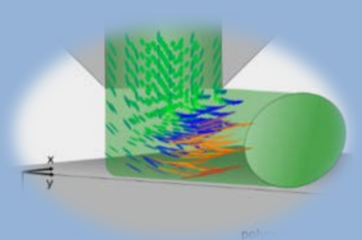

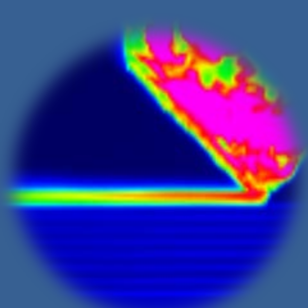

NIST Advanced Manufacturing Series 100-5

# Measurement Science Roadmap for Polymer-Based Additive Manufacturing

*Prepared for*

Material Measurement Laboratory
National Institute of Standards and Technology
Gaithersburg MD 20899

Division of Civil Mechanical and Manufacturing Innovation
National Science Foundation
Arlington, VA 22230

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Columbia MD 21046

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.100-5

National Institute of Standards and Technology
U.S. Department of Commerce

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December 2016

U.S. Department of Commerce
*Penny Pritzker, Secretary*
National Institute of Standards and Technology
*Willie May, Under Secretary of Commerce for Standards and Technology and Director*

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- Lower Middle: Numerical simulation of polymer conformations during polymers extrusion based additive manufacturing (Credit: Claire McIlroy, Georgetown University)
- Bottom: IR thermography measure of polymer extrusion additive manufacturing (Credit: Jon Seppala, NIST)

# PREFACE

The *Roadmap Workshop on Measurement Science for Polymer-Based Additive Manufacturing* was hosted by the National Institute of Standards and Technology (NIST). Sponsorship for the workshop was provided by National Science Foundation, Division of Civil, Mechanical and Manufacturing Innovation and by NIST, Material Measurement Laboratory (MML). Workshop planning, execution, and preparation of this report was conducted under the direction of Kalman Migler and Richard Ricker, NIST, Steven Schmid, University of Notre Dame, and ZJ Pei, National Science Foundation (NSF). 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 be all-inclusive of the views of the AM community.

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# ACKNOWLEDGMENTS

Many thanks to all those who participated in the *Roadmap Workshop on Measurement Science for Polymer-Based Additive Manufacturing* held June 9-10, 2016 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, moderators and to the many expert participants (listed in Appendix A).

**Speakers and Moderators**

Mark Dadmun, University of Tennessee-Knoxville
Carl Dekker, Met-L-Flo
Matthew Di Prima, Food and Drug Administration
Scott Fish, University of Texas
Courtney Fox, Carbon
Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC
Rob Gorham, America Makes
Gerald Grant, University of Louisville
Abraham Joy, University of Akron
Greg Kittlesen, FDA
Lyle Levine, NIST
Robert Maxwell, Lawrence Livermore National Laboratory
Kalman Migler, NIST
Mike Molnar, Advanced Manufacturing Program Office, NIST
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Miriam Rafailovich, State University of New York at Stony Brook
David Roberson, University of Texas-El Paso
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Steven Schmid (ND)
Katherine Vorvolakos (FDA)

Special thanks are due to the Energetics Incorporated team who provided support for workshop planning, facilitation, and preparation of the summary report. This report, the oral presentations, and supporting documents can be found on the workshop website at: https://www.nist.gov/news-events/events/2016/06/measurement-science-roadmap-polymer-based-additive-manufacturing-3d. Further information about this report can be obtained by contacting Kalman Migler at kalman.migler@nist.gov

# EXECUTIVE SUMMARY

## BACKGROUND

Additive manufacturing (AM), a process for fabricating parts directly from 3-D digital models, has been shown to have tremendous potential for producing high-value, complex, individually customized parts. Companies across the globe are using AM to reduce time-to-market, improve product quality, and reduce the cost to manufacture products. Polymers are attractive materials in this regard because they are economical, they provide for a large range of properties and they are amenable to many low energy fabrication technologies. In the industrial sector, polymers are being used in a wide range of part applications including aerospace, defense, automotive, sports, telecommunications, and medical devices. Polymers are also the most common feedstock used in 3D printers for consumer level printers.

While the use of AM has been growing, numerous challenges impede its more widespread adoption and commercialization. In many cases, new measurement methods, standards, data, and models are needed to overcome these challenges. These challenges, and the tools that will enable industry to overcome them, were explored in the *Roadmap Workshop on Measurement Science for Polymer-Based Additive Manufacturing* co-sponsored by the National Institute for Standards and Technology (NIST) and the National Science Foundation (NSF), held on June 9-10, 2016 in Gaithersburg, Maryland. The objectives of the workshop were to gain expert insights on:

- Measurement science barriers, challenges, and gaps that prevent the broad use of polymer-based AM
- Research and development needed to address the priority measurement and standards challenges
- Future measurement- and standards-related targets and goals for AM
- Pathways and approaches to address identified barriers and gaps

**Figure E-1. Workshop Breakout Topics**

- Characterization of Materials Throughout Their Lifecycle
- Process Modeling
- *In situ* Measurements
- Performance

The workshop opened with plenary presentations that provided context on AM challenges and use cases. These were followed by expert panel discussions on the major topics shown in Figure E-1. Over 100 expert participants then addressed these technical topics during breakout sessions.

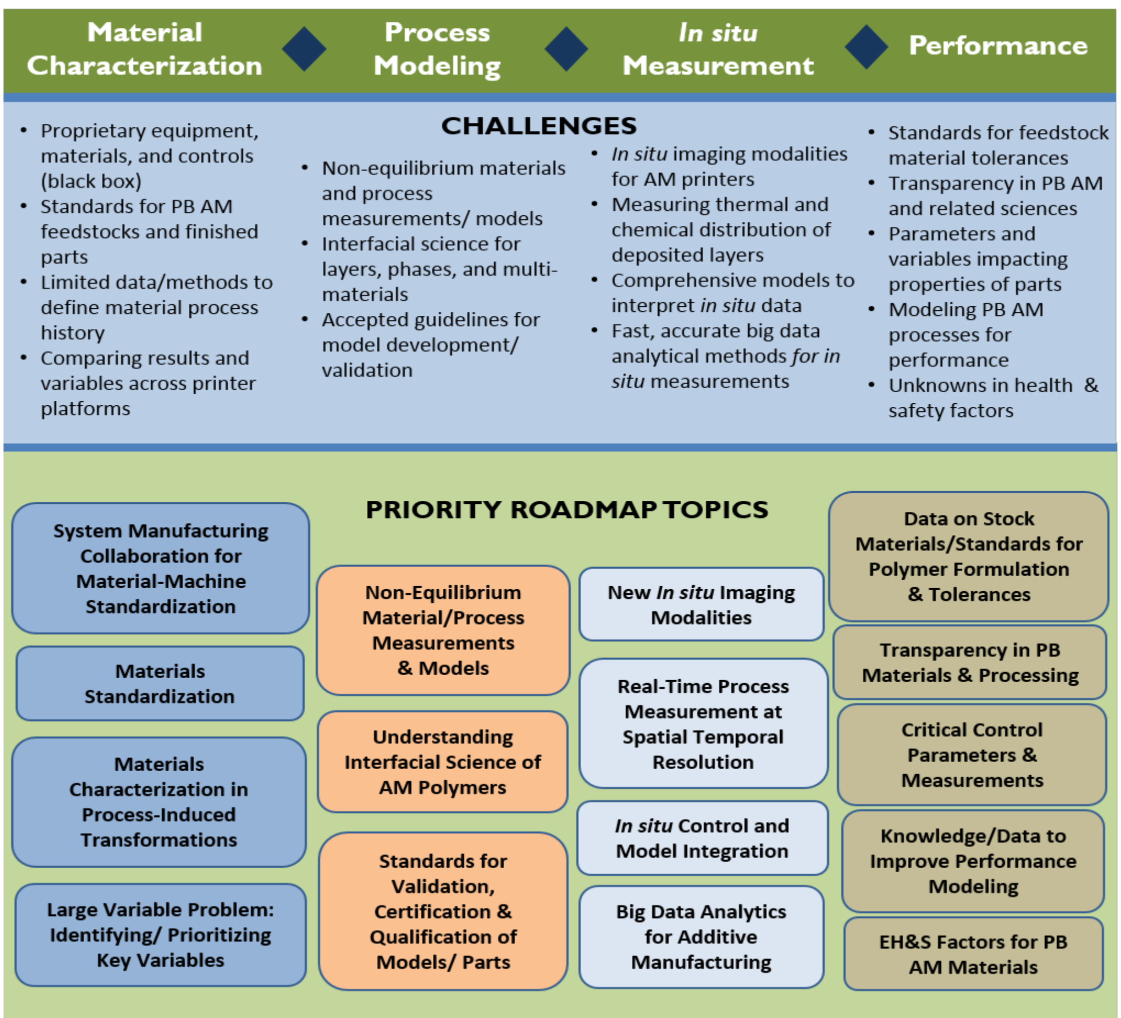
This report is based on the workshop results. It provides useful information to public and private decision-makers interested in furthering the capabilities of polymer-based additive manufacturing (PB AM) and accelerating its more widespread adoption. By focusing on polymers, the workshop was able to target the unique aspects of these materials and their processing challenges. It is hoped that the national research agenda for polymer-based AM will incorporate the consensus-based needs and priorities established during this workshop and presented in this report.

## SUMMARY OF RESULTS

Each breakout group identified future desired capabilities, challenges and barriers to achieving targets and goals, and priority R&D topics for the measurement roadmap. 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 cross-cutting challenges include:

- ***Multi-disciplinary collaboration*** – Establishing a better structure to support multi-disciplinary collaboration was identified as a high priority.
- ***Business models*** – A good business case and economic models are lacking for PB AM in general and this was identified as a priority to address. Models are needed that can identify applications where the most value is added by AM in terms of customization, flexibility and speed to market.
- ***Infrastructure issues*** – Challenges exist in balancing infrastructure requirements, materials, and use. Predictable IT infrastructure requirements need to be established to support growth.
- ***Life cycle and sustainability*** – Not enough is known about the life cycle of PB AM parts, particularly the effects of aging, and the ability to recycle/reuse parts. Ensuring sustainability via materials and processes is an objective.
- ***Printer and equipment variability*** – A universal challenge is the variability between printers and processing equipment. This issue is exacerbated by the 'black box' approach taken by equipment suppliers, i.e., there are many unknowns about equipment parameters, variability, and inner workings.
- ***Surpassing conventional manufacturing capabilities*** – The ability to surpass conventional parts processing techniques in 10 years is a challenge that should be met to ensure more widespread acceptance of polymer-based additive manufacturing.

**Figure E-2. Key Priority Topics and Challenges for Polymer-Based Additive Manufacturing**



# CHAPTER 1: OVERVIEW

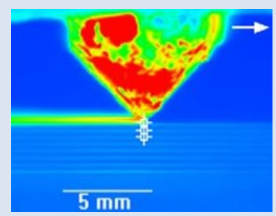
## BACKGROUND

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, 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. Polymer-based AM parts have emerged for use in a number of applications, such as bio-medical, light-weight aerospace components, custom fit protective gear, composite tooling, and functional prototypes.

**Research Highlight: *In situ Measurements of Temperature***

The ability to make *in situ* non-contact measurements of temperature during 3D printing would enable feedback loops to be established between process models, material parameters and real-time printing conditions. Recently, researchers at NIST have used IR thermography during the printing of a wall-like structure to make such measurements of the weld as it forms.

"The thermography demonstrates the crucial importance of the first tenth-of-a-second in forming a weld, because that is when inter-diffusion occurs," says NIST researcher John Seppala. See Additive Manufacturing 12 (2016) 71-76 .




Infrared image captures the hot metal nozzle and the hot printed polymer layer in real time. *Credit: NIST*

## SCOPE

The National Institute of Standards and Technology (NIST) hosted the *Roadmap Workshop on Measurement Science for Polymer-Based Additive Manufacturing* at their Gaithersburg, MD campus on June 9-10, 2016. The workshop brought together over 100 AM experts from industry, government, national laboratories, and academia to identify measurement science challenges and associated R&D needs for polymer-based AM systems. This workshop aimed to gain insights from experts on the measurement science barriers, challenges, and gaps that prevent the broad use of polymer-based AM. The workshop included stage-setting plenary sessions, panel discussions, and extended breakout sessions as described below. The full workshop agenda is provided in Appendix A.

The workshop was a follow-up to one held in 2012 entitled Measurement Science Roadmap for *Metal-Based* Additive Manufacturing, with the goal of understanding and addressing the hurdles faced by the metals community from the perspective of measurement science. The resulting roadmap played an important role in setting research priorities and funding by entities involved in Additive Manufacturing, such as America Makes. The 2016 workshop and this report are expected to play a similar role for the polymer community.

## PROCESS

The lectures and panel discussions were designed to provide context and content to the four parallel breakout groups. Each group focused on a different technical aspect of polymer-based AM, as shown in Figure 1-1. Advances in these areas are needed to address the challenges and uncertainties that currently exist around input materials and processing technologies. Uncertainties in the properties of input materials and equipment and processing lead to uncertainties in how final parts will perform as well as quality and characteristics. These relationships are described in Figure 1-2.

Within each breakout group, several key questions were posed to gain insights on the important challenges and pathways to address them. These included:

- What are the desired future capabilities (e.g., technology, processing methods, measurement techniques, performance, etc.) that we want to achieve for PB AM?
- What are the technology, measurement, and standards barriers that keep us from achieving the desired future end state, and why?
- What R&D, standards development, or other activities should be undertaken to address the barriers and enable widespread use of polymer-based additive manufacturing? What are the priorities for development of a measurement science roadmap for PB AM?

