NIST Advanced Manufacturing Series
NIST AMS 100-59

Empowering Small and Medium-Sized Enterprises Through Effective Additive Manufacturing Data Management

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

This report summarizes the results of the workshop entitled, "Empowering Small and Medium-Sized Enterprises Through Effective Additive Manufacturing Data Management." NIST co-hosted the event in partnership with the National Manufacturing Innovative Institute for additive manufacturing, America Makes, the Regional Additive Manufacturing Partnership of Maryland (RAMPMD) and Pilgrim Consulting, LLC. The workshop explored how best to foster productive working relationships between small and medium-sized enterprises (SMEs) and top-tier manufacturers through effective additive manufacturing (AM) data management by examining AM data management "Pain Points" associated with SME interactions with large system integrators (LSI) and government procurement agencies. It has found that the complex and diverse relations between LSIs, SMEs, and customers can create challenges. This increases the cost and time required to bring a product to market while concomitantly inhibiting innovation and profitability. The synopsis of the working group recommendations provides some specific actionable items for consideration.

Keywords

Additive Manufacturing, Data Management, Small and Medium-sized Enterprise, FAIR Data

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1. Workshop Overview

The workshop entitled, **"Empowering Small and Medium-Sized Enterprises Through Effective Additive Manufacturing Data Management"** was held **6-8 June 2023** at the NIST National Cybersecurity Center of Excellence (NCCOE), 9700 Great Seneca Hwy, Rockville, MD 20850. It was organized by NIST and Pilgrim Consulting, LLC. The event was cohosted by the National Manufacturing Innovative Institute for additive manufacturing, America Makes and the Regional Additive Manufacturing Partnership of Maryland (RAMPMD). Attendance at the workshop was free and registration was open to all participants. The workshop succeeded in attracting eighty-six participants (**Appendix 5.1**) from a variety of organizations (see table below).

Organization Type	Number of Participants
Academic	7
DoD	4
Gov	29
LSI	9
Non-profit	13
SME	24

The workshop explored how best to foster productive working relationships between small and medium-sized enterprises (SMEs) and top tier manufacturers through effective AM data management. The goal was to examine AM data management "Pain Points" associated with SME interactions with large system integrators (LSIs) and government procurement agencies. The complex and diverse relations between OEMs, SMEs, and customers can create challenges. This increases the cost and time required to bring a product to market while concomitantly inhibiting innovation and profitability. The agenda (**Appendix 5.2**) for the 2½ day event consisted of the following activities:

- **Keynote Presentation** (2 briefs each day)
- **Panel Discussions** – 4 panels highlighting the perspectives of LSIs, SMEs, Non-profits, and AM software tool providers.
- **Working Groups** – On Days 1 & 2, participants were divided into six working groups and asked to identify and rank challenges and approaches. They were asked to focus on 1) AM Process Development, 2) AM part production, and 3) Delta Qualification. On Day 3, two working groups examined the top ranked challenges from the perspective of the SME and LSI, respectfully.

A list of working definitions used to facilitate communication during the execution of the workshop and a table of acronyms used throughout this report may be found in **Appendix 5.3**, and **Appendix 5.4** respectively**.**

2. Results and Observations

Additive manufacturing is recognized as **essential to the supply chain resilience of the United States**. The engines that drive economic growth are the small and medium-sized enterprises. Consequently, addressing the barriers to SME entry into the marketplace is critical to our nation's economic wellbeing. There are political, economic, social, and technological (PEST) aspects to this challenge. Factors identified in this workshop which impede facile SME-LSI effectiveness may be bundled as 1) cost of compliance, 2) technological, and 3) required leadership. A summary of the results is provided below.

2.1. Key Takeaways

2.1.1. Cost of Compliance

For SMEs, cost was identified as a significant "pain point" and barrier to working with LSIs and the government. The upfront investment cost associated with compliance with regulations, policies, and procedures was identified as a noteworthy barrier to market entry. Generally speaking, the baseline requirements for an SME to be considered a qualified vendor include:

- Having an established, accredited quality management system / quality manufacturing system (e.g., ISO 9001, AS9100).
- Demonstrating compliance with cybersecurity requirements (e.g., Cybersecurity Maturity Model Certification (CMMC) 2.0 Program).
- Having an approved means of protecting controlled unclassified information (SP 800-171 Rev 2).
- Cost of due diligence associated with SME compliance with LSI and government contractual flow down requirements. These documents typically cite significant numbers of FAR/DFAR regulations by code, and each requirement document must be located, downloaded, and examined.

2.1.2. Technology Needs

Uncertainty surrounding AM process qualification and part certification was voiced as a significant challenge to the widespread adoption of AM and has stymied SME entry into the AM marketplace and the use of AM parts by LSI. The current process of qualification takes too long, costs too much, and must be replicated for each part considered.

A paradigm shift in the way AM processes are qualified and components are certified is required, i.e., a move away from fixing and controlling key process parameters. Instead, qualifying a process control methodology that operates within a defined qualified processing envelope is needed, which requires:

- The maturation and development of feed-forward controls (FFC) and iterative learning controls (ILC).
- The development and integration of in situ sensors and control systems.

- The novel use of machine learning and ICME.
- The development and use of virtual twin modeling and simulation tools for the entirety of the AM part production line.

2.1.3. Leadership

Workshop participants sent a clear message: **government leadership is required**. The government (as a neutral party) has a unique responsibility of catalyzing, developing, and promoting cooperation and collaboration amongst stakeholders (e.g., SMEs, LSIs, SDOs, etc.) to address the significant challenges facing the AM community. Specific areas include:

- Convergence on the "80% solution" as to what constitutes a qualified AM vendor by LSIs and the government.
- Defining Technical Data Package (TDP) content.
- Sharable data curation and accessibility.
- Development of the standards required to support technology adoption.

2.2. Keynote Speakers

Within this section, the messages of our Keynote Speakers are summarized. The presentations made by the keynote speakers are found at the workshop website (https://www.nist.gov/news-events/events/2023/06/empowering-small-and-medium-size-enterprises-through-effective-additive).

2.2.1. Mr. Chris DeLuca OUSD(R&E)

Mr. DeLuca stated, **"We must work together from concept development through sustainment to create a resilient and agile supply chain."** DoD has identified three priority risks, issues, and opportunities for action: 1) secure data infrastructure, 2) digital tech package requirements, and 3) pathfinding demonstrations of digital manufacturing. Mr. DeLuca OUSD(R&E) stated that for DoD to complete its mission, **"It is critical that data be of high quality, accurate, complete, timely, protected, and trustworthy."** He described a variety of DoD activities and products that are designed to accelerate the deployment of AM, e.g., DoDI 5000.92, DoDI 5000.93, MIL-HDBK-539, JAMMEX, JAMWG, etc.

2.2.2. Neil Orringer (ASTRO)

Mr. Orringer briefed the workshop on a program, AM Forward, that has the potential to mitigate the cost of compliance pain points. AM Forward is a partnership of several LSIs and the Biden-Harris administration to advance supply chain resilience via AM adoption. The focus is on helping SMEs address three challenges: 1) **Accessing capital** to procure industrial AM systems, 2) **Workforce development**, and 3) **Qualifying** AM processes. Maximizing commonality in the way LSIs qualify SME AM part suppliers is likely to significantly reduce cost and enhance SME business opportunities**. Success will depend on the promulgation and adoption of standards built in support of this approach.**

2.2.3. Dr. David Furrer (Pratt & Whitney)

Dr. Furrer advocated for the use of modeling and data to design and control AM processes. He stated that "modeling is emerging as a means to link materials and process information with component geometric design optimization." He identified several opportunities for the community including standards for digital certificate of conformance data and the development, validation, and deployment of physics-based models. Dr. Furrer's take-away "Data management through data analytics and modeling tools provides for a more complete means of knowledge capture."

2.2.4. Dr. Slade Gardner (Big Metal Additive)

Dr. Gardner discussed empowering SMEs through effective data management. He touted the benefits of wire-arc DED which include a) 80%-95% reduction in schedule and b) a 50%-63% reduction in cost. He emphasized "Manufacturing is a Key Word…manufacturing goes way beyond just 3D Printing." He went on to say, "Without a quality manufacturing system (e.g., ISO 9001, AS9100, API Spec Q1), you are irrelevant in the manufacturing world." Pain points identified were compliance with protecting controlled unclassified information and cybersecurity maturity model certification.

2.2.5. CAPT (retired) Jason Bridges (LM)

CAPT Bridges stated that "**working with LSIs is hard**." SMEs cannot afford to comply with multiple LSI requirements. LSIs are not monolithic, rather they have business units with unique requirements resulting in different means of vendor qualification and different means of data curation. Complying with the requirements of a business unit within an LSI does not mean that an SME has complied with the LSI's other business unit requirements. Consequently, a "Pain Point" is that **qualification is not transferable across LSI business units** and the SME must spend significant additional money and time to be qualified across an LSI's entire line of business.

2.2.6. Dr. Wayne King (Barnes Global)

Dr. King addressed the question of "How do we broaden the use of Laser Powder Bed Fusion Additive Manufacturing?" In a survey conducted, 56% of the manufacturers indicated that uncertain quality of the final product was a barrier to adoption of AM. Further, he stated, "Process optimization is costly and time consuming." He advocated for feed forward control (FFC) and stated that "…iterative learning control (ILC) is central to the success of feedforward control." He advocated for commercial demonstration of the value of FFC-ILC, and standardization of qualification procedures for the new methodology.

2.3. Panel Discussions

Four panel discussions examined the challenges faced by SME-LSI from the perspectives of a) SMEs, b) LSIs, c) Data Consortium and Non-Profit, d) Software & Data Analytic Tool Providers. The participants in the panel workshops are provided in **Appendix 5.1**, and the panel presentations may be found at the workshop website (https://www.nist.gov/news-events/events/2023/06/empowering-small-and-medium-size-enterprises-through-effective-additive).

2.3.1. Panel 1: Small and Medium-Sized Enterprise Perspectives

Moderator*: Bill Bihlman (Aerolytics).* ***Panelist****: Carl Dekker (Met L Flo), Youping Gao (Castheon), Neil Goldfine (JENTEK), and Dereck Hass (CCAM)*
Participants discussed the pain points from an SME perspective. The pain points included:

- AM process qualification and part certification,
- Access to machine vendor software,
- Value proposition and price point for embedded solutions, and
- Control of intellectual IP.

Regarding in situ sensor and NDT, Neil Goldfine stated, "In NDT, it is not the smallest defect you can detect that matters most, it's the largest defect your miss and its location." Youping Gao advocated for, "physical metallurgy-based AM development protocol for rapid and robust AM cross-platform development." Dereck Hass indicated the goal of CCAM was to, "develop a technology roadmap to improve the resilience and capacity of US manufacturing supply chain through the digital thread." The digital thread offers the potential of unprecedented visibility into the manufacturing supply chain, enhancing resilience. In a survey of the aerospace and defense industry, identified barriers to the adoption of the digital thread include:

- Protection of intellectual property,
- System interoperability,
- Lack of real-time supplier and production data from different systems, and
- The high cost of curating, maintaining, and managing the data quality of information being shared.

2.3.2. Panel 2: Large System Integrator Perspectives

Moderator*: William Frazier (Pilgrim Consulting).* ***Panelist****: Dave Abbott (GE), Jesse Boyer (Pratt & Whitney), Nick Mule (Boeing), and Abdalla Nassar (John Deere)*
W. Frazier indicated that a paradigm shift in the manner in which AM processes are qualified and components are certified is required to reduce cost, accelerate deployment, and allow AM TDP to be used across type, model, and series of AM equipment. He stated, "we must move away from fixing key process parameters, and instead embrace FFC & ILC. We must move towards process qualification based upon standardizing "freezing" the FFC-ILC process methodology."

