AM in MBE: Is It Really That Unique?

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engineering laboratory
MSAM

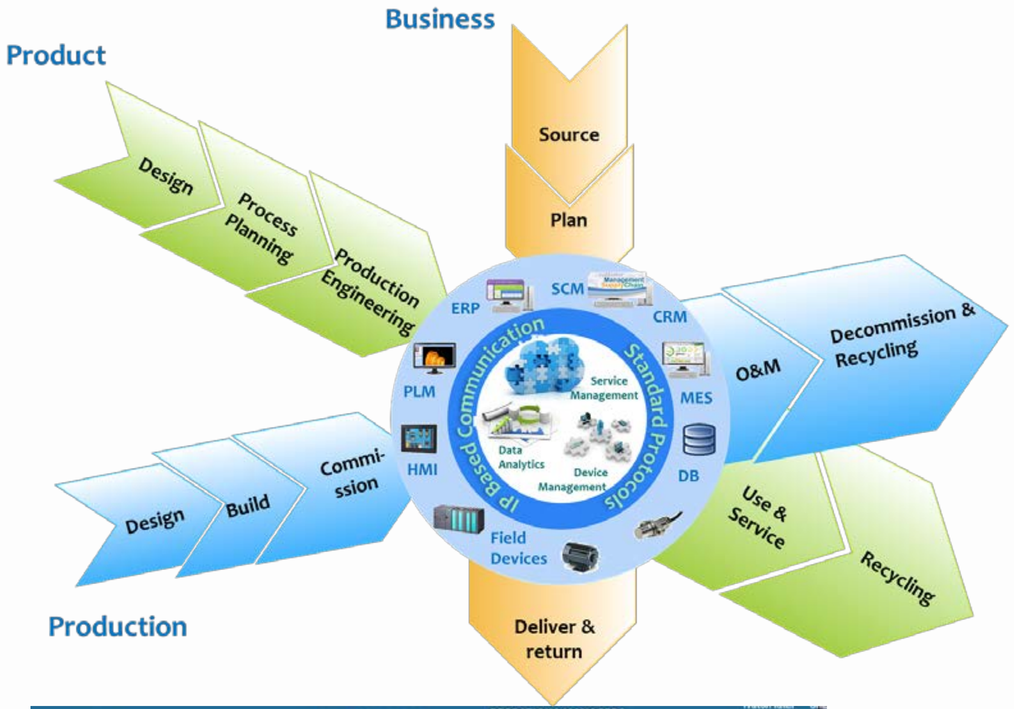
Overview

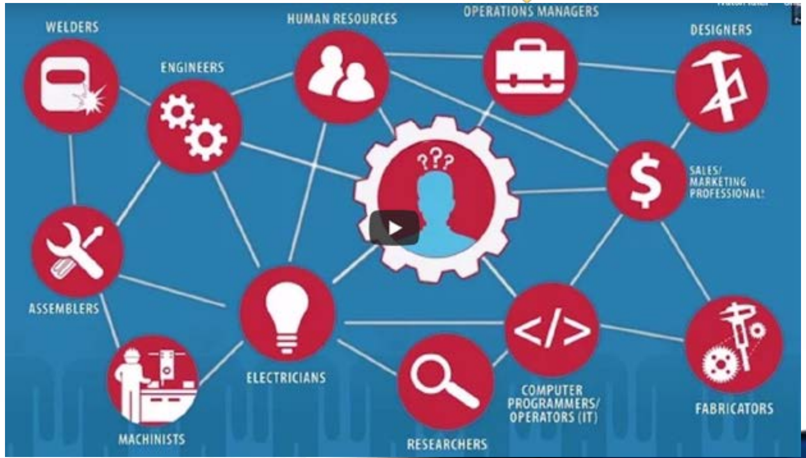
- Advanced Manufacturing in MBE
- Disruptive Technology- AM in the Supply Chain
- Cautionary Tales- Variability in AM Processes
- Establishing Provenance with a Digital Thread
- Leveraging AM- Standards
- Understanding which Data Requirements Fit Your Needs
- AM at NIST

Advanced Manufacturing in the Model-Based Enterprise

- Desire to create any part from any process
  - Product-oriented
  - Create a robust supply chain
- Customer-
  - Provide the geometry and performance specifications
- Supplier-
  - Demonstrate requirements are met

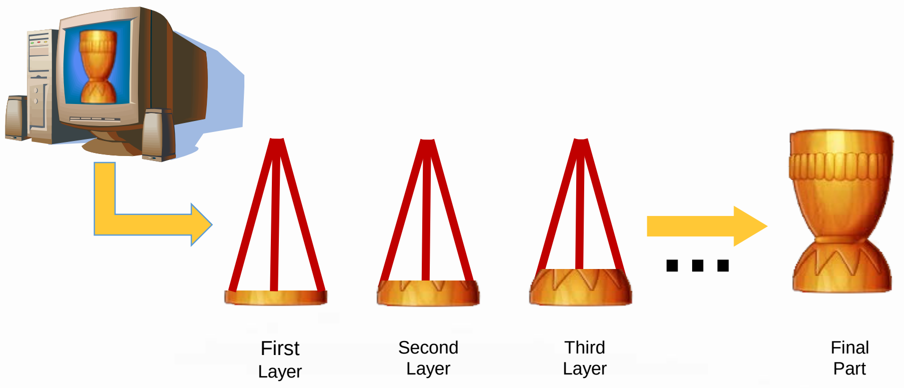
- Desire to avoid process-specific requirements
  - Castings/forgings
  - Composites
  - Additive Manufacturing?





Additive Manufacturing is Maturing

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 2018)
  - **5 fold growth in the past 6 years!**
- U.S. market for AM is currently about $ 2 B
- Metal-based AM is being used 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

Production is Here

- Drivers in commercial use remain cost savings
- Mission-oriented drivers may be performance-based
- AM creates new opportunities not available by other manufacturing processes
  - Lightweighting
  - Reduced supply chain
  - Reduced part count
  - Improved performance

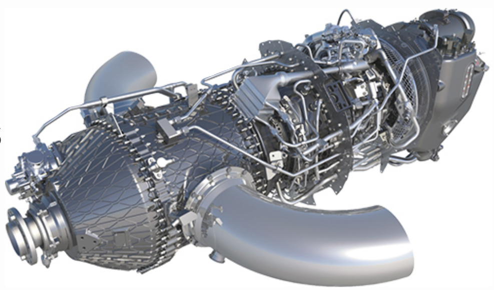
GE T25 sensor

Safran combustor swirler and fuel injector nozzle

Airbus hydraulic manifold

Unmanned undersea vehicle housing

GE Advanced turbo prop (ATP) -35 percent additive content and a huge parts-count reduction—from 855 subtractive-manufactured parts to just 12 additive-manufactured parts.

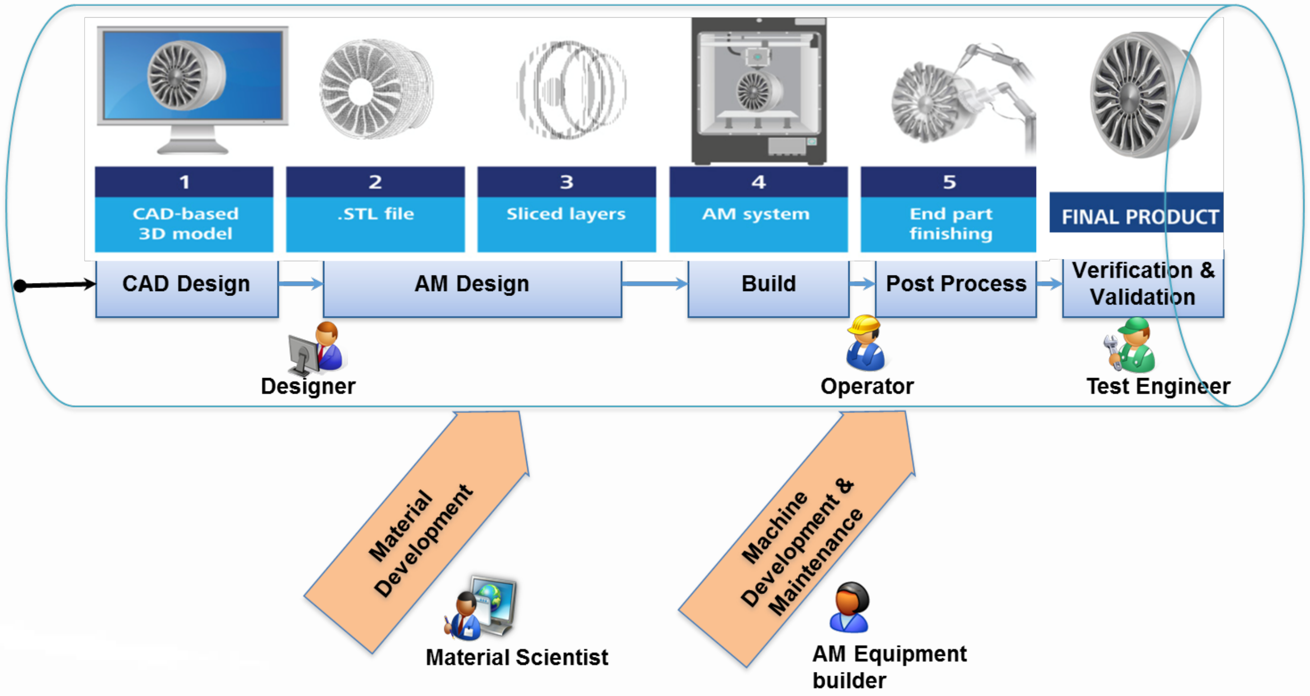


Baltic Orthoservice implant

Mercedes Benz thermostat cover

VW water connectors

The AM Part Lifecycle



- The establishment of digital provenance is critical to AM

Plug and Play into Supply Chain?

What makes the AM process unique?

-Layer by layer

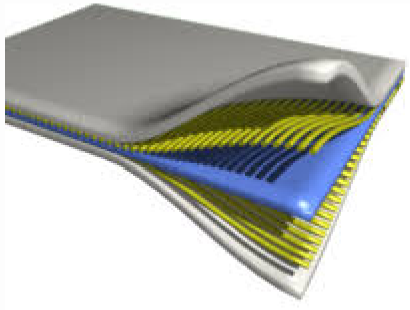
-Material properties formed during the processing

How is this different from composites?

-Provide the geometry

-Identify the material

-Specify the requirements

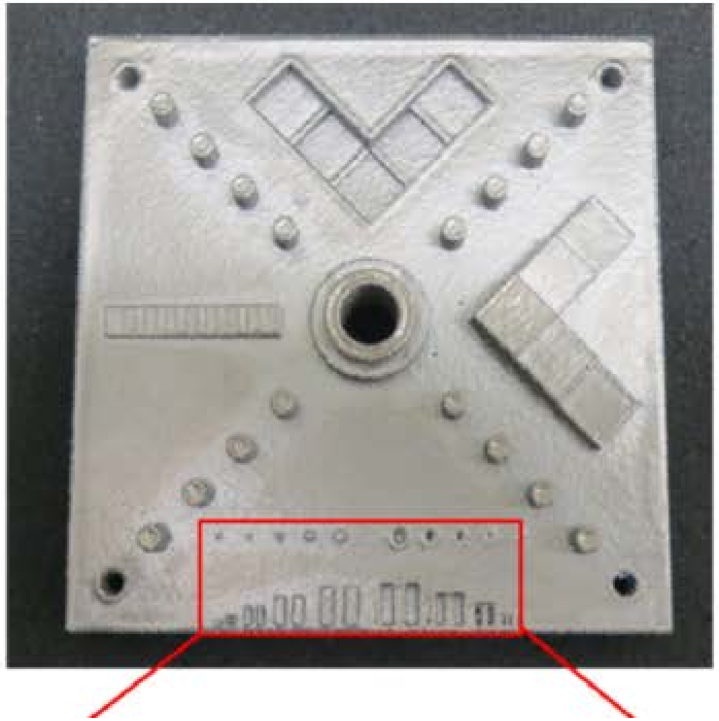


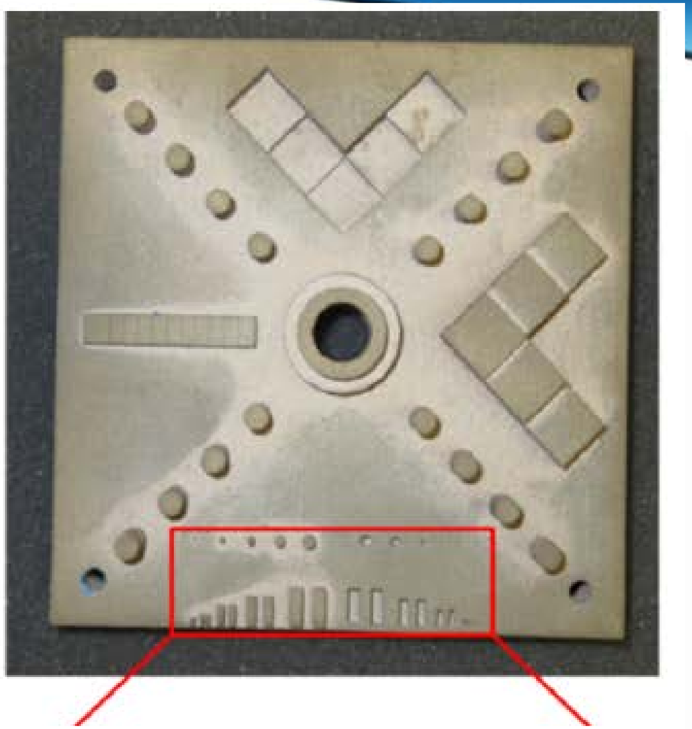
Additive Manufacturing (AM) ISO F42 ASTM TC261 Definition

n—process of joining materials to make ***parts*** *from 3D model data, usually* ***layer*** *upon layer,* ***as opposed to subtractive*** *manufacturing and* ***formative*** *manufacturing methodologies.*

Are these the same part?

