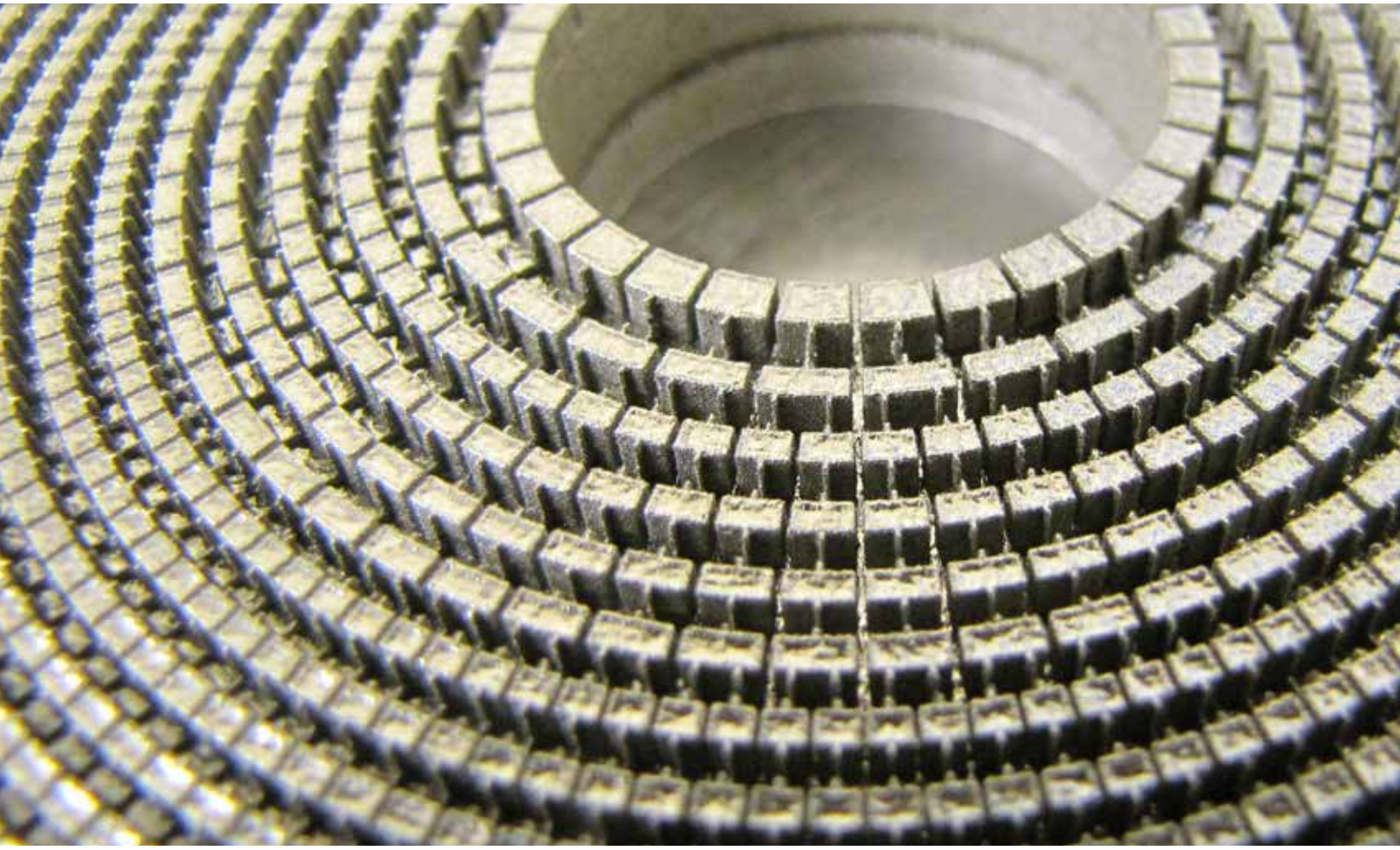
CAMM Consortium for Additive Manufacturing Materials

# Strategic Roadmap for the Next Generation of Additive Manufacturing Materials



Prepared by:

PennState CIMP-3D

NEXIGHT GROUP

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# About this Roadmap

Nearly 30 years since additive manufacturing (AM) processes were initially commercialized as an efficient and resourceful rapid prototyping method, AM technologies have evolved into an organized set of revolutionary approaches to product design and development for a variety of industrial sectors. While the AM market continues on a path of unprecedented growth, reaching $4.1 billion of revenues in 2014,[1] new innovations are required in order to propel this growing technology into new application areas. In particular, the AM industry must turn its attention toward expanding the presently stagnant collection of materials options with a brand new suite of optimized materials to shape the future of advanced manufacturing.

The Pennsylvania State University (PSU) saw the need for a materials-centric AM technology roadmap that offers a strategy focused on basic and fundamental-level research and development efforts to foster a new generation of materials for the broad AM industry. Funded by the National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology Consortia (AMTech) program, this roadmap draws upon the expertise of key stakeholders and subject matter experts from across the AM value chain to identify challenges and key activities that will expand the range of material options available to meet the growing needs of AM industry over the next 10 years.

This roadmap was developed under the direction of Todd Palmer, Senior Research Associate and Associate Professor of Materials Science and Engineering, PSU, and the technical leadership team of the Consortium for Additive Manufacturing Materials (CAMM): Greg Dillon, Gary Messing, Tim Simpson, and Rich Martukanitz. Subject matter experts and other AM stakeholders who made essential contributions through phone interviews, workshop attendance, and roadmap reviews, are also identified in Appendix A of this report. Nexight Group supported the overall roadmapping process and prepared this roadmap; Jared Kosters, Ross Brindle, Greg Hildeman, Warren Hunt, and Lindsay Pack are the primary contributors.

[1]Wohlers Associates. April 11, 2015. "20 Years Later." http://wohlersassociates.com/blog/2015/04/20-years-later/ (accessed 8 June 2015).

# Table of Contents


Executive Summary ..... 1

Priority R&D Activities ..... 2
Path Forward ..... 3

Introduction to AM Materials, Processes, and Applications ..... 7

Metals ..... 7
Polymers ..... 7
Ceramics ..... 8
Multi-materials ..... 8
AM Processing Approaches ..... 8
AM Application Areas ..... 9

Strategy for AM Materials Development ..... 11

Materials Considered ..... 13

Thrust 1: Enabling Integrated Design Methodologies for Materials, Processes, and Parts ..... 15

Current Challenges ..... 15
Priority R&D Activities ..... 15

Thrust 2: Developing AM Process-Structure-Property Relationships ..... 23

Current Challenges ..... 23
Priority R&D Activities ..... 25

Thrust 3: Establishing Part and Feedstock Testing Protocols ..... 29

Current Challenges ..... 29
Priority R&D Activities ..... 31

Thrust 4: Building AM Process Analytics Capabilities ..... 35

Current Challenges ..... 35
Priority R&D Activities ..... 35

Thrust 5: Exploring Next-Generation AM Materials and Processes ..... 41

Current Challenges ..... 41
Priority R&D Activities ..... 42

Path Forward ..... 51

Appendix A. Roadmap Contributors ..... 53

Appendix B. Acronyms and Abbreviations ..... 55

# Executive Summary

Additive manufacturing (AM) is an innovative approach to product design and fabrication that promises to change the nature of advanced manufacturing. While many manufacturers are using AM to accelerate the product design process via rapid prototyping, AM processing technologies have become an increasingly competitive option for commercial product manufacturing of near-net shape components as well as component repair.

Yet, to date, most AM applications rely on existing materials for AM feedstocks, which have not been designed or optimized for AM processes. These materials originally were designed for conventional processing routes. Their widely accepted property values can only be obtained using these conventional pathways. However, the AM process allows for the development of unique microstructures that can lead to improved component properties and performance. To fulfill its promise to revolutionize manufacturing, the AM industry must focus on the development of new materials and feedstocks that are created with AM in mind to provide advanced material properties capable of meeting next-generation design requirements and product applications.

Despite a healthy market growth rate of 81% from 2012 to 2014[2] and a rapid evolution of AM processing equipment, the selection of available materials choices for AM of metals, ceramics, and polymers has remained unchanged. Many U.S. manufacturers are integrating cutting-edge materials fabricated using more conventional routes into traditionally manufactured products. Yet manufacturers that employ AM processing approaches remain severely constrained to a limited set of conventional material compositions because many new materials are not suited or optimized to AM processing. Even though process control advancements and novel part production strategies are allowing AM users to realize equivalent performance to conventionally fabricated materials, the community must now turn its attention toward developing new materials that are optimized for AM processing systems and tailored for specific applications in order to meet the next level of performance.

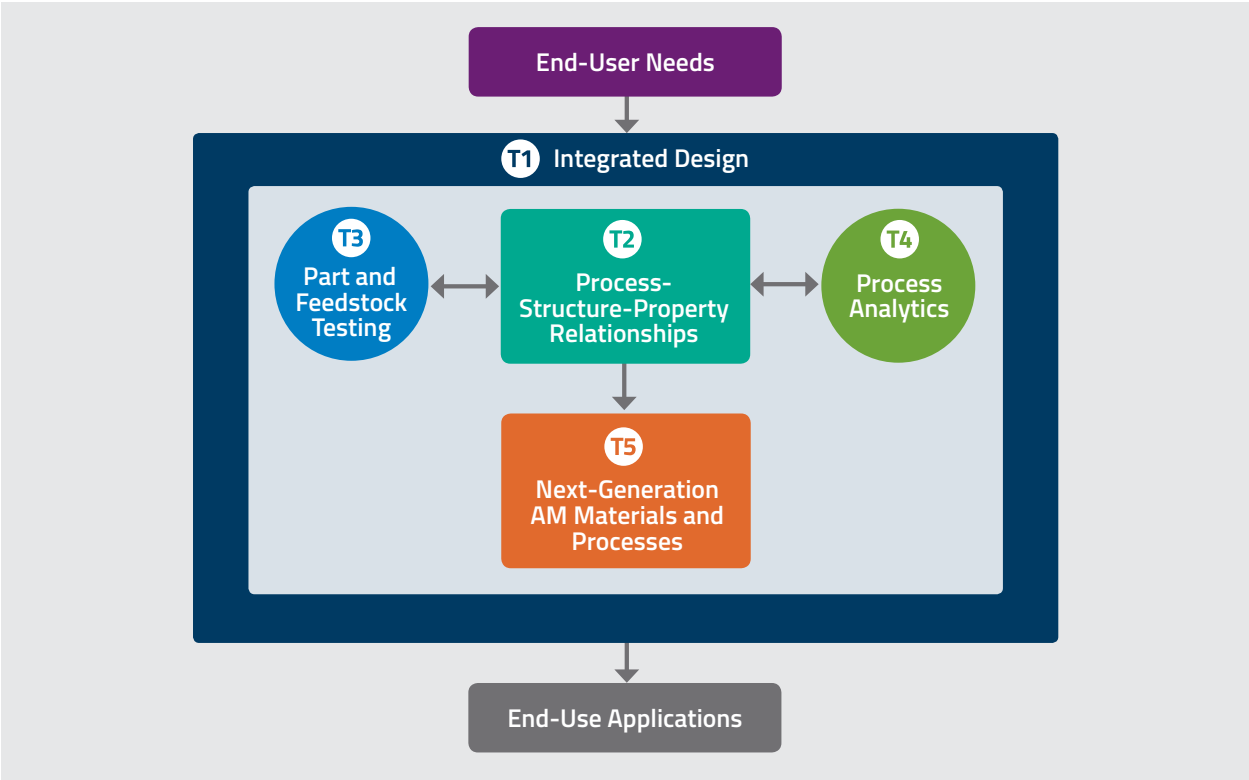
Although AM enables the fabrication of parts with complex shapes and intricate microstructural features that no other manufacturing processes are capable of producing, it is challenging for the AM community to introduce new materials into the field. While previous technology roadmaps have directed efforts toward the broad advancement of AM technologies, few have successfully addressed the challenges associated with expanding the range of materials to meet the future needs of the AM industry. Further, this roadmap is unique in its focus exclusively on fundamental research (technology readiness levels [TRL] 1–3), to promote the expansion and introduction of AM materials through the development of a strong knowledge base and key enabling technologies. For AM to empower users to create next-generation products, the AM community should embrace a materials-centric strategic approach to fundamental research and development activities aimed at accelerating the introduction of new materials optimized for AM processes.

## Roadmapping Strategy

This roadmap offers a strategy for building the fundamental knowledge needed to accelerate the design and application of new AM materials and feedstocks over the next ten years. To address the major barriers hindering materials innovation in the AM industry, this roadmap organizes research and activities into five strategic thrusts. The strategic thrusts depicted in Figure 1 represent distinct areas of fundamental research and development needed to design new AM materials and integrate them into part designs that meet end-user needs. The

[2] Wohlers Associates. April 11, 2015. "20 Years Later." http://wohlersassociates.com/blog/2015/04/20-years-later/ (accessed 8 June 2015).

Figure 1. AM Materials Development Strategic Thrust Overview




connections among the thrusts are essential. By highlighting the need for knowledge and information exchange among the thrusts, this roadmap recommends a highly integrated R&D effort that can accelerate new materials development and insertion.

## Priority R&D Activities

To make progress in each of the five R&D thrust areas, the AM community plans to focus its efforts on a series of near-, mid-, and long-term R&D activities over the next ten years, as outlined in Figure 2.

### T1 Enabling Integrated Design Methodologies for Materials, Processes, and Parts

Because the performance and quality of AM products are largely determined by feedstock material characteristics and processing conditions, AM processing variables and as-fabricated component features must be designed in tandem with the development of new AM materials. Accordingly, integrated design approaches are needed to enable designers to consider both materials and process parameters as variables that can be adjusted for optimum component design.

### T2 Developing AM Process-Structure-Property Relationships

The sophisticated nature of AM processing approaches carries an intrinsically large number of variables: processing conditions, materials composition, and feedstock characteristics, to name a few. Consequently, a robust understanding of the complex interplay among these variables is necessary for determining feasible manufacturing routes that demonstrate new AM materials in end-use applications.