Nick Mule stated that LSI want to establish a distributed AM production capability to ensure quality at-scale. Boeing's approach is to:

- Identify AM parts candidates and develop/validate AM technical data packages in-house.
- Then deliver a TDP to qualified vendors for production and post-processing.

(Note, this is similar to the approach LM is taken as described by Jason Bridges.) To accomplish this, factory integration and automation is required for rapid data retrieval. Nick Mule stated, "Tools and capabilities [are needed] so engineers can focus on decisions, not data retrieval." Automated data extraction, and machine/process monitoring are required.

Jesse Boyer described P&W's process control methodology and production implementation. He stated, "the overall process does not change for additive [manufacturing], on the content is [more] specific." A part is designed, the process is fixed, the part is manufactured, and feedback is provided.

Abdalla Nassar reported that John Deere has hundreds of polymer printers and is using them for tooling and prototyping. They have internal metal AM capability used for limited production, prototyping, and tooling. The challenges identified in working with AM suppliers are time, money, and effort:

- The AM market is small, so is it worth setting up a qualified supplier?
- There is a nontraditional customer-supplier relationship. Can't just send drawing, specification and an RFQ.
- Suppliers frequently believe prototype-level margins are acceptable and they are not.
- The management and ownership (IP) of AM data is ill-defined.

2.3.3. Panel 3: Data Consortium and Non-Profit Perspectives

***Moderator**: Brandon Ribic (America Makes). **Panelist**: Kareem Aggour (GE); Mahdi Jamshidinia (ASTM); Kevin Slattery (Barnes GA); Doug Hall (Battelle)*

Kareem Aggour emphasized the importance of developing a common AM vocabulary and exchange formats based upon a common data model. The format should be both machine and human-readable. He stated that we're not dictating an organization use a certain model internally, rather they can map their internal data to the CDM for exchange purposes.

Mahdi Jamshidinia discussed the ASTM AM COE which currently has 35 members. The goal of the COE is to develop standards, best practices, generate high pedigree data, and develop a data management strategy. He emphasized that there is a need for collaboration between SDOs and went on to say that there is always interest in collaboration, but for whatever reason it is not progressing as fast as we all desire. He also indicated that there is a need for a new microstructure representation (and standard), expressed solely through numerical data, and does not relying on visual images, i.e., micrographs.

Kevin Slattery addressed the Army's AMNOW Program designed to improve readiness by establishing a digital supply chain. Doug Hall addressed efforts and challenges associated with to incorporation of AM allowables into MMPDS. These included machine-to-machine variability, unexplained inconsistency in properties, and lack of understanding of how processing impacts properties.

2.3.4. Panel 4: Software & Data Analytic Tool Provider Perspectives

***Moderator**: Alex Kitt (EWI).* ***Panelist**: Anil Chaudhary (Applied Optimization), Vadim Shapiro (Intact Solutions), Michael Taylor (Hexagon) and Mike Vasquez (3degrees)*

Alex Kitt set the stage for the panel by discussing the needs of small and medium-sized manufacturers. When asked in a survey, 46% of these companies responded they needed more automation solutions, 13% indicated additive manufacturing, and 10% listed software. Anil Chaudhary introduced his company: Applied Optimization (AO). AO's AMP^2 software offers the capability to model the LPBF process on a track-by-track basis, and account for feature specific parameters, thus, significantly reducing surface and volumetric defects.

2.4. Work Group Products

Working groups spent 2½ days to identify the challenges facing SMEs in AM and recommending approaches to overcome these barriers (Details of their findings may be found in **Appendix 5.5**).

2.4.1. Working Groups, Days 1 & 2, Challenges & Approaches

Figure 1 illustrates the methodology of the working group activities. Day 1 was devoted to identifying and ranking the challenges / pain points. Similarly, Day 2 was focused on defining approaches to the challenges. Three phases of the AM lifecycle were examined by the working groups: a) AM Process Development (**D**), b) AM Part Production (**P**), and c) Delta Qualification and Process Requalification (**Q**). There are two working groups assembled to conduct discussions for each phase, of six total working groups named **D1, D2, P1, P2, Q1**, and **Q2**, respectively. On Day 3, two larger working groups were formed to examine the top-ranked challenges from the perspective of the SME and LSI, respectfully.

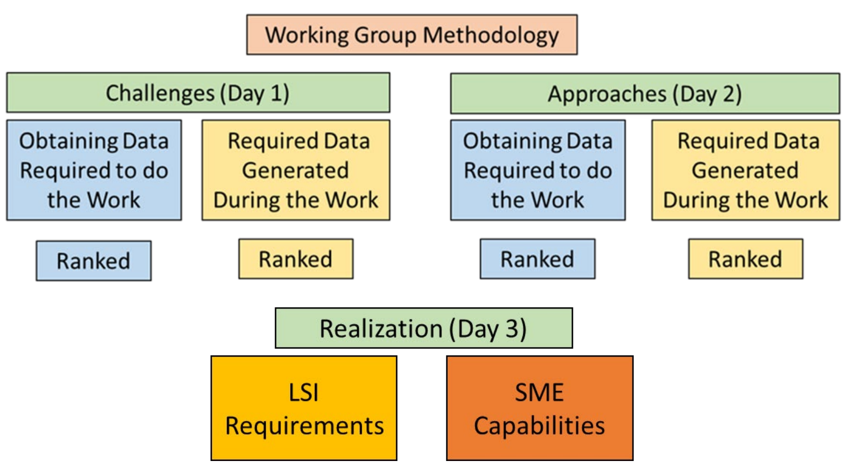

Figure 1: Working Group Methodology to Identify and Rank Challenges and Approaches**.**

A synopsis of challenges and approaches identified is provided below.

Developmental Phase: The challenges identified included issues surrounding a) Data Curation, b) Data Management, c) Non-destructive Evaluation (NDE), and d) Trust. The high cost of data curation and the lack of clarity as to the value of the data being collected were considered pain points. In terms of data management, issues included: a) cost associated with data curation, management and cyber security, b) the ambiguity over ownership of IP, c) the difficulty accessing needed data across systems and organizations, and d) the lack of automated data acquisition. NDE was of concern. In particular, our lack of certainty regarding the effect of defects, and the absence of low-cost NDE techniques comparable to CT. A perceived lack of trust between LSIs and SMEs was identified as a pain point that results in increased cost and time to product realization.

Production Phase: Challenges associated with the following were identified: a) TDP, b) AM Production Line Qualification, c) Workforce, and d) End-Item Data Package. The lack of an AM TDP standard was a source of pain for SMEs increasing cost and time. This was especially true for SMEs working with multiple LSIs. The lack of qualification standards was identified as a challenge. Quality standards addressing machine maintenance, process monitoring, and laser power monitoring, as well as the characterization, understanding, and qualification of recycled powder are needed. There were concerns resulting in a lack of trust raised regarding workforce competence, and the need to enhance automation to reduce human error. Concerns were also raised regarding the cost and time associated with preparing customer required end-item data packages. Standards for end-item data packages were proposed as a solution.

Delta Qualification / Requalification: Two noteworthy challenge areas were identified: a) Cost, and b) Data Management. It was found that the cost of delta qualification is excessively high as it often involves duplicating the original qualification process. There were concerns regarding data quality and pedigree, as well as access to the original qualification data. There is also an acknowledged lack of understanding and consensus as to what it takes to delta qualify / requalify an AM process. Consequently, standards for delta qualification and requalification are needed. It was recommended that standards for minor, moderate, and major process changes be developed.

2.4.2. Working Groups, Day 3, Synopsis of Recommendations

On the final day of the workshop, participants were divided into two working groups. One group was asked to assume the perspective of a small and medium-sized enterprise (SME); the second group was asked to assume the role of a large systems integrator (LSI). The table below summarizes these working groups' recommendations.

Synopsis of Working Group Recommendations

WG	Challenge	Approach
SME	• Lack of understanding of how effective data management can enhance profitability. • Variability in the requirements and the structure of technical data packages (TDP). • Compliance with supplier or customer fit-for-purpose requirements.	• Accelerate maturation, implementation, and development of standards for a Common Data model (CDM) and Common Data Exchange Format (CDEF) • Standardized TDP with minimum data requirements. • Develop tools and standards to automate TDP generation. • Publish specific examples of how AM data curation, analysis, and use enables decision making and provides value. • Develop standards for AM production line requalification. • Develop standards for delta qualification. • Lead and support collaboration (LSIs and government) to define the minimum viable data set required for qualification.
LSI	• The high cost of collecting and curating AM data. • Validated AM Process Controls demonstrating production conformance. • Cost effective approaches for data gathering and statistical methods to measure equivalence/automation	• Actively promote collaboration across the US industrial base to share data and access to data across databases. • Develop a standard template for contracts addressing AM-specific requirements and standards. Explain, justify, and rationalize these requirements and standards. • Standards for machine data output and data logging requirements. • Standards for AM machine preventative maintenance and maintenance and control plans. • Develop a digital twin model of AM machines for build status, health monitoring, and performance. • Develop standards to demonstrate equivalence between measured mechanical property data and extant design allowable datasets. • Develop low-cost sensors to measure key process variables. • Develop standards to validate equipment performance.

2.5. Post Workshop Feedback

Following the workshop, participants were requested to provide their major takeaways from the event. Sixteen of the eighty-six participants responded, details of their responses may be found in **Appendix 5.6**. Cost is a pain point. SMEs don't know what it takes to be considered a qualified vendor, and each LSI has a different set of requirements. A standard for AM data validation is needed. Some interesting excerpts include the following:

Stephanie Bonfiglio stated, "We have been reaching out to LSIs since the beginning and **finding the right person in the LSI to talk to has been very difficult**."

Andrew Couch stated, "A formal decision framework is needed in order to separate useful data from irrelevant data…"

William Frazier emphasized "**Data is not data (i.e., useful) unless it can be used to make decisions**. Collecting data that does not lead to decision making is costly and pointless," and that "**Models are the best repositories for data.** For example, y = mx +b can describe thousands of data points. Bayesian updating allows for model refinement."

David Furrer stated, "A SINGLE Industry-Wide Digital Certificate of Conformance Standard that provides overarching guidance and requirements for how data defined by subordinate ASTM, SAE, ISO, etc. specifications are tagged and communicated in digital format."

Slade Gardner stated that "…**there should be more people** [at these workshops] responsible for the **Profit and Loss statement of a company**." He went on to say "NIST seems focused on LPBF only. The metal DED segment is growing and there are many needs for industrial measurements."

Dereck Hass stated, "With my small business hat on (used to have a small business manufacturing company), I would say that **demand signal is more important than reduced qualification burden for SMEs** in this space. Small businesses need orders more than anything."

Elizabeth Henry pointed out "**Consider similar closed-door sessions with key stakeholders** to come to agreements (NIST, NASA, OSD Small Biz, OSD R&E, OSD A&S, MILSVCs, DoE, SDOs, LSIs)" and "Strategic messaging of this initiative - as well as other higher-level coordination AM activities by NIST (and NASA) are helpful…"

Dr. Alex Kitt (EWI) said "**The organizations who benefit from the data (LSIs) are not the same as the organizations being asked to collect the data (SMEs)**. I asked an SME manufacturer what benefits they get from collecting data. They answered "none". He stated, "One overwhelming take away was how challenging it was to isolate SME challenges given the substantial overlap between SME and LSI challenges." He pointed out that **consistent demand to justify AM investment (capital, workforce, and nonrecurring engineering) is needed**. He further stated, "**Inconsistency in requirements from different LSIs translates to substantial NRE for each new customer**."

Joshua Lubell indicated "Security was mentioned numerous times as a pain point. I got the sense that the primary concern is technical data theft…" He further stated "The **AM Common Data Model has the potential to make it easier for manufacturers to better leverage the data their machines generate**, if equipment vendors make their data available in computer-actionable CDM-compatible formats. **There is a big standardization opportunity here**." "I think more research needs to be done connecting the physics of AM processes to risk management."

