accessible to the public and SMEs and larger enterprises
- ◆◆◆ **Faster product development time:** Rapid qualification
- N/A **Other (Education):** Accessible knowledge base

FIGURE 3-4. ROADMAP ACTION PLAN: SENSORS FOR MEASURING AND MONITORING AM PROCESSES AND PRODUCTS

BARRIER: The challenge is to define measuring and monitoring requirements for AM processes, component geometries, and materials.

APPROACH SUMMARY: Develop sensors and standards, as well as validated models for data to enable standardized, repeatable, and reliable measurement and monitoring of processes and products.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> Establish a baseline of sensor technology state-of-the-art for key parameters Identify gaps Establish working groups (e.g., with industry, university, national labs, and government) for sensor development 	<ul style="list-style-type: none"> Consolidated sensor database information Assembled stakeholders Evaluated sensor adequacy 	<ul style="list-style-type: none"> Standardized sensors across multiple AM platforms Process control software to take advantage of sensor measurements Sensor monitoring to accelerate process qualification Sensor monitoring control to improve reliability and repeatability A Moore’s Law for sensor monitoring and control of AM processes
3–5 years	<ul style="list-style-type: none"> Work with original equipment manufacturers (OEMs) on details of sensor needs and plans Benchmark data/test sets for model validation Develop sensors to fill gaps and accelerate critical technologies. Validate sensor performance to provide data to monitor and control the AM process 	<ul style="list-style-type: none"> Establish widespread use of validated models Global OEM participation in sensor development (needs and plans kickoff) Multitude of sensor development initiatives bearing fruit Validated and qualified sensor technologies 	
5+ years	<ul style="list-style-type: none"> Establish standards for successful approaches Keep development open for contributions from new technologies 	<ul style="list-style-type: none"> Publish standards (i.e., ASTM, ISO) Continued and expanded collaborations 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide input, needs/requirements, and current state; and conduct demonstrations/pilot initiatives
- ◆ **Industry/AM Providers:** Establish partnering between industry and AM equipment providers
- ◆ **Academia:** Develop software, algorithms, and enhanced learning
- ◆ **Standards Committees:** Software and hardware standards, certifications, and calibration
- ◆ **Government:** Computational legacy and uniform test/development algorithms

RELATIVE IMPACTS

LOW — HIGH

- ◆◆◆ **Improves product quality:** Sensor controls lead to predictable material properties
- ◆◆ **Reduces costs:** Improves production yield
- ◆◆◆ **Accelerates innovation:** Higher quality encourages uses in a broader range of markets
- N/A **Enhances industry competitiveness:** N/A
- ◆◆ **Faster product development time:** Supports a range of innovation
- N/A **Other:** N/A

CHAPTER 4: AM QUALIFICATION AND CERTIFICATION

OVERVIEW OF THE TOPIC AREA

Each element of additive manufacturing (AM) technology (i.e., materials, equipment, processes) must be qualified and certified to reproducibly manufacture high-quality parts. Non-standardization of materials, process, and resulting products makes the manufacturing of a high-quality part difficult on the first run.

The development of AM standards for qualification and certification is complicated by the numerous permutations of machines, materials, processes, and techniques and the absence of a central repository of AM data or authority on AM methodologies. Further deployment of AM technology will require standards development to facilitate quicker and more cost-effective certification of all materials, processes, and products.

FUTURE/DESIRED CAPABILITIES

In the future, improved capabilities will be needed to certify that parts meet the desired specifications, performance, and quality. Table 4-1 provides further details on the desired capabilities and technologies for qualification and certification of AM materials, processes, and parts.

Qualification and Certification Methods

Affordable and rapid qualification and certification of parts and processes is an important desired capability and would facilitate more widespread use of AM. Predictive models, standardized testing, and development of performance metrics and measurement methods are all key aspects in developing this capability. Methods must be flexible and adaptive (rather than prescriptive) to allow for the broadest possible use. The ability to certify and qualify parts to existing specifications (e.g., aerospace grade), in the field and after secondary processing is also important.

Standards and Protocols

Standardization is an important underlying foundation for qualification and certification as it provides the basis for consistent part validation and processing, supports model development, establishes repeatability, and provides guidelines for repair/maintenance. Standards will also enable consistent handling, storing, and disposal of AM feedstock materials in the workplace.

Reliability and Repeatability

Being able to produce parts with repeatable quality and specifications is critical. Robust methods and inspection techniques will be needed to certify reproducibility of parts and ensure that process performance is repeatable. Another key issue is qualifying that parts are true to the computer-aided design (product specification), and that the first part produced is repeatable throughout the process.

Qualification and certification of repeatable processes will require better machine and system in-process feedback and control. Closed-loop control systems and other means are needed to enable quantification of process variability and performance. Quantifying part dimensioning and tolerances will also be critical to ensure parts meet specifications after repeated builds.

Data

Additional datasets and data collection capabilities will be needed to support qualification and certification of AM parts and processes. This includes standardized methods for capturing manufacturing data as well as part history.

An open source of statistical data on material and other properties would facilitate the ability to qualify and certify both parts and processes.

Table 4-1. Desired Capabilities and Technologies for AM Qualification and Certification

Qualification and Certification Methods

- Affordable, rapid, and well-documented parts and product certification and qualification
 - Adaptive qualification for products (e.g., non-prescriptive and flexible)
 - Independent physics-based simulation for part certification against specifications
 - Certification for aerospace-materials-specification-grade AM parts
 - Field process for part verification against expected specifications
 - Dashboard visibility (e.g., AS 9100 aerospace specification for e-data for parts)
 - Certification of high-value, high-reliability parts (e.g., models to relate process parameters to parts)
- Qualification for material feedstocks: supply management, quality, and storage (e.g., contamination)
 - Predictive models and computationally-assisted material qualification
 - Standardized tests for qualification of materials
 - Measuring percent of new/used material
 - Material qualification that is not platform-specific
- Affordable, rapid, and well-documented machine and process certification and qualification
 - Post-process specification (e.g., downstream processes such as hipping, annealing)
 - Secondary process certification and guidelines
 - Performance-based approval process for non-critical parts (i.e., A- and B-level parts)

Standards and Protocols

- Part qualification/certification
 - Guidelines for how to build parts (e.g., orientation), reducing the number of iterations to final part production
 - Repair standards for parts
 - Guidelines to enable freedom of design/custom designs (e.g., homogeneous parts, consistent parts)
 - Standard validation tools for parts
- Materials qualification/certification
 - Standards for handling, storing, and disposing of AM feedstock materials in the workplace
- Equipment/process qualification/certification
 - Guidelines for the number of trials that are needed to verify the properties of each build
 - Reliability and maintainability guideline adoption (e.g., SAE International (SAE) M110.2, ISBNo-7680-0473-X)
 - Single independent source for process standards
 - Guidelines for increased mean time between failure

Reliability and Repeatability

- Robust methods for establishing and predicting process repeatability, including
 - Build-to-build
 - Machine-to-machine
 - Operator-to-operator
 - In-process parameter sensing and feedback control
 - Robust modeling and simulation tools to validate process parameters
 - Underwriters Laboratory type approval (trusted third party)
- Repeatable original equipment manufacturers (OEM) equipment performance and consistency
 - Trusted third-party approval
 - Inspection techniques for internal dimensional verification for critical dimensions (e.g., for injector) and to verify part geometry (on-machine verification of geometric dimensioning and tolerance)
- Fidelity of parts to computer drawing
 - First part produced is validated against all specifications; all production parts that follow are the same as the first part
 - Trusted process generates valid component (e.g., models to enable verification, validation, and certification)
- Evaluation and non-destructive evaluation (NDE)
 - Fast, automated 3-D NDE
 - In-situ beam path verification

Table 4-1. Desired Capabilities and Technologies for AM Qualification and Certification

- In-process, in-situ NDE/closed loop control (e.g., infrared and computed tomography) with traceability
- Independent artifact that evaluates a machine's X-Y-Z accuracy for feature geometry and fidelity
- In-situ characterization and data mining software; models use data to provide feedback for certification
- Consistency in engineered materials and mechanical properties
- Closed-loop control system for machine visibility into variance, system health, and in-situ modifications
 - Quantification and reduction of process variability
- Build chamber environmental monitoring for traceability
- Ability to consistently quantify dimensioning (e.g., z direction) and tolerance capability of an AM machine

Data

- Database for functionally gradient materials
- Anonymous pool of open source data, including statistical and historical performance
 - Known materials properties database
 - Set build model
 - Sufficient information to determine performance parameters
- File format interoperability with computer aided design system
- Informatics for capturing manufacturing data
- Pedigree data collection, including known thermal history, process history, statistical process control, and feedstocks

TECHNOLOGICAL & MEASUREMENT/STANDARDS CHALLENGES

The barriers and challenges currently impeding large-scale deployment of AM processes and equipment are presented in Table 4-2, categorized by common themes. In each category, specific barriers or challenges are prioritized based on expert and stakeholder input.

One of the major challenges identified is the lack of standardized guidelines for conducting qualification and certification of parts and processes. While a common industry standard is desired, developing such guidelines is made difficult by the wide variations in machines and end uses.

A number of identified gaps in standards point to the immaturity of metal-based AM systems (e.g., some are more R&D than production-focused). A high priority is achieving technology maturation (i.e., reliable machines), which will inherently result in repeatable and predictable processes and products.

Another key challenge is the lack of feedback sensors and measurement methods for acquiring the data needed for qualification and certification. The closed loop control systems that could help provide data are lacking, as are the capabilities for in-situ measurements. Ideally, data collected could be housed in a third-party repository that could be accessible and shared by the AM community. Developing a repository of this nature is problematic as some data is proprietary, not available in consistent formats, and/or not collected so that it is usable or comparable by others.

Standards for round-robin testing are also lacking for AM and are needed to enable independent testing of processes and equipment. Test protocols currently do not exist for AM materials or processes (and technologies vary widely). Consequently, the reporting of results is inconsistent and difficult to compare.

Table 4-2. Barriers and Challenges for AM Qualification and Certification
(● = one vote)

Standard and Protocols	
High Priority	<ul style="list-style-type: none"> • Non-standard guidelines for qualification and certification ●●●●●●●●●● <ul style="list-style-type: none"> ○ Defining sufficient type and quantity of guidelines ○ Wide variations in machines and end users ○ Limited ASTM qualification and certification guidelines for AM machine components ○ Adherence to standards and proof of compliance are inconsistent ○ Addressing unique specifications with industry-wide common standards • Lack of standards based on round-robin testing (how to build) ●●●●●●●●●● <ul style="list-style-type: none"> ○ No test protocol for materials testing and inconsistent reporting of results ○ Incomplete part inspection and test standards ○ Non-standard ratio of new/used powders and associated test protocols
Medium Priority	<ul style="list-style-type: none"> • Lack of standard build parameters on different machines; no adoption of a baseline set of standard and open application programming interfaces (APIs) and file formats among vendors ●●●
Low Priority	<ul style="list-style-type: none"> • Complicated part repair due to complexity of materials and geometry, inconsistent automation, and lack of ASTM part certification standards • Lack of vector hatch and mask standards (e.g., ASTM, descriptive standards) • Difficulty of standards development (e.g., long, costly, technical work, volunteer work, intellectual property limits) ● <ul style="list-style-type: none"> ○ AM is not fully commercialized (i.e., not all technology is mature enough for standards) ○ Non-standard AM systems hardware • Incomplete post-process standards/specifications (e.g., internal, surface roughness, and measurements) ● • Lack of top level standards for dimensioning across machines ● • Lack of standards for AM materials linked to process (e.g., TI-624) • Updating the OSHA material safety data sheet materials standards for AM • Lack of industry standard materials specifications due to limited access to vendor data, no 3rd party ratings, no means to create reliability certification scorecards
Inspection, Test, and Measurement Methods	
High Priority	<ul style="list-style-type: none"> • Inadequate feedback sensors and data acquisition/measurement methods ●●●●●●●●●● <ul style="list-style-type: none"> ○ Lack of in-situ measurements for real-time process control ○ Lack of open loop/closed loop control systems for AM ○ Inability to modify AM systems and materials due to IP ownership and need to adhere to maintenance and warranty requirements ○ Creating methods to produce actionable information from data
Medium Priority	<ul style="list-style-type: none"> • Deficient feedstock-specific standards/specifications (e.g., vaporization and properties) ●●● <ul style="list-style-type: none"> ○ Lack of standard artifacts to test microstructure (e.g., custom-design microstructure)
Low Priority	<ul style="list-style-type: none"> • Limited methods for characterization of complex materials, including multi-materials, multi-components, multi-functional materials, orientation-specific factors, and functions of process and build parameters ●
Data Challenges	
High Priority	<ul style="list-style-type: none"> • Lack of shared, usable data in a 3rd party repository ●●●●●●●● <ul style="list-style-type: none"> ○ Using parts improperly based on limited data, history, and/or metadata ○ New data is not collected or shared ○ Inability to correlate data ○ Ability to produce materials based on geometric differences
Low Priority	<ul style="list-style-type: none"> • No central standard database for materials properties (e.g., high temperatures and mixed materials)

ROADMAP FOR PRIORITY RESEARCH AND DEVELOPMENT

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 4-2. Roadmap action plans are outlined in more detail in Figures 4-1 through 4-4. The key barriers being addressed and the corresponding priority roadmap topics are summarized in Table 4-3.

