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Joint FAA – Air Force Workshop (FAA CSTA Workshop) Qualification/Certification of Metal Additively Manufactured Parts

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16. Abstract

The FAA and Air Force Research Laboratory jointly organized a workshop on Qualification and Certification of Additively Manufactured (AM) Parts, which was held on August 29–31, 2017, in Dayton, OH. This was the third such workshop: previous workshops were held in 2015 and 2016, also in Dayton, OH. The workshop was conducted and sponsored within the framework of the FAA's Annual Chief Scientific and Technical Advisor Workshop (workshop organizer – Dr. Michael Gorelik). There were 126 registered attendees, representing the FAA, Air Force, NASA, Navy, National Institute of Standards and Technology, aerospace industry original equipment manufacturers (OEMs) and suppliers, academia, several international companies and organizations, and selected other invitees. The objectives were to provide additional training and reference material on AM processes to FAA employees, provide a comprehensive review of industry and OEM progress and challenges regarding AM applications, and promote collaboration both across government/academia/industry, and within the FAA, regarding qualification and certification of metal AM parts.

The workshop consisted of 33 presentations addressing background, current programs, and qualification/certification challenges regarding AM metal parts. A Training and Education Panel Session was also held. Results and conclusions from these sessions were collected and summarized.

The workshop met its stated objectives. The sustained high interest in AM, and the importance of safe and robust qualification and certification procedures for aerospace parts, was illustrated by the filled agenda and enthusiastic participation.

17. Key Words

Additive manufacturing; 3-D printing; Rapid prototyping; Rapid manufacturing; Direct metal laser sintering; Selective laser melting; Direct metal deposition; Laser engineered net shaping; Metals; Alloys; Qualification; Certification

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- Michael Gorelik from the FAA
- Rollie Dutton from the Air Force Research Laboratory

Keynote speaker:

- Mohammad Ehteshami, Vice President and General Manager of GE Additive.

Workshop host:

- University of Dayton Research Institute (UDRI)

In addition, there were more than 30 technical presentations from 4 different US government agencies, 5 international companies or agencies, and numerous US companies, universities, national laboratories, and Standards organizations. There was also a Training and Education Panel session, with six panel members from industry, academia, and agencies. This participation illustrates the high level of interest and commitment to ensuring that qualification and certification of AM parts is accomplished in a safe and robust manner.

Workshops with aggressive agendas and high expectations such as this one require a significant commitment of time, intellect, and expense on the part of participants and their organizations, especially presenters and sponsors. Thank you for your efforts.

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NN—TRAINING AND EDUCATION PANEL SESSION: PENN STATE UNIVERSITY
OO—TRAINING AND EDUCATION PANEL SESSION: SOCIETY OF MANUFACTURING ENGINEERS
PP—TRAINING AND EDUCATION PANEL SESSION: UNDERWRITERS LABORATORIES

LIST OF ACRONYMS

ACO	Aircraft certification office
AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
AMNT	Additive Manufacturing National Team
AMSC	Additive Manufacturing Standards Collaborative
ATP	Advanced turboprop (a GE Aviation engine program)
CAA	Civil Aviation Authority
DARWIN	Design Assessment of Reliability with Inspection
DED	Directed energy deposition
FSDO	Flight standards district office
MIDO	Manufacturing Inspection District Office
MMPDS	Metallic Materials Properties Development and Standardization
NAVAIR	Naval Air Systems Command
NDE	Nondestructive evaluation
NIST	National Institute of Standards and Technology
NRC	National Research Council (of Canada)
OEM	Original equipment manufacturer
PBF	Powder bed fusion
PMA	Parts manufacturer approval

EXECUTIVE SUMMARY

Additive Manufacturing (AM) is a rapidly emerging technology with the potential for broad application and impact in the aerospace industry. The approach to build a part by adding material layer by layer using structural metal alloys represents a significantly different approach than conventional wrought or cast processes. Parts or shapes may be produced with near-net or final geometry, including complex features and as-produced surfaces. The resulting material and its behavior may differ significantly from that produced by conventional processes, including the microstructure, defect species, residual stresses, inspectability, post-processing requirements, and ultimately structural performance and durability. The requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control require careful consideration in qualification and certification procedures to ensure that AM parts are safe and robust.

The FAA and U.S. Air Force Research Laboratory (AFRL) jointly organized a workshop on Qualification and Certification of Metal Additively Manufactured Parts, which was held on August 29–31, 2017, in Dayton, Ohio. This was the third such workshop: the first was held in September 2015, and the second was held at the end of August 2016, also in Dayton, Ohio. From the FAA side, the workshop was conducted and sponsored within the framework of the Annual Chief Scientific and Technical Advisor (CSTA) Workshop. There were 126 registered attendees, representing a two-fold expansion in workshop size and participation over previous years. Participants included the FAA, Air Force, NASA, Navy (NAVAIR), NIST, industry original equipment manufacturers (OEMs) and suppliers, academia, several international companies and organizations, and selected other invitees. No web conferencing was provided for the 2017 workshop. The workshop was planned as a three-day event, with four main objectives:

1. *Continue* educating FAA workforce in AM technology and applications.
2. Provide a comprehensive review of industry and OEM progress and challenges regarding AM applications.
3. Promote interagency collaboration and industry/academia/government *partnership.*
4. Provide a forum for *dialogue* between the AMNT and regional offices (ACOs, Manufacturing Inspection District Offices [MIDOs], and Flight Standards District Offices [FSDOs]).

The 2017 workshop was intended to build upon the outcomes of the 2016 AM Workshop, and to focus on progress and key considerations for qualification and certification. The workshop consisted of 33 presentations addressing background; current programs and aerospace applications; and qualification/certification challenges regarding AM metal parts. In addition, based on recommendations of the 2016 workshop, a moderated Training and Education Panel session was included this year. It was comprised of six panelists from various organizations and companies. Results and conclusions from these sessions were collected and summarized.

The workshop met its stated objectives. The sustained high interest in AM and the importance of safe and robust qualification and certification procedures for aerospace parts were illustrated by the filled agenda and enthusiastic participation.

1. INTRODUCTION AND BACKGROUND

Additive manufacturing (AM) is a rapidly emerging technology with the potential for broad application and impact in the aerospace industry. The approach to build a part by adding material layer by layer can be accomplished by many process types and is applicable to a wide range of materials, including metals, polymers, ceramics, and even composites. The focus of this workshop was only on metal AM. Key process types for structural metals include directed energy deposition (DED), such as electron beam melting and deposit of metal wire, and powder bed fusion (PBF) processes, such as direct laser sintering of pre-alloyed metal powder. These processes have significantly matured in the past few years and now offer broad potential to manufacture aerospace parts with structural metal alloys. High rate production of engine fuel nozzles manufactured by a PBF process is in its second year, and qualification/certification of other parts appears imminent. Because the capital investment required for individual AM equipment is relatively modest (as compared to wrought or cast production facilities), the potential sources for AM aerospace parts may expand beyond large aerospace manufacturers and their first-tier suppliers to include smaller and less-experienced companies.

AM using structural metal alloys represents a significantly different approach than conventional wrought or cast processes. Parts or shapes may be produced with near-net or final geometry, including complex features and as-produced surfaces. Resulting microstructures, defect species, residual stresses, inspectability, post-processing requirements, and, ultimately, structural performance and durability may differ significantly from conventional processes. Variation within part builds may be significant. Variation between AM machines may also be significant. The requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control require careful consideration in qualification and certification procedures to ensure that AM parts are safe and robust.

The FAA and AFRL jointly organized a workshop on Qualification and Certification of Metal Additively Manufactured Parts, which was held on August 29–31, 2017, in Dayton, Ohio. From the FAA perspective, the workshop was conducted within the framework of an annual CSTA workshop (sponsor: Dr. M. Gorelik / AIR-600 Division). This was the third such workshop: the previous ones were held in 2015 and 2016, also in Dayton, Ohio. The 2017 workshop was intended to build on outcomes from the previous workshops and address topics of interest that surfaced in those events. There were 126 registered attendees, twice more than in previous years. Representatives from the FAA, Air Force, NASA, Navy (NAVAIR), NIST, several Standards organizations, and several international companies and organizations participated. Notably, participation by industry greatly increased in 2017, accounting for most of the workshop expansion. The objectives were to provide additional training and reference materials on AM processes to FAA employees, provide a comprehensive review of industry and OEM progress and challenges regarding AM applications, and promote collaboration both across government/academia/industry and within the FAA. This document, sponsored by the FAA, is intended to provide a brief reference paper to summarize the background, objectives, and outcomes of the workshop.

2. WORKSHOP OVERVIEW

2.1 OBJECTIVES

The 2017 workshop focused on AM of structural metal alloys for aerospace parts manufactured by either PBF or DED processes. The workshop was planned as a three-day event, with four main objectives:

1. *Continue* educating FAA workforce in AM technology and applications.
2. Provide a comprehensive review of industry and OEM progress and challenges regarding AM applications.
3. Promote inter-agency collaboration and industry/academia/government *partnership.*
4. Provide a forum for *dialogue* between the AMNT and regional offices (ACOs, MIDOs, FSDOs).

Further, the 2017 workshop was intended to build upon the outcomes of the previous workshops and focus on industry progress with AM applications, and AM-related training and education. The first three objectives above were the focus of the technical presentations and the Training and Education Panel, which are described in this summary report. The fourth objective was addressed by expanding the time available for networking opportunities during breaks and lunches as compared to prior workshops.

2.2 WORKSHOP FORMAT

The workshop was planned as a 3-day event. All sessions were held at the River Campus facility of the University of Dayton, in Dayton, Ohio. Because the facility could accommodate many more participants than in prior years, no provisions for tele- or web conferencing were made available.

The agenda included 33 formal presentations, plus brief opening remarks. Presentations were allocated specific times on the agenda, typically 30 minutes. The single exception was for the Keynote Presentation, which was allocated 45 minutes. Time for questions and discussion was included in the allocated time. On Day 1 of the workshop, a Training and Education Panel session was held, consisting of 6 invited panel members, plus an FAA moderator. Panelists were each given 15 minutes for presentation, and after these presentations were completed, a moderated question and answer session was conducted.

All presentations were delivered by on-site participants. Presentations were grouped as best possible to promote continuity of topics and workshop flow. However, to accommodate schedules of participants with conflicts, no clear theme-based sessions were possible. This worked out surprisingly well in that each day and session contained some mix of industry, government, and institutional topics.

The agenda was full. Consequently, schedule management was very important, and allocated times were adhered to closely. Presentations were regarded as excellent: diverse, relevant, and with an appropriate level of technical detail. Audience participation was also excellent, reflecting the high level of interest and quality of the workshop content. The audience remained engaged and actively participated throughout the sessions.

The final workshop agenda is presented in appendix A. This version represents the agenda as executed. The format was generally informal, as a working meeting, with questions and discussion after each presentation.

2.3 WORKSHOP ATTENDEES

There were 126 registered attendees, representing the FAA, Air Force, NASA, Navy (NAVAIR), NIST, CAAs, aerospace industry OEMs and suppliers, academia, several international companies and organizations, and selected other invitees. FAA participation included 31 people from 13 sites, which was very similar to the level of FAA participation in the 2015 and 2016 workshops. Attendance was generally by invitation of the organizers, but all requests to attend were accommodated. This was not possible in prior workshops because of the occupancy limits of the facilities used in prior years. The significant increase in industry participation this year was a deliberate action on the part of the workshop organizers to both expand the industry engagement and the breadth of industry representation, including OEMs, Tier 1 suppliers, repair/MRO organizations, and aftermarket companies. This was also the first workshop with significant foreign participation, including foreign OEMs, AM machine makers, and foreign agencies. Three CAAs were able to send their representatives to the workshop—TCCA, CAAS, and JCAB. Foreign participation was made possible, in part, by moving the 2017 venue to an unrestricted site—University of Dayton Research Institute–River Campus.

Diversity of attendees by the organization type is illustrated in the table and graphic presented in appendix B.

3. SUMMARY OF WORKSHOP SESSIONS AND PRESENTATIONS

The workshop consisted of 3 full days of presentations, with question and discussion time for each presentation within the allocated time. A Training and Education Panel session was also held on Day 1. The Training and Education Panel Session is described in section 3.4.

All the presentations except two were cleared for public release and are appended to this report. The presentations are listed below, with a brief statement regarding topics addressed. They are listed in the order indicated by the agenda. The numbering is consecutive without regard to the day presented to facilitate ease of reference to the appendices.

3.1 DAY 1 PRESENTATIONS

Brief opening remarks to initiate the workshop were made by Dr. Michael Gorelik of the FAA and Dr. Rollie Dutton of AFRL. There were eight presentations on Day 1, plus the Training and Education Panel session. The presentations included a recap of the 2016 workshop, perspectives on qualification and certification of AM parts by large OEMs, AFRL, and NAVAIR, and the Keynote Address from Mr. Mohammad Ehteshami, VP and General Manager of GE Additive. Brief descriptions of the eight presentations follow.

1. M. Gorelik, FAA, “Welcome to the 3rd Joint FAA—Air Force AM Workshop—Opening Remarks.” This presentation summarized the key aspects of the 2015 and 2016 workshops, and noted that the 2017 workshop was the first global workshop, with foreign participants and twice the attendance of prior years. It cited the regulatory considerations for AM, with

new material and process space, and new design space now made possible. This presentation can be found in appendix D.

2. B. Cowles, Cowles Consulting, LLC, “Summary of the 2016 Workshop.” This presentation summarized the results of the previous 2016 workshop, which included 33 presentations from government agencies, industry, and academia. The 2016 workshop was regarded as very successful. It resulted in a comprehensive summary report, which documented the status of AM processes for aerospace parts, the central issues for qualification and certification, and key areas for the FAA and other agencies to focus in the near term. The summary report is available through the FAA Technical Center, or the Defense Technical Information Center (DTIC).[1] This presentation can be found in appendix E.
3. M. Crill, Boeing Commercial Airplanes, “Ti-6Al-4V Wire Feed Additive Manufacturing.” This presentation provided examples of Boeing AM applications, focused on wire-feed DED processes with titanium, and described the Boeing approach to qualification and certification. Supplier process-control documents and supplier deposition-procedure specifications were emphasized as critical. Material quality control, post-processing, and design values, including special factors, were described. Initial production parts associated with these processes are 787-9 passenger floor galley fittings, which are regarded noncritical but structural parts. This presentation can be found in appendix F.
4. M. Ehteshami, VP & GM, GE Additive, Keynote Presentation, “Additive Manufacturing at GE.” This was an excellent Keynote Presentation, describing evolution of GE AM from a complex fuel nozzle to broad application in an advanced turboprop (ATP) engine currently in development. These applications resulted in reducing the ATP part count dramatically—from 800+ conventional to less than 15 AM parts—to make a final assembly, by combining many details into a single printed part. The enterprise-level commitment to AM was clearly communicated, including a description of the new business segment “GE Additive.” GE’s approach to materials for AM, machine qualification, process/part/system validation, and specifications was described. Manufacture and sales of AM equipment, with the comprehensive machine control software Predix®, was described as a focus area. This presentation can be found in appendix X4.
5. J. Miller, AFRL, “AFRL Progress in Qualification and Certification of AM Parts.” This presentation focused on key aspects of the way forward for AM parts, including design, materials, processes, quality assurance and nondestructive evaluation (NDE). Point design and part family approaches, and the value of “model-informed process design,” were described. An overview of the AFRL program Maturation of Advanced Manufacturing for Low-Cost Sustainment (MAMLS) was presented. Phase I represents 26 approved projects to date. This presentation can be found in appendix H.
6. J. van Doeselaar, Airbus, “Airbus View on How Requirements Could Be Tailored to AM Applications.” The Airbus approach to qualification and certification of AM parts was presented, including illustration of intent to start with noncritical parts and then move to more highly loaded or critical parts in a stepwise manner. Part family approach is being considered. Interestingly, a graphic was shown depicting AM part cost breakdown (PBF processes), which showed 45% of part costs were post-processing related, and another 20% were attributable to quality inspections—or 2/3rd of total manufacturing costs. An approach for tailored requirements, based on part families and part criticality category, and the need

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[1] 2016 Workshop Summary Report: “Joint Federal Aviation Administration-Air Force Workshop on Qualification/Certification of Additively Manufactured Parts,” DOT/FAA/TC-17/35, Final report, June 2017. http://www.tc.faa.gov/its/worldpac/techrpt/tc17-35.pdf

for process-control specimens, was presented. This presentation can be found in appendix I.

7. P. Jonas, National Institute for Aviation Research (NIAR), Wichita State University, "Test and Material Allowable Development Considerations for Additive Manufacturing." The NIAR facility was described, followed by a description of the statistical approach to characterize AM materials and processes. Likely sources of variation were presented. Efforts underway for process-sensitive materials (polymer-based composites) were described as a possible approach for AM metal materials. This presentation can be found in appendix J.
8. W. Frazier, NAVAIR, "NAVAIR AM Overview." The NAVAIR roles and responsibilities were presented, and it was emphasized that NAVAIR has the regulatory responsibility for US Navy aircraft. Examples of fleet success stories with AM parts were presented, with emphasis on potential AM contribution to readiness and sustainment. The approach taken to qualify a flight-critical part for the V-22 Osprey nacelle link and fitting was presented. A brief description of roadmap elements for AM "lines of effort" in NAVAIR was presented. AM is "driving a revolution." This presentation can be found in appendix K.

Day 1 concluded following this presentation. The workshop was adjourned and a "no-host social" event was held at a local restaurant to provide additional networking opportunities.

3.2 DAY 2 PRESENTATIONS

Day 2 included a diverse mix of presentation topics, from large aerospace OEMs, smaller technical support companies, the DSTL of the UK/MoD, academia, and standards-development organizations (SDOs). In addition, the topic of residual stresses was covered by a pair of related presentations for consideration by the AM community. Brief summaries of the 11 presentations follow.

1. M. Shaw, GE Additive, "Qualification of an AM Component for Flight." The GE development of AM for the LEAP™ engine fuel nozzles was described. This included initial separate manufacture of approximately 20 small parts, which comprise the fuel nozzle, to eventually printing the entire complex shape as a single part. It is now in high-rate production, with many thousands manufactured per year. Interestingly, there was total commitment to AM processing for this fuel nozzle, and no backup made by traditional methods was carried along as the engine went through certification. Expansion of the GE team now devoted to AM, and the enterprise-level commitment, were described. This presentation was not approved for distribution and is not appended to the report.
2. A. Peles, Pratt & Whitney, "AM Informatics and Component/Material Pedigree." This presentation described the value of "informatics" for AM materials and parts, and the linkage of material pedigree to performance, including location-specific properties. Digital linkage of all aspects of the process from raw material to part geometry to processing, post-processing, testing, and designs and models was presented as the schema for a material and processes pedigree infrastructure. Potential use for process optimization was described. This presentation can be found in appendix M.
3. D. Hall, Battelle, "MMPDS Progress on Developing Equivalence Criteria and Spec Minimal Values for AM." The Metallic Materials Properties Development and Standardization (MMPDS) handbook was described, with a refresher on "A-Basis" and

"B-Basis" property definitions. Cost of characterization and benefit of having publically available property data for AM materials was presented. There was some discussion of whether the FAA would accept such an approach for AM in the near term because of variability between AM machines and processes, and the lack of specifications and standards in the public domain. Current gaps in specifications for AM in the context of MMPDS requirements were identified. An equivalency-test approach example was described. This presentation can be found in appendix N.

4. A. Chatterjee, Rolls-Royce, "Perspectives in Additive Layer Manufacturing at Rolls-Royce." The overall approach to technology qualification and demonstration was described, and additive layer manufacturing will be treated in the same manner. A case study for the XWB-97K engine front-bearing housing vanes was presented. This showed the detailed steps from process development and coupon-level testing up through full-sized component manufacture and flight test. The extensive effort required to understand process variability, microstructures, and properties was described. This presentation can be found in appendix O.
5. R. Mangham, DSTL / UK MoD, "Qualification and Certification of Additive Manufactured Critical Parts for UK Military Aviation." This presentation described DSTL's role as part of the UK Ministry of Defence, and the reason for high interest in AM. Small numbers of platforms and availability of spares for sustainment were cited. Challenges in qualification and certification of AM processed parts were described, as was DSTL's approach and the development of a guidance document. AM parts are recommended to go through a Military Certification Review Item-type process, undergo extensive testing, and use a "safe-life" approach for critical parts. This presentation can be found in appendix P.
6. A. Fischersworring-Bunk, MTU, "On-line Process Control to Assess the As-built Component Quality." The overall MTU efforts in AM were described, including the quality-assurance approach, which addressed material, machines, processes, and final components. Detailed review of the use of optical tomography for online (or in-situ) monitoring of the laser powder bed process for defects was presented. This presentation can be found in appendix Q.
7. M. Cola, Sigma Labs, Inc., "In-situ Monitoring for Additive Manufacturing: Implications for the Digital Manufacturing Age." This presentation focused on in-situ monitoring, linkage to materials science, and the analysis of sensor data to enable process-related decisions regarding quality of AM parts. Case studies showing process-monitoring output to enable real-time quality decisions were presented for illustration. This presentation can be found in appendix R.
8. M. Hill, Hill Engineering LLC, "Measurement and Modeling of Residual Stress in Structural Components." This presentation described process-related and engineered residual stresses, their importance to structural performance and fatigue capability, their relationship to Integrated Computational Materials Engineering models, and their need for validation. Application and need to address residual stresses for AM parts were illustrated with examples. This presentation can be found in appendix S.
9. D. Ball, Lockheed Martin, "A Case Study on the Incorporation of Bulk Residual Stress in Aircraft Component Design." As described by the title, a detailed case study was presented for large-scale aluminum forgings for the F-35 aircraft. It was related to a presentation by M. Hill (number 16, above) and illustrated the extensive effort devoted to prediction,

measurement, and validation of residual stress fields in the large forgings, and subsequent use of the results in design and life prediction. Considering the potential for a high level of residual stresses developed during the AM process, these two presentations were of high interest to the community. This presentation can be found in appendix T.

10. R. Gorham, America Makes, “AMSC Roadmap Overview.” This presentation described the role of America Makes as a consortium in the development of the AM-related standards and specifications roadmap, in partnership with ANSI as the AM Standards Collaborative (AMSC). AMSC does not actually develop standards, but rather drives what is hoped to be a coordinated effort amongst the many SDOs that do develop such standards. Current focus areas were described, including processes and materials, process control, post-processing, and properties. High priority gaps were identified and described. This presentation can be found in appendix U.
11. M. Seifi, ASTM, “Recent Progress on Standardization of Additive Manufacturing Technologies.” An overview of ASTM and ASTM activities regarding AM standards and recommended practices were described. The ASTM effort is in conjunction with ISO, America Makes, and other standards organizations. Many ASTM committees are active in AM, and the ASTM F42 committee now has more than 550 members. The ASTM structure for AM standards was described and activities summarized. Of special interest was current round robin NDE efforts for AM-relevant defect detection and their relationship to mechanical properties. This presentation can be found in appendix V.
12. D. Abbott, GE Additive, “SAE’s AMS-AM Committee on Standards Development for AM—Progress Report.” Activities of the SAE AMS-AM committee and their relationship to other standards-development organizations and AMSC, (presentation number 18, above) were presented. The SAE AMS-AM committee has 180+ members, with 6 subcommittees working specifications and guidance documents. This presentation can be found in appendix W.
13. B. Hann, Honeywell, “Proposed Collaboration Approach to Process and Materials Characterization Efforts.” A proposed approach for collaborative efforts for characterizing materials and AM processes was presented with the objective of reducing individual company or agency costs and possibly accelerating the schedule required while capturing the many sources of variation possible with AM processes. This presentation generated much discussion and support for the proposed approach and can be found in appendix X.
14. R. Day, Fraunhofer ILT, “AM Research at the Fraunhofer and RWTH Aachen University.” AM research at the Fraunhofer ILT and RWTH Aachen University was described. This included the description of the digital additive production (DAP) approach to establish a comprehensive digital thread for AM processes and materials. Transferability of processes across AM machines and industrial collaboration were emphasized. This presentation can be found in appendix Y.

Day 2 concluded following this presentation.

3.3 DAY 3 PRESENTATIONS

Day 3 included presentations from industry including large aerospace OEMs, aftermarket and parts manufacturer approval (PMA) suppliers, a major airline operations center, a national laboratory, and the National Research Council (NRC) of Canada. The final presentation was from the FAA and described an overview of the FAA roadmap for qualification and certification of metal AM parts. Brief descriptions of the 11 presentations follow.

1. R. Amos, NRC Canada, "Overview of NRC Additive Manufacturing Activities and Technology Development." NRC installations and scope was presented, with focus on aerospace applications. Progress and challenges in AM were presented, including manufacture and test of aerospace parts. Use of AM for hybrid-process parts was described. The NRC has a broad research initiative underway, including in-situ monitoring technology, rapid deposition processes, and AM for repairs. The approach for aerospace part certification was described. This presentation can be found in appendix Z.
2. C. Sudbrack, NASA GRC, "Powder Feedstock as a Process Variable for SLM 718 Hardware." NASA activities in AM, especially related to space, were described. This included an update on status of the NASA EM20 Engineering and Quality Standard for AM Spaceflight Hardware, due out September 2017. Results of a comprehensive study of INCO718 powder for AM were presented, including size distributions, powder morphology, flow characteristics, and, finally, build quality. This effort is part of NASA's multisite AM Structural Integrity Initiative (AMSII). This presentation can be found in appendix AA.
3. P. Guerierr, Moog, "Laser Powder Bed Fusion Process Control for Flight Critical Parts." Moog products, expertise, facilities, and commitment to AM processing were described, including a manufacturing capability with 17 laser powder bed machines. Example of part applications for ground support equipment and robotics were given. An approach to qualification of flight hardware was presented, which included comprehensive digital tracking throughout the process. This presentation can be found in appendix BB.
4. N. Mulé, Aerojet Rocketdyne. "Additive Manufacturing Qualification for Liquid Rocket Engine Applications." AM applications for numerous parts in both legacy upper-stage engines and developmental boost stage engines were described. In many cases, the parts are extremely complex. Extensive process development and testing, including rocket engine firings, were described. The development processes are supported by designed experiments and modeling to understand defects and variation, and may include in-situ process monitoring and post-build burst or proof testing. This presentation can be found in appendix CC.
5. F. Medina, EWI, "An Overview of the Additive Manufacturing Consortium (AMC) Projects and Collaborations." EWI presented their overall business interests as a nonprofit applied manufacturing company, emphasizing their role in an industry AM consortium. Current efforts address machine-to-machine variation and powder recycling effects, and NDE methods. Potential 2018 research project topics were presented. This presentation can be found in appendix DD.
6. M. Gaska and W. Fallon, Lockheed-Martin and Sikorsky, "OEM Perspectives on AM Qualification and Certification." The Lockheed-Martin approach to AM was described at the enterprise level, including space systems and rotary wing applications. The Big Area Additive Manufacturing facility can print 80 pounds/hour and has a chamber that is 5' x 6'

x 12' long. The L-M approach and challenges for AM qualification and certification were presented. For aircraft structural components, an analogy to castings was cited. However, it is believed that an AM-specific approach to life prediction and especially damage tolerance will be required. This presentation can be found in appendix EE.