Ted Reutzel replied, "A common theme I heard was that **it takes so much time and effort for SMEs to generate required data when each customer has their own, special requirements**."

Stephanie Saravia pointed out "I did not observe any women in the ~28 keynote speakers, panelists, and facilitators throughout this conference. I recognize that there are few women in this field; however, **diversity is important for driving innovation**."

Mike Vasquez stated "There seems to **be a real danger in trying to formalize/standardize a highly complex data management requirements**. It'd be great if we could come up with some guidelines that don't necessarily require 100+ data fields to be captured every build. Based on the talks, the decisions on what/to what extent things need to be captured relies on the customer/funder. An effort should be made to really get them comfortable with requirements that are not so burdensome that they restrict new suppliers from entering the space.

3. Summary & Conclusions

A robust and resilient AM supply chain is required to foster this nation's continued economic growth. The goal of this workshop was to examine AM data management "Pain Points" associated with SME interactions with LSI and government procurement agencies. The eighty-six workshop participants were asked to identify the challenges SMEs have in providing AM products and services and explore approaches to address them. Three prominent themes emerged surrounding the political, economic, social, and technological (PEST) components of this challenge: 1. Cost of compliance, 2. Technological gaps associated with uncertainty and AM process qualification, and 3. The desire for government leadership. The synopsis of the working group recommendations provides some specific actionable items for consideration. To be provided in the forthcoming full report are additional recommendations gleaned from the keynote presentations and panel discussions.

4. Acknowledgements

The organizers would like to express their sincere thanks to all the workshop participants for their engaged support and their willingness to spend their valuable time participating in this event. A special thank you to the workshop keynote speakers, panelist, panel moderators, working group facilitators, and scribes (listed below) for working assiduously to make this workshop a success. In addition, we would like to acknowledge the contributions of our cohosts, America Makes and RAMPMD, who played an integral part in planning and executing the event.

Keynote Speakers: Jason Bridges, Chris DeLuca, David Furrer, Slade Gardner, Wayne King, and Neal Orringer.

Panelist & Panel Moderators: Dave Abbott, Kareem Aggour, Bill Bihlman**, Jesse Boyer, Anil Chaudhary, Carl Decker, William Frazier**, Youping Gao, Neil Goldfine, Doug Hall, Derek Hass, Mahdi Jamshidinia, Alex Kitt**, Nick Mule, Abdalla Nassar, Brandon Ribic**, Vadim Shapiro, Kevin Slattery, Michael Taylor, and Mike Vasquez.

** Moderators

Working Group Facilitators: Bill Bihlman, Charles Fisher, Andrew Glendening, Brandon Ribic, Kevin Slattery, and Marlon Walker.

Workshop Scribes: Andrew Couch, Shaw Feng, Ailon Haileyesus, John Hoyt, Jaehuk Kim, Shengyen Li, Fahad Milatt, Yeun Park, Stephanie Saravia, Marlon Walker, and Zhuo Yang.

5. Appendices

5.1. Roster of Workshop Participants

David Abbott GE Aerospace	Fabio Agosto DAF AFLCMC/RO	Kareem Aggour GE Research
Mekonen Bayssie Nuclear Regulatory Commission	Chandler Becker NIST	Sudarsanam Babu Univ. of TN, ORNL
Linkan Bian National Science Foundation	Stephanie Bonfiglio i3D MFG	William Bihlman Aerolytics/SAE
Jason Bridges Lockheed Martin	Anna Carlson NAVAIR Lakehurst	Jesse Boyer Pratt & Whitney (RTX)
Anil Chaudhary Applied optimization, Inc.	Khershed Cooper NSF	Christopher Cosgrove RAMP MD
James Eldon Craig Stratonics, Inc.	William Cuervo 3YOURMIND	Andrew Couch Stanford University
Carl Dekker Met-L-Flo, Inc.	Ralph DeLuca USD(R&E)/SE&A	Erin Dumonski Raytheon Technologies
Charles Fisher Naval Surface Warfare Center, Carderock	Simon Frechette NIST	Shaw Feng NIST
William Frazier Pilgrim Consulting LLC	Youping Gao Castheon Inc	David Furrer Pratt & Whitney
Adam Gershen Naval Surface Warfare Center, Carderock	Andrew Glendening NASA GSFC	Slade Gardner Big Metal Additive
Neil GOLDFINE JENTEK SENSORS, INC.	Ailon Haileyesus Johns Hopkins University	Shehan Goonewardene Global Resource Solutions, Inc.
Derek Hass Commonwealth Center for Advanced Manufacturing	Elizabeth Henry Henry General Strategies	Douglas Hall Battelle Memorial Institute

John Hoyt MITRE/NCCoE	Richard Huff ASTM International	Mahdi Jamshid ASTM International
Stephen Kahmann Crown Point Technologies, LLC	Jaehyuk Kim POSTECH	Al Jones NIST
Wayne King The Barnes Global Advisors	Andrew Kitahara NASA Langley Research Center	Alexander Kitt EWI
Christopher Lauff Authentise	Rachel Levine Zeda	Boonserm Kulvatunyou NIST
Shengyen Li NIST	Joshua Lubell NIST	Yan Lu NIST
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John Milton-Benoit Commonwealth Center for Advanced Manufacturing	Laetitia Monnier NIST	Nicholas Mule The Boeing Company
Shawn Moylan NIST	Abdalla Nassar John Deere	Andrew Neils Roux Institute at Northeastern University
Neal Orringer ASTRO America	Yeun Park POSTECH	Yash Parikh EOS North America
Christopher Peitsch Avonix Imaging (Nikon Metrology)	Behrang Poorganji Morf3D	Zhijian Pei Texas A&M University
Michael Powell NIST	Brandon Ribic NCDMM/America Makes	Edward Reutzel PSU-ARL
Todd Sabin Maryland Department of Commerce	Stephanie Saravia MITRE	Brent Roeder R3 Digital Sciences, Inc.
John Schmelzle NAVAIR	Vadim Shapiro Intact Solutions, Inc	Kevin Slattery The Barnes Global Advisors
CheeYee Tang	Carl Thompson	Dusan Sormaz

NIST	ASTM International	Ohio University
Joe Veranese NCDMM	George Vasquez 3Degrees	Michael Taylor Hexagon
George Weber NASA Langley Research Center	Zhuo Yang Georgetown University	Marlon Walker NIST
Fan Zhang NIST		Paul Witherell NIST

5.2. Workshop Agenda

Day 1 June 6, 2023:

Time	Agenda Item
0700	**Registration, Badging, Refreshments**
0800	**Welcome & Opening Remarks** *Paul Witherell & Yan Lu* (NIST) "Empowering Small and Medium Size Enterprises Through Effective Additive Manufacturing Data Management" • Opening Remarks • *Charles "Chuck" H. Romine* (Associate Director of Laboratory Programs, NIST) "Welcome from NIST" • Workshop Goals, Objectives, and Approach
0840	**Keynote Speakers – Business/Procurement Focus** *William Frazier* (Pilgrim Consulting) • *R. Chris DeLuca* (OUSD) "Data and Advanced Manufacturing" • *Neil Orringer* (ASTRO) "AM Forward Explained – One year later"
0940	**Networking - Refreshment Break**
1000	**Panel 1: Small & Medium Size Enterprise Perspective** *Bill Bihlman* (Aerolytics) • *Carl Dekker* (Met L Flo) • *Youping Gao* (Castheon) • *Neil Goldfine* (JENTEK) "In-process Sensing for Metal AM Parts, Using Eddy Current Arrays"

	• *Derek Hass* (CCAM) "Gaps in the Digital Thread Across the Multiple Tiers of Manufacturing Supply Chains: An R&D Perspective"
1130	**Lunch / Networking**
1300	**Panel 2: Large System Integrator Perspective** *William Frazier* (Pilgrim Consulting) • *Dave Abbott* (GE) • *Jesse Boyer* (P&W) "Pratt & Whitney's Additive Manufacturing Journey…Then, Now, and the Future" • *Nick Mule* (Boeing) "Digital Additive Manufacturing at Boeing" • *Abdalla Na*ssar (John Deere) "Empowering SMEs Through Effective AM Data Management"
1415	**Transition & Break**
1430	**Working Groups – Identification of Data Management Challenges.** Process Development | Production | Delta Qual/Restart
1700	**Working Group Report**
1730	**Adjourn**
1830	**Networking - No Host Social** **GUAPO'S Cantina**** 9811 Washington Blvd Gaithersburg, MD 20878 (301) 977-56555 https://www.guaposrestaurant.com/location/gaithersburg-guapos-restaurant/

**Note: See map of GUAPO'S location below.

Day 2 June 7, 2023

Time	Agenda Item
0700	**Registration, Badging, Refreshments**
0800	**Welcome and Opening Remarks** Brandon Ribic (America Makes) "Perspectives on Effective AM Data Management."
0830	**Keynote Speakers – Customer/End User Perspective** *William Frazier* (Pilgrim Consulting) • *David Furrer* (P&W) "Ue of Modeling and Data to Design and Control AM Processes"

	• *Slade Gardner* (Big Metal Additive) "Small Business Data Management Points"
0930	**Networking - Refreshment Break**
1000	**Panel 3: Consortium Perspective** *Brandon Ribic*, (America Makes) • *Kareem Aggour* (GE) "Additive Manufacturing Common Data Model" • *Mahdi Jamshidinia* (ASTM) "Additive Manufacturing Industrialization Through Collaborative Research and Standardization" • *Doug Hall* (Battelle Memorial Institute) "MMPDS Framework for Characterization and Use of Additive Metals" • *Kevin Slattery* (Barnes GA) "Supporting Army readiness through a robust digital additive manufacturing supply chain"
1130	**Lunch / Networking**
1300	**Panel 4: Software & Data Analytic Tool Provider Perspective** *Alex Kitt* (EWI) "EWI SMM Observations" • *Anil Chaudhary* (AO) "Introducing applied Optimization (AO)" • *Vadim Shapiro* (Intact Solutions) "Leveraging Design, Process, and Physical Data in Simulation-First Worksflows" • *Michael Taylor* (Hexagon) "AM Data and Innovation" • *Mike Vasquez* (3Degrees) "TRACE AM - Data Organization and Analysis"
1415	**Transition & Break**
1430	**Working Groups -Approaches to Data Management Challenges** Process Development | Production | Delta Qual/Restart
1700	**Working Groups Report**
1730	**Adjourn**

Day 3 June 8, 2023

Time	Agenda Item
0700	**Registration, Badging, Refreshments**
0800	**Welcome & Opening Remarks** *Chris Cosgrove* (RAMP MD)

	Advancing Maryland's Additive Manufacturing Ecosystem Through Outreach, Education, and Collaboration" • *Todd Sabin* (Department of Commerce, State of Maryland)
0830	**Keynote Speakers** *William Frazier* (Pilgrim Consulting) • *Jason Bridges* (LM) "Challenges for Small Business Data Sharing with Primes" • *Wayne King* (Barnes Global Advisors) "How do we broaden the use of Laser Powder Bed Fusion Additive Manufacturing"
0930	**Working Groups Report** Process Development | Production | Delta Qual/Restart
1030	**AM Product Realization**
11:45	**Concluding Remarks**
1200	**Adjourn**

5.3. List of Definitions (Used to Facilitate Communication)

General

Data – Information, facts, and numbers, collected to be examined and considered and used to help decision-making.

Critical Part - A part whose failure would have significant consequences including system malfunction, injury, or death.

Pain Points – Undesired political, social, economic, or technological AM data requirements that could increase cost, reduce efficiency, or impede product deployment. Any factor that inhibits required data from being Findable, Accessible, Interoperable, or Reusable (FAIR).