Table 4-3. Key Barriers and Corresponding Priority Roadmap Topics for AM Qualification and Certification

High-Priority Challenge/Barrier	Priority Roadmap Topic
<p>Today’s feedback sensors and data acquisition/ measurement methods are inadequate for AM. Systems are lacking in-situ measurements to support real-time process control/closed-loop control.</p>	<p>Closed-Loop Process Control (Figure 4-1) Control technology development will allow for real-time process measurement and control, enable the use of closed-loop controls, and lead to reliability and repeatability in AM parts.</p>
<p>Guidelines for qualification and certification are currently not standardized. Some of the challenges include the ability to define the type and quantity of guidelines and dealing with wide variations in machines and end users. ASTM qualification and certification guidelines for AM machine components are currently lacking or inadequate.</p>	<p>Standard Guidelines and Methods for Qualification and Certification (Figure 4-2) A standard taxonomy that encompasses all AM methods and technologies needs to be developed and adopted by AM stakeholders. Standardized methods are also needed for AM part and process qualification, certification, and design.</p>
<p>The development of AM certification processes are hindered by the lack of valid data in standard formats available in an open, web-based, 3rd party database repository. The lack of data leads to using parts improperly based on limited data, history, and/or metadata. New data is not collected or shared and existing data is difficult to correlate or compare.</p>	<p>Shared, Standardized Third-Party Data Repository (Figure 4-3) Standard methods for data formats and analysis for AM materials are needed to support an open web-based capability for publishing, clearing, and sharing data. Analytical methods could include, for example, property extrapolation by statistical means. The repository would support proper choice and use of AM materials.</p>
<p>Standards and protocols are lacking for round-robin testing of AM materials and parts.</p>	<p>Standards and Protocols for Round-Robin Build and Material Testing (Figure 4-4) The development of protocols for round-robin build and material testing will enhance repeatability and enable documentation of part history and test results.</p>

FIGURE 4-1. ROADMAP ACTION PLAN: CLOSED-LOOP PROCESS CONTROL

BARRIER: AM processes are inhibited by poor process control and inadequate measurement methods and technologies. Systems are lacking for in-situ measurements to support real-time process control and open-loop/closed-loop control.

APPROACH SUMMARY: Foster closed-loop control technology development via AM industry adoption and technology advancement.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Provide feedback to equipment manufacturers to enable development of adequate closed-loop control ◆ Organize and execute a process control workshop to develop collaboration opportunities ◆ Evaluate current research and in-process control and establish programs for additional needs/requirements ◆ Develop in-situ measurement for real-time process control 	<ul style="list-style-type: none"> ◆ Approved equipment modification for research system manufacturers to adopt process control methods ◆ Comprehensive understanding of efforts in closed-loop control ◆ Annual programs announced for process control ◆ New sensors for closed-loop control 	<ul style="list-style-type: none"> ◆ Reliability and reproducibility in AM parts ◆ Six sigma production parts
3–5 years	<ul style="list-style-type: none"> ◆ Achieve early integration of process control into equipment ◆ Modify standards based on technology development ◆ Use layer-specific information for rapid part qualification 	<ul style="list-style-type: none"> ◆ Advanced strategies for real-time measurement and control ◆ Demonstrated layer-specific information can be used for NDI/NDE 	
5+ years	<ul style="list-style-type: none"> ◆ Continue process control development 	<ul style="list-style-type: none"> ◆ Reliable and reproducible critical advanced AM parts 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide input on needs, conduct demos/pilots, evaluate/produce components/parts using closed-loop control
- ◆ **Industry/AM Providers:** Commit and implement closed-loop controls
- ◆ **Academia:** Develop technology advancements, collaborate with AM software and hardware providers
- ◆ **Standards Committees:** Modify standards to incorporate closed-loop control
- ◆ **Government:** Programmatic support, technology development

RELATIVE IMPACTS

LOW — HIGH

- ◆◆◆ **Improves product quality:** Greater process control
- ◆◆◆ **Reduces costs:** Reduction of post process inspection, higher yield of parts, rapid qualification
- ◆◆◆ **Accelerates innovation:** Enabling complex parts with certainty and create graded structures and different materials
- ◆◆ **Enhances industry competitiveness:** Use of AM parts industry expands customer base
- ◆◆◆ **Faster product development time:** Use of AM parts industry expands customer base
- ◆◆◆ **Other:** Reduces variability

FIGURE 4-2. ROADMAP ACTION PLAN: STANDARD GUIDELINES AND METHODS FOR QUALIFICATION AND CERTIFICATION

BARRIER: Standard guidelines for qualification and certification are lacking. Challenges include the ability to define the type and quantity of guidelines and wide variations in machines and end users. ASTM qualification and certification guidelines for AM machine components are currently lacking or inadequate.

APPROACH SUMMARY: Develop uniform standards and a taxonomy that encompasses all AM methods and is flexible to accommodate new technologies as they emerge.

ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Collect existing worldwide standards and guidelines currently in use for AM ◆ Develop common baseline and taxonomy ◆ Coordinate with AM process models and properties development (see Figure 5-2) ◆ Develop and apply standard validation procedures to computational tools (e.g., process models and design tools, see Figure 5-2) 	<ul style="list-style-type: none"> ◆ Framework begun for ASTM standard document ◆ Modularity incorporated into the standard ◆ Established database (standards, supporting data, and generalized process models) is available to the AM community
3–5 years	<ul style="list-style-type: none"> ◆ Draft standards framework documents ◆ Develop standard methods for rapid qualification of processes ◆ Incorporate data from models and control systems 	<ul style="list-style-type: none"> ◆ Revised draft standards framework document ◆ Validated models that support qualification and certification (see Figure 5-2)
5+ years	<ul style="list-style-type: none"> ◆ Write ASTM standard for AM process qualification, ensure the standard is flexible and supports new technology development ◆ Integrate virtual testing standards with experimental testing standards 	<ul style="list-style-type: none"> ◆ Revised standards as technology progresses ◆ Rapid qualification of processes and parts

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Assist in documenting current baseline for standards and provide input on needs
- ◆ **Industry/AM Providers:** Assist in documenting current baseline for standards
- ◆ **Academia:** Enable workforce development and validate standards
- ◆ **Standards Committees:** Develop qualification, materials, characterization, and testing standards
- ◆ **Government:** Ensure applicability across agencies, support/develop database infrastructure, and test algorithms

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** Greater certainty of process and products
- ◆◆ **Reduces costs:** Gives a single source/method for reducing trial and error waste and reduces investments for qualification
- N/A **Accelerates innovation:** Supports design freedom and reduces barriers to new technology
- ◆◆◆ **Enhances industry competitiveness:** Standardization empowers the suppliers and OEMs
- ◆◆ **Faster product development time:** Streamlines the selection of processing

FIGURE 4-3. ROADMAP ACTION PLAN: SHARED, STANDARDIZED THIRD-PARTY DATA REPOSITORY

BARRIER: The lack of valid data in standard formats and a centralized data clearinghouse inhibits the development of certification processes for AM.

APPROACH SUMMARY: Collect crowd-sourced data, create standards formats, and develop a database.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Use the ASTM standard for reporting format ◆ Create licensing model for common data ◆ Design a method of execution and collection for limited processes ◆ Establish governance for materials, processes, and parties ◆ Establish a web front-end platform 	<ul style="list-style-type: none"> ◆ ASTM standard developed ◆ Data reporting standard and structure (i.e., format) ◆ Open web-based capability for publishing, clearing, and sharing data ◆ Results from 1–2 materials to validate database 	<ul style="list-style-type: none"> ◆ Standardized methodology for AM materials ◆ Property extrapolation by statistical means ◆ Proper use of process and material based on performance ◆ Reduction of 30% or more in cycle time and materials waste
3–5 years	<ul style="list-style-type: none"> ◆ Start building statistical model/link to integrated computation materials engineering (ICME) ◆ Grow invested stakeholders and data sets ◆ Define database growth strategy 	<ul style="list-style-type: none"> ◆ Utilized on a platform ◆ Crowd-sourced data ◆ Captured all publically available government-funded data 	
5+ years	<ul style="list-style-type: none"> ◆ Govern and evolve the database ◆ Link statistical database to ICME for alloys 	<ul style="list-style-type: none"> ◆ Mature database 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Contribute data and adopt crowd source model
- ◆ **Industry/AM Providers:** Contribute data
- ◆ **Academia:** Develop statistical models using the data and develop a scientific base for methods
- ◆ **Standards Committees:** Develop standards for reporting format
- ◆ **Government:** Programmatic supports and oversight

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** Reliability and consistency
- ◆◆◆ **Reduces costs:** Less money spent generating data
- ◆◆◆ **Accelerates innovation:** Part iterations faster
- ◆◆◆ **Enhances industry competitiveness:** Precompetitive/transparency
- ◆◆◆ **Faster product development time:** Reduce number of iterations
- N/A **Other:** N/A

FIGURE 4-4. ROADMAP ACTION PLAN: STANDARDS AND PROTOCOLS FOR ROUND-ROBIN BUILD AND MATERIAL TESTING

BARRIER: No documented standards and protocols exist for round-robin build and materials testing for AM.

APPROACH SUMMARY: Create a set of protocols for round-robin testing, beginning with a single source powder and going through part production, process, build, and inspection.

	ROADMAP ACTION PLAN	MILESTONES	OVERARCHING TARGETS
1–2 years	<p>Powder Metal (new powder only)</p> <ul style="list-style-type: none"> ◆ Using a single-source powder, develop written protocols <ul style="list-style-type: none"> ○ Composition (scanning electron microscope/energy dispersive spectrometer and x-ray diffraction) ○ Size measurement ○ Morphology ○ Flow-ability/sifting mesh ◆ Develop report templates and define test protocol 	<ul style="list-style-type: none"> ◆ Definition of test protocols for powder 	<ul style="list-style-type: none"> ◆ Develop pedigree parts ◆ Enhance repeatability and uniformity of terms in the AM community ◆ Deliver to the ‘owner’ a part with a documented history and test results ◆ Maintain a library of parts and test documentation (including timing for acceptance) ◆ Maintain a library/database (defined by the purpose of the specification)
2 years	<p>Part (using same powder/material)</p> <ul style="list-style-type: none"> ◆ Select Part A, process 1, Part B, process 2 and describe <ul style="list-style-type: none"> ○ Centerline part ○ Inspection datum and features ◆ Build in supports and allowances for certification as determined by the process 	<ul style="list-style-type: none"> ◆ Protocols for parts by process ◆ Design guide 	
2-3 years	<p>Build</p> <ul style="list-style-type: none"> ◆ Calibrate machine to OEM standards ◆ For both Part A and Part B define <ul style="list-style-type: none"> ○ X, Y, and Z orientation to blade, and orientation to material deposition ○ Decide where in build volume should it be specified (cold bed or heated bed) ○ Number of parts in build volume ○ Removal method ○ Post-processing (order of method of parameters) ○ Specific post-processing machining ○ Heat treatment/hipping ○ Blasting, cleaning, and powder removal <p>Inspection</p> <ul style="list-style-type: none"> ◆ Specify inspection approach ◆ Specify accuracy of coordinate measuring machine (CMM) and calibrate CMM ◆ Implement inspection plan and report on results 	<ul style="list-style-type: none"> ◆ Build protocols ◆ Part inspection protocols 	
3 years	<p>Mechanical Testing</p> <ul style="list-style-type: none"> ◆ Develop protocols for testing at a certified testing laboratory, defined by part and application ◆ Define statistical analysis <ul style="list-style-type: none"> ○ Tensile, yield strength, density/porosity, temperature, and other necessary parameters ◆ Generate statistical reports <ul style="list-style-type: none"> ○ Findings by part ○ Variability through the entire process ○ Variability of entire parts (A, B, etc.) and other findings 	<ul style="list-style-type: none"> ◆ Protocol for mechanical testing 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide input on protocol development
- ◆ **Industry/AM Providers:** Use protocols
- ◆ **Academia:** Validate models and assist in the updating process
- ◆ **Standards Committees:** Develop a report template
- ◆ **Government:** Maintain the database

RELATIVE IMPACTS

LOW — HIGH

◆◆◆
N/A
N/A
◆◆◆
N/A
◆◆◆

- ◆◆◆ **Improves product quality:** Lessons learned
- N/A **Reduces costs:** N/A
- N/A **Accelerates innovation:** N/A
- ◆◆◆ **Enhances industry competitiveness:** Useful in a design guide
- N/A **Faster product development time:** N/A
- ◆◆◆ **Other:** Uniformity of AM terms, database

CHAPTER 5: AM MODELING AND SIMULATION

OVERVIEW OF THE TOPIC AREA

Development of accurate modeling and simulation tools is an important fundamental building block as additive manufacturing technologies are being developed and deployed. The availability of good validated modeling and simulation capabilities decreases the need for real-world testing of technologies and processes and gives product designers a predictive capability to optimize part designs. Models are also the basis for developing the required control technologies and software for additive manufacturing (AM) production processes. They will also provide support for standards development as well as qualification and certification methods.

