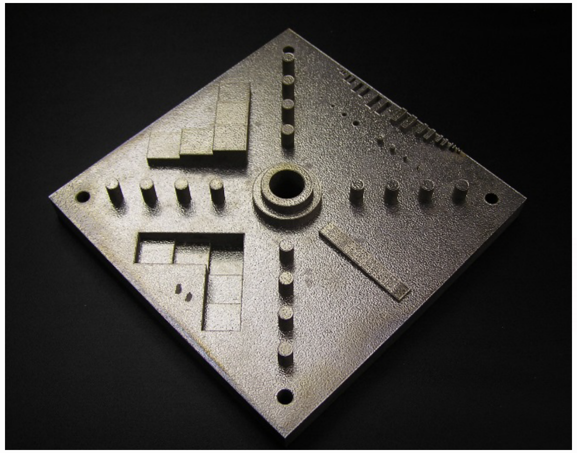
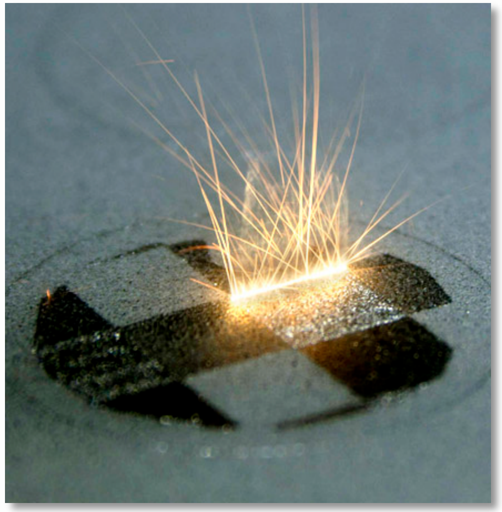
Measurement Science and Standards for Metals-Based Additive Manufacturing



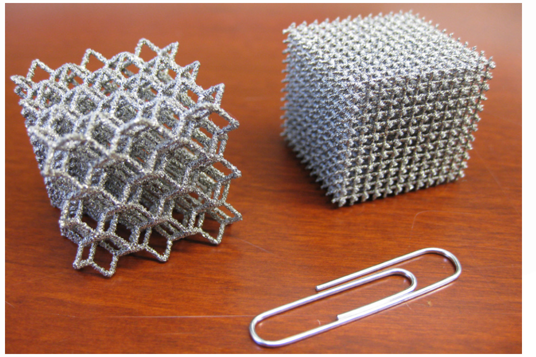


Kevin Jurrens

Deputy Chief, Intelligent Systems Division

Engineering Laboratory

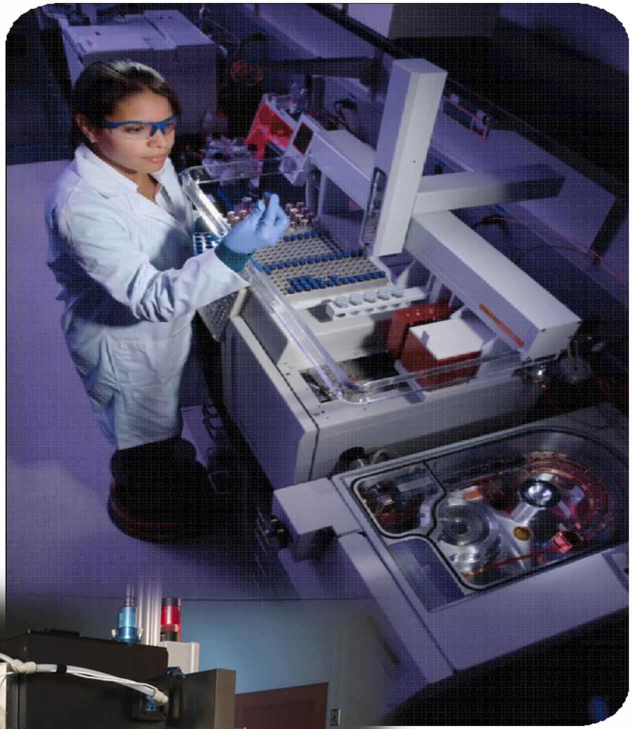
National Institute of Standards and Technology (NIST)

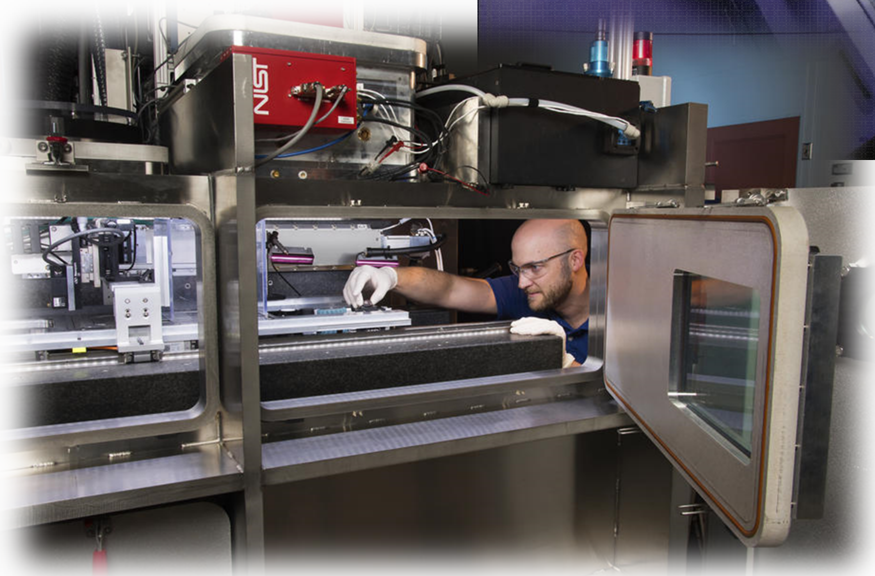


National Institute of Standards and Technology (NIST)

- Federal agency in U.S. Department of Commerce
- National Metrology Institute for the United States
- Mission:

  To promote U.S. innovation and industrial competitiveness by advancing **measurement science, standards**, and **technology** in ways that enhance economic security and improve our quality of life