Organizations

Large System Integrators (LSI) – Large businesses that bring together component subsystems into a whole and ensure that those subsystems function together, e.g., aircraft, automotive, and marine.

Service Providers – A company that produces additively manufactured parts for others or provides AM services to another party.

Small and Medium-Sized Enterprises (SME) – Businesses that fall below certain revenue, asset, or employee thresholds. Typically, companies that have less than 500 employees and annual gross sales of less than $100 million. Typically, they produce components and subsystems for LSIs.

AM Lifecycle Phase

Delta Qualification / Restart – The re-qualification of a means of additively manufacturing a part necessitated by changes to the originally qualified means of production (e.g., a software update, change in AM machine, type, model, series), or the restart and qualification of a production line that has not been out of service.

Process Development – The research, development, test, and evaluation phase of an additively manufactured part's lifecycle. During this phase, the requirements to produce a specific, quality part are identified and documented.

Production – The process of additively manufacturing a part for full use. It assumes that the process development has been completed.

Titles Of Workshop Participants

Facilitator – A person designated to lead a working group.

Moderator – A person designated to manage a panel.

Scriber – A person designated to work with the Facilitator and/or Moderator to manage the operation of a working group or panel. The primary function of a Scribe is to take notes, and if assigned to a working group, enter notes and information into an Excel spreadsheet template.

5.4. Table of Acronyms

AM	Additive Manufacturing
AMMO	Additive Manufacturing for Maintenance Operations
CCAM	Commonwealth Center for Advanced Manufacturing
CDD	Common Data Dictionary
CDEF	Common Data Exchange Format
CDM	Common Data Model
CMMC	Cyber Security Maturity Model
DFAR	Defense Federal Acquisition Regulation
DoD	Department of Defense
DoE	Department of Energy
FAR	Federal Acquisition Regulation
FFC	Feed Forward Control
HIP	Hot Isostatic Press
ICME	Integrated Computational Materials Engineering
ILC	Iterative Learning Control
IP	Intellectual Property
JMADD	Joint Metal Additive Database Definition
JAMMEX	Joint Additive Manufacturing Model Exchange
JAMWG	Joint Additive Manufacturing Working Group
LSI	Large Systems Integrator

MES	Manufacturing Execution System
M&S	Modeling and Simulation
MMPDS	Metallic Materials Properties Development and Standardization.
MRL	Manufacturing Readiness Level
NCCOE	National Cybersecurity Center of Excellence
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
OSD	Office of the Secretary of Defense
PEST	Political, Economic, Social, and Technological
QIS	Quality Information System
SDO	Standards Developing Organizations
SME	Small and Medium-sized Business
TDP	Technical Data Package
TRL	Technology Readiness Level

5.5. Completed Working Group Sheets

Day1&Day2 Q1

Required or Generated	Affinitized Category	Subcategory	Rank	Notes
R	Requirement	SME <> LSI agreed definitions of Delta Levels (small, medium, large)		
R	Requirement	What is requirement to qualify?		
R	Requirement	SME<> LSI agreed upon means of proving delta qualification		
R	Requirement	What are the 1) qualification; 2) part; 3) material; 4) drawing requirements?		
R	Requirement	What are the requalification requirements?		
R	Requirement	Actual performance requirements for prior (legacy? Or obsolete?) part		
R	Requirement	IQ, OQ, PQ: which qualification?		
R	Requirement	What is the MOC?		
R	Requirement	Part specifications geometry / material		
R	Requirement	What parts are affected? Containment		
R	Requirement	Operator certification		
R	Requirement	Industry standard for digital certificates of conformance		
R	Manufacturing Parameters	Software changes: proof of verification and validation (is the software delivering the expected and correct output ?)		

R	Manufacturing Parameters	Laser scan path		
R	Manufacturing Parameters	Original qualification data from OEM or supplier: process for reduced qualification testing (statistical, analytical)		
R	Manufacturing Parameters	Build plate configuration dimension/material		
R	Manufacturing Parameters	Laser power		
R	Manufacturing Parameters	Feedstock data, lot number, prior exposure hour, container ID, PIN		
R	Manufacturing Parameters	Potentially a new sensors: need data on how the process change affects key parameters. Sensor qualification and test plan		
R	Manufacturing Parameters	Are the parts conforming? PR + MR		
R	Manufacturing Parameters	Build platform temperature		
R	Manufacturing Parameters	What is the current process?		
R	Manufacturing Parameters	Build layout		
R	Manufacturing Parameters	Either from OEM or Vendor		
R	Post-Process Testing/Inspection	Limited testing of witness coupon based on CUASS (see Table III NASA): tensile, metallography, chemistry, HCF. Need coupon representative of texture size		
R	Post-Process Testing/Inspection	NDE Data, In-process inspection data, mechanical property data, microstructure data		
R	Post-Process Testing/Inspection	Test data compared to nearest available legacy data		
R	Post-Process Testing/Inspection	characterization data, metallography, NDE, etc. Still in family?		
R	Post-Process Testing/Inspection	Coupons, density, tensile, fatigue		
R	Post-Process Testing/Inspection	Microstructure consistency		
R	Post-Process Testing/Inspection	Mechanical consistency		
R	Post-Process Testing/Inspection	Feedstock characterization		

R	Post-Process Testing/Inspection	Mechanical testing, witness coupon properties in-family?		
R	Post-Process Testing/Inspection	Witness coupons to evaluate part-specific requirements, e.g. corrosion, low-temperature, etc./limited/based on class		
R	Post-Process Testing/Inspection	Residual stress properties if required		
R	Pedigree	* Process parameter data * process parameter validation data		
R	Pedigree	For certain part classes, testing within part (limited)		
R	Pedigree	* Data pedigree regarding where data is from - separate coupons - from product		
R	Pedigree	Data through supply-chain from powder source, AM supplier, post processer		
R	Data Access	Actual receipt of data or viewing data only due to supplier IP		
R	Definition of change	Log of the delta, what changed & when		
R	Definition of change	SW update: re-qual can be sped up if SW supplier outlines specifics, changes related to critical parameter		
R	Definition of change	* Inadvertent change? * Planned change?		
R	Definition of change	* What was changed? 1) does it change process? 2) QA question?		
R	Process Data	validation of consistent thermals (monitoring/modeling)		
R	Process Data	consistency of part-to-part interactions (multi-laser plumes thermal coupling)		
R	Process Data	process gas certification		
R	Machine Data	Machine model serial number		
R	Machine Data	Equipment health data (gas flow, laser quality)		
R	Machine Data	Ideally as much process data as possible - Gcode, laser, profile, space variability from AM vendor		
R	Machine Data	process logs		
R	Machine Data	process parameters		
R	Machine Data	exposure order		
R	Design process data	model data that may indicate unallowable changes to microstructure defect populations, or predicted bulk properties		

R	Design process data	design data for mtl as a function of build process (microstructure, porosity)		
R	Design process data	Higher part criticality may require more extensive testing. In severe cases, a full re-qual may be required		
R	Design process data	Need a new process map: process parameters, mechanical properties		
G	Supplier	Who requires? Supplier: all part and qualification requirements		
G	Supplier	Required by machine: new build parameters data (power, scan speed, hatch spacing, focus, part design, G-Code/other…)		
G	Supplier	Build Files, slice files, etc…		
G	Supplier	Machine Log Data		
G	Supplier	Melt pool data		
G	Supplier	Layer recoat data		
G	Supplier	Preheat data		
G	Supplier	Laser power		
G	Supplier	Preventive Maintenance Data		
G	Supplier	Machine configuration data: laser, gas flow, optical path		
G	Supplier	Process gas data: oxygen, dew point		
G	Supplier	Required by operator in case of build anomaly: build log, time of interruption		
G	Supplier	Part to part interaction delta (model or monitoring) on the build plate		
G	Supplier	What changed? What did not change?		
G	Supplier / OEM Manufacturing engineering	Machine Process Parameters requirements value		
G	Supplier / OEM Manufacturing engineering	As-manufactured data e.g. CT scan		
G	OEM Manufacturing engineering	Who requires? OEM manufacturing engineers for MRL confirmation, data repeatability		
G	OEM Manufacturing engineering	Who needs? OEM manufacturing engineer: OEM model data, supplied model data		
G	OEM Manufacturing engineering	Thermal history delta (model or monitoring)		
G	OEM Manufacturing engineering	Equipment health measurement delta (gas flow, laser quality…)		

G	OEM Purchasing	Who requires OEM supply-chain / purchasing leads? Lead-time, speed, capacity, cost		
G	OEM Lifting	who requires OEM, structures and lifting engineers property minima		
G	OEM Lifting	safety factors		
G	OEM Lifting	part classification (e.g. resize)		
G	OEM Lifting	ICME model validation data (if model is used)		
G	Regulators	* REO. By: purchaser/ end-user/ regulator * Description of the change and point of contact who assumes responsibility for the change		
G	Regulators	* Who: OEM, FDA, NAVY, DHS. Etc. * TDP orig. Test Data, new test data, delta qual analysis/justification		
G	OEM Quality	Microstructure data		
G	OEM Quality	who requires OEM quality organizations, all first article and batch data		
G	OEM Quality	destructive test data		
G	OEM Quality	FAT Data		
G	OEM Quality	Geometry, material qualification, OEM		
G	OEM Quality	Metrology dimensions		
G	OEM Quality	* Inspection for defects (visual, NDE, etc.) * Who? Company using part/OEM		
G	OEM Quality	ultimate strength		
G	OEM Quality	part inspection data, OEM		
G	OEM Quality	ICME data		
G	OEM Quality	CT data		
G	OEM Quality	powder characterizations data		
G	OEM Quality	Raw data (powder data, cert, lot info, storage)		
G	OEM Quality	control plan + evidence of compliance		
G	OEM Quality	common data		
G	OEM Quality	material data -chemistry -microstructure		
G	OEM Quality	machine pedigree -serial number		
G	OEM Quality	calibration data		
G	OEM Quality	CT inspection data		
G	OEM Quality	Heat treat data		
G	OEM Quality	Part-to-part interaction (in service)		
R Challenges		Data Fidelity Requirements	5	
R Challenges		Data Pedigree	5	

R Challenges		Qual levels (small -> medium -> large) with different validation	5	
R Challenges		different requirements from different LSI	5	
R Challenges		Exclusive focus on process parameters (ignoring thermals)	4	
R Challenges		defining required data by part class	4	
R Challenges		filtering the data (too much data)	4	
R Challenges		knowing what data is required	4	
R Challenges		understanding what data we need	4	
R Challenges		lack of understanding of how the change affects, key parameters	4	
R Challenges		defining required part specific data	4	
R Challenges		lack of SME available data to show equivalence to	4	
R Challenges		original part requirement data	4	
R Challenges		cost to generate data	3	
R Challenges		supplier/OEM cannot decide who is responsible	3	
R Challenges		technology development outplaces regulation development consequence: regulations may be too broad to support SME engagement	3	
R Challenges		do not have needed testing and inspection equipment on-site	3	
R Challenges		do not have expertise on site to run re-qual tests	3	
R Challenges		IP of data	2	
R Challenges		changes in model are not allowed, how do we know?	2	
R Challenges		IP of models and model outputs	2	
R Challenges		IP assertion	2	
R Challenges		no means to generate required data; surrogate data used only	1	
R Challenges		"qualification" and "certification" are/can be black box	1	
R Challenges		re-use of data for continued relevance	1	
R Challenges		downtime of production	1	
G Challenges		Some data on their own are okay to share, but aggregated may be restricted by ITAR/EAR	1	
G Challenges		For future: common sensor data formats (including meta-data requirements) must be efficient	2	
G Challenges		For storage: efficiency, retrieval, efficiency, processing, efficiency	2	
G Challenges		Data Proliferation	3	