### T3 Establishing Part and Feedstock Testing Protocols

Characterization techniques and test protocols are necessary for capturing key data such as microstructural features, AM part properties, and feedstock material characteristics. Because robust industrial AM testing standards are still evolving, rigorous procedures and methodologies are needed for extracting key test data, enabling valid comparisons across various AM platforms, and confirming sufficient degrees of repeatability and reliability in the development and fabrication of new AM materials.

### T4 Building AM Process Analytics Capabilities

Realizing the true performance potential of new AM materials requires careful control of processing conditions as part layers are fabricated during AM. Precise, calculated analysis and control of processing approaches are required to optimize the next generation of materials. Advanced sensors are also needed to provide the in-process data needed to analyze and control AM processing.

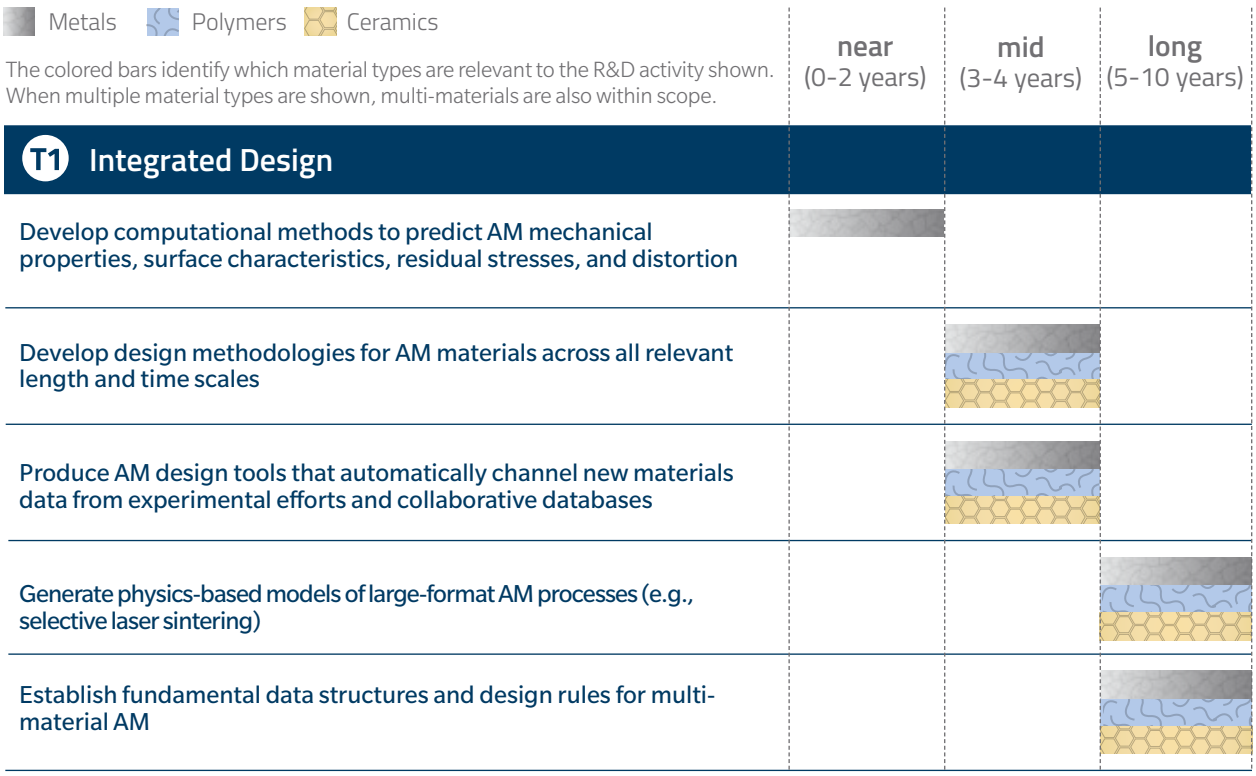
### T5 Exploring Next-Generation AM Materials and Processes

Revolutionizing AM technologies in the longer term requires an expanded set of materials options beyond incremental improvements in today's AM materials and processes. Next-generation materials designed to take full advantage of additive manufacturing and new AM processes developed to fully exploit the unique characteristics of new materials developed in novel ways will allow AM to realize its full potential to meet the end-user needs of tomorrow.

## Path Forward

Introducing new materials to the broad AM industry will drive rapid innovation and shape the future competitiveness of U.S. advanced manufacturing. Coupling focused fundamental materials research with AM's cornerstone advantage of accelerated product development through simultaneous design and manufacture will transform U.S. advanced manufacturing, helping to propel the nation into a new industrial revolution. The R&D activities identified in this roadmap will accelerate the design of new materials and encourage their widespread use by AM users in the next ten years. The Consortium for Additive Manufacturing Materials (CAMM) will undertake fundamental-level materials innovation and operate in tandem with America Makes and other entities across the AM value chain to develop and deploy new materials to the broader AM community. Implementing the research activities identified in this roadmap will lead to the proliferation of new materials to AM users and enhance the resilience of the U.S. manufacturing sector.

Figure 2. High-Priority R&D Activities

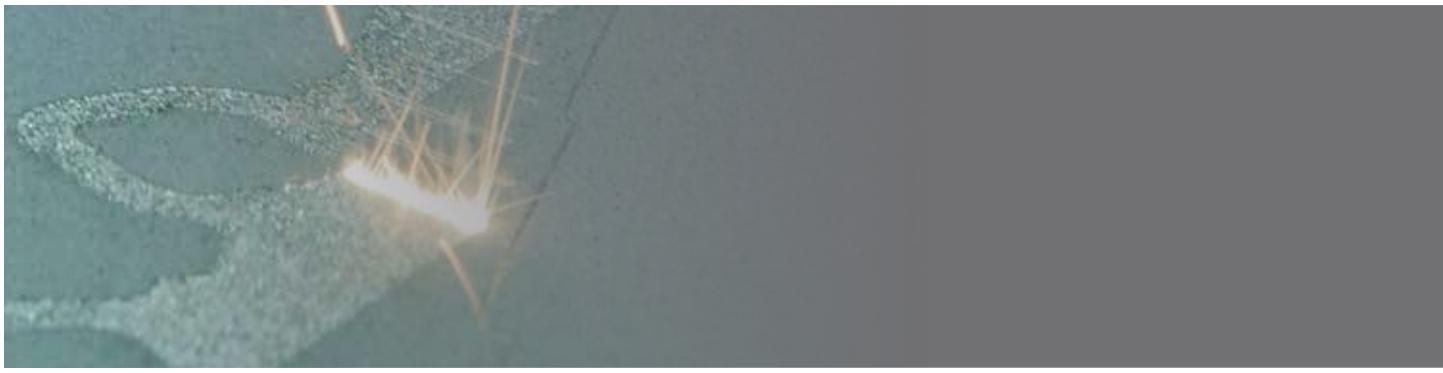


Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T2 Process-Structure-Property Relationships** | | | |
| Conduct AM materials "genome" initiatives that use computational approaches, data management, and an integrated approach to designing and engineering new materials | | | |
| Develop powder feedstock material relationships with AM part quality and performance | | | |
| Develop polymeric rheology and compatibility information for blended polymer processing | | | |
| Develop process-structure-property maps for new AM metals, polymers, and ceramics | | | |
| Characterize the compatibility of multi-material constituents at multiple length scales | | | |
| **T3 Part and Feedstock Testing** | | | |
| Establish rapid screening procedures for evaluating new AM feedstock materials | | | |
| Develop comprehensive part testing protocols for the localized measurement and characterization of AM part properties | | | |
| Investigate influence of atmospheric conditions on AM feedstock materials | | | |
| Evaluate the potential for reusing, refurbishing, and recycling powder feedstock materials | | | |
| Create laboratory-scale techniques for screening custom polymeric feedstock materials | | | |
| Introduce new techniques for characterizing the impact of feedstock material attributes on AM part quality | | | |
| Evaluate the potential for reusing, refurbishing, and recycling new multi-material powder feedstock combinations | | | |

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T4 Process Analytics** | | | |
| Identify and catalog feasibly controllable parameters of commercially available AM processes | | | |
| Conduct sensitivity analyses of AM processing parameters for fundamental materials data generation efforts | | | |
| Employ *in situ* sensors with feedback loop controls to ensure optimum steady-state processing conditions and reproducibility of AM products | | | |
| Capture accurate site-specific thermal history data of AM processes | | | |
| Develop strategies for dynamically and independently controlling AM part densification level and dimensional tolerance | | | |
| **T5 Next-Generation AM Materials and Processes** | | | |
| Develop ceramic slurry feedstock materials optimized for UV-based AM processes | | | |
| Design new multi-feed, multi-material AM feedstock delivery systems (e.g., printheads) | | | |
| Develop new AM process-compatible metal alloys that have superior mechanical or physical properties compared with alloys produced by conventional manufacturing processes | | | |
| Investigate AM processing techniques capable of printing all polymer resin grades | | | |
| Design new AM processing equipment that reduces the need for secondary processing operations | | | |
| Develop AM processing techniques capable of printing parts with low surface roughness values | | | |
| Establish AM processing techniques capable of controlling polymeric part architecture and crystallinity | | | |



# Introduction to AM Materials, Processes, and Applications

Today's AM community relies on a limited selection of conventional feedstock material choices for producing parts, functional prototypes, casting patterns, and repair solutions. Most of these feedstock materials suffer from high cost, low availability, and limited understanding and inadequate compatibility with current AM processing technologies. In spite of these shortcomings, AM stakeholders have recognized that the benefits of adopting AM solutions for manufacturing components will vastly outweigh the limitations of current material systems. These benefits include greater part complexities, tailored properties, unique functionalities, and potential for reduced costs.

A variety of commercially available machines are capable of processing metal-, polymer-, or ceramic-based material systems. New material developments —achievable through advancements to either AM processes or feedstock forms— will further extend the benefits of selecting an additive manufacturing processing route. Further, by combining the advantageous feedstock deposition capabilities of AM processes with the markedly different properties of these three material classes, the AM community is uniquely positioned to design a new generation of advanced composite multi-material systems. To expand the materials available to AM users, researchers must address the challenges and opportunities within and across each of these major material classifications.

## Metals

Most metal feedstock materials are produced in the form of fine spherical powders used primarily in powder bed fusion (PBF), and directed energy deposition (DED) AM processes. Compared with conventional manufacturing processes such as casting, AM processes yield high-density metal parts with similar and sometimes superior strength, hardness, and fatigue performance. This processing advantage is primarily attributed to the ability to modify the processing parameters to control the resulting structures, as defined by rate and direction of solidification, and create a wide range of unique, anisotropic microstructures that are otherwise difficult or impossible to manufacture by other means. Because porosity can be a major failure propagation mechanism in metal AM parts, as-fabricated AM components may require post-processing, such as hot isostatic pressing, to close pores for fatigue-sensitive components.

## Polymers

Polymer-based materials make up a large portion of the AM market. The two general classes of polymers are thermosets and thermoplastics. Thermosets are created during the AM process by an irreversible chemical reaction between resins and crosslinking agents to form networks of bonded molecular chains. In the case of photopolymer thermosets, monomers are polymerized into solid parts when exposed to ultraviolet (UV) light. Thermoplastics, such as polyamide (Nylon) and acrylonitrile butadiene styrene (ABS), are more commonly used in AM processes such as powder bed fusion and material extrusion. Unlike thermosets, thermoplastic polymers can be re-melted. Polymers can also be classified by molecular morphology, ranging from amorphous to crystalline. Polymer-based materials are available in a wide variety of compositions permitting the option to select from a variety of polymers based on a range of properties and functionalities, including strength, ductility, color, and biocompatibility.

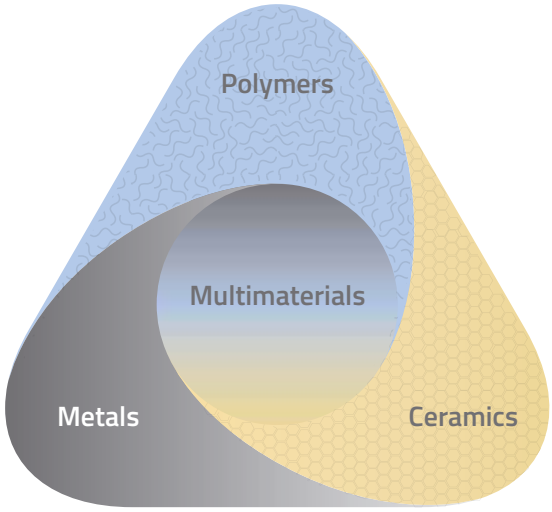
## Ceramics

Ceramic materials play a versatile role in a number of AM applications. Due to their inherently high melting temperatures and low thermal conductivities, pure ceramic powders cannot be processed using fusion-based AM processes. Instead, their thermal property characteristics are exploited by blending ceramics with sacrificial polymer binders that function as a support material during processing and are removed using a low-temperature treatment. These porous ceramic parts can be used in investment patterns for casting molten metals or they can undergo post-process infiltration techniques to create fully-dense parts. Ceramic powders can be combined with metals and polymers to produce composite material systems with unique combinations of properties. High-performance, high-tolerance composite parts have been fabricated by curing photopolymers containing homogeneously dispersed ceramic particles. The AM community has demonstrated that ceramic powders can be added to metal feedstock materials to change their overall fluidity or melting behavior, which may be useful for the development of novel AM materials.

## Multi-materials

A growing research and development topic in AM is the ability to additively manufacture components made of several different materials (e.g., metals, ceramics, and polymers). Unique aspects of AM, including the loose powder form of feedstock materials and the ability to deposit materials in successive layers, demonstrate that AM is an intrinsically suitable manufacturing method for fabricating complex combinations of materials. Pre-process feedstock blending and *in situ* alloying can already be used to formulate intricate AM parts from combinations of metal-metal, metal-ceramic, polymer-ceramic, and polymer-metal materials. The ability to blend different feedstock powders not only gives designers the freedom to customize materials that meet end-user requirements, but also offers the potential to vary the material composition during processing to fabricate high-performance, functionally-graded materials (FGMs). While multi-materials are currently produced in a rudimentary nature, the approach holds great promise for

Figure 3. Major Materials Classifications




delivering performance not currently possible. Manufacturing FGM parts with microstructural gradients exhibiting unique or tailored properties and functionalities represents a fundamentally new paradigm in the selection and design of advanced material systems.