**Figure 1-1. Workshop Breakout Topics**

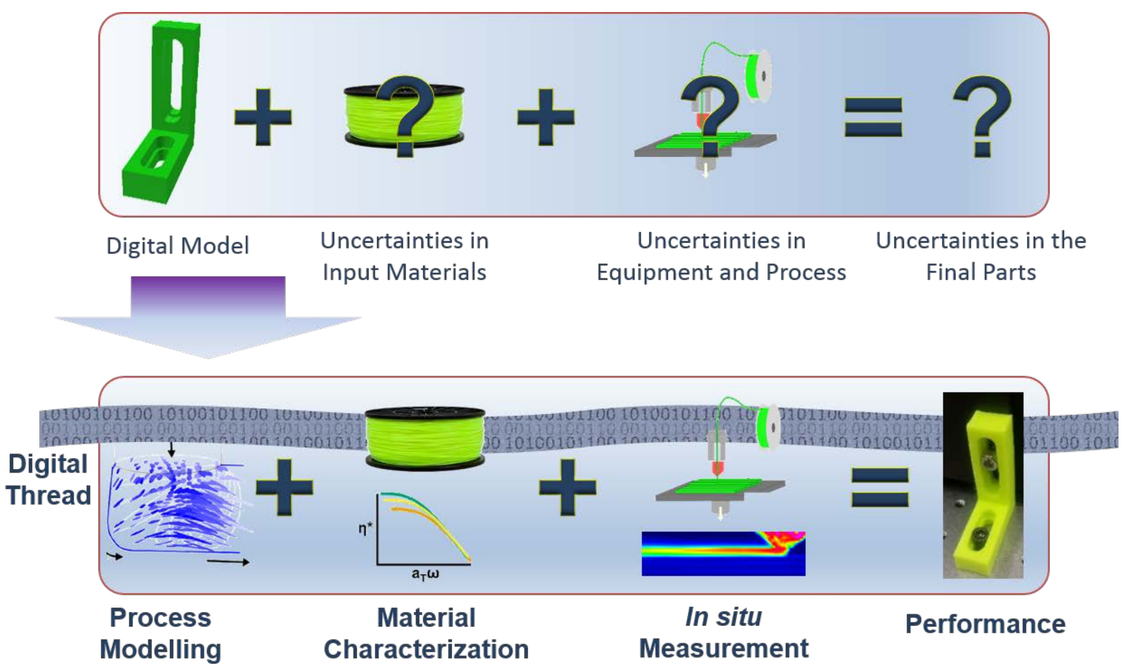
- ***Characterization of Materials Throughout Their Lifecycle*** – methods for characterization of life cycle properties and material behavior; efficient, modern processing methods
- ***Process Modeling*** – simulation and predictive tools for optimizing processing and quality
- ***In situ Processing Measurements*** – monitoring of process and part behavior and properties during manufacturing
- ***Performance*** – predicting, monitoring, and assessing the performance and quality of PB AM parts

The results of these discussions are summarized in the following report chapters, which are organized by breakout topic. Each breakout group used a 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 research and development (R&D), standards development, and other future efforts for PB AM. The results of these in-depth examinations can be found in the *Roadmap for Priority R&D* section in each chapter.

The ideas captured here reflect the expert opinions of the workshop participants and do not necessarily represent the entire polymer-based AM industry. As such, they should be viewed as a snapshot of what these experts consider to be the most important issues and not an all-inclusive summary.

This report provides useful information to both public and private decision-makers interested in furthering the capabilities of PB AM and accelerating its more widespread use in the industrial sector. It is hoped that the national research agenda for polymer-based AM will incorporate the needs and priorities established during this workshop and presented in this report.

**Figure 1-2. Current Status and Future Vision for Polymer-Based Additive Manufacturing**



# SPEAKER CONTRIBUTIONS

Presentations from leading experts were given to set the stage for the subsequent workshop discussions. Panel discussions provided additional context in specific areas of interest important to the roadmap. The full presentations can be downloaded from the workshop website, http://www.nist.gov/mml/measurement-science-roadmap-for-polymer-based-additive-manufacturing.cfm.

## PLENARY

- ***Welcome*** *~ Mike Molnar, Director, Advanced Manufacturing Program Office, NIST*
  This presentation discussed the workshop purpose of developing a common understanding of the crosscutting issues and bringing together the materials scientists and manufacturers with the hope that participants leave the workshop with a common understanding of how they can and will proceed.
- ***Workshop Scope and Objectives*** *~ Kalman Migler, Polymers and Complex Fluids Group, NIST*
  This presentation included a review of the workshop objectives, the anticipated roadmap results and impacts, and a description of the panels and breakouts.
- ***Current Status of Polymers Roadmapping*** *~ Rob Gorham, Director of Operations, America Makes*
  Provided information on the America Makes roadmapping approach and the five "swim lanes:" design, material, process, value chain, and AM genome. This presentation also provided an overview of the America Makes polymers projects.

## PANELS

Moderated panel sessions were held to discuss challenges in each of the major breakout topics, as well as technology integration and standards issues. The moderators and panelists are listed in Figures 1-3 to 1-7. 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 and expanded upon during the breakout sessions.

### *Characterization of Materials throughout their Lifecycle Panel*

- **FDA's Perspective on 3D Printing of Medical Devices, Matthew Di Prima.** This presentation provided an overview of FDA's AM experience in the context of medical devices (not drugs or biologics), and associated AM materials and technologies. In May 2016, the FDA Center for Devices and Radiological Health (CDRH) released its draft guidance, "Technical Considerations for Additive Manufactured Devices", which addresses both manufacturing and design considerations, as well as device testing considerations. These considerations include device design, software workflow, materials control, post-processing, process validation and acceptance, quality data, device description, mechanical testing, material characterization, cleaning and sterilization, biocompatibility, and additional labeling considerations.

**Figure 1-3. Characterization of Materials throughout their Lifecycle Panelists**

**Moderator, Mark Dadmun,** Paul and Wilma Zeigler Professor, Chemistry Department, University of Tennessee-Knoxville

- **Matthew Di Prima**, Materials Scientist at the Center for Devices and Radiological Health, Food and Drug Administration
- **Angel Yanguas-Gil**, Principal Materials Scientist & Institute Fellow, Argonne National Laboratory
- **Abraham Joy**, Assistant Professor of Polymer Science, University of Akron

- **Building to Last: Challenges in Additive Manufacturing Going from Prototype to Functional Component, Angel Yanguas-Gil.** Two different perspectives were presented for the characterization of materials throughout their lifecycle: the advanced manufacturing perspective (beyond prototype and design) and the characterization perspective (knowledge and cultural gaps). The first challenge is application dependence: performance metrics and degradation mechanisms of the materials are strongly application-dependent. The second challenge is materials diversity: information available on the impact of fabrication on the reliability of 3D printed materials is insufficient. Suggestions for addressing challenges include increasing focus on reliability and performance and consolidating existing published research.

- **3D Printed Polymers for Biomedical Applications, Abraham Joy**: This presentation provided advantages and disadvantages for methods for 3D printing scaffolds for biological applications such as Polymers Extrusion (also known as FDM), SLA, extrusion, and ink-jet. The challenges to process optimization include: the trade-off between printing speed and print quality and the mechanical failure of a printed structure because of adhesion failure in between layers. The needs of process optimization include: correlation between material bulk properties and print parameters, methods to quantify filament adhesion to substrate and previous layers, and quantitative methods to determine localized stress.

### *Process Models Panel*

- **Elements of Generative Design Driving the Future of Process Modeling, Slade Gardner:** The key objectives presented for process modeling include 1) quality manufacturing, to achieve design intent through processing; 2) quality control, or production according to established metrics, with uniformity and consistency throughout part; 3) quality assurance for defect prevention and confidence that requirements will be fulfilled, as well as management of raw materials and equipment; and 4) to support standards and measurement. Process models are needed for feed-forward predictions that simulate and guide the process and also feed-back correlations of process variables to guide control schemes.

**Figure 1-4. Process Models Panelists**

**Moderator, Kalman Migler,** Staff Scientist in the Polymers and Complex Fluids Group, NIST

- **Slade Gardner**, President, Slade Gardner Advanced Manufacturing and Materials, LLC
- **Peter Olmsted**, Director of the Institute for Soft Matter Synthesis and Metrology (ISM2), Georgetown University
- **David Roberson**, Assistant Professor in the Department of Metallurgical, Materials and Biomedical Engineering, University of Texas-El Paso

- **Measurement Science for Polymer- Based Additive Manufacturing, Peter Olmsted:** This presentation addressed the challenges in AM processing: limited combinations of materials, processing conditions versus materials properties, temperature monitor and control (non-isothermal), non-equilibrium phenomena, urgent need for standards, etc. If there is going to be an understanding of the physics behind modeling materials, there first must be an understanding of the melting or glass transition. Most fundamental areas of polymer science can be linked to AM.
- **Materials and Process Development, David Roberson:** Presented current and future perspectives on materials and process development for thermoplastic extrusion. Current efforts include developing new material systems and tuning the mechanical properties for a given application based on materials. Future efforts include work towards AM specific material testing – in the past printing was a better representative sample than cutting.

### *In situ* Processing Measurements Panel

- **3-D Constructs, Molded vs. Printed – Differences from a Cell-Based Perspective, Miriam Rafailovich:** This presentation discussed how cells respond to nanoscale surface structure. AM surfaces have roughness on multiple scales due to multiple factors. To move AM forward, there must be a better understanding of the underlying science. *In situ* characterization of the polymer being printed makes this possible.
- **Thermal and Fracture Characterization of Welding Zones Produced by Polymer Extrusion 3D printing, Jon Seppala (presented by Kalman Migler):** The nuances of how thermography, rheology, and fracture strength relate to printing were presented. Weld formation in material extrusion occurs over approximately one second; most of the inter-diffusion occurs over a time scale much less that one second. Temperature kinetics, rheology, and weld theory provide the foundation for understanding fracture strength as a function of temperature and feed rate. *In situ* monitoring is achievable – linking back to real time control is a challenge.
- **Molecules to Manufacturing: Expanding the Polymeric Materials Toolbox, Chris Williams:** This presentation discussed the idea of incorporating pre-process measurements that allow a computer to predict whether a product is printable. Measurements must be monitored *in situ* and post process as well. Stereolithography was the first printing modality to be considered to have all three processing steps. The model should predict how deep the cure will be based on exposure. The role of optical intensity is not yet fully understood. Additionally, AM is susceptible to cyber-attacks that are virtually unrecognizable. Side channel measurements can help protect against these cyber threats.

**Figure 1-5. *In situ* Processing Measurements Panelists**

**Moderator, Robert Maxwell,** Division Leader for the Materials Science Division in the Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory

- **Miriam Rafailovich**, Distinguished Professor in the Department of Materials Science and Engineering, State University of New York at Stony Brook
- **Jon Seppala**, Chemical Engineer in the Materials Science and Engineering Division, NIST
- **Chris Williams**, Associate Professor and the Electro-Mechanical Corporation Senior Faculty Fellow in the Department of Mechanical Engineering, Virginia Tech

### Performance Panel

- **Functional Prototyping with Polymeric Materials, Courtney Fox:** This presentation discussed the definition of functional prototyping and also introduced the concept of a *dead zone*, where chemical reactions are inhibited. If one can understand how the parts print, one can understand how they fail. Carbon has been able to increase the stress strain curve to reach injection molding standards. Field testing so far has shown no issues with printed materials.
- **Polymers Extrusion (FDM) from a Polymer Processing Perspective: Challenges and Opportunities, Bryan Vogt:** This presentation discussed the challenges of Polymers Extrusion (FDM) 3D printing: incomplete infill results in voids inside printed parts and fast solidification leads to limited chain diffusion between fibers and layers. Despite unmet challenges, there is a wealth of new possibilities to explore with FDM, such as new materials (filament extrusion and uniformity). Improved process knowledge is the key to future success.

**Figure 1-6. Performance Panelists**

**Moderator, Gregg Kittlesen,** Materials Engineer, FDA

- **Courtney Fox**, Research Scientist on the Carbon Materials Team, Carbon
- **Bryan Vogt**, Professor in the Department of Polymer Engineering, University of Akron
- **Gerald Grant**, Professor and Chair of Oral Health and Reconstruction, University of Louisville

- **Use of Additive Manufacturing in Reconstruction and Rehabilitation, Gerald Grant:** This presentation covered AM relating to medicine and dentistry. Generally, there are two approaches for fabrication using AM – medical models from medical scans, or design of a device (implant, cutting guide, reduction bars, etc.…) to fit elements of a medical/dental scan following a Scan/Plan/and Manufacture workflow. There are decisions at each step and AM has provided flexibility and speed in the process of the fabrication of a custom part. In the fields of medicine and dentistry, a Plan/Scan/ and Manufacture workflow provides the ability to deliver devices without multiple direct interactions in a more non-invasive manner with the patient via an AM fabricated mold, pattern, or a directly produced device with remarkable accuracy, contrary to the conventional fabrication methods.

**Figure 1-7 Integration & Standards Panelists**

**Moderator, Carl Dekker,** President, Met-L-Flo

- **Scott Fish**, Sr. Research Scientist, University of Texas
- **Praveen Tummala**, Manager of R&D Materials and Process, 3DSystems
- **Lyle Levine**, Physicist at the Materials Measurement Laboratory, NIST

### *Integration and Standards Panel*

- **Polymer AM Integration and Standards, Scott Fish:** This presentation covered technical and non-technical barriers to growth and how measurement science and standards help. Technical barriers include lack of tools for product design and lack of tools for fabrication planning/optimization. Non-technical barriers include lack of understanding of application opportunities and associated economic benefits, lack of widespread design experience with AM, and stigma of rapid prototyping (not for "real" manufacturing). Measurement methods must become more prolific and tailored with the growth in materials and process understanding to surmount the technical barriers.
- **Factors Affecting the Adoption of 3D Printing Technologies (SLS) as Manufacturing Platforms – Role of Standards for Adoption, Praveen Tummala:** This presentation addressed the factors affecting the adoption of 3D printing technologies. SLS uses thermoplastic semi-crystalline polymers as print materials and is can produce robust, durable, and functional parts. Factors affecting the adoption of AM include print speed, part cost, part performance, quality, and accuracy, thermal process limitations, and intelligent machine controls.
- **AM-Bench: A Proposed Benchmarking Series for Additive Manufacturing, Lyle Levine (presented by R.E. Ricker):** This presentation detailed the AM Benchmark Test Series (AM-Bench), a continuing series of highly controlled benchmark tests for additive manufacturing, in conjunction with a conference series. A fourth (and final) draft of foundational documents are being written with input from an Exploratory Committee (40 participating organizations and 59 members). The goals of AM-Bench are 1) to allow modelers to test their simulations against rigorous, highly controlled additive manufacturing benchmark test data and 2) to encourage additive manufacturing practitioners to develop novel mitigation strategies for challenging build scenarios.

# Chapter 2: Characterization of Materials Throughout Their Lifecycle

## Overview of the Topic Area

Material characterization plays a key role in additive manufacturing. Producing AM parts that have consistent, predictable, repeatable properties requires that the characteristics of the feedstock materials are well known. Characterization can also provide insights to the dependence of AM part mechanical properties on the input material properties. Characterization of materials is also important to developing appropriate measurements and standards. A number of physical characterization techniques have been employed, such as laser diffraction particle size analysis, X-ray computed tomography for size and shape analysis, and optical and scanning electron microscopy. Techniques for structure, chemistry and mechanical strength include but are not limited to X-ray diffraction and vibrational spectroscopy and fracture tests, respectively. While many techniques are available and being applied, significant challenges remain in life cycle characterization of polymer-based AM materials as well as understanding materials behavior during processing and in the final product.