7. R. Ramakrishnan, Delta Technical Operations, "Additive Manufacturing in the Airline & MRO World—Potential, Challenges and Path Forward—One Airline's Experience." An overview of the Delta Airlines Technical Operations Center and the expected role of AM in its business were presented. The broad responsibility areas include airframe, cabins, and engine overhaul and repair. The AM plan is progressive, starting with fixtures and tooling, then noncritical parts, followed by the manufacture of selected spare details or acceptance of PMA parts from suppliers. A comprehensive approach and roadmap have been developed. Delta's approach to regulatory authorization of AM parts was presented and linked to the activities of the FAA AMNT. This presentation can be found in appendix FF**.**
8. B. Jared, Sandia National Labs, "The Impact of Critical Defects on Material Performance and Qualification for Metal Laser Powder Bed Fusion." The Sandia approach to AM qualification was presented, with emphasis on material quality, stochastic quantification of defects, and their effects on mechanical property response. Methods were developed to build many test coupons on a build plate and then to efficiently test them in tension to failure. Results were combined with detailed NDE inspections to examine intrabuild process trends and determine effects of defects (e.g., porosity) on properties. This presentation can be found in appendix GG.
9. B. Neff, Sintavia LLC, "Opportunities for AM in the Aftermarket Supply Chain—an Independent Perspective." This presentation described Sintavia as a vertically integrated AM supplier to the aerospace industry. Capabilities included design, analysis, testing, manufacture, inspection, and finishing with multiple AM machines. Intent is to achieve FAA Part 145 certification and work in collaboration with OEMs to produce spares by AM as an alternative method to conventional processes for legacy spare parts. This presentation was not cleared for release and is not appended to the report.
10. J. Paust, HEICO Aerospace, "The Use of Additive Manufacturing from a PMA's Perspective." The requirements for PMA applicants under 14 CFR were compared to that for a Type Certificate Applicant, showing essentially the same requirements for design, manufacturing, quality control, and certification, which would apply to AM parts. AM benefits were described, and some categories of parts considered candidates for AM were described. Current applications of AM were for prototyping, inspection tools, assembly tools, and casting cores, with future direction toward certified/airworthy parts. This presentation can be found in appendix II.
11. M. Gorelik, FAA, "FAA AM Roadmap Overview." An overview of the FAA AIR (Aircraft Certification Service) organization after the recent realignment was presented. What were formerly four Directorates and HQ Divisions have now been incorporated into the new Functional Divisions. In the future, emerging technologies, such as AM, and requirements for new Means of Compliance (MOC) will be addressed by Innovation Centers once they are implemented. With these changes communicated for context, a high-level status of the FAA AM Strategic Roadmap was presented. Main focus areas were described, as well as key elements of the roadmap, intent for a 3-tiered document structure, and interagency collaboration. Options to address current knowledge gaps were described. The expected notional roadmap's timeline extends to 2025, with the next few years' execution covered

by a tactical project plan. The roadmap is expected to be completed by the end of the FY2017. This presentation can be found in appendix JJ**.**

The workshop concluded with a brief discussion session after the Day 3 presentations. Feedback on workshop content, organization, and venue was solicited, and a decision was made to generate a brief survey regarding these items within a few weeks of the workshop.

3.4 TRAINING AND EDUCATION PANEL SESSION

Day 1 included a 2½-hour moderated panel session for Training and Education, consisting of 6 invited panelists and an FAA moderator. Panelists were invited with intent to represent industry, academia, AM consortia, and professional society perspectives. The FAA moderator was Dave Swartz, a member of the FAA AMNT. The panelists and their organizations were as follows:

R. Gorham, America Makes. Appendix KK

P. Dufour, Boeing. Appendix LL

L. Iorio, GE Aviation. Appendix MM

R. Martukanitz, Penn State University. Appendix NN

K. Ward, Society of Manufacturing Engineers. Appendix OO

P. Bates, Underwriters Laboratories. Appendix PP

The panel session was structured to give each panelist approximately 15 minutes to present his or her perspective regarding training and education for AM. A brief description of the presentations made by the panelists follows:

1. R. Gorham, America Makes. A broad view and recommended roadmap for projects to comprehensively address AM training needs was presented. Focus for training was the America Makes “ACADEMI” program: Advanced Curriculum in Additive Design, Engineering, and Manufacturing Innovation. Focus was on hands-on training; see appendix KK.
2. P. Dufour, Boeing. This presentation represented considerations important for a global workforce and a virtual team environment. An integrated, cross-discipline approach is required, and training would be most effective if delivered in “smaller, digestible chunks.” Importance of AM processes and design, the right software and tools, and hands-on practice were emphasized; see appendix LL.
3. L. Iorio, GE Aviation. A comprehensive expertise development flow map, targeted at infrastructure to support industrialization of AM, was presented. It appeared based in large part on internal, company-developed training in AM, which was (or is being) integrated with existing engineering and manufacturing training in the company; see appendix MM.
4. R. Martukanitz, Penn State University. Academic programs for AM are being integrated with Penn State research activities in AM, including undergraduate summer internships and master’s programs in AM, beginning in 2017. In addition, many well-attended industry practicums and technology-exchange seminars have been held; see appendix NN.

5. K. Ward, Society of Manufacturing Engineers. A professional society perspective was presented, including approach by the "Tooling U-SME," the workforce development arm of SME, for training in AM. Competency-based development programs with an approach for "stackable credentials" were emphasized; see appendix OO.
6. P. Bates, Underwriters Laboratories (UL). The UL presentation emphasized safety and quality training in materials, handling, and facility operations as key AM training for everyone involved in AM processes and facilities; see appendix PP.

A moderated question and answer session followed. This was a productive element of the workshop. AM training and education needs, approaches, current availability, and future plans were addressed. The moderator made sure that each panelist was engaged in responses to ensure that a broad perspective was represented.

4. RESULTS AND CONCLUSIONS

This workshop was extensive, both in participation and content. Workshop participants represented a diverse group in terms of AM experience, professional disciplines, and organizations. As with the previous workshops, there were participants from the FAA, US government agencies, academia, national laboratories, professional societies, and industry. For the first time, there was significant participation from international companies and non-US governmental and regulatory agencies. Overall, the workshop size was substantially increased—twice that of previous years. The increased participation was primarily from industry, including large OEMs, airlines, and AM suppliers and equipment makers. Overall AM experience and expertise of the participants was perceived to be significantly higher than in the previous workshops. The workshop content included 33 significant presentations delivered over a 3-day period, plus an Education and Training Panel session on Day 1.

The following sections are intended to capture the results, conclusions, and common themes that emerged from the workshop. In addition, this section is intended to summarize general, high-level conclusions regarding the workshop itself and its objectives.

4.1 BRIEF RECAP OF THE 2015 AND 2016 WORKSHOPS

A brief recap of the previous two workshops is presented here to provide context and a reference point for the 2017 workshop. The previous workshops had four primary objectives:

- Education of the FAA workforce in AM processes, capability, and challenges
- Benchmarking of AM qualification/certification efforts by other agencies
- Providing an effective forum for networking and communication of the FAA participants, both within and external to the FAA
- Promoting interagency collaboration and industry/academia/government partnerships, which are regarded important for AM development, qualification, and certification

The previous workshops were considered very successful; they met their specific objectives, participation and interest were exceptional, and they set the stage for future productive workshops in the rapidly evolving field of AM. Several of the common and pervasive themes are listed and described briefly as follows:

- There is an extremely high, broad, and sustained level of interest and investment in AM throughout industry, government, and academia, with a broad range of potential processes and applications in aerospace parts.
- AM for structural metals is on the verge of broad implementation into selected aerospace part applications in a mass production environment, beyond tooling, prototyping, or development applications. High-rate serial production of complex parts made by AM with powder-bed processing has already been successfully implemented; qualification and production of larger parts by directed energy methods is believed imminent.
- The input or feedstock material, the specific AM process, and the resultant part are highly integrated and interdependent. This characteristic of AM poses significant challenges and affects requirements for qualification and certification.
- Traditional quality assurance, NDE methods, and detection/treatment of defects may be affected or limited by complex geometry, surface finishes, and the near-net-shape nature of parts produced by AM.
- There is potential for a high degree of manufacturing variation because of process, machines, suppliers, and input stock. Frozen-process approaches and general quality-assurance and process-control methods will need to consider and address this.
- Process models for AM are not mature today, nor are in-situ process-monitoring methods. They are currently useful for trending, but not necessarily for process control.
- A broad effort is underway for standards and specifications. However, specific AM application (at least in aerospace) will require detailed specifications in the following areas: input materials, process and property specifications, and part conformance requirements, which will likely have to come from individual OEMs and suppliers.
- There is a significant need for training and education in AM – for all levels of organizations engaged in AM, for all types of practitioners, and through many sources, including academia, industrial companies, professional societies, and dedicated training organizations.
- Current general processes for design, development, and qualification are believed adequate for AM if rigorously applied and targeted to address the specific nature and considerations required for AM processes.
- Extreme diligence on all aspects of AM processes will be required. These aspects include: input material, especially powder for powder-bed processes; machines and associated process parameters, such as qualification, control, monitoring, and any changes; and final part quality assurance, including characteristics and properties, NDE challenges, 1st article inspection and cutup approaches, test data, etc.

Results of the 2015[2] and 2016[3] workshops were documented in comprehensive summary reports, and most of the workshop presentations were appended. The reader is referred to these documents for more details.

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[2] 2015 Workshop Summary Report: "Joint Federal Aviation Administration-Air Force Workshop on Qualification/Certification of Additively Manufactured Parts," DOT/FAA/TC-16/15, Final report, June 2016. http://www.tc.faa.gov/its/worldpac/techrpt/tc16-15.pdf

[3] 2016 Workshop Summary Report: "Joint Federal Aviation Administration-Air Force Workshop on Qualification/Certification of Additively Manufactured Parts," DOT/FAA/TC-17/35, Final report, June 2017. http://www.tc.faa.gov/its/worldpac/techrpt/tc17-35.pdf

4.2 GENERAL OBSERVATIONS AND CONCLUSIONS FROM THE 2017 WORKSHOP

The following general observations were derived from the 2017 workshop:

- ***Enthusiastic participation illustrates extremely high, sustained interest in AM and associated qualification/certification challenges.*** The high interest level was demonstrated by the number of workshop attendees, which was about twice that of the 2015 and 2016 workshops. FAA, Air Force, Navy (NAVAIR), NASA, NIST, Sandia, international organizations, academia, and US industry were all well represented. The agenda was completely full. Presentations in general were invited and were tailored to ensure alignment with the workshop objectives and theme.
- ***High rate production of AM parts is now a reality:*** The GE AM fuel nozzles for the LEAP™ engine were certified with the engine in late 2015 and are now in production at a rate of thousands of units per year.
- ***Many specific applications of AM are now under development and are targeted for near-term implementation. This state of industry has significantly advanced compared to prior years, when many applications were being evaluated, but few appeared imminent.***

    - Many gas turbine engine parts, including aggressive development of part family applications. Holistic application of AM to selected part families appears imminent.
    - Many airframe parts, initially in non-safety-critical applications.
    - Many space and satellite parts, including some flight-critical applications.

    Applications include complex geometries, consolidation of many detailed parts into single printed parts, parts for which the buy-to-fly ratio was significantly improved, and parts for which reduced lead time was a significant driver for an AM approach.

- ***Extensive efforts to develop AM standards, specifications, and guidelines continue:***

    - America Makes and ANSI continue to identify and address gaps in AM standards and specifications. Although the AMSC working group does not itself generate any specifications or standards, it has generated a roadmap identifying gaps and recommended priorities.
    - The recently formed (2015) SAE AMS-AM committee is very active and now has 180+ members.
    - ASTM, ASM, and NIST continue to support extensive development efforts for AM standards, specifications, and recommended practices. It should be noted that ASTM committee F42 now has more than 500 members, demonstrating the extremely high interest level and importance of AM standards development.

- ***There is potential for high variation in AM processes, due to input materials, machines, suppliers, and the processes used. Variation may occur within the build and must be considered. Significant quality and manufacturing issues for AM processes must be rigorously addressed for qualification and certification***. This was a recurring theme from government agencies, industry, and academia. Many potential sources of variation and focus areas for control were cited and identified for detailed attention, and many of the presentations covered aspects of the following topics:

- ***Machine and supplier qualification.*** New or changed machine qualifications may require months of dedicated effort, and some similar level of effort should be expected for supplier qualification. Several presentations addressed machine comparisons to make the same part.
- ***Quality control of input powder metal.*** This topic again received a lot of attention, including a detailed presentation on powder characteristics. It was generally agreed that rigorous processes for ensuring powder quality and consistency are needed, as are controlled procedures for re-use of powder.
- ***Characterization and control of process-related defects and anomalies.*** The importance of process-related defects or abnormal microstructures was emphasized. Significant impact on fatigue capability is an especially critical concern. Some processes were shown to produce large amounts of porosity or other types of defects, as well as microstructure variations, which require rigorous attention to optimize process parameters and then fully characterize results of the process.
- ***Post-deposit processing, such as HIP, heat treatment, and stress-relief.*** HIP processing was described by several presenters, predominantly to close porosity. High levels of residual stresses are known to result from some AM processes, based on significant build distortions and even cracking that has been observed. The organizers of this workshop invited two presenters, specifically to address residual stress effects on properties and measurement methods used to quantify these stresses for consideration by the AM community.
- ***Surface finish and post-deposit finishing processes.*** Surface finishes for powder-bed processed parts were addressed by several presenters, including variation in surface roughness and finish depending upon the process and location/orientation of the deposited surface. It was recognized that some surfaces may result in subpar NDE or fatigue capability, and that some surfaces may not be accessible for additional finishing.
- ***NDE requirements and capability.*** The near-net shape or final shape parts produced by some AM processes pose significant challenges to NDE. Final surface finishes, geometric complexity, microstructure, access, and part shapes will restrict or eliminate some conventional NDE processes from use. Advanced techniques, such as micro-CT, offer potential but may require significant added time and cost. Some techniques may be suitable for part and process development and validation, but not for high-rate production inspection.
- ***Frozen processes with feedback and monitoring mechanisms established***. The need for establishing frozen processes was emphasized, along with the challenges entailed when the process will likely be part-specific to a large degree, where many machine parameters are available for selection, and numerous paths for building a particular part are possible.
- ***Software and hardware version control and protection.*** This was emphasized by a few presenters as potential significant sources of variation over time, inadvertent process changes, and even susceptibility to cybercrime.

- ***The Training and Education Panel Session:*** The Training and Education Panel session provided a focused time for discussion of this topic. High interest and participation were evident from the audience for this session. Rigorous development and training are regarded as especially important for designers, AM machine operators, and process engineers involved in actual production of parts. High-level conclusions and observations from the panel session include:

  - ***Broad and extensive training curricula and course offerings for AM are either available or under active development.*** These include safety-focused offerings as described by UL, commercial offerings as described by America Makes and SME, and academia-originated offerings as described by Penn State. The latter included both undergraduate and graduate programs (a mix of certificate, degree, and internship programs) and industry practicums held on-site at the Penn State CIMP3D center. The other general category of training and development was internal and industry-based, as was described by GE Aviation and Boeing.
  - ***The training that was described covered all levels of AM practitioners:*** this included modules or courses focused on management familiarization, designers and structures engineers, actual machine operators, and manufacturing-process engineers.
  - ***Hands-on AM environment training was emphasized:*** All the training described contained some level of either direct machine experiences or at least AM shop-environment training.
  - ***The concept of "layered credentials" was described:*** Although the term was used explicitly in the SME presentation, similar concepts were described by several panelists. The concept supports periodic, focused training, rather than single-session, extensive, broad-reaching training given all at one time. Comments were that such focused training would be more effective for actual AM practitioners.
  - ***The initial impression is that extensive AM training is commercially available; it can be tailored to the trainees and organizational needs, and it can be integrated with industry- or company-specific internal training.*** Audience interaction, moderated by Dave Swartz of the FAA, probed various aspects and approaches to the AM training following the panel presentations. ***The panel session was regarded successful both in information sharing and audience participation.***

- ***Other observations and comments:***
    - ***Potential methods and approaches for zoning parts, to address defects, variation, and risk:*** Although this was a focused topic for selected presentations in the 2016 workshop, there was much less attention given to the zoning of parts in the 2017 workshop. It may be appropriate to solicit responses on this topic for 2018.
    - ***Qualification and certification must address the manufacturing process, the specific part, and the potential system impact.*** The qualification and certification process for AM parts clearly requires attention to the material and manufacturing processes, and to the specific requirements for any candidate part. It was emphasized that the *system requirements* must also be considered and addressed for every application.

4.3 OBSERVATIONS REGARDING THE WORKSHOP OBJECTIVES AND ORGANIZATION

Many specific observations and conclusions were drawn from the workshop and the Training and Education Panel session, as were summarized in the previous section. This section is intended to summarize results and conclusions ***regarding the workshop itself and its objectives***:

- The objective to continue educating the FAA workforce in AM technology and applications was fully met: this was especially addressed by the increased participation by industry in the 2017 workshop. AM methods, materials, applications, and challenges were presented in detail. Activities of the various organizations developing AM specifications and standards were summarized to give current state and describe plans for future effort. A significant number of FAA employees involved in certification attended and benefitted directly; and many of the presentations could serve as excellent reference sources for others.
- The objective to continue benchmarking of qualification/certification efforts was also met: many US and non-US government agency and industry programs were reviewed. The extensive workshop participation also increased coverage of machine and raw material challenges, status of AM applications that are under serious consideration or actively on a path toward implementation, and excellent updates on the status of key technical topics. Presentations addressed detailed research and part applications under development and the associated current thinking and status regarding qualification/certification. Activities of consortia groups and their efforts were presented.
- The objective to promote interagency collaboration, and industry/academia/government partnerships was certainly facilitated by the workshop. Workshop attendance and participation were broad and representative, with a very significant increase in participation by industry. Many presentations highlighted active participation in AM development programs by multiple agencies, industrial companies, and universities. This workshop, although not responsible for such existing collaborations, certainly contributed to furthering and encouraging such collaborations and partnerships in the future, including potential FAA participation.
- The Training and Education Panel session was very beneficial: the topic was of high interest, the panelists represented a diverse perspective on needs, approaches, and delivery, and the panel session format provided a break from 3 full days of presentations-only

format. Future workshops should consider and accommodate some variety in day-by-day format.

- ***The 2017 Workshop was regarded as successful, beneficial, and necessary:*** in addition to the objectives of training, benchmarking, and communication, the workshop results will be useful to guide future activities (including FAA roadmap refinement) and will provide a comprehensive reference source for FAA employees, other government agencies, and the public.

In addition, lessons learned from prior workshops led to positive changes in venue and structure to make the 2017 workshop more productive. More time was allocated for breaks to ensure networking opportunities, a much larger capacity facility was used with no restriction on foreign participants' attendance, and effort was made to ensure that seating, including tables for all participants, was available for 3 full days of workshop participation.

The workshop was intended to build on outcomes of the previous workshops, with increased focus on industrial efforts and applications. This was accomplished: there was minimal redundancy and overlap with 2015 and 2016 in terms of technical content. Many presentations quickly reviewed previous information, and then focused on new information or topics. This was again an information-intensive workshop, which required full attention from the participants. Attention and active engagement of the attendees were excellent. Overall, the workshop objectives were fully met. Workshop results will be useful for future planning and actions regarding qualification and certification of AM aerospace parts.

5. RECOMMENDED NEXT STEPS

The workshop was successful in meeting its objectives. The following actions are recommended in the near term to ensure that results of the workshop are effectively utilized:

1. ***The presentations made during the workshop should be collected and archived in an accessible location for use by FAA employees.*** It is recommended that they again be appended to the summary report, if possible, for ease of reference and access. Their value may diminish with time as they become outdated, of course, but in the near term they provide useful educational and reference information.
2. ***The FAA Additive Manufacturing National Team (AMNT) should review results of the workshop for use in refinement of their roadmap and plans.*** Dr. Gorelik presented the status of the current FAA roadmap for Additive Manufacturing. It is clearly well under way, and will benefit from results of the 2017 workshop. Three specific recommendations are made:

    a. Refinement of the near-term action plans to address immediate needs, especially to extend current efforts in the development of checklists and guidance memoranda.
    b. Refinement of the longer term FAA plan consistent with an agency-level roadmap on certification of AM parts, and identification of any gaps.
    c. Increased interaction with other foreign regulatory agencies, such as the European Aviation Safety Agency and Transport Canada, should be considered specifically for AM issues and considerations.

3. ***The best means for future communication and collaboration between the FAA and industry should be addressed:*** An Aerospace Industries Association AM Working Group has been established. This is a great start, and is apparently focused on development of industry's best practices document, and on identification and prioritization of any gaps. The recommendation is for the FAA to consider expanding the WG's role, perhaps through formation of working subteams, to address a range of AM challenges that require specialized expertise. One such area could be development of industry best practices for characterization of inherent anomalies in AM parts.

6. FACILITATOR COMMENTS

The workshop summary was intended to represent the proceedings and results of the workshop in a comprehensive and objective manner. This section offers a brief set of comments from the facilitator, as an experienced observer of qualification and certification processes. In some cases, the comments are related to those presented after the prior workshops, which can be found in the referenced reports, although they have been updated significantly. They represent the opinions of the author.

Workshop Comments: The workshop was very productive and met its objectives. Content was comprehensive and detailed, and participation was outstanding. As with the previous workshops, the successful outcome is attributable to detailed agenda planning and preparation, broad preworkshop coordination within the FAA, and rigorous time management during the workshop. Technical content was excellent and built upon the foundation provided by the prior workshops. The shift to a much larger and more comfortable venue, and adjustment of the agenda to facilitate more networking, were important lessons learned from the prior workshops. These should be carried over into the future. Also, the panel session was a welcome change in format from presentations only, and was very productive. Similar sessions should be integrated into future workshops.

Qualification/Certification of Additively Manufactured Parts—as a workshop topic: It was clear that this remains a timely topic of exceptional interest. Much progress was evident in the now 3 years of these workshops. High-rate production of parts by the laser PBF process is a reality, and implementation of parts made by DED approaches appears imminent. The challenges of qualification and certification of AM parts are understood and being addressed. In the opinion of the facilitator, what was significantly different in the 2017 workshop was the apparent shift from "candidate parts for development" to ***real applications under development***—for qualification and certification. This is a very significant shift; industry activity and pressure to achieve qualification and certification will increase rapidly in the near term.

Risk Assessment of AM Parts: Several presentations in this workshop focused on process-related microstructural variations (differences from conventional cast or wrought processes) and, sometimes, extensive process-related defects. Also, challenges posed by surface finishes, post-processing, and NDE were covered extensively. For fatigue or damage-tolerance-limited applications of AM, it seems obvious that risk of failure will be location-dependent within the part. Two presentations focused on this topic and on quantification of risk as a function of location or zones within a part. In the author’s opinion, there should be near term focus on such risk assessment (or zoning) of AM parts. This could possibly be fairly simplistic in nature or could involve a more complex assessment of the entire part. One applicable tool to do this (DARWIN®) is already operational and in general use. The input distributions for defects and NDE capability are not established and would pose a challenge. However, this represents a focused challenge that would produce a quantitative result, which is useful when application risk warrants its use.

Consideration of Process Interruptions: This comment is repeated from prior facilitator comments: It may prove to be a non-issue, but it seems likely that economic pressures will eventually drive acceptance of parts for which process interruptions have occurred. Process interruption is a known issue for processes that run continuously for extended periods of time (as is the case for AM, for which it may take approximately a week for a single part build). Process interruptions may be due to machine causes, aberrations with the part build, operator-induced stoppages, or other causes. Whatever the cause, consideration of how to disposition such parts will likely be an issue as soon as significant volume manufacturing is initiated. This could go on the “checklists” initially, but may need some specific attention in the future. Several presentations again highlighted variation of microstructure and defects generated within a build, as in early deposit layers versus later ones.

Part Criticality Classification Criteria for AM: Several presentations highlighted the importance of defining “part criticality,” including the NASA Marshall Space Flight Center approach to defining criticality for AM parts. Dr. Gorelik showed a chart with expected AM target parts illustrated. It showed expected evolution of AM applications over time, from low-risk (NSE parts) to “Sub-critical” and “High Value” parts. Yet development costs and qualification/certification requirements for AM may actually drive attention to the “high-value” parts initially. It would seem beneficial to identify a standard means to determine part criticality for AM applications and to tie that criticality to qualification and certification requirements. This may be especially useful to help address part-qualification/-certification applications that will be eventually proposed by non-OEM entities.

7. SUMMARY

The FAA and AFRL jointly sponsored a workshop to address the qualification and certification of AM parts, focused on those using structural metal alloys. There was broad interest and participation. Presentations from governmental agencies, industry, and academia covered the current status and future plans for the technology, challenges, and specific programs, as well as current and planned efforts regarding standards and specifications. Many useful results and conclusions were generated, which have been summarized and organized for future use. It appears from the workshop content that broad implementation of AM parts is well under way and that qualification and certification of these parts is, and will continue to be, a critically important topic.

Results and presentations from the workshop will be made available for future reference and used to guide FAA plans and roadmaps in the near future. These plans will address training and education, guidance and policy, and appropriate tools or references needed to meet the qualification and certification challenges posed by this exciting technology.

APPENDIX A—WORKSHOP AGENDA

The 3rd Joint FAA – Air Force Workshop on Qualification / Certification of Metal Additively Manufactured (AM) Parts

Co-organized by Dr. M. Gorelik (FAA / Chief Scientist) and Dr. R. Dutton (AFRL / Senior Advisor)

August 29 - 31, 2017

Venue: University of Dayton River Campus
1700 S. Patterson Blvd., Dayton, OH 45409
MEYER ROOM – N1650

Workshop facilitator: Mr. Brad Cowles, *Cowles Consulting, LLC*

Dress code: business casual

Note to all presenters: please allow a few minutes for Q&A *within the allocated time window*

Day 1 – Tuesday, August 29

7:45 – 8:15 Registration
8:15 – 8:30 Introductions
8:30 – 8:45 Workshop Overview and Objectives (*Michael Gorelik, FAA and Rollie Dutton, AFRL*)
8:45 – 9:00 Summary of the 2016 Workshop (*Brad Cowles*)
9:00 – 9:30 Boeing Titanium Wire Feed Deposition Process Development & FAA Certification (*Matthew Crill, Boeing*)
9:30 – 10:15 **Keynote Presentation** – *Mohammad Ehteshami, Vice President of GE Additive*
10:15 – 10:45 Break / networking
10:45 – 11:15 AFRL Progress in Qualification and Certification of AM Parts (*Jonathan Miller, AFRL*)
11:15 – 11:45 Airbus View on How Requirements Could be Tailored to AM Applications (*John van Doeselaar, Airbus*)
11:45 – 12:15 Test and Material Allowable Development Considerations for Additive Manufacturing (*Paul Jonas, NIAR*)
12:15 – 13:15 Lunch (catered on site – reservation required) w/poster session (UDRI)
13:15 – 15:15 **AM Training and Education Panel** - *presentations*
Panel members:

- America Makes (*Rob Gorham*)
- Boeing (*Paul Dufour*)
- GE Aviation (*Luana Iorio*)
- Penn State University (*Richard Martukanitz*)
- Society of Manufacturing Engineers (*Kris Ward*)
- Underwriters Laboratories (*Paul Bates*)

15:15 – 15:30 Break

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15:30 – 16:00 **AM Training and Education Panel** – *roundtable* (*Moderator: Dave Swartz / FAA*)

16:00 – 16:30 NAVAIR AM Update (*William Frazier, NAVAIR*)

Optional Events (end of Day 1, Aug. 29)

16:30 – 17:00 Networking

17:15 – … No-host social - ***Warped Wing Brewery*** (26 Wyandot St, Dayton, OH / www.warpedwing.com)

Day 2 – Wednesday, August 30

8:00 – 8:30 Arrival and Networking

8:30 – 9:00 Qualification of an AM Component for Flight (*Mark Shaw, GE Additive*)

9:00 – 9:30 AM Informatics and Component / Material Pedigree (*Amra Peles, P&W*)

9:30 – 10:00 MMPDS Progress on Developing Equivalence Criteria and Spec Minimal Values for AM (*Doug Hall, Battelle*)

10:00 – 10:30 Break / networking

10:30 – 11:00 Perspectives in Additive Layer Manufacturing at Rolls-Royce (*Amit Chatterjee, Rolls-Royce*)

11:00 – 11:30 Qualification and Certification of Additive Manufactured Critical Parts for UK Military Aviation (*Rebecca Mangham, DSTL / UK MoD*)

11:30 – 12:00 On-line Process Control to Assess the As-built Component Quality (*Andreas Fischersworring-Bunk, MTU*)

12:00 – 12:45 Lunch (catered on site – reservation required)

12:45 – 13:15 In-situ Monitoring for Additive Manufacturing: Implications for the Digital Manufacturing Age (*Mark Cola, Sigma Labs Inc.*)

13:15 – 13:45 Measurement and Modeling of Residual Stress in Structural Components (*Michael R. Hill, Hill Engineering LLC*)

13:45 – 14:15 A Case Study on the Incorporation of Bulk Residual Stress In Aircraft Component Design (*Dale Ball, Lockheed Martin*)

14:15 – 14:45 AMSC*⁾ Roadmap Overview (*Rob Gorham, America Makes*)

**⁾ AMSC = Additive Manufacturing Standards Collaborative (working group)*

14:45 – 15:00 Break

15:00 – 15:30 Recent Progress on Standardization of Additive Manufacturing Technologies (*Mohsen Seifi, ASTM*)

15:30 – 16:00 SAE's AMS-AM Committee on Standards Development for AM – Progress Report *(Dave Abbott, GE Additive)*

16:00 – 16:30 Proposed Collaboration Approach to Process and Materials Characterization Efforts (*Brian Hann, Honeywell Aerospace*)