## AM Processing Approaches

Compared with traditional manufacturing approaches, AM processes provide manufacturers with a greater degree of freedom in designing parts. While producing components with highly complex part geometries is one of its most distinguishable benefits, AM processing approaches can also be used to customize microstructural features of materials by varying the process input parameters that control melt pool characteristics, solidification rates, rheology, and feedstock deposition rates.

Two aspects of AM processes are most relevant for establishing fundamental process-structure-property relationships: the form of feedstock materials and the mechanism employed to successively bind or fuse layers of feedstock into solid parts. Designers of next-generation AM materials should consider the specific feedstock form and binding/fusing mechanism of AM processes, as well as the advantages that these processes can offer over traditional manufacturing

Figure 4. Key AM Processing Characteristics

| | | MATERIAL | | | BINDER OR FUSION MECHANISM | | | | | | | FEEDSTOCK FORM | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM PROCESS CATEGORY[1] | AM PROCESS TYPE | METALS | POLYMERS | CERAMICS | LASER BEAM | ELECTRON BEAM | PLASMA ARC | ULTRAVIOLET | LIQUID BINDING AGENT | ULTRASONIC | OTHER HEAT / POST-PROCESSING | POWDER | FILAMENT | RESIN | SHEET |
| Binder Jetting | --- | ● | ● | ● | | | | | ● | | ● | ● | | ● | |
| Directed Energy Deposition | Blown Powder | ● | ● | ● | ● | | | | | | ● | ● | | | |
| | Ion Fusion Formation | ● | | | | | ● | | | | ● | | ● | | |
| | Electron Beam Direct Manufacturing | ● | | | | ● | | | | | ● | | ● | | |
| Material Extrusion | Fused Deposition Modeling | | ● | | | | | | | | ● | | ● | | |
| | Multiphase Jet Solidification | ● | ● | ● | | | | | | | ● | ● | ● | | |
| Material Jetting | --- | | ● | | | | | ● | | | | | | ● | |
| Powder Bed Fusion | Laser Sintering | | ● | ● | ● | | | | | | ● | ● | | ● | |
| | Laser Melting | ● | | | ● | | | | | | ● | ● | | | |
| | Electron Beam Melting | ● | | | | ● | | | | | ● | ● | | | |
| Sheet Lamination | Laminated Object Manufacturing | ● | ● | ● | | | | | | | ● | ● | | | ● |
| | Ultrasonic Consolidation | ● | | | | | | | | ● | ● | | | | ● |
| Vat Photo-polymerization | --- | | ● | ● | | | | | ● | | ● | ● | | ● | |

approaches (see Figure 4 for a list of key AM processing characteristics for major AM processes).

## AM Application Areas

Additive manufacturing is poised to complement or displace conventional manufacturing approaches for the fabrication of components in a wide variety of technological applications. Today, the majority of applications still require traditional manufacturing approaches to manufacture products with a high degree of quality, performance, reliability, and repeatability, particularly where large-size parts or production volumes are required.

Despite its limitations, AM is gaining a strong competitive position in the manufacturing sector by delivering high-value products and services in application areas such as turbomachinery, rapid prototypes, medical devices, and repair applications. The expanded suite of material options envisioned by this roadmap will ensure that AM users continue providing innovative manufacturing solutions in these and other application areas.

[1]ASTM International, "Standard Terminology for Additive Manufacturing Technologies," ASTM Standard F2792-12a, 2012.

# Strategy for AM Materials Development

The strategy presented in this roadmap organizes the basic and fundamental (TRL 1–3) research and development activities into five strategic thrusts that address the major barriers hindering materials innovation in the AM industry. These thrusts enable an underlying fundamental knowledge base that will accelerate the design and application of new AM materials over the next ten years. Figure 5 portrays the interrelationships among each strategic thrust and the connection to end-user needs and applications.

As shown in Figure 5, the roadmap's strategy is driven by end-user needs and is designed to result in new and improved end-use applications for new AM materials. The strategic thrusts are:

- T1 **Integrated design**, which encompasses all other thrusts into design tools for new AM materials
- T2 **Process-structure-property relationships**, the cornerstone of material and process development
- T3 **Part and feedstock testing**, which is needed to build the data required to design new materials and predict performance
- T4 **Process analytics** to better understand and measure the effect of processes on AM materials
- T5 **Next-generation AM materials and processes**, which will result in major, longer-term advances in materials and process capabilities.

These thrusts are described in more detail in the sections that follow.

## T1 Enabling Integrated Design Methodologies for Materials, Processes, and Parts

Because the material and parts are created at the same time during AM processes, component design and analysis must become more fully integrated with materials selection to ensure as-fabricated components deliver the features and performance required. Accordingly, integrated design approaches are needed to enable designers to consider both materials and processing parameters as variables that can be adjusted for optimum component design.

This thrust primarily involves the use of predictive computational modeling and AM-specific design rules and leverages fundamental knowledge developed in the other strategic thrusts to design new AM materials and processes. The iteration of knowledge, experimentation, and simulation within integrated design approaches is crucial to accelerating the adoption of new and advanced materials for the AM industry.

## T2 Developing AM Process-Structure-Property Relationships

The sophisticated nature of AM processing approaches carries an intrinsically large number of variables, including processing conditions, materials composition, and feedstock characteristics. Consequently, a robust understanding of the complex interplay among these variables and others is necessary for determining feasible manufacturing routes that demonstrate the value of new AM materials in end-use applications.

Establishing strong process-structure-property relationships bridges the gap between process analytics and part testing of new AM materials. Materials designers will analyze cause-effect correlations in this strategic thrust to build fundamental knowledge of AM processing inputs and outputs that will help the AM community diagnose design issues and determine improved processing approaches for next-generation AM materials.

### T3 Establishing Part and Feedstock Testing Protocols

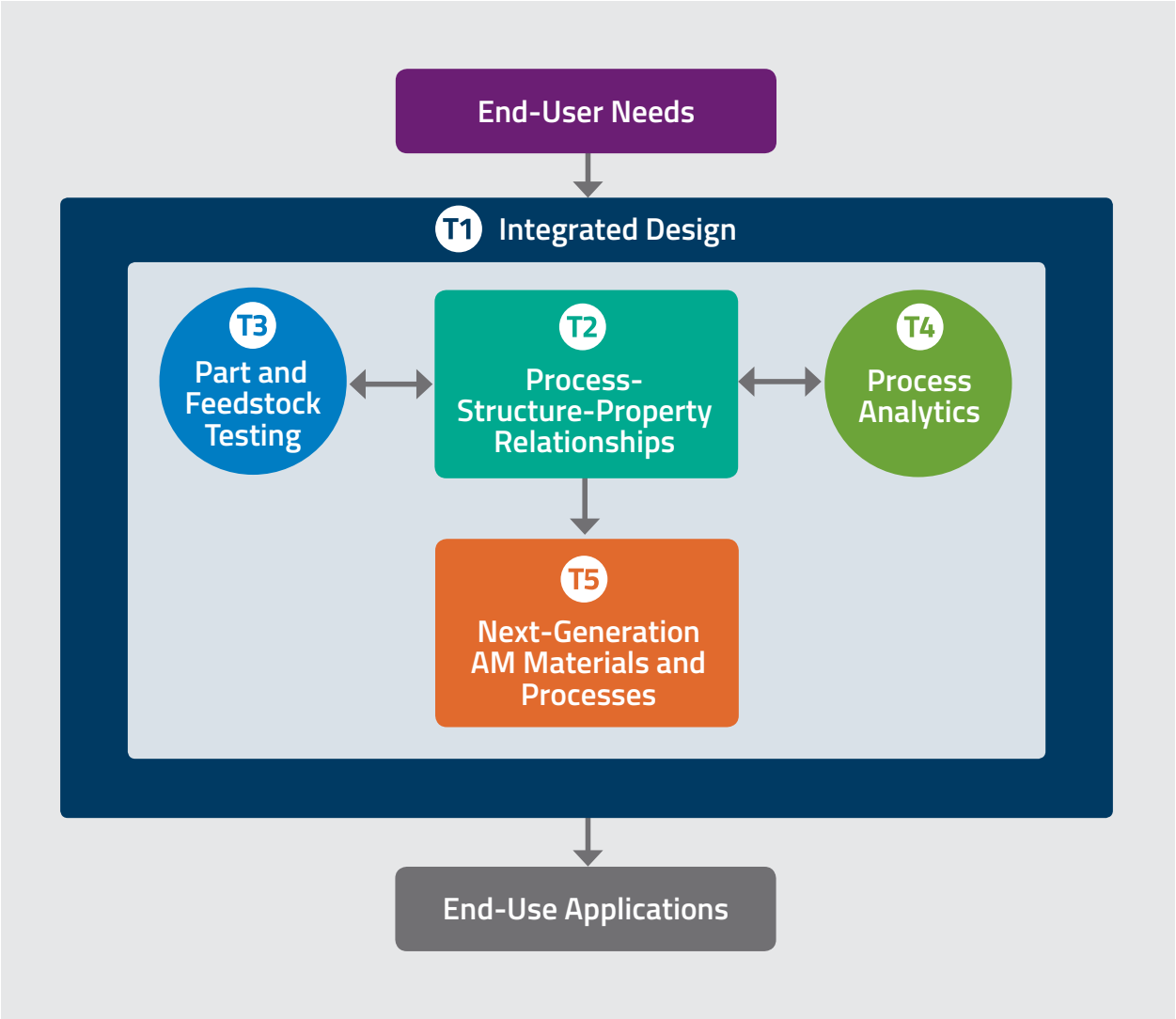
Characterization techniques and test protocols are necessary for capturing key data such as microstructural features, AM part properties, and feedstock material characteristics. Because robust industrial AM testing standards are still evolving, rigorous procedures and methodologies are needed for extracting key test data and confirming sufficient degrees of repeatability and reliability in the demonstration of new AM materials.

New test protocols facilitate the generation of materials property and part performance data to convey quantitative understandings of process-structure-property relationships, enhance the predictability of AM process models, and inform process controls to reduce the occurrence of AM part defects. These protocols enable material designers to efficiently screen new AM materials, establish material-part testing correlations, and ultimately evaluate the potential for new material adoption by the broader AM industry.

### T4 Building AM Process Analytics Capabilities

Realizing the true performance potential of new AM materials requires careful control of processing conditions as AM part layers are fabricated. Precise, calculated analysis and control of processing

Figure 5. AM Materials Development Strategic Thrust Overview



### CAMM: Defining the Future of Next Generation Additive Manufactured Materials

CAMM is focused on fundamental research of AM materials within Technology Readiness Levels (TRL) of 1 to 3. During the past several years, a number of workshops have been held to identify gaps/barriers and opportunities for AM. Although AM materials has been one of the topics in a number of workshops during the past several years, the development of new advanced metal alloys, polymeric formulations, ceramics, and functionally graded materials for AM has not received sufficient attention to enable the creation of revolutionary advanced high-performance components.

CAMM aims to address this gap by:

- Creating a strong linkage and a pipeline of CAMM fundamental R&D projects (i.e., TRL 1–3) between other AM consortia (e.g., America Makes) and other R&D activities that are focused on applied TRL 4–7 projects.
- Building on key cross-cutting actions that will address gaps and barriers to enable the development of next-generation metals, polymers, and ceramics for advanced components.
- Establishing an industry-centric consortium consisting of materials producers, research institutions, AM equipment suppliers, part manufacturers, and end users to address the development of new materials and access to state-of-the-art facilities for experimentation and testing.

approaches are required to optimize the next generation of materials.

Process analytics involve sensor technologies that gather AM materials processing data combined with analytical methodologies that allow users to make essential modifications to AM processing parameters. By enhancing the control of AM processing, material designers can more effectively draw correlative process-structure-property relationships that are crucial to increasing the reliability and reproducibility of newly demonstrated AM materials.

### T5 Exploring Next-Generation AM Materials and Processes

Revolutionizing AM technologies in the longer term requires an expanded set of material options beyond incremental improvements in current AM materials and processes. Next-generation materials designed to take full advantage of additive manufacturing and new AM processes developed to fully exploit unique material properties will allow AM to realize its full potential to meet the end-user needs of tomorrow.

Since the compositions and feedstock characteristics of new AM materials are dependent on the needs of end-use requirements, materials are treated as design variables during their discovery and development. Therefore, the characteristics of next-generation AM materials are ultimately defined by well-understood process-structure-property relationships.

## Materials Considered

In many cases, the AM community faces a number of cross-cutting challenges impeding the development of new material systems. Due to the unique characteristics exhibited by metals, polymers, and ceramics, certain fundamental research and development efforts address challenges that are specific to each class of material. Furthermore, these characteristics can add a dimension of intricacy to materials development activities as the AM community exploits the unique processing advantages of AM to create state-of-the-art multi-materials that combine more than one type of material. The five strategic thrusts in this roadmap acknowledge the fundamentally unique AM processing considerations of these material classes and call for research needed to create new AM-based metal, polymer, and ceramic materials.

# Thrust 1: Enabling Integrated Design Methodologies for Materials, Processes, and Parts

Additive manufacturing offers the unique capability of simultaneously producing a material and the part made from that material. Given this capability, integrated design approaches are essential to model the complex interactions of multiple processing variables and identify modifications in materials, processes, and part designs to optimize performance. While integrated design could help material developers demonstrate new AM materials in their respective applications at an accelerated pace, AM-specific models are currently in an early application stage. As a result, establishing integrated design tools and methodologies are a critical area of focus for the AM community in the development and deployment of new AM materials.

## Current Challenges

To capture the benefits for AM that integrated design offers and accelerate the development of AM materials, the research community must address the challenges that follow.