## Future/Desired Capabilities

In the future, a wide range of characterization tools will be needed to effectively measure and correlate materials properties and behavior. Further details on the desired capabilities and technologies for PB AM materials are provided in Table 2-1 and described briefly below.

***Predictive Capabilities for Parts/Materials***

Predictive models are needed to help correlate material properties with AM process parameters, as well as to enable production of high quality parts. The main areas of interest include correlation of material properties to the behavior of the finished part, including mechanical properties, impact of processing aids, and relationships between input material properties and how well layers forming the part are joined. Developing predictive capabilities will require wider availability and collection of data (both existing and new) on materials properties. Areas of importance that were identified include interfacial data, phase distribution behavior, and temperature-dependent chemical properties.

***Processing Parameters and Characterization***

There is a need to identify and establish open source process parameters as well as baseline data for materials used in selective laser sintering (SLS) and polymers extrusion (FDM). This will enable process optimization as well as improved material selection. Characterization technologies such as size exclusion chromatography, mass spectrometry, and thermal analysis are also needed for both pre- and post-printing measurement of polymer-based AM materials. Improved, robust measurement tools adapted for PB AM would also enable better interfacial analysis, characterization of multi-deposition orientation, and collection of needed materials properties.

***Life Cycle Sustainability and Safety***

Life cycle characterization is an important element in encouraging the future growth of AM, as it provides critical information on longevity, durability, recyclability, safety, and other sustainability factors. Some of the key capabilities for life cycle include predicting the re-usability of polymers that have been printed, and more fully understanding the cradle-to-grave aspects of materials. Safety considerations include the capability for producing feedstock materials (safety in the workplace) as well as products that are safe and non-hazardous to people and the environment (part safety throughout its use and disposal).

### *PB Materials Characterization and Design*

Characterization of starting materials is needed to enable more effective design and manufacturing processes. Fully characterizing material classes and their properties, and being able to predict their behavior will enable production of more reliable, higher quality parts. In addition, technologies (and new materials) are needed to enable the combination of materials (or hybrids) with complementary functionalities (e.g., structural strength and magnetic).

### *Materials Processing*

An overall objective is to be able to achieve reliable printing of parts in a cost-effective way that is competitive with older manufacturing techniques, and to reduce the need for machining. This would require that equipment have the capability for printing complex and reliable composites, using off-the-shelf materials and equipment. Capabilities are needed to surpass conventional manufacturing techniques such as injection molding or extrusion, and to quickly create parts with the same or better physical properties and performance. A key aspect is the reduction of post-processing.

### *Advanced Printing Technology*

While polymer 3D printing has been on the market for many years, there are still many advances that can be made. Today's printing technologies will require advances to achieve 'true' 3D printing. There are also a number of approaches needed for printing of composites and/or multi-modal materials with defined gradients, such as transitioning from stiff to flexible materials. Another approach is to explore arbitrary path conformal printing in 3D, rather by today's layer-by-layer approach.

| Table 2-1. Desired Capabilities for PB AM Materials Characterization |
| --- |
| **Predictive Capabilities for Parts/Materials** |
| • Predictive models to correlate material properties with AM process parameters to generate parts with acceptable properties<br>  o Prediction of material/mechanical properties of final part from starting material characteristics<br>  o Predictive relationships between filament scale properties and final part/weld/interface scale properties<br>  o Impact of processing aids and additives on the part and/or process<br>• Data for input into predictive models and simulations<br>  o Searchable database of material properties to accurately simulate process prior to manufacturing<br>  o High temperature polymer chemical and performance information to integrate into design and predictive models<br>  o Interfacial data – characterization of structure and strength of interfaces from nm to mm; understanding polymer phase distribution/behavior at interfaces for three (3) structures<br>  o Uniform material characterization property list for all materials (*in situ* and realized)<br>  o Data on compatibility with conventional parts (e.g., surface conditions)<br>  o Performance metrics through lifetime of printed device (ex-vivo and in-vivo) |
| **Processing Parameters and Characterization** |
| • Open source process parameters/baseline data for materials in selective laser sintering (SLS), polymers extrusion (FDM)and stereolithography (SLA)<br>• SEC (size exclusion chromatography), mass spectrometry (MS), thermal analysis (TA) to provide fast, accurate information on characterizing materials – both pre and post printing<br>• How to create variable stiffness parts by altering toolpath or modifying material during print<br>• Multi-deposition orientation capabilities and characterization<br>• Capabilities to evaluate interfaces between parts/layers – robust measurement tools |
| **Life Cycle Sustainability and Safety** |

| Table 2-1. Desired Capabilities for PB AM Materials Characterization |
| --- |
| • Ability to predict the re-usability of polymers and powders<br>• Understand cradle to grave life cycle aspects of materials (i.e., re-usability)<br>• Ability to make "safe" starting materials, non-hazardous, and safe products<br>• Assurance of workplace safety (i.e., after repeated exposure)<br>• Traceability for parts, including recycle history<br>• Data on shelf life of filaments and sustainability |
| **PB Materials Characterization and Design** |
| • Classes of materials that can reliably replace injection molded parts over long periods of time<br>• Ability to purchase filament material produced to a standard and with more consistency<br>• End-user filament that prints to a highly specified technical data sheet and comes with key processing history and material properties<br>• Understanding of how to tailor material properties voxel-by-voxel<br>• Ability to enable complementary functionalities; in addition to structural strength – electronic, magnetic, bio interface, etc.<br>• Technology to combine a variety of functional materials<br>• Hybrid material systems and blends, alloys, composites – that can be printed *in situ* |
| **Materials Processing/Printing** |
| • Successful, reliable printing of parts competitive with older manufacturing techniques<br>  o Able to use commercial off-the-shelf (COTS) materials on COTS printers<br>  o Capability to print complex and reliable structural composites<br>  o Printing processes and materials that require less/no post processing<br>  o Printing high performance AM parts with well-defined and predictable performance and lifetimes<br>  o 3D printing as fast, effective, and inexpensive as injection molding or extrusion – but with more capability and producing same or better physical properties<br>  o Understanding of part reliability with minimal verification testing<br>• Advanced Printing Capabilities Advanced printing capabilities<br>  o "True" 3D printing as opposed to layer-by-layer<br>  o Print multimodal materials with defined gradients (e.g., transition from stiff to flexible material or low to high dielectric constant)<br>  o Optimized toolpaths to minimize and/or take advantage of anisotropies in AM parts<br>  o Arbitrary path, conformal printing in 3D rather than layer-by-layer |

## Technological & Measurement/Standards Challenges

The barriers and challenges currently impeding characterization of PB AM materials are presented in Table 2-2, categorized by common themes. In each category, specific barriers or challenges are prioritized based on expert and stakeholder input.

One of the most important challenges identified is navigating the enormous amount of interacting and complex variables of materials and processes. A major issue is identifying the most important parameters and determining which are common to many materials, and which are unique to specific materials. Adding to the complexity is large number of machine variables and types of machines, plus additives and other external factors. Closely linked to this is the challenge presented by the black box approach used by suppliers of materials as well as printers (e.g., closed loop systems), leading to a lack of transparency in processing parameters and ability to optimize.

Another important barrier is the lack of research grade, standardized feedstocks. In particular, standards are lacking for filaments, plastics additives, and basic material formulation requirements (e.g., powders for specific processes). This makes it difficult to design a part or experiment to take advantage of specific material properties. Other key barriers include lack of data on the life cycle of PB AM parts and materials, and a poor understanding of how feedstock properties affect the finished part.

| Table 2-2. Barriers and Challenges for PB AM Materials Characterization | |
|---|---|
| **Materials** | |
| *High Priority* | • Lack of techniques to understand non-equilibrium path of materials during the deposition process<br>• Lack of materials, suitable for AM having comparable functional performance as conventional materials |
| *Medium Priority* | • Highly fragmented market requiring niche resins/polymers as feedstocks |
| *Low Priority* | • High cost of analytical tools that enhance collection of information and characterization of polymers |
| **Standardization of Materials** | |
| *High Priority* | • Lack of research grade materials (feedstocks) or standards; unpredictability between batches making it difficult to design to that material; lack of minimum baseline capabilities for materials; standards lacking for:<br>o Filaments<br>o Wetness of particles<br>o Plastic additive materials – composition, etc.<br>o Material formulation requirements (e.g., powder for SLS) |
| *Medium Priority* | • Closed source companies that use English vs. metrics |
| *Low Priority* | • Poor understanding of what should be included in standards and what should be standardized (e.g., composition vs. mechanical properties, material parameters vs. end-user applications, etc.) |
| **Properties/Process Variables and Data** | |
| *High Priority* | • Enormous number of variables, all interacting, leading to nearly infinite parameter space; highly multifactorial, but not always clear what factors matter; some factors are polymer and application-specific; makes correlations with property performance difficult; hard to establish properties that can provide suitable guidance to repeatable, robust processes<br>○ Number of printers<br>○ Number of print settings on each printer<br>○ Number of materials (matrix)<br>○ Number of additives (fiber, flow agents, minerals)<br>• Lack of experimental AM data on part lifetime/aging performance with respect to conventional parts; insufficient understanding of layers and effect of machine-material interface<br>• Ability to benchmark at multiple scales (nm to mesoscopic)/interfaces against known "conventional" materials and processes and final product<br>• Poor understanding (lack of data) regarding impact of process parameters and material properties on finished part performance; knowing what the key best printing parameters are |
| *Medium Priority* | • Data and understanding of one polymer does not translate to another, even in the same application<br>• Lack of understanding what occurs at the interfaces<br>o Studies (properties data) applying polymer physics to interfaces in 3D print parts to predict strength<br>o Understanding what affects properties at interfaces<br>• Lack of studies into key "rate limiting" steps of AM (chemistry, heat transfer, mass transfer, etc.)<br>• Lack of transparency in available technical data (How were samples made?)<br>• Lack of awareness of analytical technologies that effectively characterize and ensure the safety of polymers used in additive manufacturing<br>• Polymer microstructure not widely characterized in AM literature |
| *Low Priority* | • Lack of consistency between printers, slicing routines, print paths, same materials, and ambient conditions<br>• Polymer properties depend on molecular weight, polydispersity index (PDI), degradation, orientation/stretch, and other factors (unlike metals/ceramics) |

**Table 2-2. Barriers and Challenges for PB AM Materials Characterization**

| Machine/Process Issues | |
|---|---|
| *High Priority* | • Black box approach in 3D printers and materials suppliers (closed loop suppliers); high variability of machines and processing conditions and associated documentation; material patents are owned by machine manufacturer and not material manufacturer; multiple machine manufacturers are not supported; inability to catalog all the properties due to the black box of machine; closed loop supply chains for commercial AM materials |
| *Medium Priority* | • Slow speed, high cost, poor mechanical properties<br>• Understanding the properties of finished parts compared to test specimens<br>• Lack of certification qualification standards and protocols<br>• Understanding how to quantify variable stiffness parts (e.g., models, multiple bend/tensile tests)<br>• Designing of printers around narrow process window of materials (narrowly designed now)<br>• No standard characterization of relevant material properties and process parameters<br>• Insufficient fidelity of material/process history and reporting data<br>• Cost and schedule for generating statistical data<br>• Lack of understanding of what needs to be controlled |
| *Low Priority* | • Additive, layer-wise part build-up makes use of existing monitoring equipment obsolete<br>• Machines/technology continue to evolve while feedstocks are being developed/optimized (moving targets)<br>• Lack of modeling or commercial *in situ* process for monitoring inter-layer adhesion in the hands of the user |

## Roadmap for Priority R&D

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 2-2. Roadmaps were articulated for the individual R&D priorities listed below and are outlined in more detail in Figures 2-1 through 2-4.

**Table 2-3. Key Barriers and Corresponding Priority Roadmap Topics for Characterization of Materials Throughout Their Lifecycle**

| High-Priority Challenge/Barrier | Priority Roadmap Topic |
|---|---|
| Companies have proprietary process control, material limits, and a wide breadth of materials and process optimization within the black box of equipment, making parameters non-transparent. | System Manufacturing Collaboration – Material-Machine Standardization (Figure 2-1)<br>An internal database of materials properties and variability is needed, including data sharing, to enable material-to-machine standardization. |
| Materials standards are lacking for polymer AM feedstock or polymer AM finished parts. | Standardization of Materials (Figure 2-2)<br>Guidelines are needed to which polymer AM material standards can be written; this will require material feedstock reporting requirements and understanding of industry-specific needs. |
| There is a lack of techniques and information to define the process history of the material during the print process. | Materials Characterization – Process-Induced Transformations (Figure 2-3)<br>Characterization and modeling techniques should be developed to monitor structure and interface development during printing, including *in situ* techniques to define reactions, heat transfer, and stress relaxation. |
| Capability is lacking to compare results and separate process variables, material variables, and process conditions to obtain reproducible results across all printer platforms. | Large Variable Problem: Identify/Prioritize Key Variables (Figure 2-4)<br>Methods and data are needed to enable a standard material printed on a standard tolerance printer to yield reproducible results; requires an open source database of materials in use. |

## FIGURE 2-1. ROADMAP ACTION PLAN: SYSTEM MANUFACTURING COLLABORATION – MATERIAL-MACHINE STANDARDIZATION

**MAJOR BARRIER:** Companies have proprietary process control, material limits, and a wide breadth of materials and process optimization approaches, and related patents. This black box around the system precludes access to material history, composition, and other parameters; many are unknown and non-standard. The build sheet is proprietary. Machine design is narrowed to the material properties; this creates a limited process space with no known properties at the quality control (QC) stage.

**APPROACH:** The objective is to create a database of materials properties and variability, including data sharing on feedstocks. Conflict of interest, policies, and other issues may need to be resolved. The approach is to catalog and disseminate material data relevant to AM, and apply to the supply chain (and use policy pressure to enact changes). The end result would be a material database, better QC tools, a certified supply chain and standardized polymer grades.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Measure feedstock variability<br>• Identify most relevant variables for qualification<br>• Establish dissemination method for data (Who, how, etc.)<br>• Consider packaging and storage and pre-molding | • Material database<br>• Parameter space narrowed down | • No more single supplier – redundant, flexible supply chain<br>• Good material leads to good fundamental research<br>• More robust processing |
| MID (3-5 YRS) | • Develop the material standards<br>• Work with regulatory agencies and customers to adopt standards<br>• Develop production for feedstock QC – water content, etc. | • Certified supply chain<br>• Grading of material identified<br>• New production QC tools | |
| LONG (>5 YRS) | • Uniform machine standards to take advantage of material standards | • Processes that can be certified<br>• Machines that can be graded | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • Industry/AM Users: Push machine supplies towards new model.<br>• Industry/AM Providers: Push back? Better process control (feedback, process) populate database.<br>• Academia: Make measurements. Develop/perform improvements to process.<br>• Standards Committees: Write and publish material standards.<br>• Government: Government researchers similar to academia; supporting role; regulatory role. | High — Improves Product Quality: Better control of material and equipment<br>Medium — Reduces Costs: Graded options may be more expensive for more complex parts, less expensive due to competition and existing offset<br>High — Accelerates Innovation: More material choices, less boundaries, better understanding of capabilities<br>High — Enhances Competitiveness: More players<br>High — Reduces Time to Develop Products: Understanding of the machines and polymers<br>Other: N/A |

## FIGURE 2-2. ROADMAP ACTION PLAN: STANDARDIZATION OF MATERIALS

**MAJOR BARRIER:** No materials standards exist for polymer AM feedstock or polymer-based AM finished parts. The current scope and of materials available for use is too small.