16:30 – 17:00 AM Research at the Fraunhofer and RWTH Aachen University (*Robin Day, Fraunhofer ILT*)

Day 3 – Thursday, August 31

7:45 – 8:15 Arrival and Networking

8:15 – 8:45 Overview of NRC Additive Manufacturing Activities and Technology Development (*Rob Amos, NRC Canada*)

8:45 – 9:15 Modified title – Powder Feedstock as a Process Variable for SLM 718 Hardware (*Chantal Sudbrack, NASA GRC*)

9:15 – 9:45 Laser Powder Bed Fusion Process Control for Flight Critical Parts (*Paul Guerrier, Moog*)

9:45 – 10:15 Additive Manufacturing Qualification for Liquid Rocket Engine Applications (*Nicholas Mulé, Aerojet Rocketdyne*)

10:15 – 10:45 Break

10:45 – 11:15 An Overview of the Additive Manufacturing Consortium (AMC) Projects and Collaborations (*Frank Medina, EWI*)

11:15 – 11:45 OEM Perspectives on AM Qualification and Certification (*Marilyn Gaska, Lockheed Martin*)

11:45 – 12:30 Lunch (catered on site – reservation required) and networking

12:30 – 13:00 Additive Manufacturing in the Airline & MRO World – Potential, Challenges and Path Forward – One Airline's Experience (*Ramesh Ramakrishnan, Delta Tech Ops*)

13:00 – 13:30 The Impact of Critical Defects on Material Performance and Qualification for Metal Laser Powder Bed Fusion (*Bradley Jared, Sandia NL*)

13:30 – 14:00 Opportunities for AM in the Aftermarket Supply Chain – an Independent Perspective (*Brian Neff, Sintavia LLC*)

14:00 – 14:30 The Use of Additive Manufacturing from a PMA's Perspective (*Jeffery Paust, HEICO Aerospace)*

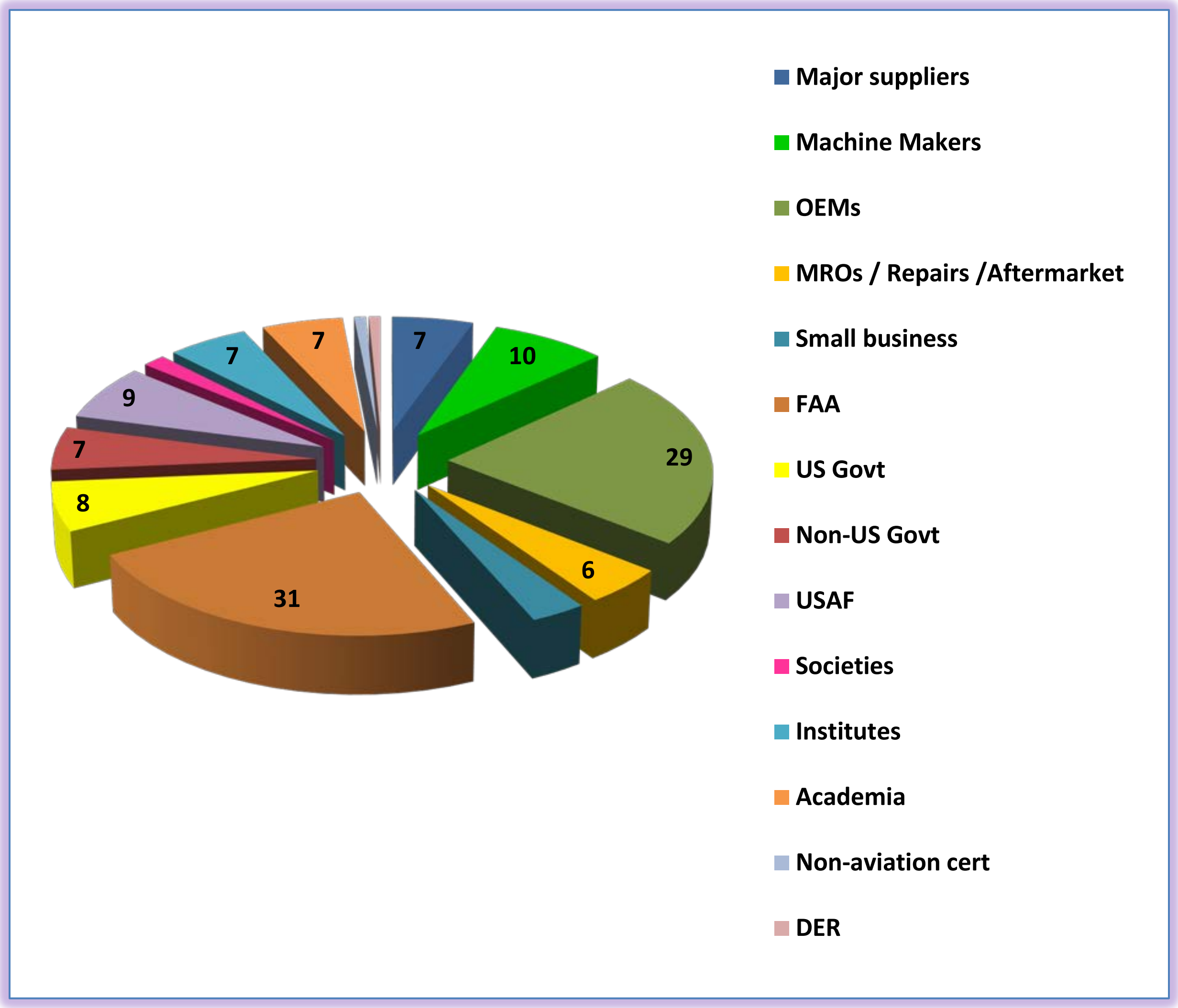
14:30 – 14:45 Break

14:45 – 15:15 FAA AM Roadmap Overview (*Michael Gorelik, FAA*)

15:15 – 15:30 Workshop summary and closeout (*Brad Cowles / All*)

15:30 -- *Adjourn*

APPENDIX B—WORKSHOP DEMOGRAPHICS



APPENDIX C—TABLE OF PRESENTATIONS

From the Presentation Sessions:

1. M. Gorelik, FAA, “Welcome to the 3rd Joint FAA—Air Force AM Workshop—Opening Remarks.” Appendix D.
2. B. Cowles, Cowles Consulting, LLC, “Summary of the 2016 Workshop.” Appendix E.
3. M. Crill, Boeing Commercial Airplanes, “Ti-6Al-4V Wire Feed Additive Manufacturing.” Appendix F.
4. M. Ehteshami, VP & GM, GE Additive, **Keynote Presentation**, “Additive Manufacturing at GE.” Appendix G.
5. J. Miller, AFRL, “AFRL Progress in Qualification and Certification of AM Parts.” Appendix H.
6. J. van Doeselaar, Airbus, “Airbus View on How Requirements Could Be Tailored to AM Applications.” Appendix I.
7. P. Jonas, National Institute for Aviation Research, Wichita State University, “Test and Material Allowable Development Considerations for Additive Manufacturing.” Appendix J.
8. W. Frazier and L. McMichael, NAVAIR, “NAVAIR AM Overview.” Appendix K.
9. M. Shaw, GE Additive, “Qualification of an AM Component for Flight.” (This presentation was considered proprietary and is not appended to the report).
10. A. Peles, P&W, “AM Informatics and Component/Material Pedigree.” Appendix M.
11. D. Hall, Battelle, “MMPDS Progress on Developing Equivalence Criteria and Spec Minimal Values for AM.” Appendix N.
12. A. Chaterjee, Rolls-Royce, “Perspectives in Additive Layer Manufacturing at Rolls-Royce.” Appendix O.
13. R. Mangham, DSTL / UK MoD, “Qualification and Certification of Additive Manufactured Critical Parts for UK Military Aviation.” Appendix P.
14. A. Fischersworring-Bunk, MTU, “On-line Process Control to Assess the As-built Component Quality.” Appendix Q.
15. M. Cola, Sigma Labs, Inc., “In-situ Monitoring for Additive Manufacturing: Implications for the Digital Manufacturing Age.” Appendix R.
16. M. Hill, Hill Engineering LLC, “Measurement and Modeling of Residual Stress in Structural Components.” Appendix S.
17. D. Ball, Lockheed Martin, “A Case Study on the Incorporation of Bulk Residual Stress in Aircraft Component Design.” Appendix T.
18. R. Gorham, America Makes, “AMSC Roadmap Overview.” Appendix U.
19. M. Seifi, ASTM, “Recent Progress on Standardization of Additive Manufacturing Technologies.” Appendix V.
20. D. Abbott, GE Additive, “SAE’s AMS-AM Committee on Standards Development for AM – Progress Report.” Appendix W.
21. B. Hann, Honeywell, “Proposed Collaboration Approach to Process and Materials Characterization Efforts.” Appendix X.
22. R. Day, Fraunhofer ILT, “AM Research at the Fraunhofer and RWTH Aachen University.” Appendix Y.
23. R. Amos, NRC Canada, “Overview of NRC Additive Manufacturing Activities and Technology Development.” Appendix Z.

24. C. Sudbrack, NASA GRC, “Powder Feedstock as a Process Variable for SLM 718 Hardware.” Appendix AA.
25. P. Guerierr, Moog, “Laser Powder Bed Fusion Process Control for Flight Critical Parts.” Appendix BB.
26. N. Mule’, Aerojet Rocketdyne. “Additive Manufacturing Qualification for Liquid Rocket Engine Applications.” Appendix CC.
27. F. Medina, EWI, “An Overview of the Additive Manufacturing Consortium (AMC) Projects and Collaborations.” Appendix DD.
28. M. Gaska and W. Fallon, Lockheed-Martin and Sikorsky, “OEM Perspectives on AM Qualification and Certification.” Appendix EE.
29. R. Ramakrishnan, Delta Technical Operations, “Additive Manufacturing in the Airline & MRO World – Potential, Challenges and Path Forward – One Airline’s Experience.” Appendix FF**.**
30. B. Jared, Sandia, “The Impact of Critical Defects on Material Performance and Qualification for Metal Laser Powder Bed Fusion.” Appendix GG.
31. B. Neff, Sintavia LLC, “Opportunities for AM in the Aftermarket Supply Chain—an Independent Perspective.” This presentation was considered proprietary and is not appended to the report.
32. J. Paust, HEICO Aerospace, “The Use of Additive Manufacturing from a PMA’s Perspective.” Appendix II.
33. M. Gorelik, FAA, “FAA AM Roadmap Overview.” Appendix JJ**.**

Note: Presentations above numbered 9 and 31 either had limited distribution notices or were not made available for inclusion in this report.

From the Training and Education Panel Session:

TE-1**.** R. Gorham, America Makes. Appendix KK.
TE-2**.** P. Dufour, Boeing. Appendix LL.
TE-3**.** L. Iorio, GE Aviation. Appendix MM.
TE-4**.** R. Martukanitz, Penn State University. Appendix NN.
TE-5**.** K. Ward, Society of Manufacturing Engineers. Appendix OO.
TE-6**.** P. Bates, Underwriters Laboratories. Appendix PP.

APPENDIX D—WELCOME TO THE 3RD JOINT FAA—AIR FORCE AM WORKSHOP—OPENING REMARKS

Welcome to the 3rd Joint FAA – AFRL AM Workshop

Opening Remarks

August 29-31, 2017

Dayton, OH

Presented by:

Michael Gorelik

Disclaimer

- **While this workshop is an FAA-sponsored event, the specific content of the presentation materials has not been vetted or approved by the FAA.**
- **Technical presentations in this workshop are being offered to the participants in the spirit of government – industry – academia *technical interchange*, and as such, the specific messages in individual presentations are not endorsed by the FAA.**

Workshop Evolution (*2015 → 2017*)

2015 Workshop

- First in the series (*for FAA*)
- Focus on overview of AM technologies and identification of potential certification concerns and considerations
- First exposure to AM for many FAA attendees
- Main focus on getting perspective from the government agencies and major OEMs

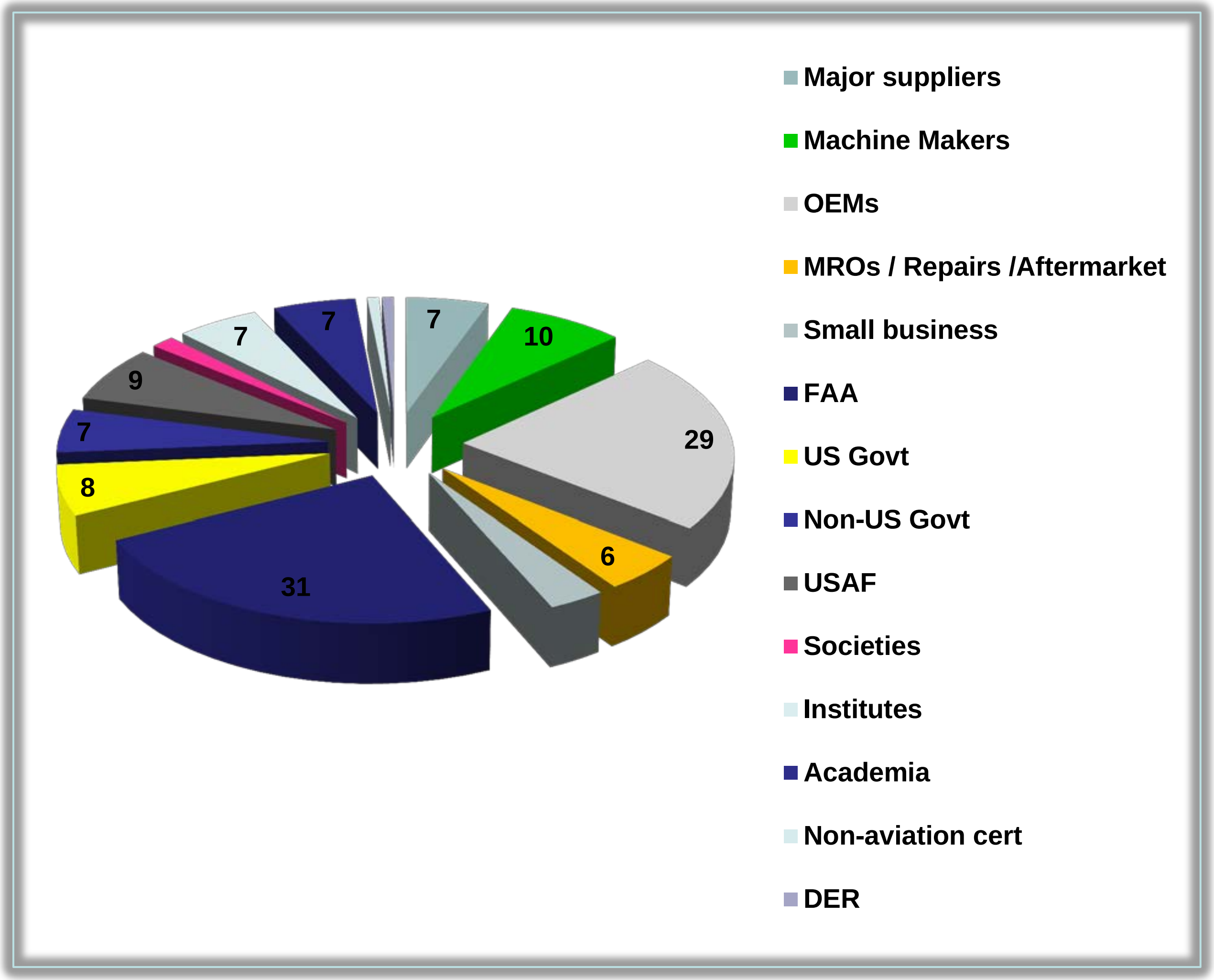
2016 Workshop

- More in-depth discussions on specific qualification approaches reflect industry progress (some presentations are benchmarked by industry working groups)
- Expanded coverage to include supply chain perspective (Tier 1, raw materials, …)
- Continued education of FAA workforce
- Significant coverage of government AM activities

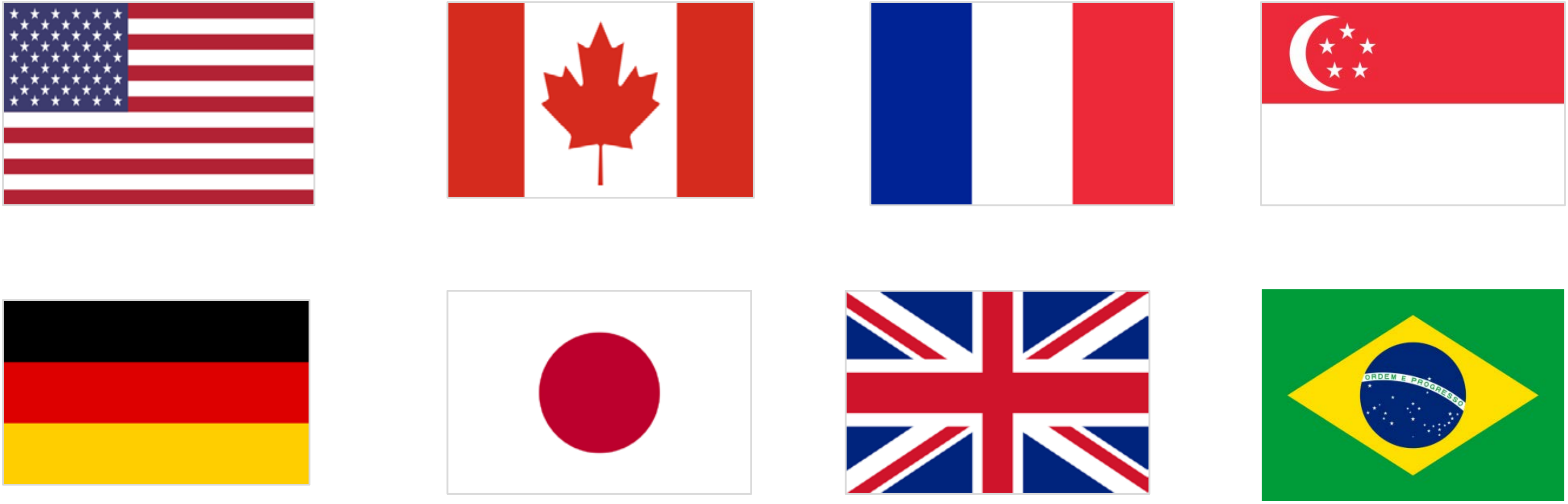
2017 Workshop

- First "global" workshop – open to foreign participants, including several NAAs
- Twice bigger than the prior workshops – significantly expanded industry "demographics"
- Focused Training & Education panel
- Continued Q&C topics coverage, including process monitoring, part family and feature-based qualification etc.
- Progress on AM standardization

2017 Workshop “Demographics”



Global Participation in 2017



US Government

FEDERAL AVIATION ADMINISTRATION

U.S. AIR FORCE

NASA

NAVAL AIR SYSTEMS COMMAND

Sandia National Laboratories

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Foreign Governments

Transport Canada

JCAB
Japan Civil Aviation Bureau

[dstl]®

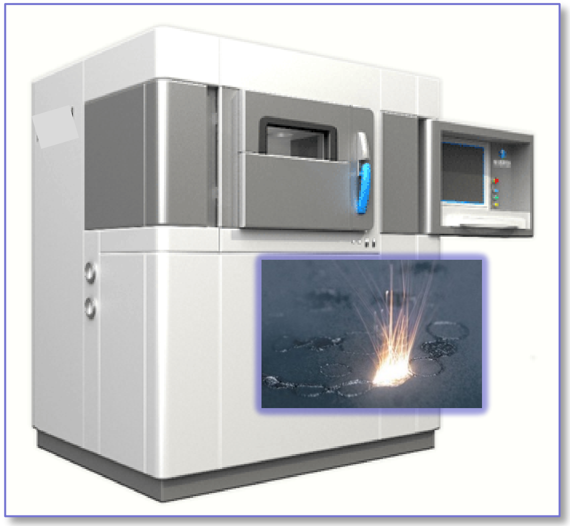
NRC·CNRC

CAAS
Civil Aviation Authority of Singapore

Additive Manufacturing – New Paradigm:

Manufacturing Capabilities Ahead of Design Vision..?

> **"Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…"**
>
> *Mr. David Joyce, GE Aviation President and CEO*



Regulatory Considerations for AM

- **New Material and Process Space**
  - *Common consideration for new material or manufacturing technology*

- **New Design Space**
  - *Unique to Additive Manufacturing..?*

Agenda at a Glance

- **Keynote – VP and GM, GE Additive**
- **Over 30 presentations from industry, government and academia**
- **Panel on AM Training and Education**
- **Professional Networking**

U.S. AIR FORCE

The Third Joint FAA – Air Force Workshop
on Qualification / Certification of Additively Manufactured (AM) Parts

Co-organized by Dr. M. Gorelik (FAA / Chief Scientist) and Dr. R. Dutton (AFRL / Senior Advisor)

August 29 - 31, 2017

***Venue**: University of Dayton River Campus*
1700 S. Patterson Blvd., Dayton, OH 45409
MEYER ROOM – N1650

UNIVERSITY of DAYTON

Workshop facilitator: Mr. Brad Cowles, *Cowles Consulting, LLC*

Thank you for your continuing support. Enjoy the Workshop !

APPENDIX E—SUMMARY OF THE 2016 WORKSHOP

Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured Parts - 2017

Summary of the 2016 Workshop

29 August 2017

University of Dayton, Dayton, OH

Brad Cowles
Workshop Facilitator

Cowles Consulting, LLC
Aerospace Materials and Structures

Joint FAA-Air Force Workshop on AM Parts - 2017

Specific objectives for last year's (2016) workshop …

Objectives:

- ***Continue** educating FAA workforce in the area of AM technology*
- *Benchmark **evolving** qualification / certification considerations and requirements across the regulatory agencies*
- *Promote inter-agency collaboration and industry / academia / government **partnership***
- *Continue dialogue between the AMNT and regional offices (ACOs, MIDOs, FSDOs)*

***Intent:** build upon outcomes of the 2015 AM Workshop, and focus on "enablers" for qualification and certification of metal AM…*

***AMNT**: Additive Manufacturing National Team; **ACO**: Aircraft Certification Offices;
MIDO: Manufacturing and Inspection District Offices; **FSDO**: Flight Standards District Offices

Joint FAA-Air Force Workshop on AM Parts - 2017

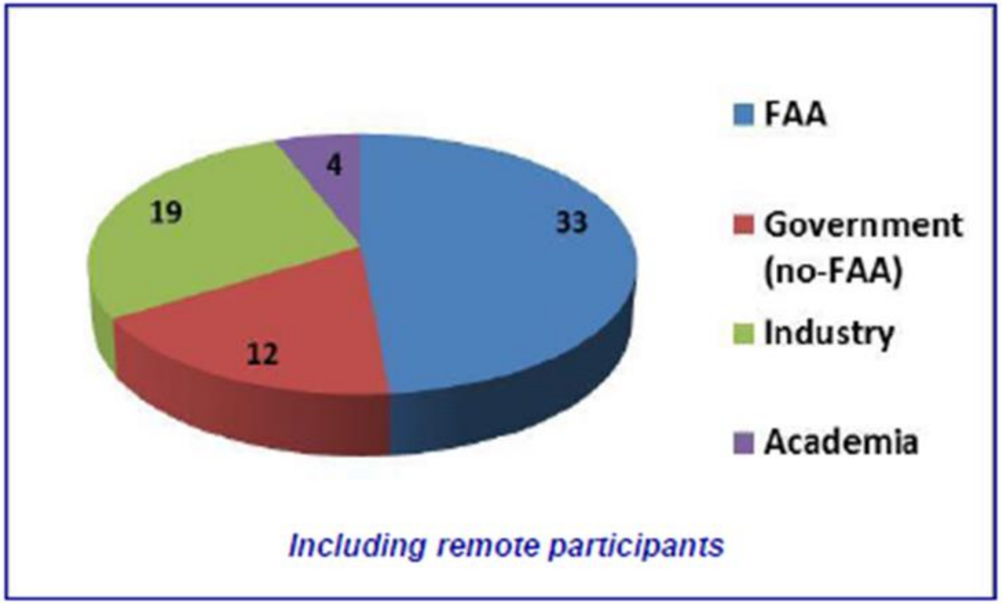
Ambitious agenda in 2016…

Three full days – at TecEdge – with 68 registered participants:

- *Thirty-three (33) presentations – from academia, government, industry: AM education, agency perspectives, industry status*
- *Government agency program summaries – AFRL, AFMC, NavAir, NASA, NIST, FDA*
- *Increased industry participation – OEMs, Suppliers*
- *Academia and technology companies*
- *Status of standards and specifications*
- *Update by the FAA Additive Manufacturing National Team (AMNT)*

Joint FAA-Air Force Workshop on AM Parts - 2016

2016 Workshop: diverse attendance – 68 participants…*



Including remote participants

14 FAA Sites Represented at the Workshop:

- **HQ**
- **Four Directorates:**
  - Transport Airplane
  - Engine and Propeller
  - Small Airplane
  - Rotorcraft
- **Tech Center**
- **LAACO**
- **Chicago ACO**
- **Denver ACO**
- **Atlanta ACO**
- **Wichita ACO**
- **Scottsdale FSDO / MIDO**
- **Vandalia MIDO**
- **Memphis FSDO**

ACO – *Aircraft Certification Office*
FSDO – *Flight Standards District Office*
MIDO – *Manufacturing Inspection District Office*

**Notes: Plus additional attendees via web connections. About 75% overlap with 2015 FAA attendance - promotes continuous learning process.*

Joint FAA-Air Force Workshop on AM Parts - 2016

2016 Workshop Report…

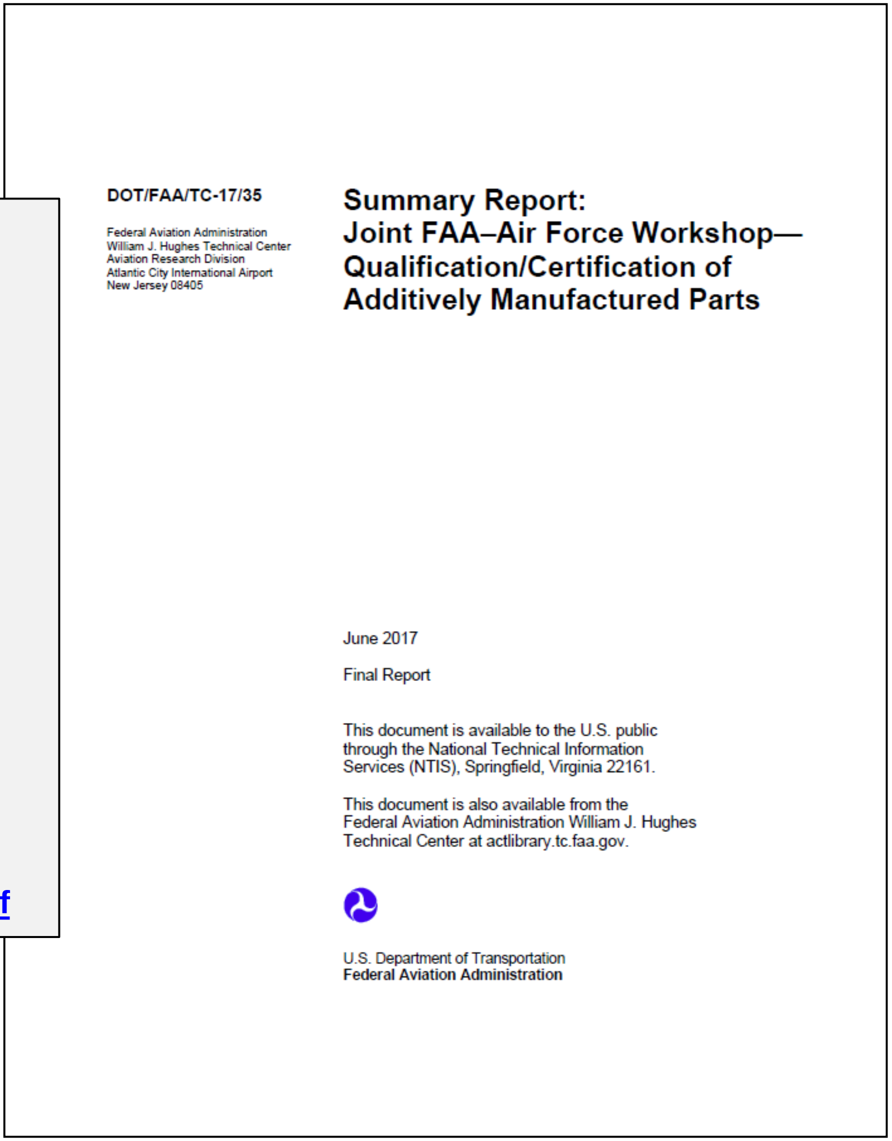
Comprehensive Proceedings - recorded in:

DOT/FAA/TC-17/35:

- 22 page summary
- 30 presentations, attached as appendices

Available through DTIC or from the FAA Tech Center:

http://www.tc.faa.gov/its/worldpac/techrpt/tc17-35.pdf



DOT/FAA/TC-17/35

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Summary Report:
Joint FAA–Air Force Workshop—Qualification/Certification of Additively Manufactured Parts

June 2017

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation
Federal Aviation Administration

FAA-AFRL Workshop on AM Manufactured Parts

2016 Workshop Summary Comments and Observations:

General Comments:

- *Enthusiastic , diverse participation illustrates sustained high interest in AM and associated qualification/certification challenges*
- *Presentations by Airbus and EASA indicate maturity and challenges of AM are consistent and universal between the US and European industry*
- *A variety of prototype and low-count hardware - with various criticality classifications - is flying or imminent*
- ***High rate production of parts has been initiated*** *(e.g. GE fuel nozzles)*

Four (at least) general considerations were highlighted:

- *AM is a "tool, not a solution for everything": Industry consensus is to proceed on a "thoughtful and deliberate" basis.*
- *There is potential for high degree of manufacturing variation – due to process, machines, suppliers, input stock.*
- ***Qualification and certification must address the manufacturing process, the specific part, and the potential system impact***
- *Potential methods and approaches for zoning parts should be considered – to address defects, variation and risk*

FAA-AFRL Workshop on AM Manufactured Parts

2016 Workshop Summary Comments and Observations:

Other General Observations:

- *There is considerable and sustained supporting effort to mature AM processes in agencies: AFRL, AFMC, NASA, NavAir, DARPA…*
    - *These efforts span method development (early TRL/MRL) through specific part qualification, and include support activities like modeling, microstructure characterization, process monitoring, and NDE development*
- *Significant, sustained university efforts are in progress:*
    - *Development of processes and models, microstructure and property predictions, and experimental assessments*
    - *University efforts ensure a trained professional work force for future AM*
- *Efforts to develop AM standards, specifications, and guidelines are being integrated and focused:*
    - *NIST and standards organizations are addressing general standards and specifications for AM*
    - *America Makes and ANSI are identifying and addressing "gaps" in AM standards and specifications*
    - *An initial FAA checklist for a MIDO "Job Aid" and an FAA AM Engineering Memorandum have been issued or are imminent (as of the time of 2016 Workshop)*

FAA-AFRL Workshop on AM Manufactured Parts

2016 Workshop - Specific Comments and Observations:

- ***Potential for high variation in AM processes requires rigorous attention:***
  - *Machine and supplier qualification*
  - *Frozen processes with feedback and monitoring mechanisms established and validated*
  - *Software and hardware version control and protection*
  - *Personnel development and training*

- ***Significant quality and manufacturing issues for AM processes must be rigorously addressed for qualification and certification***
  - *Process variation, controls, and in-process monitoring*
  - *Characterization and control of process-related defects and anomalies*
  - *Post-deposit processing such as stress-relief, HIP, and heat treatment*
  - *Surface finish and post-deposit finishing processes*
  - *Quality and control of input powder metal*
  - *NDE requirements and capability*
  - *AM-specific considerations for development of material design allowables*

Joint FAA-Air Force Workshop on AM Parts - 2017

Summary for the 2016 Workshop…

The 2016 workshop was intense, but successful:

- *Four key FAA objectives were met: education, benchmarking, collaboration and partnership, continued AMNT integration*
- *Participation and content were excellent: outstanding and focused presentations from all*
- *Outcome was useful for future planning, education, and reference*
- *Documentation is complete and accessible*

Lessons Learned: - Secure more spacious venue; and
- Allow more time for participant interaction

Challenge for the 2017 workshop:
Make it even more productive than 2015 and 2016!