NIST and Manufacturing

"It is therefore the unanimous opinion of your committee that no more essential aid could be given to manufacturing […] than by the establishment of the [National Bureau of Standards]."
House Committee report, May 1900

Infrastructural Metrology

Measurement Uncertainty

Rigorous Traceability

Neutral and Unbiased

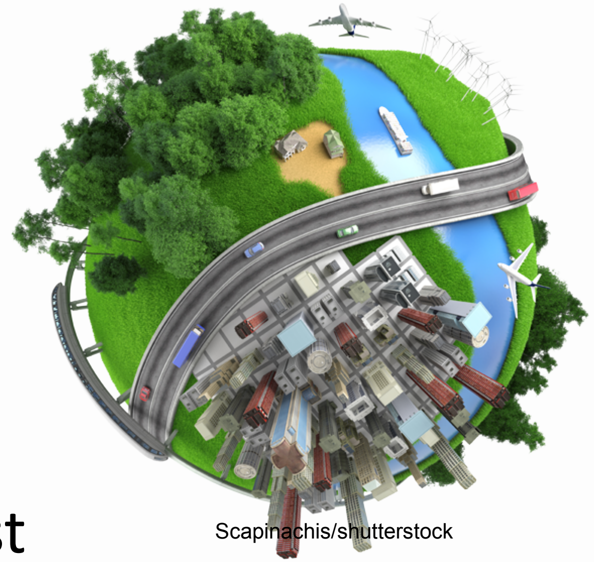
A partner to US manufacturers for more than a century, NIST helps the nation's manufacturers to invent, innovate, and create through:

- **Measurement science** – manufacturers and technology providers use NIST test methods, measurement tools, performance measures, and scientific data every day
- **Advanced materials** – NIST is building a materials infrastructure to accelerate the timeline from design to deployment of new materials
- **Standards development** – NIST provides the scientific and technical basis for voluntary consensus codes and standards
- **Partnerships** – collaborations with the private sector and academic organizations help advance and disseminate research and support US manufacturers

➢ **Measurements and Standards**

Manufacturers Face Many Competitive Challenges

- Increase **product variety** and **customization**
- Get products **to market faster**
- Design and sell to **global markets**
- **Reduce risks** of sourcing from **global supply chains**
- Increase **productivity**, reduce costs
- Increase **quality** without increasing cost
- Reduce **environmental impacts** without increasing cost
- **Guard against security risks** without increasing costs
- Generate **value from services** throughout the product life-cycle



Scapinachis/shutterstock

Technology Solutions are Advancing

- **Internet of Things**/Ubiquitous Sensing
- **Big data** & advanced analytics
- **Cloud computing**
- **Broadband** communications, **wireless**
- **Mobile computing**/apps
- **Security** technologies
- **Model-based** everything
- **Cyber-physical systems** engineering
- Advanced **materials**
- **Additive processes**/3D printing
- Advanced **robotics**

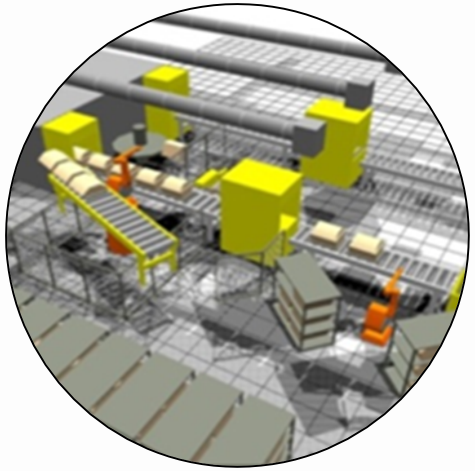
<u>Smart Manufacturing</u>: synthesis of advanced manufacturing capabilities and digital technologies to produce highly customizable products faster, cheaper, better, and greener

NIST Smart Manufacturing Research Programs

Enabling Disruptive Process Technologies

Enabling System Level Technologies

Additive Manufacturing



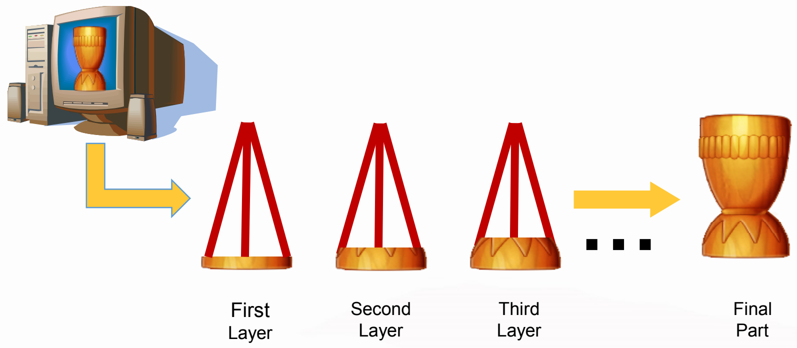
System Design and Analysis

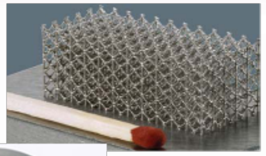
Robotic Systems

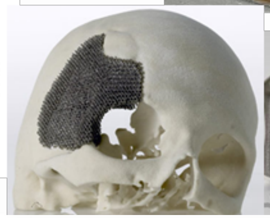
Operations Planning and Control

Why Focus on Additive Manufacturing?

<u>Definition:</u> The process of joining materials, usually layer upon layer, to make objects from 3D model data.