- Photographs of test artifacts built by two service providers built in Ti6Al4V





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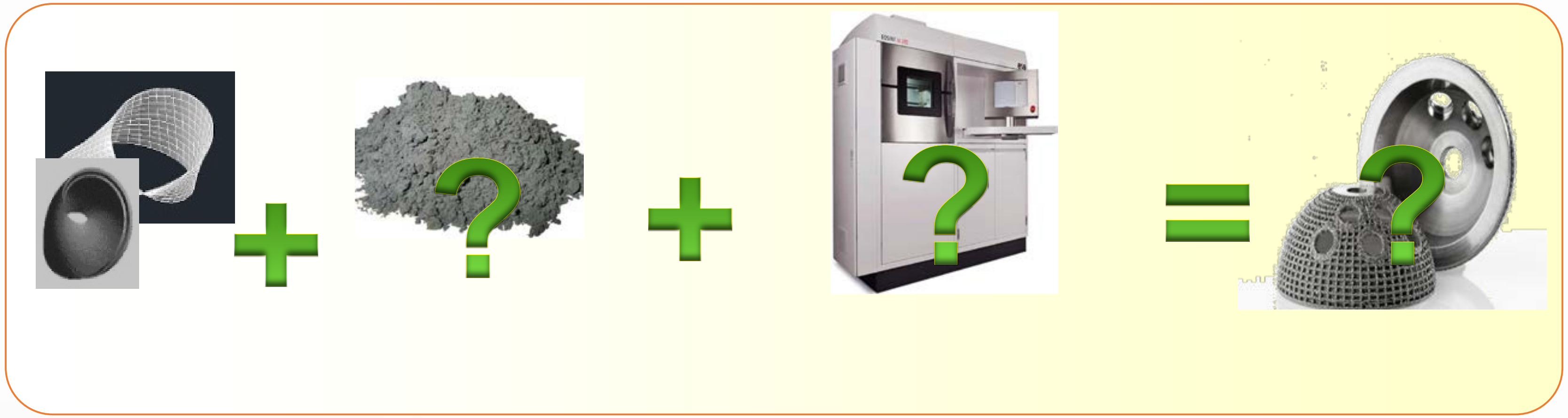
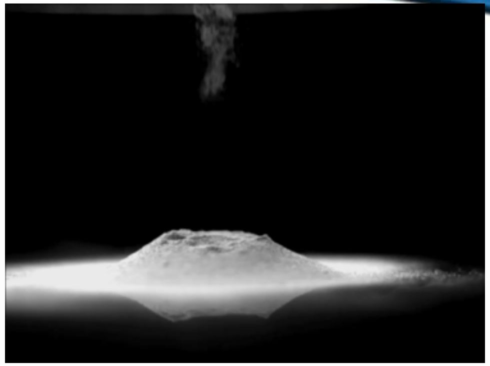
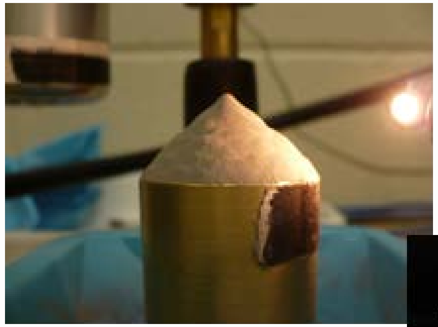
More Uncertainty in Additive Manufacturing?

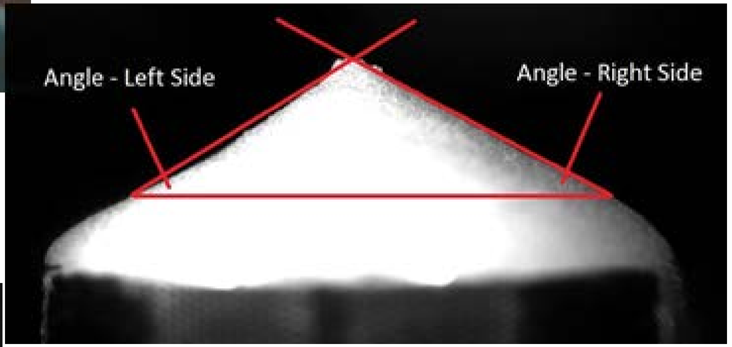


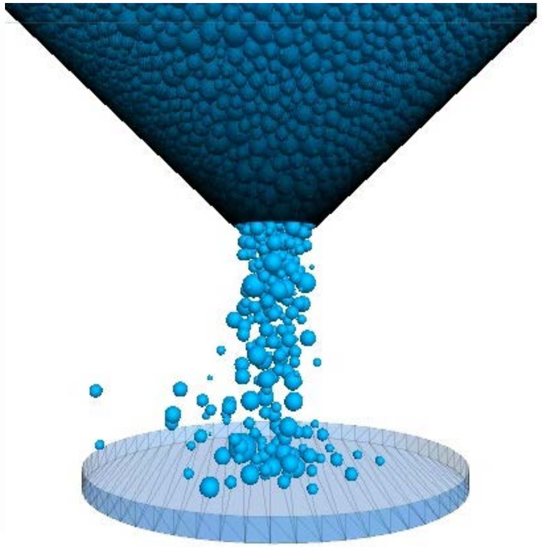
Design Material Process Part

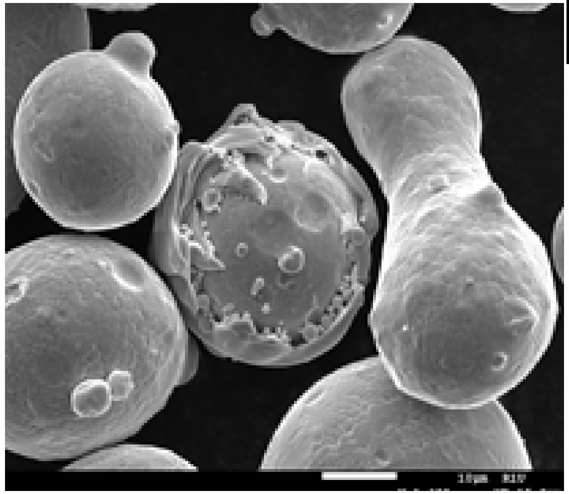
New Variability in Material



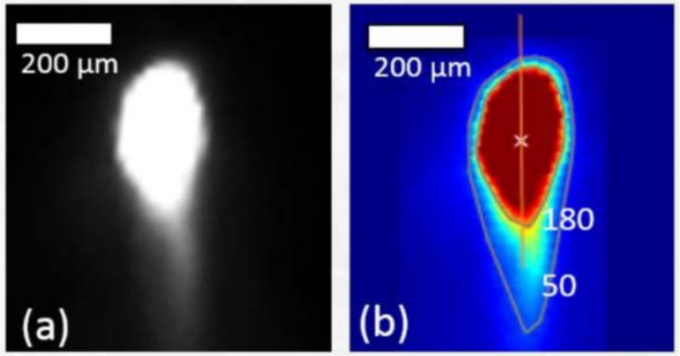


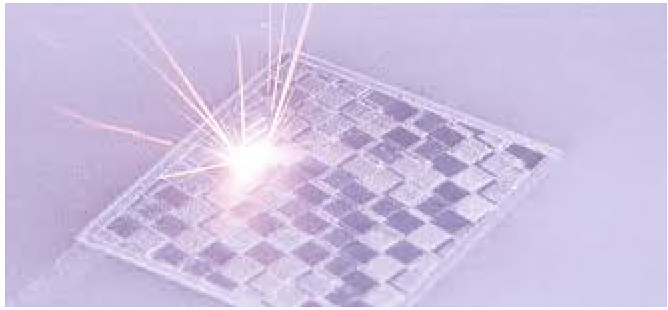


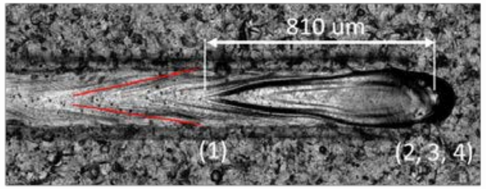




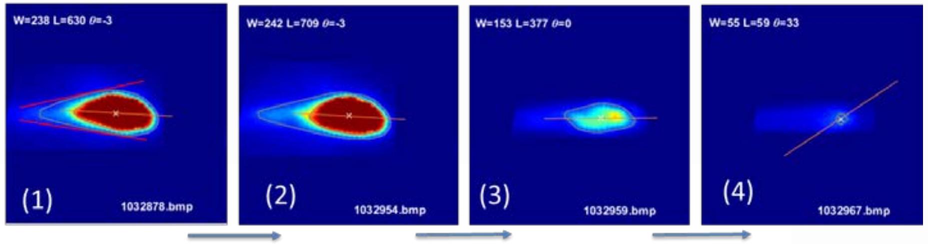
New Variability in Process

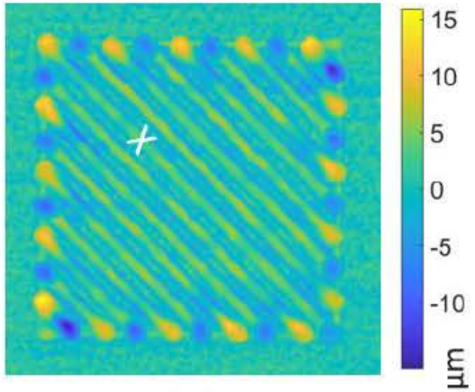


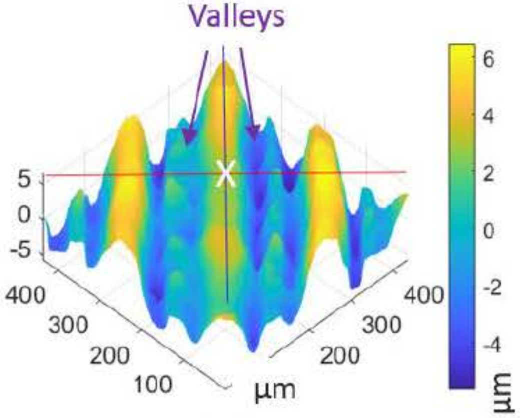


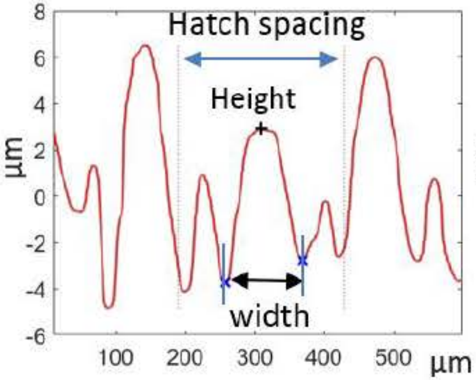


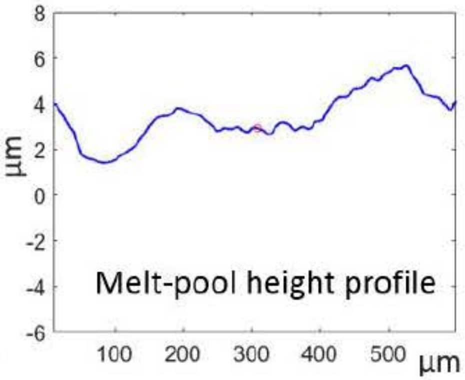
Laser power = 450 Watt
Speed = 500 mm/s
fps = 50 k
Distance per frame = 10 um
Time per frame = 20 us
'Cooling down distance' = 80 um