FAA-AFRL Workshop on AM Manufactured Parts

Closing comments: Planned "Rules of Engagement" for a productive workshop…

1. We will follow the agenda, with any directed or consensus changes.

2. Please let presenters finish prior to questions.

3. Agenda is full: *time management is critical*. Time will be monitored and speakers alerted.

We recognize the time, effort, and expense that goes into supporting a workshop like this. Please help us ensure that it is productive…

Joint FAA-Air Force Workshop on AM Parts

Discussion?

Contact Information:

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Cowles Consulting, LLC.
Brad.Cowles@gmail.com
860-872-9347 Home, 860-833-4428 Cell

Joint FAA-Air Force Workshop on AM Parts - 2016

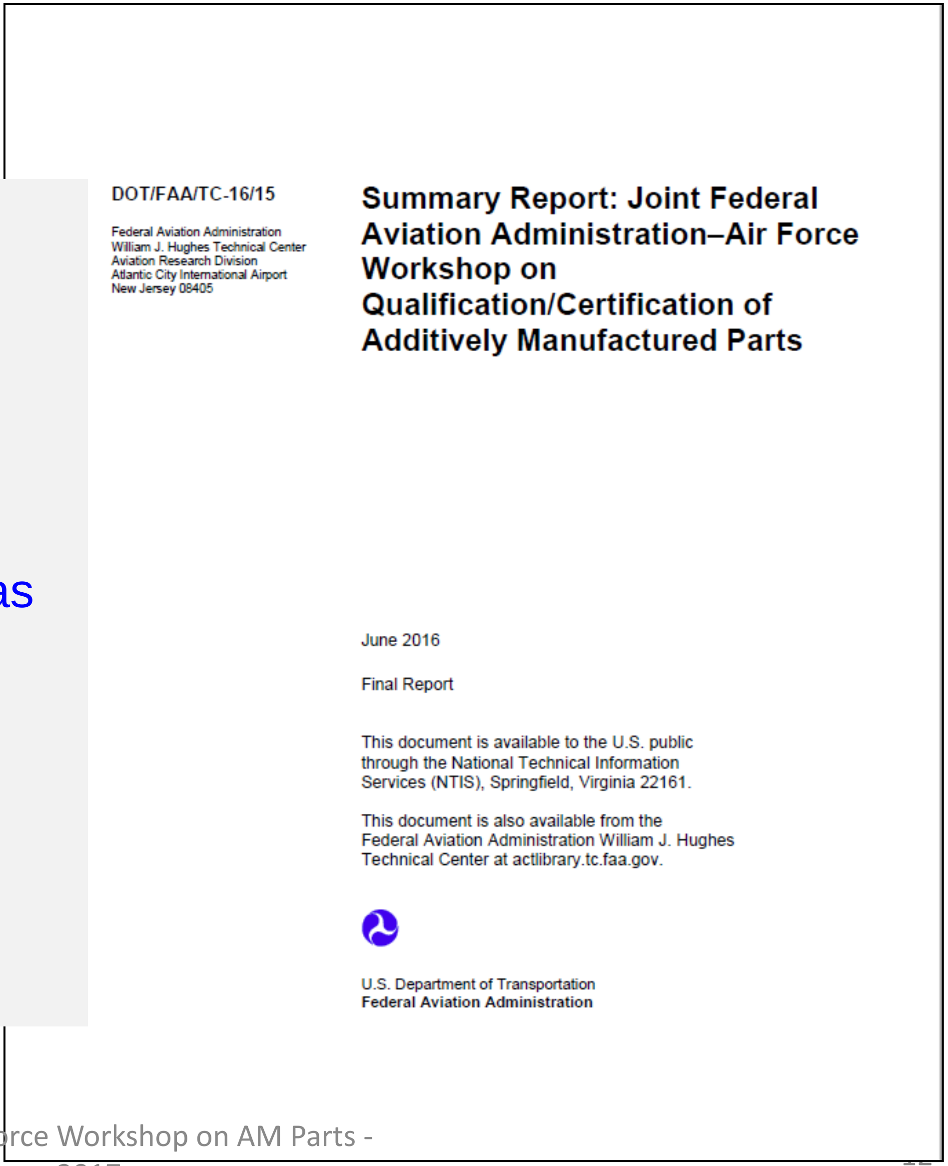
2015 Workshop Report…

Comprehensive Proceedings - recorded in DOT/FAA/TC-16/15:

- 17 page summary
- 6 workshop appendices
- 16 presentations, attached as appendices

Available through DTIC or from the FAA Tech Center:

http://www.tc.faa.gov/its/worldpac/techrpt/tc16-15.pdf



DOT/FAA/TC-16/15

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Summary Report: Joint Federal Aviation Administration–Air Force Workshop on Qualification/Certification of Additively Manufactured Parts

June 2016

Final Report

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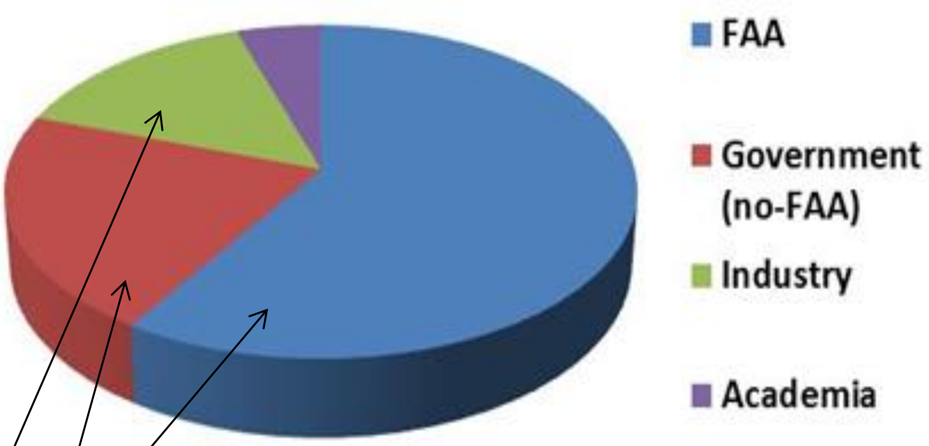
U.S. Department of Transportation
Federal Aviation Administration

Joint FAA-Air Force Workshop on AM Parts - 2016

2015 Workshop: diverse attendance – 61 participants…



FAA: 36

Air Force: 6

NASA: 3

NavAir: 1

NIST: 1

DARPA: 1

Academia: 3 CMU, MSU

Industry: 9

Boeing, L-M, P&W, GE,
Honeywell, Bell, GKN

FAA CSTA Workshop Attendees (Sept 1-3, 2015)

	Location	Site Attendees	AMNT	Total
1	Burlington	4	2	6
2	Chicago	3		3
3	Atlanta	2		2
4	DC	3	2	5
5	San Antonio	1		1
6	Wichita	1		1
7	Kansas		1	1
8	Renton	3	1	4
9	Phoenix		1	1
10	Los Angeles	3		3
11	Hartford, CT	2		2
12	Ft Worth		1	1
13	New York	1		1
14	Atlantic City	1	1	2
15	Vandalia	2		2
16	Denver	1		1
		27	**9**	**36**

APPENDIX F—TI-6AL-4V WIRE FEED ADDITIVE MANUFACTURING

Commercial Airplanes

Ti-6Al-4V Wire Feed Additive Manufacturing

Implementation of 787-9 Section 47 Passenger Floor Galley Support Fittings

Aug 29th, 2017

Contact Focals:
Matthew Crill
BCA PD Materials
matthew.j.crill@boeing.com

Agenda

- **Boeing metallic additive manufacturing examples**
- **Wire feed technology - introduction**
- **Certification approach**
  - 787-9 floor galley diagonal fitting productions application
  - Means of compliance to FAA certification

Metallic Additive Manufacturing
Boeing Application Examples

2001

X-37A

- First Flying Laser Additive Manufacturing Part (LAM)

2003

F15 Pylon Rib

- Additively Manufactured Ti replacement (LAM)
- Implemented on 8 Aircraft

2004

C17 Pylon Panels

- Additively Manufactured Ti replacement (LAM)
- 41 Articles Installed

2011

- Juno Satellite Components
- ARCAM - supplied to L-M under MAI
- Launched August 5th, 2011

2016

702 MP Satellite

- Receive Antenna Deployment Actuator (RADA) Cage

June 2017

4 parts per shipset at 787 production rates

787-9 Passenger Floor Galley Diagonal Fittings

- First Flying Ti Wire Feed Additive Manufacturing Part

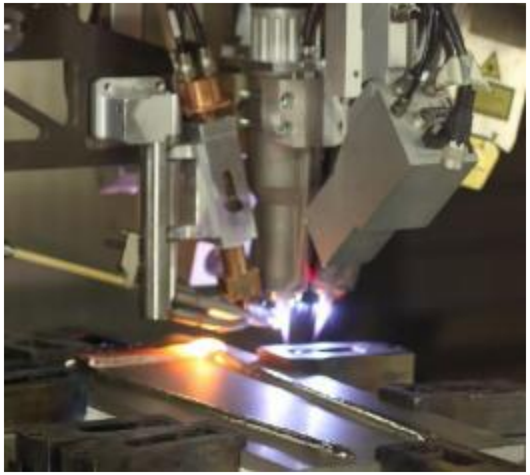
Agenda

- **Boeing metallic additive manufacturing examples**
- **Wire feed technology - introduction**
- **Certification approach**
  - Production application
  - Means of compliance to FAA certification

Titanium Wire Feed Deposition

Process Overview

- **Technology focus on reducing Ti part buy-to-fly ratios to reduce raw material and machining costs**
  - Depositing near-net shape preforms which are finish machined to produce similar end-item Ti parts as conventionally machined from plate, bar, forgings, etc.
  - Variety of energy sources and supplier options available



Part deposition in MERKE IV^{TM} RPD^{TM} Machine

Picture courtesy of Norsk Titanium

- **Initial Boeing qualification focused on Norsk Titanium RPD™ (Rapid Plasma Deposition) process**
  - Parts produced to BMS 7-361 specification

Electron Beam Additive Manufacturing (EBAM^{TM}) Machine

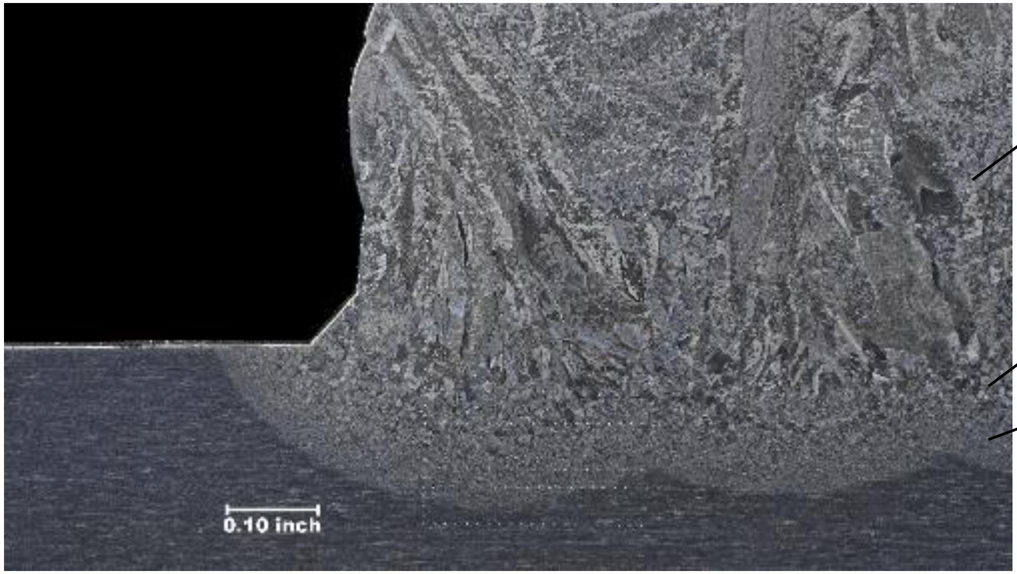
Picture courtesy of Sciaky

MERKE IV^{TM} RPD^{TM} Machine

Picture courtesy of Norsk Titanium

Design Overview: Initial Part Implementation
Titanium Wire Feed Deposition Process

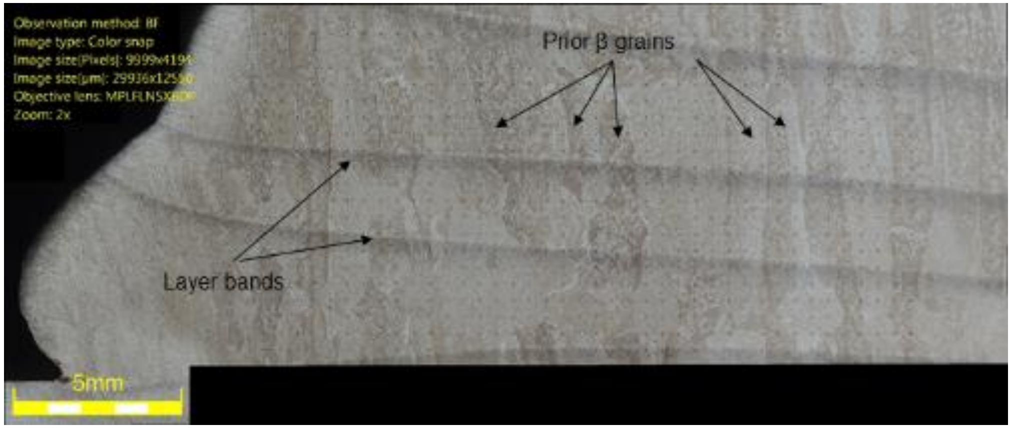
Common macrostructural and microstructural features within deposits

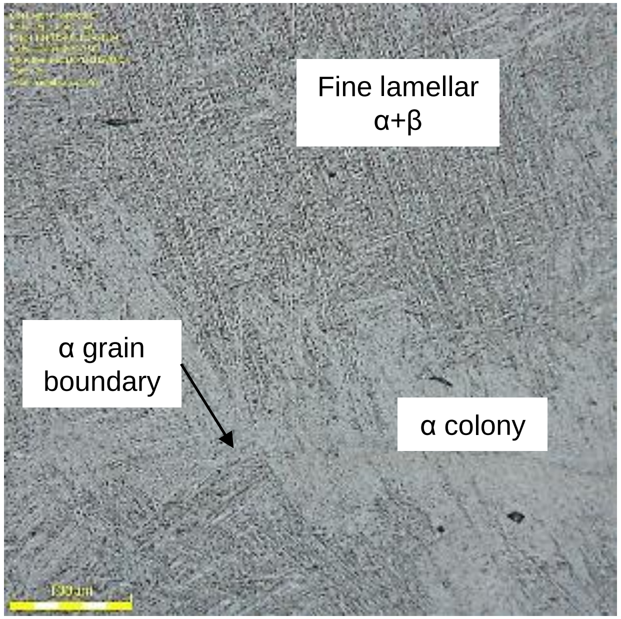


Columnar prior β grains

Equiaxed grains - transformed

Heat Affected Zone (HAZ)



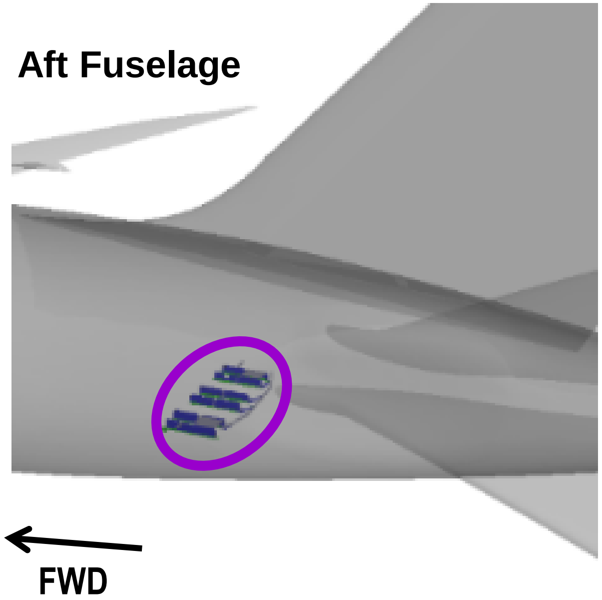


Agenda

- Boeing metallic additive manufacturing examples
- Wire feed technology introduction
- **Certification approach**
  - Production application
  - Means of compliance to FAA Certification

Design Overview: Initial Part Implementation

787-9 Passenger Floor Galley Diagonal Fittings



Agenda

- **Boeing metallic additive manufacturing examples**
- **Wire feed technology introduction**
- **Certification approach**
  - Production application
  - Means of compliance to FAA certification

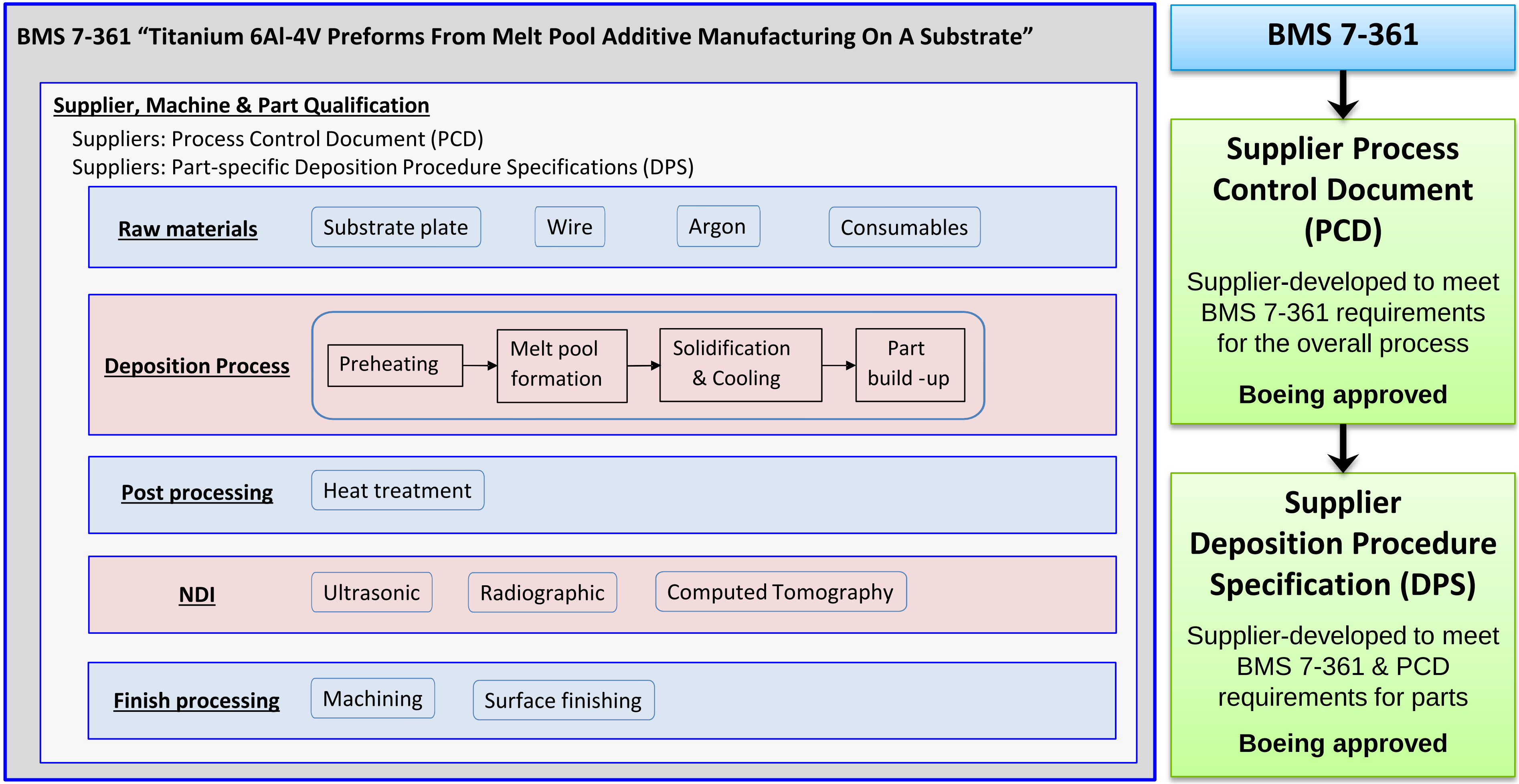
FAA Compliance Approach

787-9 Passenger Floor Galley Diagonal Fittings

- **Compliance to regulatory requirements achieved through Boeing standard approach to specifications & design value testing**
- **Compliance requirements**
  - §25.603, Materials
  - §25.605, Fabrication Methods
  - §25.613, Material Strength Properties & Design Values
  - §25.619, Special Factors

Titanium Wire Feed Deposition

Material & Process Specification Controls



BMS 7-361 "Titanium 6Al-4V Preforms From Melt Pool Additive Manufacturing On A Substrate"

Supplier, Machine & Part Qualification

Suppliers: Process Control Document (PCD)
Suppliers: Part-specific Deposition Procedure Specifications (DPS)

Raw materials: Substrate plate | Wire | Argon | Consumables

Deposition Process: Preheating → Melt pool formation → Solidification & Cooling → Part build -up

Post processing: Heat treatment

NDI: Ultrasonic | Radiographic | Computed Tomography

Finish processing: Machining | Surface finishing

BMS 7-361

↓

Supplier Process Control Document (PCD)

Supplier-developed to meet BMS 7-361 requirements for the overall process

Boeing approved

↓

Supplier Deposition Procedure Specification (DPS)

Supplier-developed to meet BMS 7-361 & PCD requirements for parts

Boeing approved

Compliance Approach – §25.603 Materials

§25.603 Materials.

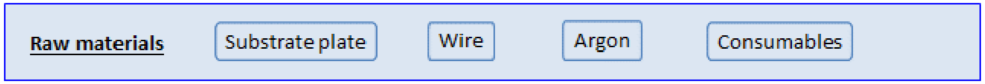
The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must—

- (a) Be established on the basis of experience or tests;
- (b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
- (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

Means of Compliance

§25.603 Materials

- **Material control approaches**
  - Boeing specification addresses key raw material requirements
    - Industry specification baselines utilized with additional cleanliness or chemistry requirements where needed
    - Includes deposition chamber atmosphere requirements
  - Standard quality practices in place to ensure compliance of raw materials being used in additive manufacturing deposition



BMS 7-361 Specification Appropriately Controls the Materials

Compliance Approach –
§25.605 Fabrication Methods

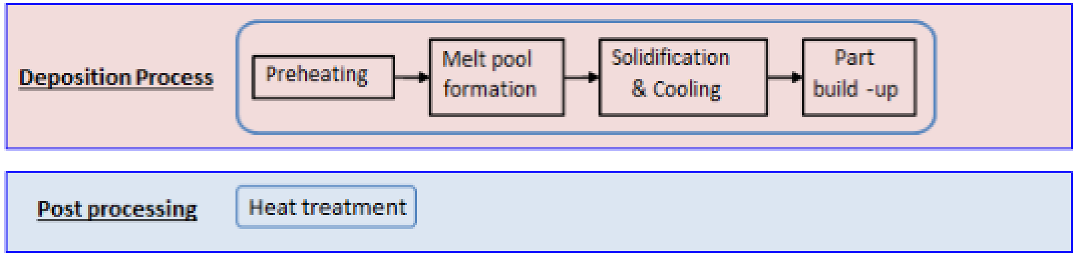
§25.605 Fabrication methods.

(a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.

(b) Each new aircraft fabrication method must be substantiated by a test program.

Means of Compliance
§25.605 Fabrication Methods

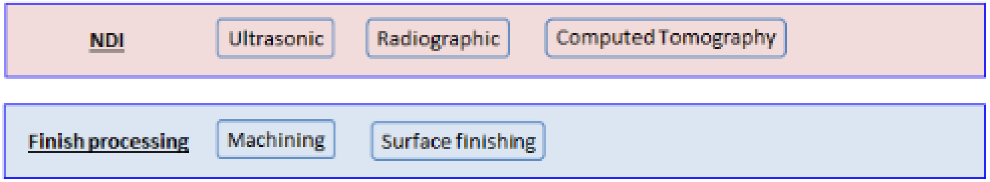
- **Fabrication methods control**
  - Deposition Process
    - Process Control Document (PCD) defines overall deposition elements including critical process parameters, ranges & tolerances which require Boeing approval
    - Deposition Procedure Specification (DPS) addresses part-specific processing details including lot acceptance testing
    - Production reports required to be automatically generated for each part to show adherence to the DPS requirements
  - Post Processing
    - Industry specification baselines utilized for defined heat treatments
    - Detailed within the DPS to account for differences in part section thicknesses



BMS 7-361 Specification Appropriately Controls the Manufacturing Process

Means of Compliance
§25.605 Fabrication Methods

- **Fabrication methods control**
  - Non-Destructive Inspection
    - Utilizes Boeing inspection specifications with additive deposit reference standards and performance of Probability of Detection studies
  - Part finish machining & post-processing
    - Utilizes standard Boeing specifications and approved suppliers
    - No differences from conventional machining or finishing practices for Ti parts



BMS 7-361 Specification Appropriately Controls the Manufacturing Process

Compliance Approach –
§25.613 Material Design Values

§25.613 Material strength properties and material design values.