G Challenges		AM data standards do not currently support ICME tools	3	
G Challenges		Data standards for taxonomy of data	3	
G Challenges		Compiling data into corporate knowledge via models	3	
G Challenges		Need software tools to use/qualify generated data	3	
G Challenges		SME may EOF have resources physical/software to use data	3	
G Challenges		CT inspection data for: 1) dimensional; 2) quality. Large files > analysis challenging	3	
G Challenges		CMM Inspection data : large files, resolution, analysis challenging	3	
G Challenges		Lack of simple software for equivalence stats	4	
G Challenges		Lack of standard test methods for equipment health measurements	4	
G Challenges		Can't measure real time process parameters data, e.g. laser power, scan speed, layer thickness	4	
G Challenges		Generating process map for process qualification is costly	4	
G Challenges		For some process changes, lack of automation of data generation/acquisition	4	
G Challenges		Time (i.e. fatigue test) is cost prohibitive	4	
G Challenges		Requirement shift (harder) for delta qualification	5	
G Challenges		Suppliers don't understand qualification / delta qualification	5	
G Challenges		Delta qualification = Full qualification	5	
G Challenges		Cost of delta qualification is too high	5	
R & G Challenges		What data should be stored and maintained? How long?	1	
R & G Challenges		Cyber control of data defense/commercial	2	
R & G Challenges		How do we share data?	2	
R & G Challenges		Checking process qualification data from vendor	2	
R & G Challenges		Digital communication of data between organization	2	
R & G Challenges		Define common data requirements (for Part classes) across DOD, NASA, FDA, commercial, etc., e.g. number of tensiles	3	

R & G Challenges		Define common part classes across NAVAI, NAVSEA, AF, NASA, FDA, commercial	3	
R & G Challenges		Delta qualification may be based on previous delta qualification data rather than requirements	5	

Day1&Day2 Q2

Required or Generated	Affinized Category	Subcategory	Rank	Notes
	Print, Lot accept, Part accept	Printer mechanical chemical NDT dimensional associated with a production build		
	Print, Lot accept, Part accept	Heat transfer material properties		
	+Powder Test	Feedstock characteristics		
Generated	Literature + LLM AI	Chat GPT		
	+ Sensors and Analytical tools	Temperature		
	+ Sensors and Analytical tools	Mechanical		
	+ Sensors and Analytical tools	Chemical		
	+ Sensors and Analytical tools	Geometric equivalence		
	Modeling, simulation tools, Some testing	physical properties to feed Model-based qual for reduced testing; simulation;		
	Modeling, simulation tools, Some testing	Model output		
	Modeling, simulation tools, Some testing	some chemical microstructure mechanical validation test		
	More testing	Selected testing from part qualification build		
	More testing	Selected testing from machine qualification and part qualification builds		
	Max testing	Full Range of Material Properties from development, machine qualification, and part qualification builds		
	Understanding Requirements	# of witnessing required based on minor vs major repairs	5	
	Understanding Requirements	do not understand geometrical equivalency	3	
	Workforce	understanding what was included in the original qual	3	

	Understanding Requirements	geometry of parts is not included in original qual	4	
	Data Characteristics	Data formats, storage, interpretation, migration	4	
	Data Characteristics	do not know relevant T, E, X vs. time even in original qual	5	
	Data Characteristics	software upgrade not related to AM	2	
	Data Characteristics	inconsistency in data formats	4	
	Data Characteristics	correlation between sensor data and part performance	5	
	Equipment Challenges	machine to machine variabilities	5	
	Equipment Challenges	within a machine variability (location dependent)	5	
	Equipment Challenges	new model of machine from same vendor	4	
	Workforce	Workforce challenges	5	
	Workforce	Psychological readiness level	1	
	Demonstration	less effort, # poor quality, Proof needed	5	
	Demonstration	(see picture) property vs distribution, statistical significance	5	
	Demonstration	statistical equivalency	5	
	Demonstration	minimum number of physical test coupons	5	
	Demonstration	in family material performance	5	
	Understanding Requirements	how to establish equivalency	3	
	Demonstration	establishing equivalency with a subset of data	5	
	Demonstration	data related challenges: cost, KPVs	5	
	Demonstration	lower coupon count & higher K99 factor	4	
	Demonstration	showing simulation is valid	5	
	Demonstration	correlation between simple tests & key part properties	5	
	Material challenges	stock materials from new vendor	3	
	Material challenges	powder reuse for delta quals	2	
	Material challenges	determine PSD based on virgin/refreshed powder	2	
	Requirements	ITAR Restrictions on data (e.g. log files, build files, data files)	1	
	Requirements	Define the data requirements without buzz words	1	

	Requirements	develop business model to share data	4	
	Standard	who is to say what is pedigree	2	
	Organization	look for open source sharing of data	3	
	Sharing	Put all materials data openly; open science government funded	3	
	Organization	consortium - data; open process, data, properties to validate models	3	
	Analysis	if data from initial qual nearly covers delta, then effort can be reduced	2	
	Analysis	enable SMEs to establish data pedigree quickly; having white papers / poster child cases	3	
	Analysis	machine learning and AI tools can be trained to detect anomalies	4	
	Analysis	develop/validate ML/AI/Simulation to reduce testing	4	
	Analysis	use sensor tools that can be part of a simple I-Phone	5	
	Data Collection	funding agencies of mechanisms needs to be clarified for data sharing	5	
	Data Collection	reduce testing requirements	2	
	Data Collection	data before & after any minor/major maintenance/repairs; test data connected to processing	4	
	Data Collection	Collect data: temperature, strain, chemistry as a function of space & time with cheap sensors	4	
	Analysis	microstructure correlated with properties	3	
	Data Collection	monitoring of more or all KPVs	5	
	Analysis	compositional process inputs correlated with properties	3	
	Analysis	compositional process inputs correlated with microstructures	3	
	Standard	publish best practices for collecting data with limited capital expenditure	4	
	Standard	Solution/standards for data reduction	4	
	Standard	Data schema according to standards (NIST, ASTM, ASME)	4	
	Requirements	flow down of data management requirement through project calls (& make data available)	2	
	Generate	generation of high quality data (through automated data acquisition)	2	

	Generate	a data recorded at common time stamps	5	
	Generate	calibration data before every build	1	
	Generate	consistent and appropriate sampling rate	5	
	Manipulate	develop chatGPT for data analysis	2	
	Manipulate	Know what to look for in data; recognize patterns / behaviors in data	2	
	Manipulate	use DOE-ORNL, peregrine software	1	
	Manipulate	Use "databricks" available tools to ingest and manage data	2	
	Manipulate	Do not reinvent software tools again and again	2	
	Manipulate	translate all temperature signatures to higher dimensions	2	
	Manipulate	data is costly (storage, retrieval, analyzing)	2	
	Storage	Data; how much is sufficient?	5	
	Storage	data storage can be challenge for qualification	3	
	Storage	the best data repository is a physics-based model	1	
	Storage	capture and document meta data	5	
	Storage	standardized data persistence plan	2	
	Transport	gov't launch data highway for SME	5+	
	Format (Standard)	All OEM output data in same format	4	
	Format (Standard)	Development of translators (following common data exchange format)	2	
	Format (Standard)	universal coordinate system and planes for location in build envelope	1	
	Format (Standard)	SI units only	1	
	Format (Standard)	Standardized data format; standardized reporting format	4	
	Format (Standard)	well organized schema that is easily readable	4	
	Control	Feedback control	5	
	Analyze	2D & 3D data visualization tool to inform investigation of relationships	2	
	Qual Architecture	Implement part family qualification	4	
	Sharing	Develop incentive for generation & sharing of high pedigree data	4	
	Sharing	give-a-penny, take-a-penny depository	2	

Day 1 & Day2 D1

Required or Generated	Affinized Category	Subcategory	Rank	Notes
R	Capital Limitations	Supplier Out of Business	5 (#1)	
R	Capital Limitations	High Cost for Nonstandard Feedstock	4 (#2)	
R	Capital Limitations	Limited In-House Machining Bandwidth	1 (#3)	
R	Capital Limitations	Machine Calibration	1 (#4)	
R	Capital Limitations	Machine Type Limitations	1 (#5)	
R	Process Parameters	Uncharted Territory	5 (#1)	This would include a new manufacturing method.
R	Process Parameters	Process Specific Parameters	5 or 1 (#2)	This includes HIP, power, orientation, and machine. If the process-specific parameters are provided, then this pain point would only be a 1. However, if they are not provided, then they would be a 5.
R	Process Parameters	K.C.C. Definition	5 or 1 (#3)	This relates to inspection specifics. Likewise, if K.C.C. definitions are not provided, then the pain level would be 5. However, if they are provided, then the pain level would only be a 1.
R	Process Parameters	Permissible Type is Number of Parameter Sets	1 (#4)	An example of this would be 32 sets of parameters for up/down skin angles.
R	Process Parameters	Feed stock Conformance	1 (#5)	This includes COC and COA.
R	In-Process Material Properties	Material Properties	4 (#1)	For instance, the high temperature in the liquid phase would be a consideration.
R	NDE	Uncertainty in Critical Flow Sizes	5 (#1)	This could also carry implications towards the Requirements affinity group (below).

R	NDE	No Capability Study	3 (#2)	The field of Design of Experiments (DOE) helps to uncover the relationship between controllable input factors and the corresponding desired outputs (response variable).
R	NDE	Limited Bandwidth for NDE/Testing In-House	1 (#3)	
R	Requirements	Unclear Requirements	5 (#1)	This includes related ideas such as original part requirements being unclear form drawings, mismatched property definitions, and mismatched units (for instance, differing units for temperature utilized in requirements documentation).
R	Requirements	Material Allowable Requirements	5 (#2)	This invokes requirement considerations such as MMPD-3 and CMH-17.
R	Requirements	Developing Processes Acceptable to Multiple LSI OEMs	3 (#3)	
R	Requirements	Lack of Transparency on Data for Supplier Process Capabilities	2 (#4)	
R	Requirements	"Unknown" unknowns	1 (#5)	This pertains to not knowing the unknown critical factors that exist in designing a, perhaps, complex engineered system.
R	Information Technology	Cost of Buying "Data" as a Separate Line Item	5 (#1)	
R	Information Technology	Secure Data Transfer	5 (#2)	This pertains to CMMC.
R	Information Technology	What Data Needs to be Saved?	3 (#3)	
R	Information Technology	Authority Data Set Preservation	3 (#4)	
R	Information Technology	Big Data Transfer	3 (#5)	
R	Engineering Planning	Identifying Key Variables that	4 (#1)	This pertains to optimizing specification parameters to make

		Actually Influence Output		the material wanted without "damaging" other properties that are not tested. Also, it is important to consider the influence of geometry on part properties compared to tested properties.
R	Engineering Planning	Limited Data to Support Decisions or Paths	3 (#2)	
R	Engineering Planning	Data used to Derive Process Requirements	3 (#3)	
R	Engineering Planning	Control Plan Specifics	2 (#4)	For instance, gas flow considerations plan into the control plan specifics.
R	Intellectual Property	Intellectual Property Roadblocks	5 or 1 (#1)	
R	Intellectual Property	Uncertain Intellectual Property Requirements	4 (#2)	
R	Intellectual Property	Scan Path	3 (#3)	
R	Outputs	Illegible Photocopies of Drawings	5 (#1)	
R	Outputs	Black and White Microstructure Images	2 (#2)	
R	Organization / Human Resources	Data and Organizational Stovepipes	4 (#1)	In many situations, there is no visibility of data or it may come with a significant delay. Organizational stovepipes may negatively influence the authenticity of the data.
R	Organization / Human Resources	Graybeards Who "Just Know"	4 (#2)	
R	Organization / Human Resources	Program Scope	1 (#3)	This includes delivery dates, order quantities, specifications, finishing operations, and more considerations.