### Lack of feedstock-dependent AM design rules

Many characteristics of feedstock materials—including chemical composition, rheology, and binding and melting mechanisms—impact AM processing variables and the resulting microstructure and performance of AM parts. Designers currently do not have a set of AM design rules based on specific attributes of feedstock materials, slowing the development of advanced AM parts with properties and performance attributes that are able to be tailored to the application.

### Lack of robust process models for AM processes

Process model simulations help material designers predict part properties and product performance before components are manufactured. The accuracy of these predictions is dependent on how well the process simulation models incorporate AM process physics. Due in part to the wide variety of employable AM processing conditions, the AM community lacks the robust predictive process models needed to enable the integrated design of AM materials, processes, and parts.

### Lack of modeling tools for predicting AM part structures

Computational modeling tools help designers predict the final microstructure or molecular architecture of AM parts. The AM community, however, lacks physics-based models that adequately simulate the subscale material structure of as-fabricated AM parts, limiting the ability to make these predictions. To validate the predictability of AM models and ensure that part designs containing new AM material concepts are fully optimized, the AM community must generate well-characterized microstructural datasets from controlled experimental studies.

## Priority R&D Activities

Addressing these challenges will require focused fundamental R&D activities. A complete set of R&D needs for this thrust is presented in Figure 6, along with the material classes to which the activity applies

Figure 6. Thrust 1 R&D Activities (priorities in **bold**)

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T1 Integrated Design** | | | |
| **Develop computational methods to predict AM mechanical properties, surface characteristics, residual stresses, and distortion** | | | |
| Construct AM process maps based on relevant processing characteristics to predict locations of defects in AM components | | | |
| Integrate existing empirical data sets of AM materials into theoretical models | | | |
| Leverage materials and processing models to develop AM-specific topology optimization software with interoperable computer-aided design (CAD), computer-aided manufacturing (CAM), and finite element analysis (FEA) models | | | |
| Initiate an ongoing integrated AM modeling framework with various processing capabilities for the design of multi-materials with anisotropic properties | | | |
| Generate process models for predicting processing characteristics (e.g., melt pool) of AM processes (e.g., direct metal deposition (DMD), binder jetting, material extrusion) | | | |
| **Develop design methodologies for AM materials across all relevant length and time scales** | | | |
| **Produce AM design tools that automatically channel new materials data from experimental efforts and collaborative databases** | | | |
| Develop AM modeling tools for predicting mechanical behavior, thermal energy profiles, and curing radiation in polymer-ceramic multi-materials | | | |
| Establish ICME (integrated computational materials engineering)-based multiscale surrogate modeling approaches for AM materials development | | | |
| Develop cost-effective design optimization software for translating models from traditional processes (e.g., casting) into AM-specific models while preserving part geometries | | | |
| **Generate physics-based models of large-scale AM processes (e.g., selective laser sintering)** | | | |
| **Establish fundamental data structures and design rules for multi-material AM** | | | |

| Metals Polymers Ceramics | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| Create modeling tools that enable designers to prescribe AM process parameters for specific material lots | | | |
| Establish design techniques for functionally graded materials (FGMs) as a function of the physical and chemical composition of feedstock materials | | | |
| Identify *in situ* process monitoring requirements based on variable input requirements of predictive integrated design methodologies | | | |
| Launch design tools for optimizing performance of multifunctional materials (e.g., thermal, electrical, optical properties) as a function of AM processes | | | |

and the expected time frame. High-priority R&D activities are presented in bold in this table and discussed in the following section in greater detail.

## Develop computational methods to predict AM mechanical properties, surface characteristics, residual stresses, and distortion (0–2 years)

The AM community should develop computational methods that predict the mechanical properties of metallic AM parts and link to microstructural features (e.g., phase, defects) at specific locations within the part. By giving designers the ability to accurately predict a part's mechanical response at desired part locations, these computational microstructure modeling approaches can provide a cost-effective alternative to conducting an extensive series of mechanical property tests. To develop AM models that successfully simulate specific microstructural features, researchers must design controlled AM part processing experiments with a sufficient degree of repeatability to reproduce the desired microstructures. Researchers must also conduct microscale mechanical property tests of these parts and use the resulting data to validate the accuracy of the AM models, boosting designers' confidence to predict the mechanical behavior of AM parts.

## Develop design methodologies for AM materials across all relevant length and time scales (3–4 years)

To help materials designers demonstrate the potential of new AM materials and maximize the ability for AM processes to create components with optimized properties, the AM community should develop new multiscale design methodologies informed by evolving materials databases, state-of-the-art AM processing capabilities, evolving microstructural and phase stability models, and user-friendly modeling software capable of predicting spatially variable material compositions and part properties. These multiscale design methodologies must provide well-defined printing orientation rules and empirical structural design methods based on existing sets of experimental AM part data. At the macroscale level, AM design methods must combine geometric reasoning with part feature resolution limits to reduce manufacturing costs by minimizing the need for printing support structures in AM builds. New integrated AM design methodologies should also employ continuum-level predictive modeling approaches to increase the strength-to-weight ratio of AM parts. In addition, design tools should be created to leverage both existing and future AM process capabilities for incorporating composite metamaterial data from various compositions that yield novel materials structures.

## Produce AM design tools that automatically channel new materials data from experimental efforts and collaborative databases (3–4 years)

A dynamic set of material design tools that can predict the type, size, distribution, morphology, and phase of parts produced from new feedstock compositions would help the AM community

discover and develop the next generation of feedstock materials for advanced AM parts. Initial design tools should leverage existing design criteria (e.g., rapid solidification processing (RSP) alloy design criteria) and materials data for current AM materials that are commonly produced by traditional manufacturing approaches such as casting, cladding, welding, powder pressing, and injection molding. Ongoing experimental efforts will ensure that the dynamic design tools are always drawing from an expanding knowledge base of phase transformation kinetics, thermodynamic property data, rheological data, and other critical information needed to design new AM materials.

### Generate physics-based models of large-scale AM processes (e.g., selective laser sintering) (5–10 years)

In many AM processes, the management of thermal energy is critical for controlling solidification rates and phase transformations, which influence material microstructures. Validated models of AM processes would allow designers to predict and control thermal gradients to achieve desirable structures and properties using next-generation AM materials. It would also serve as a key design tool for adjusting thermal processing steps to regulate the structural properties of highly advanced AM materials, including functionally graded materials (FGMs).

### Establish fundamental data structures and design rules for multi-material AM (5–10 years)

To enable the design and optimization of multi-material systems and lay the groundwork for the development of FGM design methodologies, the AM community should collaborate with software developers to create state-of-the-art modeling tools for multi-material AM parts. Design rules for multi-material systems should be based on those developed for the synthesis of traditional AM materials, and existing optimization methods should be modified to enable the predictive design of AM parts with multiple feedstock material compositions. In addition, multi-material process models will need targeted, ongoing part testing and data characterization activities to feed mechanical and chemical property test data into integrated design approaches to ensure that the model physics are truly representative of actual AM multi-materials under development. To encourage the sharing of material and mechanical property data for process model validation, an open-access architecture should be created for the storage and dissemination of multi-material test data.

## Case Study: **Integrated Design of High-Performance AM Ceramic Components**

*Spinworks Inc.*

### CHALLENGE

The use of heat recovery systems to transfer thermal energy from flue gases and preheat combustion air in fuel-fired industrial heating processes helps to reduce fuel consumption and improve thermal process efficiencies. The materials used to fabricate these metal alloy heat exchanger components must have sufficient formability to yield high surface area shapes while satisfying elevated heat transfer rate requirements. Traditionally, high-temperature materials typically have insufficient formability needed to fabricate shapes with high surface area. This combination of requirements makes it challenging to design materials via traditional manufacturing methods. Relying on AM techniques to exercise superior control over the process can help users overcome these material fabrication challenges. Integrated design methodologies are thereby necessary for enabling the next generation of AM materials and parts that meet the rigorous design requirements of critical heat recovery applications.

### APPROACH

With support from Penn State Erie's Advanced Manufacturing and Applied Energy Research Center, designers at Spinworks in Erie, PA jointly developed AM-fabricated furnace components and advanced waste-heat recovery systems made from advanced silicon carbide materials—materials that would not be feasible to use without AM. Spinworks uses a proprietary AM processing approach to design ceramic-based helical recuperators and furnace exhaust leg components that effectively recover and transfer heat from outgoing flue gases to the incoming combustion air.[2] By using an integrated design approach to optimize material properties and maximize the amount of surface area available for heat transfer, 3-D-printable silicon carbide components can be custom-designed to fit both new and existing industrial heating processes. The application of these advanced ceramic-based AM materials in novel heat recovery components significantly improves heat transfer and temperature uniformity, thereby resulting in lower fuel consumption, reduced emissions, and decreased industrial process heating costs.

### IMPACT

AM techniques allow users to exhibit significant control over processing variables and component features, thereby enabling the design of high-performance application-specific materials. Using integrated design methodologies to tailor components from silicon carbide materials, Spinworks developed and commercialized heat exchanger designs that reduce heat loss and energy demands by 15–20%.[3] Spinworks' success with recuperators and furnace exhaust components has opened the door to a line of custom silicon carbide products that can only be made via AM processing approaches. The AM community can adopt these integrated design approaches in fundamental-level research and development activities to accelerate the pace of AM materials discovery and deployment.

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[2]Spin-Works International Corp, "Spin-Works Products," 2015, http://www.spin-works.com/products (accessed 8 June 2015).
[3]DOE EERE (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy), March 2013. Impacts: Results Summary for CY 2010. http://www1.eere.energy.gov/manufacturing/about/pdfs/impacts2010_full_report.pdf.

## Case Study: **GE LEAP Jet Engine Fuel Nozzles**
*General Electric*

### CHALLENGE

GE's next-generation LEAP jet engine developed by CFM International will have nearly 20 fuel nozzles. These nozzles all need to be consistently produced so that they are as durable, lightweight, and cost-effective as possible.[4] While traditional manufacturing methods would require each nozzle to be produced by brazing and welding a number of separate parts together, GE plans to produce the LEAP nozzles by taking advantage of the benefits AM processing methods offer.

3D-printed fuel nozzle for LEAP jet engine

### APPROACH

GE is installing AM—specifically, direct metal laser melting (DMLM)—in the world's first factory for printing jet engine fuel nozzles in Auburn, Alabama. The mass production process will build the nozzle directly from a 3D computer drawing by melting together 20 micron layers of a cobalt-chrome metal alloy powder with a high-powered laser.[5] Sensors will be used to constantly monitor the process and ensure quality throughout the build process.

In addition to using AM for production, GE also performed extensive modeling of the fuel nozzles using numerical simulation on super computers. Researchers used between 500,000 to 1 million CPU hours of time to simulate atomization of the liquid jet fuel and spray. Small changes in nozzle geometry can lead to significate changes in engine performance by helping to understand how air and fuel mix and burn.[6]

### IMPACT

The new AM-produced fuel injector nozzles are five times more durable and 25 percent lighter than the previous nozzle. 3D printing allowed engineers to design the nozzles as one part rather than 20 individual parts, simplifying the design and reducing the number of brazes and welds from 25 to just 5. These nozzles have contributed to making the LEAP engine 15 percent more fuel efficient with an equivalent reduction in $CO_2$ emissions, as compared with previous engines built by CFM International. The first LEAP engine is scheduled to enter service in 2016.

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[4]CFM International, "The LEAP Engine," 2015, http://www.cfmaeroengines.com/engines/leap (accessed 8 June 2015).
[5]Kingsley, Jeremy, "This fuel consumption-cutting engine could power flights," WIRED.co.uk (18 November 2014), http://www.wired.co.uk/magazine/archive/2015/01/start/giant-steps-for-leap (accessed 8 June 2015).
[6]Kellner, Tomas, "Scientists Use 'Big Bang' Supercomputer To Build Better Jet Engine," GE Reports (8 June 2014), http://www.gereports.com/post/87903401185/scientists-use-big-bang-supercomputer-to-build/ (accessed 8 June 2015).

# Thrust 2: Developing AM Process-Structure-Property Relationships

As with other manufacturing processes, AM processing parameters that affect thermal histories—including thermal gradient profiles and cooling rates—control the microstructural features and mechanical properties of end-use parts, but may also vary significantly based on the physical characteristics and chemical composition of feedstock materials. As a result, it is critical to have an in-depth understanding of the interdependent process-structure-property (PSP) relationships of new AM metal, polymer, ceramic, and multi-material systems. A concentrated effort to define these relationships for new AM materials has not yet been conducted due to the large number of materials and process variables that affect the properties of AM parts. Pursuing the fundamental research needed to establish these relationships for AM will enable the AM community to accelerate the development of new AM materials that meet or exceed current and future requirements.

## Current Challenges

While significant progress has been made for the current selection of AM metals, polymers, and ceramics, the insufficient understanding of critical PSP relationships for these material types is hindering the development of new AM materials that can maximize the benefits that AM offers. The AM community must address the following challenges to drive the development of next-generation AM materials including multi-materials and functionally graded materials (FGM).

### Limited understanding of melt-pool-microstructure relationships

Melt pools are regions of newly deposited layers of materials that undergo phase transformations during solidification. Depending on the processing variables employed, melt pools will exhibit certain sizes, shapes, and temperature profiles that lead to the formation of particular microstructures, yet little is known today about quantifying melt pool characteristics or their impact on the final product. A complete understanding of how specific melt pool characteristics collectively influence the microstructures of processed parts would enable material designers to define suitable processing approaches for new AM materials that display desirable performance characteristics.

### Limited understanding of root causes of AM part defects

AM-produced parts may contain defects such as unfavorable porosity, distortion due to residual stress, partially melted or fused feedstock, and poor surface quality. Factors that can lead to the formation of defects include physical or chemical variations of feedstock materials or inert processing atmospheres, thermal processing instabilities, and inadequate mixing or fusion of deposited layers during processing. Although many of these individual factors are generally known, AM part defects currently cannot be traced back to their specific root causes. Developing a better understanding of these root causes would enable the AM community to identify process and feedstock material alterations that will reduce the occurrence of part defects.