**APPROACH:** The objective is to establish guidelines to which polymer AM material standards can be written. The approach will be to establish reporting requirements, which can then be used to establish guidelines for standards. This will enable better prediction of materials performance and upfront design, and will facilitate development of new polymer materials for AM.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Establish reporting requirements for AM material feedstock<br>• Establish guidelines for polymer AM material standards<br>• Encourage standards committees to begin work on polymer AM material standards | • Consistent quality in polymer AM feedstock<br>• Establishment of horizontal material standards for polymer AM feedstock/incoming materials | • Consistent and predictable material performance – both feedstock and finished part<br>• Database of polymer AM materials – develop library of materials for different applications<br>• Facilitate development of polymer materials to be used in AM processes |
| MID (3-5 YRS) | • Expand feedstock requirements to capture/minimize lot to lot variation – Both composition and geometry<br>• Conduct market research to define the needs for polymer AM materials | • Established and acceptable variability in feedstock – leads to increased finished part property confidence | |
| LONG (>5 YRS) | • Identify use-specific and/or industry-specific polymer AM material needs<br>• Public database of polymer AM material properties – Feedstock and Finished-part | • End-user ability to select appropriate material and process for specific part end-use | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • Industry/AM Users: Needs and requirements establishment. Participate on standards committees. Publish data for materials database.<br>• Industry/AM Providers: Provide guidance to chemical/material industries on material needs. Participate on standards committees.<br>• Academia: Develop new materials, processes, analysis tools, measurement tools. Lead creation of polymer AM database.<br>• Standards Committees: Develop horizontal and vertical standards (see above).<br>• Government: Participate on standards committees. Develop test methods. Anticipate impact in regulatory realm. | High — Improves Product Quality: Improved quality control of finished parts<br>Medium — Reduces Costs: Reduces need/frequency of testing<br>High — Accelerates Innovation: Incentivizes material development<br>Medium — Enhances competitiveness: See above<br>High — Reduces Time to Develop Products: confidence in feedstock leads to confidence in finished parts<br>High — Other: Expanded capability of materials. Lower barrier to entry. |

## FIGURE 2-3. ROADMAP ACTION PLAN: MATERIALS CHARACTERIZATION – PROCESS-INDUCED TRANSFORMATIONS

**MAJOR BARRIER:** There is a lack of techniques and information to define the process history of the material during the print process. Multi-scale models to describe reaction, flow, heat transfer, and stress relaxation for a given print process are also lacking.

**APPROACH:** The objective is to improve reproducibility and performance through better monitoring and understanding of structural and thermal parameters that impact part properties. The approach is to develop characterization and modeling techniques to monitor structure and interface development during printing. Implement *in situ* characterization techniques are needed to define reaction, flow, heat transfer, and stress relaxation during printing; these can provide input to process models and controls.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Define all parameters that define process history and that are needed for multi-scale model<br>• Begin to identify important parameters that impact structure and interface formation with printing<br>• Aggregate known data on correlation between process history and properties | • Repository of current information on importance of processing space | • Reproducibility improvement<br>• Tuning part performance from printing process knobs<br>• Identify inherent limitations of a given printing process<br>• Provide foundation to implement feedback control during printing |
| MID (3-5 YRS) | • Development of *in situ* techniques to monitor important parameters that impact structure and interface during processing<br>• Separation of impact of material parameters and processing parameters<br>• Develop multi-scale models<br>• Prioritize importance of processing parameters | • Tailored properties of final structure from processing protocol<br>• Validation of models against tested parts | |
| LONG (>5 YRS) | • Develop methods to control important processing parameters during printing process<br>• Establish round robin to evaluate universality | • Report on and complete round robin<br>• Offer control of processing during print | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS | |
|---|---|---|
| • **Industry/AM Users:** Provide input on needs, problems, and current state of characterization and modeling techniques. Conduct demo/pilot/round robin.<br>• **Industry/AM Providers:** Provide tools, software and material information (non-IP or IP with NDA).<br>• **Academia:** Develop data, experiments, and analyses.<br>• **Standards Committees:** Develop standards document on terminology and certification processes. Documentation of definitions and experimental methodologies.<br>• **Government:** Maintain repository, oversize round robin. Develop/test algorithms. | High | **Improves Product Quality:** Provide foundation for reproducibility tailor-ability |
| | Low | **Reduces Costs:** Foundational information will not impact cost initially |
| | High | **Accelerates Innovation:** Foundation for models and reproducible tailor-ability |
| | Medium | **Enhances competitiveness:** Offers path to compete with other manufacturing techniques |
| | High | **Reduces Time to Develop Products:** Provides foundation |
| | | **Other:** N/A |

## FIGURE 2-4. ROADMAP ACTION PLAN: LARGE VARIABLE PROBLEM: IDENTIFICATION/PRIORITIZATION OF KEY VARIABLES

**MAJOR BARRIER:** Currently the capability is lacking to compare results and separate key process variables, material variables, and process conditions to aid in achieving reproducible results across all printer and material platforms.

**APPROACH:** The objective is to identify and prioritize the key variables for all parts of the process, from material to finished part. The approach will first develop standard process settings for standard materials, define parameter requirements, and provide data sets to create technical data sheets for research grade materials. This will ultimately help to enable standardized printing and tolerances with reproducible results and part properties.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Obtain standard material set for each printing technology<br>• Well-defined machine tolerances defined for R&D test bed (dimensional, temperature)<br>• Define DOE parameter space for each printing technique | • Reporting standard process settings used in a given print (i.e., metadata, G-code) | • A standard material printed on a standard tolerance printer with a fixed programming code (G-code) yields reproducible results and properties<br>• Open source database of materials used for R&D/industrial 3D printing process→ this is preferably provided by the manufacturer of the feedstock material |
| MID (3-5 YRS) | • Revisit material test standards to ensure the key identified parameters are included in standards<br>• Execute DOE and generate shared data-sets | • "Research grade" materials that come with technical data sheet<br>• Plethora of data available for analysis to uncover critically sensitive variables | |
| LONG (>5 YRS) | • Extend paradigm to exotic and innovative materials (composites, hybrid materials, graded materials)<br>• Input shared data-sets into informatics based material genome project to predict material performance | • New measurement techniques developed specifically for additive manufacturing processes<br>• Input for modeling material performance | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS | |
|---|---|---|
| • Industry/AM Users: Participate in characterization of standards. | High | Improves Product Quality: Improves repeatability and product confidence |
| • Industry/AM Providers: Provide data and tolerances as set forth by appropriate governing bodies (NIST, ASTM, ISO). | Medium | Reduces Costs: Less redundant data collection/faster optimization |
| • Academia: Participate in generation of DOE and characterization metrics. | Medium | Accelerates Innovation: Predictive analysis unlocks new material potential |
| • Standards Committees: Demand compliance for current published standards and/or generate new standards specific to polymer AM. | High | Enhances competitiveness: Make AM competitive with existing manufacturing techniques |
| • Government: Support research initiatives financially in order to achieve stated manufacturing goals for USA | High | Reduces Time to Develop Products: More upfront knowledge of materials and machines |
| | High | Other: Facilitates scientific knowledge |

# CHAPTER 3: PROCESS MODELING

## OVERVIEW OF THE TOPIC AREA

Development of accurate process models is an important fundamental building block as additive manufacturing technologies are being developed and deployed. Good validated models decrease the need for real-world testing of technologies and processes, and give product designers a predictive capability for optimization of part designs. Models are the basis for developing the required control technologies and software for PB AM production processes, and they will also provide support for standards development as well as qualification and certification methods.

Accurate models cannot be developed without comprehensive and validated data on materials and processes. These models also require an excellent understanding of the fundamental processes and physical phenomena that underlay PB AM feedstock inputs, approaches, and technologies.

Note that the modeling needs outlined in this chapter are relevant to PB AM processes and production, but may also broadly encompass other aspects of modeling.

## FUTURE/DESIRED CAPABILITIES

In the future, enhanced AM process modeling capabilities will enable manufacturers to minimize product development time and cost and improve part quality. The desired future process modeling capabilities are described briefly below and listed in Table 3-1.

***Models to Inform Design***

There is a need to better understand the process-structure-property links in PB AM. Better understanding of these relationships will enable designers to predict certain part characteristics based on used materials and manufacturing processes. This knowledge and resulting capabilities will enable parts to be designed for their desired function and performance, greatly streamlining product development and manufacturing processes.

***Processing and Engineering***

Enhanced process modeling capabilities will allow for significant advances in PB AM processes and systems. Better understanding of the processes will enable the manufacture of nearly any conceivable product in needed size and resolution. Once PB AM processes are more thoroughly understood, material properties of printed parts can be predicted without regard to the print geometry of the part. Models that encompass everything from molecular level to device scale enable connecting the part manufacturing process to the performance of the completed part. The development of high-quality models will require well-defined, and accepted, standards along with common nomenclature for PB AM.

***Build Variability and Performance***

For future success of PB AM processes and products, it is important that build variability is minimized and part performance maximized. To achieve this goal, process models need to account for the impact of feed material properties on printed part quality. Because build variability is process-dependent, variability must be characterized by process.

***Multi-component Materials Models***

For PB AM to gain further market share it will need to become a viable technology for parts containing multiple materials. There is not only a need to have processing models for the different materials, but comprehensive multi-material models that incorporate several single-material models also need to be developed.

| Table 3-1. Desired Capabilities for PB AM Process Modeling |
|---|
| **Models to Inform Design: Process – Structure – Property (P-S-P)** |
| • Prediction of strength and ductility (i.e., parameters a designer can actually use); predict properties from *in situ* measurements of the structure (e.g., voids, orientation, temperature)<br>• Full understanding of process-structure-property links to enable design for performance<br>o Predictive capabilities to drive design, material, and process parameters based on the desired part function<br>• Fully characterized mechanical properties of printed products<br>• Characterization of interfaces (structures, formation, dynamics, effects, properties, etc.)<br>• Thermal history predictions for printed part that takes into account property changes with phase change<br>• Models consistent with non-equilibrium thermodynamics |
| **Processing and Engineering** |
| • Design of optimal materials and processing conditions to manufacture any conceivable product of any size and resolution<br>• Molecule to device-scale model connecting processing to performance (trends then numbers)<br>• Ability to relate strength of the part to the printing parameters and material properties<br>• Ability to have fully user-defined processing parameters<br>• Achieve near-isotropic (or simply predictable) material properties regardless of print geometry (thermal history, microstructure, toolpath, etc.) on x, y scale at least<br>• Model to relate final properties from shape to processing to individual filament to the microscale (at multi-length scale)<br>• In extrusion (fusion deposition modeling – FDM, Big Area Additive Manufacturing – BAAM), predict interlayer bond strength as a function of temperature<br>• Real-time modeling of P-S-P<br>• Temperature measurement accuracy on a certain scale (scale TBD) across time and space<br>• *In situ* molecular information in real-time and nanometer to millimeter scale (not via synchrotron) with or without coupons<br>• Defined and accepted standards to model additive manufacturing processes (i.e., nomenclature)<br>• Distributed data infrastructure (standardized/integrated) models |
| **Build Variability and Performance** |
| • Predictive models and understanding of build variability (process-dependent, so characterization of variability by process)<br>• Tighter control of process variation and impacts of feed material properties<br>• Optimization of materials and process to minimize/eliminate voids in polymers extrusion (FDM)<br>• Prediction of deformation and accuracy: "as printed" vs. "as modeled"<br>• Nonlinear material models for failure mechanisms (e.g. temperature constrained properties) |
| **Multi-component Materials Models** |
| • Optimal placement of reinforcing phase for lightweight structural component design<br>• Multi-material and multi-scale modeling (length scale of carbon or other additive)<br>• Controllable fiber orientation (short fiber) throughout bead/voxel processing volume for any volume fraction composite<br>• Models for different materials (melts, semi-crystalline, containing particles) |

## Technological & Measurement/Standards Challenges

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

One of the most significant barriers to develop high-quality models for PB AM processes is the lack of a comprehensive understanding of the material and process sciences that are involved. The interfacial science between different voxels, layers, phases, and multi-materials is an area where more research is needed. There is also a lack of non-equilibrium material and process measurements and models. Physical models are needed for factors such as polymer relaxation, kinetics, diffusion kinetics and rheology.

Lack of standards to guide model development is another high priority challenge. There are no agreed-upon guidelines and standards for PB AM model development and validation. A widely accessible and standardized material and process metadata collection structure and a central data repository are also lacking.

