Perspectives on Effective AM Data Management

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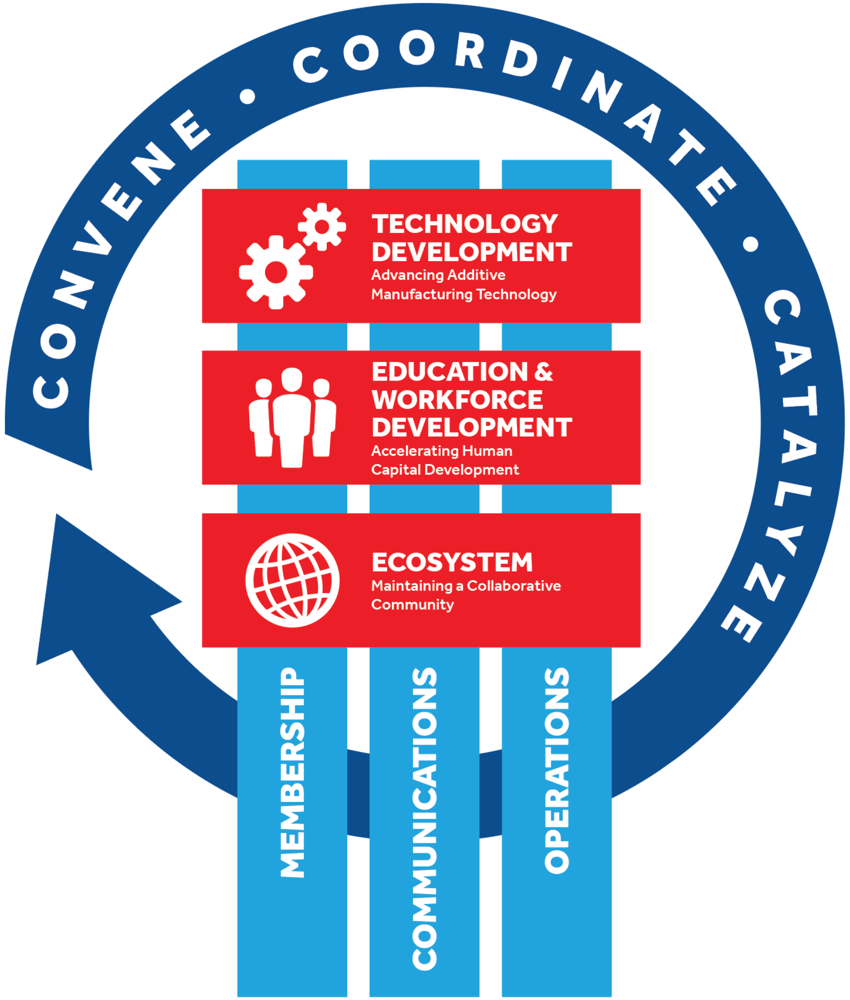
Overview

The three core activities of the Institute are:

- **Develop Additive Manufacturing Technology:** Projects, Innovation, Technology Transfer, Implementation
- **Accelerate Human Capital Development:** Workforce, Education, Training, Outreach
- **Maintain Collaborative Ecosystem:** Government, Membership, Community

These focus areas are enabled by:

- **Membership:** Driving engagement and collaboration with our nation's brilliant minds from government, industry and academia to advance Additive Manufacturing
- **Communications:** Driving awareness and spreading the word to government, members, stakeholders, community
- **Operations:** Run by a not-for-profit organization with a lean and collaborative structure



Technology advancement and collaboration through partnership

- Coordinating known stakeholder needs
  - Unique by member type
  - Academia, Industry, Gov't, Non-profit, National Labs
- Establishing priorities
  - Defining gaps and opportunities
  - Milestone, objective, and requirement-based approaches
  - Leveraging diverse expertise to target benefits and impact
- Leveraging collective intelligence/capabilities for applied learning
  - Execution mechanism
  - Many similarities to supply chain development

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Coordination
- Gaps
- Needs
- Opportunity

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Collaboration
- America Makes Membership

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Catalyzation
- Strategic Execution

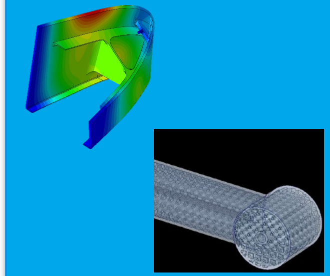
Engagement offers unique opportunity to detail a comprehensive strategy for AM industrialization

- Publications, Events, Digital StoreFront
  - What we are learning or what is known
  - What we can understand better
- Advisory and working groups
  - Active learning (knowledge capture, analysis, and sharing)
  - Prioritization
- Workshops
  - What we need or what we do not have
- Roadmaps
  - Organized, prioritized opportunities defined in one place utilizing a common taxonomy
  - Four roadmaps – AMSC, EWD, AM Technology, and DoD

Considerations for Production/Acquisition of AM Products

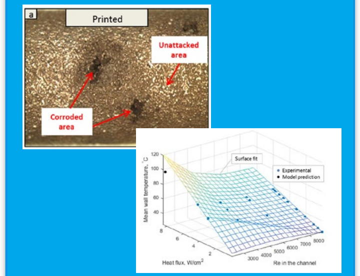
Supply Chain & Sourcing

- Capacity
- Capability
- Technical Resources
- Standards and Specifications
- Quality Control



Design

- Design data
- Manufacturability
- DfAM
- Data Management
- Standards and Specifications
- Materials Selection
- Tools/Methods



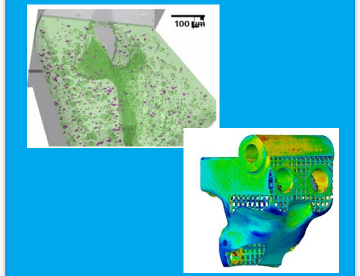
Performance & Durability

- Mechanical properties
- Component/
- Subsystem behavior
- Environmental Factors
- Standards and Specifications
- Maintenance/ Repair

Image Courtesy Quintus Technologies

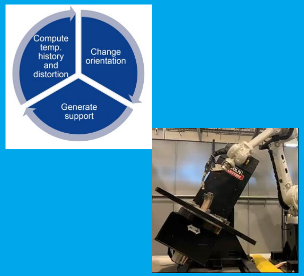
Post-Processing & Finishing

- Heat treatment
- Coating
- Machining
- Polishing
- Joining/Brazing
- Standards and Specifications



Inspection/ NDE

- Reasonable criteria
- Inspectability
- Tools/methods
- Standards and Specifications



Cost & Rate

- Complexity
- Cost drivers
- Yield
- Productivity drivers

Qualification and Certification Goals & Objectives

- Gathering and understanding actionable data
  - What to look for
  - How to measure (tools, techniques, and frequency) accurately and reliably
  - What the evidence suggests
  - If the evidence coincides with acceptable and unacceptable material or product conditions
  - How to react – managing potential for success