Accurate modeling and simulation tools cannot be developed without comprehensive and validated data on materials and processes. These tools also require an excellent understanding of the fundamental processes and physical phenomena that underlay AM feedstock inputs, approaches, and technologies. Note that the modeling and simulation needs outlined in this chapter are relevant to AM processes and production, but may also broadly encompass other aspects of modeling and simulation.

FUTURE/DESIRED CAPABILITIES

Table 5-1 includes a summary of the desired future modeling and simulation capabilities that were identified. These illustrate the range of impacts that modeling and simulation have on the use of AM.

Process and Materials Models

AM modeling and simulation solutions are moving toward increased accuracy, with the eventual goal of 100% fidelity between modeling and simulation and reality. Increased computational capabilities will make models fast enough for real-time applications. Future models will use in-situ measurements to be able to predict structure properties and defects. Increased computational capacity will enable the development of real-time models that can be used for process control. Desired capabilities include the ability to model residual stress direction, grain size distribution, spatial and temporal homogenization, complex lattice design, and surface finish solutions. Future models will be multi-scale in nature and could support AM process selection based on key standards.

Model Inputs

Model improvement, validation, and verification will benefit from enhanced in-process measurement and non-destructive inspection (NDI) methods. To attain real-time functionality, sensing and feedback capabilities for in-situ measurement throughout AM processes will be critical. Increased understanding of thermal properties and the capability to measure data file transfer accurately are also critical.

Standards and Metrics to Support Modeling

Standards for data inputs to modeling and simulation systems are needed to improve characterization of dimensional accuracy, process capability, distortion, surface finish modeling, density, micro properties, and verification and validation (V&V). Standardization of these data inputs and key process parameters will enable development of more accurate, reliable models that can be used in real-time process applications.

Model Accessibility/Usability

Greater balance between open source and proprietary modeling and simulation would aid technology advancements and may increase simulation access for small- and medium-sized organizations. In addition, increased user education may lead to better technical understanding of model and simulation behavior, which has been lacking in the industry.

Table 5-1. Desired Capabilities and Technologies for AM Modeling and Simulation

Process and Materials Models

Accuracy

- One-hundred percent fidelity between modeling/simulation and reality
- High-accuracy, fast converging models for AM processes
- Accurate operational and sustainment models, enabling model-based lifecycle control

Fast/Real-Time Capabilities

- In-situ measurement of composition, temperature, cooling rate, dimension, and distortion leading to the ability to predict dimensions, surface characteristics, material properties spread, and defects
- Real-time computation
- Real-time modeling to enable process adjustments
- Rapid-cost and capacity modeling, ideally physics-based
- Rapid process qualification leading to a decreased need for testing
- Capability to measure the accuracy of data file transfers

Improved Capabilities

- Residual stress direction and magnitude
- Grain-size distribution
- Spatial and temporal homogenization
- New design capabilities, such as complex lattice structures or alloy transitions
- Solutions for distortion and surface finish modeling to optimize build orientation, including supports
- Increased energy input efficiency (e.g., loss via reflection and conduction)

Compatibility

- Compatible models that support understanding and linking of all transformations
- Supplier independent process models that can predict outcome from programmable attributes

Comprehensive Models

- Generalized modeling that combines high- and low-fidelity and continuum laws
- Integrated multi-scale, multi-physics models from complex to dimensionless numbers
- Technologies to model design reproducibility for AM
 - Repeatable for a minimum feature size
 - Modeling to support selection of AM processes based on key standards

Model Inputs

- Sensing and feedback to provide data for process control models
- NDI methods for complex parts to provide inputs for model development and validation
- Better knowledge of the thermal properties of materials from loose powder to dense metal

Standards and Metrics

- Validation and verification (V&V) metrics for models and simulation tools
- Standards for modeling dimensional accuracy and process capability
- Standards for distortion and surface finish modeling to optimize build orientation, including supports
- Criteria for convergence time, accuracy calibration, and applicability for various materials and processes
- Modeling to compare the performance of one machine to another
- Transferability studies and metrics, taking into account intellectual property (IP) rights
- Consistent and increased security of data file contents

Model Accessibility/Usability

- Access to simulations for small- and medium-sized enterprises
- Complete technical understanding by user of model and simulation behavior and outputs
- Balance between “open source” and proprietary modeling and simulation

ROADMAP FOR PRIORITY RESEARCH AND DEVELOPMENT

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 5-2. Roadmap action plans are outlined in more detail in Figures 5-1 through 5-3. The key barriers being addressed and the corresponding priority roadmap topics are summarized in Table 5-3.

Table 5-3. Key Barriers and Corresponding Priority Roadmap Topics for AM Modeling and Simulation

High-Priority Challenge/Barrier	Priority Roadmap Topic
<p>Modeling systems available today lack the capabilities to couple AM design, materials selection, and manufacturing processes.</p>	<p>Expert System for AM Design (Figure 5-1)</p> <p>A significant expansion of validated AM design rules is needed to build expert model-based design systems that can be used to select optimum AM materials and processes and exploit unique AM capabilities.</p>
<p>Validated physics-based, multi-scale predictive models that account for geometric accuracy, spatial material properties, defects, surface characteristics, and other variations (temperature-dependent properties) are not available for AM.</p>	<p>Validated Physics- and Properties-Based Predictive Models for AM (Figure 5-2)</p> <p>Validated, physics-based, multi-scale models that incorporate multiple characteristics and properties need to be developed. Effective models will optimize part fabrication processes and reduce cost, performance, and schedule risks.</p>
<p>Standards are lacking to support consistent data inputs to modeling and simulation, including key process and product parameters. Validation and verification metrics are also lacking for AM models and simulation tools (both design and process). The definition of common data standards and metrics for AM is complicated by the diversity of AM equipment and process types.</p>	<p>Standard Data Structures, Definitions, and Metrics for AM Models (Figure 5-3)</p> <p>The attributes of multiple additive processes and supporting models need to be identified, defined, and classified in a consistent way to support effective modeling and simulation tools. Standard data structures need to be established to enable collection of needed model inputs while protecting IP.</p>

FIGURE 5-1. ROADMAP ACTION PLAN: EXPERT SYSTEM FOR AM DESIGN

BARRIER: Expert systems for AM design do not exist, and there are few known/validated design rules for AM design. Tools are lacking to help select optimum AM materials and processes, or a design for a given AM process (e.g., feature capabilities, surface finish/post-treatment, and tolerances).

APPROACH SUMMARY: Capture design rules for various AM processes and materials and create design advisors, tools, and expert systems linked to computer-aided design (CAD) tools.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Capture available design rules from vendors for various metal-additive processes and materials ◆ Survey industry and academia for metal AM design best practices ◆ Conduct targeted R&D to address gaps in design rule coverage ◆ Evaluate/create CAD-like infrastructure (computer-aided AM with properties) with linkable expert system design advisor software, reformulate best models, and then pilot test and release 	<ul style="list-style-type: none"> ◆ Year 1: Design rules/best-practices captured from vendors and users ◆ Years 1–2: New design rules developed to address gaps ◆ Years 1–2: CAD-linkable expert system design advisor software developed and pilot-tested, models validated through specific case applications 	<ul style="list-style-type: none"> ◆ Formalized design rules and expert advisor models and software for AM, widely disseminated in the United States ◆ Innovative parts design via use of comprehensive models and understanding ◆ Accelerated industry adoption of AM capabilities ◆ Design teams able to exploit unique AM capabilities ◆ Design rule database easily extensible by users (e.g., for company-specific applications) ◆ Determine ownership, maintenance, and distribution model for expert advisor software
3–5 years	<ul style="list-style-type: none"> ◆ Validate best models using high-performance computing and experiments ◆ Refine and update software and expert advisor rules ◆ Create techniques for efficiently mapping entire design space 	<ul style="list-style-type: none"> ◆ AM Human Genome-like process established ◆ Comprehensive map for computer-aided AM with properties and the ability to rapidly map properties and validate ◆ Mechanism in place to capture and incorporate user-developed design rules ◆ Design rules and best practices for emerging AM processes and materials 	
5+ years	<ul style="list-style-type: none"> ◆ Integrate ‘AM Genome’ capability into computer-aided AM with properties ◆ Develop accessible user interface for engineers and other users in commercial space ◆ Incorporate emerging AM processes and materials 	<ul style="list-style-type: none"> ◆ Real-time performance achieved ◆ Continued capture and incorporation of new user-developed design rules ◆ Optimized design of parts and microstructures 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide metal AM design best practices and case studies, conduct collaborative R&D on design rule gaps
- ◆ **Industry/AM Providers:** Provide known design rules for various metal-additive processes and materials, conduct collaborative R&D on design rule gaps, input on machine capabilities for Genome
- ◆ **Academia:** Provide metal AM design best practices, conduct collaborative R&D on design rule gaps
- ◆ **Standards Committees:** Create taxonomy and terminology, certification/validation methods
- ◆ **Government:** Conduct collaborative R&D on design rule gaps, support programs, serve as repository for AM Genome

RELATIVE IMPACTS

LOW — HIGH



Improves product quality: Designs optimized for reproducibility and quality control



Reduces costs: Reduced product development time and cost, maximizes efficient use of AM for production



Accelerates innovation: Enables design teams to exploit the unique capabilities of AM and streamlines transfer of models to industry



Enhances industry competitiveness: Accelerates adoption of AM capabilities by U.S. industry and positions industry to compete



Faster product development time: Fewer design iterations and integrate disparate tools



Other: Accelerates knowledge transfer, best-practice sharing, and on-shoring of manufacturing, also spawns new companies and products

FIGURE 5-2. ROADMAP ACTION PLAN: VALIDATED PHYSICS- AND PROPERTIES-BASED PREDICTIVE MODELS FOR AM

BARRIER: There is a lack of validated physics- and properties-based predictive models for AM that incorporate geometric accuracy, material properties, defects, surface characteristics, residual stress, microstructure properties, and other characteristics.

APPROACH SUMMARY: Apply fundamental physics principles, material property measurements, and model validation methods to create multi-scale models. Apply standardized verification, validation, and uncertainty principles.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Survey universities and labs for <ul style="list-style-type: none"> ○ Appropriate material property data ○ Physics-based models ○ Defect characterization ○ Temperature-dependent properties of AM materials (density, conductivity, and absorption) ◆ Do a gap analysis on surveyed data ◆ Generalize the process for developing optimized models ◆ Prioritize material properties list, the models to be enhanced, and defects requiring greater research 	<ul style="list-style-type: none"> ◆ Prioritized lists of material property data, models, and defects ◆ Properties and model database open to AM community ◆ Generalized models 	<ul style="list-style-type: none"> ◆ “Batch of One” (i.e., the ability to economically and correctly fabricate a unique part with a batch size of one) ◆ Reduced cost, performance, and schedule risks ◆ Ability to generate controlled microstructures
3–5 years	<ul style="list-style-type: none"> ◆ Generate platform-independent, generalized models incorporating all variables ◆ Carry out round-robin evaluation of models via standard part application (e.g., evaluate dimensions, distortion, and surface finish) ◆ Generate material data supporting prioritized material list ◆ Identify multiple machines, carry out model validations, compare machine-to-machine, day-to-day, and platform-to-platform variations 	<ul style="list-style-type: none"> ◆ Validated, generalized process and part models ◆ Identification of prioritized model and source variability ◆ Material database ◆ Process database 	
5+ years	<ul style="list-style-type: none"> ◆ Expand material property data to new materials ◆ Commercialize model software ◆ Expand models to include multiple scales 	<ul style="list-style-type: none"> ◆ Development of new models and tools 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide input on needs
- ◆ **Industry/AM Providers:** Provide an open architecture machine, improve machine specifications to support models (e.g., beam diagnostics and infrared imaging)
- ◆ **Academia:** Provide models, trained personnel, and data analysis
- ◆ **Standards Committees:** Develop standard test articles and software standards
- ◆ **Government:** Support for database infrastructure and develop and test algorithms

RELATIVE IMPACTS

Low — High



Improves product quality: N/A



Reduces costs: Achieving “Batch of One,” has a high impact on cost



Accelerates innovation: Reduces barriers to new technology and products



Enhances industry competitiveness: Enables better design and quality at lower cost



Faster product development time: Determine best processing parameters

FIGURE 5-3. ROADMAP ACTION PLAN: STANDARD DATA STRUCTURES, DEFINITIONS, AND METRICS FOR AM MODELS

BARRIER: Differing AM processes and equipment types with different attributes complicate the creation of common standards and metrics definitions. Foundational data and knowledge for standard models is also lacking.