Non-technical infrastructural issues are also hindering modeling progress. Because development of comprehensive PB AM process models requires multi-disciplinary collaboration, there is need to implement better programmatic structures at universities and other research entities to enable and encourage such collaborative efforts

**Table 3-2. Barriers and Challenges for PB AM Process Modeling**

| | |
|---|---|
| **Chemistry** | |
| *High Priority* | • Fully understanding the interfacial science (between voxels, layers, phases, or multi-materials) |
| *Medium Priority* | • Ability to/support for design of new polymer chemistries optimized for additive manufacturing (including reinforcement compatibility) |
| *Low Priority* | • Understanding of post-processing chemistry<br>• Unknown feedstock variability |
| **Standardized Data and Protocols** | |
| *High Priority* | • Lack of agreed-upon model systems for development/validation (e.g., benchmarks)<br>• Limited test protocols for testing additive manufacture parts (mechanical) |
| *Medium Priority* | • Lack of standardized material and process metadata collection structure or a central repository that is widely accessible<br>• Model repurpose and reuse is limited<br>• Lack of cyber-secure and pedigreed datasets (with traceability, schema) |
| **Non-Equilibrium Physics** | |
| *High Priority* | • Lack of non-equilibrium material and process measurements and models Physical models of polymer relaxation, kinetics and diffusion modes with temperature, orientation, stress, etc.<br>o Reliable physics-based constitutive models far from equilibrium<br>o Rheology measurements near glass transition temperature, $T_g$ |
| *Medium Priority* | • Large range of length and time scales – physical descriptions<br>• Bridging multiple time/length scales |
| *Low Priority* | • Lack of flexible *in situ* time (t) and space ($\underset{\sim}{r}$) resolved molecular measurements (3D, nanometer scale, millisecond scale)<br>• Understanding the appropriate levels of description for reliable modeling of the important dynamic processing variables (different length scales, minimum number) |
| **Design and Engineering** | |
| *Medium Priority* | • Tools to tailor structural designs (better than 3DCAD) to take maximum advantage of unique capabilities of additive manufacturing<br>• Part quality and variability |
| *Low Priority* | • Lack of sensors for measuring fusion |

## Roadmap for Priority R&D

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 3-3. 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 PB AM Process Modeling**

| High-Priority Challenge/Barrier | Priority Roadmap Topic |
|---|---|
| Lack of non-equilibrium material and process measurements and models hinders development of accurate PB AM process models. | Non-equilibrium Material and Process Measurements and Models (Figure 3-1)<br>Predictive models of variations in multiple properties of materials in the non-equilibrium state need to be developed. |
| The interfacial science between different voxels, layers, phases, and multi-materials is not fully understood. | Understanding Interfacial Science of AM Polymers (Figure 3-2)<br>Data, characterization methods, and ultimately models for the interfacial property prediction and control need to be developed. |
| There are no agreed-upon guidelines and standards for PB AM model development and validation. | Standards for Validation, Certification, and Qualification of Models and Parts (Figure 3-3)<br>The approach is to standardize and evaluate data to enable development of standards for validation, certification, and qualification of process models and AM parts. |

## FIGURE 3.1. ROADMAP ACTION PLAN: NON-EQUILIBRIUM MATERIAL AND PROCESS MEASUREMENTS AND MODELS

**MAJOR BARRIER:** There is currently a lack of physics-based constitutive modeling and measurements of chemical, thermal, mechanical and diffusive properties in the non-equilibrium spectrum of materials that can be both liquid and solid.

**APPROACH:** The objective is to develop predictive models of variations in multiple properties of materials in the non-equilibrium state. The approach is to apply existing tools, develop new tools (experiments and models) and integrate all into predictive physics-based multi-scale models.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Conduct combined temperature/flow (non-isothermal rheology) modeling and experiments<br>• Perform stress and structural relaxation and aging measurements of common feedstocks for PB AM<br>• Measure relevant thermodynamic properties (e.g., coefficient of thermal expansion) | • Existing tool to design some aspects of AM<br>• Better reproducibility and known initial conditions<br>• Materials database for feedstocks | • Predictive models of variation in residual stresses, strength of interface, mechanical properties, dimensional tolerances, void volume fraction, and surface finish |
| MID (3-5 YRS) | • Develop diffusion measurement methods for polymers in non-isothermal situations<br>• Develop a rheology model valid both above and below glass transition or melting temperature development<br>• Investigate effects of fillers and processing conditions on properties of the printed part | • Reliable measurement methods and measurements<br>• Reliable validated rheological models spanning solids and fluids | |
| LONG (>5 YRS) | • Incorporate physics-based rheological models into larger multiscale computational framework<br>• Validate property prediction of printed part | • Computational tools that can predict final properties for given processing conditions | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • Industry/AM Users: Identify desirable properties to control; provide problems.<br>• Industry/AM Providers: Provide feedstocks and printing parameters; provide printers that can be controlled.<br>• Academia: Develop measurement methods, physics based models computation models.<br>• Standards Committees: Develop standardized testing methods, standards for feedstocks.<br>• Government: Support high performance computing enabled infrastructure for collaborative and multidisciplinary research. | High — Improves Product Quality: Reduced variation in product properties<br>Low — Reduces Costs: Reduced defects; small effect on costs<br>High — Accelerates Innovation: Facilitates design<br>Medium — Enhances Industry Competitiveness: Eliminates barrier for quality control<br>High — Faster Product Development Time: Predictive models as design tools reduce design time<br>Other: N/A |

## Figure 3-2. Roadmap Action Plan: Understanding Interfacial Science of AM Polymers

**Major Barrier:** Interfaces are naturally formed during most polymer AM processes. These interfaces control many properties (mechanical, thermal, optical, electrical, etc.) because of the high interface/volume ratio with uncontrolled and often negative effects.

**Approach:** The objective is to better understand interfacial science of polymers in AM to improve ultimate part performance and properties, as well as processing variations. The approach is to develop data, characterization methods, and ultimately models for interfacial property prediction and control.

| Time | Roadmap Action Plan | Milestones | Performance Targets |
|---|---|---|---|
| Near (1-2 yrs) | • Identify molecular features necessary for modeling different interfaces (melt/solid for amorphous, crystalline or composite polymeric materials; solid/solid diffuse interface for SLS, solid and pre-polymer/resin for SLA, chemical reaction kinetics in *in situ* polymerizing/crosslinking situations…)<br>• Develop characterization methods for interfacial properties, which will inform model development | • Sets of variables necessary to model various interfaces in different AM processes<br>• Data sets for models to implement and target | • Suite of characterization methods for interfacial properties |
| Mid (3-5 yrs) | • Model mechanical properties of interfaces at multiple scales (atomic, mesoscale, …)<br>• Understand aging and evolution of interfaces during processing and post-processing: characterize and model | • Interfacial models for mechanical properties | • Materials whose overall part anisotropies are not impacted by interfacial anisotropies and properties |
| Long (>5 yrs) | • Develop models for the mechanical, thermal and optical properties of a final part based on interfacial properties<br>• Model the effects of additives (e.g., carbon nanotubes, fibers, nanoparticles, surfactants, plasticizers, . . . ) on interfacial formation and properties<br>• Incorporate the effects of phase changes in materials on interfaces | • Predictive models of part performance that incorporates the formation process and input material properties | • Processes that have fewer or no internal interfaces |

| Stakeholders & Potential Roles | Relative Impacts |
|---|---|
| • Industry/AM Users: Provide input on needs, problems and current state; conduct demos/pilots.<br>• Industry/AM Providers: Provide tool solutions, software, and prototyping.<br>• Academia: Develop software algorithms, learning/adaptive frameworks, conduct data analysis.<br>• Standards Committees: Develop software standards certification processes.<br>• Government: Maintain computational repository, cyber infrastructure, and develop/test algorithms. | High — Improves Product Quality: All parts depend on interfacial properties<br>Low — Reduces Costs: Not an immediate cost benefit<br>Medium — Accelerates Innovation: Provides flexibility in design<br>High — Enhances Competitiveness: Better material properties<br>Medium — Reduces Time to Develop Products: By removing a constraint, development should be faster. Less testing and more confidence in properties.<br>Other: N/A |

## FIGURE 3-3. ROADMAP ACTION PLAN: STANDARDS FOR VALIDATION, CERTIFICATION AND QUALIFICATION OF MODELS AND PARTS

**MAJOR BARRIER:** Accepted standards to feed and support process models are currently lacking, as are standards to validate process models. Insufficient validation of process models and resulting uncertainties in predictive capabilities limits their practical use.

**APPROACH:** The objective is to standardize and evaluate data to enable development of standards for validation, certification and qualification of process models. The approach will benchmark the state-of-art in process modeling of AM; establish new protocols; and create and demonstrate standards that will feed and validate AM process models and support part certification and qualification.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Standardized/evaluated data for input of relevant physical, chemical, and thermal properties<br>• Inventory existing models, data, tools to help identify needs (i.e., standardization "Gap Analysis") | • Established benchmark standards for geometry and mechanical performance for specified materials<br>• Established first stage repository location for existing shared access tools, data, and models | • Protocols for rapid qualification of AM parts and processes<br>• 30% reduction in cycle times<br>• Ability for decision making in risky environs<br>• Central software warehouse (virtual repository with source of record to enable part and model certification) |
| MID (3-5 YRS) | • Develop/revise multi-variable and multi-physics models (using standard input data)<br>• Create standard test protocols specific to AM parts<br>• Explore rapid qualification/certification routes (ICME)<br>• Establish protocols/procedures to allow data sharing | • Demonstration of revised process models utilizing initial standardized input data<br>• Protocol developed for rapid part qualification<br>• Evaluation of benchmark case using ICME model or using AM-Bench framework | |
| LONG (>5 YRS) | • Identify standard components (data format) needed to deliver validated component (digital thread)<br>• Develop fundamental model (based on Process – Structure – Property) that allows transition of certification protocols to other platforms as they are discovered | • Demonstration of rapid certification of part<br>• Validation of a model across multiple platforms | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • Industry/AM Users: (e.g., Boeing) — Provide input on needs, problems and current state; conduct demonstrations/pilots.<br>• Industry/AM Providers: (e.g., Stratasys) — Provide tool solutions, software, prototyping, models, access to process parameters, and adopt established standards.<br>• Academia: Develop software, algorithms, learning/adaptive frameworks, conduct data analysis.<br>• Standards Committees: Develop software standards, certification processes, and testing procedures.<br>• Government: Lead effort to establish and periodically review roadmap. Maintain computational repository, cyber infrastructure, cyber security; develop/test algorithms; support of fund models. | High — Improves Product Quality: Supports qualification/certification of parts leading to better quality<br>Medium — Reduces Costs: Leads to fewer part defects, certified performance<br>High — Accelerates Innovation: Speeds up the design process<br>High — Enhances Competitiveness: More reliable, proven parts and performance<br>High — Reduces Time to Develop Products: Speeds up the design process |

# CHAPTER 4: *IN SITU* PROCESSING MEASUREMENTS

## OVERVIEW OF THE TOPIC AREA

In order to manufacture high quality parts using PB AM technology, it is essential to be able to identify and then monitor the critical material and process parameters as a part is being manufactured. These *in situ* measurements are key to further understanding AM processes, improving process efficiency and quality, and producing parts with desired qualities. *In situ* measurements are used to monitor process temperature and various material properties, detect defects, and provide feedback for process control. There are, however, many challenges to effectively obtaining and utilizing needed *in situ* measurements. In many cases, it is difficult to integrate required measurement technology into the actual manufacturing equipment and process. Because the goal is that data from the measurements be used for process control, the measurements must be obtained at a very high speed and the gathered data interpreted in real time. For certain properties of materials adequate techniques may not yet exist to obtain desired measurements. Thus, further deployment of PB AM requires continued technology development to improve *in situ* measurement capabilities.

## FUTURE/DESIRED CAPABILITIES

Improved *in situ* measurement capabilities will be needed to enhance PB AM processes and to produce high quality parts. The desired *in situ* measurement capabilities and technologies are described briefly below and listed in Table 4-1.

***Monitoring/Controls Technology***

There is a need to develop and enhance technologies that allow capture of *in situ* measurements during PB AM manufacturing processes. In particular, the speed and resolution of these measurement capabilities needs to be improved. To capture all needed information, multi-sensor measuring capabilities—instead of technologies measuring only one variable, such as temperature—need to be developed. More comprehensive measurements will enable the development of better control systems for the manufacturing processes.

***In situ Measurement for Build/Part Quality***

For further deployment of PB AM technologies, it is important that part quality and build-to-build consistency is improved. Enhanced *in situ* measurement capabilities play a key role in these improvements. Capabilities such as in-process defect detection, characterization of material properties, and real time layer-to-layer adhesion strength measurements will lead to enhanced process control and better part quality.

***In situ Characterization of Structure, Composition, and Thermal Properties***

AM offers great potential to understand and record key information about a part's micro-level characteristics, such as molecular structure, fiber orientation, thermal properties, and strain. This type of detailed information could one day enable manufacturers to build parts to very exact specifications and validate that parts meet those specifications. Manufacturers will also be able to provide detailed product maps that include data on the micro-level characteristics of each individual part. Being able to conduct *in situ* characterization and control will enable manufacturers to optimize a part's molecular structure, which will lead to improved part quality. In order to gather this micro-level information, technologies need to be available to measure the temperature, geometry, and chemical characteristics of every deposited layer at high speeds.

### *Knowledge and Data*

Improved *in situ* measurement capabilities will create a vast amount of new data, which will be both an opportunity and a challenge. The new data being generated will enable improvements on multiple fronts, from AM modeling and process improvements to machine learning and being able to provide a detailed, informative record for every part that is manufactured. When the data is combined with new real-time data interpretation capabilities, *in situ* process control becomes feasible, which will lead to improved part quality and consistency of product. However, improvements in data processing power, efficiency and speed are needed in order to fully realize these benefits.

**Table 4-1. Desired Capabilities for PB AM *In situ* Measurement**

**Monitoring/Controls Technology**

- Capability for *in situ* monitoring while processing during small and large scale production
  - High speed, high resolution *in situ* measurements (optical, IR thermography, x-ray, ultrasound, vibrational spectroscopy)
  - 3D sensors with high speed and precision
  - Multi-sensor, multiplex monitoring
  - Monitoring stress with high speed and full field capability
  - Engineering control within a given AM technology to obtain a range of properties from a single feedstock

***In situ* Measurement for Build/Part Quality**

- Build-to-build consistency: material properties and part tolerance (99% acceptance)
- *In situ* scans of evolving shape over the build duration (i.e., more than just layer) for all processes
- Accurate, reproducible repeatable, and fast builds
- Automated in-process defect detection
- Online defect distribution (voids, particles or secondary matter)
- Layer to layer adhesion strength measurements in real time
- New sensing technology for *in situ* characterization of material properties
- Quantitative imaging of the build process at the layer level; dynamic deformation (Doppler) imaging
- *In situ* measurements for rheology (either directly or by correlation of inference)
- *In situ* measurements for tack (either directly or by correlation of inference)

***In situ* Characterization of Structure, Composition, and Thermal Properties**

- Ability to measure the geometry of every layer *in situ* to 5 µm accuracy at high speeds (in real time)
- Optimization of molecular structure via *in situ* characterization and control
- Real-time validation of micro structure
- *In situ* characterization and control over graded composition: fiber orientation, reactive materials, suspension
- Ability to monitor surface roughness with high speed and in full field
- Strain field mapping for entire part
- Measures for online polymer entanglement
- Measurement of temperature and chemistry distribution of every layer at high speeds *in situ* (in real time)
- Capability for *in situ* monitoring of thermal profiles and molecular orientation interface properties and profiles in polymers extrusion (FDM)
- Imaging through "dense" liquids in stereolithography (SLA); real-time *in situ* viscosity characterization in SLA (for resins)

**Knowledge and Data**

- Machines that produce an informative record of *in situ* monitoring data with every part; machine learning, i.e., evolving process controls from aggregated build data sets
- Real-time data interpretation to support *in situ* process control
- Ability to obtain and interpret feedback during processing
- AM machines that use feedback from property sensing monitors for control

## TECHNOLOGICAL & MEASUREMENT/STANDARDS CHALLENGES

The barriers and challenges currently impeding large scale deployment of PB AM *in situ* measurement technologies 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.