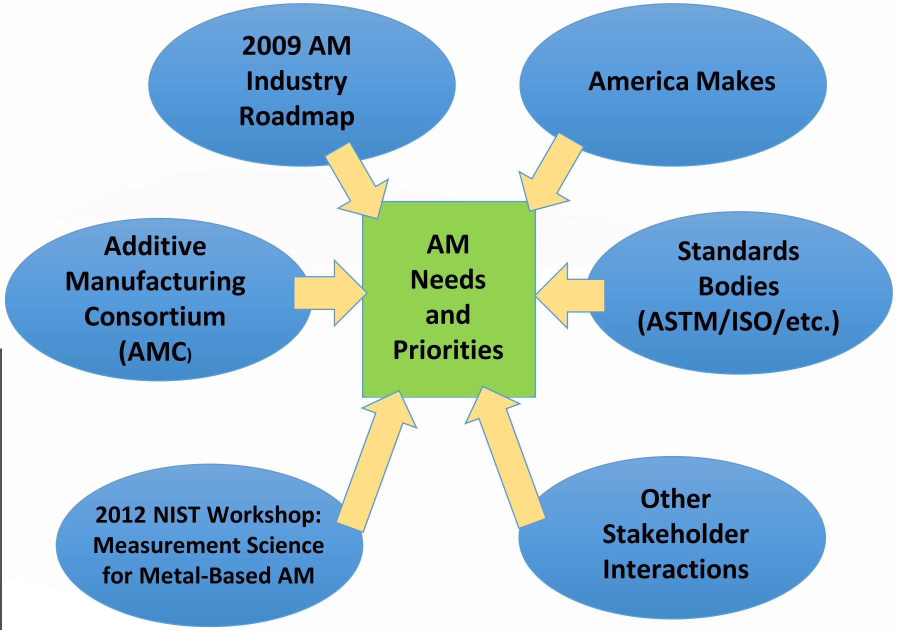


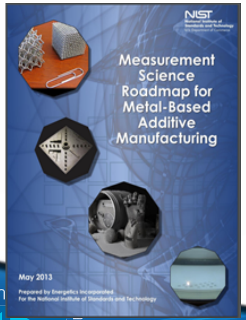


- AM provides rapid art-to-part capability of fabricating **complex, high-value, highly-customized parts** – significant revolutionary potential for U.S. manufacturing
- Worldwide AM products and services - $ 5.1 B (Wohler's report)
    - **5 fold growth in the past 6 years!**
- U.S. market for AM is currently about $ 2 B
- Metal-based AM is still in its infancy for applications in aerospace, biomedical, dental, and automotive industries
- Much momentum and rapid changes – the AM industry is poised for growth, innovations, and new products

Measurement Science Needs for AM

Uncertainties in feedstock material characteristics coupled with uncertainties in the AM process lead to uncertainties in the final product



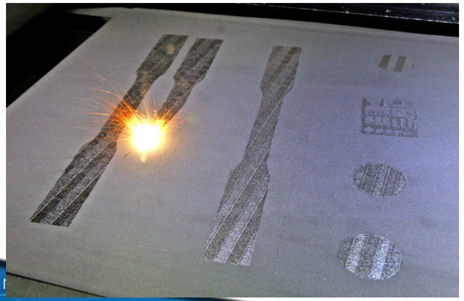


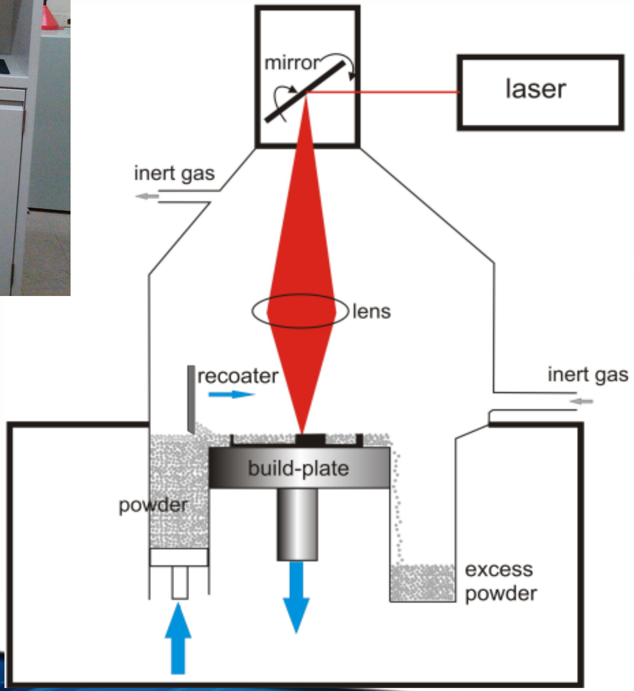
Major barriers to broad adoption of AM include:

- Limited material types and **unknown / non-uniform properties**
- Lack of **process repeatability** and inconsistent system performance
- Consensus protocols and test data for **qualification and certification** do not exist
- Insufficient **part accuracy** without significant post-processing
- Insufficient **surface finish**
- Lack of **AM standards**
- **Insufficient data** to develop robust material specifications
- Need for improved **non-destructive evaluation methods** for complex defects and part geometry
- Requirements for secondary post-processing
- Lack of AM-specific **design tools / design guidelines** to take advantage of new AM capabilities

NIST Measurement Science for Additive Manufacturing (MSAM) Program

- Measurement science advancements in four program thrust areas
- Focus on metals-based AM processes and systems
- Goal: Enable rapid design-to-product transformation





Laser
Powder
Bed
Fusion
Process

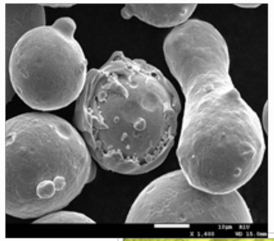
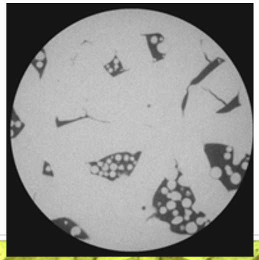
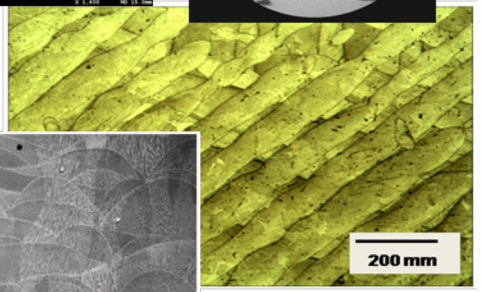
Program thrusts:

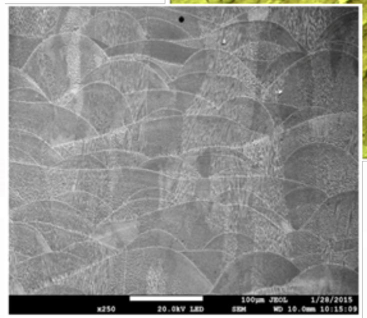
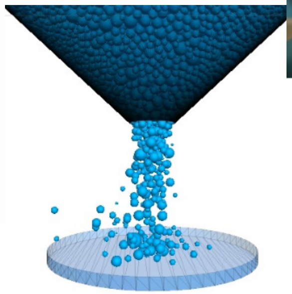
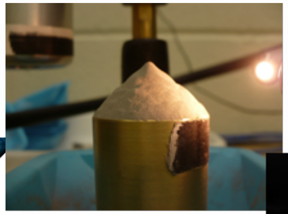
- Characterization of AM Materials
- Qualification of AM Materials, Processes, and Parts
- Real-Time Monitoring and Control of AM Processes
- Systems Integration for AM

Characterization of AM materials

Objective: Deliver new standardized material characterization methods, exemplar data, and databases to accelerate the design and use of additive manufacturing parts in high-performance applications

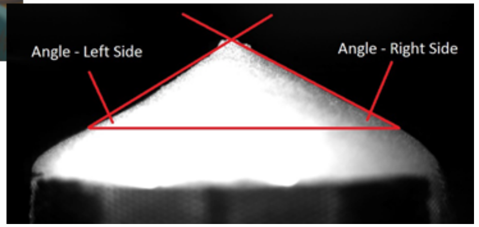
- Methods to characterize metal powder
  - Dimensional – mechanical – thermal – powder bed density – powder condition for recyclability
- Methods to characterize built materials
  - Mechanical – microstructure – porosity – density – post processing
- Exemplar data
  - Round robin studies – variability analyses – powder/process/material relationships
- AM Material public database
  - AM schema/ database –- populate with round robin data

Measurement methods

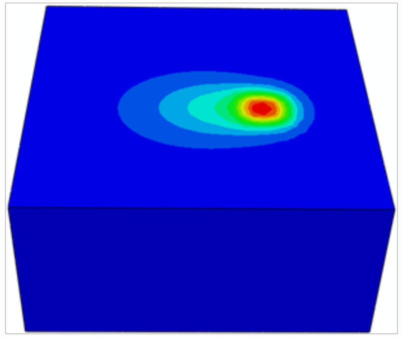
- SEM (size, morphology)
- Quantitative X-Ray Diffraction (chemical composition)
- Laser Diffraction (size distribution)
- Dynamic imaging (size distribution)
- X-Ray Computed Tomography (porosity)
- X-Ray Photoelectron Spectroscopy (elemental chemical states)



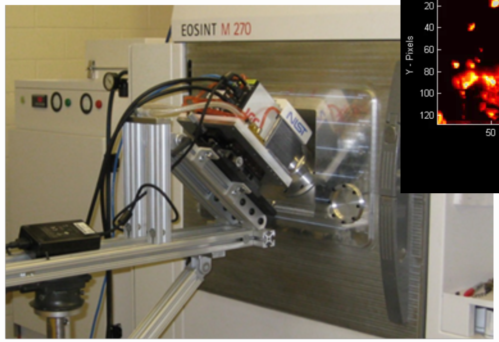
Qualification of Additive Manufacturing Materials, Processes, & Parts

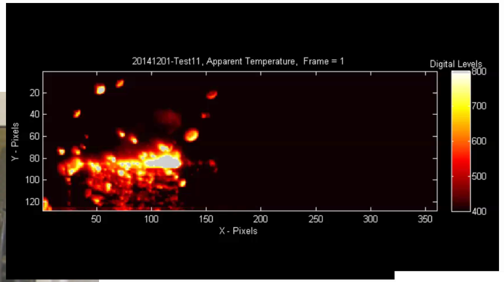
Objective: Develop test methods and protocols, provide reference data, and establish requirements to reduce the cost and time to qualify AM materials, processes, and parts.

- **Reference data** to be used by modeling community to improve model inputs and validate model outputs
    - Temperature – Microstructure – Residual stress
- **Pre-process and post-process test methods** to characterize performance and assess part quality
    - Machine performance characterization – XCT of AM parts
- **Minimum requirements for testing data** supporting material and process specifications

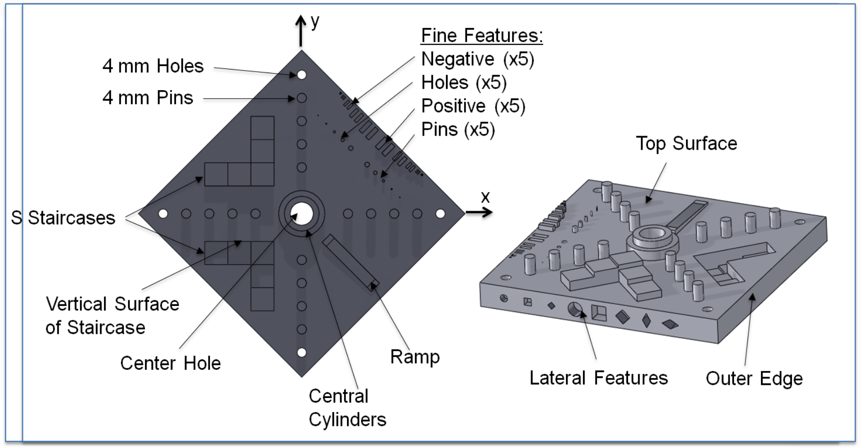


Finite element modeling





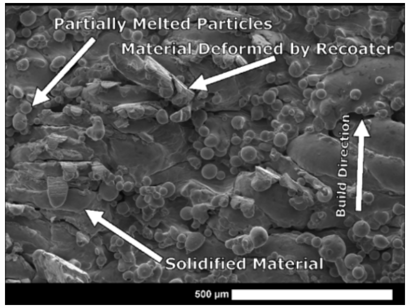
NIST AM Test Artifact



Surface roughness

Traditional roughness parameters (*Ra*) are insufficient or non-descriptive

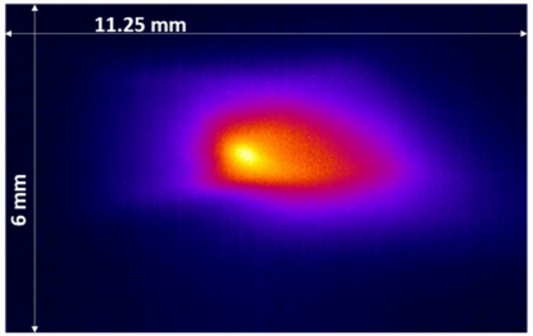
Initial study on down-facing surfaces shows two potential parameters: *Rpc* and *RSm*