- Can be influenced by all steps within the value stream
  - Demand and associated productivity
  - Feedstock, interim material forms and conditions, and final product form
  - Application environment and operating conditions
  - Full product lifecycle – production, service, inspection, and maintenance

- Cost and pace to attaining sufficient understanding
  - Rigor, tenacity, and wisdom
  - Sensible to partner given the technology readiness level in many instances

Integration of AM within the Larger Manufacturing Industrial Base

- Understanding various facets of value stream allow us to respond accordingly to our own/customer's/supplier's/member's needs

- The utility and value of AM is conditional
  - Application
  - Manufacturing Capability
  - Performance
  - Productivity
  - Cost

- The benefits of AM are known, the impact remains to be conditionally verified

Utility of AM Digital Tools and Analytics are Similarly Conditional

- System of systems
- Communication efficiency
- Connectivity and interoperability of pedigreed data
- Collaboration
- Traceability – single source of truth
- Enabling adaptation, agility, and resilience
- Design, processing, quality, and supply chain management and optimization
- Accounting for full product life cycle – design, make, test, service
- Workforce and training

What do we mean by "model-based enterprise"?

And what types of models are included?

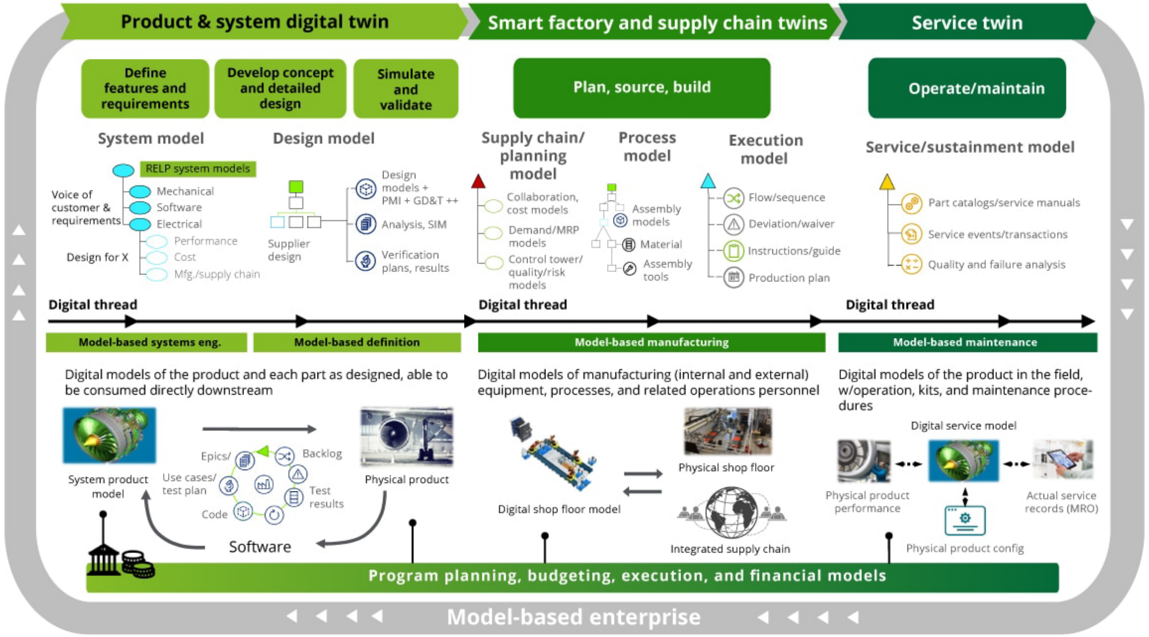


Image courtesy of Deloitte

Successful application of digital tools and analytics should deliver agility, resiliency, and cost reduction

Known Challenges Since 2019/2020

- Resources
  - Human and financial
  - Knowledge/skills
- Supply Chain Coordination
  - Global, all encompassing solutions
  - Easing barriers to collaboration
  - Facilitation of standardization
- Technology Gaps
  - Software
  - Hardware
  - Methods
- Operations/Best Practices

- Must avoid duplication of effort
- Any single entity generates but a subset of data
- External data not well characterized, or value is unknown
- External data incorporation
- Readily searchable
- Opportunities for advanced analytics
- Securing collaboration and innovation

2019 Data Management Workshop Findings

- Dec 2019 Collaboration with ASTM CoE
  - Data Management and Schema Workshop
- Outcomes
  - Action plan and strategy guide
    - Common Data Dictionary
    - Common data exchange format
    - Automated data acquisition
    - Public use cases
    - Minimum viable data package
- ASTM Data Subcommittee – ASTM F42.08
- Several standards published and in-process
- Findings and priorities have played an influential role in our actions since then

Standards Prioritization from AMMO AM Workshop 2021 and 2022

- 2021
- **Gap QC2: AM Part Classification System for Consistent Qualification Standards**
- **Gap PC4: Machine Qualification**
- **Gap D17: Contents of a TDP**
- Gap QC1: Harmonization of AM Q&C Terminology
- **Gap FMP4: Design Allowables**
- Gap PC2: Machine Calibration and Preventative Maintenance
- **Gap FMP1: Material Properties**
- **Gap PC7: Recycle & Re-Use of Materials**
- Gap PM7: AM Process-Specific Metal Powder Specifications
- Gap D15: Design of Test Coupons

- 2022
- Gap PC4: Machine Qualification
- Gap QC2: AM Part Classification System for Consistent Qualification Standards
- Gap D17: Contents of an AM TDP
- Gap PC7: Recycle & Re-use of Materials
- Gap FMP1: Material Properties
  - Gap FMP4: Design Allowables

Existing AMSC Roadmap v2 Gaps Pertaining to Digital Manufacturing

Design

- D6: Software-encodable/Machine-readable Guidelines
- D8: Machine Input and Capability Report
- D9: AM Simulation Benchmark Model/Part Requirement
- D12: Imaging Consistency
- D13: Image Processing and 2D to 3D Conversion
- D17: Contents of a TDP
- D18: New Dimensioning and Tolerancing Requirements
- D19: Organization Schema Requirement and Design Configuration Control
- D20: Neutral Build File Format
- D22: In-Process Monitoring – Coupling predictive analytics (product performance) with monitoring data
- D26: Design for Measurement of AM Features/Verifying the Designs of Features such as Lattices, etc.
- D27: Standardized Design for Additive Manufacturing (DFAM) Process Chain

Qual and Cert

- QC6: Importing Ultrasound Data
- QC7: Protocols for Image Accuracy
- Gap QC8: Phantoms
- Gap QC9: Personnel Training for Image Data Set Processing
- Gap QC10: Verification of 3D Model
- Gap QC13: Material Control Data and Procedures

Process Control

- PC1: Digital Format and Digital System Control
- PC2: Machine Calibration and Preventative Maintenance
- PC3: Machine Health Monitoring
- PC4: Machine Qualification
- PC5: Parameter Control
- PC6: Adverse Machine Environmental Conditions: Effect on Component Quality
- PC15: Configuration Management: Cybersecurity
- Gap PC16: In-Process Monitoring - registration