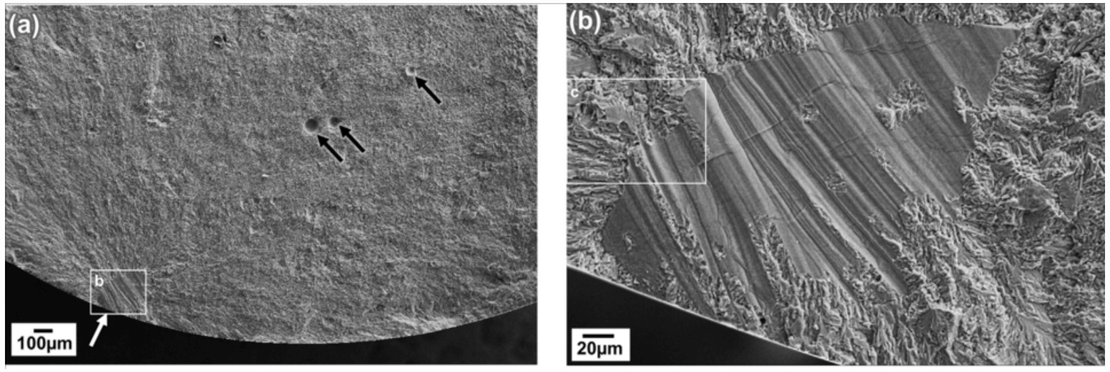




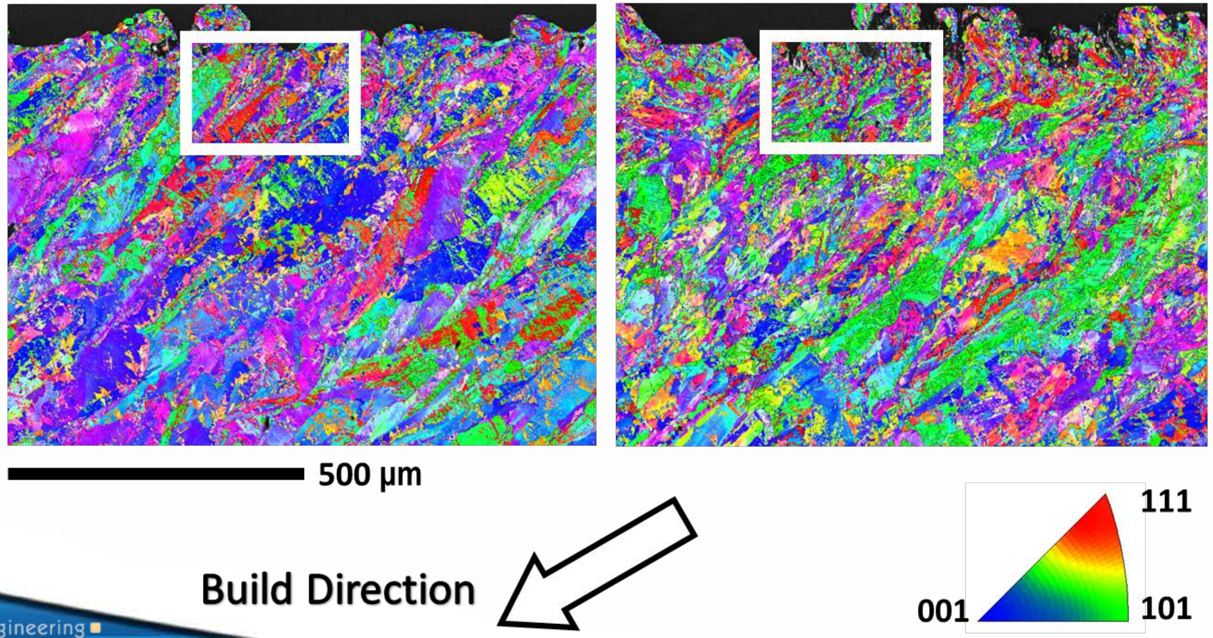


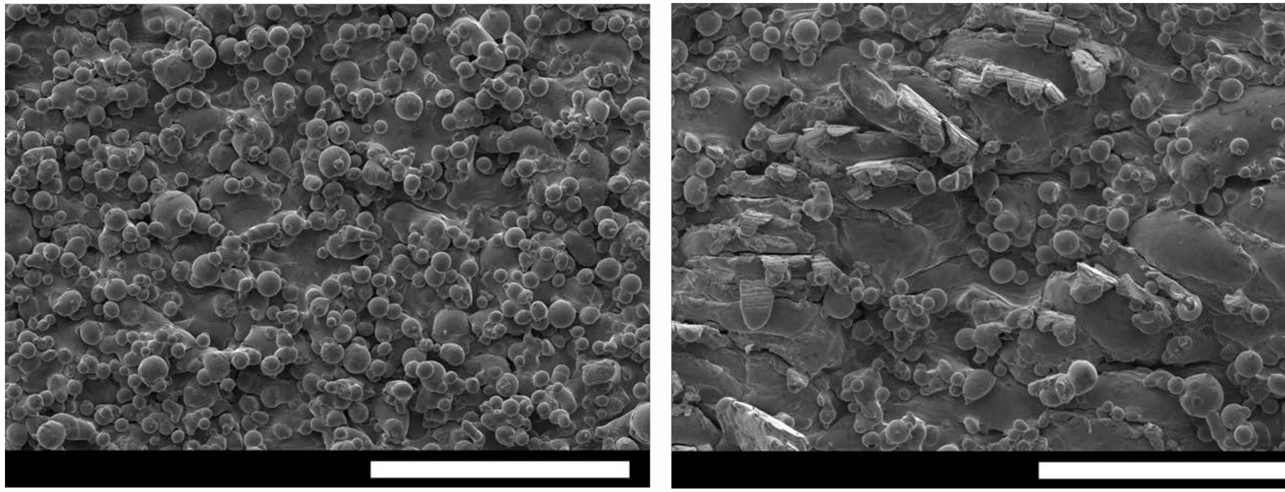


New Variability in Part



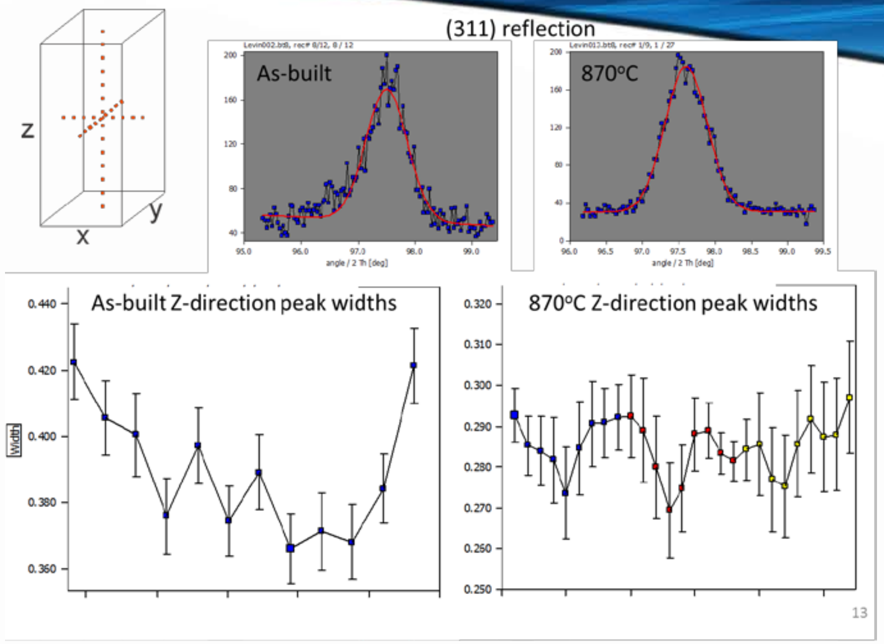
α = 60°, *v* = 700 mm/s, *P* = 40 W   α = 60°, *v* = 700 mm/s, *P* = 195 W

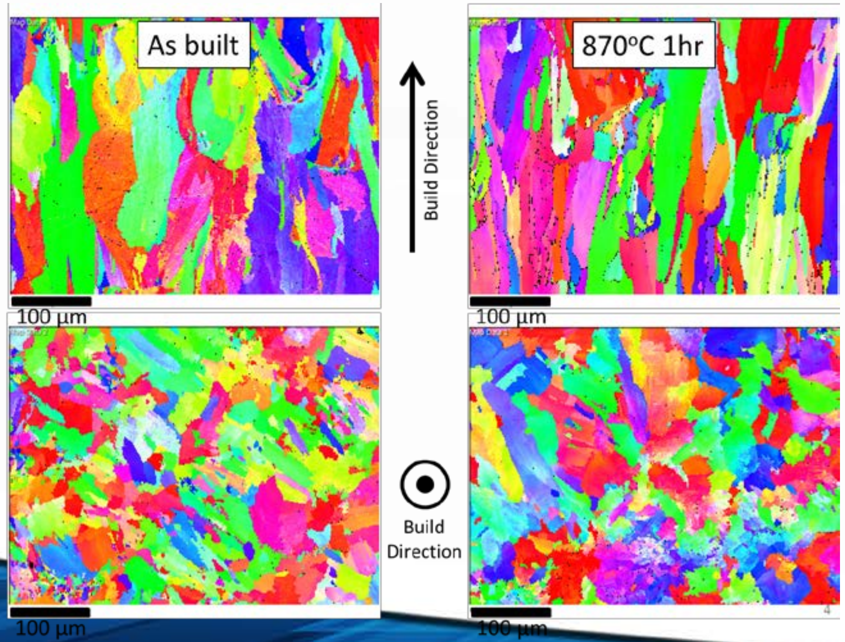


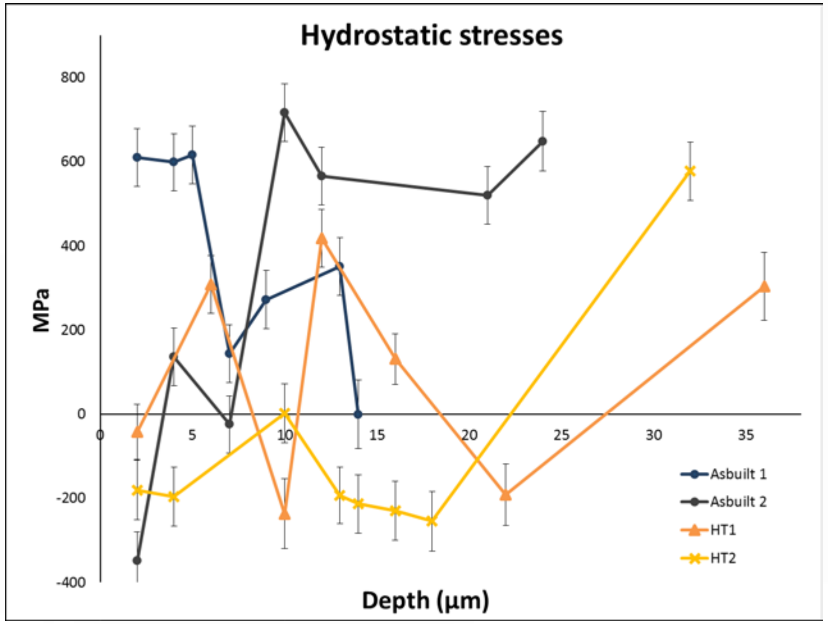


Ra = 20.9 µm   *Ra* = 21.2 µm

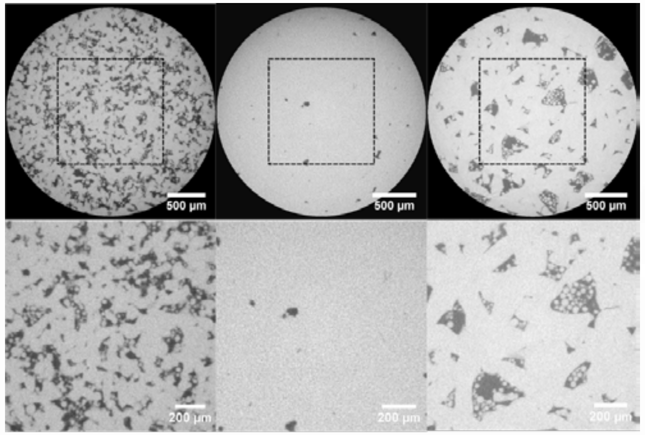
New Variability in Part Microstructure







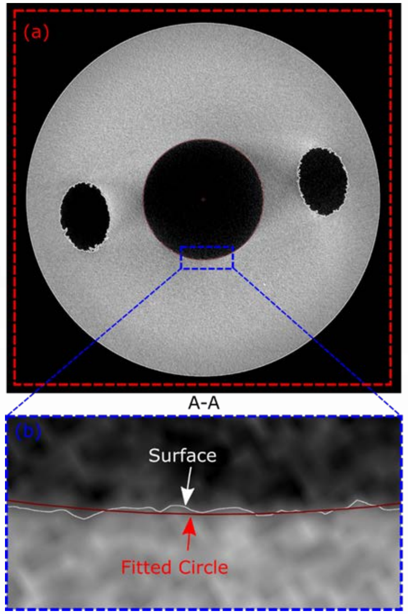
New Concerns in Part Qualification

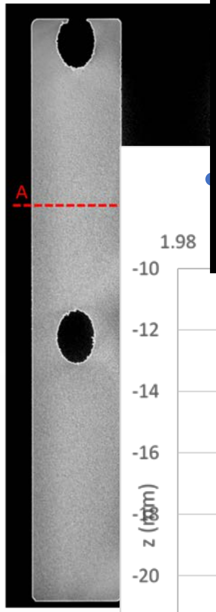


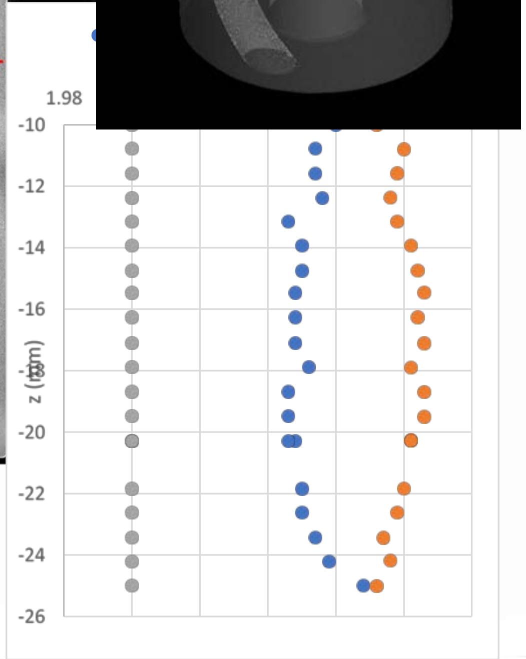
Sample 3
v = 3200 mm/s
h = 0.1 mm
φ = 18.2 %

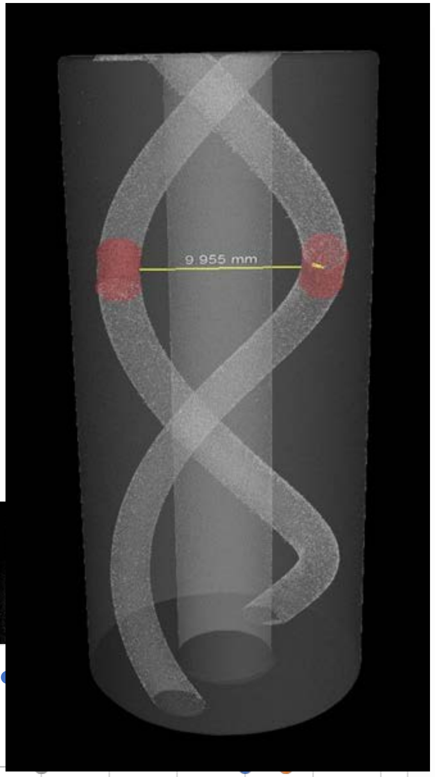
Sample 4
v = 800 mm/s
h = 0.2 mm
φ = 2.07 %

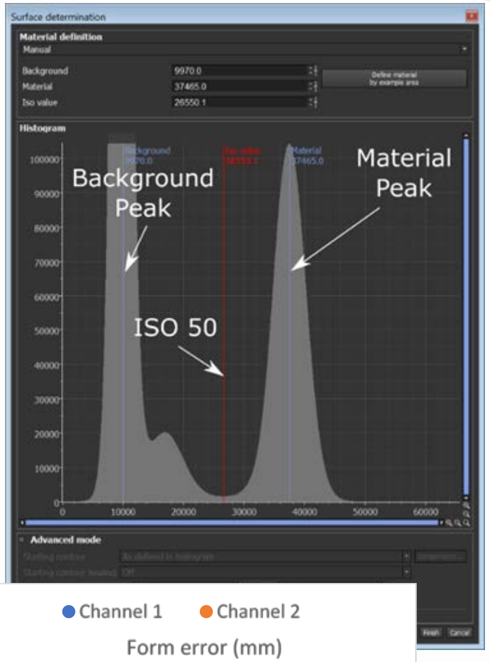
Sample 5
v = 800 mm/s
h = 0.4 mm
φ = 10.19 %