### Lack of established rheological and compatibility data on blended polymer systems

Compared with conventional injection molding, AM gives part producers the flexibility to tailor the structure and properties of high-performance polymeric parts by enabling unique blends of polymers and filler materials that may not otherwise

Figure 7. Thrust 2 R&D Activities (priorities in **bold**)

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T2 Process-Structure-Property Relationships** | | | |
| **Conduct AM materials "genome" initiatives that use computational approaches, data management, and an integrated approach to designing and engineering new materials** | | | |
| **Develop powder feedstock material relationships with AM part quality and performance** | | | |
| Develop cracking sensitivity curves and phase stability data for AM-processed non-weldable alloys with high solidification rates | | | |
| Compare conventional wrought microstructures with AM microstructures and identify the impact of chemical composition on precipitation kinetics | | | |
| Establish post-process heat treatment cycle strategies and approaches | | | |
| Develop transfer function equations that define the relationship between AM process parameters and polymer characteristics (e.g., rheology, particle size, flowability) | | | |
| Identify characteristics of selective laser sintering (SLS) processes at the microscale and investigate the effects of production scale-up | | | |
| Develop compatibility information for reactive ceramic-infiltrant combinations | | | |
| Explore the effects of deposition environments (e.g., vacuum, inert gases) on material properties | | | |
| Develop and implement powder flow principles and validation protocols for AM powder processing approaches at smaller scales | | | |
| Identify correlative multiscale relationships between micro- and macrostructural properties of AM materials to support efforts in scaling AM part production | | | |
| **Develop polymeric rheology and compatibility information for blended polymer processing** | | | |
| **Develop process-structure-property maps for new AM metals, polymers, and ceramics** | | | |

| Metals / Polymers / Ceramics | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| Correlate melt pool features with AM part quality and mechanical properties of as-built and/or post-processed parts | | | |
| Identify, measure, and catalog AM materials properties that are unique to AM, compared with conventional processing methods | | | |
| Generate fatigue and fracture toughness data for specific AM materials as a function of scale and variations in material characteristics | | | |
| **Characterize the compatibility of multi-material constituents at multiple length scales** | | | |
| Conduct theoretical analysis of phase formation, extended solubility, and stability limits for AM materials | | | |
| Identify combinations of ceramic feedstock materials and laser/energy inputs that yield optimal part performance | | | |

be compatible. For polymers to be compatible with one other, they must exhibit favorable rheological characteristics and processing temperature requirements. Materials developers need established rheological and compatibility data to develop customized blends of polymer materials capable of meeting a variety of end-user requirements.

## Priority R&D Activities

Addressing these challenges will require focused fundamental R&D activities. A complete set of R&D needs for this thrust is presented in Figure 7, along with the material classes to which the activity applies and the expected time frame. High-priority R&D activities are presented in bold in this table and further discussed in the following section.

### Conduct AM materials "genome" initiatives for metals, polymers, and ceramics (0–10 years)

The AM community should form specific "genome" initiatives—initiatives that use computational approaches, data management, and an integrated approach to designing and engineering new materials—to accelerate the development of each AM material class. Each of these ongoing activities would involve a series of parallel tasks including the generation, cataloging, and characterization of experimental test data; development of datasets based on first-principle calculations to store and exchange materials information within the AM community; and use of software tools that simulate physics-based models of AM materials and processes. This AM-focused activity could be aligned with the U.S. Federal government multi-stakeholder initiative known as the Materials Genome Initiative, which is aimed at creating an infrastructure for rapidly and cost effectively discovering and deploying advanced materials.

### Develop powder feedstock material relationships with AM part quality and performance (0–2 years)

The AM community must define relationships that correlate the key physical and chemical characteristics of powder feedstock materials with the quality of post-processed AM parts. Key tasks within this effort include the use of specially designed experimental AM test builds with specific boundary

conditions and the deployment of iterative validation procedures that identify the root causes of defects and other part performance issues. These activities could reveal key PSP relationships that will provide material suppliers with guidance to manufacture new AM feedstock materials with greater uniformity and consistency, as well as supplemental information for developing new powder purchasing standards and specifications across the supply chain.

### Develop polymeric rheology and compatibility information for blended polymer processing (3–4 years)

The AM community should generate rheological data that describes the melt behavior, flowability, ideal processing temperatures, and quantitative stress-strain behaviors of the resulting molecular structures of processed AM parts. Blended polymer rheological and compatibility data provides designers with an instrument to predict the behavior of a virtually limitless set of custom polymeric feedstock options and to define relationships between blend polymer feedstock composition and processing parameters.

### Develop process-structure-property maps for new AM metals, polymers, and ceramics (0–4 years)

The creation of key process-structure-property maps will help material designers determine the effects of adjusting processing variables on the performance of newly developed AM materials. To develop these maps, the AM community should establish a fundamental understanding of the influence of poor wettability caused by interlayer oxidation, as well as the impact of other impurities from feedstock materials and the processing atmosphere on materials properties and part performance. Material designers should also understand how processing variables affect deviations in part chemistry, including alloying element partitioning due to high solidification rates and through vaporization due to high processing temperatures and vacuum-processing environments. Processing parameters such as laser beam characteristics and feedstock deposition rate should be correlated with materials microstructure and mechanical and physical properties as a function of production scale. The development of specific process-structure-property maps that include these variables and processing parameters will help maximize the performance potential of new AM materials.

### Characterize the compatibility of multi-material constituents at multiple length scales (5–10 years)

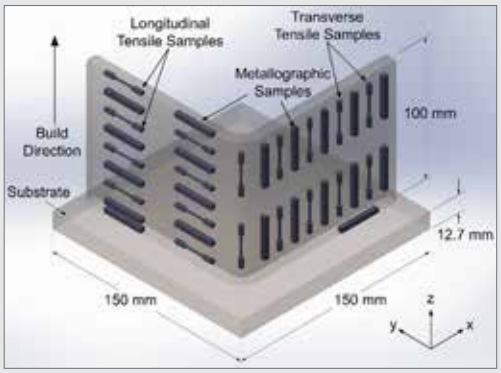
Designers of new AM materials must develop a sound fundamental understanding of the numerous possible combinations of multi-material constituents such as metal-metal, metal-ceramic, polymer-ceramic, and polymer-metal interfaces across the range of part length scales. To achieve favorable interlayer bonding between new AM materials and produce parts free of voids and cracks, the AM community should characterize the compatibility of constituent materials by examining their response to temperature, changes in viscosity, laser radiation absorptivity, wettability, etc. Understanding the compatibilities between multi-material feedstock combinations will help the AM community more effectively take advantage of the design freedom of AM processes to create next-generation AM materials with high-performance tailored microstructures.

## Case Study: **Quantifying Process-Structure-Property Relationships of DED-Fabricated Ti-6Al-4V Components**[7]

*Applied Research Laboratory, The Pennsylvania State University*

### CHALLENGE

Process-structure-property relationships (PSP)—a fundamental element of integrated design approaches—provide guidance for determining suitable processing routes of new AM materials. The complex thermal histories applied to AM-fabricated components, including melting, solidification, and thermal cycling, are subject to considerable variation depending on the part geometry and build path. Since material properties are a function of processing history, it is necessary to capture extensive details of the processing conditions applied to AM components to avoid introducing uncertainty in the mechanical property values. To accurately quantify PSP relationships, the AM community must characterize the relationship between the microstructure and mechanical behaviors of new AM materials across a range of processing parameters and part geometries.




Schematic of the L-shape wall structures showing locations where the tensile and metallographic titanium samples were extracted.

### APPROACH

PSU researchers of have studied the impact of processing conditions on the mechanical properties of titanium components fabricated through different directed energy deposition (DED) AM processing approaches; both laser-based DED with powder feedstock and electron beam-based DED with wire feedstock have been investigated. An essential component of this research included an investigation of the microstructural anisotropy of AM components, which is a result of the layer-by-layer nature of the AM processes. This particular nuance of PSP relationships was analyzed by introducing a hot isostatic pressing (HIP) post-process heat treatment to as-built titanium AM components and characterizing the impact of this post-processing step had on resulting mechanical behaviors and microstructures. By observing the alloy response to an assortment of thermal histories and feedstock forms, as well as post-processing, AM researchers can more effectively identify sets of processing conditions that yield optimum part performance.

### IMPACT

As new materials are developed by the AM community, it is crucial to recognize how specific processing parameters and geometric requirements correlate with mechanical behavior and microstructural features. Penn State's work in quantifying PSP relationships of titanium AM components over a large processing range provides fundamental insight into role of microstructure in both location- and orientation-dependent properties of AM fabricated components. Therefore, demonstrating that the performance potential of new AM materials depends on building a robust understanding of thermal processing histories to reduce uncertainty for the design community.

[7]Carroll, Beth E., Todd A. Palmer, and Allison M. Beese, "Anisotropic Tensile Behavior of Ti–6Al–4V Components Fabricated with Directed Energy Deposition Additive Manufacturing," Acta Materialia 87 (2014): 309-20.

Max: 44,590.8

# Thrust 3: Establishing Part and Feedstock Testing Protocols

Developing the next generation of advanced AM materials will require new specialized testing techniques for generating AM part property data and characterizing feedstock materials, due in part to the complex geometries and multi-material combinations that are possible via AM. In contrast to the established protocols of conventional manufacturing processes, AM processes lack sufficient test methodologies for gathering fundamental data about the relationships between microstructural features, AM part properties, and feedstock material characteristics. These data are critical to the design of new AM materials that achieve the desired quality and performance requirements of advanced end-use applications. New specialized testing and characterization methods will enable materials suppliers to develop new AM feedstock materials with physical and chemical compositions tailored for AM processes.

## Current Challenges

Without well-established test methodologies, the AM community cannot efficiently generate the material property data needed to assess the potential of new AM materials. To overcome this barrier, the AM community must address the following challenges.

### Limited fundamental knowledge of AM feedstock materials and relationship to part quality for development of qualification and part certification protocols

Current AM technologies lack adequate repeatability to consistently fabricate products with desired properties and structural features. With the lack of protocols for the qualification of processes and certification of AM parts, the AM community needs to conduct fundamental investigations of standardized material testing techniques for different forms of feedstock to better understand how AM feedstock powder compositions and alloys impact final AM part quality. Defining the relationships between powder feedstock characteristics and their impact on quality and performance will enable materials suppliers and feedstock producers to identify necessary changes to feedstock processing routes or AM processing approaches to leverage the full potential of new AM materials. Without this knowledge, industry cannot establish qualification and part certification protocols. This work will increase the reliability and consistency of fabricated parts and accelerate the development of new materials that can make those parts a reality.

### Lack of defined AM design allowables

Design allowables are sets of test-derived material property data that help material designers confirm that parts meet the minimum property requirements for the intended application. The lack of defined AM-specific design allowables and material test protocols limits the ability for AM material designers to methodically test and design new parts with acceptable degrees of performance. Reducing the cost and time to develop new AM materials will require designers to investigate material property testing techniques for enabling the creation of design allowable material property datasets based on detailed histories of processing variables used to fabricate AM parts.

### Limited ability to characterize variation in chemical composition, microstructure, and properties within AM parts

The inherently complex nature of physical and chemical processing mechanisms in AM makes it challenging to precisely characterize variations in

Figure 8. Thrust 3 R&D Activities (priorities in **bold**)

material composition, microstructure, and properties of AM parts. It is similarly difficult to distinguish inconsistencies in particle size distribution (PSD) and morphology of powder feedstock materials that can influence part properties. Fundamental evaluation of unique equipment and advanced characterization approaches to ensure accuracy and precision in capturing AM part and feedstock data would be of significant value in validating design, executing process controls, and defining robust process-structure-property relationships for new materials in AM parts.

## Priority R&D Activities

Addressing these challenges will require focused fundamental R&D activities. A complete set of R&D needs for this thrust is presented in Figure 8, along with the material classes to which the activity applies and the expected time frame. High-priority R&D activities are presented in bold in this table and further discussed in the following section.

### Establish rapid screening procedures for evaluating new AM feedstock materials (0–2 years)

Rapid screening procedures are needed to assess the ability for new materials to be processed using today's AM machines. Screening procedures should leverage currently available AM materials information, including phase transition diagrams, microstructural data, rheological data, and material reactivity and compatibility information. These protocols will significantly reduce the time and expense associated with researching the suitability of new AM feedstock materials.

### Develop comprehensive part testing protocols for the localized measurement and characterization of AM part properties (0–2 years)

The AM community should define the key mechanical properties used to determine the quality, reliability, and reproducibility of AM parts in current conventional part testing protocols and should identify additional properties that merit new testing methodologies and experimental apparatuses. Advanced AM part testing should include existing and emerging subscale mechanical property testing approaches, such as high-frequency mini-fatigue techniques, to determine properties at localized regions within AM parts. Key material properties should be prioritized in terms of a user's ability to realistically conduct subsequent property tests (e.g., beginning with non-destructive evaluation tests), the results of which will help build a more comprehensive provenance of materials metadata. Ensuring that key AM material and part properties are evaluated and linked to processing history metadata will help the AM community more effectively assess the potential of new materials.

### Investigate influence of atmospheric conditions on AM feedstock materials (0–2 years)

Understanding the role of atmospheric conditions on AM feedstock materials will help ensure consistency in the quality of AM feedstock materials, thereby reducing variability between material property measurements. The AM community should use this knowledge to effectively minimize feedstock material exposure to light and extreme temperature swings which, in turn, would avoid unintentional polymerization of UV-curable polymeric materials. AM users should also take precautions to prevent feedstock materials from adversely reacting with storage containers or absorbing moisture from the atmosphere. These fundamental research studies underpin the future development of standardized industrial protocols for the storage, handling, and testing of new AM feedstock materials, thus ensuring their physical and chemical integrity and significantly reducing waste.

### Evaluate the potential for reusing, refurbishing, and recycling powder feedstock materials (0–2 years)

The AM community must define and implement recycling methods for AM metal, polymer, and ceramic feedstock materials. Researchers should conduct fundamental studies to investigate factors that negatively impact part quality, thus limiting the reusability and recyclability of powder feedstock materials. These research studies will support the development of novel recycling processes and process control and validation procedures for

powder feedstock materials, which will make AM a more efficient process when fabricating AM parts to demonstrate new types of feedstock materials.