Existing AMSC Roadmap v2 Gaps Pertaining to Digital Manufacturing

Non-Destructive Evaluation

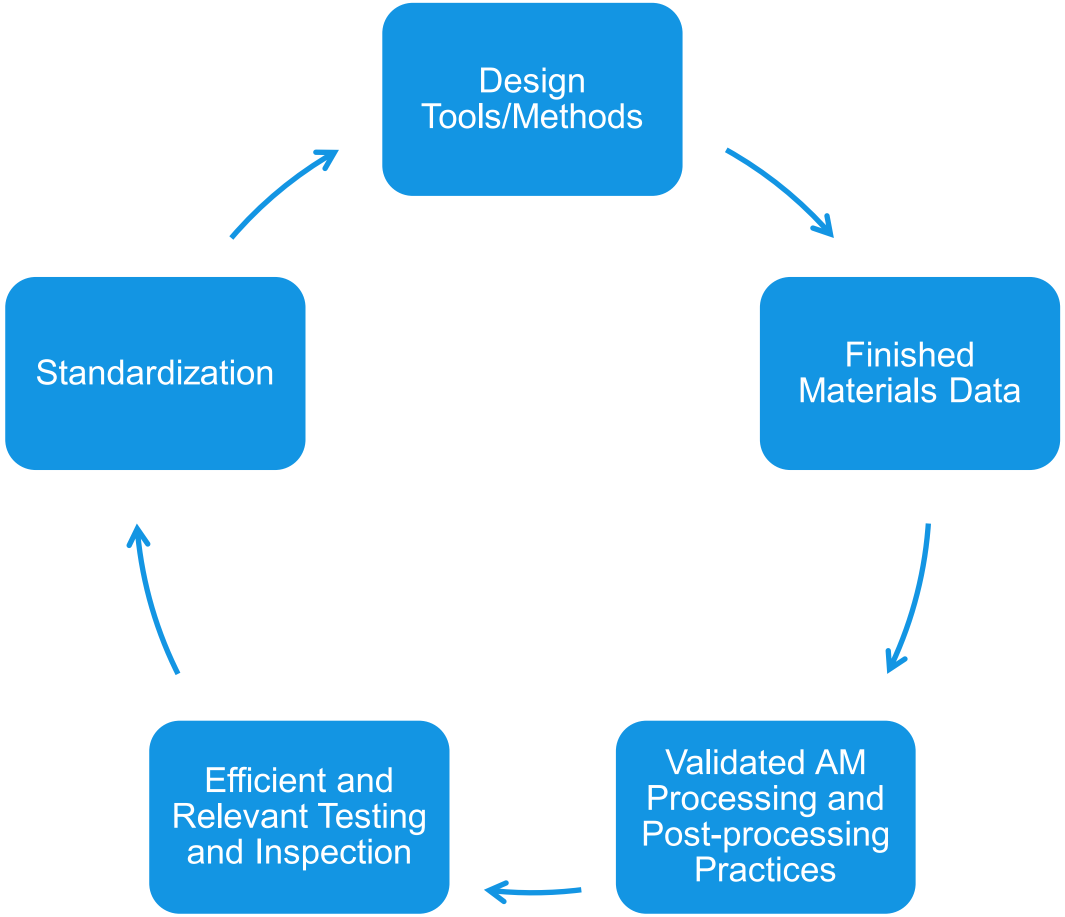
- NDE2: Standard for the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability.
- NDE3: Standard Guide for the Application of NDE to Objects Produced by AM Processes.
- NDE4: Dimensional Metrology of Internal Features.
- NDE5: Data Fusion
- NDE7: NDE of Counterfeit AM Parts

Maintenance and Repair

- M1: AM Analyses in RCM and CBM.
- M3: AM Level of Repair Analysis.
- M5: Model-Based Inspection.
- M6: Tracking Maintenance.
- M7: Cybersecurity for Maintenance.
- M8. Surface Preparation for Additive Repair.

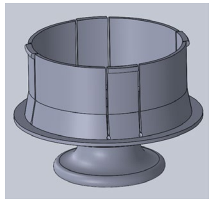
Objectives for AM Research and Development

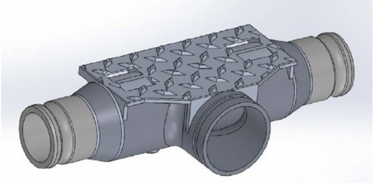
- **Stability** – repeatable, predictable
- **Producibility** – scale up to production
- **Characterization** – as-fabricated properties available
- **Predictability** – validated methods to quantify performance
- **Supportability** – cost-effective inspection and repair



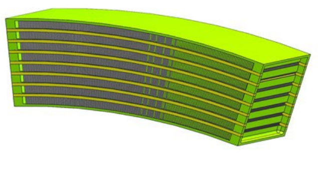
Various Areas of Ongoing Investigation

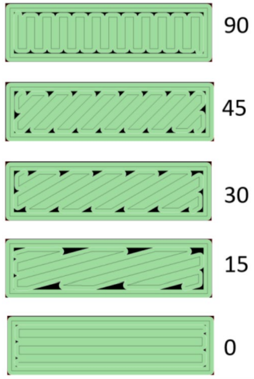
- Acquisition Methods, Tools, and Protocols
- Design Tools
- Feedstock Characterization
- AM Process KPV's
- Various AM modalities
- Post-processing – HIP, Heat treatment, Finishing
- Inspection – Limits of detectability
- Process Monitoring
- Materials Data (allowables)
- Coatings
- Joining, Part Consolidation, and Integration
- Qualification Methods and Testing