R	Organization / Human Resources	Training Records	1 (#4)	
G	Pre-Build	Build Layout Optimization Criteria	2 (#1)	
G	Pre-Build	Laser Spot Size Variability With Position	2 (#2)	This concern also involves laser power calibration.
G	Pre-Build	Machine Time Stamp	1 (#3)	
G	Pre-Build	Inspection Equipment Calibration Certificates	1 (#4)	
G	Pre-Build	Powder Chemistry by Size Distribution	1 (#5)	This also concerns powder recycling history and powder chemistry by size distribution due to powder recycling.
G	In-Build	In-Situ Sensors	4 (#1)	
G	In-Build	Time Synchronization of Sensors	4 (#2)	
G	In-Build	In-Situ Data Registration to Build Coordinates	4 (#3)	
G	In-Build	Parameter Distributions	2 (#4)	This pertains to determining what is acceptable.
G	In-Build	Hopper Refill Schedule	1 (#5)	
G	Post-Build	NDE Inspection	4 (#1)	Uncertainties of dimensional inspection measurements presents a primary concern.
G	Post-Build	Heat Treatment Post-Processing Surface Treatment	3 (#2)	
G	Post-Build	Final Machining	3 (#3)	
G	Post-Build	Assembly Parameters	2 (#4)	
G	Post-Build	Mechanical, Thermal, and Physical Properties Required by the Customer	2 (#5)	

G	Post-Build	Other Data Required by the Specification(s)	1 (#6)	
G	Post-Build	Weight and Density	1 (#7)	
G	Post-Build	Lot-Release Test Specifications	1 (#8)	
G	Statistics	Process Capability And/Or Control Chart With Output Variables	Not Ranked (Ran Out of Time)	
G	Statistics	Control Charts or Other Statistical Process Control of Process Parameters During the Build	Not Ranked (Ran Out of Time)	
G	Data Management	Data Management	Not Ranked (Ran Out of Time)	
G	Data Management	Storage Solutions for Large Data Sets	Not Ranked (Ran Out of Time)	
G	Data Management	XCT Data File Size	Not Ranked (Ran Out of Time)	
G	Data Management	Engineering Burden to Analyze ALL Build Data	Not Ranked (Ran Out of Time)	
G	Data Management	Utilizing a Matured Data Framework	Not Ranked (Ran Out of Time)	This invokes CDD and standards.
G	Data Management	Lack of Thresholds to drive Decision-Making	Not Ranked (Ran Out of Time)	
G	Data Management	Data Registration for CMM/NDE	Not Ranked (Ran Out of Time)	

G	Data Management	Cannot Roll Up 1 Build Into a Single File/Folder	Not Ranked (Ran Out of Time)	
G	Data Management	Geometric Registration	Not Ranked (Ran Out of Time)	
G	Data Management	File Naming Conventions	Not Ranked (Ran Out of Time)	
G	Data Management	Securely Sharing Large Data Sets	Not Ranked (Ran Out of Time)	

Day 1 & Day 2 D2

Required or Generated	**Affinized Category**	**Subcategory**	**Rank**	**Notes**
R		Standards (Trust data)	5	Define process, define scope, characterize output (industry must be involved)
R		Standards (Trust data)	5	Agree on Best Practices
R		Standards (Trust data)	5	Data processing tool sets - companies can adjust in their own ways with a common data model
R		Accreditation (Trust data)	5	AS9100, NADCAP, OEM Standards/qualified suppliers
R		Accreditation (Trust data)	5	AMQ Program - ISO 9001 but more additive focused
R		Connectivity	4	Have a non-proprietary file format (Creo and SolidWorks, etc.)
R	Approaches to **data required** challenges?	Connectivity	4	Similar to a Financial Exchange, there needs to be interoperability
G		Standards (Trust data)	5	Industry consortia, participation - more people need to be engaged - avoid silos
G		Consolidation	2	Reviewing historical lessons learned in manufacturing
G	Approaches to **data generated** challenges?	Consolidation	2	Have a Sematech (consortium of firms in the United States semiconductor industry) but for AM

G		Standards (Trust data)	5	**Software to support the database and automate the workflow (challenge: what do you do with the data you already have on different data architecture?)**
G		Accreditation (Trust data)	5	Proving trust with data - technologies enables adherence to processes and procedures
G		Consolidation	2	Share, model, and aggregate data to feed to designers/others Grouped by those with shared interest via impartial third parties (such as NIST)
G		Publication (Trust data)	5	Document what's not IP
G		Connectivity	4	Move to machine readable formats (AI - replace PDFs/Excels)
G	What data items/artifacts are needed or are pain point? What types of data are required?	Impact of Data	4	Repeatability, cost, time
R		Trust	5	OEM's IP, accreditation, pedigree
R		Impact of Data	4	Powder: properties, variation
R		Connectivity	5	Connectivity to machines - standardization of hardware and software (Application Programming Interface (API)) connectivity to systems (legacy ERPs)
R		Impact of Data	4	Dimensional, material certification, print parameter, thermal image, melt pool
R		Impact of Data	4	Design intent, model for the design, requirement specifications
G		Connectivity	3	Equipment meta data - who manufactured the equipment, sensors, what data will it produce, link through the change
D		Impact of Data	4	Designer needs to know what the processes are capable of doing
R		Impact of Data	4	Statistical process controls
-		Consolidation/ Prioritization	2	Data reduction (or "Data ignoring") - the more data we have, the more we think we have to do something with it
-		Impact of Data	4	Variability across data collection is a pain point

R		Impact of Data	4	Printing process, heat treat process, characterization, machine connectivity, digital threading - need to build common structures
R/G	Who is generating that data	Manual	4	Program managers
R/G		Manual	4	Engineers
R/G		Manual	4	Supply chain managers
R		Manual	5	Manual touch labor has much room for error
R		Digital	4	AI generated
R	How does data get from point A to point B?	Internal connectivity	4	ERP system - looking at the molecular level of AM processes - feeding into SAP system
R		Internal connectivity	5	A process between people, hardware, and software
G		External communication	4	Research projects, publications, responsible variables
R		Internal connectivity	5	Handover/transition points are biggest pain points (internally within organization)

Day 1 & Day 2 P1

Required or Generated	Affinized Category	Subcategory	Rank	Notes
	Feedstock	Feedstock conformance		Feedstock cert plan/conform/report
	Feedstock	Powder handling storage		Handling, Environment of the storage
	Feedstock	Powder reuse methodology		Powder reusability
	Feedstock	Scalability		Scalability of feedstock during production
	Feedstock	Supply chain		Feedstock suppliers
	Machine	KPV		Key process variable
	Machine	Data format		Difference in data detail/collects
	Machine	Environmental conditions		Temperature, gas flow etc.
	Machine	Delta		Nominal conditions vs actual condition; Laser output conditions, spot size, calibration conditions are needed

	Machine	Calibration data		Consistent calibration process should record the health conditions of the machine/laser
	Machine	Variability		Variability of the machine, vendor of 3rd party equipment
	Process	KPO		Key process outputs: Layer thickness, build layout,
	Process	Structure-properties		Microstructure; tensile from witness coupon testing
	Process	In-process monitoring		IR, melt pool monitoring, Location dependent identifications, abnormal observations in non-critical location
	Process	Control system		Feedforward controlled system
	Inspection	Surface roughness		
	Inspection	Flaw size		
	Inspection	Dimension		Part size, density, minimum criteria for the measurement
	Inspection	Part criticality		Unique requirements for part
	Inspection	Periodic functional testing		The inspection usually scheduled a period after processes
	Inspection	Chamber temperature		Polymer
	Inspection	Cooling rate		Polymer
	Inspection	Surface finish		Polymer
	Inspection	Appearance		Polymer
	Data requirements from OEM	Large OEM acquires data on their specific system	1	Minimum terminology defined processes for process control in context of CDD
	Part conformance data in incompatible format	sometimes the data are saved in PDF, binary, or other formats that is not directly usable	2	Searchable mineable data format (continuous improvement)
	Perceive uncertainty	Known sources of uncertainties	3	Software tools to implement Common Data Dictionary/Common Data Models
	Learning curve	learning how to control	4	AM forward-ish activities
	Lack of standards for 3D printing outputs	the output files from AM machine is inconsistent	5	Industry led, OEM led, or NIST led
	Demand signal	demands from customers	6	
	Sunk cost	Un-recoverable budget cost	7	

Day 1 & Day 2 P2

Required or Generated	Affinized Category	Subcategory	Rank	Notes
	Process Controls	Minimum process control data not defined	1	
		Production process control change (obstacles) unavoidable		(Obstacles)
		Machine data not standardized		
		Variances in Bed Environment		
		Jams, build pauses		
		early notification of qualified process drift		(Health monitoring
		Data Requirement		1) Process Stability 2) Inputs (powder,…) 3) Machine conditions
		Data Record of laser power		
		Calibration/Validation AM process data		(machine sensors)
		Standard/validation		data from AM machines - by process
		Not possible to reconstruct build from monitoring data. Precludes use of build data for QC disposition		
		Serialization complexity with "build" vs "part" for multiple builds		
		Recordable machine data is not completely descriptive of the process output.		
	Pre-Qualification (Barrier to Entry)	Cost of data collection to support acceptance	2	
		OEMs return IP - how to cleanup multiple suppliers		
		Continue need for process dependence		
		SME integration with LSI		
		Pre-Qual data standardization (80% solution)		

		Build trust that part was built to process spec.		
		cost process development cycle, a problem for SMEs		
		Matching equipment to OEM requirement / SME capabilities.		
		Clear understanding of customer motivations, cost models		
		Differences in customer requirements		
		Data Requirement: what is customer motivation for ordering the part		1) NRE/Cost, 2) suppliers dev. 3) multiple suppliers
		Supply chain problems for SME		
	Technical Data Package (TDP)	Fully developed TDPs / Standards to make the part	3	
		TDP is portable from supplier A to supplier B		
	End-Item Data Package (EDIP)	Part examination by OEM upon delivery	4	
		End Item / Data package standards		
		Time to generalize end item data package		Currently manual!!
		What data does LSI require for right production from SMEs		
		Part examination by SME before delivery		
	<u>Qualification:</u> Machine Maintenance	Machine maintenance replacement of a machine part	5	
		Data standard for AM equipment preservation maintenance		
		Key AM process monitoring + Reference standards / laser power monitoring causalities		Galvo/Scanner wear
	<u>Qualification:</u> Feedstock Issues	Raw material issues / changing vendors due to no inventory	5	
		consistent quality of powders		

		How to convey recycled feedstock composition		
	<u>Qualification:</u> Workforce Factors	Human error in setting up builds	5	
		Competency of SME staff		
		Invariant status update between OEMs		
		Competency of OEM staff		
	Long-Term Consideration	Challenge: what will AM metal production companies look like in 10-20 years?	6	1) small machine shops, 2) medium shops with 100+ machines, 3) Industry LSIs
		Fabless additive manufacturing		(Like fabless manufacturing for semiconductors, chips) in the long term.
	Challenges			
	Process Controls	Accessible Digital Twin model to share build status	1	
		Open API for process monitoring		
		Open access interpretation, sensor trigger controls		
		Validation of machine settings		
		Accelerate ASTM working group on aerospace data requirement for LPBF		Working group activity
		ASTM In-situ monitoring working group - integrate with data standards		Working group activity
		In-process monitoring - Minimum data requirements (Current state + Future needs)		Future needs < 3 years
		Standardized machine data output / log requirements (sensor types / output)		
		Production data to accelerate re-qualification		
		More mixed workshops with LSIs , SMMs , developers		