(a) Material strength properties must be based on enough tests of material meeting approved specifications to establish design values on a statistical basis.

(b) Material design values must be chosen to minimize the probability of structural failures due to material variability. Except as provided in paragraphs (e) and (f) of this section, compliance must be shown by selecting material design values which assure material strength with the following probability:

  (1) Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component, 99 percent probability with 95 percent confidence.

  (2) For redundant structure, in which the failure of individual elements would result in applied loads being safely distributed to other load carrying members, 90 percent probability with 95 percent confidence.

(c) The effects of environmental conditions, such as temperature and moisture, on material design values used in an essential component or structure must be considered where these effects are significant within the airplane operating envelope.

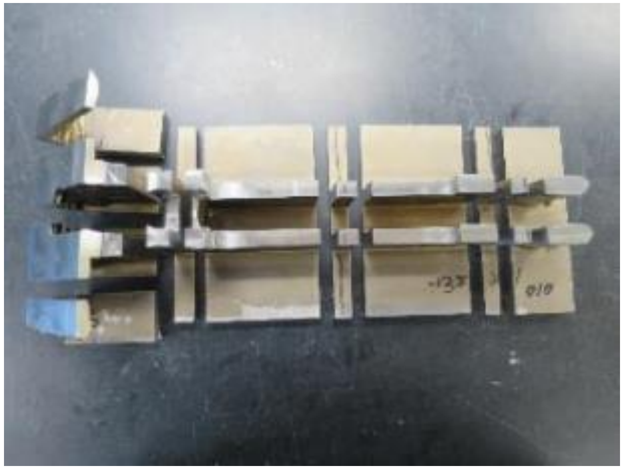
(d) Reserved.

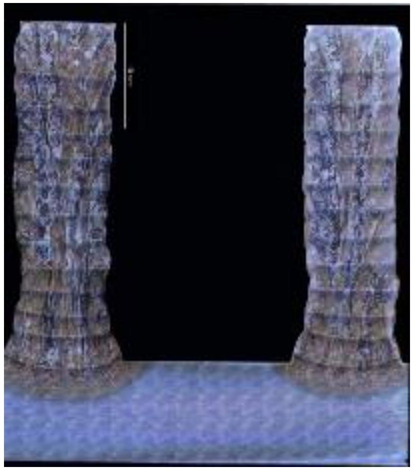
(e) Greater material design values may be used if a "premium selection" of the material is made in which a specimen of each individual item is tested before use to determine that the actual strength properties of that particular item will equal or exceed those used in design.

(f) Other material design values may be used if approved by the Administrator.

Means of Compliance

§25.613 Material Design Values & §25.619 Special Factors





- **Preform Testing Activities**
  - Fabricated multiple part production runs for testing prior to directly testing deposited preforms from multiple wire lots
  - Utilized documented BCA procedures and statistical methods for wrought products approved by the FAA to develop design values
  - Demonstrated the ability to use the same analysis methods relative to that used for original 787-9 type certification

- **BMS7-361 spec separately defines required supplier, machine and preform qualification testing**

- **§25.619 Special Factors**
  - *Requires special factor of safety (§25.621 – §25.625) be applied "for each part of the structure whose strength is – (a) Uncertain; (b) Likely to deteriorate in service before normal replacement; or (c) Subject to appreciable variability because of uncertainties in manufacturing processes or inspection methods."*
    - Demonstrated to not require a special factor of safety through material testing approaches, process control approaches, inspection methods and lot acceptance testing approaches

Summary

- **Boeing additive manufacturing strategy keys on rational implementation consistent with expanding process knowledge**
- **Initial implementation - 787-9 Passenger Floor Galley Diagonal Fittings**
  - Intentional selection of non-critical parts for initial application
- **Compliance shown to FAA requirements**
  - BMS 7-361 material & process specification controls
  - Material design values developed based on coupon test program
  - Means of compliance consistent with original 787-9 type certification

APPENDIX G—ADDITIVE MANUFACTURING AT GE

Additive Manufacturing at GE

Mohammad Ehteshami
VP & GM, GE Additive

August 29, 2017

It started with 1 part ...

Capabilities of full production
35,000 – 40,000 per year

20 › 1
PARTS

5x MORE
DURABLE

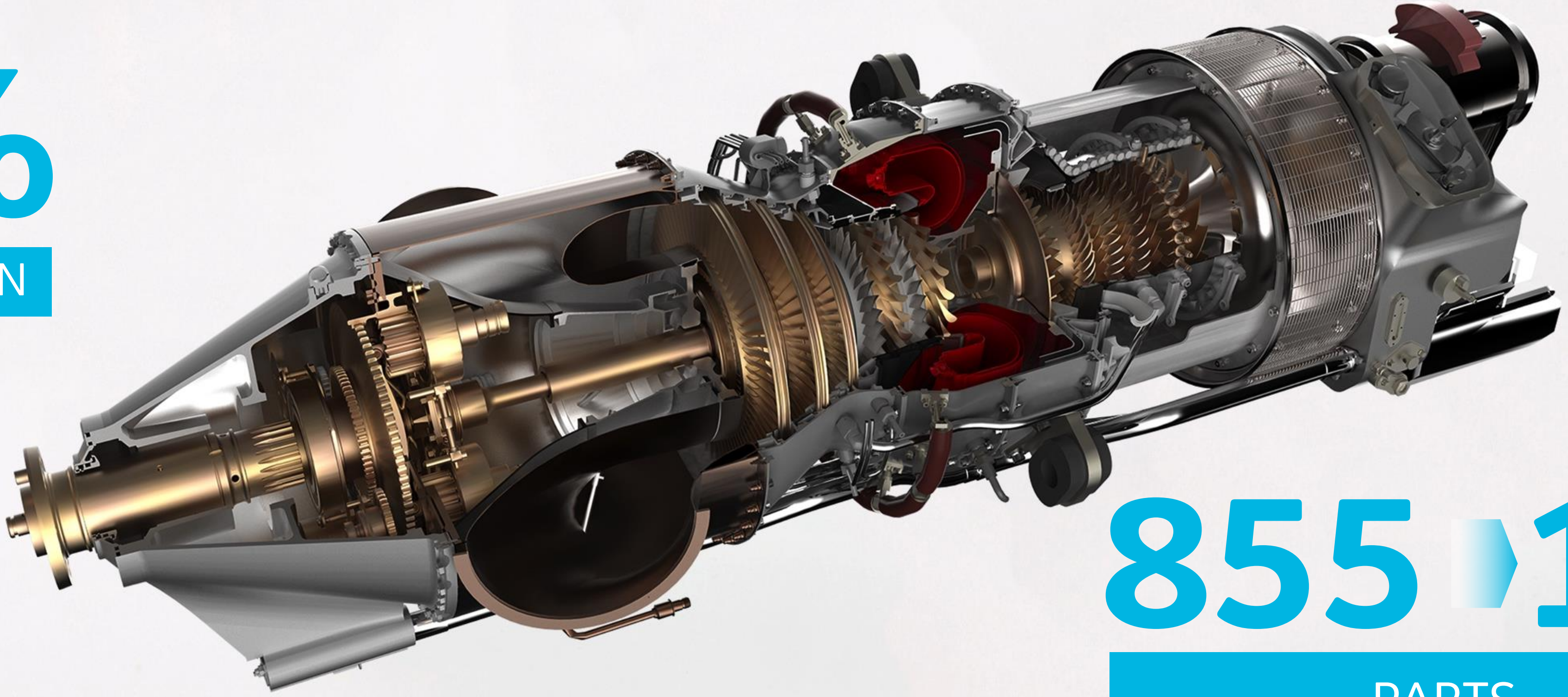
25%
WEIGHT
REDUCTION

Then a system … Advanced Turboprop

Combustor test schedule reduced from **12 months** to **6 months**

5%
WEIGHT REDUCTION

20%
LOWER FUEL BURN

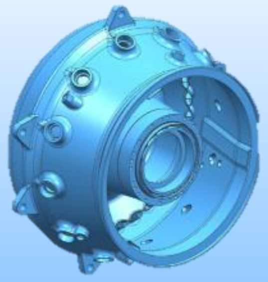


855 ▶ 12
PARTS

At an enterprise level

Design → **Manufacturing** → **Services**

Additive



Turbine frame

1 Digital Twin

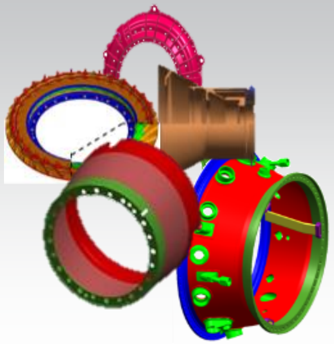
6-8 Engineers

1 Mfg. sources & Inspection Sys.

1 Component to Repair

← **1** data lake →
...powering PREDIX

Conventional



Same frame

300 parts

60 Engineers

50+ Mfg. sources

5 Repair Sources

← **40** data systems →

GE Additive

Focused on three main offerings:

- Materials
- Machines
- Engineering Consultancy Services

Today…

- **1100 employees**
- **22 sites**
- Stakes in **Concept Laser** & **Arcam AB**

Arcam
a GE Additive company

- **HQ in Mölndal, Sweden**
- **340+employees**
- **Products**:
  - Metal additive machines (Electron Beam technology)
  - Materials (from AP&C)
  - Additive Service Bureau for Medical Industry (DTI)
- **Industries served:** Aerospace, Medical, Auto, Tooling

CONCEPTLASER
a GE Additive company

- **HQ in Lichtenfels, Germany**
- **400+ employees**
- **Products**:
  - Metal additive machines (Laser technology)
- **Industries served:** Aerospace, Medical/Dental, Auto, Jewellery

Machine Qualification

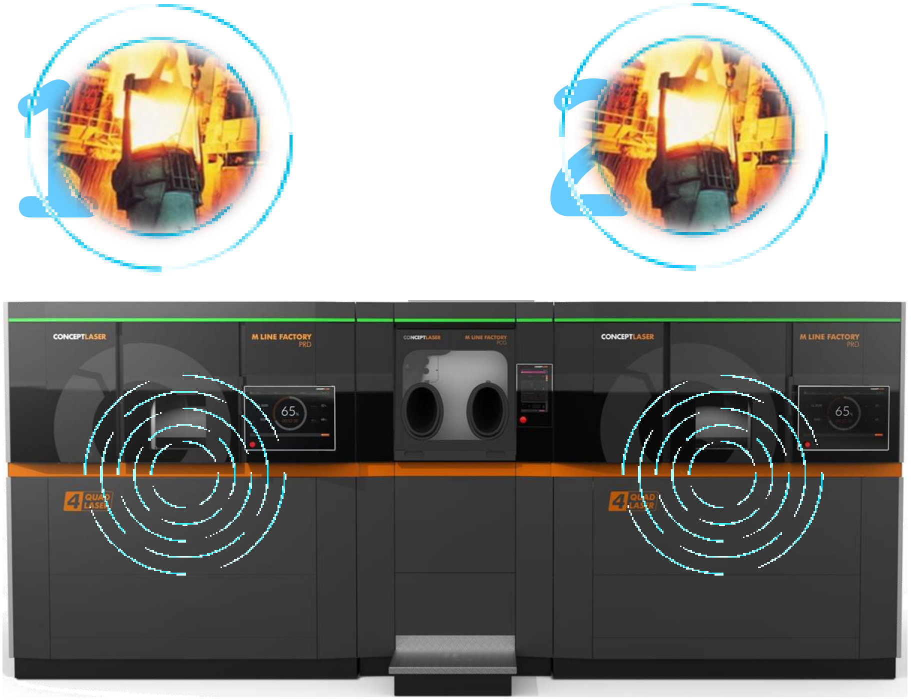
Every Machine is a "Micro" Foundry

Qualification ... and then fixed process control

Material Qualification ... must buy-into material allowable curves, must meet material specs

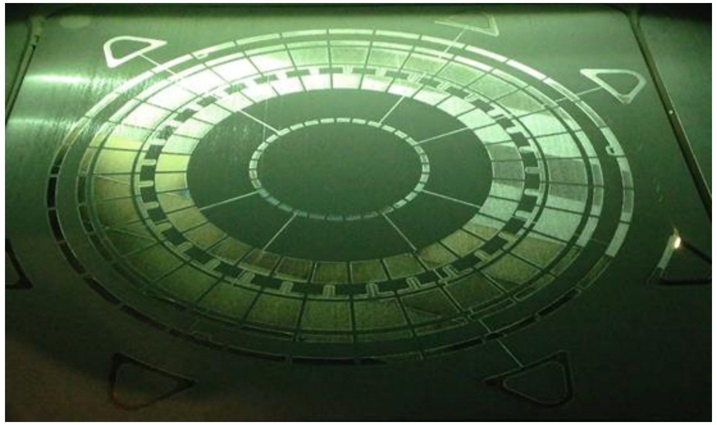
Part Qualification ... process must be in control, dimensional, functional

Part Inspection ... methods based on traditional castings (gage, white light, FPI, X-Ray, CT)



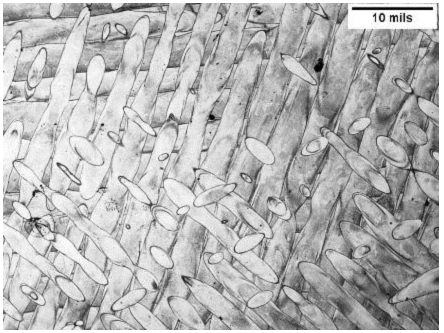
Certification: Material Qualification

Process

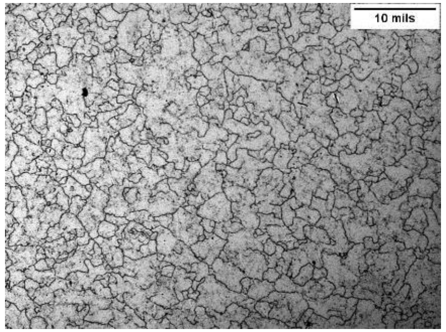


Powder specification
Machine parameters
Build chamber environment
Machine calibration
Thermal processing
Post processing
Powder re-use

Structure

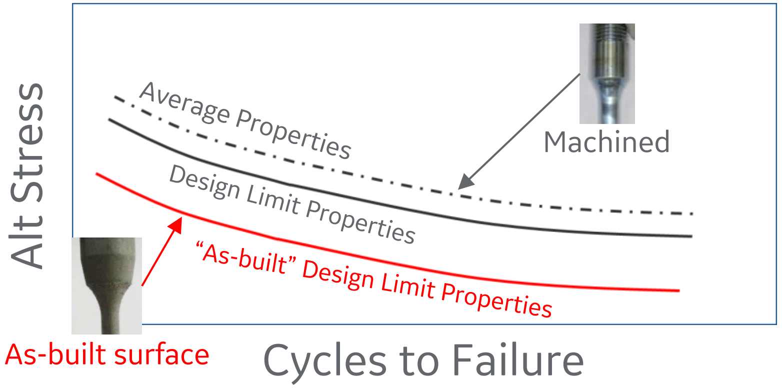


As-Built Structure



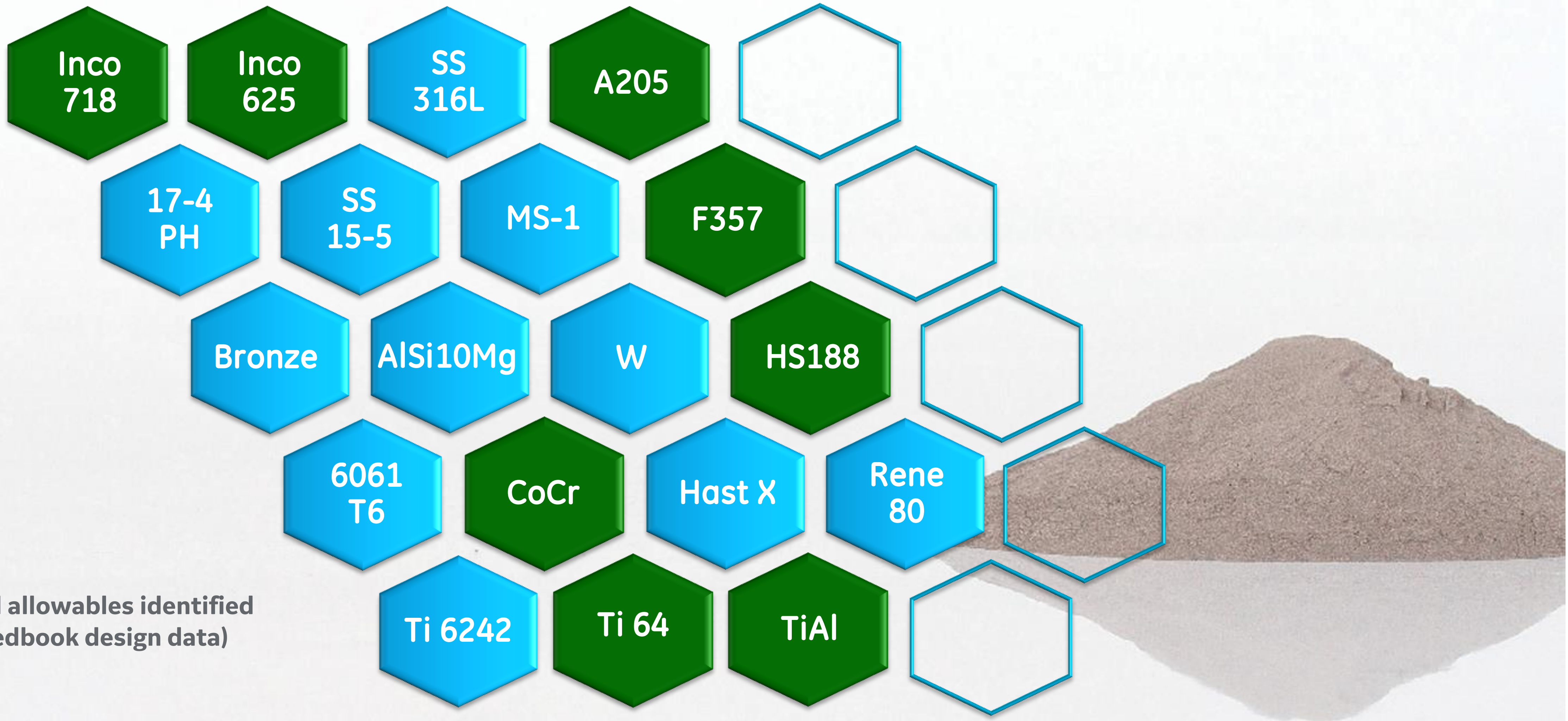
Isotropic Structure
After Thermal Processing

Properties



Physical properties
Strength properties (static, fatigue)
Damage Tolerance
Variation (Lots, machines, etc)
X, Y, & Z Build direction
Surface finish factor
Part feature factor (e.g. thin wall)

Expanding Materials Capability

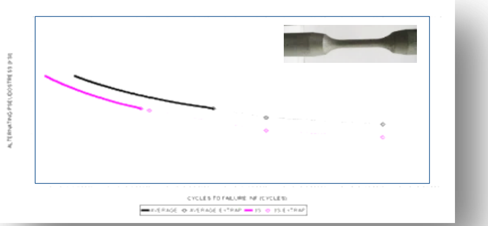


Inco 718
Inco 625
SS 316L
A205
17-4 PH
SS 15-5
MS-1
F357
Bronze
AlSi10Mg
W
HS188
6061 T6
CoCr
Hast X
Rene 80
Ti 6242
Ti 64
TiAl

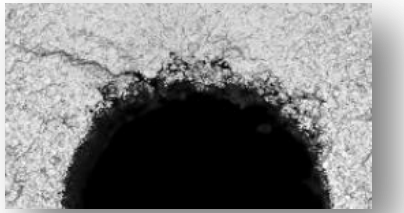
🟩 Material allowables identified (GE Redbook design data)

Process/Part/System Validation

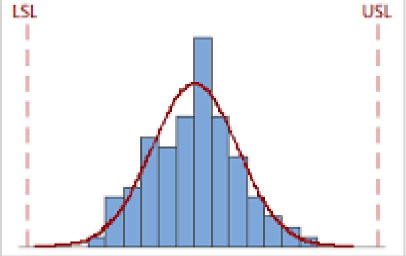
Fuel Nozzle Example



DESIGN ALLOWABLE



FEATURE DEBIT



DIMENSIONAL

9x

PREDICTED LIFE

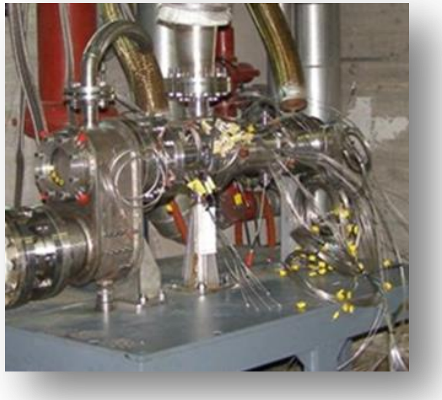
COMPONENT TESTING

low cycle fatigue test

100%

TIME AT TEMP

RIG TESTING



1-cup coking rig

500+

NOZZLES TESTED

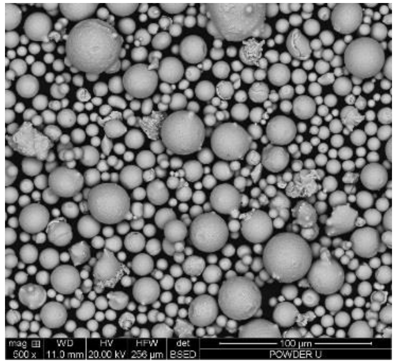
CERT TESTING

LEAP-1A Icing test

Additive Specification Control

Powder Specification

- Chemical composition
- Melting and atomization method
- Powder quality
- Process control
- Particle size distribution (PSD)

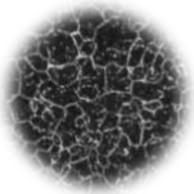


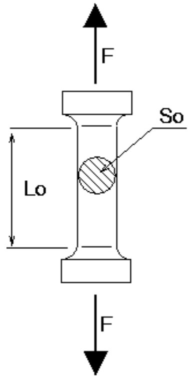
DMLM Process Specification

- Fixed Process Controls
- Equipment qualification & Preventative Maintenance
- Power level verification
- Facility environmental controls
- Powder handling and reuse
- Software control
- Operator training
- Record keeping
- Machine restarts

Component Specification

- Chemistry & Composition
- Structure/ Porosity
- Properties
- Surface finish
- Thermal processing





Proprietary specs evolving to industry wide specs

Building Industry Capability

Specifications

SAE INTERNATIONAL

Nadcap

AWS
American Welding Society

ASME
SETTING THE STANDARD

ASTM INTERNATIONAL

MMPDS

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Industry Groups

AIA
AEROSPACE INDUSTRIES ASSOCIATION

GAMA

NDIA
National Defense Industrial Association

America Makes
National Additive Manufacturing Innovation Institute

AMUG

ASD
AeroSpace and Defence Industries Association of Europe

Accelerating the Additive Revolution

We’re focused in three areas…

Engineering

Machines + PREDIX

Materials

GE Additive Customer Experience Centers

Pittsburgh

Munich

More coming soon…

Our Customer Experience Centers are designed to help customers understand the additive process; from design to prototyping to production and support them along the way

Customer Collaboration

- Application Engineering
- Rapid Prototyping
- Low Rate Manufacturing

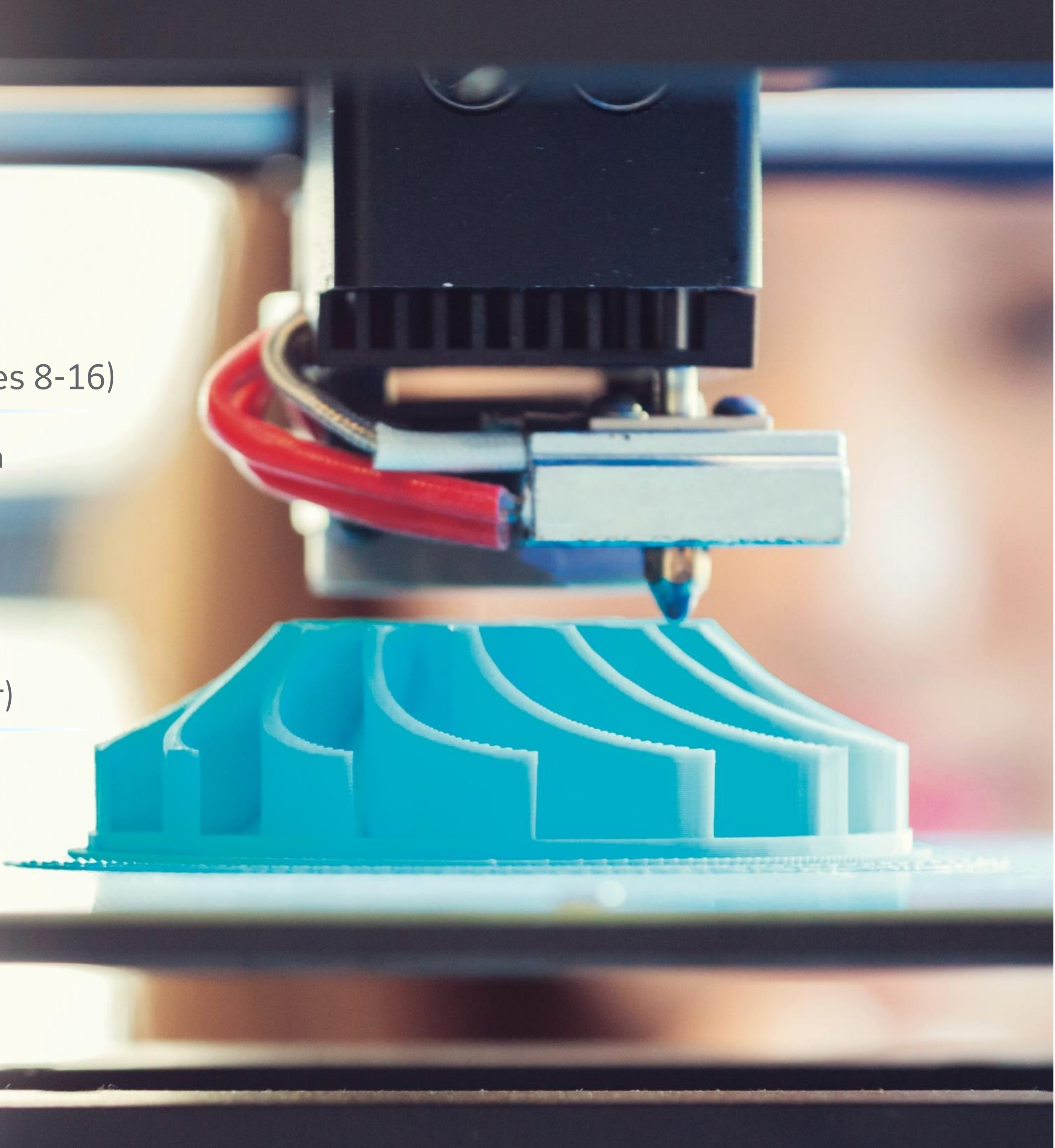
Customer Training

- Additive Design
- Additive Machines
- Additive Materials

Customer Support

- Field Support
- Spare Parts
- Materials
- Logistics

Investing in a limitless future



PRIMARY AND SECONDARY SCHOOLS (ages 8-16)

- **$2 million** for 3D-printing equipment and curriculum
- Focus on **STEM/STEAM** programs
- Over 400 recipients in 2017

COLLEGES AND UNIVERSITIES (2 and 4-Year)

- **$8 million** for metal additive manufacturing equipment
- Focus on **additive learning** efforts
- 8 recipients in 2017