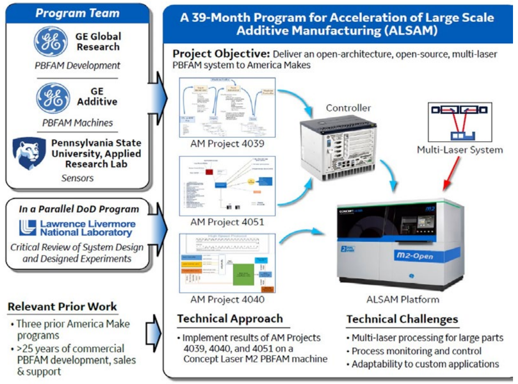


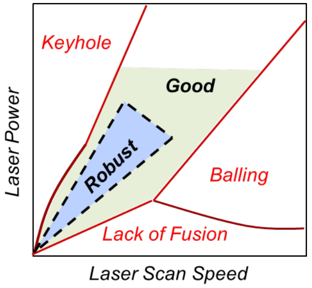


Demo part 1: aircraft vent









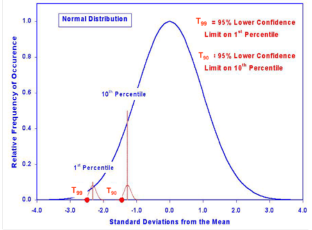
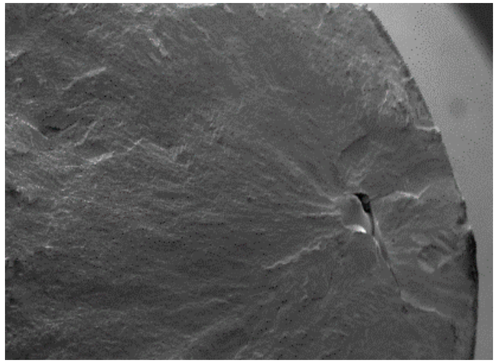
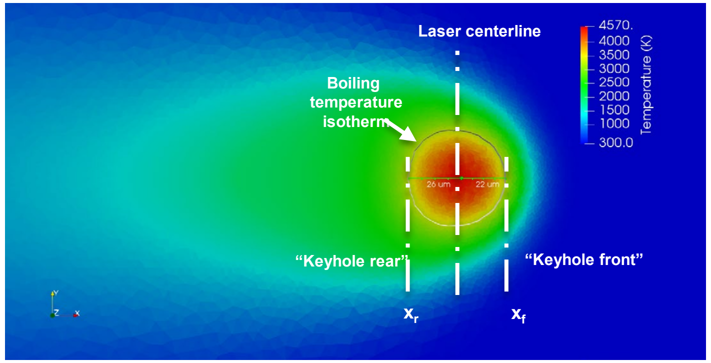


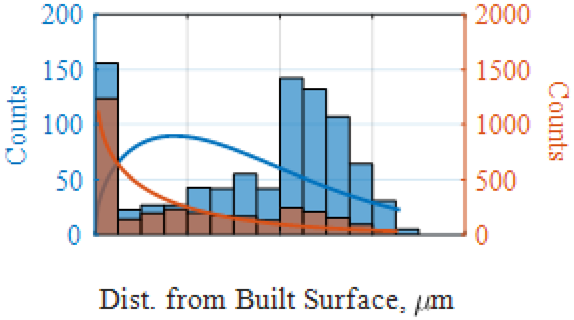
Figure Courtesy of MMPDS Battelle FAA/EASA Workshop 2020

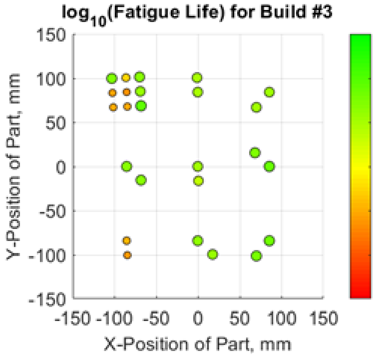
Characterization of Process Dynamics on Material and Product Quality

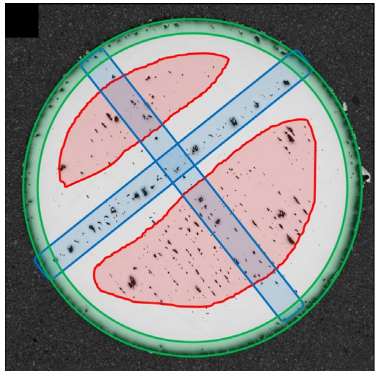
- Addressing interdependencies of process features on material quality
  - Physical/mechanical properties
- Key AM process features – outcomes arising due to multiple physical processes
- Sources of Microstructural Variation
  - Heat flux
  - Ambient conditions
  - Remelting
  - Geometry/ location
- Systematic processing of discontinuities
  - Effects of remelting indications
- Accelerate material qualification
  - Understanding sensitivities
  - Control
  - Acceptance criteria
  - Process specifications

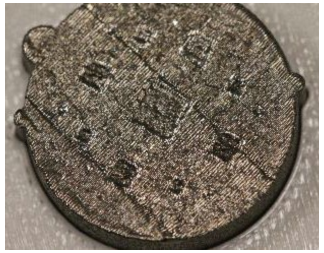


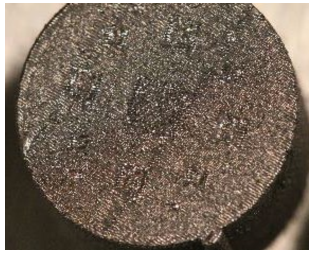


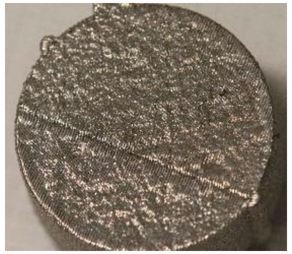






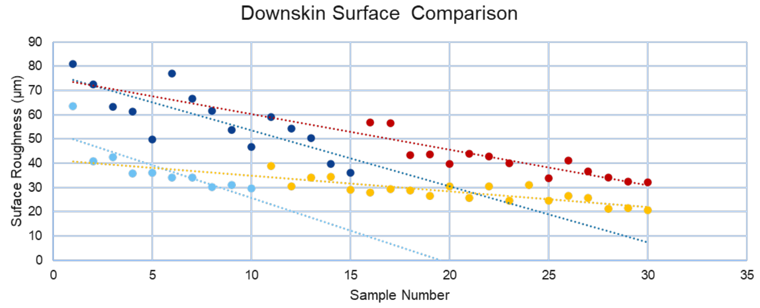


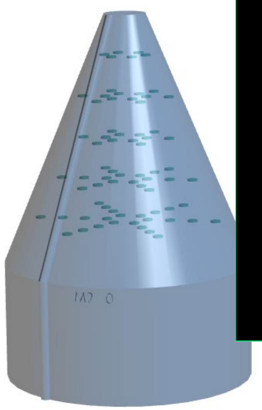


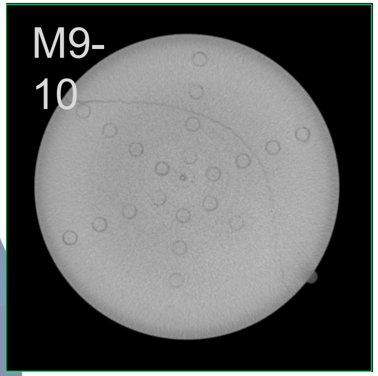


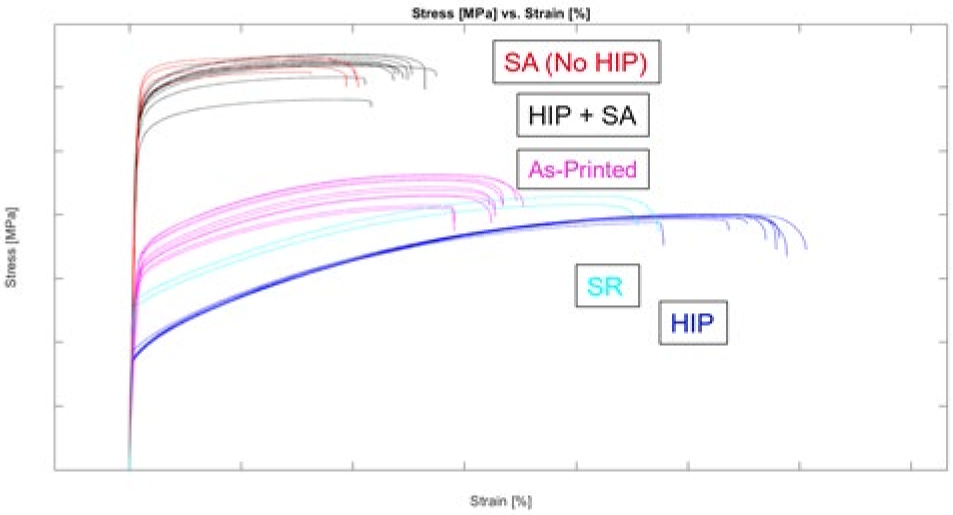
Systematic Experimentation to Address Material and Product Quality Risks