In the area of monitoring and control technology, one of the most significant challenges is the inadequate speed and resolution of current measurement technologies. Existing equipment is not capable of measuring thermal and chemical distribution of each deposited layer accurately and in real time during the AM process. In addition, most current imaging technologies are not easily integrated into AM printers. There is need for imaging solutions that are effective through scattering media, unobtrusive, and tailorable to different printer geometries.

Other major barriers concern knowledge and data. There is a lack of comprehensive models that can be used to interpret *in situ* data and develop automated control systems. To develop such models, there is need for *in situ* measurement data to inform the models. Fast and accurate big data analytical methods for handling *in situ* measurement information and to develop physics-based models are also lacking.

| Table 4-2. Barriers and Challenges for PB AM *In situ* Measurement | |
|---|---|
| **Monitoring/Controls Technology** | |
| *High Priority* | • Time scale of measurement compared to print speed<br>o No existing equipment capable of measuring the thermal and chemistry distributions of each layer to satisfactory resolution in real time during the AM process<br>o Measurement acquisition speed and incorporation on commercial instruments<br>o Spatial resolution response time<br>• Imaging and measurement modalities through scattering media<br>o Interfacing a printer with an x-ray beam or next generation focused neutron beam<br>o X-ray flux in lab based sources is too low for process control<br>o Analysis of materials below surface (ex. SLS, Vat polymerization)<br>o *In-situ* spectroscopic measurements |
| *Medium Priority* | • Monitoring/imaging equipment not designed to accommodate needed temperature and size requirements<br>• Lack of *in situ* controls on OEM equipment<br>• Cost benefit ratio of measurement to reliability<br>• Computer processing power needed for real-time data analysis and feedback |
| *Low Priority* | • Lack of large area, small-size sensors for fast high resolution measurement<br>• Ability for 3D sensor (triangulation) - size 10 µm , 1 MHz rate )<br>o 3D sensing microscope precision; sensing volume X $mm^3$; speed 20 kHz for small volume<br>• Sensor simplification: simple interpretation; data reduction )<br>• Lack of sensors that do not affect part performance (i.e., non-intrusive)<br>• Sensor interference – information from one sensor can invalidate information/guidance from others |
| **Measurement Techniques** | |
| *High Priority* | • Accuracy and precision of measurements, impacted by temperature fluctuations, environmental changes (stress or strain)<br>o Inability to register true temperature or rheology for a material that is changing temperature, density and surface structure (real-time) |
| *Medium Priority* | • Limited technology for *in situ* non-contact measurement of mechanical properties<br>• Lack of high throughput characterization; variability among applications |

**Table 4-2. Barriers and Challenges for PB AM *In situ* Measurement**

| Knowledge/Data | |
|---|---|
| *High Priority* | • Lack of process structure property (PSP) models to interpret *in situ* data; full understanding of what parameters are most important is lacking<br>o No capability for automated feedback into system and self-correction<br>o Limited process simulation technology (models)<br>o Lack of design tools for structural compositional heterogeneous materials<br>o Inadequate/limited upstream part layout simulation tools<br>o Lack of validated sintering models for polymer and polymer composite powders<br>• Lack of big data analytics methods that can be employed for *in situ* measurement data analysis in conjunction with physics-based modeling; challenges to address include:<br>o Data volume, processing capability, storage<br>o Complexities of real-time analysis for multi-sensors ( both speed and accuracy)<br>o Limited big data computer science researchers engaged in AM |
| *Medium Priority* | • Layer by layer interactions that bring very large variations, and lack of fundamental models to formulate |
| *Low Priority* | • Consensus on coherent set of needs<br>• Ability to detect breaches in data integrity<br>• Dynamic chemistry not completely controlled<br>o How to define standards for different raw materials; machine vendor, machine specs, operator environment |

## ROADMAP FOR PRIORITY R&D

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 4-2. Roadmaps 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 PB AM *In situ* Measurement**

| High-Priority Challenge/Barrier | Priority Roadmap Topic |
|---|---|
| There is a lack of *in situ* imaging modalities that are effective and can be easily incorporated into AM printers. | New *In situ* Imaging Modalities (Figure 4-1)<br>New and improved *in situ* imaging technologies that are effective and unobtrusive need to be developed. |
| Existing equipment is not capable of measuring thermal and chemical distribution of each deposited layer accurately and in real time during the AM process. | Real-Time Process Measurement at Required Spatial Temporal Resolution (Figure 4-2)<br>Next generation high performance modular sensing technologies are needed in order to verify part quality and inform closed loop feedback. |
| Comprehensive models that can be used to interpret *in situ* data and develop control systems are lacking. | *In situ* Control and Model Integration (Figure 4-3)<br>The relevant process parameters that have significant impact on finished material properties need to be identified and control algorithms to make process adjustments need to be developed and validated. |
| Fast and accurate big data analytical methods for handling *in situ* measurement information and developing physics-based models are lacking. | Big Data Analytics for AM (Figure 4-4)<br>New methods to analyze big data sets from *in situ* measurement need to be developed and incorporated into process models. |

## FIGURE 4-1. ROADMAP ACTION PLAN: NEW *IN SITU* IMAGING MODALITIES

**MAJOR BARRIER:** Current imaging technologies are not easily integrated into 3D printers. Technologies must cover a large spatial area, very quickly, and preferably be hyperspectral. In addition, they must be cost effective and easily integrated.

**APPROACH:** Imaging modalities are needed that are unobtrusive and customizable to the type of printer geometry. Technology will need to be either reflectance or transmittable through material or equipment, and have the capability to be integrated with other measurement technologies. The approach is to understand gaps in imaging and develop technologies with desired capabilities.

<table>
<tr><th>TIME</th><th>ROADMAP ACTION PLAN</th><th>MILESTONES</th><th>PERFORMANCE TARGETS</th></tr>
<tr><td>NEAR (1-2 YRS)</td><td>• Inventory of imaging types with strengths and weaknesses as well as needs for integration<br>• Understand gaps within as well as between each technology type</td><td>• Gaps have been identified and quantified</td><td rowspan="3">• Integration of printer vendors, OEM imagers and software developers<br>• Simplify data analysis<br>• Data decision tools<br>• Reduce variation in printed parts; reduce defects<br>• Develop unobtrusive imaging technologies in line with printer capabilities<br>• Develop cost effective technologies</td></tr>
<tr><td>MID (3-5 YRS)</td><td>• Develop technologies to close these gaps<br>• Develop integration of imaging technologies with printer systems</td><td>• Gaps closed by developing novel imaging sources and better detectors<br>• Requirements developed for industry for integration<br>• Prototype printer and imaging system integration</td></tr>
<tr><td>LONG (>5 YRS)</td><td>• Provide integration to modeling<br>• Provide data for active feedback efforts</td><td>• Data provided for modeling, simulations, and instrumentation feedback<br>• Validation of imaging measurements<br>• Real-time closed-loop software</td></tr>
</table>

### STAKEHOLDERS & POTENTIAL ROLES

- **Industry/AM Users:** Set requirements for performance; e.g. frame rate, cost, resolution.
- **Industry/AM Providers:** Open architecture of integration of imaging systems; open hardware and software; printer and imaging manufacturers.
- **Academia:** Demonstrate the integration, software control, feedback to printer conditions, develop imaging technologies.
- **Standards Committees:** Set imaging standard, develop calibrates that are amenable to 3D printer environments.
- **Government:** Provide user facilities with novel light sources and detectors that are multimodal.

### RELATIVE IMPACTS

| | |
|---|---|
| High | **Improves Product Quality:** Reduces defects and variation by identifying their causes |
| Medium | **Reduces Costs:** Identifies anomalies, reduces waste before post validation |
| Low | **Accelerates Innovation:** Little benefit to innovation but improves quality of product |
| High | **Enhances Competitiveness:** Feedback for high performance and certification |
| Medium | **Reduces Time to Develop Products:** Eliminates problems and makes model development quicker |
| | **Other:** N/A |

## FIGURE 4-2. ROADMAP ACTION PLAN: REAL-TIME PROCESS MEASUREMENT AT REQUIRED SPATIAL TEMPORAL RESOLUTION

**MAJOR BARRIER:** Existing measurement techniques lack the required speed, resolution, and instrument footprint to enable and verify build-integrity throughout part volume.

**APPROACH:** Next generation high performance modular sensing is needed to verify part quality and inform closed loop feedback. The approach will investigate existing technologies and capabilities, understand critical parameters to be measured, and develop sensor capabilities to fill gaps. Sensor technology would then be tested at pilot scale, and then optimized/integrated into AM processes.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Conduct inventory of sensing technologies and determine what process variables need to be measured for each additive technology<br>• Understand gaps in existing capabilities and create plan for development<br>• Start developing sensor capabilities and categorize cost benefits | • List of critical parameter for each additive process<br>• Initial sensor technique development as a stand-alone prototype | • Void content detection of 10 micron<br>• Temperature gradient<br>• Voxel based material property build history throughout the volume<br>• Measurement resolution throughout build<br>– Local – 10 micron<br>– Thermal<br>– Chemistry<br>– Density<br>– Dimensional measurement<br>• Data exchange to big data cloud for analysis |
| MID (3-5 YRS) | • Down-select and validate for specific AM process<br>• Conduct data flow interface integration for closed-loop control and data visualization. Collaborate with other AM initiatives | • Integration of sensor technique into prototype AM equipment<br>• Successful proof-of-concept of *in situ*, real-time process measurements | |
| LONG (>5 YRS) | • Optimize and integrate sensing technologies<br>• Evaluate next generation control systems | • Completion of demonstrations for practical applications | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • Industry/AM Users: Early technology adopters and provide feedback.<br>• Industry/AM Providers: Integration of sensors into commercial equipment.<br>• Academia: Fundamental sensor development and equipment integration.<br>• Standards Committees: Define/recommend part quality.<br>• Government: Define requirements for certification and qualification. | High — Improves Product Quality: Verifying quality, six-sigma improved reproducibility<br>Medium — Reduces Costs: Less material waste, higher equipment cost<br>Medium — Accelerates Innovation: Reduces time to validate material properties for new products<br>High — Enhances competitiveness: Part quality in-line with conventional manufacturing<br>High — Reduces Time to Develop Products: Reduced part testing<br>Other: N/A |

## FIGURE 4-3. ROADMAP ACTION PLAN: *IN SITU* CONTROL AND MODEL INTEGRATION

**MAJOR BARRIER:** There is a lack of multivariate modeling that can account for material and process variability in real time. *In situ* measurement is lacking but necessary to inform those models. Models and measurements can be integrated to drive closed loop control.

**APPROACH:** The objective is to reduce waste, improve quality, and have greater real-time control of finished parts through better understanding and sensing of controllable parameters. The approach is to identify the measurable and controllable process parameters that make an impact on or influence the properties of final desired product. Next-generation non-linear control algorithms are needed to make process adjustments based on the complex, coupled physical-chemical interactions at relevant processing speeds.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Understand the relevant process parameters that have significant impact on finished material properties<br>• Identify the strongly coupled physical-chemical interaction | • Inventory of controllable parameters with highest variance<br>• Determination of speed-accuracy-property relationships | • Reduce waste (failed prints)<br>• Improved quality (precision and accuracy) across technologies<br>• Intelligent decisions on speed-accuracy-property trade-offs<br>• Realization of voxel-level control of material properties<br>• Measurement, analysis, and control techniques |
| MID (3-5 YRS) | • Identify relevant sensors/transducers for measuring significant physical-chemical interactions<br>• Identify appropriate validation tools<br>• Test and validate process models<br>• Incorporation of empirical process variable-property control | • Integration of relevant sensors into process<br>• Dissemination of signal/sensor validation<br>• Proof-of-concept of empirical process control | |
| LONG (>5 YRS) | • Integrate process models and *in situ* sensors into control scheme for validation across technology platforms<br>• Iterating printing technology based on model-driven process control | • Completion of validation and demonstration experiments | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS | |
|---|---|---|
| • Industry/AM Users: Provide input on needs, problems, and current technologies.<br>• Industry/AM Providers: Provide tool solutions, capabilities.<br>• Academia: Develop and validate process models through theory and experiment.<br>• Standards Committees: Develop software standards and certification processes.<br>• Government: Validate sensor capabilities, maintain model database. | High | Improves Product Quality: Improved precision and accuracy in shape and composition |
| | High | Reduces Costs: Reduction of waste/failed prints |
| | High | Accelerates Innovation: Ability for increased complexity |
| | High | Enhances competitiveness: Enables production of qualified parts |
| | High | Reduces Time to Develop Products: Reduced iteration time |
| | High | Other: Increased workforce effectiveness and development |

## Figure 4-4. Roadmap Action Plan: Big Data Analytics for AM

**Major Barrier:** There is a lack of fast and accurate big data analytics methods for *in situ* measurement data and physics-based model predictions.

**Approach:** New methods must be developed for analyzing big data sets from *in situ* measurement. This will enable better quality control and ability to optimize processing parameters. Measurement data can be combined with process model predictions to generate robust quality measures. The approach is to catalogue current big data methods, translate/refine for AM applications, then establish a repository for open source AM big data software.

<table>
<tr><th>Time</th><th>Roadmap Action Plan</th><th>Milestones</th><th>Performance Targets</th></tr>
<tr><td>Near (1-2 yrs)</td><td>• Review of state-of-the-art big data analytics methods applicable to in situ AM measurements<br>• Generate big AM in situ measurement data from optical thermal images, make them an open source database<br>• Initial development of big data analytics methods for AM quality measure</td><td>• Established repository for data sets from in situ measurement</td><td rowspan="3">• Real-time conversion of in situ measurements of quality<br>• Enable process enhancement through validated process models and in situ measurements<br>• Certify quality of AM parts with in situ measurements</td></tr>
<tr><td>Mid (3-5 yrs)</td><td>• Refine the development of big data analytics methods for AM quality measure<br>• Define the desired output of physics-based models based on in situ measurement capabilities<br>• Establish open source software repository of developed big data analytics methods</td><td>• Established repository for open source AM big data analytics software<br>• Demonstration of open source AM big data analytics software for part quality measure</td></tr>
<tr><td>Long (>5 yrs)</td><td>• Benchmark different developed big data analytics methods and software<br>• Validate the model predictions with in situ measurement data for AM part qualification<br>• Expand the big data analytics methods for new in situ measurement data, such as chemical, x-ray, etc.</td><td>• Fully validated and expandable open source AM big data analytics software for part quality measure</td></tr>
</table>

| Stakeholders & Potential Roles | Relative Impacts |
|---|---|
| • Industry/AM Users: Provides input on quality requirements, problems, and test cases.<br>• Industry/AM Providers: Provide tool solutions, software.<br>• Academia: Develop process models, big data analytics algorithm, conduct data analysis.<br>• Standards Committees: Develop software standards.<br>• Government: Establish repository for data sharing and open source software. | High — Improves Product Quality: Produce defect free parts<br>Medium — Reduces Costs: Increase yield<br>Medium — Accelerates Innovation: Enable process improvement<br>High — Enhances competitiveness: Improve quality: reduce cost<br>Low — Reduces Time to Develop Products: Not much impact<br>Other: N/A |

# Chapter 5: Performance

## Overview of the Topic Area

The viability of PB AM technologies will ultimately depend on the ability of the technologies to produce parts that meet their end use requirements. This will require PB AM parts to meet, or exceed, the performance of conventionally manufactured products.  Thus, part performance is where all aspects of PB AM—materials, printer technology, processes, and post-processing—come together.