APPENDIX H—AFRL PROGRESS IN QUALIFICATION AND CERTIFICATION OF AM PARTS

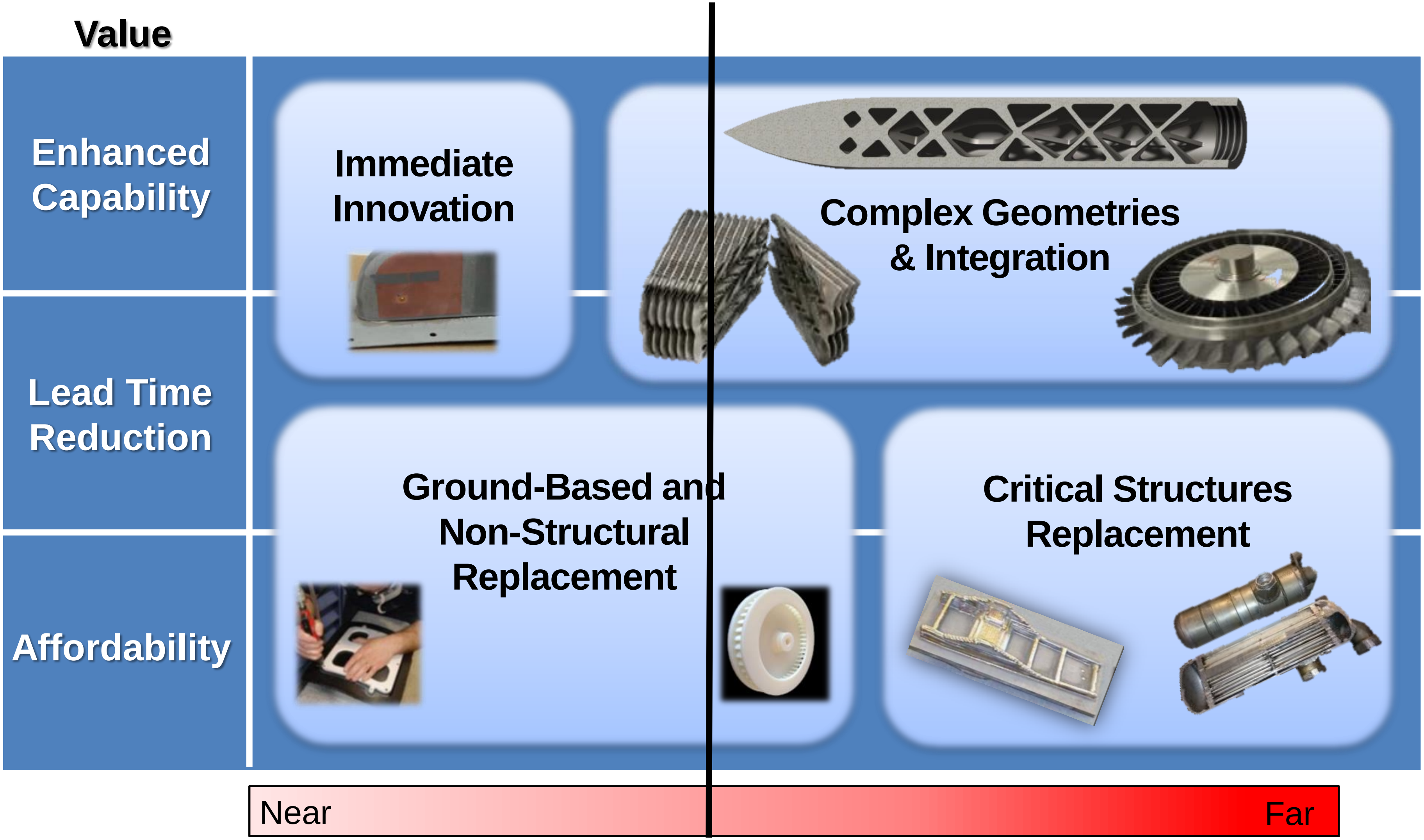
AFRL Progress in Qualification and Certification of AM Parts

October 2017

Dr. Jonathan Miller
Materials and Manufacturing
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

AF Opportunities for AM



Value

Enhanced Capability

Lead Time Reduction

Affordability

Immediate Innovation

Complex Geometries & Integration

Ground-Based and Non-Structural Replacement

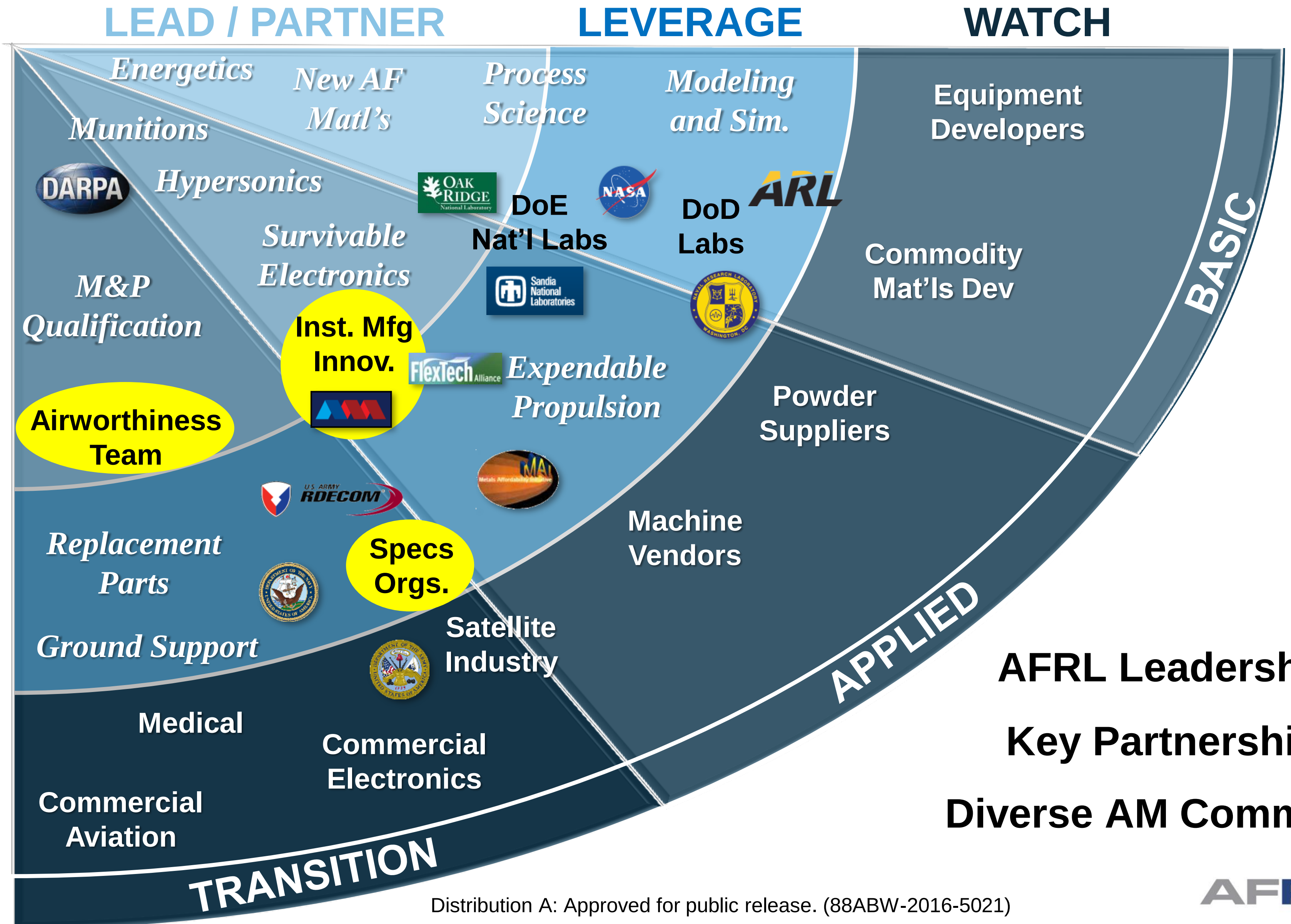
Critical Structures Replacement

Near

Far

Implementation Timeframe

AFRL Technical Approach for Additive Manufacturing



LEAD / PARTNER **LEVERAGE** **WATCH**

Energetics

Munitions

New AF Matl's

Process Science

Modeling and Sim.

Equipment Developers

Hypersonics

DoE Nat'l Labs

DoD Labs

Survivable Electronics

M&P Qualification

Commodity Mat'ls Dev

Inst. Mfg Innov.

Expendable Propulsion

Airworthiness Team

Powder Suppliers

BASIC

Replacement Parts

Specs Orgs.

Machine Vendors

Ground Support

Satellite Industry

APPLIED

Medical

Commercial Electronics

Commercial Aviation

TRANSITION

AFRL Leadership

Key Partnerships

Diverse AM Community

Distribution A: Approved for public release. (88ABW-2016-5021)

USAF Qualification Requirements

- **Material & Process Qualification Considerations**
  - Demonstrated Process Controls
  - Statistically-Relevant Mechanical Property Database
  - Validated Nondestructive Evaluation & Quality Assurance
  - Post-Processing & Residual Stress Management

- **Airworthiness**
  - Stability
  - Reproducibility
  - Sustainability
  - Characterized Mechanical & Physical Properties
  - Predictability of Performance

Dr. John W. Lincoln, *"Materials & Process Technology Transition to Aging Aircraft*, Proceedings: Aging Aircraft Fleets – Structural & Other Subsystem Aspects, NASA 20010028491, March 2001

- **Highest Priority Research for Qualification**
  - Determining Essential Process Variables
  - Characterizing Effect of Defects

Key Aspects of a Way Forward

- **Design**
  - for Additive Manufacturing … different from "Design for Function"
  - Requirements for specific applications
- **Materials**
  - Feedstock specifications (composition, particle size, storage) AMS
  - Properties per point design (welding approach?)
- **Processes**
  - Specifications (per AWS D20 and process-savvy SDOs)
  - In-situ sensing & control as a means to assure process control
  - Post-processing requirements & residual stress knowledge
- **Quality Assurance (Inspection)**
  - Validated inspection methods independently identifying rogue flaws
  - Unacceptable defects quantified (**surface** & **volumetric**)
- **"Touchstones"**
  - AM is a process … not a material … and must be qualified accordingly
  - Form + Fit does not necessarily equal Function
  - You don't inspect in quality: process control + inspection
  - Crawl – Walk – Run

Defining Essential Process Variables

- **In the absence of validated knowledge – POINT DESIGN**
  - all process variables are essential: 100+ machine knobs, as well as the machine serial number, calibration procedures, maintenance protocols and powder characteristics
  - The geometry is also an essential variable due to the inherent coupling of geometry with local processing conditions
- **Developing Validated Knowledge – PART FAMILY DESIGN?**
  - Conventional process specification protocols being developed to manage "**outside the bed**" design influences: machine, operator, machine settings, calibration, feedstock, etc.

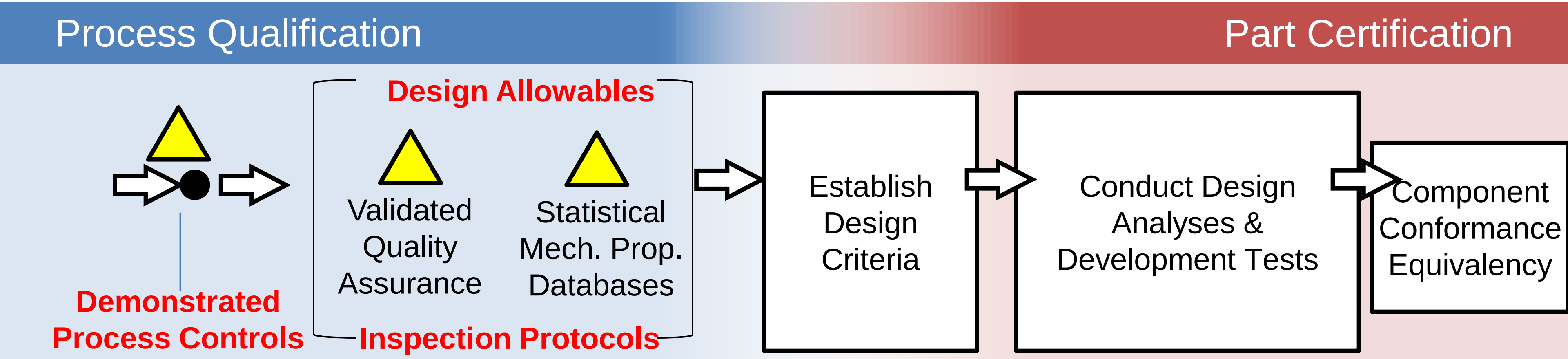
    power & velocity necessary but not sufficient for control
  - R&D to investigate the "**inside the bed**" influences. Can geometry influences to process be generically characterized for process design:

    melt area, interpass temperature, part thicknesses, … others

Distribution A: Approved for public release. (88ABW-2016-5021)

Defining Essential Process Variables

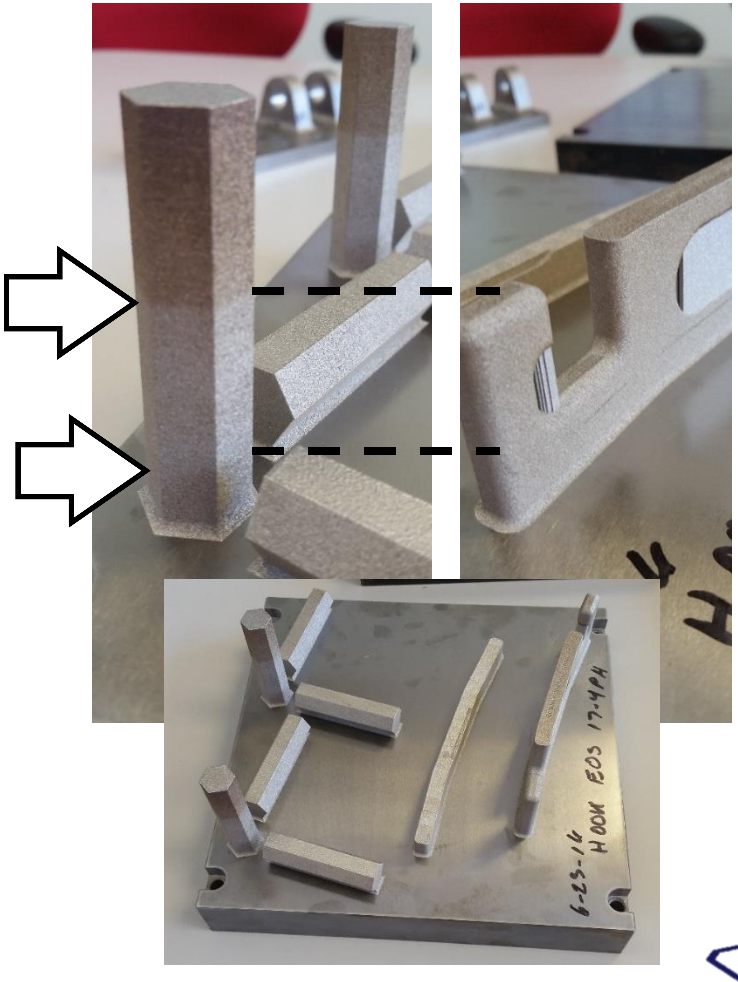
- **Model-Informed Process Design – “RAPID” QUALIFICATION**
  - The “fixed process” is adaptable to control *local processing state*, rather than macroscopic essential process variables & geometry
    - Conventional “predictability of performance” approach propagated to design allowables development, effect of defects and process control validation!!
  - The vision & promise speak for themselves
  - Likely significant opportunities to reduce qualification iterations as well as “optimize” process design without affecting final certification
  - What is the engineering authorities confidence in this approach?



Departing from a Point Design Approach

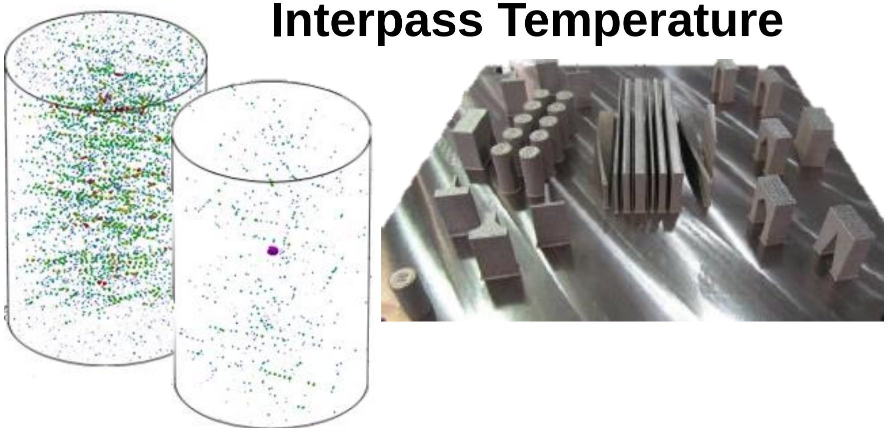
Controlling “Inside the Powder Bed” Influences

Melt Area



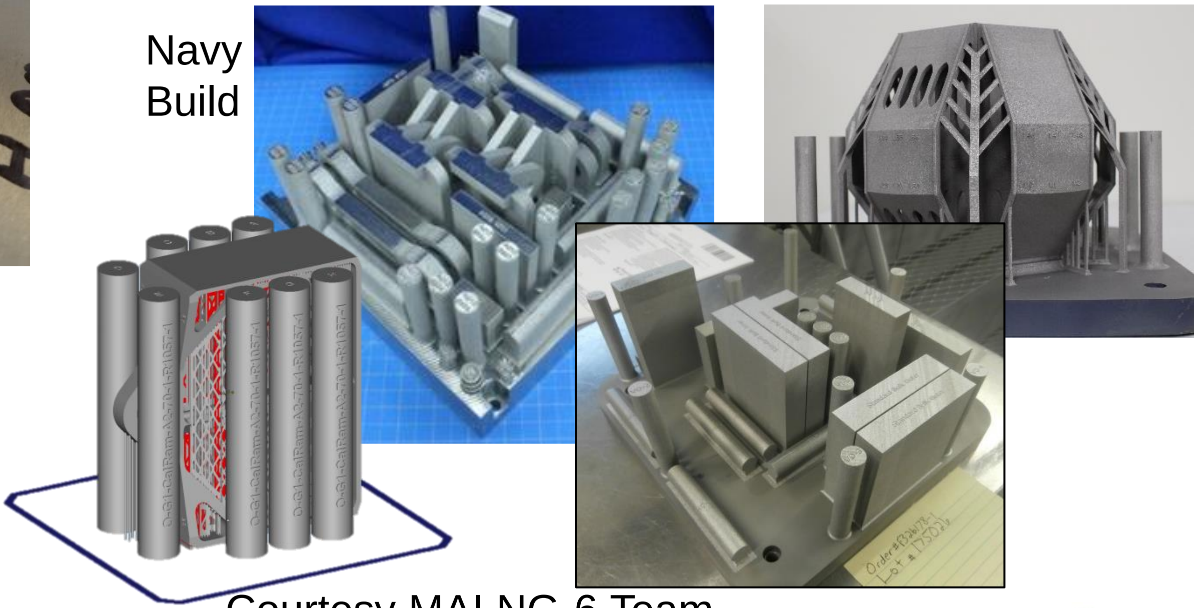
Courtesy UDRI, AFLCMC/EZP

Interpass Temperature



Component Performance Equivalency ???

Navy Build



Courtesy MAI NG-6 Team

Qualification Readiness by Material

Powder Bed Fusion

- CoCr, IN 625, IN 718
  - Insensitive to “inside the bed” process influences
- Ti-6Al-4V
  - Melt area & inter-pass timing dependence
  - Alpha case effects and basketweave microstructure familiarity
  - Variability: 20% yield & ultimate, 50% modulus, 5-30% elongation
- Other alloys with some experience at AFRL:
  - AlMgSi, CuCr, Haynes 230

Directed Energy Deposition

- More sensitive to geometry & toolpath
- Higher residual stresses

Research to Support Qualification & Certification

- Mechanical Properties & Effects of Defects
- Feature-Based Material Integrity
- Nondestructive Inspection Development & Validation
- Statistically-Based Manufacturing Variability

- Open Architecture Protocols & Machine Platforms
- Multi-Power-Source PBF AM Machines
- Processing Science to Inform Process Control
- Modeling & Simulation (primarily process models)
- In-Situ Monitoring Validation (process control assurance)

Maturation of Advanced Manufacturing for Low-cost Sustainment (MAMLS)

Program Overview

What is MAMLS?

- MAMLS is a Congressionally directed program executed by America Makes with the AF as the executive agent. The program goal is to:

  Enhance and improve AF sustainment operations through the development, demonstration, and transition of additive manufacturing and related advanced manufacturing technologies.

- MAMLS has a strong interface with AF sustainment operations and a large part of the program targets improving the efficiency of organic sustainment operations for rapid part replacement of legacy aircraft and accelerating the adoption of additive manufacturing.

- MAMLS program success is enabled through:
  - The collaborative infrastructure of America Makes teamed with AF sustainment operations.
  - Leveraging cross-cutting enabling technologies from America Makes members focused on AF sustainment opportunities.
  - Technology deployment through continued support and alignment with AF and industry implementation requirements.
  - Development of commercial supply chains for rapid part replacement.

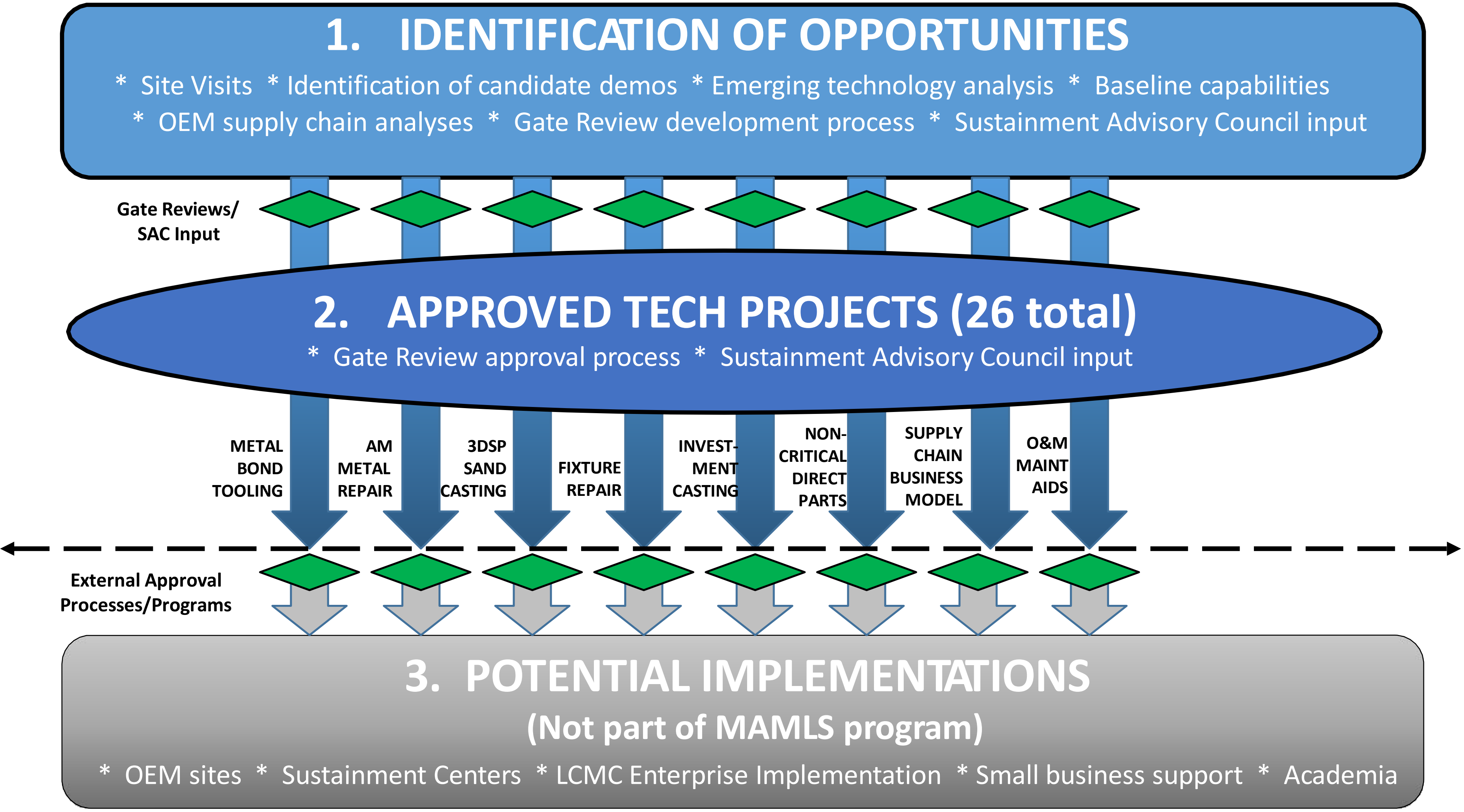
Objectives

- Develop and demonstrate advanced manufacturing technologies related to additive manufacturing that improve rapid part replacement/maintenance for legacy aircraft.
- Enable on-demand replacement of critically damaged or obsolete components that do not meet economic requirements of conventional supply chains.
- Develop and demonstrate rapid fabrication of shop tools such as assembly aids, jigs, and fixtures for sustainment center utilization.
- Identify technology gaps and workforce issues that need to be solved prior to effective implementation.

Benefits

- Reduction of the cost and lead time to fabricate replacement components for legacy aircraft as well as for rapid tooling, masks, fixtures, etc.
- Technology demonstrations and learning for future implementations both in industry and AF organic sustainment operations.