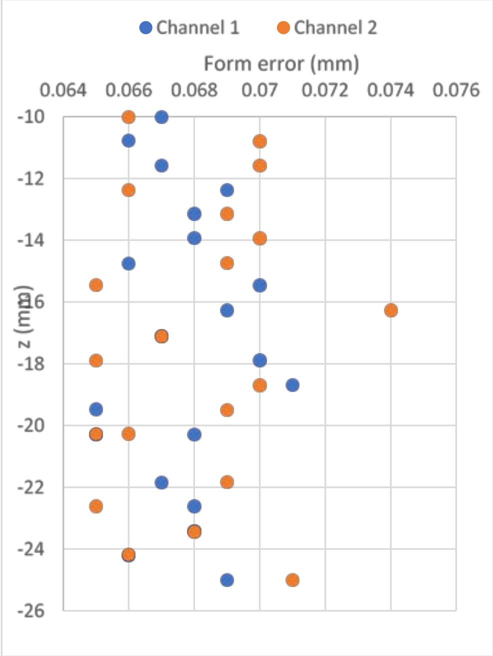












- Product definition
- Direct slicing
- Schema
- Design rules
- Design allowables
- Predictive modeling

- Powder size distribution
- Powder condition and recyclability
- Powder size and morphology
- Chemical composition
- Porosity
- Rheology

- Melt pool temperature
- Melt pool profiles
- Melt pool volatility
- Emissivity
- Powder bed density
- In situ and ex situ melt pool characterization
- Cooling patterns
- Phase Changes
- Scan strategies

- Microstructure
- Surface profiles
- Grain size
- Grain orientation
- Void characterization
- Internal feature measurements
- Stress/Strain tensors
- Residual stress
- Distortion
- Effects of post processing
- Failure propagation

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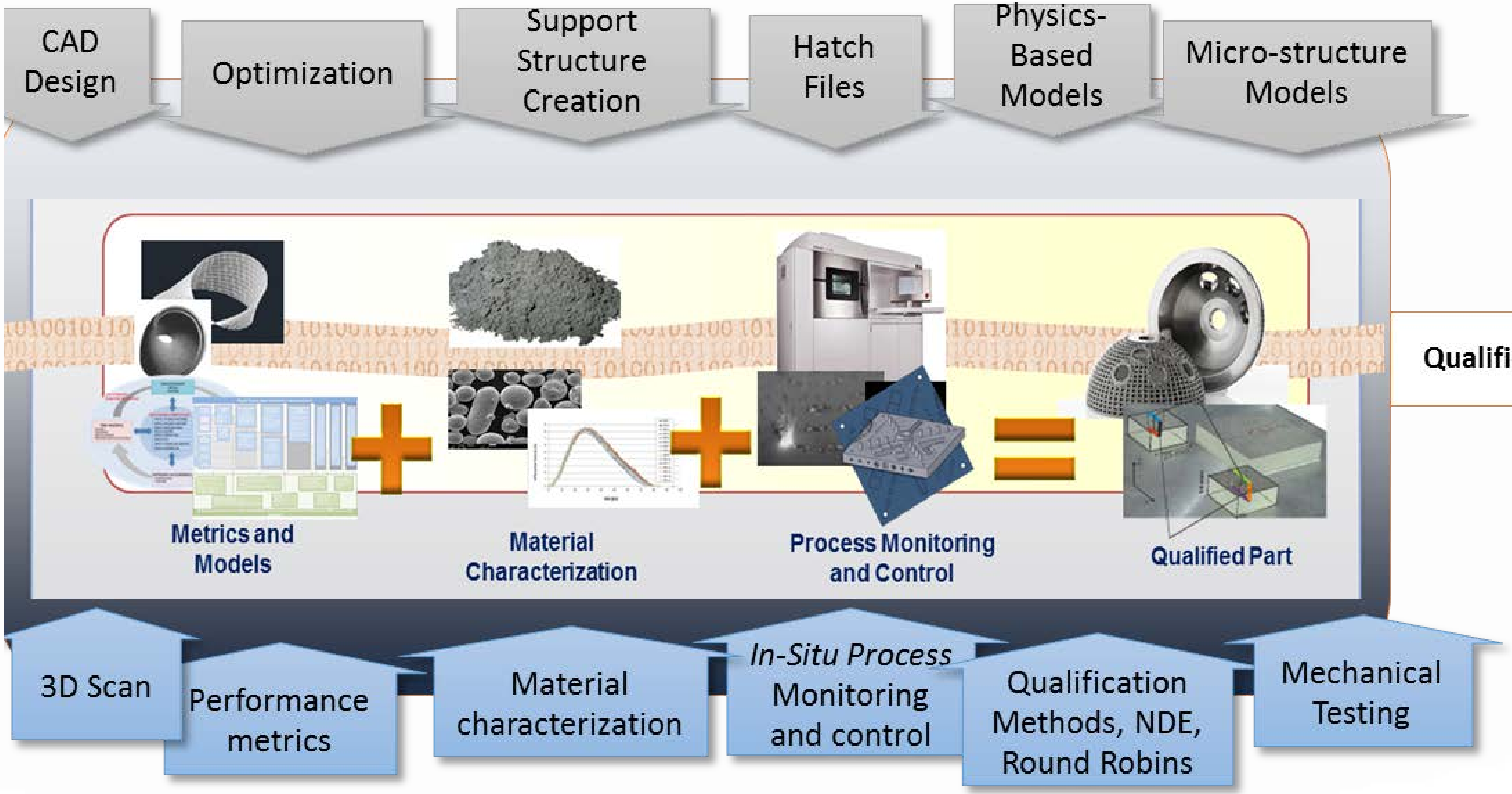
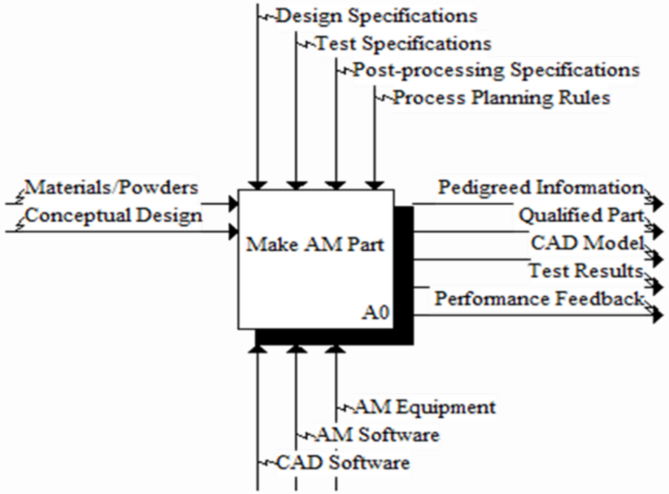
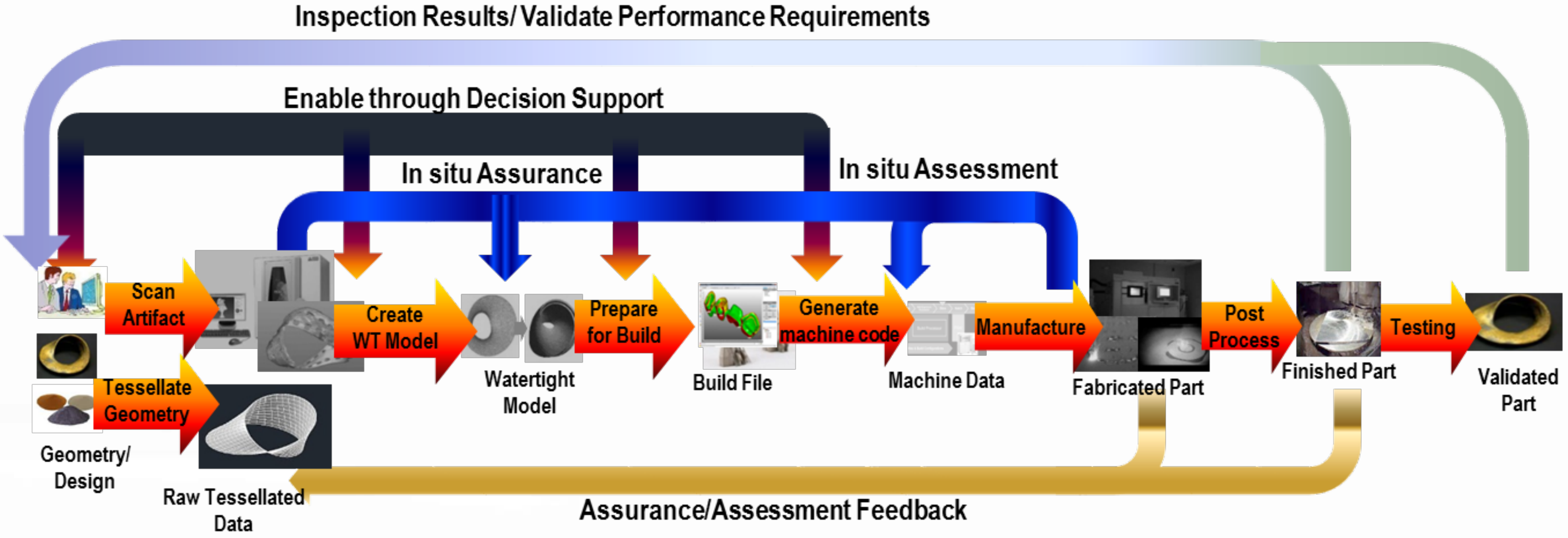
Digital Thread … plus…

- Measurement Science, through metrics, models, data, verification, and validation methods, can be used to reduce uncertainties in direct part manufacturing. Integrated through a digital thread, we can facilitate and achieve rapid part qualification leading to widespread adoption of trusted AM technologies



Decomposing the AM Lifecyle by Information Requirements





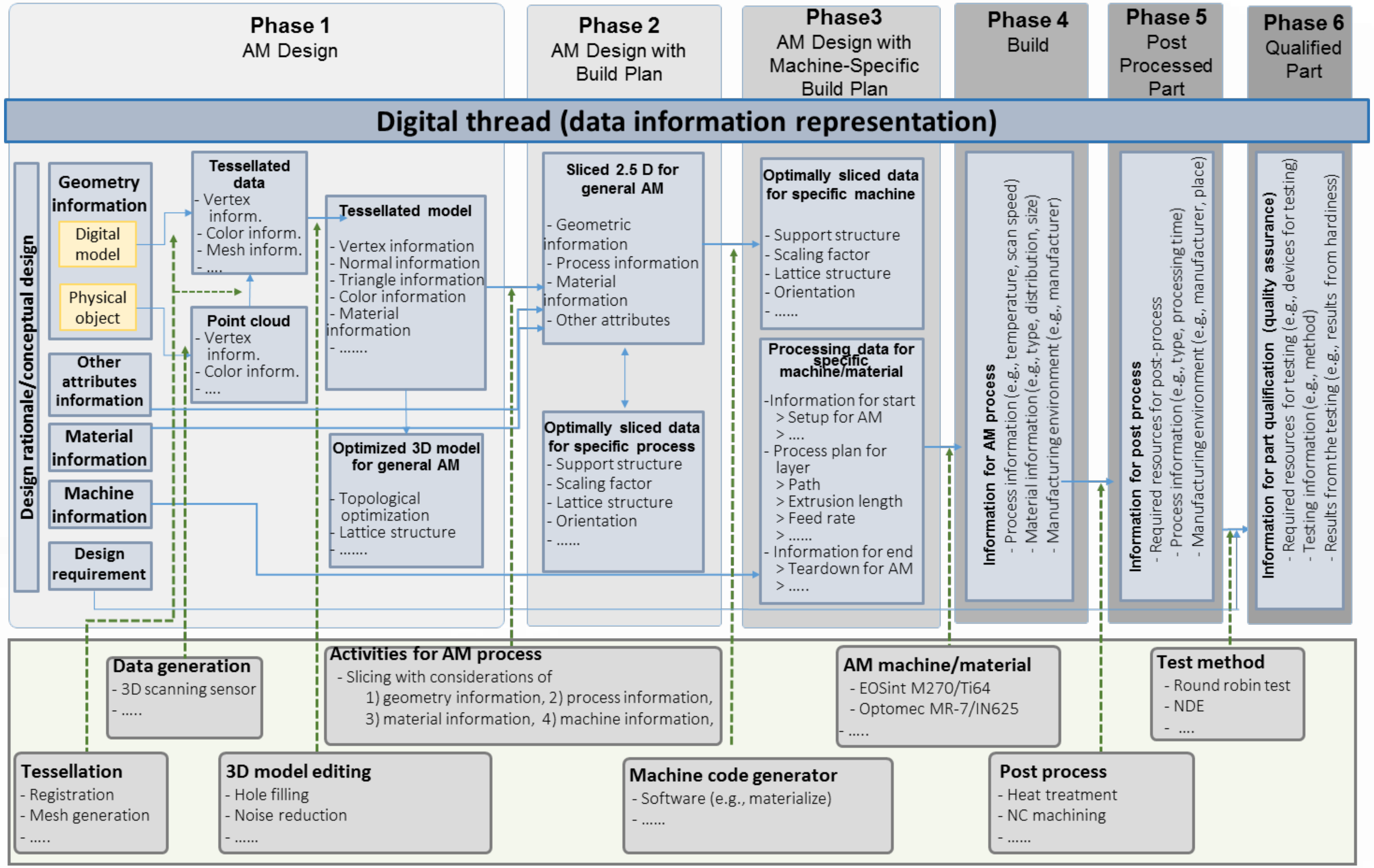
- During an AM process, several different activities are necessary
- These activities become “transitions” between different phases
- Eight phases to outline the AM digital spectrum
- Each phase is defined by the transformation of its digital footprint

- Capture as much data as possible to establish provenance (pre, during, and post process)

Establishing a Digital Thread

- Identify key information elements is critical to establishing a digital thread (including schema and data packages) for reproducibility, verification, and conformance.