Output repeatability and part durability are important elements of PB AM performance. In order to achieve high levels of reproducibility, qualification and certification processes for each element of PB AM technology (i.e., materials, equipment, processes, performance) need to be developed. The development of 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 PB AM data.

## Future/Desired Capabilities

Parts produced using PB AM technologies will need to meet product performance expectations of end users. The desired performance capabilities and expectations are described briefly below and listed in Table 5-1.

***Reliability/Repeatability***

When it comes to PB AM part performance, the reliability and repeatability of produced parts is very important. There also needs to be reduced variance in the material properties of the printed parts. To produce such consistently high-quality parts, PB AM printers themselves must become more reliable and have better tolerances, and used material feedstocks need to be more consistent and better controlled. The mechanical properties of produced parts must be equivalent or superior to traditionally manufactured parts.

***Product Lifetime***

Parts produced must not only be of high quality, but they also need to provide reliable functionality over an extended time-period. The expected product lifetime and required level of performance over that time-period varies greatly depending on the application.

***Post-Processing***

In many PB AM technologies, post-processing steps, such as removal of support material and surface finishing, are used to produce high quality parts. For many products, there is also a need to conduct testing of the finished parts and establish traceability for used materials and process parameters. To ensure that PB AM technologies will be economically viable, it is important to reduce these post-processing costs and time needed for those steps.

***Material/Part Design and Functionality***

As PB AM technologies are used for an increasing number of applications, there is a need to be able to produce more complicated parts consisting of multiple materials. Some of the parts will also need to be multifunctional, where each component of a part performs a different role to achieve synergistic goals. To produce such complex parts, printing methods that use multiple materials in one build need to be developed. Adequate material libraries and catalogues are also needed.

### *Product Characteristics*

Characteristics of parts that are produced with PB AM techniques need to meet the expectations of the market. For example, printed materials and surfaces are expected to be void-free and their mechanical properties must, at a minimum, be equivalent to injection molding. Flexibility will continue to be a distinct advantage of AM, as capabilities to produce parts with tailored properties for specific applications will be further enhanced.

### *Medical Applications*

The medical market is an area where PB AM technologies show significant future growth potential. The potential to efficiently and quickly produce customized and unique parts and devices is particularly important for medical applications. In many cases, medical parts and devices must meet very stringent criteria for accuracy, performance, and safety. Issues such as biocompatibility are of utmost importance in this market.

| Table 5-1. Desired Capabilities for PB AM Performance |
| --- |
| **Reliability/Repeatability** |
| • Reliable/repeatable, better tolerances on printers<br>• System output repeatability; reliability of the end product<br>• Reduced variance in material properties (as printed)<br>• Consistent or controlled feedstock for machines<br>• Predictive properties of final parts based on input process/material parameters; improvement in predictability/repeatability of "as built" parts<br>• Full bonding across layers – equivalent properties in all directions<br>• Mechanical properties equivalent or superior to those traditionally manufactured<br>• Ideal mechanical properties (e.g., modulus, failure mode) – based on the intended application<br>• Performance tied to version of the process (e.g., lot number) |
| **Product Lifetime** |
| • Reliability of functionality over an extended period<br>• Maintenance of initial properties over time vs. changing properties (e.g., degradation kinetics)<br>• Chemical reactivity, including intentional degradation capability (e.g. biodegradation)<br>• Chemical stability: 10 years; human implant; 50 years |
| **Post-Processing** |
| • Reduced post processing time/cost<br>• Finished part Particle Generation Test Method<br>• Electronic pedigree traceability (from model-based definition to inspection) |
| **Material/Part Design and Functionality** |
| • Designer multi-functional parts through print design and multiple materials<br>• Multifunctional – composites with each component performing different roles to achieve synergistic effects<br>• Validation of the usefulness of composite lamination theory (CLT) in modeling polymers extrusion (FDM) structures<br>• Design tailor-ability towards lightweight structures<br>• Printing with multiple materials in one "build"<br>• Expanded "library" of materials |
| **Product Characteristics** |
| • Void free (reliable surface characteristics)<br>• Silicone-like material to color (prostheses, simulation)<br>• Mechanical properties equivalent to injection molding<br>• Tailored properties for applications (e.g., patient-specific, geometry, property topography, etc.)<br>• Fatigue criteria for polymers extrusion (FDM) printed polymers (considering current standards) |

| Medical Applications |
| --- |
| • Performance tied to large validation data sets: pictures, videos<br>• Speed with accuracy for medical products<br>• Analysis of surface porosity for medical devices (e.g., to enable cleaning)<br>• Application-dependent performance requirements for biomedical (biocompatible, biodegradable)<br>• Analytical methods to verify biocompatibility<br>• Application-dependent performance requirements – bio-printed organs (*in vitro* diagnostics, research purposes, actual implants) |

## TECHNOLOGICAL & MEASUREMENT/STANDARDS CHALLENGES

The barriers and challenges currently impeding enhancements in the performance of PB AM technologies and parts are presented in Table 5-2, categorized by common themes. In each category, specific barriers or challenges are prioritized based on expert and stakeholder input.

One of the most significant challenges to be overcome is the lack of fundamental understanding of PB AM processes. Research is needed to understand complex non-equilibrium systems, interfacial layer-by-layer adhesion of AM materials, and the process changes and other factors that have significant impact on variance. Once the science of PB AM is better understood, enhanced process models can be developed. Accurate and validated process models, in turn, will result in better PB AM technologies and high-performing parts.

Standards development is another priority area where further work is needed to help ensure consistency in performance. Developing standards for feedstock materials and tolerances is particularly important. In addition, adequate safety standards for PB AM processes, and manufacturing facilities, are needed. Addressing potential safety concerns will help support acceptance and the future growth of this emerging industry.

**Table 5-2. Barriers and Challenges for PB AM Performance**

| | |
| --- | --- |
| **Fundamental Understanding of PB AM Processes** | |
| *High Priority* | • Lack of understanding and (and subsequently performance modeling) of PB AM processes<br>• Poor interfacial adhesion – layer by layer – how does understanding of bulk materials translate to AM process?<br>• Lack of focus on how fundamental science fields are juxtaposed in a complex, non-equilibrium system |
| **Inspection and Certification** | |
| *Medium Priority* | • Lack of accepted/validated inspection methods to detect voids<br>• Certification and inspect-ability (e.g., complete geometries)<br>• Burdensome testing to verify cleaning/biocompatibility |
| **Stock Materials and Standards** | |
| *High Priority* | • Lack of standards for feedstock materials tolerances |
| *Medium Priority* | • Undisclosed material composition<br>• Lack of nomenclature for polymers |
| *Low Priority* | • High sensitivity to material/molecular weight/polydispersity changes |
| **Variable/Parameter Impacts on Part Properties** | |
| *High Priority* | • High sensitivity to small process changes<br>• Designing experiments to identify significant variables and those with high impacts on variance |
| *Medium Priority* | • Black boxing of parameters and profile setting<br>• Understanding/identifying critical variables for process control<br>• Understanding how material properties are altered as a result of printing |

**Table 5-2. Barriers and Challenges for PB AM Performance**

| | |
|---|---|
| **Transparency in PB AM** | |
| *Medium Priority* | • Closed ecosystems (e.g., narrowly designed machines)<br>• Lack of choice of machine vendors<br>• Minimal/limited stated performance requirements for a given application: materials, design, medical |
| **Safety Standards** | |
| *High Priority* | • Lack of/insufficient safety standards (facility standards – none are federally recognized) |

## ROADMAP FOR PRIORITY R&D

A roadmap action plan was developed to enumerate the activities and approaches for overcoming the most critical barriers identified in Table 5-2. Roadmaps action plans are outlined in more detail in Figures 5-1 through 5-5. 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 PB AM Performance**

| High-Priority Challenge/Barrier | Priority Roadmap Topic |
|---|---|
| Lack of standards for feedstock material tolerances. | Information on Stock Materials and Standards for Polymer Formulation and Tolerances (Figure 5-1)<br>The standardization needs of stakeholders are identified, information gathered to formulate standards, and predictive models and design tools developed. |
| Lack of transparency in PB AM and related sciences. | Increasing Transparency in PB Materials and Processing (Figure 5-2)<br>Gaps in industry transparency need to be assessed, needed standards developed, and results disseminated. |
| Limited understanding of the full set of parameters and variables impacting the properties of the finished part. | Critical Control Parameters, Variables, Measurements, and Concepts for PB AM (Figure 5-3)<br>Critical process variables need to be identified, measurements developed, impact on final product properties understood, and control mechanisms developed. |
| Lack of understanding and modeling of PB AM processes, where many types of fundamental science fields are juxtaposed in a complex, non-equilibrium system. | Knowledge and Data to Improve Performance Modeling of PB AM Processes (Figure 5-4)<br>Critical gaps in existing materials and process knowledge need to be identified, research efforts directed to address identified gaps, and infrastructure and framework for sharing information established. |
| Details about polymer powder volatiles, dust and other emissions are unknown; potential health impacts and other risks from the emissions are not understood. | Environmental, Health and Safety Factors for Polymer AM Materials (Figure 5-5)<br>Methods to quantify fugitive polymer particles need to be developed, risks related to the emissions understood, and acceptable emission levels and mitigating technologies identified. |

## FIGURE 5-1. ROADMAP ACTION PLAN: INFORMATION ON STOCK MATERIALS AND STANDARDS FOR POLYMER FORMULATION AND TOLERANCES

**MAJOR BARRIER:** Multiple instances of material formulation and processing (e.g., raw materials, polymer formulation, feedstock to AM equipment, and post printing processing) limit understanding and clarification of composition and properties. It is unclear what the appropriate level of material composition and properties specifications are at these various levels of material integration.

**APPROACH:** The objective is to establish a framework (standards, data, tools) needed to support availability of stock polymer materials for AM. The approach is to identify the needs of stakeholders for standardization, gather information to formulate standards, and develop predictive models and design tools.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Determine when it is appropriate to identify feedstock material composition<br>• Identify appropriate mechanisms to understand stakeholder concerns about raw materials | • Stakeholders convened to discuss raw material concerns<br>• Identification of attainable consensus standards topics | • Materials properties and composition specifics at appropriate levels needed for formulation and processing<br>• Usable and accessible predictive models and design tools that cover full range from raw materials to formulation and integrate with AM equipment and processing |
| MID (3-5 YRS) | • Determine how to use information obtained from stakeholders to develop a framework for standards<br>• Identify application areas, the environment in which part is used, and expectation on its useful lifetime<br>• Work with stakeholders to determine appropriate material composition information and material properties | • Materials standards<br>• Information gathered for framework development (key applications, data and materials information required) | |
| LONG (>5 YRS) | • Use modeling to design AM parts based on knowledge of material composition | • Design tool for material composition selection to achieve performance standards | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • **Industry/AM Users:** Input on material uses and concerns<br>• **Industry/AM Providers:** Input on material properties and formulations where possible<br>• **Standards Committees:** Input to standards development<br>• **Government:** N/A | High — **Improves Product Quality:** Validated modeling tool for selection of material composition would decrease number of development cycles, leading to accelerated innovation, faster product cycles and subsequently achieving cost reductions<br>Medium — **Reduces Costs:** N/A<br>High — **Accelerates Innovation:** N/A<br>Medium — **Enhances Competitiveness:** N/A<br>High — **Reduces Time to Develop Products:** N/A<br>**Other:** N/A |

## Figure 5-2. Roadmap Action Plan: Increasing Transparency in PB Materials and Processing

**Major Barrier:** There is a general lack of transparency in polymer-based AM and related science, ranging from raw materials composition to formulation, processing, equipment, and finished parts and quality. Materials and products are often seen as a 'black box' without sufficient understanding of fundamental science.

**Approach:** There is a need to improve the transparency of materials and processing to enable better design and performance of PB AM parts. This effort will assess the gaps in industry transparency by using a systems approach to analyze projects and refine standards. The approach will include gathering sufficient information from stakeholders to develop, prove and disseminate results via publication of standards.

| Time | Roadmap Action Plan | Milestones | Performance Targets |
|---|---|---|---|
| Near (1-2 yrs) | • Conduct gap analysis of transparency in basic polymer science in AM | • 1 year - develop survey, forum or meeting to address the basic science needs of polymer AM<br>• 1 year-18 months – Identify correct stakeholders and owners: government, academia and industry<br>• 18-24 months – Formalize gap analysis document and disseminate | • Ability to move from a known scientific state to an unknown scientific state in the science of polymer AM technologies – per type of PB AM technology (FDM, SLS, etc.) |
| Mid (3-5 yrs) | • Document the process science of advancing from a known state to an unknown (in a specific PB AM technology) | For each technology<br>• Material – Subset of standard materials<br>• Hardware – References program<br>• Software – References program | |
| Long (>5 yrs) | • Conduct system analysis of a range of projects | • Implementation of testing at multiple sites<br>• Verification of results and publication into standard(s) | |

| Stakeholders & Potential Roles | Relative Impacts |
|---|---|
| • **Industry/AM Users:** Year 1 survey of industry.<br>• **Industry/AM Providers:** Drive gap analysis, offer insight into documentation, focus on known to unknown paths.<br>• **Academia:** Test process controls (3-5+ years).<br>• **Standards Committees:** Compile results and formalize document.<br>• **Government:** Decree standards, hold industry certifications/regulations. | High — **Improves Product Quality:** Falls into manufacturing and associated QA science<br>Med/High — **Reduces Costs:** Can lower the cost in the long run<br>High — **Accelerates Innovation:** Lets academia document base science, which can then translate into innovation.<br>High — **Enhances competitiveness:** Lets any supplier or OEM or channels enter the market.<br>High — **Reduces Time to Develop Products:** Product is no longer starting from the First Principles.<br>High — **Other:** Education across the community of interest. |

## Figure 5-3. Roadmap Action Plan: Critical Control Parameters, Variables, Measurements, and Concepts for PB AM

**Major Barrier:** Limited understanding of the full sets of parameters and variables impacting the ultimate part properties creates uncertainties in part performance and quality and impacts the ability to effectively control the process.