Phase 1 Program Plan



1. IDENTIFICATION OF OPPORTUNITIES

* Site Visits * Identification of candidate demos * Emerging technology analysis * Baseline capabilities * OEM supply chain analyses * Gate Review development process * Sustainment Advisory Council input

Gate Reviews/
SAC Input

2. APPROVED TECH PROJECTS (26 total)

* Gate Review approval process * Sustainment Advisory Council input

METAL BOND TOOLING

AM METAL REPAIR

3DSP SAND CASTING

FIXTURE REPAIR

INVESTMENT CASTING

NON-CRITICAL DIRECT PARTS

SUPPLY CHAIN BUSINESS MODEL

O&M MAINT AIDS

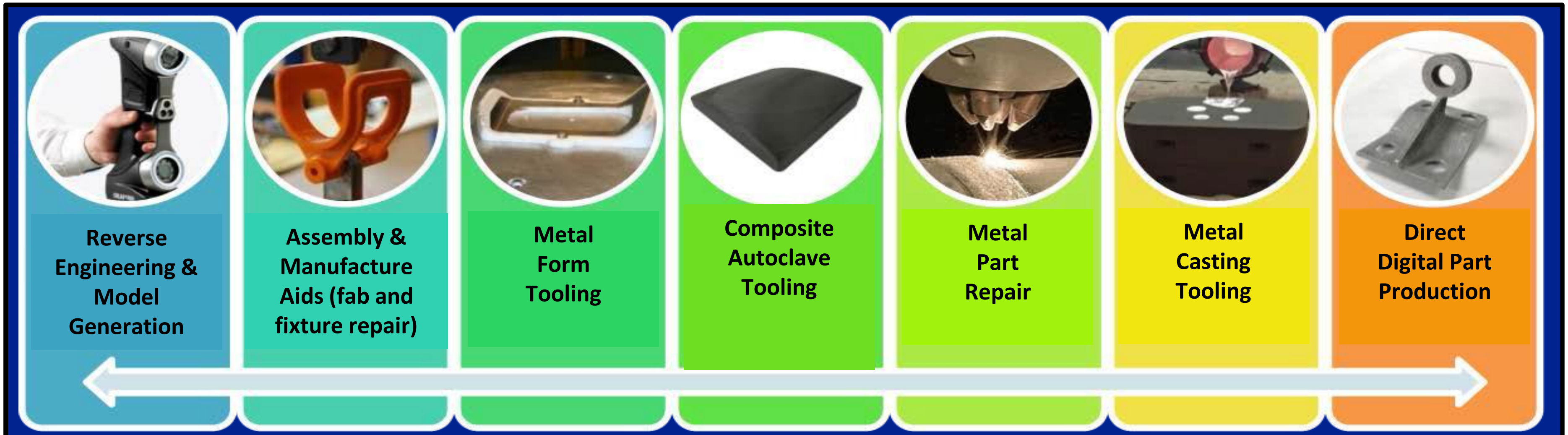
External Approval
Processes/Programs

3. POTENTIAL IMPLEMENTATIONS

(Not part of MAMLS program)

* OEM sites * Sustainment Centers * LCMC Enterprise Implementation * Small business support * Academia

MAMLS Phase 1 Technologies



- Reverse Engineering & Model Generation
- Assembly & Manufacture Aids (fab and fixture repair)
- Metal Form Tooling
- Composite Autoclave Tooling
- Metal Part Repair
- Metal Casting Tooling
- Direct Digital Part Production

- Handy Scan
- Fused Deposition Modeling (FDM)
- Big Area Additive Manufacturing (BAAM)
- FDM
- Directed Energy Deposition (DED)
- 3D Sand Printing (3DSP)/ Quickcast
- Direct Metal Laser Sintering/ Powder Bed Fusion/FDM

MAMLS Phase 1 Highlights

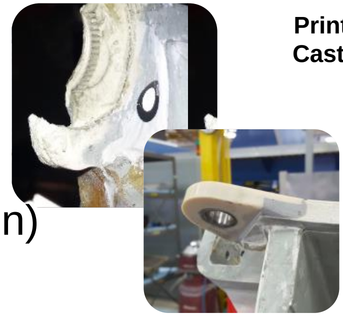
- Printed Casting Molds
  - C-130 Aerial Spray Casting for 910th Airlift Wing
  - *Availability* – >10x Lead Time Improvements
  - Add’l Opportunities – B1 Fuel Tee Casting, Quickcast

- Ground Support Equipment
  - F-16 Assembly Fixture Repair (80% Cost Reduction; 94% Lead Time Reduction)
  - TF33 Gearbox Housing Paint Masks
  - *Availability & Affordability*
  - Add’l Opportunities – other paint masks, tool repair, maintenance support applications

- Non-Structural Parts Repair/Replacement
  - C-17 Avionics Cooling Duct Replacement
  - Completed Airworthiness Qualification Process
  - *Availability* – 10x Reduction, from “no bid” or 26 weeks
  - Add’l Opportunities – Other ducts, honeycomb core, …


Printed Sand Casting Mold


Final Al Casting


Assembly Fixture Pre- and Post-repair


Paint Masks for Engine Housings


Environmental Ducting

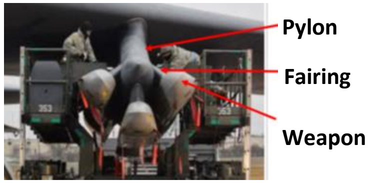

Digital Scanning Tools

MAMLS Phase 2 Summary

Direct Part Manufacturing Demonstrations for Part Families

- Focused on more challenging applications for direct part fabrication.
- Benchmark qualification readiness: repeatability, producibility, quality assurance

1. **Bell crank family (YSU, PSU, YBI, M-7 Technologies, Boeing, Oerlikon)**
   - Safety critical part with varying thicknesses & complex geometries
   - A specific bell crank design used for demonstration
   - Aluminum powder bed fusion technology
2. **Fuel oil cooler family (UDRI, YSU, YBI, DRT, 3DSIM, GE Aviation)**
   - Complex geometry, functional requirements
   - Generic oil cooler core demonstration
   - Aluminum powder bed fusion technology
3. **Structural sandwich panels using hybrid AM approach (Boeing)**
   - Alternate approach to traditional core/skin manufacturing
   - B-52 pylon fairing design used for demonstration
   - FDM technology using ULTEM core



MAMLS Phase 3 Planning

- Stay tuned. . . . .

Summary

- **AFRL is the AF SME for development, maturation and qualification of materials & processes**
- **AF has been flying AM structural parts since 2003**
- **AFRL has demonstrated AM value for fleet readiness**
  - **Prototyping**
  - **Ground Support Equipment**
  - **Non-Structural and Non-Critical Structures**
- **AFRL is actively evaluating AM for flight-critical parts**
- **AFRL believes performance gains through novel architectures and systems integration is highest value**

APPENDIX I—AIRBUS VIEW ON HOW REQUIREMENTS COULD BE TAILORED TO AM APPLICATIONS

Airbus view on how requirements could be tailored to AM Applications

John VAN DOESELAAR
Alain SANTGERMA

Workshop on Additive Manufacturing – Dayton (OH) – August 29-31, 2017

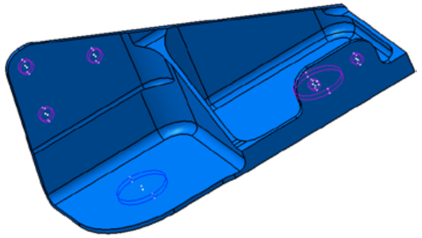
Objective

In case of similar parts, can we create a family for qualification?

Can requirements be reduced when maturity and process stability increases?

Must all parts have same requirements independent of importance, loading, complexity?

≠



Tailoring of requirements to AM applications is crucial

Content

- AM Metallic Alloys introduction in AIRBUS
- Key features of the E2E cycle
- Tailoring of requirements
- Examples
- Conclusions

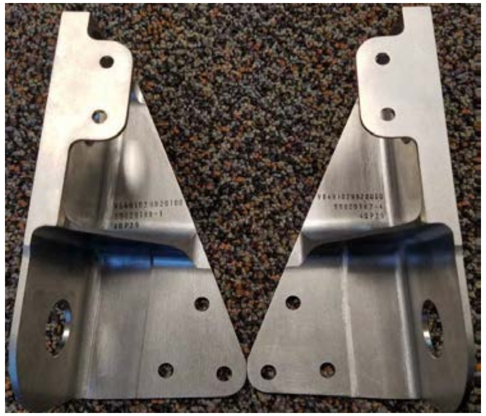
AM metallic alloys introduction in AIRBUS

Stepwise introduction

Powder Bed Fusion and Directed Energy Deposition technologies

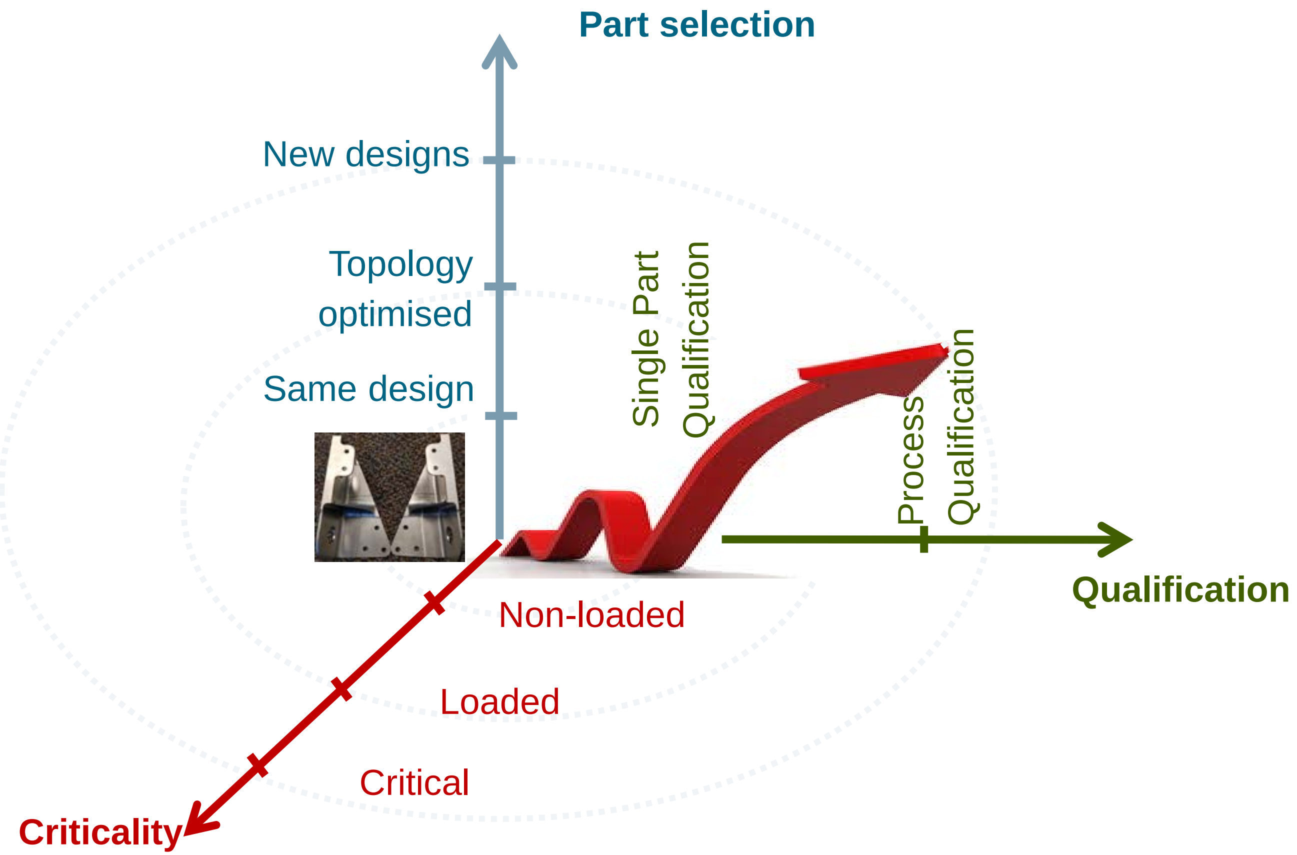
Competences developed in AIRBUS with internal network of machines

Specifications developed for material and manufacturing process.



Step by step approach to ensure maturity

Stepwise introduction

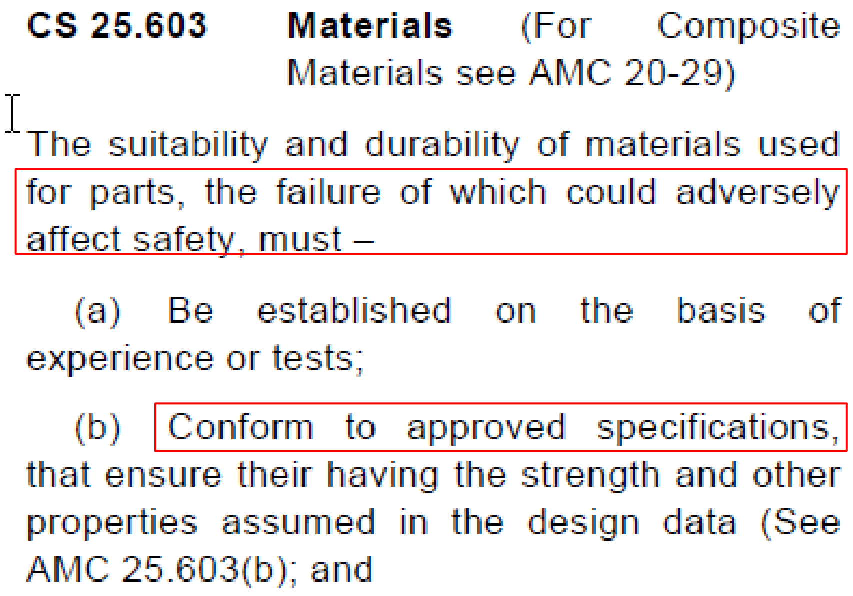


Key features of the E2E cycle

Regulatory context

CS25 and FAR25 require approved material and process specifications

Relevance of parts for safety is indicated

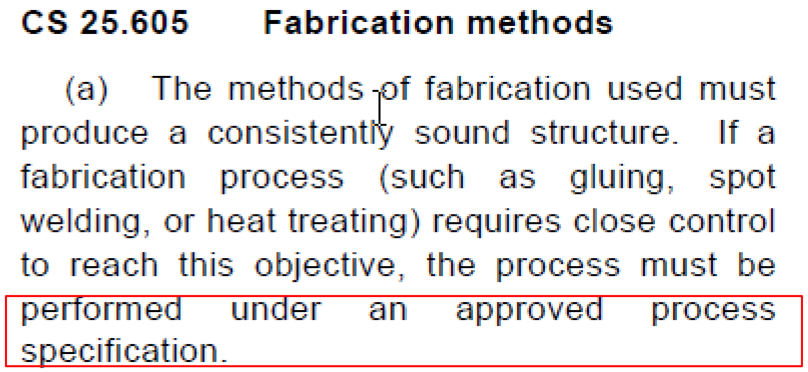


CS 25.603 Materials (For Composite Materials see AMC 20-29)

The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must –

(a) Be established on the basis of experience or tests;

(b) Conform to approved specifications, that ensure their having the strength and other properties assumed in the design data (See AMC 25.603(b); and



CS 25.605 Fabrication methods

(a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.

Current features

High level of requirements applied on initial qualifications and serial applications

Raw material

POWDER CONTROL

- Powder characteristics
- Powder Batch
- Storage conditions
- Re-use policy
- …

Manufacturing Process

CONTROL KEY PROCESS PARAMETERS

- KPP
- Personnel
- Equipment
- Calibration

Post - processing

POST PROCESSING ACTIONS

- Stress release
- Support removal
- HIP
- Surface finish
- Machining

Final Part

QUALITY INSPECTIONS

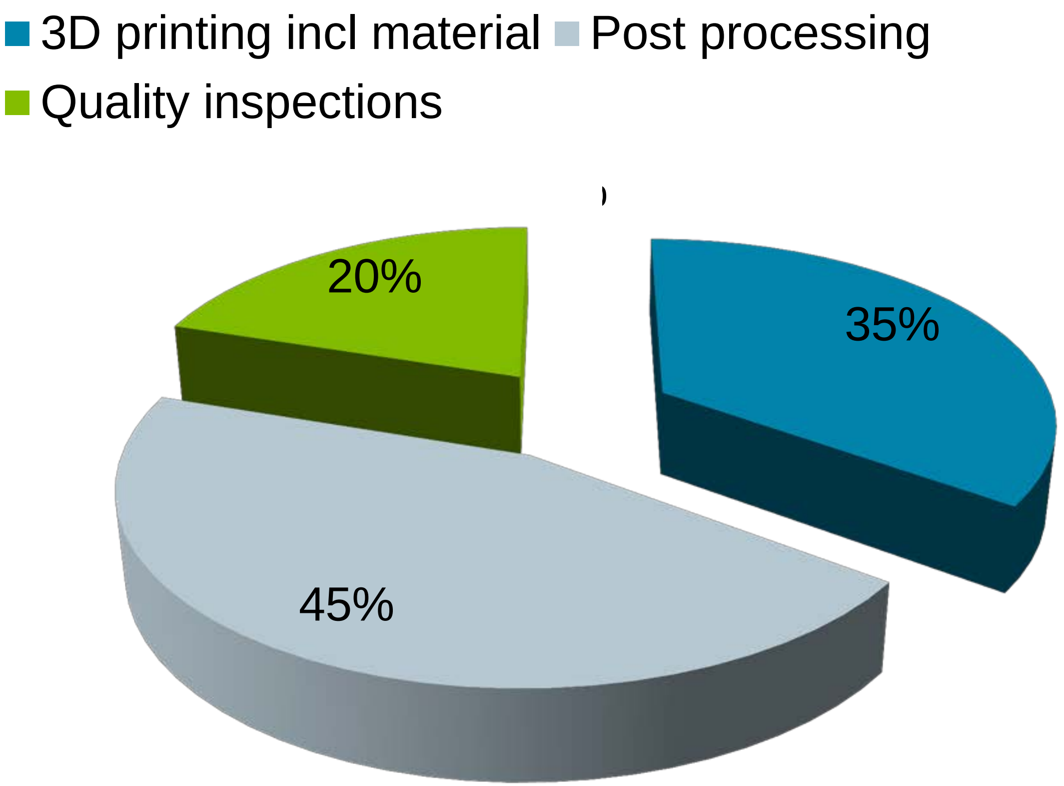
PROCESS CONTROL MECHANICAL TESTS

Typical cost break down

Structural part

Powder bed techno

Indicative only



2/3 of manufacturing costs are post printing

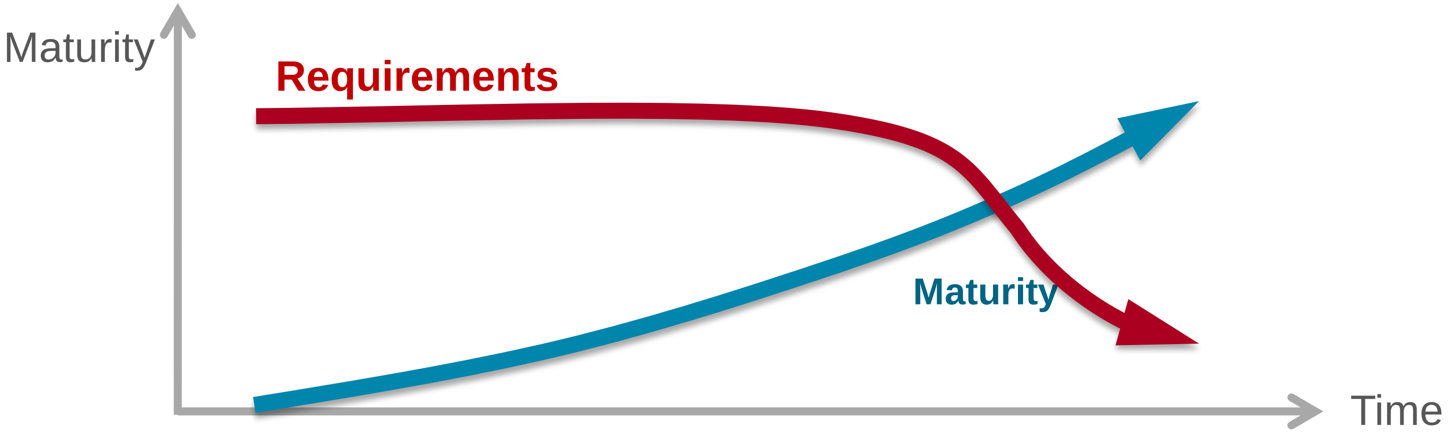
Tailoring of requirements

Maturity

High level of requirements for qualification, process monitoring, quality

Essential as the AM technology matures

Use lessons learnt, also from existing technologies (casting, composite)

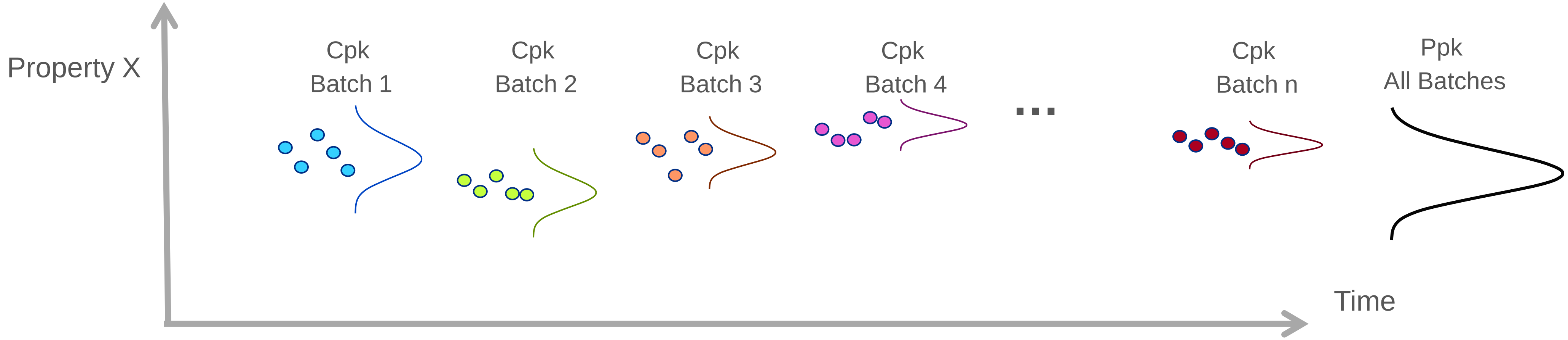


Pre-requisite for tailoring: Understand effect of defect & KPP mastered and controlled

Process Control Specimen

Monitor Process variability

Process Capability (Cpk or variability index per batch) and Process Performance (Ppk or variability index over all batches).

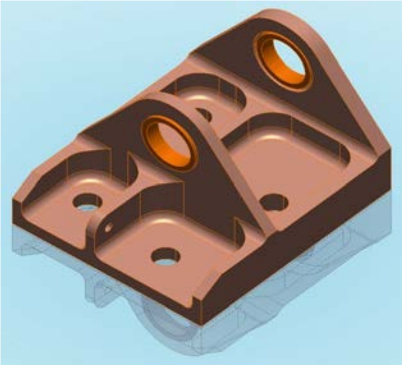


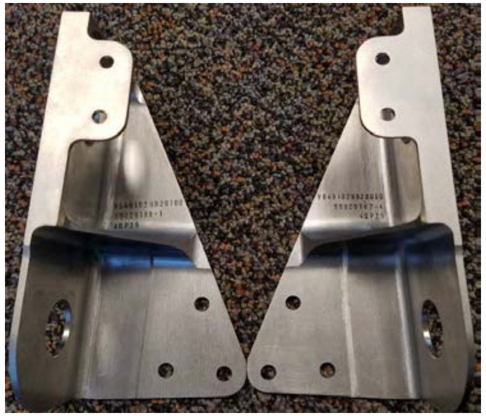
Reduce number of PCS when process shows stability

Part categories

4 different part categories can be distinguished:

- **Fatigue critical parts**
- **Fatigue sized parts**
- **Static sized parts**
- **Non-loaded/ remaining parts**





Requirements should be tailored to the category of part.
Zoning of areas in parts could achieve even further refinement.

Tailoring vs part category: focus on qualification, post processing and quality inspections/ testing

Families for qualification

Successful qualification can be used to qualify a number of similar parts

Separate qualification of each AM part is not necessary.

To be considered as a 'family', the parts shall satisfy the following criteria:

- **Same material and post processing conditions**
- **Same classification of part and part function**
- **Same manufacturing and inspection programme**
- **Similar geometry and section thickness**

Qualification of a number of similar parts = qualification by 'families'

Summary tailoring of requirements

1. Qualification

2. Distinguish part categories

4. …..amount of inspections …

Raw material

Manufacturing Process

CONTROL KEY PROCESS PARAMETERS

Post - processing

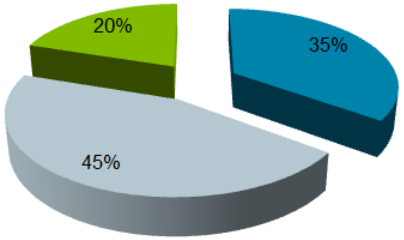
POST PROCESSING ACTIONS

Final Part

QUALITY INSPECTIONS

3. Tailor post processing....

5.… and test requirements



Examples

Example: possible tailoring of requirements for post processing treatment

Type of Parts	HIP	Support removal	Surface finish	Machining
Non-loaded/ remaining parts	✗	✓	As needed (*1)	As needed (*1)
Static sized	✗ (*2)	✓	As needed (*1)	✓ Contact surfaces
Fatigue sized	✓	✓	✓	✓ + fatigue critical areas as needed
Fatigue critical parts	✓	✓	✓	✓ + fatigue critical areas as needed

(*1) – as needed (for paint/primer, cosmetic, corrosion protection, secure crack inspection, tight tolerance for assembly…)

(*2) – When needed, HIP could be applied when low RFs. Qualif program should cover yes/no HIP.

Example: possible tailoring of requirements for quality inspections

Type of Parts	X-ray or CT	Penetrant	Visual	Surface Roughness
Non-loaded/ remaining parts	✗	✗	🔍 100%	✗
Static sized	🔍 Sampling	🔍 Sampling	🔍 100%	🔍 Sampling
Fatigue sized	🔍 Structural significant internal areas + high likelyhood	🔍 100%	🔍 100%	🔍
Fatigue critical parts	🔍 Structural significant internal areas + high likelyhood	🔍 100%	🔍 100%	🔍

Example: possible tailoring of requirements for quality testing

Type of Parts	PCS mechanical testing	PCS surface Roughness	PCS metallurgy
Non-loaded/ remaining parts			
Static sized	✓ Sampling, reduce further after process stability (Cpk and Ppk)	 Sampling	✓ Sampling, reduce further after process stability (Cpk and Ppk)
Fatigue sized	✓ Sampling, reduce further after process stability (Cpk and Ppk)		✓ Sampling, reduce further after process stability (Cpk and Ppk)
Fatigue critical parts	✓ 100%, then sampling after process stability (Cpk and Ppk)		✓ 100%, then sampling after process stability (Cpk and Ppk)

Conclusions

Stepwise approach for serial introduction

Currently high level of requirements in Qualification and Serial production

Tailor requirements to part categories as technology matures:

- Qualification
- Post processing treatment
- Quality inspections
- Process control specimens

Pre-requisites: Effect of defect understood & KPP are mastered/controlled

Thank you,

Do you have some Questions?

APPENDIX J—TEST AND MATERIAL ALLOWABLE DEVELOPMENT CONSIDERATIONS FOR ADDITIVE MANUFACTURING

Wichita State University

National Institute for Aviation Research

WHERE TEST PLANS BECOME **RESULTS**

Test and Material Allowable Development Considerations for Additive Manufacturing

Paul Jonas
Wichita State University
National Institute for Aviation Research
August, 2017

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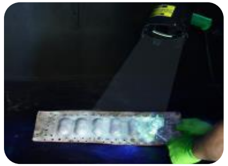
Electromagnetic Effects & Environmental Test Labs
Air Capital Flight Line
3501 S Oliver St, Wichita

NIAR LABORATORIES

Advanced Coatings

Aging Aircraft



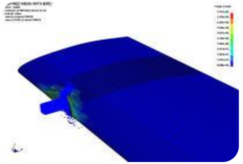
Ballistics/ Impact

CAD/CAM

CIBOR

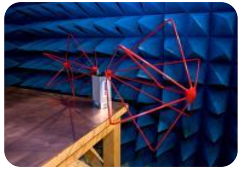
Composites

Computational Mechanics



Crash Dynamics

Electromagnetic Effects



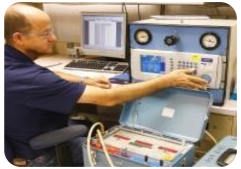
Environmental Test

Full-scale Structural Test

Human Factors

Mechanical Test

Metrology



NDT

Oil Analysis

Research Machine Shop

Reverse Engineering

Virtual Reality

Beech Wind Tunnel

NIAR ranks #1 in Industry Financed Aero R&D

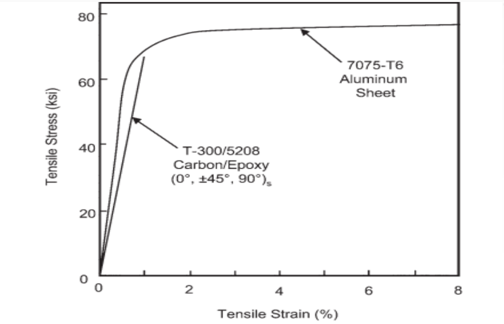
AM Design Allowables

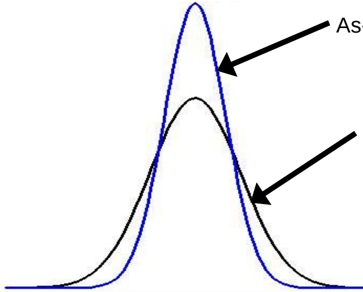
Design Allowable Development

- Additive Manufacturing is quickly moving from development to production and thus highlighting the need for reliable design allowables
  - Understanding the process for generating these allowables is as important as understanding the basic AM processes
  - Working with Industry and regulators provides a unique perspective on allowable development, status and issues.
- *The items provided today are for your consideration. Regulators and Standard Design Organizations will determine the final outcome.*
- *Any reference to the FAA and or EASA is only this authors perspective any and formal guidance should come directly from the requisite Certification Office.*

Design Allowable Status

- Material behavior and variability varies widely between material types, processes and machines.
- Additively manufactured materials are relatively new and have not been extensively studied in terms of factors affecting variability.
- AM contains more process variables that can have an effect on process variability
- Experience with other process dependent materials, like composites, shows that we need to generate a substantial amount of data to properly characterize the behavior and create statistical guidance.





As-Measure Data Usually Has Smaller Scatter

Actual Production Data Usually Has Larger Scatter

Source: Structural Composite Materials, F.C. Campbell

Little Standard Public Data Available

Regulatory Guidance

- FAA Regulations governing materials - CFR 14 2x.603, 605, 613
  - 603 – Shown by test to be suitable and purchased to approved specifications
  - 605 - Shown by test to produce repeatable processes
  - 307 – Analytical tools must be demonstrated by experience or test
  - 613 – Design Values must be generated by test using approved materials and process specifications.