APPROACH SUMMARY: Identify, classify, and group the attributes of additive processes and supporting models to the nearest “generic” level. Define useful standards and metrics that apply to the groups and can be extended to specific applications while building the foundational data, information, and knowledge.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	<ul style="list-style-type: none"> ◆ Establish and prioritize process and equipment groupings ◆ Establish a standard data structure that assures needed input while protecting IP ◆ Collect data and define initial metrics and standards for priority processes and equipment 	<ul style="list-style-type: none"> ◆ Definition of families of processes, equipment, and models ◆ Architecture and standard data structure ◆ Initial data collection using standard structure 	<ul style="list-style-type: none"> ◆ Ability to accurately model and verify the transformation of raw material to products using standard data, information structures, measurements, and methods and extendable models (i.e., models that address defined categories and are extended to detailed applications)
3–5 years	<ul style="list-style-type: none"> ◆ Conduct controlled experiments to verify initial metrics and standards ◆ Extend metrics and standards from initial sets to broad coverage of AM ◆ Provide the structure to unify modeling and simulation systems with standards to support the evaluation of system performance (inputs to transfer function provides expected output) 	<ul style="list-style-type: none"> ◆ Pilot implementation and verification of metrics and standards ◆ Metrics and standards for a “basic” set of AM processes and equipment ◆ Completed evaluation of standard model representation and defined performance attributes (i.e., metrics) of the models 	
5+ years	<ul style="list-style-type: none"> ◆ Provide integrated capability ◆ Standards and metrics to accurately model the transition of raw materials to product 	<ul style="list-style-type: none"> ◆ Integrated modeling and simulation demonstrated across AM processes and equipment 	

STAKEHOLDERS & POTENTIAL ROLES

- ◆ **Industry/AM Users:** Provide data and test case definition, provide V&V criteria, and support V&V testing
- ◆ **Industry/AM Providers:** Provide data and data access to support process modeling, actively engage in equipment modeling and standards development
- ◆ **Academia:** Conduct research to develop models that enable and implement standards
- ◆ **Standards Committees:** Work with ASTM Committee F42 on Additive Manufacturing Technologies to assure that the standardization process is followed, including buy-in from all stakeholders and delivery of authorized standards
- ◆ **Government:** Infrastructure capability; Provide unbiased coordination of standards and measurement development, facilitate implementation

RELATIVE IMPACTS

Low — High

- ◆◆◆ **Improves product quality:** V&V performance assures product quality
- ◆◆ **Reduces costs:** Eliminate trial-and-error, reduce iteration
- ◆◆ **Accelerates innovation:** Robust models enable cost-effective modification and “what if” scenarios
- ◆◆◆ **Enhances industry competitiveness:** Reduces failure and enables useful product production with less risk and lower cost
- ◆◆◆ **Faster product development time:** Enables rapid error correction
- ◆◆◆ **Other:** Lowers the risk of AM deployment and opens new opportunities and applications

CHAPTER 6: CROSS-CUTTING CHALLENGES

CROSS-CUTTING TECHNICAL CHALLENGES

A number of technical challenges were identified that cut across materials, processing and equipment, qualification and certification, and modeling and simulation.

Standards and protocols for all aspects of AM: Standards, protocols, and guidelines are a pervasive need for additive manufacturing (AM) and impact all aspects, from materials design and use to part build, inspection, and certification. Standards are not only critical to processing and control, but also impact the ability to qualify and certify parts and process performance, as well as the development of effective models for design and AM operation. The time and cost to develop standards was noted as a continuing challenge, particularly to keep up with rapidly shifting or emerging AM technologies. The key standards needs are summarized in Table 6-1.

Table 6-1. Summary of Standards Development Requirements

<p>Part Quality, Consistency, and Conformance to Specifications</p>	<ul style="list-style-type: none"> • Standards and guidelines for part conformance, qualification, and certification, including: <ul style="list-style-type: none"> ○ Geometric accuracy, material properties (spatial), defects, distortion, surface characteristics, and variation in these characteristics ○ Microstructure quantification, artifacts to test microstructure ○ Characterization of multi-material parts • Standardized measurement test pieces/specimens and lot-based testing standards • Standardized part validation tools • Post-process standards and specifications for parts (e.g., internal, surface roughness, measurements) • Standards for building (e.g., orientation) and repairing of parts <ul style="list-style-type: none"> ○ Round-robin testing for building and testing parts ○ Test protocols for materials testing and reporting of results ○ Repair protocols
<p>Materials Specifications</p>	<ul style="list-style-type: none"> • Specification standards (machine-independent) for all aspects of materials (e.g., microstructure, vaporization, properties, powder chemistry, size distribution), including alloys, deposited metals, virgin and recycled feedstocks, and finished build • Standardized tests and protocols for design and qualification of materials • Standardized ratios for new/used powders and associated test protocols • Standards for materials that are linked to processing (e.g., TI-624) • Handling, storing, and disposal of AM feedstock materials <ul style="list-style-type: none"> ○ Update of OSHA / material safety data sheet materials handling standards for AM materials
<p>Process and Control Standards and Metrics</p>	<ul style="list-style-type: none"> • Standards and metrics for measuring and characterizing AM processes and artifacts to support qualification, certification, modeling, and data collection, including: <ul style="list-style-type: none"> ○ Machine-to-machine consistency ○ Standard build parameters among machines ○ Dimensioning across machines ○ Repeatability of results ○ Machine metrics and standards for design allowables ○ Guidelines for “boundary conditions” ○ Utilization of sensor technology and open system in-process materials control ○ Guidelines for trials needed to verify the properties of each build ○ Reliability and maintainability guideline adoption (e.g., SAE MI 10.2) ○ Mean time between failure ○ Descriptive vector hatch and mask standards

Table 6-1. Summary of Standards Development Requirements

	<ul style="list-style-type: none"> • Common, baseline set of standard and open application programming interfaces and file formats among vendors (aligned/reconciled with ASTM International formats) • Standards for AM system hardware
Machine and Equipment Calibration	<ul style="list-style-type: none"> • Consistent machine and equipment calibration standards (beyond machine variability), including: <ul style="list-style-type: none"> ○ Prototyping, production-quality-parts-capable machines ○ Features and properties requirements ○ Calibration frequency • Calibration parameters for processes and equipment (existing and future)
Data collection and Storage	<ul style="list-style-type: none"> • Standards for mining, creating, reporting, storing, and comparing data on AM materials, processes, equipment, and testing • Data file format compatibility protocols • Standardized databases for materials properties

Measurement and monitoring techniques and data: Current technologies and techniques for measurement, monitoring and control are inadequate and can significantly impact part quality, functionality, and performance. New sensors, integrated models, and measurement methods will be needed to enable integration of materials and processing control and feedback.

Modeling systems that couple design and manufacturing: Modeling systems for AM do not integrate design and manufacturing aspects which impacts development of materials and products as well as new processing technologies. The ability to understand and predict outcomes would greatly contribute to better designed parts with fewer defects in production.

Closed loop control systems for AM: These systems are vital for processing and equipment performance, assurance of part adherence to specifications, and the ability to qualify and certify parts and processes. Deficiencies in modeling systems are integrally linked to and impact monitoring, control and feedback systems. Data from control systems can feed model development and good models can help to provide higher levels of sophistication and utility for control systems.

Insufficient research on AM materials: Metallurgical research on materials for AM is lacking, materials manufacturing research is lagging overall. Insufficient resources are being applied to grow the knowledge base, and coordination of resources and priorities is lacking.

NON-TECHNICAL CHALLENGES

Bias toward conventional manufacturing: Product designers in the industry are familiar with conventional manufacturing technologies and are naturally biased toward them. As a result, most parts are optimized for conventional manufacturing.

Difficult business case: The business case for AM can be unfavorable, partially due to high capital and material costs, as well as parts optimized for conventional manufacturing. Technologies in some cases are not demonstrated at scale, which creates additional uncertainty about potential return on investment and hinders investments in research and development. Further education of managers and company decision makers about AM technologies may alleviate some hurdles. The industry is also characterized by vast but diverse product and market niches which can limit interest in investments.

IP rights vs. open source: Company protection of intellectual property is important to recuperate investments made in the development of AM technologies. “Black box” solutions are often the result, precluding open

source code for software programs. While this approach by individual companies is understandable, it can hinder broader efforts to further develop and improve the technologies. Additive manufacturing would ideally allow for precision in the reproducibility of a range of metal parts, but robust, comprehensive, and pro-active anti-piracy and counterfeit protections and safety mechanisms and protocols would be required. Such measures would help ensure ethical use of the technology and can allow for competitive markets to lower the price of AM parts and allow this technology to diffuse into the marketplace. Whether anti-counterfeiting measures or systems are embedded into AM parts or otherwise, it is important to protect these issues that are uniquely relevant to metal-based AM technologies. Unique identifiers such as Radio Frequency ID tags or embedded serial numbers have emerged as one approach. Such tags could also provide life-cycle part history.

Educational challenges: Within the AM sector, lack of interdisciplinary knowledge and research is a barrier. AM technologies involve a variety of disciplines, including modeling, laser and electron beam physics, metallurgy, and statistics. Thus, it is difficult for one person to have adequate expertise in each of these diverse areas to fully understand all aspects of technology development. On the manufacturing side, highly skilled machine operators are in demand. Broader concerns about the state of science, technology, engineering, and mathematics (STEM) education in the United States can impact the AM industry as well. National technician certification, education, and training will be needed for AM across all platforms

Materials capacity, cost and supply base. In terms of material inputs, the availability of reliable sources of quality, economically feasible raw materials or feedstocks could pose a significant challenge. Growing suppliers of AM technology in the U.S. is also a challenge, and will require focused efforts to develop a domestic AM marketplace that encourages development of the technology and incentivizes suppliers to locate in the United States. A larger U.S.-based original equipment manufacturer supplier base for technology and equipment is needed. AM parts manufacturers would like to have access to AM production machines that are produced in the United States.

APPENDIX A: PARTICIPANTS

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APPENDIX B: AGENDA

Tuesday, December 4, 2012

7:30 am Registration and Continental Breakfast

8:30 am Opening Plenary Session

- **Welcome** ~ Shyam Sunder, Director, Engineering Laboratory, NIST
- **Stage-setting Presentations**
 - **Workshop Scope and Objectives** ~ Kevin Jurrens, Deputy Chief, Intelligent Systems Division, NIST
 - **Highlights of Prior Additive Manufacturing Roadmaps** ~ Dave Bourell, Temple Foundation Professor, University of Texas at Austin, Co-Chair 2009 Roadmap for Additive Manufacturing
 - **ASTM F42 Strategic Framework for Additive Manufacturing Standards** ~ Brent Stucker, Professor, University of Louisville, Chair of ASTM F42
 - **NAMII Additive Manufacturing Pilot: Priority R&D Needs** ~ Gary Fleegle, Vice President and Chief Operating Officer, National Center for Defense Manufacturing and Machining, NAMII Acting Deputy Director for Technology Development

10:00 am Break

10:30 am Industry Panel

- **Moderated session and Q&A on AM user perspectives**
 - **Moderator** ~ Ed Herderick, EWI, Chair of Additive Manufacturing Consortium (AMC)
 - **Panelists** ~

Agnes Klucha, Program Manager, Engineering Innovation Center, Pratt and Whitney

John Hunter, Director of Marketing & Sales, Carpenter Powder Products, Inc.