### Create laboratory-scale techniques for screening custom polymeric feedstock materials (3–4 years)

The AM community must develop and adopt novel screening approaches to evaluate new compositions of polymeric feedstock materials. These techniques should assess whether custom polymer compositions can be processed with the current generation of AM machines using rheological and compatibility data for blended polymer systems. In addition, the use of laboratory-scale screening methods will help materials designers identify optimum blends of polymers and other additives to tailor the strength, weight, flexibility, color, and other key characteristics of polymeric AM parts. Such combinational approaches may also have uses in exploring metal and ceramic materials and multi-material combinations.

### Introduce new techniques for characterizing the impact of feedstock material attributes on AM part quality (3–4 years)

New characterization protocols for AM feedstock materials are needed to gain a better understanding of the impact of feedstock material features, such as particle size distribution (PSD) of powder feedstock materials, on the mechanical properties, surface quality, and density of AM parts. AM material designers should consider adopting protocols for characterizing powder feedstock flow behavior in terms of viscosity, particle morphology, and wetting behavior to help determine the propensity of powder feedstock materials to successfully mix when sintered or melted and to mitigate the occurrence of defects such as oxidation and spheroidization. In addition, measuring impurities and contaminants imparted by the processing atmosphere or feedstock production process could help designers draw a clearer connection to undesirable AM part qualities. New feedstock characterization techniques must clearly identify key variables that contribute to final part characteristics to aid the AM community in establishing process-structure-property relationships for new materials.

### Evaluate the potential for reusing, refurbishing, and recycling new multi-material powder feedstock combinations (5–10 years)

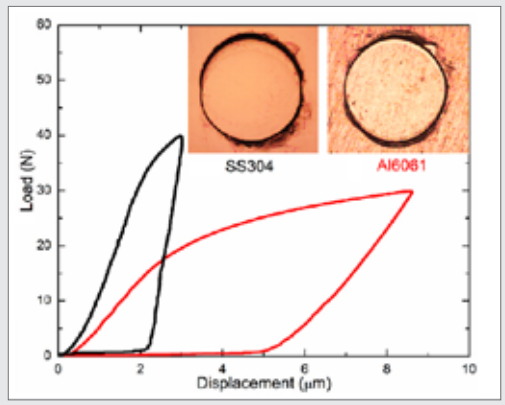
As new AM multi-materials are developed, tested, and integrated into end-use applications, the AM community will need to rely on cost-effective techniques for recycling unused multi-material powder feedstock combinations, including metal-metal, metal-ceramic, polymer-ceramic, and polymer-metal part compositions. Such fundamental studies may explore novel techniques that enable the separation of unique multi-material powder combinations. With AM expected to be the principle manufacturing method for fabricating the next generation of advanced multi-materials and functionally graded materials (FGMs), AM material developers will benefit from the ability to reuse, recycle, and refurbish AM feedstock materials to reduce waste.

## Case Study: **Applying Micromechanical Techniques to Measure Mechanical Properties of AM Parts**

*Nanovea, Inc.; Hysitron, Inc.*

### CHALLENGE

Standard tensile testing machines measure the mechanical properties of manufactured parts by applying a load to test bars to obtain stress-strain curves. These tests are costly and time consuming, as ASTM standards require the use of large amounts of test material. AM parts, however, can be produced as near-net shapes with thin cross-sections, making it a challenge to obtain tensile test specimens large enough to meet ASTM standards. In addition, AM offers the ability to produce layered materials, functionally graded materials, or multi-materials, where the composition and mechanical or physical properties may change over micron-scale distances.




Displacement versus load curves for a stainless steel and aluminum alloy generated by Nanovea's microindentation equipment.

### APPROACH

A number of companies have developed advanced micromechanical testing equipment and methods with the ability to measure a wide range of mechanical properties in AM parts. Nanovea Inc. has produced specialized microindentation equipment that is used to generate displacement versus load curves.[8] Data from microindentation is used to calculate yield strength (YS) and ultimate tensile strength (UTS) values that are comparable to that measured by conventional tensile tests. The small indentation size makes it possible to perform multiple measurements on a single sample and allows YS and UTS measurements on small samples and localized areas, which can be used for mapping the strength of critical sections of the AM part.

Hysitron, Inc. has also developed a micromechanical testing tool: *in situ* Scanning Probe Microscopy (SPM) imaging. This technique provides high-resolution SPM images at the location of the test by imaging with the same probe that performs the micromechanical testing.

### IMPACT

In addition to stress-strain behavior, strength, and hardness, micromechanical techniques using specialized equipment can be used to obtain elastic modulus, creep strength, fracture toughness, and fatigue behavior of metals, polymers, and ceramics. Using specialized micromechanical equipment to measure a wide range of properties within AM parts will improve understanding of the relationships between composition and processing variables, enabling researchers to accelerate the rate of development of the next generation of materials and advanced processes for high-performance AM parts.

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[8]Nanovea, "Microindentation Using Patented Direct Depth Measurement," 2015, http://nanovea.com/micro-indentation-tester (accessed 8 June 2015).

# Thrust 4: Building AM Process Analytics Capabilities

The effective control and optimization of AM process parameters requires a thorough understanding of the impacts of process variable manipulation on materials and the resultant part. Process analytics can provide this data using *in situ* sensing techniques and advanced monitoring devices to analyze AM process characteristics that enable control of material microstructures; yet, these tools and techniques have not been fully developed nor sufficiently leveraged by the AM community. The implementation of new AM process analytics will provide materials developers with critical insight on AM processes that will enable them to improve production efficiencies and increase part reliability and expand the use of new AM materials.

## Current Challenges

The current lack of advanced process analytics in AM limits materials developers' ability to design new AM materials with optimized part performance. To overcome this barrier, the research community must address the following challenges.

### Limited *in situ* process monitoring techniques

*In situ* process monitoring is a real-time, non-destructive approach for measuring key information about material and process variables during AM part fabrication. Currently, part producers lack robust and reliable sensing devices and monitoring techniques to accurately detect microstructural features, defects, and melt pool characteristics. These tools are needed to accelerate materials development by enabling the AM community to analyze process variables and draw conclusions that can inform cost-effective process adjustments when fabricating test specimens of new types of AM materials.

### Inadequate control of critical AM process parameters to tailor microstructures

Precise control of AM processing variables allows designers to intentionally and consistently modify the structures and properties of build materials. Currently, the AM community does not sufficiently understand the impact of variations in processing parameters—including feedstock deposition rate, heat input, beam power, diameter, scanning speed, and melt pool dimensions—on microstructures of parts made with new AM materials. Acquiring a deeper understanding of process control sensitivities and how they impact AM builds is especially crucial to the development of next-generation functionally graded materials (FGMs) with highly tailored microstructures.

## Priority R&D Activities

Addressing these challenges will require focused fundamental R&D activities. A complete set of R&D needs for this thrust is presented in Figure 9, along with the material classes to which the activity applies and the expected time frame. High-priority R&D activities are presented in bold in this table and further discussed in the following section.

### Identify and catalog feasibly controllable parameters of commercially available AM processes (0–2 years)

The AM community must identify and catalog key processing parameters—including feedstock deposition rate, layer resolution, thermal energy input, beam power, beam diameter, scanning speed, and atmospheric composition of the build chamber—that directly impact the structure and properties of

Figure 9. Thrust 4 R&D Activities (priorities in **bold**)

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T4 Process Analytics** | | | |
| **Identify and catalog feasibly controllable parameters of commercially available AM processes** | | | |
| **Conduct sensitivity analyses of AM processing parameters for fundamental-level materials data generation efforts** | | | |
| Develop AM processing procedures that minimize the inclusion of residual stresses (e.g., auxiliary heating) | | | |
| Develop case studies on process parameter optimization for multi-material systems | | | |
| **Employ *in situ* sensors with feedback loop controls to ensure optimum steady-state processing conditions and reproducibility of AM products** | | | |
| **Capture accurate site-specific thermal history data of AM processes** | | | |
| **Develop strategies for dynamically and independently controlling AM part densification level and dimensional tolerance** | | | |
| Develop advanced AM equipment tool paths with embedded process controls | | | |
| Develop *in situ* analytical sensing techniques for measuring site-specific chemical properties of build materials | | | |
| Develop an experimental imaging system to analyze the microstructure or composition of processed materials | | | |
| Develop *in situ* surface chemistry modification methodologies to enhance the interfacial interactions between layers of multi-materials | | | |

AM parts. Increased knowledge of the key process parameters unique to each AM process would allow AM materials developers to exploit advantageous combinations of processing parameters, such as desired thermal gradient profiles and cooling rates, to create highly tailored material structures.

### Conduct sensitivity analyses of AM processing parameters for fundamental-level materials data generation efforts (0–2 years)

The AM community must conduct sensitivity analyses of AM processing parameters to understand their impact on part microstructure and performance. Increasing this knowledge would allow materials designers to quickly modify the most relevant AM processing steps to achieve a desired change in the microstructural characteristics of build materials.

### Employ *in situ* sensors with feedback loop controls to ensure optimum steady-state processing conditions and reproducibility of AM products (3–4 years)

The AM community must employ *in situ* sensors that capture and transmit real-time processing information. These *in situ* sensors should be designed with closed-loop adaptive controls that give users the ability to adapt or maintain processing conditions within defined ranges. This capability will enable material designers to achieve consistent levels of reliability and reproducibility when investigating new AM materials in test builds.

### Capture accurate site-specific thermal history data of AM processes (3–4 years)

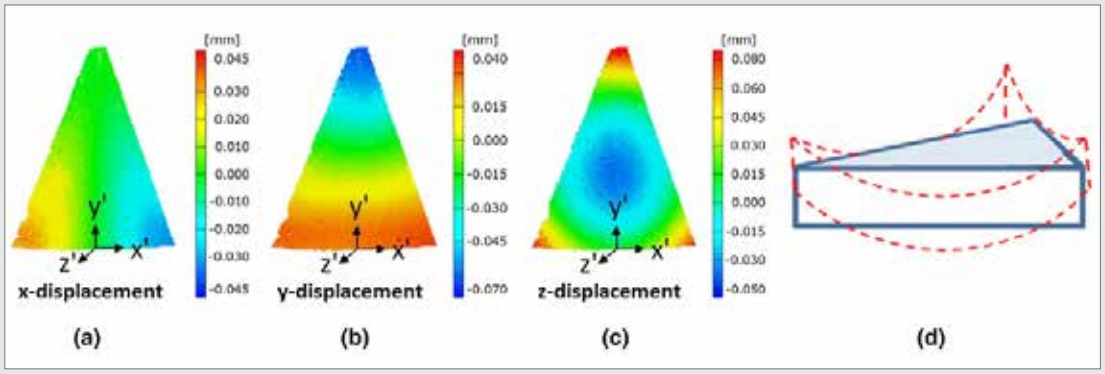
Thermal histories of AM processes capture key processing variables of part fabrication, such as energy input, heat dissipation, and melt pool dimensions. These datasets can help process engineers gain a better understanding of the correlation between heat input from laser- and electron-beams and the microstructural features and performance of AM parts, which allows designers to more proficiently tailor microstructures and molecular architectures of new AM materials. To develop thermal histories, materials designers need to integrate *in situ* sensors into AM machines to capture data such as melt pool features, extent of interlayer melting or fusion, and thermophysical properties (e.g., thermal conductivity and thermal diffusivity) under controlled processing procedures. The AM community should also develop data management strategies to collect and analyze the large datasets captured by *in situ* process monitoring techniques. This thermal history data can then be correlated with mechanical test data and part microstructures to understand how melt pool behavior influences microstructural solidification and phase transformations.

### Develop strategies for dynamically and independently controlling AM part densification level and dimensional tolerance characteristics (3–4 years)

To optimize the density or dimensional tolerance of AM parts, the AM community must identify specific parameters of a process that impact porosity, residual stress, and dimensional tolerance during a build, and then conduct controlled experiments to identify combinations of these variables that achieve desired densities or dimensionally accurate geometries of AM parts. Ensuring that the part densification level and dimensional tolerance characteristics can be independently modified requires separate R&D activities for developing strategies to control specific AM part properties. The AM community should also produce a set of recommendations for calibrating the appropriate processing parameters as a function of feedstock characteristics and compositions to optimize AM part properties and more effectively screen new feedstock material options.

## Case Study: **Parametric Study of Powder Bed Fusion AM for Reducing Residual Stresses**

*Lawrence Livermore National Laboratory*




LLNL researchers evaluated the surface deformation of 316L stainless steel to understand the influence of processing parameters

### CHALLENGE

The formation of residual stresses in AM materials is an undesirable yet inherent aspect of powder bed fusion (PBF) AM. Due to repeated melting and solidification of build layers in AM PBF processes, deformations caused by thermal gradient-induced internal stresses result in loss of net shape, crack formation, or delamination. Mitigating these undesirable properties through enhanced control of AM processing parameters is crucial to achieving consistent repeatability and reliability in the demonstration of new AM materials.

### APPROACH

To establish a fundamental understanding of factors that influence the formation of residual stresses in AM parts, researchers at LLNL conducted a parametric study into the effects of scanning pattern, power, speed, and build direction on 316L stainless steel specimens.[9] By coupling a destructive surface residual stress measurement technique with a nondestructive volumetric evaluation method (i.e., neutron diffraction), researchers successfully evaluated the effects of build direction and scanning strategy on residual stress development in 316L stainless steel specimens. These results revealed significant insight into optimum combinations of processing parameters that yield lower residual stress levels in powder bed fusion AM parts.

### IMPACT

LLNL's parametric study of residual stress development represents an experimental technique that the AM community can use to apply beneficial process control solutions that address the current challenge of limited parametric control in AM processing approaches. Such investigations not only help to define key PSP relationships of new AM materials, but offer key insights to the broad AM industry that will help reduce the need for post-processing heat treatments of AM-fabricated parts. Although the focus of this LLNL study is on metal-based powder bed fusion AM, these results address a growing urgency for the open-sourcing of parametric controls in other AM approaches to accommodate the processing requirements of next generation AM materials.