	Pre-Qualification (Barrier to Entry)	Open reference base / threshold database / minimum viable	2	
	Technical Data Package (TDP) Documentation	Standard scenario-driven requirements (modular)	3	Data package requirements
		Tool / standards to automate TDPs		(Multiple in work)
	End-Item Data Package (EIDP) Documentation	Standardize / automate / witness coupons data (Common Data Exchange)	4	
		Standard scenario-driven package req. (modular)		
	<u>Qualification: Machine Maintenance</u>	Laser Caustics / KPV Reference standard	5	
		AM machine maintenance / control plan standards (By industry)		
		Preventative maintenance standard		
		Survey of standards for different application within the economy		
		Digital Twin of Machine: Decay/Deterioration, plots of machine life / performance		
		Digital Twin of Machine: for health monitoring (Standard implementation)		
	<u>Qualification: Feedstock Issues</u>	Standard for electronic certification for feed stock & special process	5	
	<u>Qualification: Workforce Factors</u>	Propose / develop training programs to raise awareness of AM standards for new AM SME entrants	5	Program or tool
		Standards for training operators on appropriate machines		
	Long-Term Consideration	Accelerate maturation + implementation of Common	6	Accelerate (Fund)

		Data model + Data Exchange Format		

Day 3 Q1 & Q2 Combined

	Challenge	Approach
1	Supplier/Customer Fit for Purpose Requirements	Create common definition and requirements
		Collaborate on common or easily translated formats
		Supplier Requirement - develop requalification levels based on type and amount of data generated level (example 0-machine calibration, 1- chem, met, lot acceptance, 2- level 1 to room, 1-level 2 to more
		Supplier Requirement - Develop requirements that are quantifiable and measurable
		Supplier Requirement - Develop procedure for evaluating, qualifying, approaching a delta
		Customer Requirement - Start with existing part classifications (NAVAIR) and have (NIST? Other?) pull together NASA/FAA/FDA to agree on pieces of it
		Customer Requirement - Start with existing data requirements by class (NAVAIR?) and have (NIST? Other?) pull together (NASA/FAA/FDA/GE/Rolls/P&W) to define minimum viable data set
		Customer Requirement - Develop application specific requirements for requalification
		Customer Requirement - Establish requirements for legacy hardware
2	Cost effective approaches for data gathering and statistical methods to measure equivalence/automation	Development of low-cost sensors to measure key process variables
		Collaboration on data and hosted databases that can be shared across the US industrial base
		Develop statistical methods to build confidence for delta qual. Based on past class. Use to down select min. viable dataset
		Tag data with risk potential aggregations with risk >= threshold triggers review
		Tools and clear SOPs for SME to show equivalence with public design allowable datasets
		Develop measurement solutions to directly validate equipment performance such as gas flow
		Reduce data acquirement cost with automation of data capture with IIOT
		In-situ sensing and models for virtual test/qual

<u>**Day 3 D1 & D2 Combined**</u>

	Challenge	Approach
1	Lack of Focus/Impact: What are the "killer" AM applications and how can be the vast amount of data be distill and applied to those applications.	Publication of specific examples where AM allowed you to do something you couldn't otherwise do AND PROVIDE ASSOCIATED DATA.
2	Cost of data collection (how many microstructures, tensile tests, etc.) and data storage (hard drives, lots of hard drives)	Contracts: point to specific requirements/standards
		Be able to justify/rationalize *why* those requirements/standards apply

<u>**Day 3 P1&P2 Combined**</u>

	Challenge	Approach
1	Data requirements from OEM, Technical Data Package (TDP)	Standardized TDP with minimum data requirements
		Standard scenario-driven requirements (modular)
		Tool / standards to automate TDPs
		Large OEM acquires data on their specific system
		Minimum terminology defined processes for process control in context of CDD

		Accelerate maturation + implementation of Common Data model + Data Exchange Format
2	Validated AM Process Controls demonstrating production conformance	Accessible Digital Twin model to share build status
		Open API for process monitoring
		Open access interpretation, sensor trigger controls
		Validation of machine settings
		Accelerate ASTM working group on aerospace data requirement for LPBF
		ASTM In-situ monitoring working group - integrate with data standards
		In-process monitoring - Minimum data requirements (Current state + Future needs)
		Standardized machine data output / log requirements (sensor types / output)
		Production data to accelerate re-qualification
		Laser Caustics / KPV Reference standard
		AM machine maintenance / control plan standards (By industry)
		Preventative maintenance standard
		Survey of standards for different application within the economy
		Digital Twin of Machine: Decay/Deterioration, plots of machine life / performance
		Digital Twin of Machine: for health monitoring (Standard implementation)

5.6. Participant Post Workshop Feedback

Chandler Becker

Thanks again for the invitation to participate in the AM Data workshop. I found it interesting and hope I was able to contribute in a positive way, even if I couldn't participate in the entire thing.

The discussions and presentations reminded me in some ways of the discussions around ICME and integration of materials modeling into materials design. There are common challenges around trust, adoption, levels of technological (especially IT and software) maturity, hesitancy to adopt something new and unproven, cost/benefit analysis, and (last but not least) the need to produce a product that won't fail and will meet the customer needs.

A few more specific recommendations and thoughts, probably already in line with your thinking given the speakers and discussions:

- More interactions between materials data and engineering data communities would be beneficial to learn from each other and address common challenges or identify where one community has solved a problem relevant to the other. (Really it isn't two communities, it's a number of communities that need to interact.)

- Examples of good data management and challenges overcome would be helpful for adoption. That is easier to grasp than concepts such as why human- and machine-readable file formats would be helpful (especially when people don't know what 'machine-readable' means, for example).

- Connections with data efforts outside of AM (e.g., through RDA) could be fruitful when thinking about AM data management. The ICME community could also be a good resource here since technical materials and processing data management is also relevant there, and (based on my experience) common data and interfaces can be used to facilitate information transfer and lower the impedance mismatch across systems and applications.

- Perhaps this is already being done, but it could be helpful to convene focus groups specifically focused on the technical aspects of AM data management. Note that this isn't the same as the SDO's, though they would probably play a part. I'm thinking more about something centered on the software and data service providers and what could facilitate interoperability and adoption of good practices.

- Software is key, particularly looking to automated capture of data from sensors and equipment. Personally, I found that panel to be very interesting and would have enjoyed a discussion group with some of the people involved in implementing these systems. What are their challenges in developing their systems and customer adoption? What have the successful ones done well? Again, I think there are parallels with ICME and materials design.

- Incorporating materials data into models and data management is also important for AM. Dave Furrer's talk covered this well, I think.

- It would be good to consider ways to encourage large enterprises (with more money for IT) to share lessons learned with their smaller suppliers as a way to make it easier to get compatible information and data. Encourage collaboration through consortia and pre-competitive technology sharing.

Anyway, those are my initial thoughts, hopefully reasonably clear. I'll let you know if I think of anything else, and please let me know if you have questions.

Stephanie Bonfiglio

Thank you for hosting this workshop and thank you sending out this email.

The major takeaways for me was getting to network with the diverse group of attendees. As well as learning the different perspectives from the speakers and attendees about integrating AM SMEs with the LSIs.

Having America Makes, NIST, and the government help create a layout of what requirements/certifications are needed to be a supplier for a LSI. Along with trying to generate funding to help the SMEs become qualified. We don't know everything that the LSIs require to become qualified, and they all have different requirements. The cost is also a pain point. I think creating a list of almost qualified SMEs for the LSIs to start talking to, my company for example I would say is 75% there. If a LSI saw us on the list and then started the conversation that would be helpful. We have been reaching out to LSIs since the beginning and finding the right person in the LSI to talk to has been very difficult.

Anil Chaudhary

Reasons for data management:

1. Get 80% of the way before starting a new part (i.e., pre-qualification) (Nick Mule, Boeing)
2. Instead of designing a part based on min properties, move to (model-based) material properties definition as a function of path (Dave Furrer, P&W)
3. Get the part right the first time because 1st prototype locks in 70% of lifecycle cost. (Chris DeLuca)
4. Perform Bayesian update on the models by combining virtual vs. measured data (Dave Furrer, P&W)
5. Support the largest trend in AM, which is metal and critical parts (Nick Mule, Boeing)

Create data management method to:

1. Qualify data (Doug Hall, Battelle)
2. Enable a validation standard (Nick Mule, Boeing)
3. Get information from the data (Charles Fisher, NSWC)

Methods to Empower SMEs:

4. In one of the working group sessions, our conversation transitioned to a discussion between the favorability of training versus the favorability of hiring individuals carrying particular skillsets. As it turns out, literature in human factors psychology states that hiring people with the necessary skills is a far superior strategy compared to training the existing workforce to adapt to the latest objectives. However, these observations should not promote an environment of high turnover. Rather, these observed phenomena should support the notion that hiring practices should share close association to the long-term strategy of the organization. Thus, if hiring standards are strict in skill requirements and closely align with a defined long-term vision, there is a low probability of needing to train employees to cover deficient skills. The same principles may be applied to Additive Manufacturing (AM). Promoting AM knowledge to become more commonplace will ease the burden on SMEs on the basis of training requirements. This may be achieved though a few different avenues. It is important to note that job rotation has been shown to increase one's general knowledge on a topic while also reducing the monotony of the

existing job. In the AM context, SMEs are uniquely postured to embark in these types of activities. Between SMEs, information or personnel agreements may be established in order to help individuals gain exposure to AM processes as they are implemented in other contexts. At the most basic level, an apprenticeship arrangement where interns rotate through different AM contexts (perhaps at entirely different organizations) would help to diversify the AM knowledge of those entering the AM field. These arrangements are most convenient when multiple SMEs share physical proximity in operations, but information sharing arrangements are far less restricted by these limitations. Some SMEs experience a tremendous burden when undergoing qualification for processes, materials, parts, or other items. This is an area of opportunity for LSIs to contribute even if LSIs are expending resources on qualifications for parts/processes that exist internally to SMEs. For LSIs, there are several benefits. First, LSIs may govern the precise approach to qualification. This guides the resultant quality and output of SME processes towards the LSI's desired standards. Second, such a venture establishes a collaborative working relationship between the LSI and SME. From a quality perspective, this uniquely postures the SME to meet the quality standards of the corresponding LSI for any future collaborative work. Moreover, SMEs benefit by having meaningful support from LSIs during qualification and advancing their overall operational capabilities. Such a relationship also represents a valuable source of business for SMEs engaged in such an arrangement.

Andrew Couch

- Uniquely, Additive Manufacturing (AM) faces challenges pertaining to standards and protocols for data management, data maintenance, and data transmission.
    - What data should be kept? A formal decision framework is needed in order to separate useful data from irrelevant data in the AM context.
- Although government entities have the ability to bridge the gap between LSIs and SMEs and promote AM at large, this transformation carries many complexities that are unlikely to be agreed upon by all parties.
    - Action today is better than action tomorrow. In general, waiting on a government solution to problems is not a suitable plan.
- The strength of AM exists in versatility and adaptability to produce parts of varying sizes, shapes, and material compositions.
    - This serves as yet another tool that may be leveraged in a low-volume/high-mix environment.
- Broadly, there are issues concerning the clarity of requirements and how the interaction between requirements translate to manufacturing considerations.
    - As voiced at the conference, requirements seemingly adapt as a large-scale project unfolds. Correspondingly, this introduces uncertainty into manufacturing operations. If a requirement is likely to change in the future, manufacturing to barely satisfy a threshold requirement is not a reliable practice.
- AM faces many challenges that are similar to those faced by other emerging technologies.
    - A lack of knowledgeable talent, lack of resources, and poorly understood application areas are generally common challenges that are faced by new technologies.

- (Observation) When LSIs impose data requirements, standards, or other requirements on SMEs, it carries the potential to work counterproductively against the true objectives of LSIs.
    - The three core pillars of good service (also applying to manufacturing) are cost, quality, and time. Extensive qualifications for parts, processes, and the introduction of excess requirements are often present. SMEs uniquely struggle to meet these demands. In turn, even though these actions increase quality (in theory), they also increase costs and production time for both SMEs and (as a result) LSIs.
- AM application cases are needed to more broadly support AM implementation.
    - This helps SMEs to understand when AM should/shouldn't be applied.