Dean Robinson, Manager, Model-Based Manufacturing Lab, GE Global Research Center

Hank Phelps, Advanced Development Programs, Lockheed Martin Aeronautics – Marietta

11:40 am Morning Wrap up and Instructions for Breakout Sessions

11:45 am Lunch

1:00 pm Breakout Session I: Desired Capabilities for Additive Manufacturing

- Envisioned future: What capabilities do we want and need the most

3:00 pm Break

3:20 pm Breakout Session II: Challenges and Barriers for Achieving the Capabilities

- Barriers limiting the broad use of additive manufacturing
- Measurement and standards barriers, challenges, and gaps

5:00 pm Adjourn Day I

Wednesday, December 5, 2012

8:00 am Continental Breakfast

8:30 am Breakout Session III: Prioritization of Challenges

- Review, clarify, and vote on the top challenges
- Determine R&D priorities
- Identify standardization priorities for ASTM F42

10:15 am Break

10:30 am Breakout Session IV: Pathways for Measurement Science Roadmap

- **Small groups work to develop roadmap elements:**
 - R&D, standards, and other approaches for addressing priority challenges
 - Next steps and actionable plan

11:45 am Lunch

1:00 pm Breakout Group Reports (Part 1)

1:30 pm Plenary Talk: Manufacturing the Road to Success

- **Tom Kurfess**, Assistant Director for Advanced Manufacturing, Office of Science and Technology Policy, Executive Office of the President

2:00 pm Breakout Group Reports (Part 2)

2:15 pm Workshop Wrap up and Next Steps

2:30 pm Adjourn Workshop

3:00 pm Interagency Roundtable (government only) ~ Tentative

APPENDIX C: WHITE PAPERS

Participants were invited to create white papers specifically for the workshop to address the following two questions:

1. What are the key measurement science barriers that prevent innovation in metal-based additive manufacturing (AM)?
2. What are the most important areas where research and development (R&D) is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

Eleven participants created white papers, presenting ideas for the common good. These voluntary submissions were much appreciated and used to shape workshop discussions. The complete white papers are listed below and contained in this appendix:

Author	Title
Stacey Kerwien <i>U.S. Army</i>	Using Measurement Science to Drive Design Guide Development for Additive Manufacturing
Dan Maas and Jesse Blacker <i>The Ex One Company, LLC</i>	Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop
Shane Collins <i>GROWit</i>	Laser and Electron Beam PBF
Frank Liou, Michael Bytnar, and Joyce Bytnar <i>Missouri University of Science and Technology</i>	Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop
Jennifer G. Bryant, John E. Benfer, and Anthony B. Petrizzo <i>NAVAIR</i>	Measurement Barriers in the Implementation of Metals Additive Manufacturing for Military Aircraft Repair and Maintenance
Ken Patton (RapidTech), Dr. Imelda Cossette (MatEd), Ed Tackett (RapidTech), and Frank Cox (MatEd) <i>ASTM F-42 Educational Working Group</i>	Additive Manufacturing Competencies
Kevin Chou <i>The University of Alabama</i>	Process Metrology for Metal-Based Additive Manufacturing
Jyoti Mazumder <i>University of Michigan at Ann Arbor</i>	Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop
Tom Campbell <i>Virginia Tech University</i>	Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop
Vito Gervasi <i>Milwaukee School of Engineering</i>	Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop
Constance J.S. Philips <i>National Center for Manufacturing Sciences</i>	Production and Use of Standard Parts and Our Lessons-learned Thus Far

Using Measurement Science to Drive Design Guide Development for Additive Manufacturing

*Stacey Kerwien, U.S. Army
(UNCLASSIFIED)*

It is clear that for the U.S. Army to utilize Additive Manufacturing (AM), concise design guides must be developed.

Successful design guides, such as the AWS D1.1 for Welding, require measurement science in the areas of machine parameters and feedback, surface preparation, filler metal composition, and joint configurations.

Thus, for Additive Manufacturing, it is our position that measurement sciences are needed in the areas of:

- Part Support Protocol
- Powder Properties (Composition, Size, Morphology)
- Build Environment (Temperature, Atmosphere, Sensor Feedback)
- Recoater Blades (Type, Amount of Wear)
- Build Plate (Material)
- Part Positioning
- Part Removal
- Beam Focus
- Filters (Amount of clogging)
- Final Part Dimensions & Roughness (and the correlation to the original 3-D model)
- Machine Software & Design Software

Once the part is produced with a known set of parameters, the challenge is to define the mechanical and metallurgical properties to be measured and ensure part-to-part and machine-to-machine consistency.

In developing a design guide, many of the items listed above merely need to be recorded so that lessons can be learned for future builds (i.e., Part support protocol, build plate material, part positioning, and design software used). Other items need to be measured in a more quantifiable way that NIST may already have experience with (i.e., Final dimensions and roughness, amount of clogging on the filters, amount of wear on the recoater blade). Finally, new sensors need to be developed/enhanced to provide real-time feedback on the build environment and the beam focus to ensure consistent part quality.

Thus, a combination of generally accepted practices, standard measurement techniques, and sensor development is needed to ensure the continued improvement of additive manufacturing. With improvements to AM, the industry and government will finally achieve a provisional design guide at the very least.

Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop

Dan Maas and Jesse Blacker, The Ex One Company, LLC

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

Dynamic Measurements and Control:

- In-process, real-time sensing and control
- Real-time, model-based feed-forward control
- Transient changes in process characteristics with real-time dynamic feedback
- Process mapping—both for control and for process learning

Scale:

- Nano/micro/millimeter AM for metals and metal/ceramics
- Large-scale (measured in meters) AM machines and equipment

Material Composition (not just metals):

- Functionally gradient materials, metal matrix composites, ceramic/metal mixtures
- Embedded nano-particle/nano-fiber structures

Environmental Impact:

- Temperature, humidity, and dew point
- Reuse, recycle, ratios of virgin to reused
- Thermal cycling, oxidation, and atmospheres

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

Atomic-scale to meso-scale modeling and simulations:

- An integrated modeling platform addressing atomistic-informed meso-scale modeling has applications for functionally gradient materials, ceramic/metal interface structures, metal matrix composites, etc.
 - “Atomistic-informed meso-scale modeling: Interfaces and their interactions with defects influence a wide range of behaviors from crystal reorientation, slip, twinning, boundary sliding, migration, phase stability, etc. Little of this can be predicted by treating only one type of defect/interface interaction alone. Models are packed with information. For one model to ‘inform’ another means that the transfer of knowledge of dominant mechanisms, phenomena, or physical properties, at the lower scale measurably transforms the way in which the higher scale is modeled and/or performs. In this regard, scientific expertise has to be exercised to determine what atomic scale information is useful and applicable to the rate conditions applied at the meso-scale.” Irene J. Beyerlein, Office of Science, U.S. Department of Energy.

- NIST has already started the Materials Genome Initiative (MGI) to develop a materials innovation infrastructure.

3. Some comments/suggestions for near-term consideration regarding the current Artifact Standard.

- Provide guidelines for the inspection methodology
 - Example: should the artifact sit upon 3 spheres to establish a plane?
 - Example: explain the purpose of the steps/incline/ramp
- Use the artifact to produce specimens for mechanical property testing
 - Provide guidelines for compression, tensile, fatigue, impact, etc.
- Consider several size artifacts for micro and meter size AM build boxes

Laser and Electron Beam PBF

Shane Collins, Director, Additive Manufacturing Technologies, GROWit3d

Note: Included in this article is background information on powder bed fusion. The chart at the end lists what I believe are the necessary parameters that need to be measured and monitored for powder bed fusion. Standardization, measurement, and monitoring of these parameters are necessary for a robust powder bed fusion process.

Powder bed fusion (PBF) is the ASTM-accepted term for an additive manufacturing process where a point heat source selectively fuses or melts a region of a powder bed. In the United States, the metal powder bed fusion processes are known by the trade names SLM® and DMLS® for the laser beam process and EBM® for the electron beam processes. Curiously, there are no machines that perform the PBF process manufactured in the United States. That fact notwithstanding, PBF has become a popular method of creating high-value medical and aerospace prototype components as well as production components in safety critical applications. This article compares the electron beam and laser beam technology while taking a look at the practical aspects of the two systems for future PBF process development.

My first home computer was a 386 PC clone running Windows 3.1. For the time it was pretty fast and had enough power to run my wife's CAD program, CADKEY. What made it fast for the time was the upgraded video bus from the normal ISA to the faster VESA local bus that moved data from the microprocessor back and forth to the video card. It was fast enough to run a 2D CAD program, but displaying video on the CRT was not possible. That was what TVs were for.

About that same time in my professional career I was involved in the digital imaging revolution that paved the way for image processing, calibrated measurements, and digital image archiving. However, before digital cameras existed, digital imaging involved the acquisition of video signals where NTSC or PAL video was captured with a computer board called a frame grabber. The frame grabbers for the aforementioned 386 PC cost \$12,000–\$20,000 because of buffering circuitry necessary for displaying the video on the computer's CRT. With the introduction of the 486 and the PCI bus the data transfer rate was significantly improved and uncompressed video signals were easily transferred to the video card for display on the CRT. The cost of the frame grabbers plunged to a few hundred dollars while the image capture quality greatly improved. The 486 PC computer with the speed of the PCI bus facilitated a revolution in video image capture and digital image analysis.

Fast forward to 2004 and a similar revolution can be seen in the field of metal laser sintering with the introduction of the solid-state Yb-doped fiber laser that replaced the ubiquitous CO₂ lasers. The advantages of the fiber laser over the gas laser were the low cost of ownership, better absorption due to the emission wavelength, continuous wave nature of the beam, and fine focus capability of 100 μ and lower beam diameter. This intensity produced 25 kW/mm² and allowed for 20 μ powder layers to be completely melted several layers deep on each pass of the laser beam. The development and introduction of the fiber laser was an enabling technology for metal laser sintering and will be discussed in more detail, but first a look at the early years.

Laser beam PBF systems have their roots in the 1990s from technology developed and commercialized by the Fraunhofer Institute, Triumph, EOS, Concept Laser, and Fockel and Schwartz, all from Germany. These early systems used gas or disk lasers and processed primarily bronze-based composite materials. One of the first fully dense alloy (55% Au-28.5% Ag) systems was introduced by Bego at the 2003 IDS conference as a solution for making dental copings for porcelain fused to metal restorations. Shortly after the 2003 IDS, EOS and Sirona Medical Systems were working in a cooperation to commercialize the manufacture of fully dense CoCr dental materials using laser beam PBF. Due to the high cost of gold powder becoming entrapped inside the machines, it would be many years later that sealed machines would make gold alloy processing feasible, whereas lower-cost

CoCr (ASTM F75) processing found many applications in general industry and led to other alloy processing, including 316L and 17-4 stainless steels.

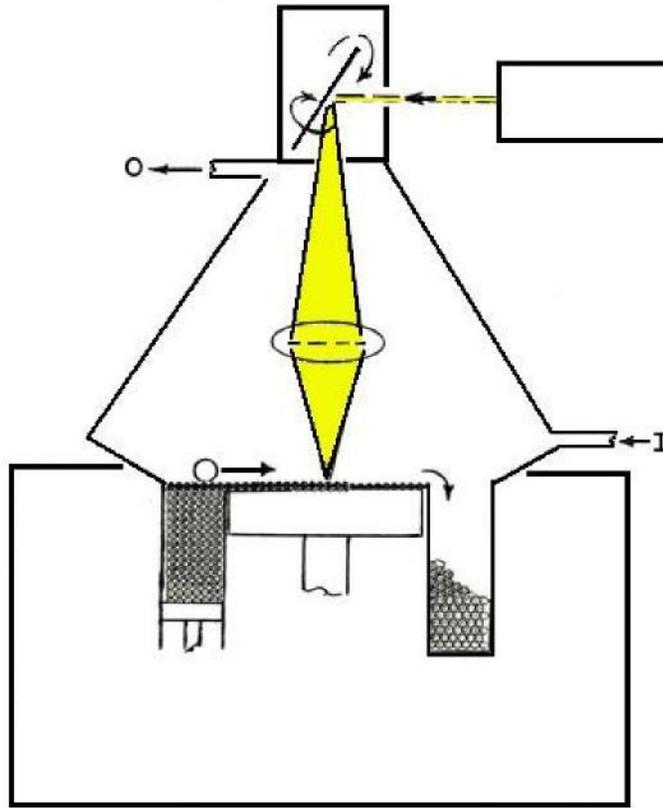
About the same time that laser beam PBF systems adopted the fiber laser and started processing true ISO and ASTM alloys, Arcam from Sweden was processing fully dense titanium components in its electron-beam-based PBF system. Although internal tests proved it possible to process most electrically conductive metal powders, Arcam concentrated on titanium, particularly Ti 6Al-4V.

Both the laser and electron beam systems have nearly a decade in manufacturing and marketing commercial systems. Today, there are about a half dozen companies selling laser-beam-based PBF machines with a worldwide installed base of nearly 900 systems. Arcam is the only commercial electron-beam-based PBF system with an installed base of 100 systems worldwide. So, in about the same amount of time there are multiple manufacturers of laser-beam-based systems with an installed base nearly 9 times greater than electron-beam-based systems.

Having more manufacturers and significantly more machines installed, one might draw the conclusion that laser-beam-based systems are superior to electron-beam-based systems. If this is the case, what is it about laser-beam-based systems that make them highly accepted and what is it that makes electron-beam-based systems less prevalent? Although this article is not meant to be a feature-by-feature comparison, the fundamentals presented help to explain the current status.

Laser Beam System Overview

As previously discussed, the laser-beam-based PBF systems use a fiber laser as the fusion heat source. The two manufacturers that supply fiber lasers to the laser beam PBF machine manufacturers are U.K.-based SPI, which was founded in 2003 and acquired by Trumpf in 2008, and Oxford, MA, IPG, which boast sales of more than 40,000 fiber lasers since 1990. The engines that power the laser beam PBF systems are supplied by competent companies that also supply lasers for laser drilling, laser ablation, laser cutting, laser marking, and laser cladding where PBF is a small percentage of their overall business.