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[9]Wu, Amanda S., Donald W. Brown, Mukul Kumar, Gilbert F. Gallegos, and Wayne E. King, "An Experimental Investigation into Additive Manufacturing-Induced Residual Stresses in 316L Stainless Steel," Metallurgical and Materials Transactions A 45, no. 13 (2014): 6260-270

# Thrust 5: Exploring Next-Generation AM Materials and Processes

AM processing approaches enable the production of complex parts—such as parts with tailored, high-performance microstructures and compositional gradients—that could not otherwise be fabricated easily or economically using conventional subtractive manufacturing processes. While new AM approaches will offer greater control of feedstock deposition rate and interlayer fusion, the next generation of materials must be compatible with and optimized for AM processing methods to yield parts with properties and performance characteristics that meet or exceed those produced using other manufacturing techniques.

## Current Challenges

The current generation of AM materials have not been optimized to fully exploit AM processing. Further, the AM community currently has an incomplete understanding of process-structure-property relationships of AM materials, processes, and parts. These limitations constrain efforts to efficiently explore and develop next-generation materials customized to the unique processing conditions of additive manufacturing. To overcome this barrier, the AM community must address the following challenges.

### Limited availability of small-lot, customized AM feedstock materials

Because feedstock materials currently used in AM were originally designed for use by conventional manufacturing approaches, the AM material supply chain is immature compared with other manufacturing industries. Current powder feedstock materials are prohibitively expensive in small-lot sizes, and it is not economically feasible for AM materials suppliers to customize feedstock compositions and characteristics for increased compatibility with AM processing. Granting material designers greater accessibility to highly customized alloys, blends, and particle size distributions (PSDs) of powder feedstock materials is critical to the accelerated development of next-generation AM materials.

### Limited ability to fabricate fully-dense AM parts

To meet end-use requirements, AM part producers are often challenged to fabricate components without undesirable porosities. Several factors—including complex binding and melting mechanisms coupled with inherently high-frequency thermal cycling from successive layer fabrication—limit the ability for AM designers to fabricate fully dense parts. Understanding the effect of key processing parameters on porosity could help to address this issue for new AM materials.

### Limited ability to achieve surface finish and accuracy comparable to conventional manufacturing techniques

Currently, AM part producers are unable to fabricate polymers with high-resolution part features comparable to those produced using conventional manufacturing techniques, such as injection molding. The ability to modify feedstock material characteristics, exploit binding and melting mechanisms of processing build layers, and strategically manage thermal processing energy could all benefit the development of new AM materials that meet surface finish requirements.

### Lack of AM machines with broad temperature and rheological processing limits

Next-generation polymeric AM materials will have temperature requirements and viscosity

characteristics that exceed the processing capabilities of current AM machines, yet most of today's AM machines are designed to handle and process a limited set of conventional polymeric feedstock materials at finite temperature and viscosity ranges. Extending the temperature and rheological processing limits of AM machines will enable materials designers to create a broader range of AM materials.

### Limited ability to print multi-materials

The ability to print multi-materials could enable the development of new AM materials with novel microstructures and advantageous anisotropic properties. However, AM designers do not currently have commercially available machines capable of accurately printing more than one material and have limited fundamental knowledge of relationships between combinations of metal, polymer, and ceramic feedstock materials.

## Priority R&D Activities

Addressing these challenges will require focused fundamental R&D activities. A complete set of R&D needs for this thrust is presented in Figure 10, along with the material classes to which the activity applies and the expected time frame. High-priority R&D activities are presented in bold in this table and further discussed in the following section.

### Develop ceramic slurry feedstock materials optimized for UV-based AM processes (0–2 years)

In UV-based AM processes, high-density layers of powders are made from ceramic slurries that have been cured using UV lasers or projected light and sintered to form porous AM parts. These parts typically require post-process heat treatment to reach higher densities. To yield post-sintered high-density AM parts with enhanced surface quality, new ceramic slurry feedstock materials must be developed to match the processing capabilities of UV-based AM systems.

### Design new multi-feed, multi-material AM feedstock delivery systems (e.g., printheads) (0–2 years)

To achieve unprecedented control of AM processes and enable the AM community to demonstrate a limitless number of multi-material combinations, AM

### Capturing the Benefits of Rapid Solidification Processing with AM

Research on rapid solidification processing (RSP) shows that it has great potential to improve ductility and fracture toughness by refining dendrite arm spacing and reducing the size of intermetallic phases. However, conventional casting processes, such as shape casting and ingot casting, have cooling rates that are too low to substantially improve alloy properties. AM processing could enable the materials community to take advantage of the benefits of RSP by enabling: 1) the ability to **refine as-built microstructures** and 2) the **extension of solid solubility** of alloy additions.

**1. Refine As-Built Microstructure**: RSP by AM processing can greatly refine the dendrite arm spacing of alloys. For conventional-shaped castings and direct-chill ingot casting, dendrite cell spacings of 25 to 250 microns are typical. But because AM solidification rates can be 1,000 degrees per second, refined dendrite cell sizes of 1 to 5 microns are possible. The refined microstructures that result could reduce solution heat treatment time and intermetallic particle size, potentially improving properties such as ductility, fracture toughness, and fatigue.

**2. Extension of Solid Solubility**: RSP by AM processing can also enable the production of new alloys by extension of solid solubility. Because AM can rapidly solidify higher concentrations of alloy elements, new alloys can be produced. Through the use of RSP, AM has a unique capability to produce near net-shaped parts from new advanced alloys with refined microstructures and improved properties that would not be possible by conventional casting processes.

Figure 10. Thrust 5 R&D Activities (priorities in **bold**)

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T5 Next-Generation AM Materials and Processes** | | | |
| **Develop ceramic slurry feedstock materials optimized for UV laser-based AM processes** | | | |
| **Design new multi-feed, multi-material AM feedstock delivery systems (e.g., printheads)** | | | |
| Investigate existing laboratory-scale rapid solidification alloys as potential candidates for new commercial-scale AM materials | | | |
| Conduct feasibility studies of new low-energy consumption feedstock production techniques beyond gas atomization, plasma rotating electrode process (PREP), and hydrogenation/dehydrogenation (HDH) that achieve commercially acceptable particle size distribution | | | |
| Enhance the processing capabilities of directed energy deposition (DED) processing machines to enable the fabrication of FGMs | | | |
| Explore surface treatment and impregnation techniques of polymeric AM parts | | | |
| Design novel AM processing equipment capable of 3-D versus traditional 2-D layering methods | | | |
| Optimize new lasers based on specific characteristics of new/desired feedstock materials | | | |
| **Develop new AM process-compatible metal alloys that have superior mechanical or physical properties compared with alloys produced by conventional manufacturing processes** | | | |
| **Investigate AM processing techniques capable of printing all polymer resin grades** | | | |
| Construct a laser-based hot wire feedstock deposition method that uses low-level heat input to enable greater process control for fabrication of functionally graded metallic materials | | | |
| Implement low-energy, high-yield gas atomization strategies for producing metallic feedstock materials | | | |

Metals Polymers Ceramics

| | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T5 Next-Generation AM Materials and Processes** | | | |
| Formulate multifunctional (e.g., thermal, electric, optical properties) polymer parts via fused deposition modeling (FDM) with tailored material properties comparable to that of injection molded parts | | Polymers | |
| Create AM machines or equipment peripherals that combine thermal curing with ultraviolet (UV) curing or photo-curing to accommodate new thermosetting polymer materials | | Polymers | |
| Generate new thermoplastic polymer nanocomposites via SLS that exhibit less anisotropy than traditional AM polymers | | Polymers | |
| Develop processes for fabricating reactive thermosetting polymeric materials | | Polymers | |
| Create new AM processes that enable the fabrication of functionally graded ceramic materials | | Ceramics | |
| Evaluate the potential for high-temperature infrared (IR) transparent optical ceramic materials | | Ceramics | |
| Develop reactive sintering approaches for fabricating ceramic AM parts | | Ceramics | |
| Develop and integrate laser-assisted cold spray techniques into open-source hybrid AM processing approaches to fabricate solid-state electronic components | | Metals, Ceramics | |
| Introduce novel sintering strategies to achieve fully dense powder-based AM parts | | Metals, Polymers, Ceramics | |
| Formulate fundamental scaling laws that expose realistic pathways for modifying AM equipment to reduce processing cycle times (e.g., altering the size and shape of the printhead/nozzle) | | Metals, Polymers, Ceramics | |
| Democratize open-source laboratory-scale AM processing equipment that allow users to modify parameters to use a more diverse set of feedstock materials | | Metals, Polymers, Ceramics | |
| **Design new AM processing equipment that reduces the need for secondary processing operations** | | | Metals, Polymers, Ceramics |
| **Develop AM processing techniques capable of printing parts with low surface roughness values** | | | Metals, Polymers, Ceramics |

| Metals, Polymers, Ceramics | near (0-2 years) | mid (3-4 years) | long (5-10 years) |
|---|---|---|---|
| **T5 Next-Generation AM Materials and Processes** | | | |
| **Establish AM processing techniques capable of controlling polymeric part architecture and crystallinity** | | | |
| Design new AM nickel-based superalloys for hot gas path component applications | | | |
| Design new AM processing routes for manufacturing optically functional photonic materials | | | |
| Develop AM processes capable of processing speeds that are greater than 1,000 times faster than currently available machines by concurrently designing the machine and material | | | |
| Develop AM processing techniques that combine additive printing techniques (e.g., powder- and extrusion-based) to create hybrid AM parts | | | |

machine developers must design new types of multi-material feedstock delivery systems (e.g., printheads) capable of accurately processing AM parts with desired compositional gradients or blends. These new AM printheads must be able to independently control the deposition of multiple feedstock materials to tailor the microstructural characteristics of AM parts.

### Develop new AM process-compatible metal alloys that have superior mechanical or physical properties compared with alloys produced by conventional manufacturing processes (3–4 years)

The AM community should explore the development of new AM alloys with superior strength, hardness, and fatigue resistance compared to traditional alloys fabricated through conventional manufacturing processes such as casting, forging, welding, and extrusion. To achieve superior properties in new AM alloys, material designers should leverage the unique rapid solidification processing advantages of AM to create extended solubility and functionally graded alloys with highly refined microstructures. The AM community should determine the appropriate feedstock characteristics, compatible AM processing techniques, and required processing variables to achieve performance targets. The development of new alloys will help AM processing approaches become increasingly competitive with conventional manufacturing techniques for direct part production, functional prototyping, and repair applications.

### Investigate AM processing techniques capable of printing all polymer resin grades (3–4 years)

The next generation of AM polymer processing equipment must be designed to accommodate the specific temperature and viscosity requirements of new polymeric feedstock materials and should include integrated process controls that allow users to precisely adjust processing approaches. These techniques will reduce the number of machines AM part designers need to rely on and will enable them to process a greater variety of new polymeric feedstock materials.

### Design new AM processing equipment that reduces the need for secondary processing operations (5–10 years)

Post-processing methods are often needed to eliminate residual stresses, close porosity defects, and improve the surface quality of AM

parts. To enable material designers to fabricate higher-performance parts in fewer steps, new AM techniques should enable processing parameters to be adjusted as a function of the feedstock material's viscosity and wettability, and must allow materials developers to control thermal gradient profiles to mitigate solidification instabilities that lead to undesirable part features. In addition, thermal processing energy should be managed through independent control of the laser heat source and auxiliary chamber heating and cooling techniques to achieve desired microstructural features without the need for costly post-processing.

### Develop AM processing techniques capable of printing parts with low surface roughness values (5–10 years)

New AM processing techniques must allow the AM community to carefully manage the application of thermal energy to control the viscosity and surface tension of feedstock materials during AM builds. The resulting reduction in thermal gradient fluctuations could help the AM community achieve surface roughness values as low as 5 microns. Material designers should also consider the impact of feedstock material characteristics on surface roughness of parts and investigate changes to feedstock variables that could result in higher-resolution features.

### Establish AM processing techniques capable of controlling polymeric part architecture and crystallinity (5–10 years)

New AM processing techniques that control the molecular orientation of polymers should be developed to expand the range of AM materials suitable for end-use applications that require parts with anisotropic properties and enhanced fatigue life. The most common AM application of this controlled part morphology is a flexible "living hinge"—a thin web of plastic material that connects two segments of a part. New AM processes should rely on novel equipment tool paths that manipulate solidification rates through control of thermal gradients in the build material. These machine processing procedures must also achieve the appropriate melting and viscosity behavior of polymeric feedstock materials to yield adequate strength and fatigue and to mitigate part shrinkage and porosity.

## Case Study: **Spatial Characterization of Additively Manufactured Blended-Powder Shape Memory Alloy**

*Applied Research Laboratory, The Pennsylvania State University*

### CHALLENGE

Shape memory alloys (SMA) are used in a number of commercial applications—including aerospace morphing structures, biomedical devices, and sensors—due to their ability to revert back to their original shapes upon heating. However, SMAs are extremely challenging to process because their shape memory behavior is highly susceptible to local geometric discontinuities or cracks formed during shaping, heat treating, and machining of cast ingots. The manufacturing community has consequently turned its attention toward AM processing as a prospective solution for controlling thermal-induced shape memory behavior of SMAs while providing exceptional density and geometric complexity in fabricated parts.

### APPROACH

Using a commercially successful SMA cast ingot alloy composed of nickel and titanium (i.e., NiTi), a team of researchers at Penn State's Applied Research Laboratory employed a laser-based directed energy deposition (DED) technique with preheated substrates to process blended NiTi powders and investigate how the shape memory behavior can be controlled.[10] Researchers studied the impact of different thermal histories on various ratios of nickel and titanium by measuring the thermal-induced martensitic phase transformation (TIMT) temperature at selected locations of as-deposited builds. This temperature can be used as a means for determining the shape memory response of the material. Their investigation confirmed that coupling the DED AM process with preheated substrates enables systematic and controlled heat treatment of SMA transformation temperatures. Furthermore, the use of elementally blended powders in this fundamental AM research study is not only a low-cost alternative to fabricating parts with pre-alloyed powders, but also enables a more extensive range of alloy concentrations to be investigated.