- Driven by lifecycle approach, input data (part and process), basic testing data



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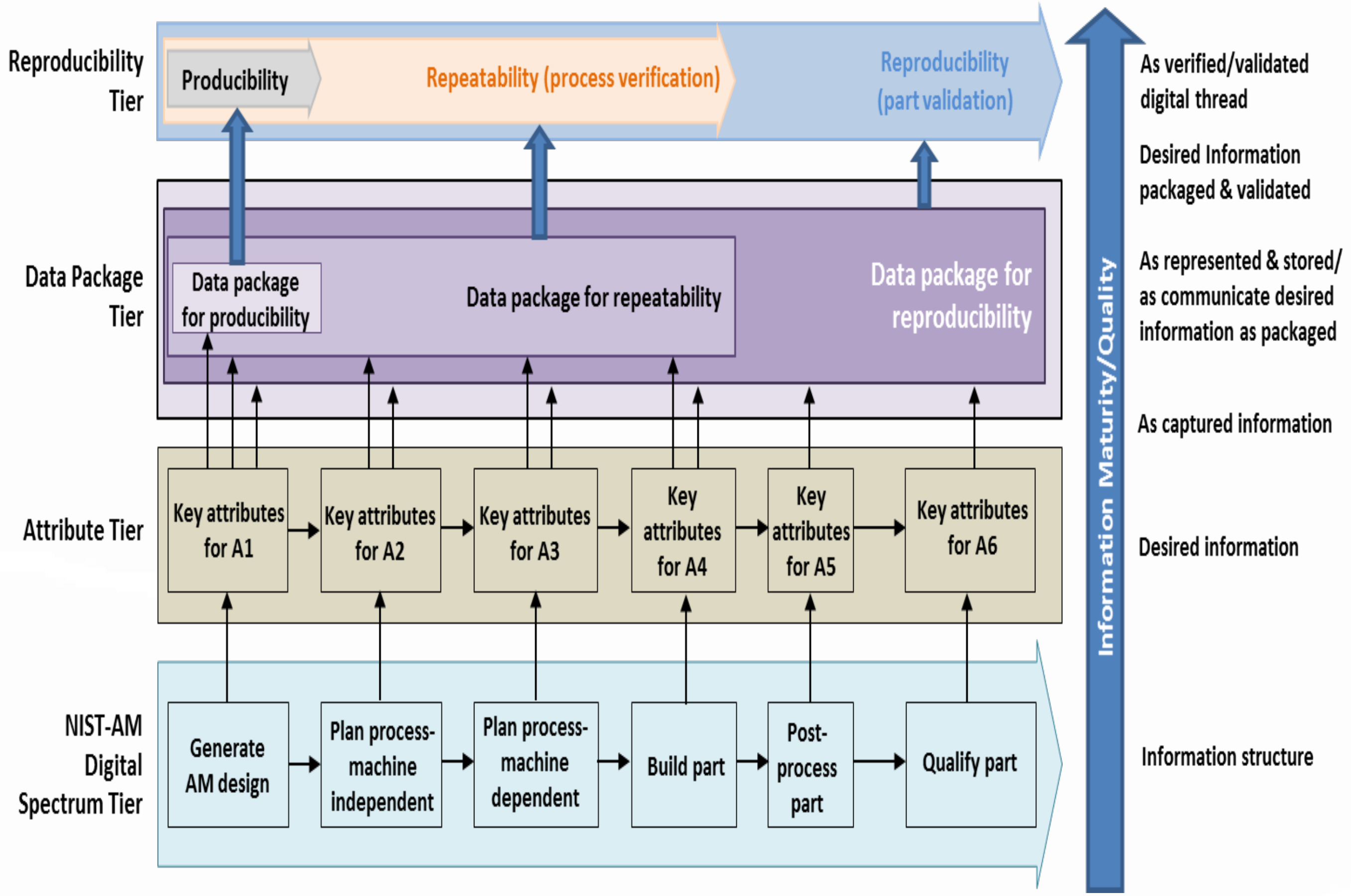
Establishing Provenance with the Right Data

- Many AM-Specific Standards Development Efforts
- Standards will provide AM parts with
  - Extended geometry control
  - Better material control
  - Better process control
  - Better quality control
- Communication is key to realizing better control



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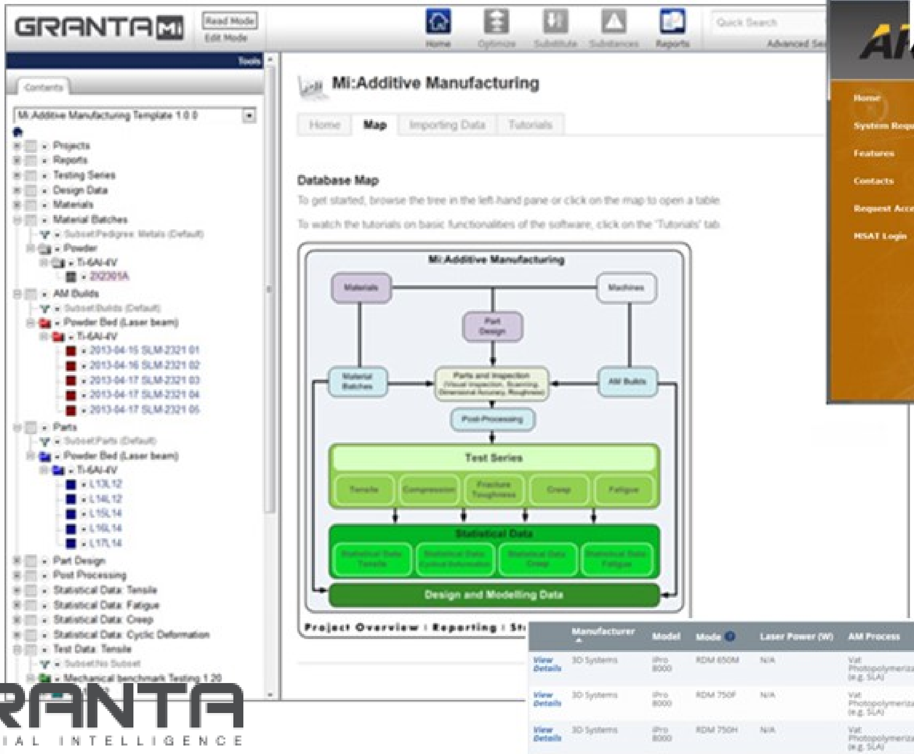
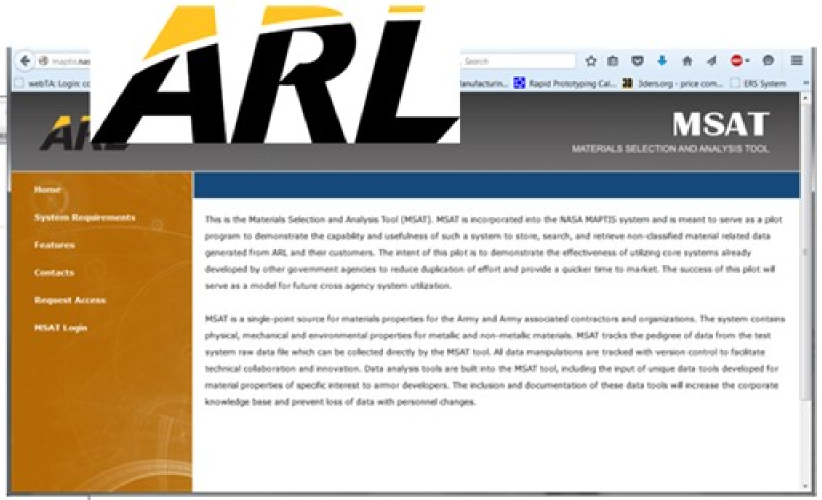
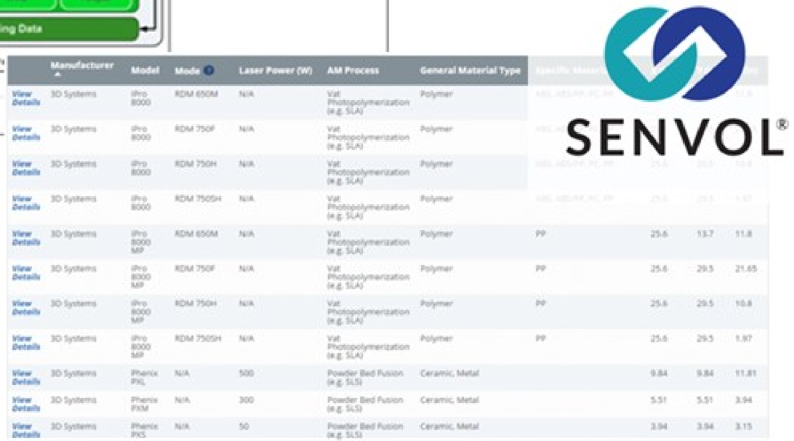
Various AM Material Database Efforts

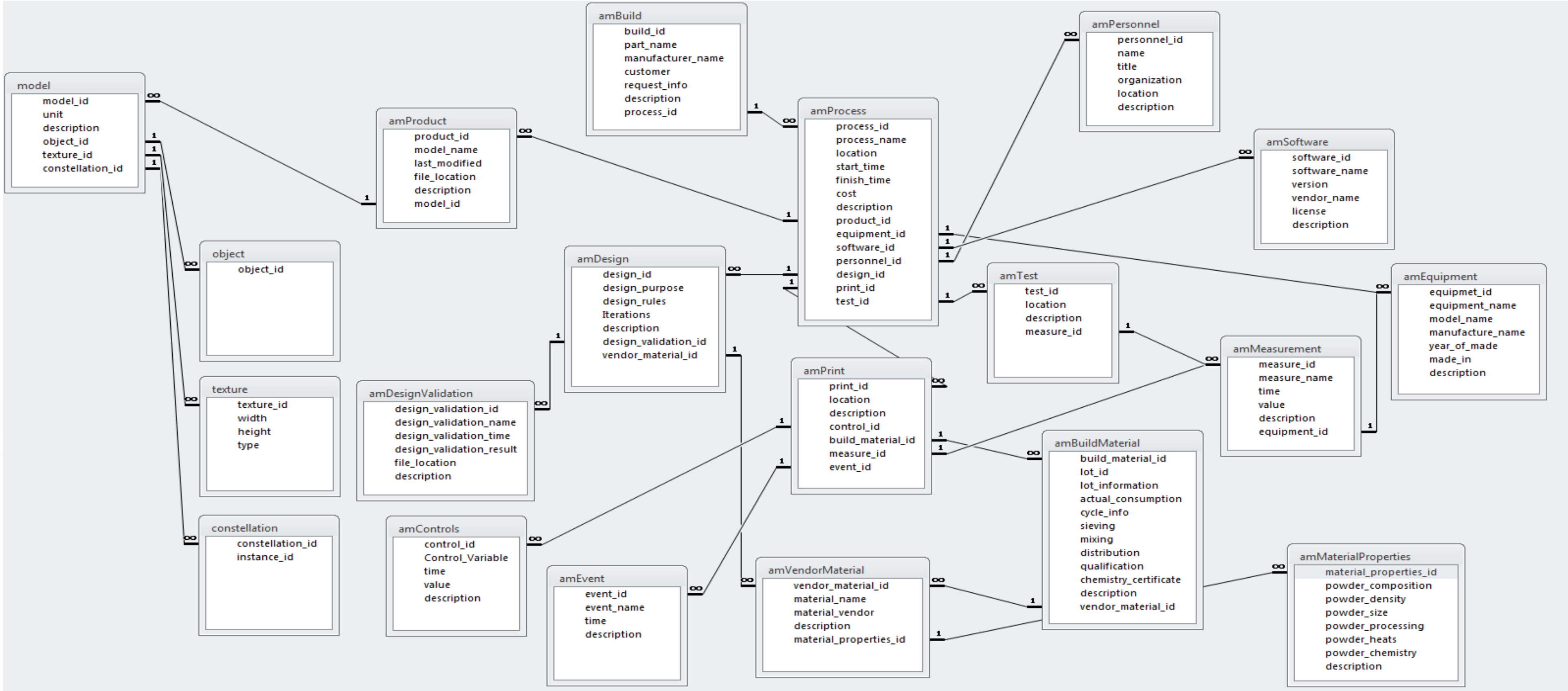






Design Allowables in AM: Establishing Material-Process-Structure Relationships

- Look to establish repeatable correlations between processed material and:
  - surface finish
  - microstructure
  - tensile strength
  - etc.



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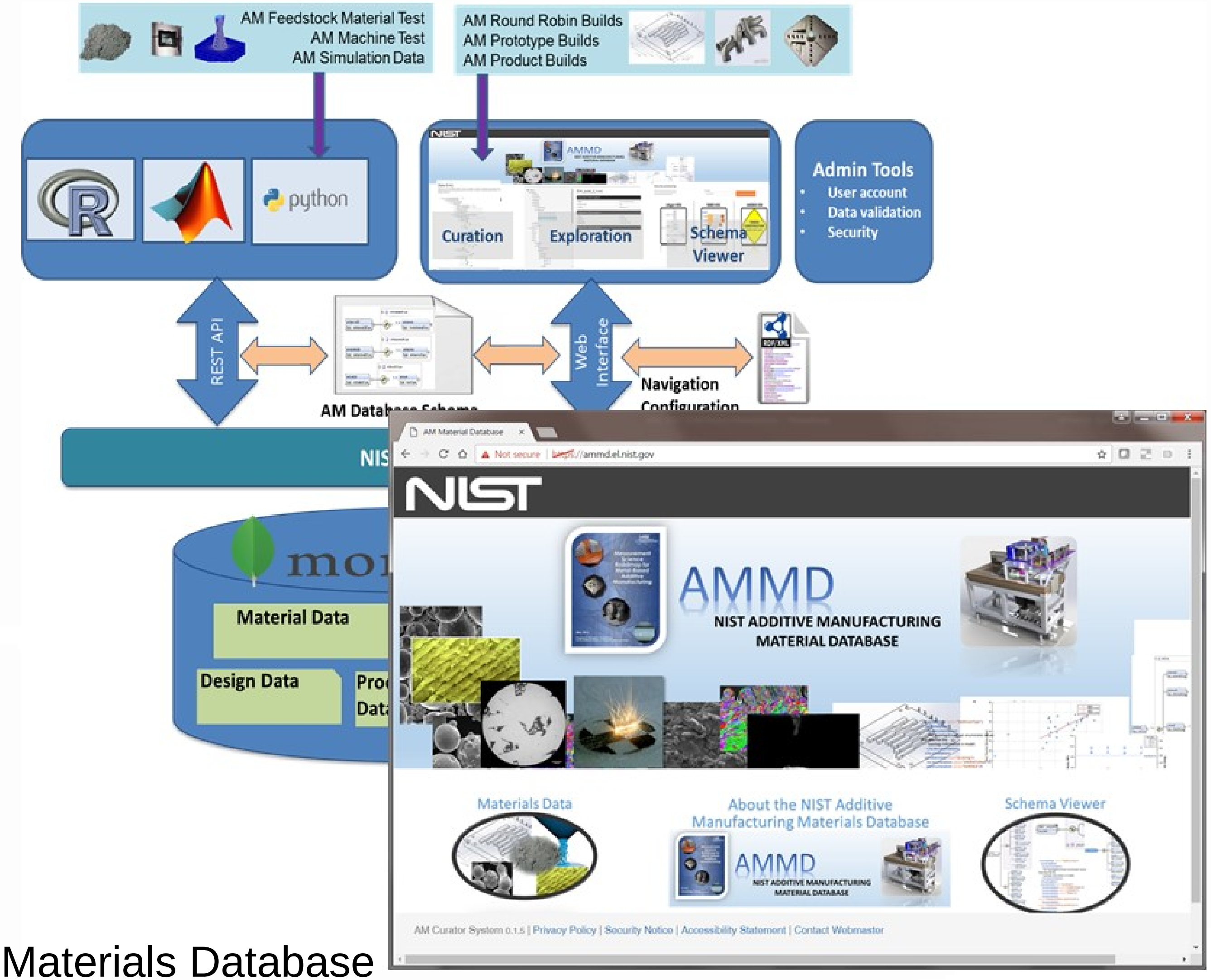
NIST Additive Manufacturing Material Database - AMMD