Optical diagram of laser beam PBF system

Next to the heat source, the most important component of the laser beam PBF systems is the beam deflection optics that provide the scanning capability for selectively melting areas of the powder bed. With scan speeds up to 15 m/s, the scanning mirror must be fast, accurate, and reliable. Most of the laser-based PBF machine manufacturers use scanning optics from Scanlab of Germany. Scanlab manufactures a wide variety of 2D and 3D scanning systems for OEM applications including micro-machining, DNA Sequencing, laser cutting, and additive manufacturing. Again, as in the fiber laser business, the PBF component of Scanlab's sales is small in comparison to the total market for these devices.

The final significant optical element is the correction lens that ensures the beam is round as it traverses the build platform and keeps the beam velocity proportional to the angular velocity of the scanning mirror. Most of the systems use the f-Theta lens design with anti-reflection coatings to help prevent damaging laser reflections back into the laser. There are a number of f-Theta lens manufacturers that sell off-the-shelf solutions as well as custom OEM applications. However, there appears to be a limit to the intensity of laser power that is possible when employing the f-Theta lens design. Somewhere in the 300 W laser power range the f-Theta lens heats up and causes optical distortions as the lens changes temperature. In order to overcome this shortcoming and to meet the increased power needs of laser-based PBF systems, Scanlab recently introduced varioSCAN focusing units that dynamically vary the focal length in conjunction with the scanning mirrors. With the varioSCAN units installed, f-Theta lenses are no longer needed and this optical layout supports 1 kW laser power as well as multiple laser inputs for increased scan speeds or multiple laser power modes. Another recent development with the scanning optics is the linear beam intensity profile. Unlike the typical Gaussian distribution beam profile where the beam intensity decreases from the beam center to the outside circumference, it is now possible to have a nearly equalized beam intensity across the entire profile. This has a profound effect on the overlap of the hatch spacing necessary to ensure fully melted surfaces. It is like the difference in mowing your lawn with a

lawnmower having a blade that is all the same distance above the ground, versus mowing your lawn with a lawn mower where the blade curves up at the wheels. In the latter example it would be necessary to overlap your rows quite a bit to cut the grass all the same length, whereas in the former example the wheels only have to be overlapped to achieve the same length. The equalized beam intensity profile has the potential to improve surface finish, decrease scan time, and reduce subsurface porosity when fully implemented.

To summarize the laser-based PBF systems, the lasers and scanning optics are supplied by companies that manufacture many times more ship-sets than what are used for laser-based PBF machines. This means the heart of the systems can be acquired with off-the-shelf items and to some degree the development of laser-based PBF technology is paced by IPG, SPI, and Scanlab. To be sure there is much more work to integrate the optics, electronics, and electro-mechanical bits, not to mention the man-years in process development, but it is more execution rather than development.

Electron Beam System Overview

Powerful electron beams used for welding have their roots back in the late 1950s from the German physicist Karl-Heinz Steingerwald. Today, two of the oldest electron beam welding machine manufacturers claim to have combined machine installations of over 1,800 systems worldwide. The main benefit to the electron beam over the laser beam in welding is in the higher beam energy density without effects due to reflectivity.

Arcam adapted the electron beam technology for freeform fabrication in 1997 with sights on building net shape plastic injection mold tooling using steel alloy powders. By 2003, Arcam had 4 electron beam PBF machines in house and another 4 machines at external installations. After a few years working with steel powders, Arcam turned its focus to titanium alloys and that remains its most widely used alloy today, both internally and at user installations. Arcam currently supplies machines, materials, and parameters for Ti CP, Ti 6Al-4V, Ti 6Al-4V ELL, and CoCr (ASTM F75), but electron beam PBF machine users have successfully processed many more alloys including high-nickel and intermetallic compounds.

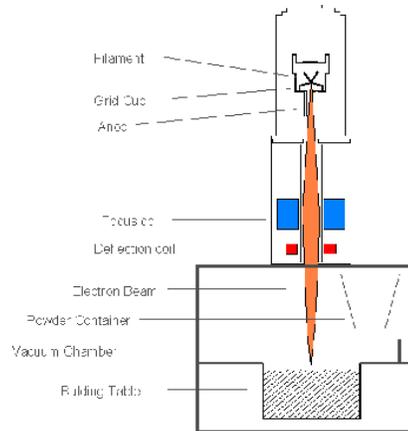
In the electron beam PBF system the electrons are generated from the filament and attracted toward a positively charged anode where a beam is formed. The focusing coil produces a converging, Gaussian beam and the deflection coil directs the scanning of the beam. The focusing and deflection coils are the electronic counterparts of the scanning and f-Theta optics of the laser beam systems. Since there are no moving parts in the electron beam PBF system, the scan speed can approach 3,000 m/sec (compared to 15 m/sec with lasers) with usable beam power in the several kW range.

The physics of the electron beam interaction with the powder bed is complex. In addition to the kinetic energy from the electrons irradiating the surface, there are four other forces at play that have been modeled by Christian Eschey (Technische Universitaet Muenchen): pulse transmission, hermodynamics, electrostatics, and electrodynamics. These forces can create unwanted consequences during the electron beam PBF process and are dependent on the powder morphology and chemical composition due to different electrical resistance from powder particle to powder particle. One such unwanted consequence is the powder's propensity to disperse upon contact by the electron beam. Powder dispersion, aka "smoke" usually results in a total build failure.

As a means of mitigating the powder dispersion failure, Arcam learned to partially sinter the powder layer prior to selective melting. This caused the powder layer to adhere to the previous layer and also to itself, thus preventing powder dispersion. The elegant solution for the heat needed for sintering the powder came directly from the electron beam, which was possible due to the high beam energy and fast scan speed.

Whether it was intentional or not, the need to sinter the powder prior to selective melting meant the powder bed had to be heated to very high temperatures, approaching 650°C to 700°C for titanium and up to 1100°C for intermetallic compounds. This created a difficult operating environment for electro-mechanical components in the build chamber, but it had advantageous affects compared to a cold process on component microstructure and was self-annealing, which reduced the requirement for unwanted support contacts.

The electron beam PBF machines require a vacuum in the build chamber in order to have a focused beam. The added complexity from the vacuum pumps, chamber reinforcement, and seals necessary to maintain 1×10^{-4} mbar vacuum adds a level of machine integration difficulty not required for the laser-based PBF systems. In addition to the vacuum requirement, the electron beam interaction with the powder makes the electron beam PBF machines more difficult to develop and optimize.



Electron beam PBF diagram

Comparison between laser and electron beam PBF

Visual inspection of as-built components made on the electron beam PBF machines shows a much rougher surface finish and less accuracy to the CAD model than components made with laser beam PBF machines. This is due to coarser powder, thicker layers, and a larger melt pool in the electron beam PBF machines. There is nothing inherent with the electron beam technology that would prevent the same or better surface finish for the electron-beam-based system. It has been the historical implementation of the technology for freeform fabrication that created this disparity, specifically the trade-off between build speed and surface finish.

However, surface finish alone is not a sufficient reason that in the same amount of time there are 9 times more laser-beam-based PBF systems installed as there are electron-beam-based PBF systems. Some of the difference can be attributed to the higher cost of the electron-beam-based machines and the marketing efforts of multiple laser beam machines, but the underlying advantage of the current state-of-the-art laser-beam-based PBF systems is higher levels of successful first-time component builds. This supports the job shop prototype business model, while having to build a component several times in order to dial-in the build parameters for success is relegated to the production business model. To date, we are seeing more demand for prototype components than demand for production components and while the ratio of prototype to production components will likely shift to production in the coming years, much of the process development and certification work is currently being done on the laser beam systems.

Another contributor to the success of the laser-beam-based PBF machines is their ability to routinely process many different alloys including maraging steel; high-nickel super alloys; 316L, 17-4, and 15-5 stainless steel; CoCrMo; and aluminum, to name the most popular. Because of the complexity of the electron beam interaction with the powder surface and the need for high-temperature processing, optimization of build parameters is tedious and time consuming on the electron beam PBF machines. A build failure entails a several-hour cool downtime followed by a lengthy restart process. Compare that to a build failure on a laser-based PBF machine, where the operator immediately opens the chamber door; pounds down a high spot, for example; closes the chamber door; and restarts the build with modified parameters. The iterative process is much faster and allows a higher degree of experimentation by general users. On the electron beam PBF machine side, sophisticated modeling that accounts for feedstock particle size, shape, and composition along with electron beam dynamics needs to be developed to qualify interesting alloys.

Conclusion

Intellectual property rights and patents held by Arcam could help to explain why there is only one electron beam PBF machine manufacturer. However, one only needs to look at the litigation in the laser beam PBF market along with the various distribution agreements that have emerged to understand this is not the whole story. Usually, when markets are viable, competition finds a path around and forward. The primary reasons why there are multiple laser-beam-based PBF machine manufacturers are: ease of acquiring off-the-shelf components to manufacture the machines, ability to process in a cold build chamber, relative ease of qualifying new materials, and demand for components made from the process. Having said that, the technology that has the most upside in terms of additive manufacturing of metals in a powder bed is the electron beam process. This is due to the electronic control of the beam diameter and deflection that can scan so fast it appears to have multiple beams hitting the surface at once. As long as the scanning optics in a laser-based system have mass, it won't be possible to meet the scan speed or beam dynamics of the electron beam system.

Other than beam dynamics, features that create the total PBF solution can be implemented with either electron beam or laser beam systems. Both types of processes can have vacuum, can have heated powder beds, can have thin or thick layers, can be scaled up or down for component size (electron beams have an advantage for sub micron spot sizes), and can utilize different powder morphology and composition (laser beams have an advantage on non-conductive powders). In fact, we are already starting to see thicker layers to speed up processing on laser-based machines as the 400 W and now 1 kW lasers are available from IPG and SPI. We find vacuum pumps installed on a laser-based machine from at least one machine manufacturer, and the surface finish on electron-beam-based PBF components has improved significantly with the introduction of thinner layers and multi-beam contour scanning. In short, we are witnessing a convergence of the two technologies.

As the two PBF technologies converge, there is a need for measurement and control of the process fundamentals in order to produce safety critical components. Here is a comprehensive list of those parameters:

Parameters	Measurement	EB PBF	LB PBF	Requirements
	Powder Flow	H	H	S, I, MP
	Chemical Composition	H	H	S, I, MP
	Particle Size	H	H	S, I, MP
	O2	H	L-H	MP
	Spread Coherence	H	H	
Power Density at Part Bed	Beam Diameter	H	H	
	Beam Profile	H	H	
	Consistency of Part Bed Area	H	H	
	Consistency of Build Time	H	H	
Process	Melt Pool	H	H	
	Hatch Space	H	H	
	Contour Space	L-H	L-H	
Part Bed Temp	Build Platform	H	H	
	Top Layer	H	L-H	
Machine	Z axis movement	H	H	
	Recoater Contamination	H	H	
	Build Atmosphere	H	H	
	Gas Flow	L	H	
Component	Mechanical Properties	H	H	
	Porosity	H	H	
	Microstructure	H	H	
	Surface Finish	H		
	Internal Stress	L	H-L	
	Dimensions	H	H	
	Remaining Powder	H	H	

Notes: EB PBF and LB PBF: H=High; L=Low Requirements: S= Supplier; I= Incoming Inspection; MP=Required in Manufacturing Plan

Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop

Frank Liou, Director, Manufacturing Engineering Program Missouri University of Science and Technology

Michael Bytnar Professor, Mechanical Engineering Department

Joyce Bytnar Professor, Mechanical Engineering Department

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

- **Quantify the dimensioning and tolerancing capabilities of an AM machine.** AM parts can be used for functional models and for fit and assembly, thus it is important to quantify the dimensioning and tolerancing capabilities of an AM machine. This capability may be complex due to possible shrinkage issues in the AM build process. In some AM processes, shrinkage may be a function of the part geometry.
- **Comprehensive material specifications and standards for each AM process.** Without these specifications and standards, engineers will not consider AM as a method of manufacturing.
- **Measurement of material properties at high temperatures.** Some metal AM processes build metals in high temperature that is above the melting point of the metal. In order to fully understand these processes and predict the resulting microstructure, the material properties at elevated temperatures are needed. The measurement of these properties is expensive. Since each material is different, a lot of effort is needed.
- **Measurement of the key process parameters at high temperatures.** In some metal AM processes, measurement of the key process parameters at extreme environment, such as high temperature, may be needed to ensure quality and reliability of the parts.

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

- **Open-architecture controllers and reconfigurable machine modules for integrated processes.** Just like CNC machining centers, AM machines need to take advantage of the open-architecture controllers and machine modularity so that more innovative processes can be created.
- **Creation of comprehensive material specifications and database.** Research and development is needed to find the material properties at elevated temperatures. This should also include the mixing of materials in high temperatures for applications in functionally graded material (FGM).
- **Better understanding of the processing-structure-property relationships of materials.** It will involve physics-based modeling and accurate measurement of the key parameters involved in the process. This will help establish the ability to accurately fabricate complicated shapes with a minimum number of experiments.
- **In-process measurement and feedback control to help improve reliability, repeatability, and uniformity across machines.** Nondestructive evaluation technology should be developed to enable early defect detection, which is important.
- **Machine qualification standards to ensure part-to-part consistency.** The standards will include all areas such as material input, preparation, processing, and post-processing if applicable.
- **Repair qualification standards.** If a part or product can be repaired and reused for its initial product function, not only will the material waste and amount of landfill be reduced, but also energy and matter consumption during manufacture will be reduced because existing components are utilized.