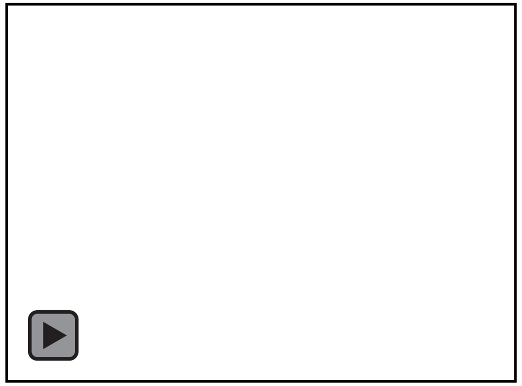


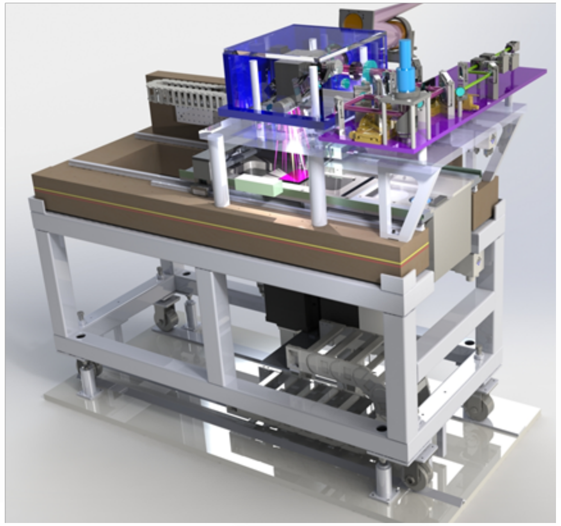
Real-Time Monitoring and Control of Additive Manufacturing Processes

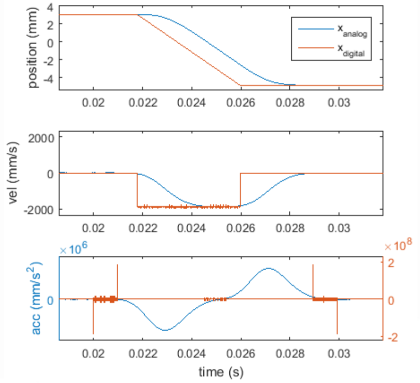
Objective: Develop process metrology, in-process sensing methods, and real-time process control approaches to maximize part quality and production throughput in additive manufacturing

- Methods enabling **in-situ process monitoring and control** to robustly predict part quality
  - Process metrology – signature analysis – uncertainty quantification – AM G-Code for machine control
- **Reference data** comparing high fidelity measurements to low-fidelity sensor signals
  - Process dynamics – temperature gradients/cooling rates
- **Reference data** identifying correlations to enable intelligent controller design
  - **Process parameters ←→ Process signatures ←→ Part quality**
- The Additive Manufacturing Metrology Testbed (AMMT)