Goal: To develop an open database system set for:

- *–deep understanding of AM geometry-material-process-property relationships*
- *–better AM process control and optimization*

Features:

- – *Lifecycle and value chain data*
- – *Openly accessible*
- – *Community effort of data curation*
- – *Consensus/ co-developed schema*
- – *Integration support for data analytics*

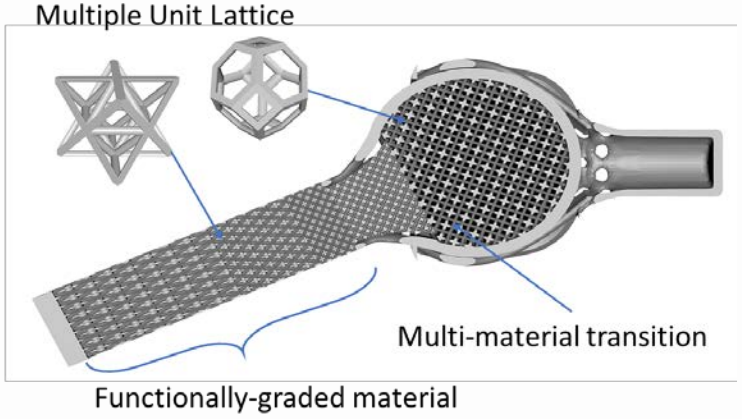


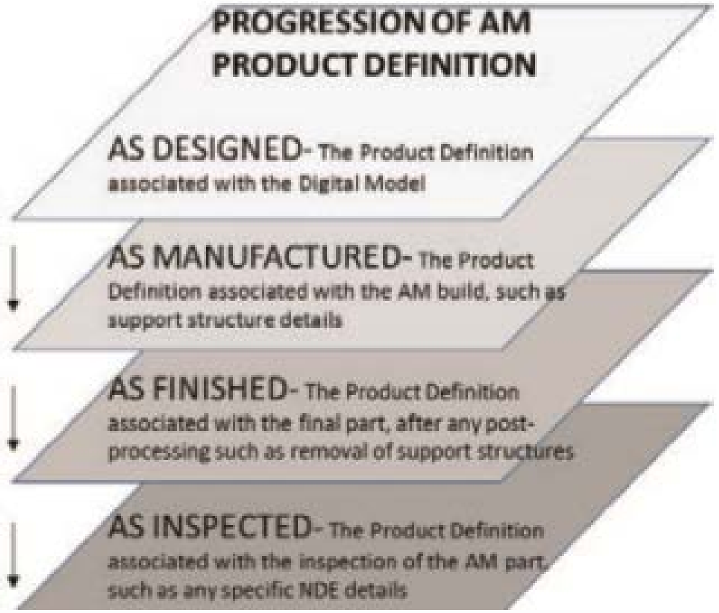
AM Materials Database
https://ammd.nist.gov

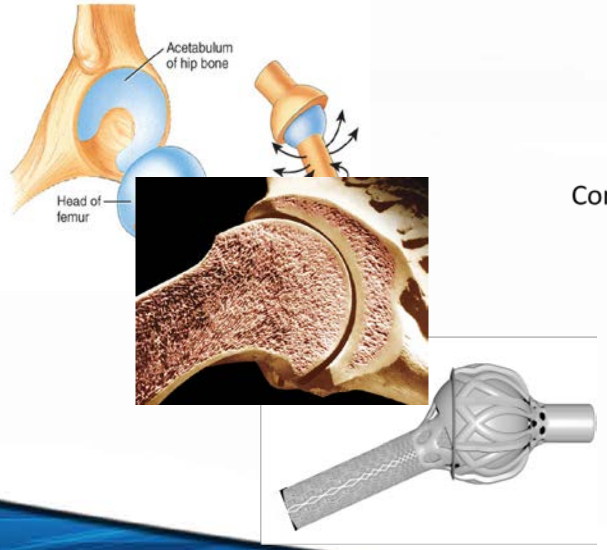
Product Definition and Geometric Dimensioning & Tolerancing (GD&T)

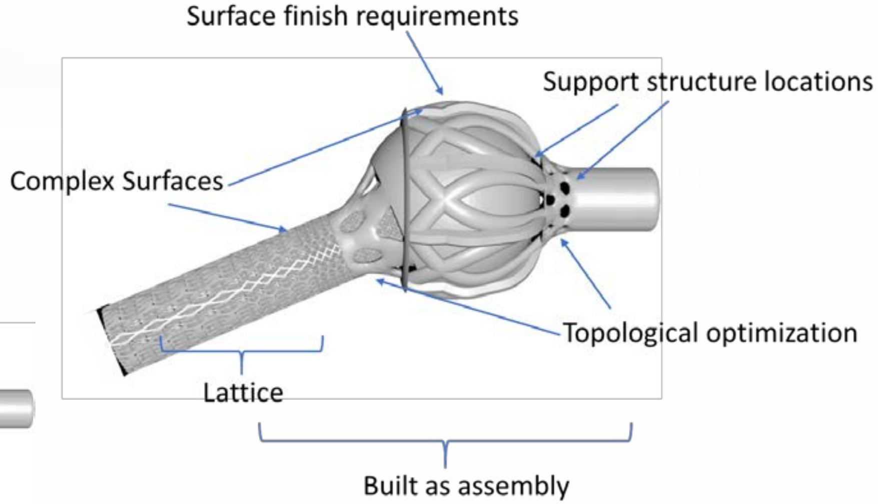
Incorporated into ASME Y14.46

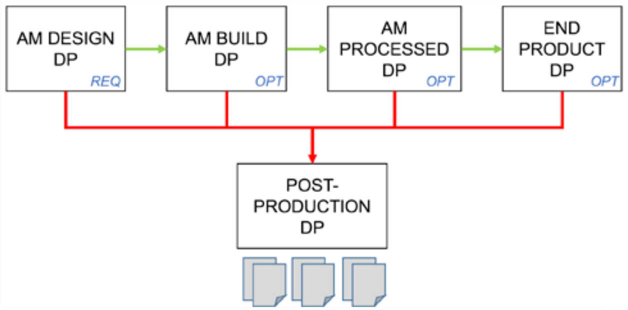
- Language for communicating geometric tolerance specification and design intent between
  - Designers – Manufacturers
  - Designers – Inspectors
- Previously there were no formal mechanisms to communicate many AM-enabled concepts









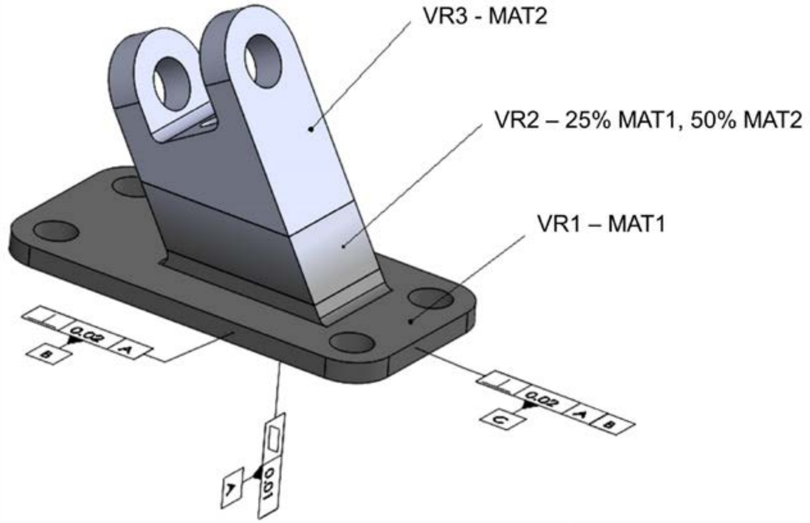


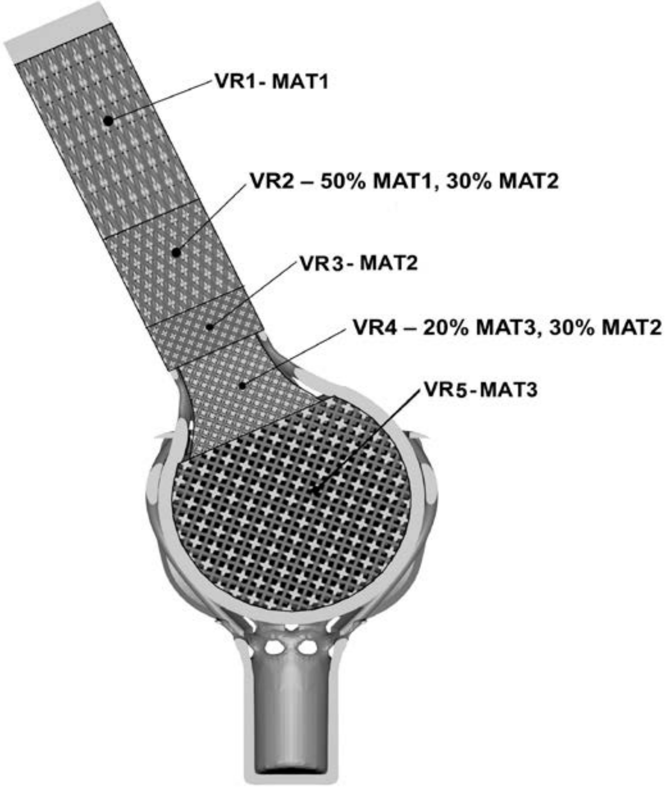
Product Definition and Geometric Dimensioning & Tolerancing (GD&T)

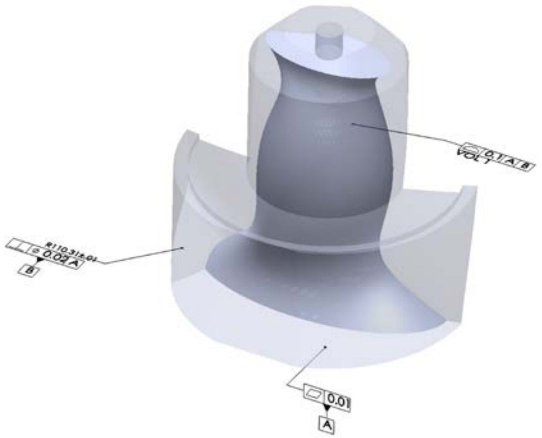
Incorporated into ASME Y14.46

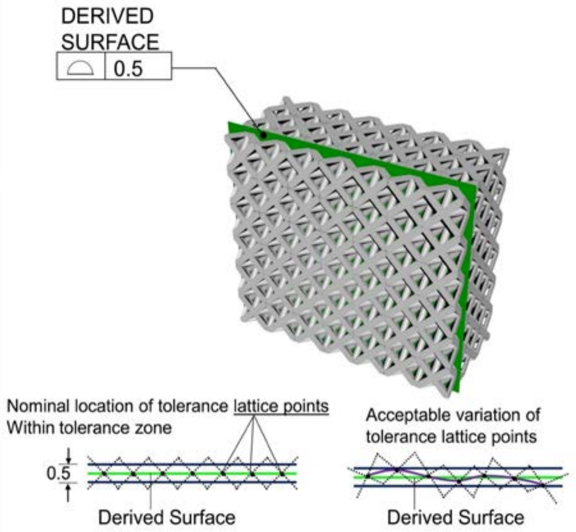
Y14.46 provides AM-driven definitions and representations for:

- Communicating process-specifics
- Tolerancing free-form complex surfaces
- Topology optimized shapes
- Graded materials
- Lattice/ Fill patterns
- Internal features
- Post processing
- Data packages









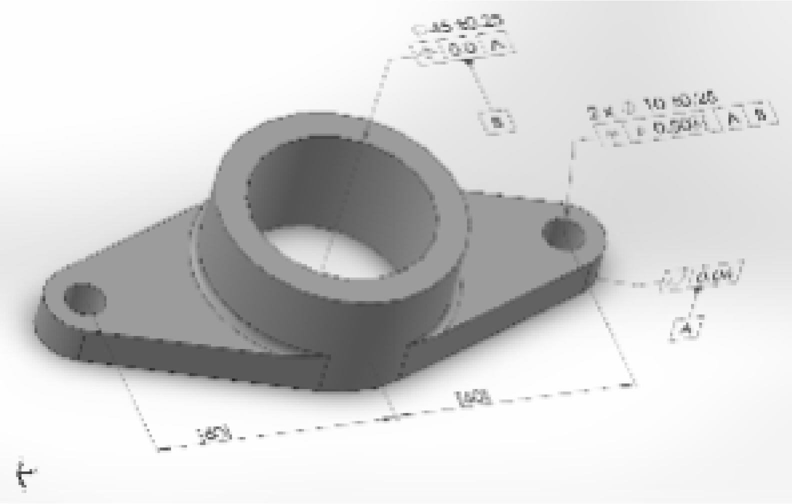
Figures using callouts for various AM-specific capabilities and needs