However, some companies have a need for parts that require repair or replacement frequently, but without a robust qualification process, repair may not be an option such as in the aerospace industry. The lack of standards in repair impedes the use of AM for parts remanufacturing.

- **Updated AM software research and development.** AM processes can potentially produce very innovative materials that could not be made before, thus updated AM software to support such capability should be researched and developed. For example, functionally graded material (FGM) may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The current standard CAD models do not have such capability.
- **Technologies to improve dimensional accuracy and surface finish.** All techniques to improve accuracy of AM processes, either in-processing or post-processing, are needed to widen the applications and the market for AM processes.

Measurement Barriers in the Implementation of Metals Additive Manufacturing for Military Aircraft Repair and Maintenance

Jennifer G. Bryant, John E. Benfer, Anthony B. Petrizzo, NAVAIR

Additive manufacturing (AM) of metals (e.g., titanium, nickel, aluminum) has many potential benefits in numerous industries, particularly in the field of aerospace engineering. Titanium alloys (i.e., Ti-6Al-4V) are of specific interest because their high cost could be mitigated by AM's low "buy-to-fly" ratio. Of particular interest to NAVAIR Jacksonville (FRCSE) is implementing direct digital manufacturing (DDM) to produce parts for legacy aircraft from drawings or reverse engineering when replacements parts are no longer commercially available. Additionally, DDM could be implemented during aircraft maintenance and repair to improve operational availability and cost savings by avoiding long lead times associated with obtaining one-off-repairable parts (OOR) from traditional manufacturing methods.¹

However, there are still many measurement science barriers that prevent innovation in metal-based AM and aspects that must be further evaluated prior to extensive implementation in industries seeking to adopt AM, such as the aerospace industry. Primarily, a database of the mechanical properties of materials produced by AM must be established. Characteristics (e.g., fracture toughness, yield strength, etc.) from material produced by AM must be compared with the current Metallic Materials Properties Development and Standardization (MMPDS) data for the same alloy produced by a traditional method. As parts produced by AM are anisotropic and vary by fabrication method, careful consideration must be made in measuring and reporting mechanical property values.² A clear understanding of the mechanical properties of parts produced by AM prior to industrial (e.g., aerospace) applications is critical. However, the AM parts do not necessarily have to match or exceed the mechanical properties of parts made by traditional manufacturing, because as long as the mechanical properties are known and are reproducible the part may still be engineered to specification. For example, if ultimate tensile strength of a material is reported in the MMPDS as 100 ksi from a traditional manufacturing method but the ultimate tensile strength for the AM part is measured at 80 ksi, a structural engineer can perform a static strength and/or fatigue analysis to determine acceptability or make alterations in the design such that the new material is still usable for a particular application. However, without a clear understanding of the mechanical properties of metallic material produced by AM, it is not known which industrial applications are realistic. Documented databases of mechanical properties and the establishment of industry specifications and standards for parts produced by AM are crucial.

Furthermore, advancements in measurement science must address necessary parameters for parts qualification, such as statistical reproducibility in AM for process control. Many industries seeking to adopt AM will require the ability to reproducibly manufacture drop-in replacement parts or parts from novel designs (e.g., military applications of metal alloy AM may utilize new and improved designs, as well as the ability to rapidly manufacture and reverse engineer drop-in replacement parts for numerous platforms to ensure operational availability). Therefore, the ability to rapidly qualify parts is of key importance. Understanding, measuring, and controlling inter-part, inter-machine variation and reproducibility for the implementation of repeatable and predictable processes during part manufacturing will be one key aspect of rapid qualification needed for the implementation of AM in military aircraft repair and maintenance, as well as in other industries requiring process control. Further R&D is required in this area to accelerate innovations in metal-based AM.

Finally, predictive modeling and simulation tools will be an important aspect of innovative structural design using AM. A benefit of AM is design flexibility and alleviation from some traditional manufacturing constraints. However, in order for design freedom to be fully realized, predictive modeling and simulation tools are required that can calculate mechanical properties in relation to structural variables (e.g., geometry, payload, etc.). Physics-based models are also needed to predict microstructure, properties, and defects during the AM process.¹

References:

1. William E. Frazier and Malinda Paget, Additive Manufacturing Direct Digital Manufacturing of Metallic Components, 2011 CTMA Symposium, Quantico, VA.
2. Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies*. 2010, Springer Science + Business Media, LLC, New York, NY.

Additive Manufacturing Competencies

Patton, Cossette, Tackett, and Cox, ASTM F-42 Educational Working Group

Ken Patton, Principal Investigator, RapidTech

Dr. Imelda Cossette, Principal Investigator, MatEd

Ed Tackett, Director, RapidTech

Frank Cox, Director, MatEd

With ASTM's establishment of Standard F-42, an Educational Working Group (EWG) was established to develop core competencies for emerging student technicians working in the field of additive manufacturing. This effort is funded by a National Science Foundation grant instrument to Edmonds Community College (MatEd, the National Resource Center for Material Science) in partnership with RapidTech (National Center for Additive Manufacturing). The goal of the grant is to develop student core and professional competencies supporting the developed global standards for additive manufacturing and to disseminate those competencies to the nation's educational community for inclusion in technician education and engineering programs, helping to ensure that manufacturing technicians and engineers are prepared to enter the workforce with the knowledge and skills necessary to work in the manufacturing environments of tomorrow.

As the Task Force develops the various standards, they are supplied to the EWG for transformation into core and professional competencies with the STEM area identified for each.

RapidTech and MatEd synthesize the standards into core and professional competencies, which are then distributed, to the EWG as a whole to make recommendations for edit. The final results are then shared with the Executive Committee of ASTM F-42, which is chaired by Bret Stucker.

The "Student Core and Professional Competencies" document is a living document that is modified each time a standard is approved or modified. The results are then disseminated nationally to the educational community for inclusion in their manufacturing technician and engineering instructional programs.

Ken Patton, Principal Investigator of RapidTech, chairs the educational working group with membership of over 25 educational and industry leaders in additive manufacturing. Those members include Ed Tackett, Director of RapidTech; Dr. Imelda Cossette, Principal Investigator of MatEd; Frank Cox of MatEd; Tim Gornet and Dr. Bret Stucker of U. of Louisville; Dr. David Rosen of Georgia Tech; and many other leaders of additive manufacturing education. It should be noted that industry also participates on the EWG and provides excellent guidance in the development of the Student Core and Professional Competencies document.

Skill and Knowledge Methodology

The underlying methodology behind the core and professional competencies is that each individual competency can be defined as either a skill or knowledge. A knowledge-based competency is well suited for distance education while a skill competency is more tactile in nature, requires a practicum, and would not be generally suitable for distance education, but it would be suitable for a hybrid educational model.

Science Technology Math & Engineering

Each individual competency is categorized by the major STEM category. This allows educators to measure how STEM competency can be defined.

For more information please visit: www.rapidtech.org or www.materialseducation.org.

Process Metrology for Metal-Based Additive Manufacturing

Kevin Chou, Mechanical Engineering Department, The University of Alabama

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

For metal-based additive manufacturing (AM) processes, the key measurement science barriers include process variable measurements (i.e., process metrology), e.g., temperatures and metal molten pool sizes and evolutions during the process. Meaningful, accurate, and reliable process variable data offers detailed, insightful information to understand the process physics and to monitor the process characteristics and performance and part quality and consistency. Moreover, process variable measurements often serve as necessary to validate the process modeling/simulations, which are also for fundamental process understanding, a key to enhance process performance and part quality.

From literature, for virtually every manufacturing process, process metrology (process variable measurements) was widely studied and considered necessary for process advancements. However, process metrology has not been seriously addressed in metal-based AM technologies including selective laser sintering/melting and electron beam melting, etc. In literature, there is very limited data on process variable measurements of metal-based AM in the public domain.

It is understandable that the process metrology in metal-based AM is very challenging because of extreme high temperatures, temperature gradients, complex material states (solid/liquid), and some having unique environments such as vacuum. Further, limited accessibility to the process chamber adds additional challenges to integrating instruments.

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

Current sensor technologies including infrared imagers and high-speed cameras seem to have the capability for process variable measurements in AM; for example, the desired temperatures ranges, spatial and temporal resolutions, etc.

Some of the most important areas where R&D is needed may include:

- 1) How to integrate sensors with an AM machine. How to be flexible for different machine platforms (same of different process principles).
- 2) How to process the vast amount of data. How to interpret the data correctly. How to use sensors and data analysis to obtain meaningful results.

The other areas of importance for R&D in AM process metrology, with benefits in process advancements and part improvements, may include:

- 3) How to apply acquired/analyzed sensor data for process modeling and simulation validations.
- 4) How to correlate acquired/analyzed sensor data with AM part properties from other measurements.

Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop

Jyoti Mazumder, University of Michigan at Ann Arbor

Metal-based additive manufacturing is almost two decades old and primarily includes two broad types: 1) powder bed such as Selective Laser Sintering (SLS) and 2) pneumatic powder delivery such as Direct Metal Deposition (DMD). Powder bed has the advantage of support materials and can prototype complicated parts relatively easily, but the deposition rate and work envelop are limited. Deposition of multiple materials is also a challenge. For DMD, high deposition rate, work envelop, multiple material deposition, and repair and reconfiguration of real components are advantages, but surface roughness increases with high deposition rate.

Presently both processes are evaluated post mortem. In order to promote broad use of additive manufacturing (AM), online measurement and control techniques are needed. Moreover, to further enhance the AM technology and realize the full potential of AM for fabrication of Meta-materials with properties not normally observed in mother nature, complicated online measurement of composition and phase transformation are needed. In order to achieve close, near net shape dimension, measurement techniques have to be non-contact and fast (\sim ms). Some of the critical needs for measurement are listed below.

1. Future measurement and standards for metal-based AM

Measurement techniques for AM need to be in situ, not post mortem, to control the process to achieve desired dimension, structure, and properties. Some of the urgent needs for measurements are:

- i. Deposition layer thickness for micron-level accuracy
- ii. Surface roughness with micron-level accuracy
- iii. Composition of the deposited layer
- iv. Phase transformation during the deposition and solidification process
- v. Detection of defects such as cracks, porosity, undercut/underfill, residual stress, and distortion
- vi. Develop the feedback control utilizing the above-mentioned measurement techniques to produce the desired properties

2. Measurement science barriers, challenges, and gaps preventing broader use

Major scientific barriers and challenges are:

- i. *Lack of materials and process database* that is universally acceptable. AM-produced materials properties are highly dependent on the process parameters. Therefore, drawing any scientific conclusion from the literature data becomes extremely difficult.

Suggested Solution: Develop a group of dimensionless numbers so that data can be extrapolated for different conditions (Ref: T Chande and J Mazumder, Metallurgical Transactions B, Vol. 14B, 181-190, 1983). This is a practice widely accepted in scientific and engineering communities. For example, Reynolds's number for flow, Biot's number for heat transfer, etc. With a single number we will be able to describe the process and properties connection.
- ii. *Detection defects resolved within milliseconds* or travel time to cross one heat source beam diameter.

Suggested Solution: Fast data acquisition for non-contact measurement techniques (e.g., Reflective topography [U.S. Patent #5,446,549], Spectroscopic characterization [Real time Cr measurement using optical emission spectroscopy during direct metal deposition process, *IEEE Sensors Journal*, (vol 12(5) 958-964, May 2012]) with fast feature extraction using machine learning algorithm.

- iii. Deploying measured data for process control.
- iv. Integrated simulation and measurement techniques for fabrication of “Designed Materials” with unique properties.

3. ASTM 42 priorities

- i. All the constituent parameters for energy sources (e.g. Laser, Electron Beam) need to be standardized. Some of it already exists.
- ii. All the constituent parameters for the powder and raw stocks need to be standardized.
- iii. AM-fabricated materials characterization for the certification process need to be standardized.

4. R&D needs

R&D needs are described in the “*Suggested Solution*” next to the scientific barriers.

Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop

Tom Campbell, Virginia Tech University

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

- Powder consistency (shape, properties, agglomerates, etc.)
- Closed-loop metrology capability within additive manufacturing systems (temperature, pressure, raw materials remaining, etc.)
- Post-build measurements (certifications, calibrations, etc.)