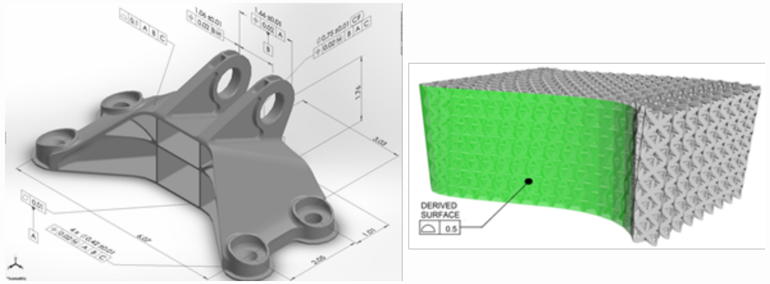


engineering laboratory

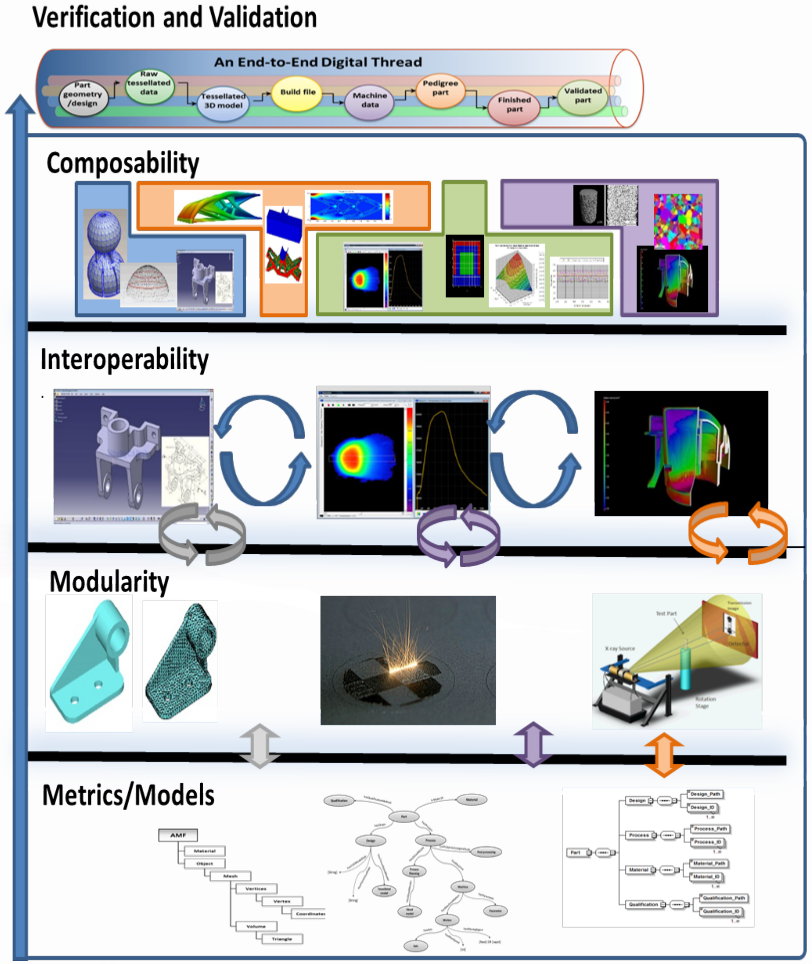
MSAM

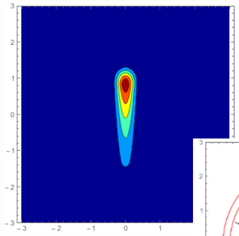
Systems Integration for AM

Objective: Deliver an **information systems architecture,** including metrics, **information models**, and **validation methods** to shorten the design-to-product cycle time in additive manufacturing

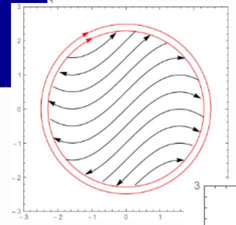


- Product definition and tolerance representation (GD&T) for AM
- AM design rules and their fundamental principles
- Characterization, composition, and UQ for PBF predictive models
- Data structure & support for AM parts, processes, and materials
- Path and process planning at the mesoscale for PBF

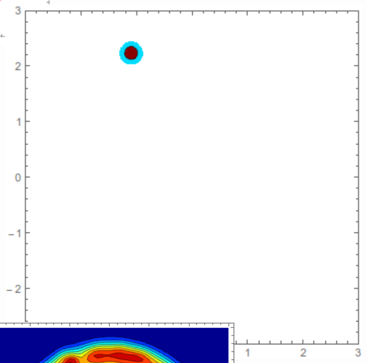




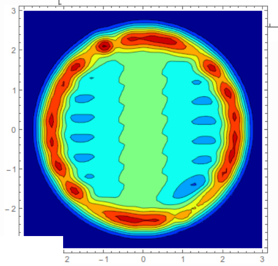
Analytical thermal model



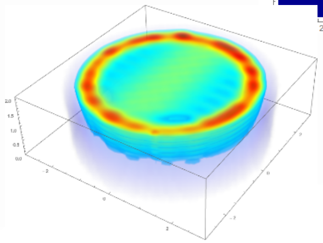
Scan paths



Dynamic slice model – combination of physics and geometry



Process composition

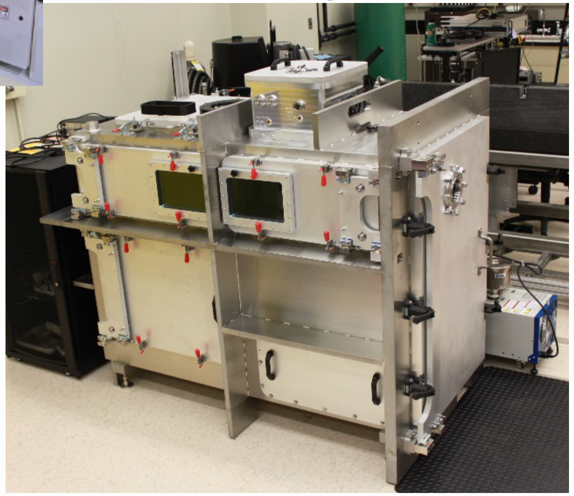
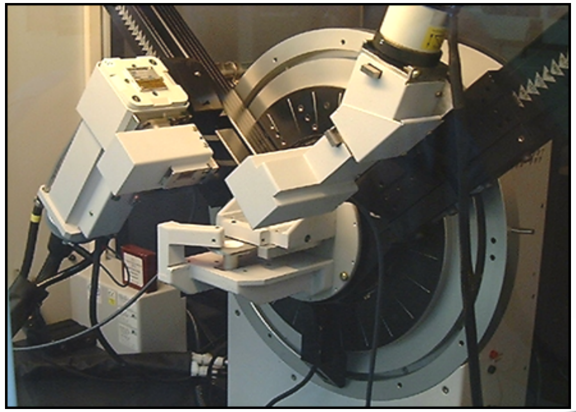


Final model by repeated stacking

Research Testbeds and Facilities

- Additive Manufacturing Research Center (AMRC)
- Commercial AM platforms
  - EOS M270, EOS M290
  - Optomec LENS MR7, ExOne
- AM Metrology Testbed (AMMT)
- Powder Characterization Laboratory
  - Dynamic imaging for particle size distribution
  - Laser flash for thermal properties
  - Rheometer and powder spreading test platform
- Post-processing and testing facilities
  - High temperature heat treatment furnace, electrical discharge machining
  - X-ray computed tomography, white light interferometry, mechanical testing, electron microscopes



Interactions and Collaborations

- **NIST internal collaborations**
  - **Materials Measurements Laboratory** – AM material property measurements, material testing and modeling
  - **Center for Neutron Research** – neutron imaging, residual stress measurements
  - **Physical Measurements Laboratory** – thermal emissivity measurements for AM processes, laser power measurements
  - **Information Technology Laboratory** – statistical analysis of AM Round Robin studies, AM Materials Database development
  - **Manufacturing Extension Partnership** – industry outreach
  - **Office of Advanced Manufacturing Programs** – Measurement science for advanced manufacturing awards
- **Consortia**: America Makes, Additive Manufacturing Consortium, GO Additive, AM-Bench
- **Roadmapping Activities**: America Makes, ANSI/AMSC, DoD, AMTech
- **Federal collaborators**: LLNL, ORNL, BIS, DARPA, AFRL, ARL, NRL, NSF, NASA, DOE, FAA, FDA, NRC
- **Industry**: GE Aviation and GE Global Research, Honeywell Aerospace, Pratt & Whitney, Carpenter Powder, NCMS, APL, ExOne, Northstar, Nikon, Xometry, TA Instruments, Ansys, SigmaLabs, Granta, EWI, and others
- **Academia**: CMU, Virginia Tech, NC State, Penn State, Rutgers, UT Austin, U of Arkansas, U of Alabama, NIU, U of Michigan, U of Louisville, U of Nebraska, U Mass, UNCC, UDC, U of Maryland, Purdue, and others
- **Local outreach**: National Maker Faire, Capitol Hill Maker Faire, US Science and Engineering Festival