### IMPACT

Penn State's study of AM-fabricated SMAs demonstrates that the unique processing advantages offered by AM can accelerate the pace of materials discovery, design, and development. While the use of elementally blended powders permitted the research team to more easily modify the materials composition of NiTi-based SMAs, the application of process controls for substrate-preheating mitigated residual stresses that otherwise compromise material integrity. These innovative techniques demonstrate how the research community can leverage the inherent design freedom of AM fabrication methods to accelerate fundamental materials research and maximize the performance characteristics of next-generation AM materials.

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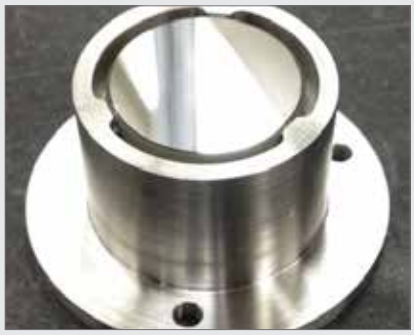
[10]Hamilton, Reginald F., Todd A. Palmer, and Beth A. Bimber, "Spatial Characterization of the Thermal-induced Phase Transformation throughout As-deposited Additive Manufactured NiTi Bulk Builds." Scripta Materialia 101 (2015): 56-59.

## Case Study: **Compositionally Graded Metal Alloy Fabrication via AM Gradient Processing**

*Jet Propulsion Laboratory, California Institute of Technology and Penn State University*

### CHALLENGE



JPL's prototype of a compositionally graded mirror mount made by a new metal-based AM powder deposition technique.

To withstand extreme temperature fluctuations in outer space environments, spacecraft components are designed with a range of mechanical and physical property targets that can only be attained through the use of multiple materials. Although these spacecraft components can be manufactured through traditional joining processes—including epoxy adhesive bonding—to assemble dissimilar materials, engineers are exploring innovative pathways for designing parts as singular objects that exhibit unique property combinations and geometric complexities. Since advanced composite materials with such property combinations cannot be fabricated through the use of traditional manufacturing techniques, engineers must rely on novel AM techniques as the principal method for developing a new generation of compositionally graded materials to meet increasingly demanding design requirements of end-use applications.

### APPROACH

JPL scientists developed an innovative metal-based AM processing technique in which the feedstock powder composition gradually changes as part layers are additively printed.[11] Through collaborations with Penn State University, JPL scientists successfully applied their gradient alloy concept to produce a mirror mount component for a space optics application. The gradient alloy component design—which contains a nickel and nickel-iron alloy at the top of the part and stainless steel at the base—replaces epoxy bonding techniques and mitigates the effects of thermal expansion caused by the extreme temperatures of outer space. As a result, this game-changing AM gradient processing technique increases the robustness and longevity of critical spacecraft components on future missions.

### IMPACT

Gradual modification of material composition represents a groundbreaking new tool that can be leveraged by the AM community in pursuit of fundamental materials research and development. While JPL's processing approach allows users to exploit unique, advantageous combinations of material properties in individually processed AM parts, it may also be used for the development and validation of fundamental phase diagrams. Such phase diagrams can help researchers generate predictive process maps between various material compositions to identify suitable gradient alloy systems that achieve the property requirements for a given application.

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[11] Hofmann, Douglas C., Joanna Kolodziejska, Scott Roberts, Richard Otis, Robert Peter Dillon, Jong-Ook Suh, Zi-Kui Liu, and John-Paul Borgonia, "Compositionally Graded Metals: A New Frontier of Additive Manufacturing," Journal of Materials Research 29, no. 17 (2014): 1899-910.

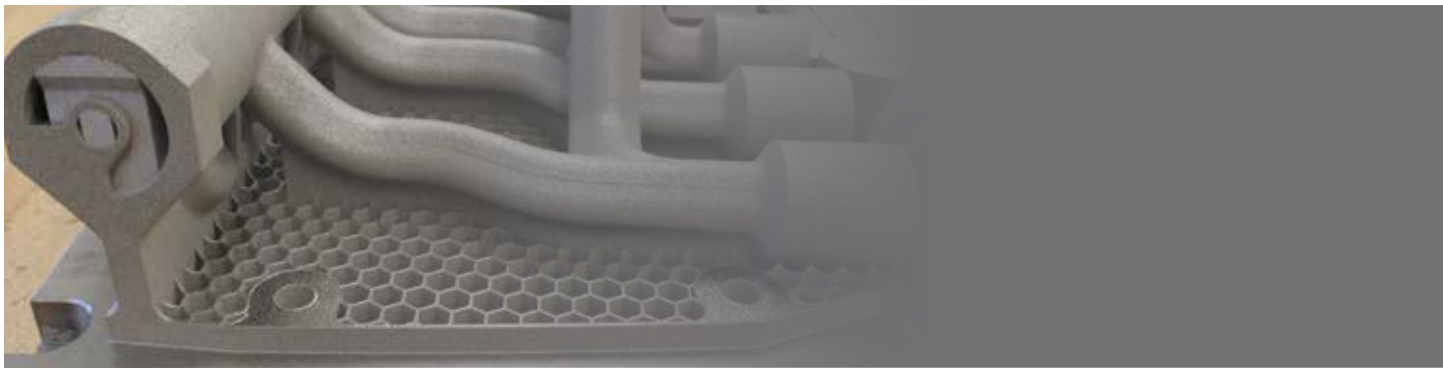
# Path Forward

Development of new advanced materials will facilitate growth of the AM industry and enable AM technologies to drive rapid innovation and shape the future competitiveness of advanced manufacturing in the United States. This roadmap defines the challenges that currently impede materials innovation in the AM field and identifies fundamental research and development activities to accelerate the design of new AM materials. The roadmap outlines a strategy for the next 10 years that will enable manufacturers to extensively integrate new AM materials into high-value products and services that take full advantage of AM processing capabilities.

Although many applied research and development efforts to advance the state of AM technologies are currently under way, successful materials innovation will require an alignment of efforts throughout the AM community. To help coordinate these efforts, the Pennsylvania State University (PSU) will launch the Consortium for Additive Manufacturing Materials (CAMM), which is envisioned as a self-supporting entity that will help direct fundamental materials innovation in the AM field. The goal of CAMM is to enable materials producers, research institutions, AM equipment suppliers, part manufacturers, and end users to collectively focus on the fundamental research and development (Technology Readiness Levels [TRL] 1–3) of new AM materials and processes. The fundamental understanding derived through CAMM projects will provide valuable information for applied R&D projects conducted by America Makes and other entities along the AM value chain, ultimately accelerating materials innovation and commercial deployment.

Pursuing the fundamental research activities identified in this roadmap will lay the groundwork for a new generation of advanced AM materials and processes that can enhance competiveness of U.S. manufacturing. Achieving these advances, however, will require significant R&D resources to pursue these activities and an emphasis on education and training opportunities to build a robust and skilled AM workforce. Implementation of these actions by the broad AM community will help transform the landscape of manufacturing and innovative product design and address the nation's growing need for improved manufacturing productivity and efficiency and for the creation of new jobs. Coupling fundamental materials research with AM's cornerstone advantage of accelerated product development through integrated design and manufacturing will help transform U.S. advanced manufacturing and propel the nation into a new industrial revolution.

Figure 11. CAMM's Role in the Advanced AM Materials and Process R&D Pipeline



# Appendix A. Roadmap Contributors

**Iver Anderson**
Ames Laboratory

**Clinton Armstrong**
Westinghouse Nuclear

**Katy Ashby**
University of Louisville

**Suresh Babu**
University of Tennessee, Knoxville

**Alex Bailey**
Northrop Grumman

**Holly Barth**
Lawrence Livermore National Laboratory

**Travis Beaulieu**
RTI International

**Jim Beckman**
Crucible Industries

**Allison Beese**
Penn State University

**Michael Blaszkiewicz**
SABIC Innovative Plastics

**Jesse Boyer**
Pratt & Whitney – United Technologies

**Ross Brindle**
Nexight Group

**Tom Briselden**
SpinWorks

**Dhiraj Catoor**
Medtronic

**Long-Qing Chen**
Penn State University

**Bill Cleary**
Westinghouse Nuclear

**Teresa Clement**
Raytheon Company

**Peter Collins**
University of North Texas

**Shane Collins**
Incodema3D

**Rob Cooney**
Plastikos

**Bill Cowan**
EOS e-Manufacturing Solutions

**Keith Cox**
SABIC Innovative Plastics

**Bill Crider**
Northrop Grumman

**Suman Das**
Georgia Institute of Technology

**Mark DeAngelo**
SAE International

**Tarasankar DebRoy**
Penn State University

**Ryan DeHoff**
Oak Ridge National Laboratory

**Jason Detsch**
Amphenol Corporation

**Greg Dillon***
Penn State University

**Michael Durina**
MD Plastics

**Tahany El-Wardany**
United Technologies Research Center

**Amanda Grow**
The Timken Company

**Richard Grylls**
Optomec

**Jesse (Jiaxi) Guo**
Penn State University

**Ian Haggerty**
Battelle

**Gary Halada**
Stony Brook University

**Reggie Hamilton**
Penn State University

**Ed Herderick**
GE Advanced Manufacturing Initiatives Group

**Mike Hickner**
Penn State University

**Greg Hildeman**
Nexight Group

**Patricia Hubbard**
Polyone Corporation

**Thomas Hughes**
Polyone Corporation

**Warren Hunt**
Nexight Group

**John Hunter**
LPW Technology

**Christian G. Joest**
Imperial Machine & Tool Co.

**David Saint John**
Penn State University

**Philip Katen**
Plastikos

**Ryan Katen**
Micro Mold

**David Keicher**
Sandia National Laboratories

**Jayme Keist**
Penn State University

**Jared Kosters**
Nexight Group

**Howard Kuhn**
ExOne Company

**Libby Kupp**
Penn State University

*Member of the CAMM technical leadership team

**Jeff Lantz**
FMC Technologies

**Bruce Lawton**
Bausch & Lomb

**Chris Layer**
Moog

**Lyle Levine**
National Institute of Standards and Technology

**Sarah Lichtner**
Nexight Group

**Michael Lister**
SECO/Warwick Group

**Zi-Kui Liu**
Penn State University

**Andrew Lucibello**
EOS e-Manufacturing Solutions

**Stephen Luckowski**
U.S. Army Armament Research, Development and Engineering Center (ARDEC)

**Rich Martukanitz***
Penn State University

**Scott Mayes**
Truck-Lite Co.

**Jyoti Mazumder**
DM3D Technology

**Tom McDonald**
Optomec

**Brian McTiernan**
ATI Powder Metals

**Gary Messing***
Penn State University

**Brent Mitchell**
Stryker

**Wojciech Modrzyk**
SECO/Warwick Group

**Byron Mohr**
Dresser-Rand Group

**Jason E. Morris**
Zurn

**Ray Moses**
Controlled Molding

**Alan O'Connor**
RTI International

**Neal Orringer**
3D Systems

**Richard Otis**
Penn State University

**Lindsay Pack**
Nexight Group

**Vandita Pai**
SABIC Innovative Plastics

**Todd Palmer***
Penn State University

**Matt Pantano**
Sciaky

**Nathan Parsons**
Caterpillar Inc

**Adam Pilecki**
Molex

**Paul Prichard**
Kennametal

**Stephen Prichard**
GE Transportation

**Scott Rawson**
Lord Corporation

**Paul Rehrig**
Saint-Gobain

**Markus Reiterer**
Medronic

**Jerry Rhinehart**
Delphi Packard Electrical/Electronic Architecture

**Marina Rogunova**
Bayer Material Science

**Brian Rosenberger**
Lockheed Martin

**David Rowatt**
Schlumberger

**Litsa Rubino**
Delphi Packard Electrical/Electronic Architecture

**Michael Schmidt**
Carpenter Powder Products

**Troy Scott**
RTI International

**James Sears**
GE Global Research

**Al Segall**
Penn State University

**Tim Simpson***
Penn State University

**John Slotwinski**
The Johns Hopkins University Applied Physics Laboratory

**Steve Smalley**
Northrop Grumman

**Mark Stoudt**
National Institute of Standards and Technology

**Rajiv Tandon**
Magnesium Elektron

**Talbot Thrasher**
Orbital ATK

**Jason Ting**
Retech Systems

**Jason Travitz**
Molex

**Charles Tuffile**
NanoSteel

**Emma White**
Ames Laboratory

**John Wilczynski**
America Makes

**Jim Williams**
3D Systems

**Paul Witherell**
National Institute of Standards and Technology

**Amanda Wu**
Lawrence Livermore National Laboratory

**Cagatay Yanar**
Alcoa

*Member of the CAMM technical leadership team

# Appendix B. Acronyms and Abbreviations

| | |
|---|---|
| **ABS** | acrylonitrile butadiene styrene |
| **AM** | additive manufacturing |
| **AMTech** | Advanced Manufacturing Technology Consortia program |
| **CAD** | computer-aided design |
| **CAM** | computer-aided manufacturing |
| **CAMM** | Consortium for Additive Manufacturing Materials |
| **CFD** | computational fluid dynamics |
| **DED** | directed energy deposition |
| **DMLM** | direct metal laser melting |
| **DMD** | direct metal deposition |
| **FDM** | fused deposition modeling |
| **FEA** | finite element analysis |
| **FGM** | functionally graded material |
| **HDH** | hydrogenation/dehydrogenation |
| **ICME** | integrated computational materials engineering |
| **IR** | infrared |
| **NDE** | non-destructive evaluation |
| **NDT** | non-destructive testing |
| **NIST** | National Institute of Standards and Technology |
| **PBF** | powder bed fusion |
| **PREP** | plasma rotating electrode process |
| **PSD** | particle size distribution |
| **PSP** | process-structure-property |
| **PSU** | Pennsylvania State University |
| **RSP** | rapid solidification processing |
| **SLS** | selective laser sintering |
| **SPM** | Scanning Probe Microscopy |
| **UTS** | ultimate tensile strength |
| **UV** | ultraviolet |
| **YS** | yield strength |