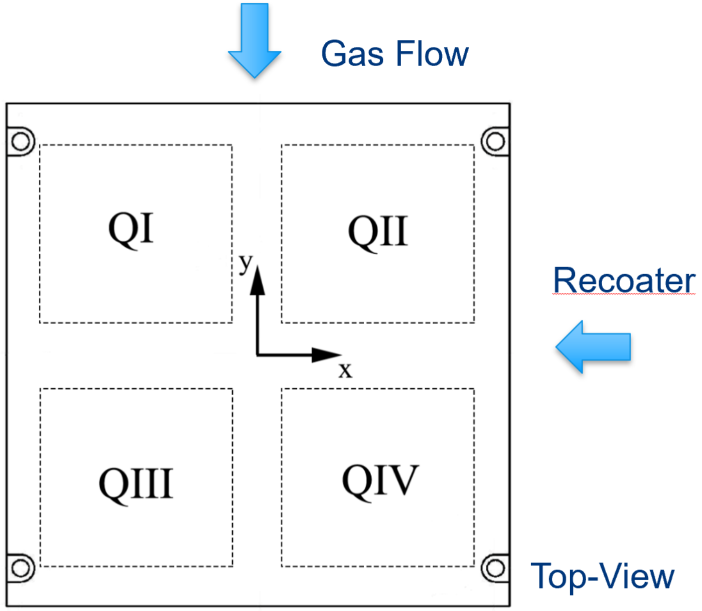
- Evaluation of key process parameters
  - Processing location
  - Melt sequence
  - Laser power
  - Travel speed
  - Component orientation/geometry
- Influence of heat treatment
  - Microstructure
  - Mechanical/Physical Properties
    - Tensile, Fatigue, Corrosion
- Surface condition
  - Coating, machining, as-built
  - Corrosion, strength, fatigue
- Standardization
- Training
  - Lessons learned
  - Key details





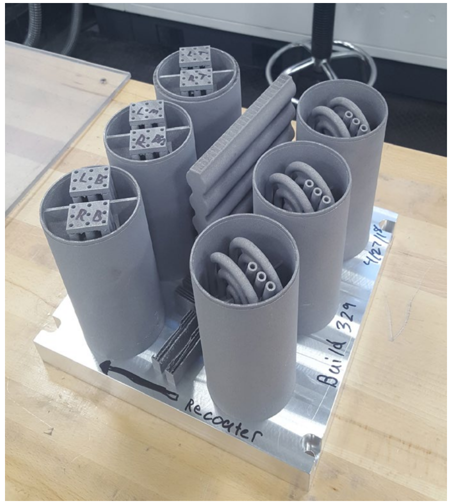


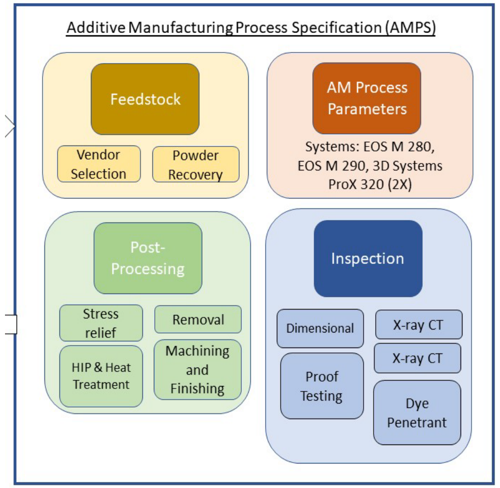


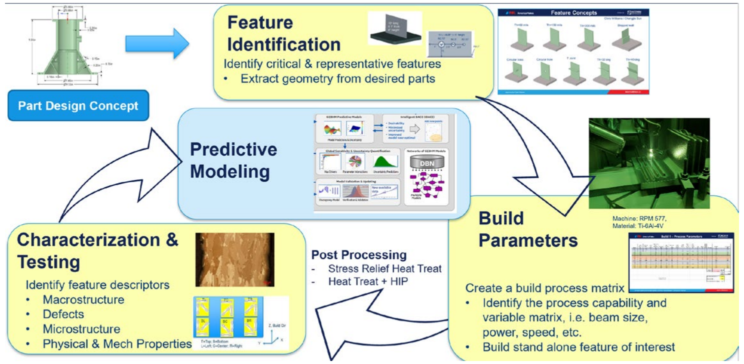


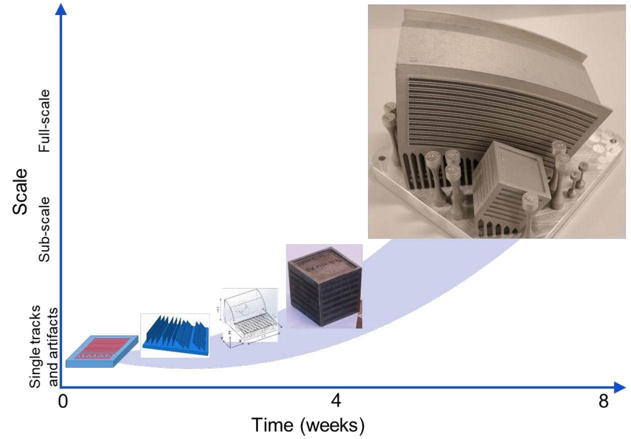
Addressing Operational Risks and Documenting Relevant Operational Qualification Considerations

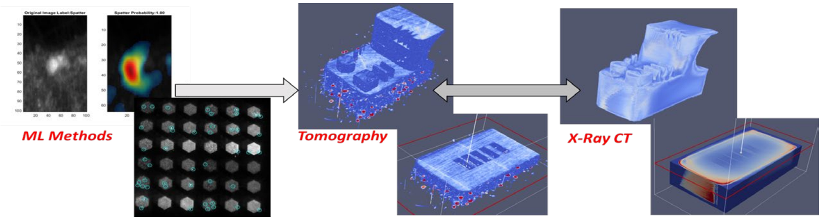
- Going beyond design point solutions
  - "Everything" is an essential variable
- Feature-Based Qualification
  - Part family
  - Machine learning to predict performance
  - Sub-element testing
  - Building block approaches
  - Demonstrating equivalence
  - Quantifying confidence
- Specifications and metrics
  - Expansion of process specification protocols
  - Commoditizing AM materials/products
    - Digital thread approaches
- Addressing Producibility and Supportability
  - Yield, Cost, Rate
- Accelerating inspection processes
  - Demonstrating alternatives to CT
  - Limiting CT through in-situ monitoring
  - Data registration – deriving actionable data