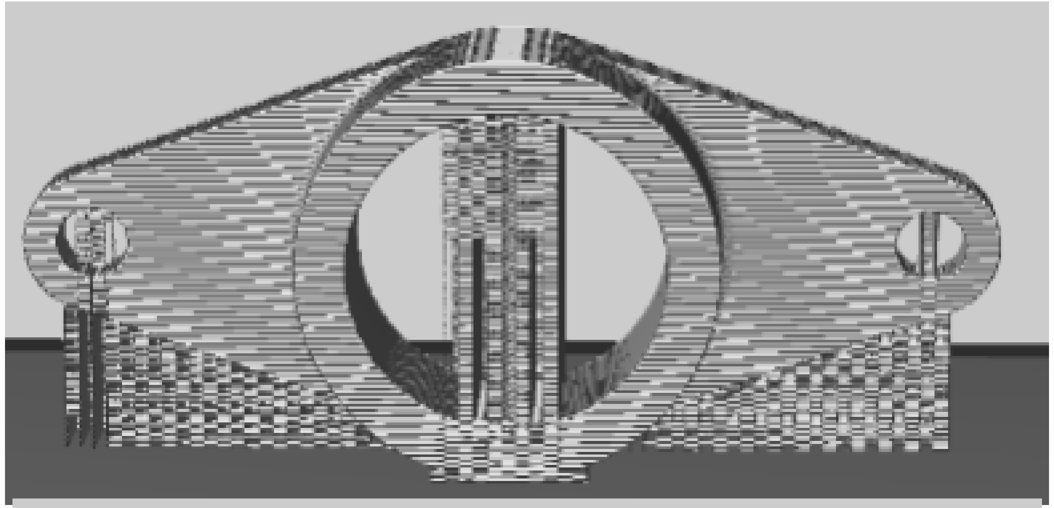
Incorporated into ASME Y14.46

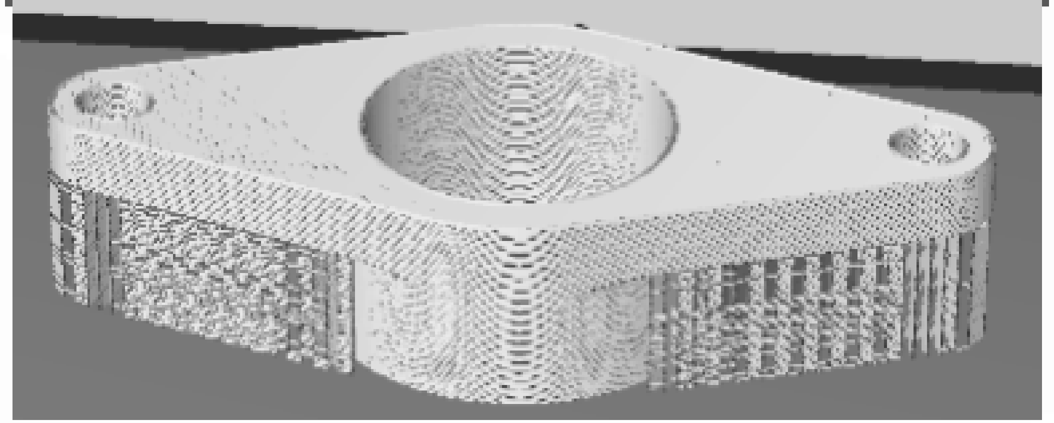
AM Challenges Include Process Planning

Many AM process planning decisions will impact the final part, such as

- Build direction
- Support structures







Many Standards Bodies are Involved in 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 / SC1, SC4, STEP-based data representation for AM
- ASME B46 Project Team 53, Surface Finish for AM
- ASME BPVC
- <others – the list is growing>

NIST Contributes to All of These Efforts

Some Challenges: 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 Structure

General AM Standards

- Terminology
- Data Formats
- Qualification Guidance
- System Performance & Reliability
- Round Robin Test Protocols
- Design Guides
- Test Methods
- Test Artifacts
- Safety
- Inspection Methods
- etc.

General Top-Level AM Standards

- General concepts
- Common requirements
- Generally applicable

Feedstock Materials

Material Category-Specific

- Metal Powders
- Ceramic Powders
- Photopolymer Resins
- Polymer Powders
- Metal Rods
- Polymer Filaments
- etc.

Material-Specific

- Titanium Alloy Powders
- Steel Rods
- Nylon Powder
- Nickel-Based Alloy Powders
- ABS Filament
- etc.

Application-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

Process / Equipment

Process Category-Specific

- Material Jetting
- Powder Bed Fusion
- Binder Jetting
- Directed Energy Deposition
- Material Extrusion
- Sheet Lamination
- Vat Photopolymerization

Process-Material-Specific

- Powder Bed Fusion with Nylon
- Material Extrusion with ABS
- Directed Energy Deposition with Titanium Alloy
- Powder Bed Fusion with Steel
- etc.

Application-Process-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

Finished Parts

All Finished Parts

- Mechanical Test Methods
- NDE/NDT Methods
- Post-Processing Methods
- Bio-Compatibility Test Methods
- Chemical Test Methods
- etc.

Material-Specific

- Titanium Alloy
- Paper
- Sand
- Nylon
- ABS
- Aluminum Alloy
- Nickel-Based Alloy
- etc.

Application-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

Category AM Standards

Specific to material category or process category

Specialized AM Standards

Specific to material, process, or application

ASTM INTERNATIONAL ISO

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Examples of AM-specific Standard Development

- Terminology
- Standard test artifacts
- Requirements for purchased AM parts
- Design guidelines
- Specification for extrusion-based AM of plastic materials
- Practice for metal powder bed fusion to meet rigid quality requirements
- Specific design guidelines for powder bed fusion
- Qualification, quality assurance, and post processing of powder bed fusion metallic parts

- Nondestructive testing for AM parts
- Intentional seeding of flaws in AM parts
- Anisotropy effects in mechanical properties of AM parts
- Conducting round robin studies
- Additive manufacturing format support for solid modeling
- AM of stainless steel alloy with powder bed fusion
- Specification of metal powders
- Design of functionally-graded AM parts

ISO

ASTM INTERNATIONAL
Standards Worldwide - Home

- Product Definition
- Surface Characterization
- Boiler and Pressure Vessel Codes

ASME
SETTING THE STANDARD

- Material and Process Specifications
- Material Data Specifications

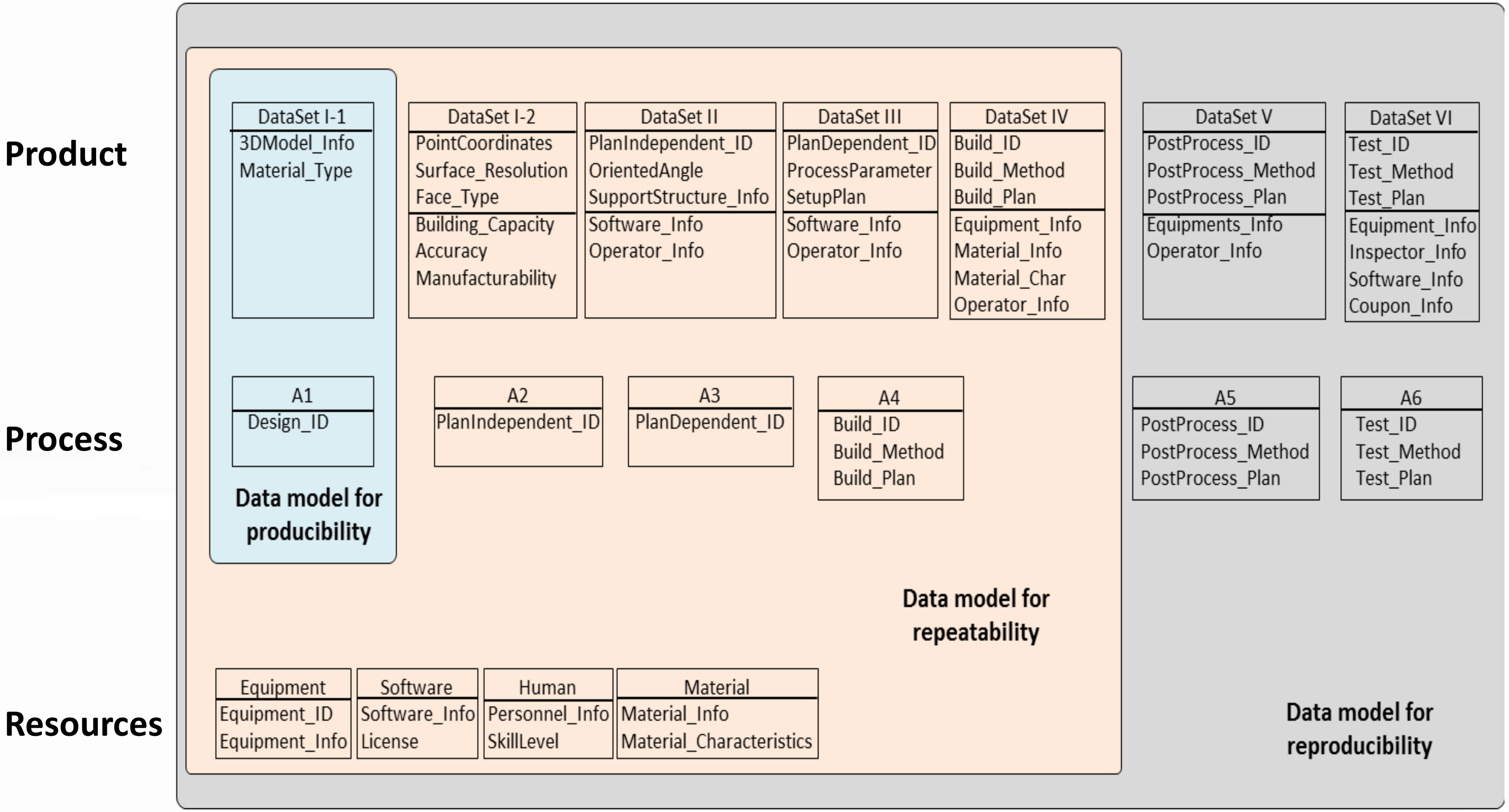
SAE INTERNATIONAL

- Process-specific Aerospace Requirements

AWS

Joint ISO/TC 261-ASTM F 42 Group JG 73
ISO/ASTM PWI 52923 - “Additive manufacturing - Data packages for AM parts”

- Recently established standard effort to help capture AM data package requirements
- Will cover data related to all phases of the AM lifecycle
    - From design to qualification
- Will leverage AM-specific standards to maximize established provenance
- First Draft Fall of 2019



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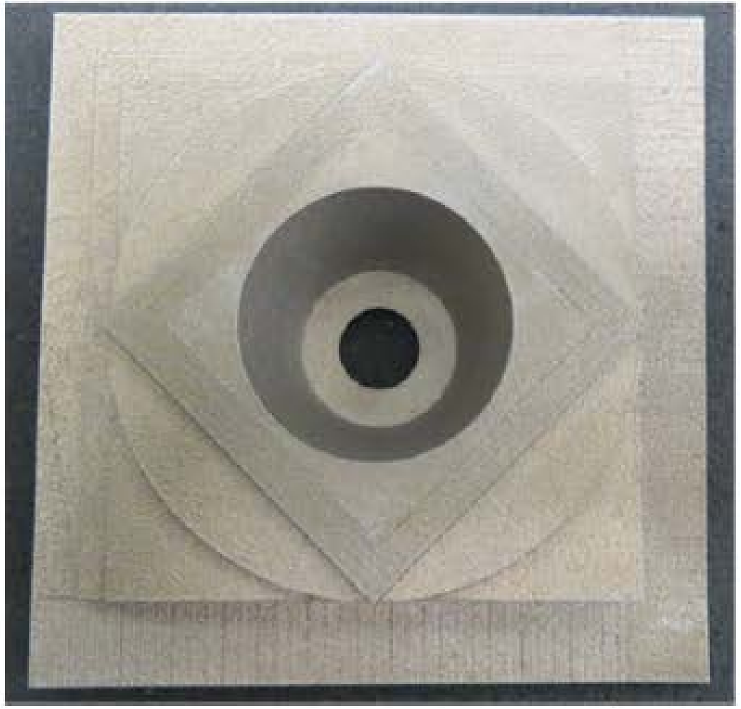
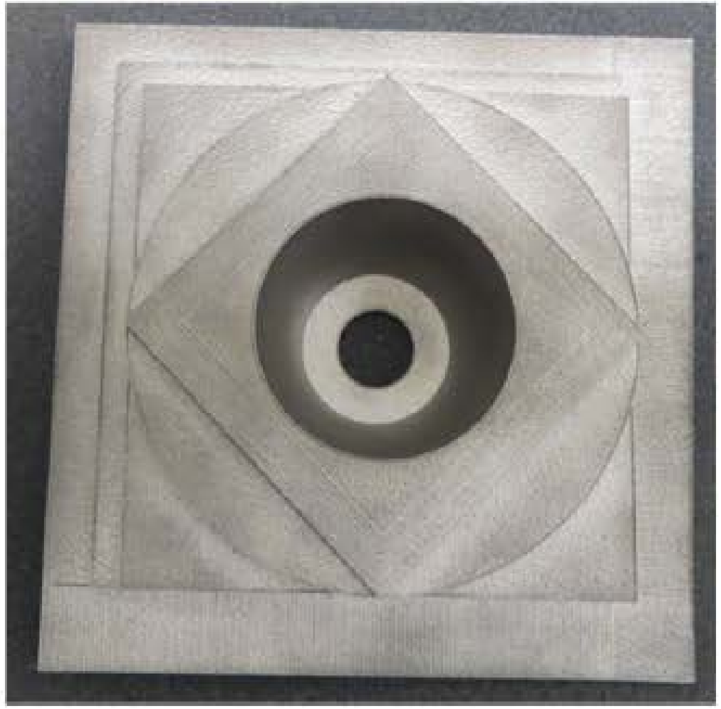
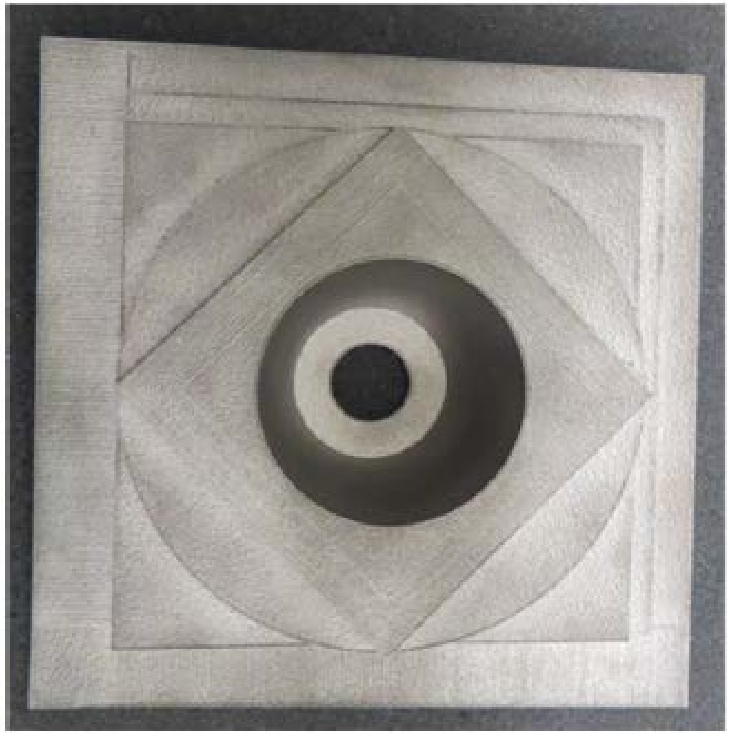
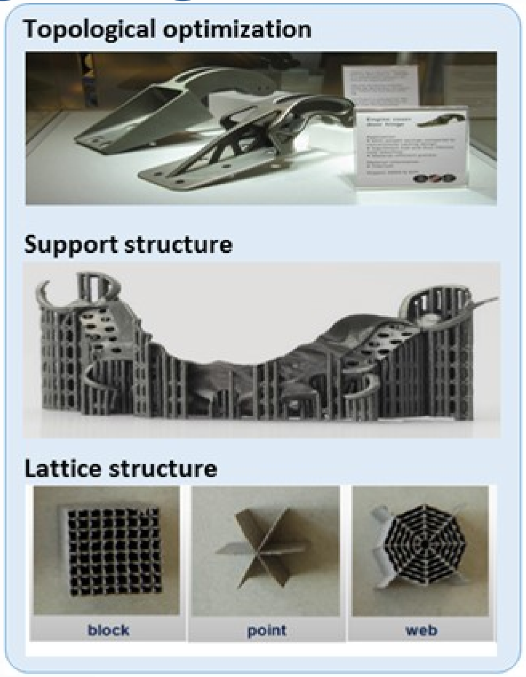
Are these the same part?