William Frazier

- Data is not data (i.e., useful) unless it can be used to make decisions. Collecting data that does not lead to decision making is costly and pointless.
- Models are the best repositories for data. For example, $y = mx + b$ can describe thousands of data points. Bayesian updating allows for model refinement.
- Process equivalent test specimens are needed to facilitate process optimization of part geometric feature specific locations.
- Machine shops typically do not have the engineering, modeling, and simulation capabilities required to be a service provider of critical parts.
- Foundational quality elements (e.g., ISO 9001 AS9000) must be established by SMEs if they are to be AM parts producers.
- High cost of cybersecurity compliance limits SME participation.
- The perspective of AM service providers and SMEs is difficult to obtain and lacks visibility amongst decision makers as these businesses cannot afford the cost or lost opportunity time to participate in conferences, the national network of manufacturing institutes. Many of the service providers and SMEs invited to this workshop told us that they could not participate because it did not add to their bottom line.
- LSI are not monolithic, rather they have business units with unique requirements resulting in different means of vendor qualification and different means of data curation.
    - SMEs cannot afford to comply with multiple LSI requirements.
- Consensus on an 80% solution as to what industry needs to be considered qualified in the AM space is required to lower cost and democratize AM. This requires robust collaboration.

David Furrer

Thank you for your efforts to lead this great workshop.
I think some of the major issues that came out that should be further addressed are:

1. A SINGLE Industry-Wide Digital Certificate of Conformance Standard that provides overarching guidance and requirements for how data defined by subordinate ASTM, SAE, ISO, etc. specification are tagged and communicated in digital format. This should be for ALL materials/processes and NOT just for AM. AM-Only may lead to

hindered implementation within companies that manage many types for materials and processes.

   a. ASM committee is working this and would like to link with the AM community.
   b. Need Standards Organizations involved and looking at this holistically.

2. Efforts to determine what DATA is really required for Qual/Cert basis the various strands of NASA 6030. Is there a means to define success for Qual/Cert plans?
3. A survey of the primary AM Production Bureaus relative to their willingness to share DATA deemed required by the OEMs/Customers for Qual/Cert would be useful. Seems that we discussed data as though it will be fully shared up-and-down supply chains; but I am not sure this is the case. Should there be a standard??
4. Development of NDE methods capabilities relative to AM component geometries and AM processes. Eddy Current capabilities look good, but want is possible for in-situ and post process inspection??? A report on all applied NDE methods might be useful and can lead to what DATA on NDE is possible and needed.

Slade Gardner

I have two bits of feedback for the event. I really enjoyed participating and I found value in the discussions.

The first is that there should be more people responsible for the Profit and Loss statement of a company. This would be a tall order for an LSI but maybe not for an SME. I counted a few people responsible for the 'commerce' of the technology. I think this is critical. I know from being at an LSI that the perception at the technical front line is sometimes different than the business front line. The perspective from the finance department would be helpful to blend with the tech assessments.

Second, a specific concrete step to empower SMEs would be to put a focus on Measurement Science for large AM. NIST seems focused on LPBF only. The metal DED segment is growing and there are many needs for industrial measurements. The attractive part of large DED might be that in process sensing is more accessible – that could provide a roadmap of measurement science development that could later become miniaturized for LPBF or other AM methods. There are several standards organizations that are focusing on DED-arc (ASME, AWS, API) but these manufacturing standards are leaning on legacy welding inspections and welding acceptance criteria. With the right kind of measurement science bringing in process monitoring to maturity, we may be able to accelerate part acceptances in the future.

Derek Hass

Below are some takeaways / comments based on the workshop experience:

1. The collection, storage and use of data can certainly be used to ease the qualification burden place on SMEs especially if not siloed. Transition from part based to material / process-based qualification is, of course, one key and where continued government agency efforts are

needed. This requires additional effort to actually reduce barrier to entry for SMEs and not increase them (there is some risk for the latter by adding to the technical requirements without significantly reducing the qualification burden).

2. Recognizing that not all SMEs are the same may help in creating a better understanding of data requirements and connections to supply chains for SMEs. AM specific suppliers (like Big Metal Additive) are not necessarily the same as a casting /forging house that want to also utilize AM. Companies that specialize in making part assemblies could/will also have a different viewpoint. Think that increased interactions with different types of SMEs would provide useful information. Current workshop would have benefitted from greater participation from the SME community interested in being AM suppliers. Some discussion during the breakout sessions with OEMs indicated that which category an AM supplier falls into makes a big difference to the OEM.
3. While increasing the use of data both in terms of process / performance relationships, in-process monitoring, and process modeling offers great potential to reduce qualification burdens to SMEs it does not appear to be that near term as far as readiness. With my small business hat on (used to have a small business manufacturing company), I would say that demand signal is more important than reduced qualification burden for SMEs in this space. Small businesses need orders more than anything. So, a question is: How can use of data / process intelligence increase the usage of AM in new part design to increase the demand signal? Needs parts that are designed for AM and can only be produced by AM. I think companies like BMA can figure out how to make parts, how to qualify and how to transfer / store data. Knowing that the demand is there seems more important than all the rest.

Really enjoyed the workshop and format. Learned a lot.

<u>Elizabeth (Liz) Henry</u>

Thank you all for coordinating and supporting this activity. I particularly admire and appreciate the focus on actionable outcomes.

As for take-aways and specific concrete outcomes, here is my list:

1. Consider a comprehensive "Literature Review" of past USG-led AM Data activities, workshops, reports since 2016. I would be glad to support this activity as I have been involved in many of the cross agency, DoD, and America Makes activities since this time. Some of the brief outs will be more useful than others for this activity, but some of the AMMO AM Wargames/Workshops have some proceedings that I think would be helpful to document as precedent.
2. Strategic messaging of this initiative - as well as other higher-level coordination AM activities by NIST (and NASA) are helpful to AM practitioners, project managers, and policy makers across other government agencies (DoE, DoD, and even Commerce, Education, and Labor). Visuals are gold. Congress asks about this kind of thing often.
3. Leverage existing Data Frameworks from other industries that are invested in advanced manufacturing technologies, such as Oil and Gas and Automotive. I would be glad to help identify future workshop participants to support this activity.

4. Leverage former government folks who are now in industry to help strategize the big picture: the systems level plan for accelerating the adoption of additive.
5. Consider similar closed-door sessions with key stakeholders to come to agreements (NIST, NASA, OSD Small Biz, OSD R&E, OSD A&S, MILSVCs, DoE, SDOs, LSIs)
6. Understand the dissemination pathways (national strategy to specific/regional implementation) for any strategy or plan that might result from this group's future efforts. They may include Apex Accelerators (fmr PTACs), MEPs, SBDCs, MIIs, DMCSPs, NSF Engine grant recipients, Tech Hubs, National Labs, FFRDCs.
7. Remember that OSD R&E ManTech funds and oversees America Makes from the USG.

Mahdi Jamshid

Going through some old emails, I just realized that I never responded to the request for providing our take aways form the workshop. I understand that it might be too late, but still wanted to share one observation. We discussed in length about the role of LSIs and how they should/can help startups as it related to providing suitable conditions for involvement of startups. However, what I though was missed from the discussions (to my knowledge) to hasn't received a fait attention was the topic of "incentives". IMHO, if LSIs haven't done XYZ yet, it doesn't necessarily mean that they understand the problem statement or aren't aware of the problem or opportunity. Rather, it may very well mean that while XYZ is the right thing to do, there is no incentive for a LSI to prioritize XYZ over many other tasks and take an action. Therefore, one of the messages that the workshop may communicate could be encouraging the government to create reasonable incentives for LSIs to do the right thing. I'd be happy to elaborate more or speak with you, if necessary.

Again, my apologies for a very late response, and thanks again for all the great works.

Alex Kitt

One overwhelming take away was how challenging it was to isolate SME challenges given the substantial overlap between SME and LSI challenges.

These items jumped out as SME specific challenges:

1. Consistent demand (not just demand signals) to justify AM investment (capital + workforce + NRE)
2. Inconsistency in requirements from different LSI's translates to substantial NRE for each new customer
3. (I think this is similar to one of the takeaways from your FAIR workshop) The organizations who benefit from the data (LSI's) are not the same as the organizations being asked to collect the data (SME's). I asked an SME manufacturer what benefits they get from collecting data. They answered "none".

Joshua Lubell

- Security was mentioned numerous times as a pain point. I got the sense that the primary concern is technical data theft, which is a potentially big problem for additive because (1) flexible business models increase an attacker's opportunities for stealing data and (2) design freedom plus the sheer amount of data increases the ease of counterfeiting.
- Compliance with Cybersecurity Maturity Model Certification requirements, which is based on the guidance in NIST SP 800-171, seems to be a concern, particularly among SMEs.
- AM is more than just 3D printing. Post-processing, qualification, inspection, material specification are all critical elements of AM.
- From David Furrer's talk, I learned that AM processes are high-gradient (small parameter changes can cause big changes to part properties), unlike forging and casting which are low-gradient.
- From Wayne King, I gained a greater appreciation of the challenges to controlling metal L-PBF processes. I really liked his video showing how the melt pool behaves as a "complex weather system." I also learned that the semiconductor industry uses feed-forward process control, and that FFC might be able to better control AM processes.
- The AM Common Data Model has the potential to make it easier for manufacturers to better leverage the data their machines generate, if equipment vendors make their data available in computer-actionable CDM-compatible formats. There is a big standardization opportunity here.

Specific Steps that would help SMEs adopt AM technology**:**

- Education outreach, as was discussed in the group conversation at the end of the workshop.
- AM-specific security guidance to supplement SP 800-171 and other existing guidance. MxD's CMMC 2.0 playbook might be a good exemplar to follow, although it does not address additive specifically. I think more research needs to be done connecting the physics of AM processes to risk management. Doing so would enable AM experts to determine which of the many attacks on AM processes documented in the research literature are most likely to occur in the real world, and would cause the most damage to companies, their customers, and stakeholders.

Ted Reutzel

I will need to look through my notes to find other things, but one thought I had was that it would be really beneficial to have some uniform guidance on minimum data requirements for various classes/categories of application. A common theme I heard was that it takes so much time and effort for SMEs to generate required data when each customer has their own, special requirements.

It would be great for SMEs if there was consensus on these from NAVAIR, NAVSEA, Army, OEMs (GE, P&W, Lockheed), NASA, perhaps FAA, FDA. These should map to ASTM data standards, for common naming and common data formats. Recognizing that each organization may have different needs, these "minimum data requirements" could serve as a common baseline, and each organization can provide "add-ons" as required.

I won’t claim to be familiar with all the standards that are emerging, but I suspect NAVAIR may be out-in-front, and their guidelines may serve as a useful starting point.

I hope this is useful feedback! Making this happen (getting various standards organizations to “relinquish” pieces of this) will certainly be a challenge but may be worth the struggle.

Stephanie Saravia

I did not observe any women in the ~28 keynote speakers, panelists, and facilitators throughout this conference. I recognize that there are few women in this field; however, diversity is important for driving innovation. I want to make you aware for future planning purposes, and I’d recommend being intentional about inclusive going forward.

Mike Vasquez

There seems to be a real danger in trying to formalize/standardize a highly complex data management requirement. It'd be great if we could come up with some guidelines that don't necessarily require 100+ data fields to be captured every build. Based on the talks, the decisions on what/to what extent things need to be captured relies on the customer/funder. An effort should be made to really get them comfortable with requirements that are not so burdensome that they restrict new suppliers from entering the space.

We didn't spend much time outside of DMLS or DED during the session. There's a lot of non-metallic work going on so how do we incorporate the learnings in these other modalities?

We'd love to continue to support the group and share our lessons learned from implementing data management tools in a variety of applications.