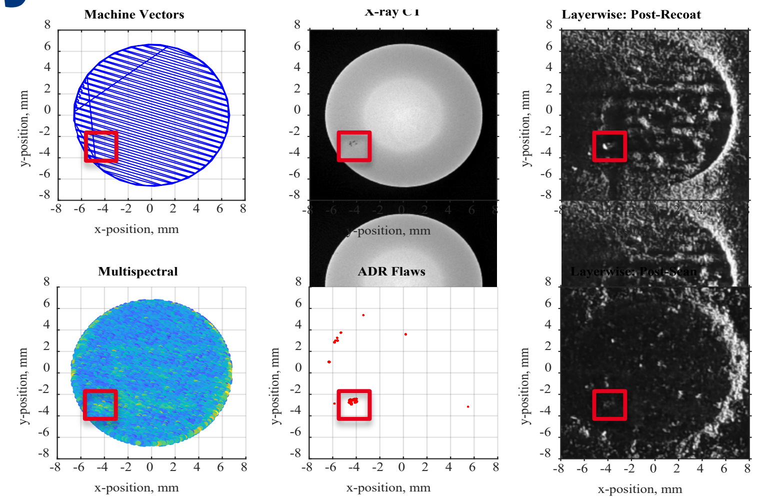


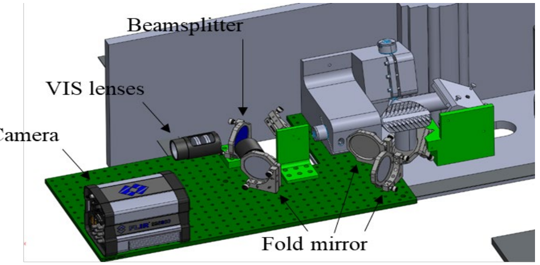


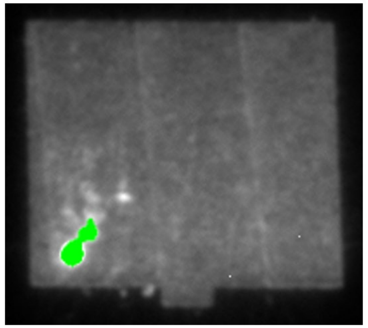


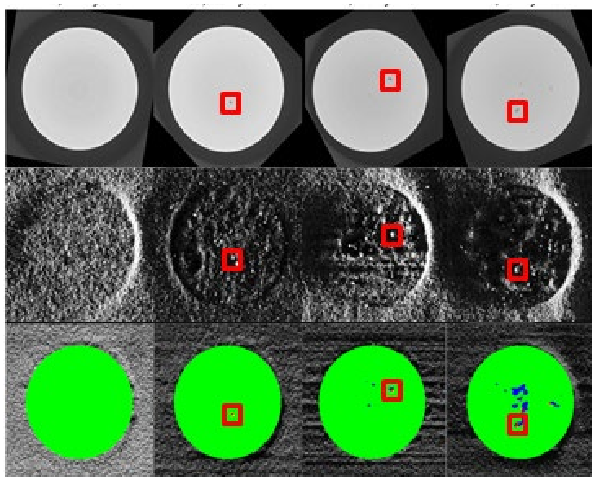
Advanced Sensing and Data Analytics for Evaluating AM Material and Product Quality

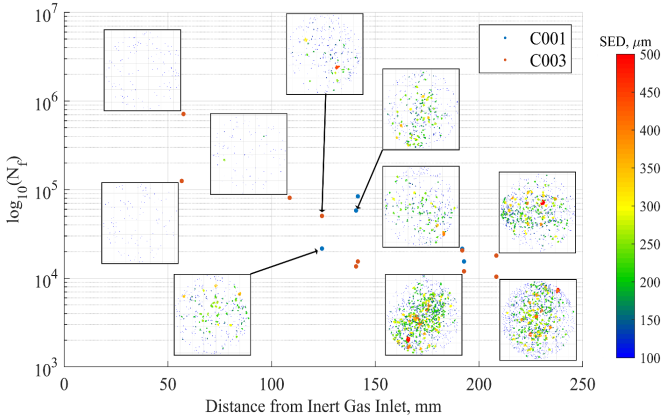
- Emerging, now-term opportunities
  - Measurement to quantify physical phenomena
  - Enabling comparison of ex-situ inspection and in-situ measurement
- Hardware and software development
  - Sensing and detection
  - Registration
  - Correlation – physical processes and material properties
  - Analysis and Validation
- Advanced analytical techniques
  - Artificial Intelligence/Machine Learning
  - Statistical analysis - correlation





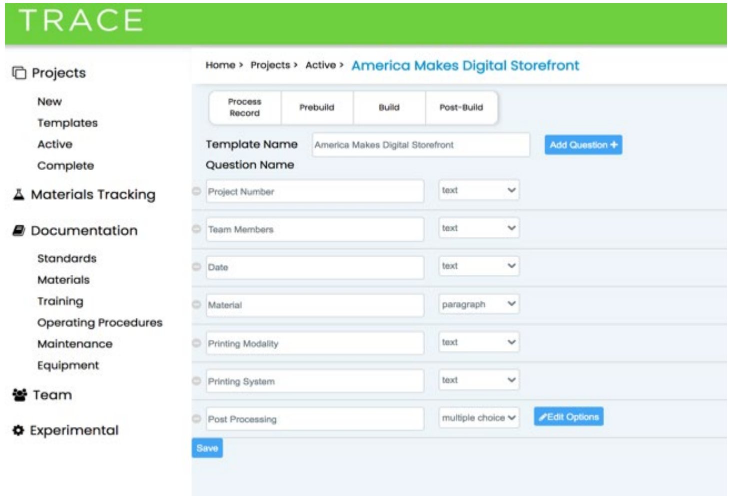






Enabling Expansive Adaptation/Utilization of the Technology

- Enabling novel design development with relevant, pedigreed materials data
- Reduce barriers for otherwise marginal applications
  - Development time/cost
- Development of MMPDS Recognized Design Allowables
  - LPBF of Ti-6Al-4V
  - Tensile and fatigue
- Searchable Materials Database
  - Data pedigree
  - Minimum standard schema
  - Accessible and Secure
  - Visualization and analysis
- Driving focus on data management practices
  - Rigor and wisdom