Photographs of test artifacts built by different service providers

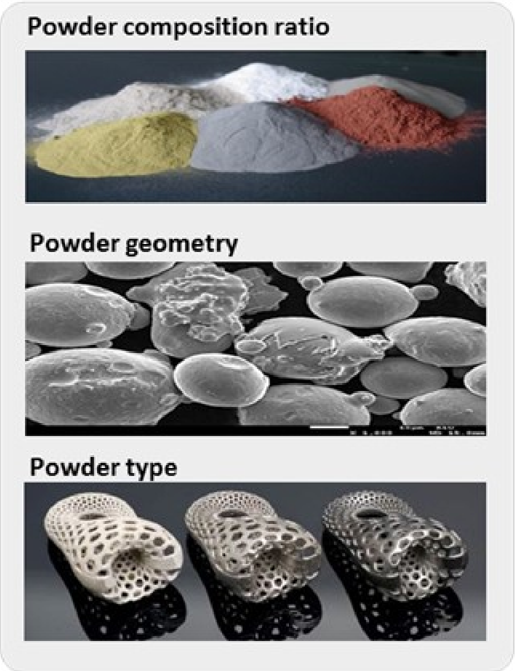




What am I designing for, what am I qualifying for?

- **AM Information can be classified into**
  - **Design/Geometry**
  - **Material**
  - **Process**
  - **Part**

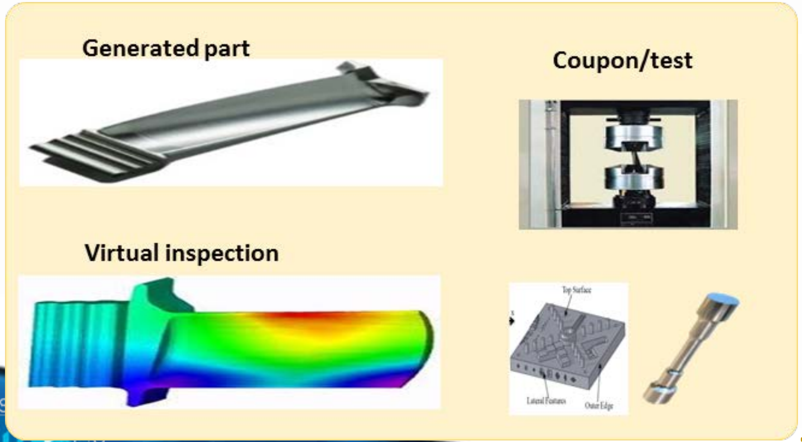


<Design/Geometry>



<Material>

<Process>



<Part/Qualification>

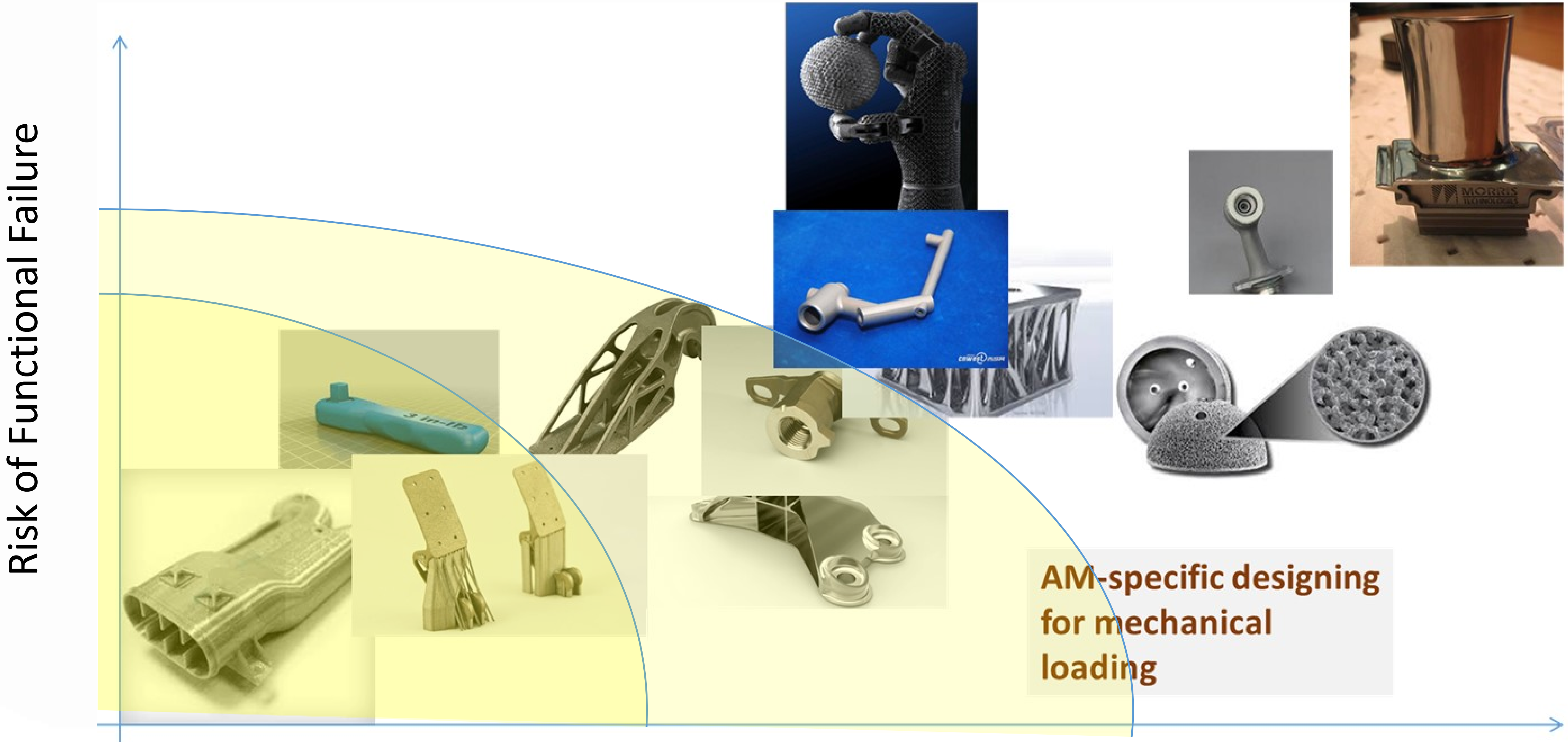
A qualified part is one that falls within the range of all ***critical*** design tolerances, has the specified surface attributes, and maintains part integrity and *stability during any functional tests*, ***as determined by the customer***.

http://www.moldmakingtechnology.com/articles/a-modern-moldmaking-trend

When is a part deemed to be satisfactory?

- What is qualification?
  - What is necessary to qualify against the *customers' (functional) needs*
    - What part/process characteristics are most likely to lead to failure?
    - What are the failure modes that will determine how the performance of the part is measured?
  - What data is necessary to "establish provenance"?
    - What data is available to create an established/quality dataset?
    - What type of requirements were placed on the part?
    - What type of relationship has been established with the manufacturer?
  - Does this have to be done for all parts? Only different geometries? Only different maintenance cycles? Only different machines?

What can we do to push the line further?



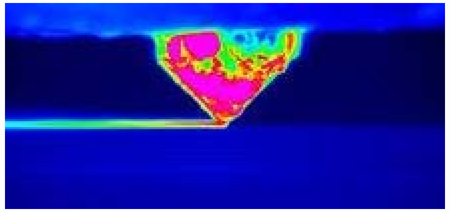
Takeaways

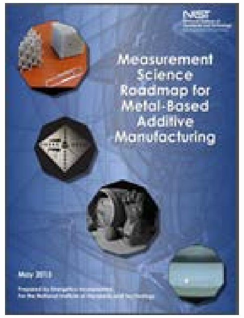
- AM is a unique process, but parts do not always have unique requirements
- It is important to understand how variability in a process may affect your part
- As processes mature, AM production capabilities will continue to grow
- AM standards provide a source for articulating AM-specific requirements
- Qualification is in the “eye of the beholder” and subject to the criticality of the part and risk of functional failure

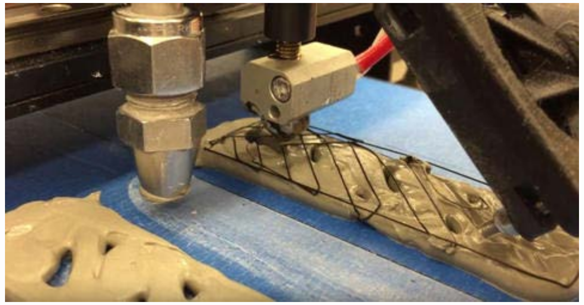
Additive Manufacturing at NIST

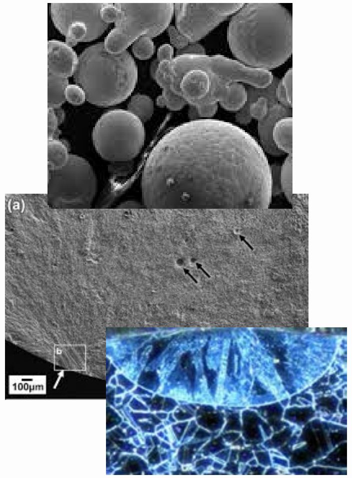
- Multiple Lab effort
  - Engineering Lab
  - Materials Measurement Lab
  - Physical Measurement Lab
  - Information Technology Lab
  - NIST Center for Neutron Research
- Multiple Technologies
  - Metals
  - Polymers
  - Concrete

- Activities Include
  - Workshops
  - Roadmaps
  - Standards Development
  - Measurement Technology Development



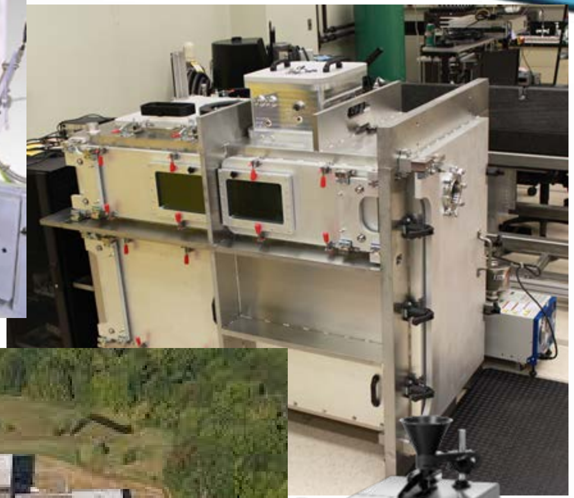


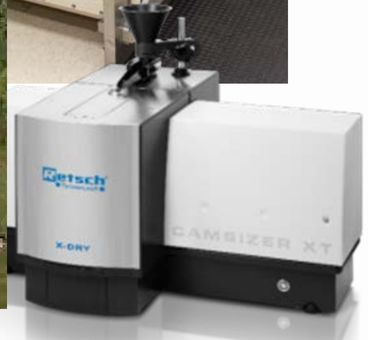


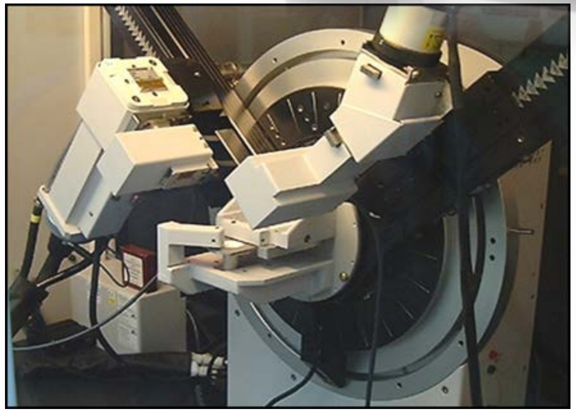


Facilities

- Commercial AM platforms
  - EOS M270, EOS M290
  - Optomec LENS MR7,
  - ExOne Mlab
- AMMT/TEMPS Laboratory
- Powder characterization laboratory
  - Dynamic imaging for PSD
  - Laser flash for thermal properties
  - Rheometer and powder spreading test platform
- Post-processing and testing facilities
  - High temperature heat treatment furnace, EDM
  - XCT, White light interferometry, mechanical testing, SEM, XRD
- Additive Manufacturing Research Center (AMRC)







Additive Manufacturing Research Center

AMRC

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