**Approach:** The approach includes four components: 1) identify critical variables in manufacturing process; 2) develop (or modify existing) measurements that provide full history of each critical variable through the building of the printing process; 3) understand how changes in these variables impact desired final part properties; and 4) active control to maintain critical variables with an acceptable window for all properties.

| Time | Roadmap Action Plan | Milestones | Performance Targets |
|---|---|---|---|
| Near (1-2 yrs) | • Conduct inventory of software, tools, materials and existing measurements across all AM platforms<br>• Define all parameters that are changing during build process<br>• Determine how to measure and control/influence the defined variables | • Clear inventory of what is measured by platforms<br>• Expanded inventory to include newly identified parameters<br>• Identification of technical gaps between current measurements and parameters that impact part properties | • Reduction in quality deviation<br>• Reliable parts quality<br>• Improved *in situ* measurement<br>• Improved active control of process<br>• Standardized measurements to control the printing process |
| Mid (3-5 yrs) | • Down-select appropriate control methods<br>• Test controls that are defined for variables<br>• Confirm/identify any remaining variables | • Proof of concept of controls on build variables<br>• Reduced variability of part quality through control of identified parameters | |
| Long (>5 yrs) | • Integrate controls on a representative set of machines<br>• Define variables that are a result of machine inconsistency and method to control | • Method to apply controls and adjustments for machine variability by platforms | |

| Stakeholders & Potential Roles | Relative Impacts |
|---|---|
| • Industry/AM Users: Provide input on needs, problems and current state; conduct demos/pilots.<br>• Industry/AM Providers: Provide tool solutions and integrated solutions.<br>• Academia: Develop measurement control algorithms and conduct data analysis.<br>• Standards Committees: Develop measurement standards, certification of process.<br>• Government: Maintain repository, and develop/test correlations between advanced measurements and those more applicable to *in situ* control. | High — Improves Product Quality: N/A<br>Medium — Reduces Costs: N/A<br>High — Accelerates Innovation: N/A<br>High — Enhances competitiveness: N/A<br>Low — Reduces Time to Develop Products: N/A<br>Other: N/A |

## Figure 5-4. Roadmap Action Plan: Knowledge and Data to Support Better Modeling of PB AM Processes

**Major Barrier:** Understanding and modeling AM processes, where many types of fundamental science fields are juxtaposed in a complex, non-equilibrium system, represents a difficult challenge.

**Approach:** The objective is to improve performance (predictability, repeatability, etc.) through a better understanding of the fundamental and applied science behind PB AM. The approach will assess existing research knowledge to determine the gaps in materials, process parameters, printing methods, and other factors that influence printed part quality and performance.

| Time | Roadmap Action Plan | Milestones | Performance Targets |
|---|---|---|---|
| Near (1-2 yrs) | • Engage community of users, researchers, manufacturers (materials and equipment) to truly identify field/refine understanding of field that needs to be surveyed for gaps<br>• Conduct survey of above-mentioned field to identify gaps<br>• Create infrastructure/framework for public sharing of fundamental material properties (rheology, thermal, surface, etc.) | • Development of a series of recommendations/justifications for investment in the fundamental science which is indispensable for broader application of polymer AM<br>• Establishment of database for properties, processes, etc. | • Predictability, repeatability, quality and inspect-ability of printed products<br>• Enhanced education/ communication/collaboration of community, i.e., via international standards |
| Mid (3-5 yrs) | • Establish working groups to explore the impact of fundamental science as it pertains to method, material, application, etc.<br>• Develop *in situ* meta-analytical tools to: systemically correlate process and fundamental properties with product; auto-archive data; identify dominant process parameters, identify feedback loop needs | • Publish findings/reflections/ recommendations to reach wider community, which is usually commercially driven<br>• Be able to calibrate/correlate/design process based on desired product/properties<br>• Prototype of tools | |
| Long (>5 yrs) | • Demonstrate integrated measurement science techniques in hardware/software systems<br>• Create linking activity with design roadmap and modeling roadmap<br>• Ideally, these analytical tools should inform/influence/drive the design tools | • Prediction of properties in printed parts (so that eventually, predictability starts at the design phase)<br>o creation of software that would allow robust, feasible design flexibility | |

| Stakeholders & Potential Roles | Relative Impacts |
|---|---|
| • Industry/AM Users: Identify needs, provide support, perform applied research.<br>• Industry/AM Providers: Link users and researchers, including applied researchers.<br>• Academia: Conduct fundamental research, identify knowledge gaps.<br>• Standards Committees: Establish best practices.<br>• Government: Facilitate conversations/collaborations, provide support, perform basic research. | High — Improves Product Quality: N/A<br>Low/High — Reduces Costs: Research costs, but eventually people will benefit; cannot achieve this now.<br>High — Accelerates Innovation: N/A<br>Medium — Enhances competitiveness: Depends on adoption of ideas/collaboration<br>Medium — Reduces Time to Develop Products: Not until analytical tools are integrated with design.<br>High — Other: Without the fundamental science, AM will not grow quickly. |

## FIGURE 5-5. ROADMAP ACTION PLAN: ENVIRONMENTAL, HEALTH AND SAFETY FACTORS FOR POLYMER AM MATERIALS

**MAJOR BARRIER:** The amount, size, distance, etc. of powder, volatiles, dust, etc. within and escaping from current polymer AM machines is not known.

**APPROACH:** Methods and technologies are needed to quantify 'fugitive' polymer particles and set levels (acceptable levels to which safety standards could be written). The approach will assess existing quantification technology, current/potential risks, identify needed technologies for mitigation, and provide input for future standards and regulations.

| TIME | ROADMAP ACTION PLAN | MILESTONES | PERFORMANCE TARGETS |
|---|---|---|---|
| NEAR (1-2 YRS) | • Identify current/potential risks (health, fire, explosion, etc.)<br>• Develop a "systems" approach to the integration and use of existing technologies<br>• Assess/validate existing "fugitive" polymer quantification technology | • Known "efficacy" of existing technologies<br>• Integration of existing technologies and "efficacy" of "systems" approach known<br>• Identification of any risks | • Safe, transparent, growing industry<br>• Issues addressed/resolve rather than holding back growth of future industry |
| MID (3-5 YRS) | • Research and develop new technologies<br>• Further mitigation of technologies through collaborations (OEMs, supplies, industry, government)<br>• Evaluate effect of cross contamination between machines (of different processes) | • New technologies developed/ tested and deployed<br>• Partnerships established (e.g.,. user groups) working together<br>• Effects known and better understood | |
| LONG (>5 YRS) | • Develop regulations and standards as needed<br>• Enforce as needed | • Regulations and standards that help propel growing AM industry<br>• Unsafe practices stopped/eliminated and minimized | |

| STAKEHOLDERS & POTENTIAL ROLES | RELATIVE IMPACTS |
|---|---|
| • **Industry/AM Users:** Lead role with OEMs<br>• **Industry/AM Providers/Suppliers:** Lead role in understanding how what they supply contributes to risks.<br>• **Academia:** Lead R&D role in "quantification" in all aspects as well as new preventative methods, maximum limits, etc.<br>• **Standards Committees:** Create of standards.<br>• **Government:** Enforce, regulate standards. | Medium **Improves Product Quality:** Eliminates cross contamination<br>Low **Reduces Costs:** Not likely<br>High **Accelerates Innovation:** Won't seem like it at first but over longer term<br>High **Enhances competitiveness:** Safe/transparent<br>**Reduces Time to Develop Products:** N/A<br>High **Other:** Safety – less/mitigation of EH&S impacts |

# Chapter 6: Cross-cutting Challenges

A number of technical and non-technical challenges were identified that cut across materials characterization, process modeling, *in situ* measurements, and performance. These are described below.

- ***Multi-disciplinary collaboration*** – Establishing a better programmatic structure to support multi-disciplinary collaboration was identified as a high priority. A variety of scientific and engineering disciplines are needed to accelerate advances, from computer science to mathematics, chemistry, physics, engineering, and the manufacturing sciences.
- ***Business models*** – A good business case and economic models are lacking for PB AM in general and this was identified as a priority to address. These would help to promote more widespread acceptance. Models are needed to demonstrate that AM is good, fast, and cheap – and comparable to conventional technologies.
- ***Infrastructural issues*** – Challenges to maintaining a 30 % CAGR (compound annual growth rate), including balancing infrastructure requirements, materials, and how to best utilize. Predictable IT infrastructure requirements need to be established to support AM industry growth overall.
- ***Life cycle and sustainability*** – Not enough is known about the life cycle of PB AM parts, particularly ability for recycle and reuse and aging. Ensuring sustainability via materials and processes is an objective but not attainable at present. There is a need to understand and predict value creation over a part's entire lifecycle, which requires understanding and characterization of materials and parts from cradle to grave. Recyclable and/or reusable materials for PB AM are also currently lacking.
- ***Printer and equipment variability*** – A universal challenge is the variability between printers and processing equipment. This issue is exacerbated by the 'black box' approach taken by equipment suppliers, i.e., there are many unknowns about equipment parameters, variability, and inner workings.
- ***Surpassing conventional manufacturing capabilities*** – The ability to surpass machining and other conventional parts processing techniques in 10 years is a challenge that should be met to ensure more widespread acceptance of polymer-based additive manufacturing.

# Appendix A: Agenda

| Thursday, June 9, 2016 | |
|---|---|
| 7:30 am | Registration |
| 8:30 am | Opening Plenary Session **Portrait Room**<br>Moderator: ZJ Pei, National Science Foundation<br>▶ **Welcome** ~ Mike Molnar, Advanced Manufacturing Program Office, NIST<br>▶ **Workshop Scope and Objectives** ~ Kalman Migler, NIST<br>▶ **Current Status of Polymers Roadmapping** ~ Rob Gorham, America Makes |
| 9:00 am | Panel Session: Characterization of Materials Throughout Their Lifecycle<br>Moderator: Mark Dadmun, University of Tennessee-Knoxville<br>▶ Matthew Di Prima, Food and Drug Administration<br>▶ Angel Yanguas-Gil, Argonne National Laboratory<br>▶ Abraham Joy, University of Akron |
| 10:15 am | *Break* |
| 10:30 am | Panel Session: Process Models<br>Moderator: Kalman Migler (NIST)<br>▶ Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC<br>▶ Peter Olmsted, Georgetown University<br>▶ David Roberson, University of Texas-El Paso |
| 11:45 am | *Lunch and Posters* **NIST Cafeteria** |
| 1:00 pm | Panel Session: *In situ* Processing Measurements **Portrait Room**<br>Moderator: Robert Maxwell, Lawrence Livermore National Laboratory<br>▶ Miriam Rafailovich, State University of New York at Stony Brook<br>▶ Jon Seppala, NIST<br>▶ Chris Williams, Virginia Tech |
| 2:15 pm | Instructions for Breakout Sessions<br>▶ Joan Pellegrino, Energetics Incorporated |
| 2:20 pm | *Move to breakout rooms* |
| 2:30 pm | Breakout Session I: Targets/Capabilities for Polymer-based Additive Manufacturing<br>*This round of concurrent breakout sessions will look at the envisioned future: desired capabilities, characteristics, and performance.*<br>*Topic* — *Room*<br>**Materials** — Heritage Room<br>**Process Modeling** — Portrait Room<br>***In situ* Measurements** — Lecture Room C<br>**Performance** — Lecture Room D |
| 3:15 pm | *Break* |

| | |
|---|---|
| 3:30 pm | Breakout Session II: Challenges and Barriers to Achieving Targets/Goals<br>*Participants will return to their breakout session to consider barriers limiting the broad use of polymer-based additive manufacturing and measurement and standards barriers, challenges, and gaps, and identify priority topic areas for the measurement roadmap.* |
| 5:00 pm | Adjourn Day 1 |
| **Friday, June 10, 2016** | |
| 8:00 am | Early Networking |
| 8:30 am | Welcome and Recap of Day 1<br>**Portrait Room** |
| 8:40 am | Panel Session: Performance<br>Moderator: Greg Kittlesen, FDA<br>▶ Courtney Fox, Carbon<br>▶ Bryan Vogt, University of Akron<br>▶ Gerald Grant, University of Louisville |
| 10:00 am | *Break and Move to Breakouts* |
| 10:15 am | Breakout Session III: Pathways for Measurement Science Roadmap<br>*Participants will return to their breakout session and review and clarify top challenges and potential roadmap topics. After consensus on priority topics, small groups will work together to develop priority roadmap action plans and next steps, which will be presented in the afternoon plenary.* |
| 11:45 pm | *Lunch and Posters*<br>**NIST Cafeteria** |
| 1:15 pm | Panel Session: Integration and Standards<br>**Portrait Room**<br>Moderator: Carl Dekker, Met-L-Flo<br>▶ Scott Fish, University of Texas<br>▶ Praveen Tummala, 3DSystems<br>▶ Lyle Levine, NIST |
| 2:15 pm | Breakout Group Reports |
| 2:45 pm | Workshop Wrap-up and Next Steps |
| 3:00 pm | Workshop Adjourns |

# APPENDIX B: PARTICIPANTS

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# APPENDIX C: ACRONYMS/ABBREVIATIONS

| | |
|---|---|
| 3D | three dimensional |
| AM | additive manufacturing |
| ASTM | American Society for Testing and Materials |
| BAAM | big area additive manufacturing |
| CAD | computer aided design |
| COTS | commercial off-the-shelf |
| DOE | design of experiments, Department of Energy |
| EHS | Environment, Health and Safety |
| FAA | Federal Aviation Administration |
| FDA | Food and Drug Administration |
| FDM | fusion deposition modeling, used synonymously in this report with FFF and polymers extrusion |
| FFF | fused filament fabrication |
| HIP | hot isostatic pressing |
| HPC | high performance computing |
| ICME | integrated computational materials engineering |
| IR | infrared |
| ISO | International Organization for Standardization |
| LLNL | Lawrence Livermore National Laboratory |
| NSF | National Science Foundation |
| NAMII | National Additive Manufacturing Innovation Institute |
| NIST | National Institute of Standards and Technology |
| OEM | Original Equipment Manufacturer |
| ONR | Office of Naval Research |
| PB | Polymer-based |
| PSP | process structural properties |
| QA | quality assurance |
| QC | quality control |
| R&D | research and development |
| RFID | radio frequency identification |
| RM | rapid manufacturing |
| ROI | return-on-investment |
| SLA | stereolithography |
| SLS | selective laser sintering |
| STEM | science, technology, engineering, and mathematics |