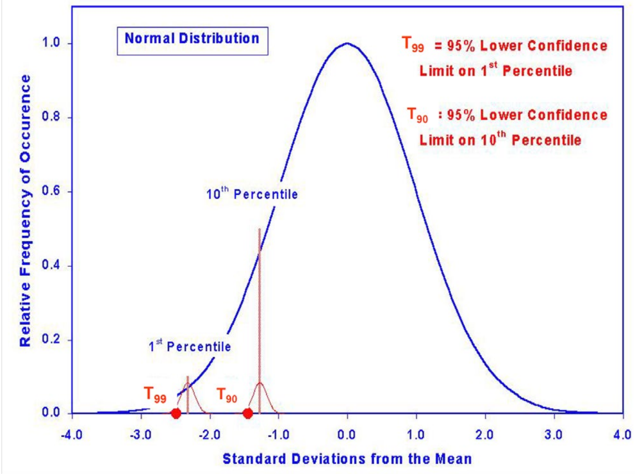
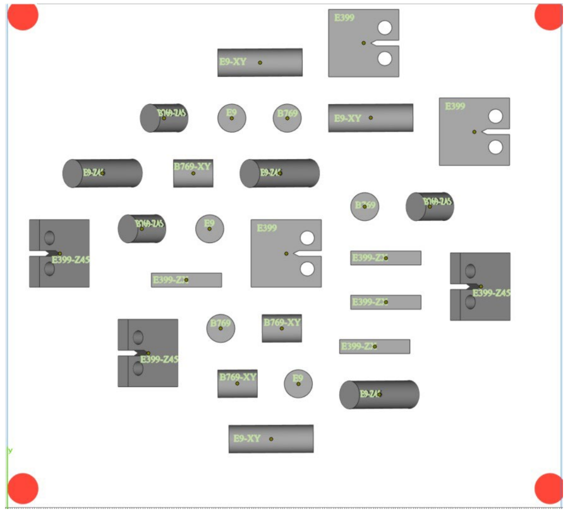


Figure Courtesy of MMPDS Battelle FAA/EASA Workshop 2020

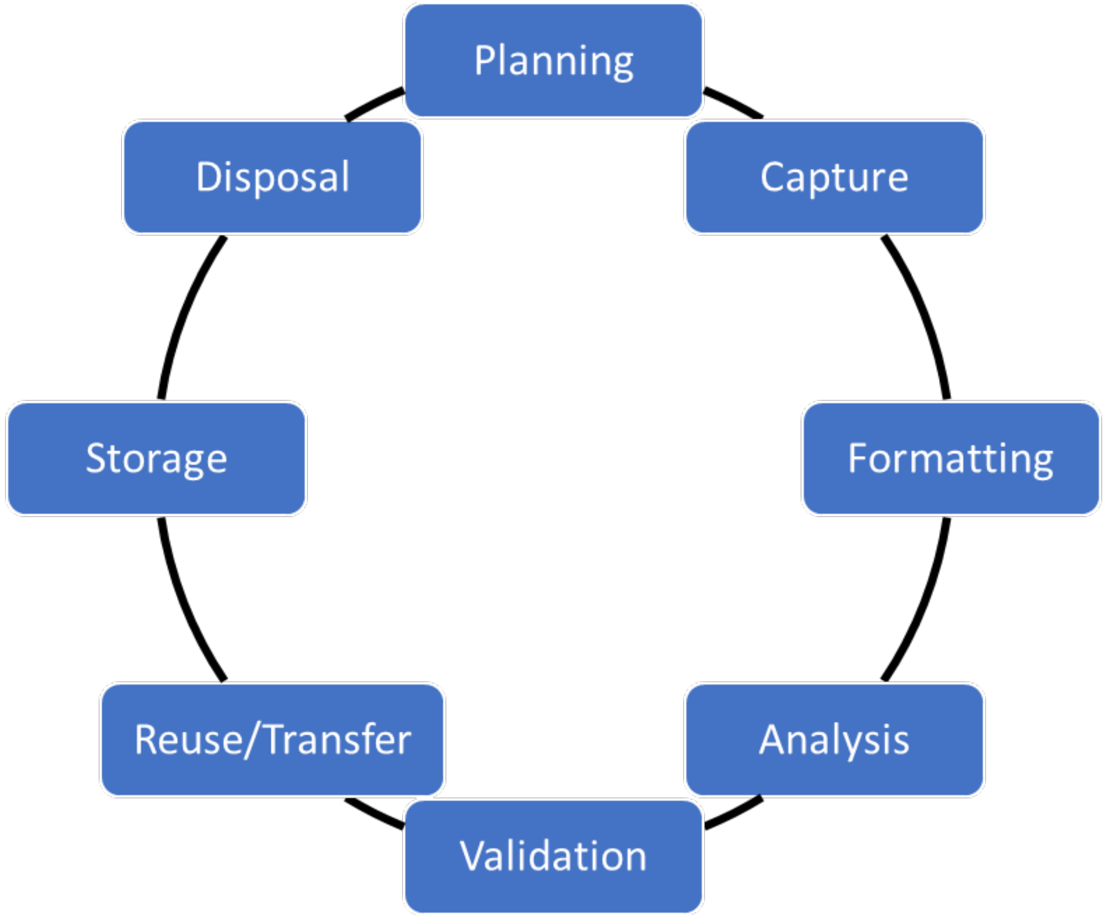
Processing Window	Build Logistics	Post Processing
Static & Dynamic Parameter-Structure Mapping	Data Pedigree and Management	MFG definition: Stress relief, HIP, heat treatment, etc.
Effect of Defects	Best known Practices on Operations	Inspection Techniques and Sampling Rate
Machine to Machine Variability	Partner & Supplier Audits	Plate removal, machining vs. as-printed, dimensioning
Within Chamber Variability		



Project/Program Data Life Cycle

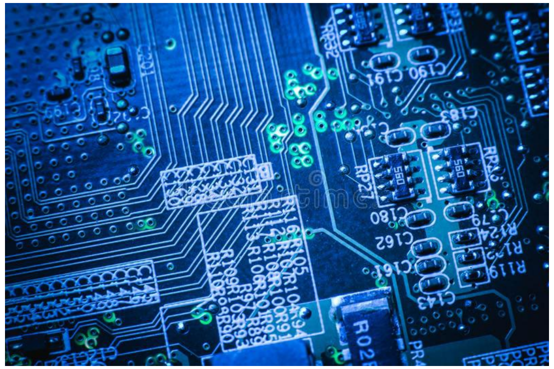
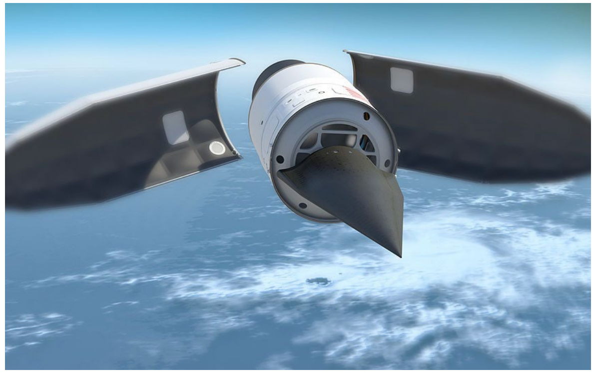
- Facilitated by
  - Value Assessment – Goals/Significance
  - Tools
  - Training
  - Methods
  - Standards/Specifications/Work Instructions
  - Security and auditing