Role of Additive Manufacturing Standards

- Standards can be used for (among others):
    - specifying requirements
    - communicating guidance
    - documenting best practices
    - defining test methods and protocols
    - documenting technical data
    - accelerating the adoption of new technologies
- Certifying bodies typically reference publicly available standards in their procedures
- Standards development in the U.S. is conducted through voluntary participation and consensus

ASTM Committee F42 on Additive Manufacturing Technologies

- Established in January 2009 to address high-priority standards needs
- F42 subcommittees:
  - *Terminology*
  - *Test Methods*
  - *Materials and Processes*
  - *Design (including data formats)*
  - *Environment, Health, and Safety*
  - *U.S. Technical Advisory Group (TAG) to ISO TC 261*
- F42 roster: ~600 members; 22 countries represented
- Status: 22 approved standards; 25+ work items in development
- http://www.astm.org/COMMITTEE/F42.htm

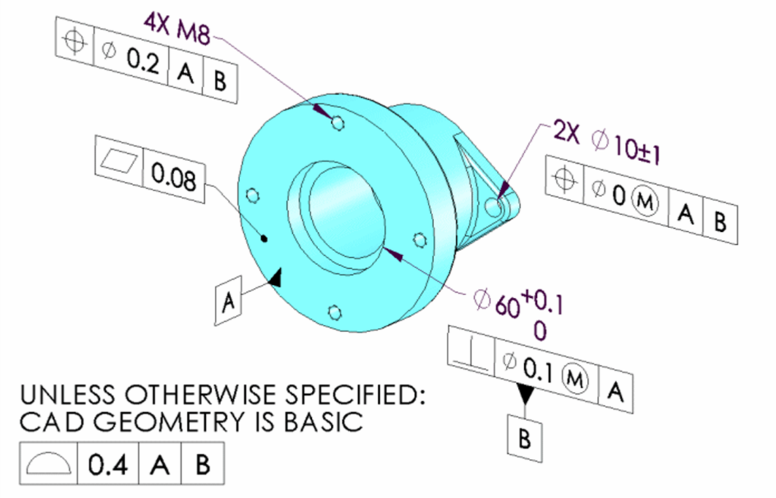
INTERNATIONAL
Standards Worldwide - Home

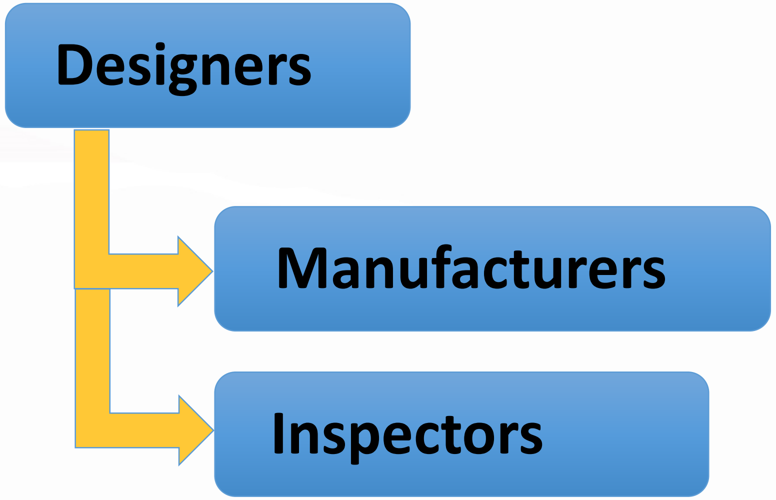
Formal Agreement Established between ASTM F42 and ISO Technical Committee 261

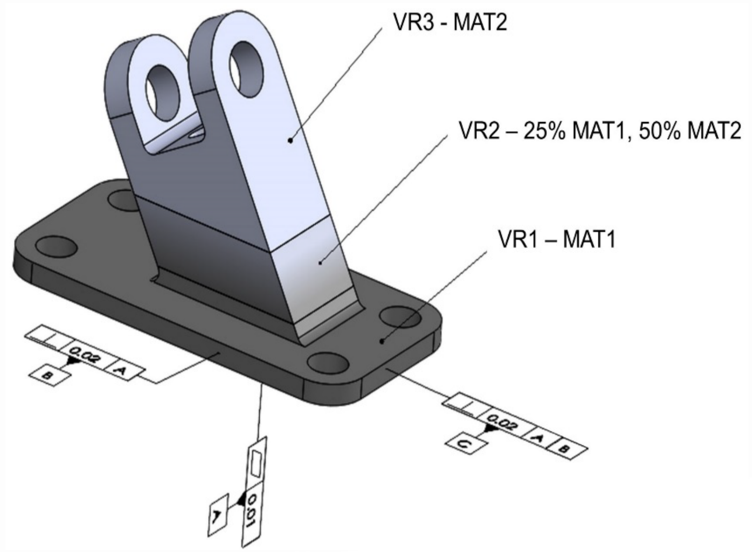
- Formal collaboration established between ASTM and ISO (first of its kind!) for joint development of AM standards
- Results in co-branded ISO and ASTM standards (same content, no need for future harmonization)
- Guiding principles and specific procedures for how ASTM and ISO will cooperate and work together are defined in the "Joint Plan for Standards Development"
    - One set of AM standards to be used all over the world; common standards roadmap and organizational structure; use and build upon existing standards, modified for AM when necessary; co-located meetings; emphasis on joint standards development and joint working groups; etc.