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

- Measure effects of aging (e.g., oxidation) of raw materials on process repeatability
- Full life cycle measurement capabilities must be put in place to ensure consistent and usable metals products (see [1] above)
- Funding increases from NIST, NSF, DOE, etc., to pay for metals measurements research in universities and corporate entities

Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop

Vito Gervasi, Director R&D, RP-Research, Milwaukee School of Engineering

I. What are the key measurement science barriers that prevent innovation in metal-based AM?

- a) Detection and characterization of inconsistencies and defects at a reasonable resolution within each layer (and perhaps some number of layers combined) of AM parts.
- b) Detecting and predicting final geometry relative to CAD intent, real-time and/or at build completion.
- c) High-resolution metallurgical inspection of quality of metallic AM component using NDA methods on a layer-by-layer basis.
- d) Measurement and detection of “grown-in” stress within the component.
- e) For Bi-metallic FGM’s the properties of the interphase are important to measure and characterize.
- f) Highly complex components are difficult to test and evaluate (i.e., a complex optimized cellular structure). Also, statistically, with build history known, the load capabilities of an optimized cellular structure could be predicted.
- g) Non-destructive detection and measurement of anisotropic properties.
- h) Monitoring and controlling grain size and direction is critical for some AM metal applications.
- i) For some AM parts, due to variable density, there is some challenge associated with specifying where the part begins/ends. For example, intentional or unintentional porosity needs to be detected and characterized for some applications. Now, with “variable density steel” available, part inspection presents many new challenges not prevalent in wrought or cast materials. Each density region may need to be handled as a separate material.

Note 1: Defects are often created in AM components due to the layer-wise build method of metallic parts. The defects occurring within a layer or between layers of AM components are sealed in by subsequent layers. One method/opportunity of detection may be real-time layer-by-layer quality inspection and image analysis for components. This information should be archived and tied to the specific part throughout its life cycle.

Note 2: The AM community needs to be able to statistically predict the behavior of a component during its intended use (especially in critical applications such as aerospace or medicine).

Note 3: Scanning during AM part growth has huge potential of detecting potentially high-risk parts before they are placed in service. This tracking combines with statistics can reduce the risk and liability of using AM-metal components.

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

Challenges abound:

- i) Tools for real-time scanning and evaluation of AM parts during or after being grown.
- ii) Software tools to data-mine the enormous amounts of data from scans and imaging.
- iii) Harsh environment inspection. Inspection during builds will be challenging due to atm and temperatures. Optics will become metalized under vacuum or could become clouded depending on the process. Protective measures or robust scanners are needed.
- iv) Development of a standard or benchmark tool(s) to easily assess a range of capabilities of a process will be key and software to help designers recognize what is and isn't possible will also be beneficial. There are direction-dependent opportunities/challenges that should not be ignored.
- v) Two phase materials present unique and strategically critical opportunities and challenges. The ability to use combinations of materials (intermingled in some manner) to realize the best properties of both materials in one component has great potential. These high-performance materials will require advanced inspection methods to verify the CAD intent was realized and to ensure material density and metallurgy is maintained within spec throughout.

Production and Use of Standard Parts and Our Lessons-learned Thus Far

Constance J.S. Philips, Sr. Program Manager, RARE Parts Collaborative Program, National Center for Manufacturing Sciences

The collaborative AM program at NCMS has been ongoing for 21 years, and for at least a decade we have used a standard part for assessment of AM machine-material capability. Historically, this part was only an assessment tool for a user's determination of his machine's feature-building capabilities using differing materials. The user's knowledge was then used in his operations and in his AM part design or part redesign for AM. Our part design evolved over several years of trying other test part designs coming primarily from machine OEMs and was designed to be particularly challenging to any AM system. NASA Marshall Space Flight Center, Ken Cooper specifically, designed the **NASA Benchmark Part** to contain features encountered frequently in our work with DoD maintenance and repair depots and the challenges of legacy part replacement. We shared the stl file with several others over the years including NIST most recently.

While our original use of the NASA Benchmark Part was to better understand the feature-building capabilities and limitations of the various AM machines and materials we use, we view the NASA Benchmark Part as potentially useful in generating a feature database eventually yielding Design Allowables. We are currently in the beginning stages of building parts with this hypothesis in mind. Before embarking on this adventure, we inquired of NIST if there was an overarching protocol in use in the conducting of such a study. NIST staff shared with us the files associated with the building and measurement of its Standard Part under study. Thus far in our study we find it necessary to establish a well-defined set of protocols and are only learning now to what degree their definition is needed.

Control Needs:

Build Documentation Protocol

In an attempt to be able to attribute feature attributes and measurements to a process and to a specific material used, we anticipated that documentation of the build process would be needed. Our first attempt at specifying a build documentation sheet and the first article built and submitted for measurement revealed immediately the need for additional controls to be specified. Additional facets of the build needing definition and control are surely to emerge as we proceed. The latest Build Documentation Sheet is attached as Exhibit 1. You will note that the level of fidelity of data is low without having process monitoring and feedback available as an intrinsic part of the build processes.

Feature Measurement and Documentation Protocols

Anticipating that the measurement of specific features against the CAD file will be another learning process and will require additional protocols, our study is not placing the responsibility for these measurements and reporting on the Part's builders at this time. It is our desire to utilize a third party having diverse measurement expertise, perhaps NIST itself, to devise a measurement protocol for the diverse set of features contained in the NASA Benchmark Part by actually applying the best measurement instrumentation available, measuring the features in each of our test articles, and then defining a protocol for the recording of that data. These combined protocols would then be available for use in future Part builds and provide the needed control to minimize the variations introduced into data via the measurement devices themselves and establish basic rules for measurement documentation.

A picture of the NASA Benchmark Part CAD rendition is attached as Exhibit 2.

Call for a Set of National Standard Protocols

We believe if these NASA Benchmark Part protocols or protocols such as these were developed via an organization with the capabilities of NIST, we could realize a set of national standard protocols for the conducting of Part and feature studies in the future. We need to have the ability to replicate any such study. We believe basic tenets must be defined before embarking upon costly process, materials, and Part research and development. As users of these AM technologies, we want the best data possible, with the highest degree of reliability and repeatability possible within this constantly emerging AM landscape. Having a nationally adopted set of protocols would facilitate and contribute to not only the eventual definition of Design Allowables but also to the advancements developed by AM OEMs for machines, process controllers, operating systems, software, materials, inspection, and process monitoring systems.

Exhibit I

Commercial Technologies for Maintenance Activities (CTMA)



RARE Parts Program

Benchmark Part Build Sheet

Submit with Part to: C. Philips, NCMS, 3025 Boardwalk Dr., Ann Arbor, MI 48108

PART NO. _____ NASA Benchmark Part or NIST Test Artifact

CALIBRATE MACHINE PER OEM INSTRUCTIONS PRIOR TO STARTING BUILD¹

Company ID: _____

Build Address: _____

Date of Build: _____ Build Location Coordinates²: _____

Process: _____

Machine model: _____

Material specification & source of supply: _____

Parameter settings: _____

Special settings, eg. pre-heated chamber, pre-heated material, etc.: _____

Support structure software used: _____

Nozzle size: _____

Laser type & power: _____

Laser spot size: _____

E-beam current: _____ E-beam spot size: _____

Total lapse build time: _____

Note any build interruptions, issues experienced, etc.: _____

Note any other factors that may have influenced the build outcome: _____

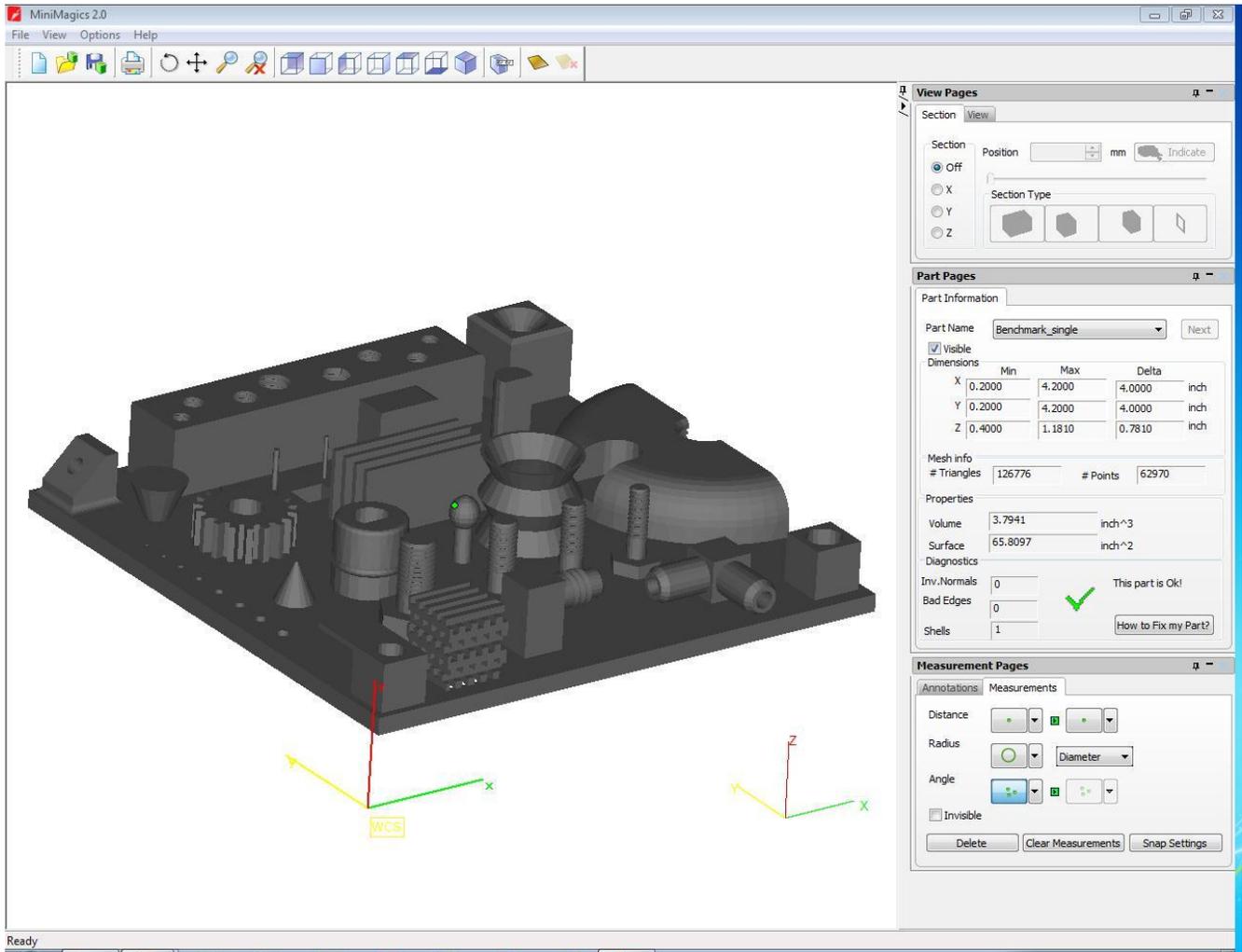
Hand-mark Company ID and PART NO. on part bottom, this build sheet is to accompany each Benchmark Part. Retain a copy for your records.

Signed by: _____ Part built by: _____

¹ Per OEM instructions per material if so specified.

² Per ASTM F2921-11e2 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

Exhibit 2



APPENDIX D: ACRONYMS/ABBREVIATIONS

ABAQUS	engineering analysis and product simulation software tool
AI	artificial intelligence
AM	additive manufacturing
AMC	Additive Manufacturing Consortium
ANSYS	engineering analysis and product simulation software tool
API	application programming interface
ASTM	ASTM International (standards organization)
ASTM F42	ASTM Committee F42 on Additive Manufacturing Technologies
CAD	computer aided design
CMM	coordinate measuring machine
CPU	computer processing unit
CT	computed tomography
DARPA	Defense Advanced Research Projects Agency
DDM	direct digital manufacturing
DFAM	design for additive manufacturing
DM	direct metal
DMLS	direct metal laser sintering
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
EB	electron beam
EBM	electron beam melting
EDS	energy dispersive spectrometer
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
FGMs	functionally graded materials
GPUs	graphical processing units
HIP	hot isostatic pressing
HPC	high performance computing
ICME	integrated computational materials engineering
IP	intellectual property
IR	infrared
ISD	NIST Intelligent Systems Division
ISO	International Organization for Standardization

M&S	modeling and simulation
MHz	megahertz
MMCs	metal matrix composites
MSDS	material safety data sheet
MTBF	mean time between failure
NAMII	National Additive Manufacturing Innovation Institute
NASA	National Aeronautics and Space Administration
NAVAIR	U.S. Navy, Naval Air Systems Command
NCMS	National Center for Manufacturing Sciences
NDE	non-destructive evaluation
NDI	non-destructive inspection
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OEE	overall equipment efficiencies
OEM	original equipment manufacturers
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Administration
PM	powder metal
ppm	parts per million
R&D	research and development
RFID	radio frequency identification
RM	rapid manufacturing
ROI	return-on-investment
RP	rapid prototyping
SEM	scanning electron microscope
SLM	selective laser melting
SMEs	small- and medium-sized enterprises
SPC	statistical process control
STEM	science, technology, engineering, and mathematics
UL	Underwriters Laboratory
V&V	validation and verification