- Enduring value derived (reuse/interoperable) by
  - Planning – structure (pedigree)
  - Transfer
  - Storage



Market Opportunities for AM Product Development Go Beyond Aerospace




Images courtesy of DARPA and Dreamstime.com

We must consider the utility and impact of AM technologies across various application domains

Near term efforts and long-term prioritization

Request for Information

- Methods and Approaches for Sustainable AM Operations
- Announced April 12, 2023
- Responses due May 12, 2023

- Industrialization of AM represents an opportunity to convert demonstrated manufacturing capability to capable manufacturing capacity

- There is a need for widespread understanding of manufacturing operational practices that address sustainability and robust quality control

- America Makes is looking for inputs from the domestic AM supply chain and the membership to offer perspective on needs which address two topic domains:
  - Needs and priorities for the development and demonstration of sustainable AM practices and products
  - Needs and priorities for the development and demonstration methods and approaches which deliver validated objective evidence to substantiate robust AM manufacturing operations (operational qualification)

Operational Qualification

- Borrowed definitions from 2020 AIA publication, "Recommended Guidance for Certification of AM Component"
- Operational qualification (OQ) is a myriad of tasks which leads to process control documentation substantiated through characterization, analysis, and testing to confirm the process can deliver to material specification requirements.
- OQ commonly occurs between the time the machine is deemed passing site acceptance testing and when product qualification starts.
- Quantitatively analyzing AM processes through serial production and over time becomes more substantial.

OQ may include:

- Facility controls
- Operator training and qualification
- Work instructions
- Software configuration controls
- KPV controls and documentation
- Machine configuration controls
- Preventative maintenance
- Machine calibration
- Machine requalification
- Feedstock control, management, handling, and reuse
- Build interruptions
- Monitoring
- Documentation and records keeping
- Powder removal
- Thermal processing - stress relief, HIP, and heat treatment
- Machining including build plate and support removal
- Surface finishing/conditioning

Observations

- The amount, type, and means of sampling, documentation, testing, analysis, etc. can vary depending upon the operator, AM process, material, application, and customer.
- There is a need for establishing consensus balanced with practicality and rigor when it comes to the number, practices, types, and methods of testing to foster operational qualification (establishing the amount of objective evidence necessary to show an AM process is yielding stable material performance)
- It is worth noting that executing OQ also assumes one has a sufficient understanding of the processes, microstructures, and properties which constitute AM material performance
- There is a desire to understand how the supply chain can execute OQ more effectively, not to be confused with product acceptance or PQ
- It is believed that with more suppliers understanding the details of effective AM OQ, the time to achieve PQ will shorten and we will be able to convert more AM capability to capable AM manufacturing capacity.

Delta Qual

- Qualification of additive manufacturing (AM) machines and materials is a major barrier for the broad adoption of AM
- Generating data and models requires significant investment of resources and time in order to produce statistically significant data
  - Generating test coupons under a controlled process, performing testing, and analysis of the resulting data
- Established processes are “frozen”
  - No changes to key process variables allowed
  - Currently no standards-based guidance for what is required when change to the process is necessary or desired
- Common route forward for implementing change to a qualified process is total requalification
  - Can cost more than $3M per machine/material combination
  - Takes several years to complete
- Execute effort which demonstrates the ability to rapidly and affordably update and/or establish a qualified AM process that can allow for changes in key AM process, post-processing, and/or material feedstock variables

Important Considerations to Approaches

- Establishing validated feedstock material forms, process controls, and repeatable and statistically significant quality (physical and mechanical properties) in a manner that is industrially relevant
- Consider factors such as maintenance, calibration, and auditing to substantiate a controlled process workflow
- Material and process specifications, control documentation, and other relevant controls will be communicated and reviewed by others to establish a valid delta qual is successfully demonstrated
- Discussions of approach, data management, and workflow control will occur between teams executing novel delta qualifications and other teams executing baseline qualification efforts.

Our Approach to Data Management Remains Firm

- Assessing value proposition of data management and digital based approaches for AM industrialization is critical
  - We are actively exploring this question
- Technology development transitioning focus from feasibility to repeatability, transferability, efficiency
  - Representative of TRL >4 and driving towards 6/7
- Promoting a culture of data management
  - Data management is a cornerstone to our efforts
  - Alignment of effort and deliverables to roadmap taxonomy
  - KPP’s – success measures
  - Transfer of data to membership – America Makes CORE
- Promoting engagement with technical community – consensus building
  - Working groups
  - Events
  - Publications
  - Ensuring we identify opportunity to disseminate value, reuse, interoperability of outcomes
- Exploring opportunities to improve organization, storage, and sharing of datasets

Design Offers Expansive Opportunity for Digital Tools and Methods

- Product definition alignment to application specific requirements (MBSE) – safety, performance, manufacturing capability, service life cycle
- Cost savings
- Accelerating certification by analysis
- Promoting inspectable complexity
- Light weighting while ensuring rapid qualification and certification
- Accounting for manufacturability limits
- Accounting for process specific thermal history and post-processing
- Multi-physics, multi-objective optimization

Material Characterization, Prediction, Development, and Optimization

- Feedstock chemical composition development and qualification
- Virtual testing
- Property prediction and product lifing
- Material process-structure-property relationships
- Tailoring processing conditions to optimize microstructure, quality, and performance
- Diminishing risk of process drift or outliers through material desensitization
- Tailoring material characteristics to limit post processing

Process Selection, Development, and Optimization

- Process models or digital twins for achieving productivity, production volumes, product scale requirements
- Process control schemes and optimization – material and geometry desensitization
- Integration of multiple manufacturing operations and promoting high yield
- Connecting process data to product quality and certification
- Process health monitoring
- Distributed manufacturing
- Connecting manufacturing technology capability with application requirements – the right tool for the right job

Value Chain Integration and Verification to Enable Rapid Qualification and Certification

- Manufacturing operations/workflow management
- Life cycle analysis tools
- Training, specifications, and interdisciplinary skills
- Common technical data packages
- Cost and value of in-situ process monitoring
- Digitally-based inspection technologies
- Layered solutions for product certification (ex-situ and in-situ) – data registration
- Probabilistic tools for product acceptance
- Digital analytics for validating product quality and certification
- Reduced development, qualification, and certification cycles/costs

Opportunities within the AM Genome for Physics-Based Modeling and Predictive Analytics

- Reusable AM data – data management and pedigree are paramount
- Modeling material evolution – process or application operating environment
- Validated predictive modeling (performance, PoD, effect of defects)
- Artificial intelligence and machine learning coupled with physics-based understanding
- Trusted approaches to validating models – confidence is necessary for adoption
- Model based inspection
- Certification by analysis

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