ASME Y14.46 Standards Committee

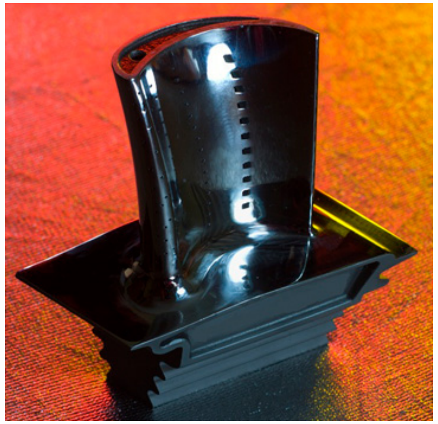
- Geometric Dimensioning & Tolerancing (GD&T) requirements that are *unique to additive manufacturing*
- Builds on long-standing expertise and several GD&T standards developed by ASME Y14 committee
- GD&T: the language for communicating geometric tolerance specification and design intent between:

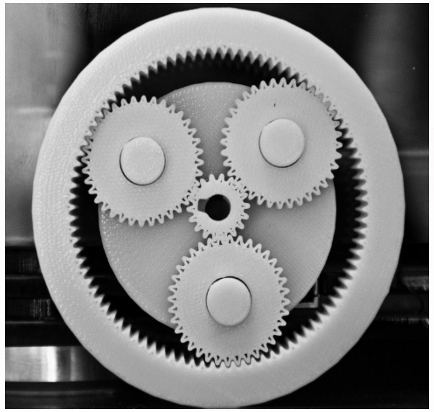




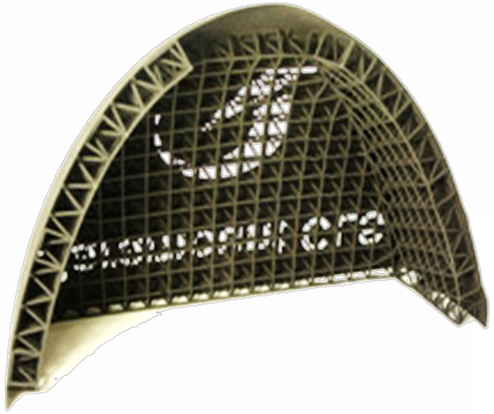


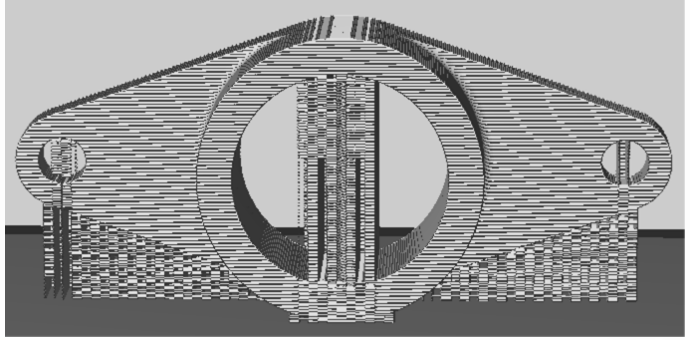
GD&T Issues for Additive Manufacturing

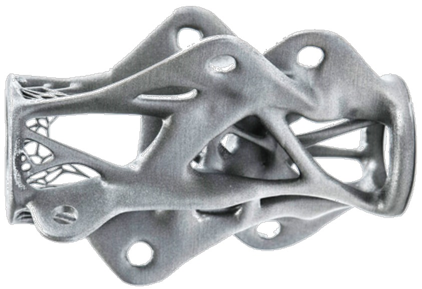




- Free-form complex surfaces
- Internal features / lattice structures
- Support structures
- Build direction dependent properties
- Multiple materials / functionally-gradient materials
- As-built assemblies







Multiple Standards Bodies Relevant to Additive Manufacturing

- ASTM Committee F42 on Additive Manufacturing Technologies
- ISO Technical Committee 261 on Additive Manufacturing
- ASME Y14.46 Committee on Geometric Dimensioning & Tolerancing (GD&T) Requirements for Additive Manufacturing
- SAE Aerospace Material Specifications for Additive Manufacturing (AMS-AM) Committee
- AWS D20 Committee on Additive Manufacturing
- ISO TC184 / SC4, STEP-based data representation for AM
- ASME B46 Project Team 53, Surface Finish for AM
- <others – the list is growing>

NIST Contributes to All of These Efforts

<u>Some Challenges:</u> high risk of duplication of efforts and overlapping content; potential for inconsistencies or even contradictions; conflicting standards create ambiguity and confusion; increased requirements for communication and coordination; need for liaisons; limited resources

Additive Manufacturing Standards Collaborative (AMSC)

- ***Purpose:*** coordinate and accelerate development of additive manufacturing standards consistent with stakeholder needs and facilitate growth of the additive manufacturing industry
- AMSC launched in March 2016 following two planning meetings
- Facilitated by American National Standards Institute (ANSI) through cooperative agreement with America Makes; experts from many sectors working to identify standards gaps and priorities
- ***Phase 1 Outcome:*** "Standardization Roadmap for Additive Manufacturing" released in February 2017
    - 88 gaps identified; 18 high priority, 51 medium priority, 19 low priority; 57 require R&D
- Phase 2: Kick-Off in September 2017; Draft roadmap v2 in review; expect June 2018 release

NIST Perspectives on AM Standards

- NIST has been influential in leading and developing AM standards from the start
  - Contributions to more than 40 AM standards activities across 7 standards bodies
  - Multiple leadership roles in ANSI Additive Manufacturing Standards Collaborative
- NIST continues to support AM standards development through measurement science research and service on standards committees
- **NIST Motivations:**
  - High quality, technically accurate standards
  - Usable and high impact standards that meet stakeholder needs
  - Integrated and cohesive set of standards: consistent, non-contradictory, non-overlapping
  - No duplication of effort
  - Use of existing standards, modified for AM when necessary
- Coordination, communication, and cooperation are necessary among AM users, standards bodies, and regulatory agencies
  - AMSC established to serve this role; NIST contributes to the coordination and communication

Conclusion

- NIST Measurement Science for Additive Manufacturing program is addressing high priority **pre-competitive challenges** faced by the metal AM industry
- Program develops **metrology** driven methods and tools for the benefit and use of AM stakeholders
- Results of the research activities are **publicly disseminated** broadly throughout the AM community
- Results of the research activities are used as the basis for new AM **standards**
- Program’s world-class **staff and facilities** are widely recognized for their critical contributions to AM field

Questions and Discussion

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NIST AM Publications and Reports:
https://www.nist.gov/topics/additive-manufacturing/am-publications