Statistical Validation of the Processes

- Design Value Considerations
  - Stock Materials – Purchased to meet specifications – MMPDS, AMS, etc..
  - Externally Engineered Materials – Variability in process introduced in process – EG: Forgings and castings
  - Internally Engineered Materials – Material and form produced during the part fabrication. Fabrication controls most of product performance and variation

Part Conformity is a Process not an Event

Transitions in Manufacturing

- Material Based - Conventional
  - Purchase stock material, cut, machine, bend form, etc,
  - Not much variation in material, good understanding how the process and the addition of design features affect part performance
    - Standard and well practiced QA
  - Companies invest in feature based design allowables - DRM
    - Bend, fillet radius, fastener spacing, splice joint configurations, standard extrusions, etc…
  - Scales easily to production and site to site.

- Process Based - AM
  - Little general understanding of the material and part to part variations
    - Process optimized to specific part
    - Little understanding of process changes
    - Subjective QA
    - Part is typically certified as a point design
  - Companies store lessons learned and try and extrapolate part knowledge to processes controls.
    - Little information on how design and build features affects material performance.
  - Processes difficult to scale and replicate

AM Shifts Sources of Variability

- Material Based
  - Material is produced in large batches
  - Easy to verify and replicate
  - Process for making parts has little effect on the material variation
- Process Based
  - Makes parts - not material in small batches
  - The batch is were most of the process variation is introduced
  - More difficult to predict part performance.

AM Combines part and material variation

Process Sensitive Qualifications

The Composites Approach

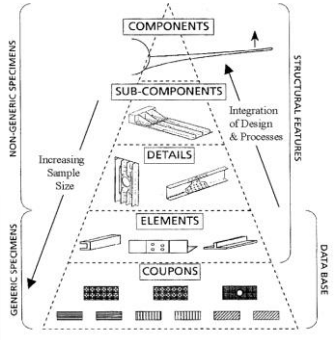
- Composites are a Process Sensitive Material
  - Material is typically not in final form
  - Requires process to make parts (material)
- NCAMP is a process utilized to develop design allowables
  - Utilizes an Equivalency process to qualify other manufactures and installations
  - Currently working on developing process to include polymer based Additive Manufactured materials within NCAMP

Utilize the processes and structure for AM design allowables.

What Does NCAMP Produce?

- Industry-shared materials and process specifications
- Industry-shared material property data and allowables
  - ✓ May fulfill some coupon level building block requirement

Most are available publicly



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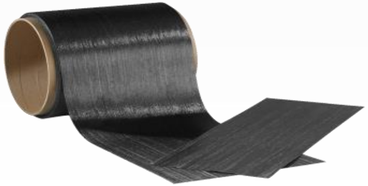
NCAMP
NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

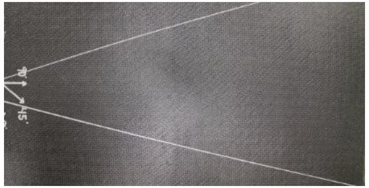
Focuses on *basic* lamina & laminate properties in support of higher level building blocks

http://www.niar.wichita.edu/coe/ncamp.asp

Equivalency Process Overview



Prepreg from
Material Supplier



Composite Panel
Fabricated by
Equivalency
Companies

Specimens Machined
by NCAMP

Specimens Tested by
NCAMP

If Equivalency is demonstrated, Qualification’s data may be used in certified aircrafts such as:

- Materials and Processes Specifications
- Material Property data and Allowables

NCAMP Polymer AM

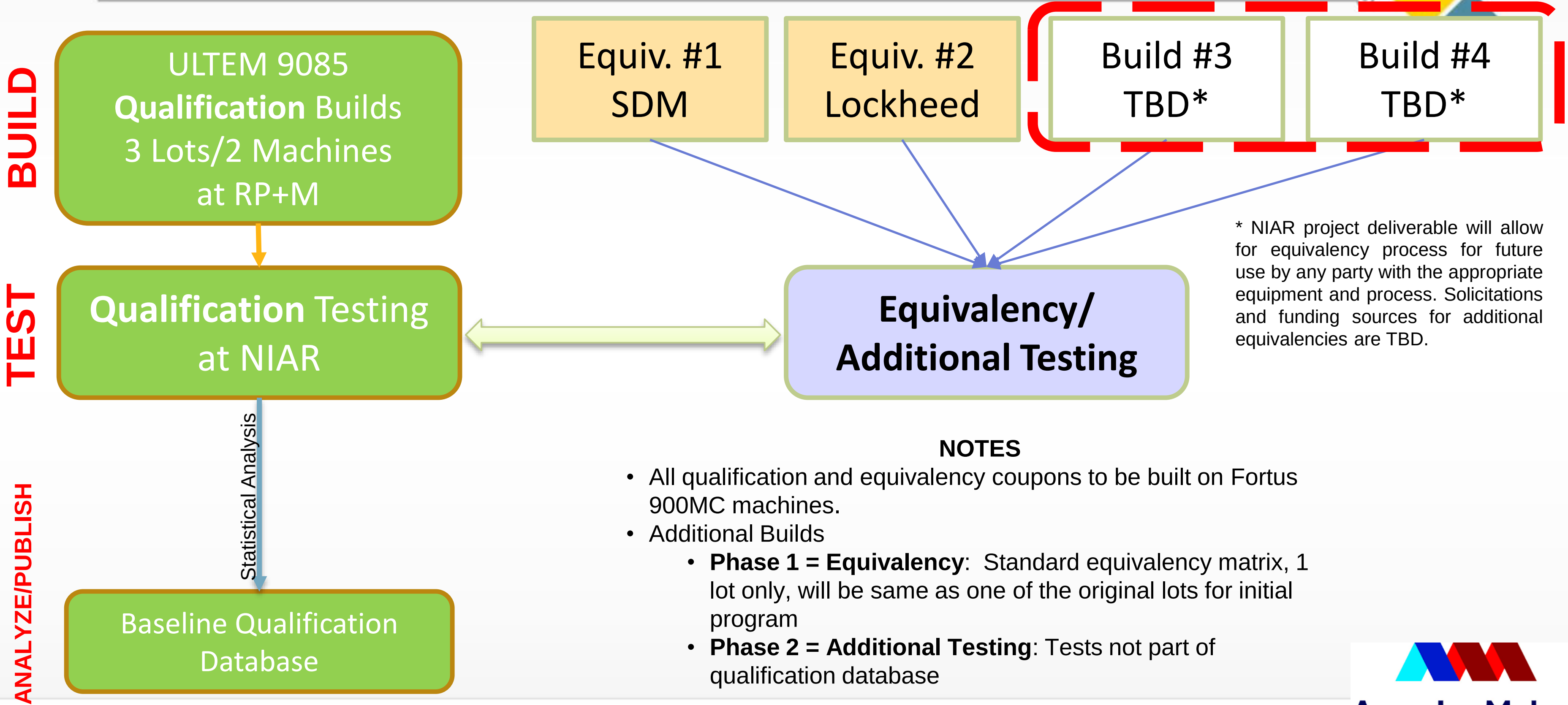
Technical Approach

- Develop a framework to advance polymer-based additively manufactured materials into the aerospace industry.
- Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.
- Assess the validity with equivalency testing.

9/2016 - 12/2016	11/2016 - 2/2017	2/2017 - 11/2017	10/2017 – 3/2018	3/2018 – 12/2018
Establish Steering Committee	Develop Qualification Framework	**Validate framework with selected Polymer AM material**	Establish statistical guidelines	Transition -Data and guidance to CMH-17 - Specifications to SAE

QUALIFICATION

ADDITIONAL BUILDS



BUILD

ULTEM 9085
Qualification Builds
3 Lots/2 Machines
at RP+M

TEST

Qualification Testing
at NIAR

Statistical Analysis

ANALYZE/PUBLISH

Baseline Qualification
Database

Equiv. #1
SDM

Equiv. #2
Lockheed

Build #3
TBD*

Build #4
TBD*

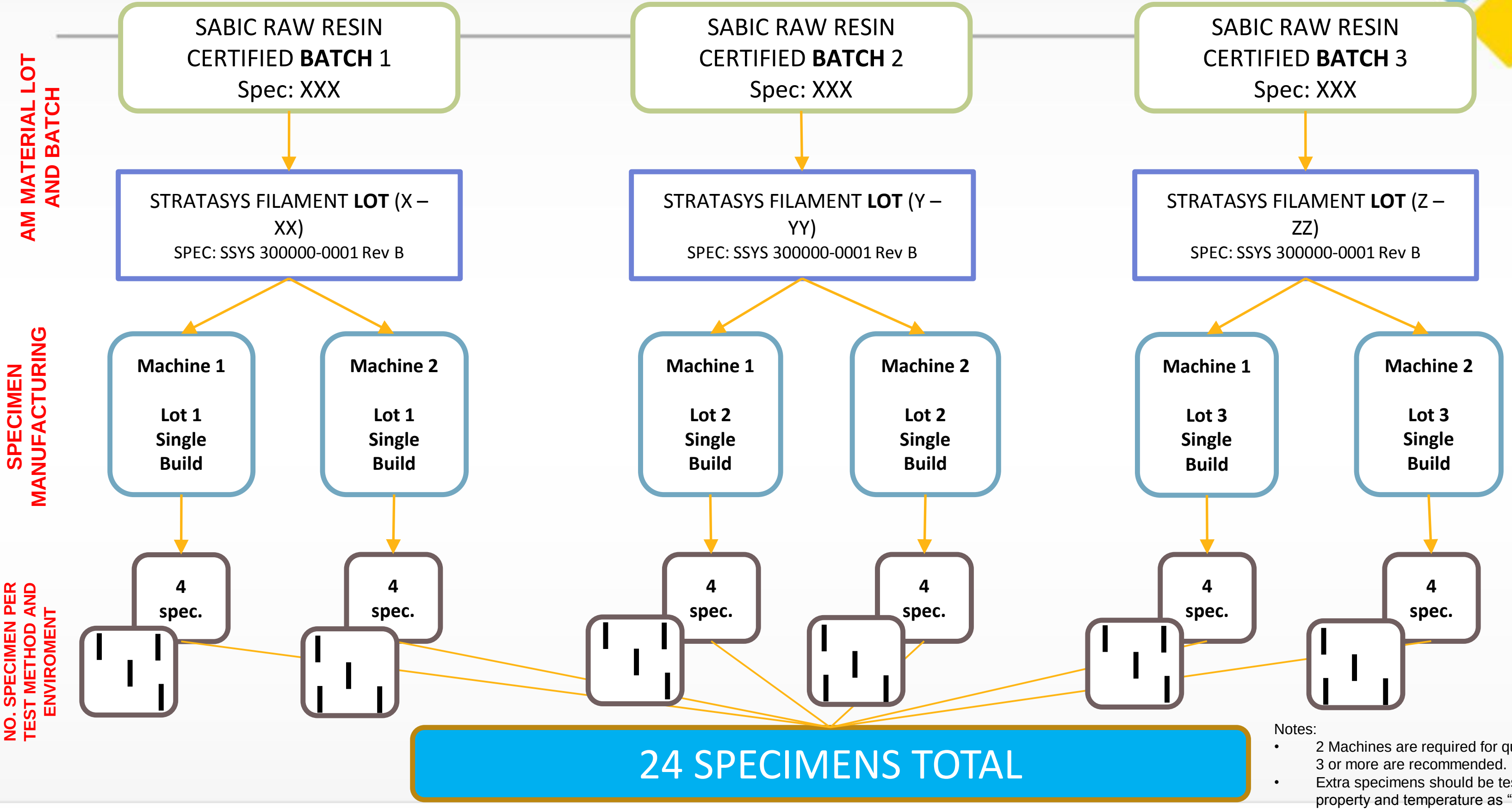
Equivalency/
Additional Testing

* NIAR project deliverable will allow for equivalency process for future use by any party with the appropriate equipment and process. Solicitations and funding sources for additional equivalencies are TBD.

NOTES

- All qualification and equivalency coupons to be built on Fortus 900MC machines.
- Additional Builds
  - **Phase 1 = Equivalency**: Standard equivalency matrix, 1 lot only, will be same as one of the original lots for initial program
  - **Phase 2 = Additional Testing**: Tests not part of qualification database

ULTEM 9085 QUALIFICATION PLAN



AM MATERIAL LOT AND BATCH

SABIC RAW RESIN CERTIFIED **BATCH** 1
Spec: XXX

SABIC RAW RESIN CERTIFIED **BATCH** 2
Spec: XXX

SABIC RAW RESIN CERTIFIED **BATCH** 3
Spec: XXX

STRATASYS FILAMENT **LOT** (X – XX)
SPEC: SSYS 300000-0001 Rev B

STRATASYS FILAMENT **LOT** (Y – YY)
SPEC: SSYS 300000-0001 Rev B

STRATASYS FILAMENT **LOT** (Z – ZZ)
SPEC: SSYS 300000-0001 Rev B

SPECIMEN MANUFACTURING

Machine 1
Lot 1
Single Build

Machine 2
Lot 1
Single Build

Machine 1
Lot 2
Single Build

Machine 2
Lot 2
Single Build

Machine 1
Lot 3
Single Build

Machine 2
Lot 3
Single Build

NO. SPECIMEN PER TEST METHOD AND ENVIROMENT

4 spec.

4 spec.

4 spec.

4 spec.

4 spec.

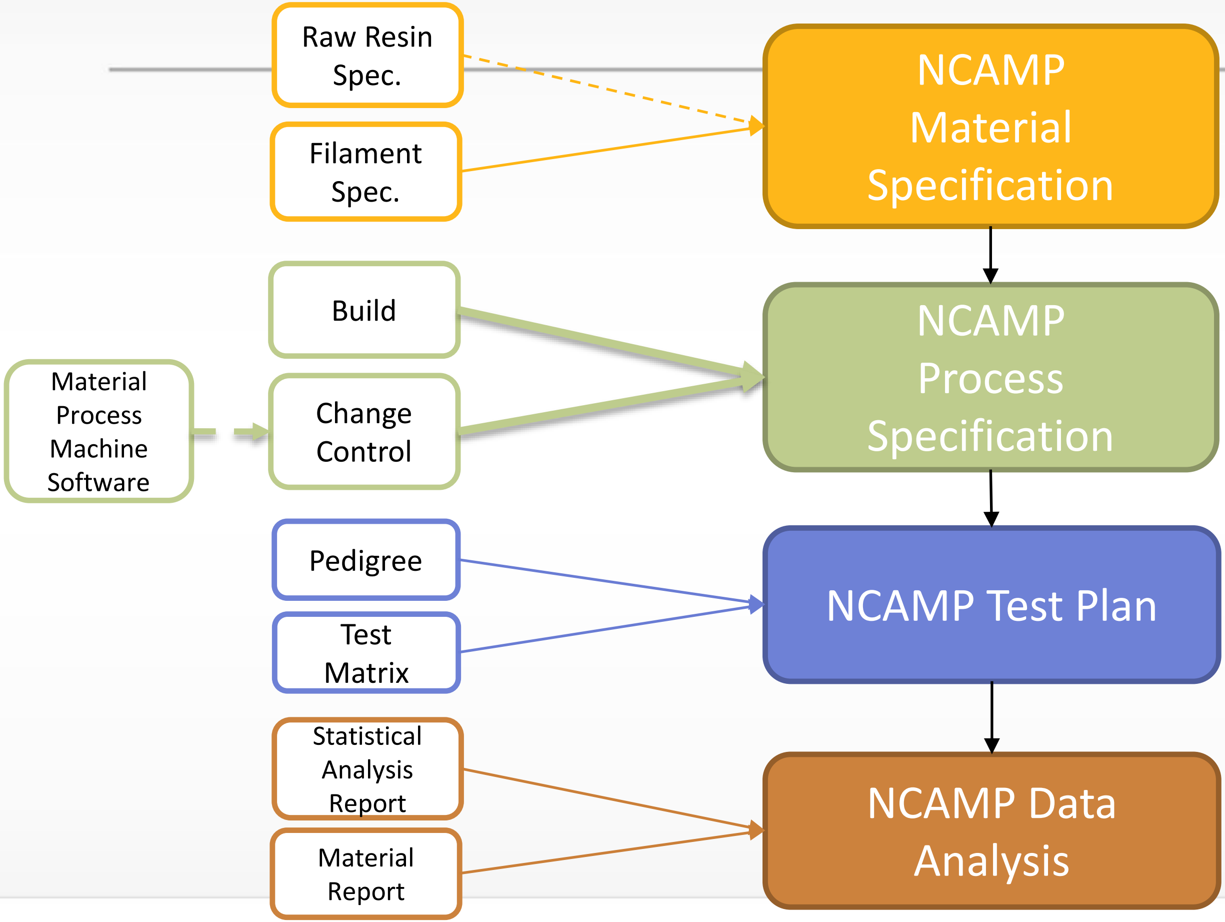
4 spec.

24 SPECIMENS TOTAL

Notes:

- 2 Machines are required for qualification however 3 or more are recommended.
- Extra specimens should be tested for each property and temperature as “spares” to ensure desired quantity (min of 3 specimens).

NCAMP DOCUMENTATION STATUS



Raw Resin Spec.

Filament Spec.

NCAMP Material Specification

Build

Material Process Machine Software

Change Control

NCAMP Process Specification

Pedigree

Test Matrix

NCAMP Test Plan

Statistical Analysis Report

Material Report

NCAMP Data Analysis

STATUS

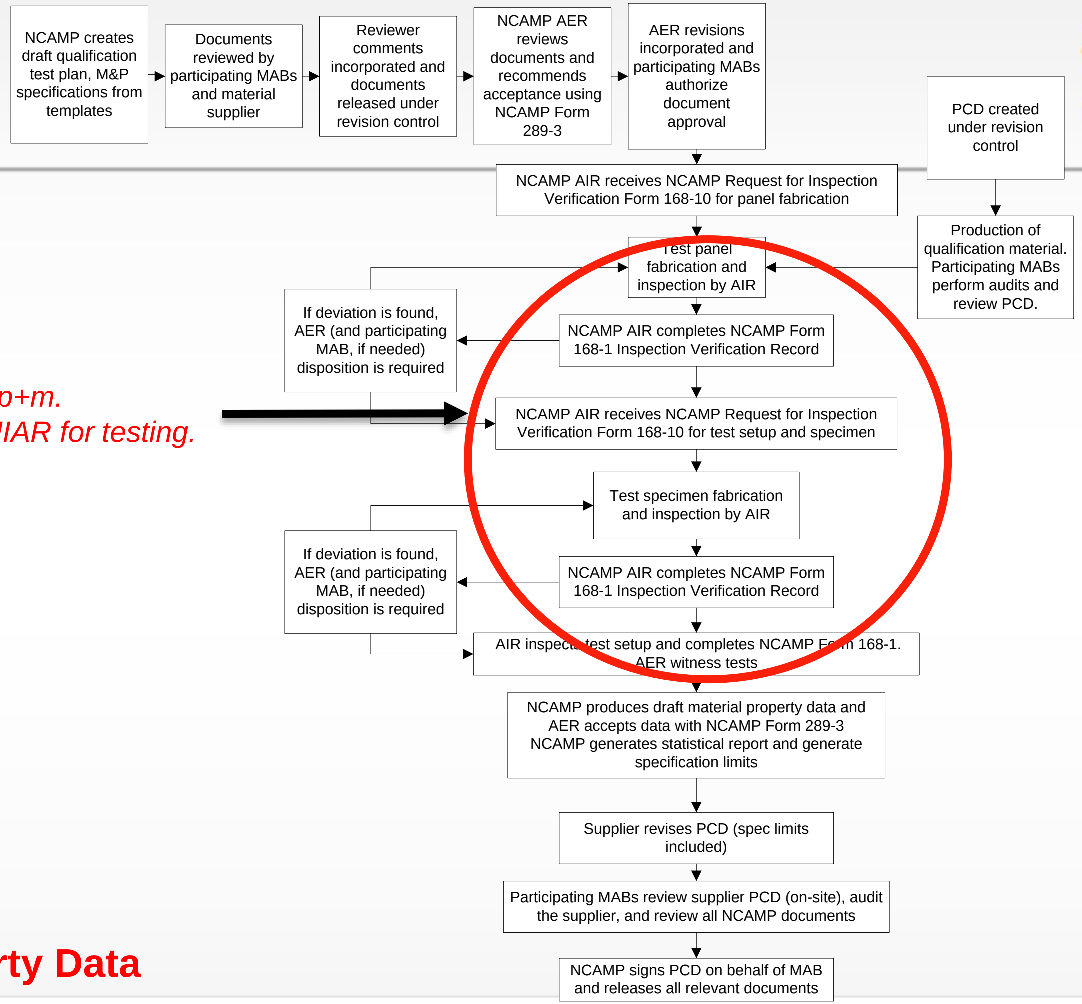
- Final drafts of material and process specs are complete (will be available to the team after testing is complete)
- Build and Pack files included to reduce variation.

- Test Plan finalized
- Equivalency test plan being drafted
- Site Inspections – complete

Controlling the process is essential to success.

Flowchart of Material Qualification and Property Data Acquisition Process

Coupon builds are continuing at rp+m.
Coupons are being delivered to NIAR for testing.



NCAMP creates draft qualification test plan, M&P specifications from templates

Documents reviewed by participating MABs and material supplier

Reviewer comments incorporated and documents released under revision control

NCAMP AER reviews documents and recommends acceptance using NCAMP Form 289-3

AER revisions incorporated and participating MABs authorize document approval

PCD created under revision control

NCAMP AIR receives NCAMP Request for Inspection Verification Form 168-10 for panel fabrication

Production of qualification material. Participating MABs perform audits and review PCD.

Test panel fabrication and inspection by AIR

NCAMP AIR completes NCAMP Form 168-1 Inspection Verification Record

If deviation is found, AER (and participating MAB, if needed) disposition is required

NCAMP AIR receives NCAMP Request for Inspection Verification Form 168-10 for test setup and specimen

Test specimen fabrication and inspection by AIR

NCAMP AIR completes NCAMP Form 168-1 Inspection Verification Record

If deviation is found, AER (and participating MAB, if needed) disposition is required

AIR inspects test setup and completes NCAMP Form 168-1. AER witness tests

NCAMP produces draft material property data and AER accepts data with NCAMP Form 289-3 NCAMP generates statistical report and generate specification limits

Supplier revises PCD (spec limits included)

Participating MABs review supplier PCD (on-site), audit the supplier, and review all NCAMP documents

NCAMP signs PCD on behalf of MAB and releases all relevant documents

Ongoing Industry Research

KART Research - Ongoing

- Build and Coupon Sensitivity Study
  - Basic study of test methods and build strategies
- Surface finish enhancement study
  - Additive and subtractive processes and effect on part performance
- Validity and limits of material allowables based on coupon and build geometries
  - Help define limits of how coupons are made and parts they represent
- Use of the Witness Coupon
  - How are they used and what data can be extracted relative to part performance

Answering Industry Driven Questions

For Your Consideration

Observations and Lessons so far

- Companies slow to include AM in production processes – DVT vs production
- Need for machine maintenance plans
  - How do you know that the machine is capable of producing conforming material? What causes bad builds?
- Configuration control is bigger than we thought and needs control
  - Machine maintenance and hardware
  - Build and pack files, orientation, location
  - Operators & training vs best practice

- Don't assume ~~everyone~~ anyone knows the definitions
- Need to remove subjective nature of QA – What constitutes a good part
  - Definitions, limits, methods all need definition
  - Some processes have unique features, and defects to consider
  - What does the witness coupon provide and how is it used?
- Material Control Matters
  - Not all wire is equal, know your powder.

Aerospace OEM's farther along in a TC/PC approach to AM.

Insight into the AM Project

America Makes Project 3003

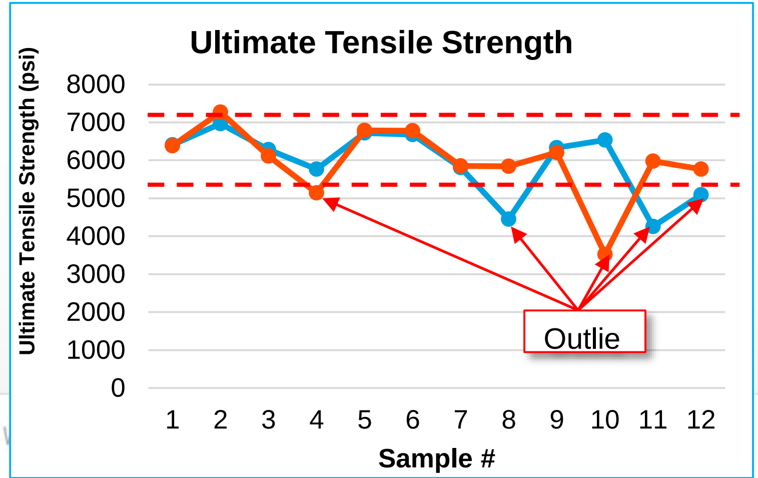
- Develop Material Allowables for the FDM Process and Ultem 9085
  - Understood to be a Mature Process widely utilized by industry
  - First Phase of testing revealed large variability in the results
  - Extensive root cause test and analysis found process induced defects
  - Required hardware and software upgrades

Many Process Changes Incorporated Need to Address Variability.

Defect Characterization

- Defects categorized into 11 different types via fractography
- Defects occur in every batch (12 samples)
- Burnt material (T1) appeared in ~40% of the lowest performers and was found to be the driving defect in 80% of those samples
- Burnt material also produced the highest and most consistent knockdown in UTS out of all other defects

Defect Type	Description
T1	Burnt material
T2	Microstructure anomaly (exterior)
T3	Microstructure anomaly (interior)
T4	Poor Interlayer adhesion (contour)
T5	Poor interlayer adhesion (raster)
T6	Poor contact area (contour)
T7	Poor contact area (raster)
T8	Voids
T9	Bead width variation (contour)
T10	Bead width variation (raster)
T11	Abnormal porosity

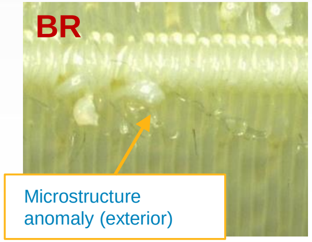


Defect Characterization: Defect Types

T1

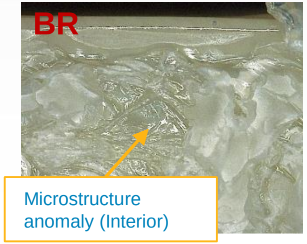
Burnt material

T2



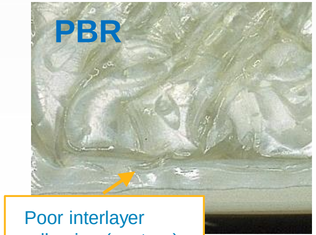
Microstructure anomaly (exterior)

T3



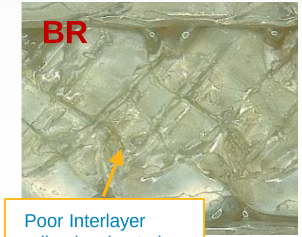
Microstructure anomaly (Interior)

T4



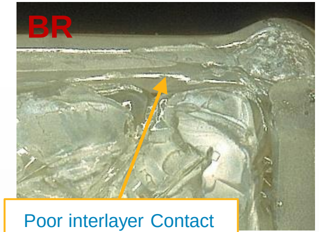
Poor interlayer adhesion (contour)

T5



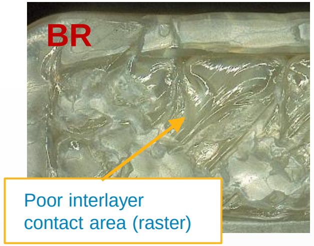
Poor Interlayer adhesion (raster)

T6



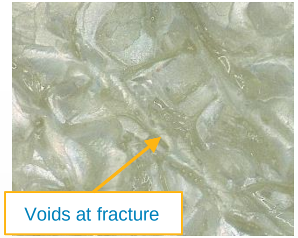
Poor interlayer Contact area (Contour)

T7



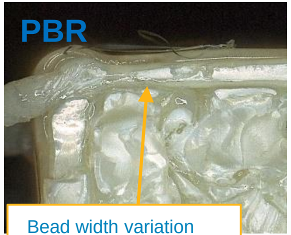
Poor interlayer contact area (raster)

T8



Voids at fracture

T9

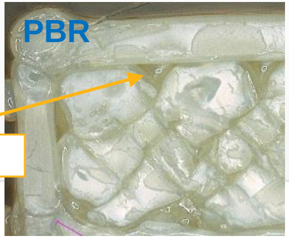


Bead width variation (contour)

T10

Bead width variation (Raster)

T11

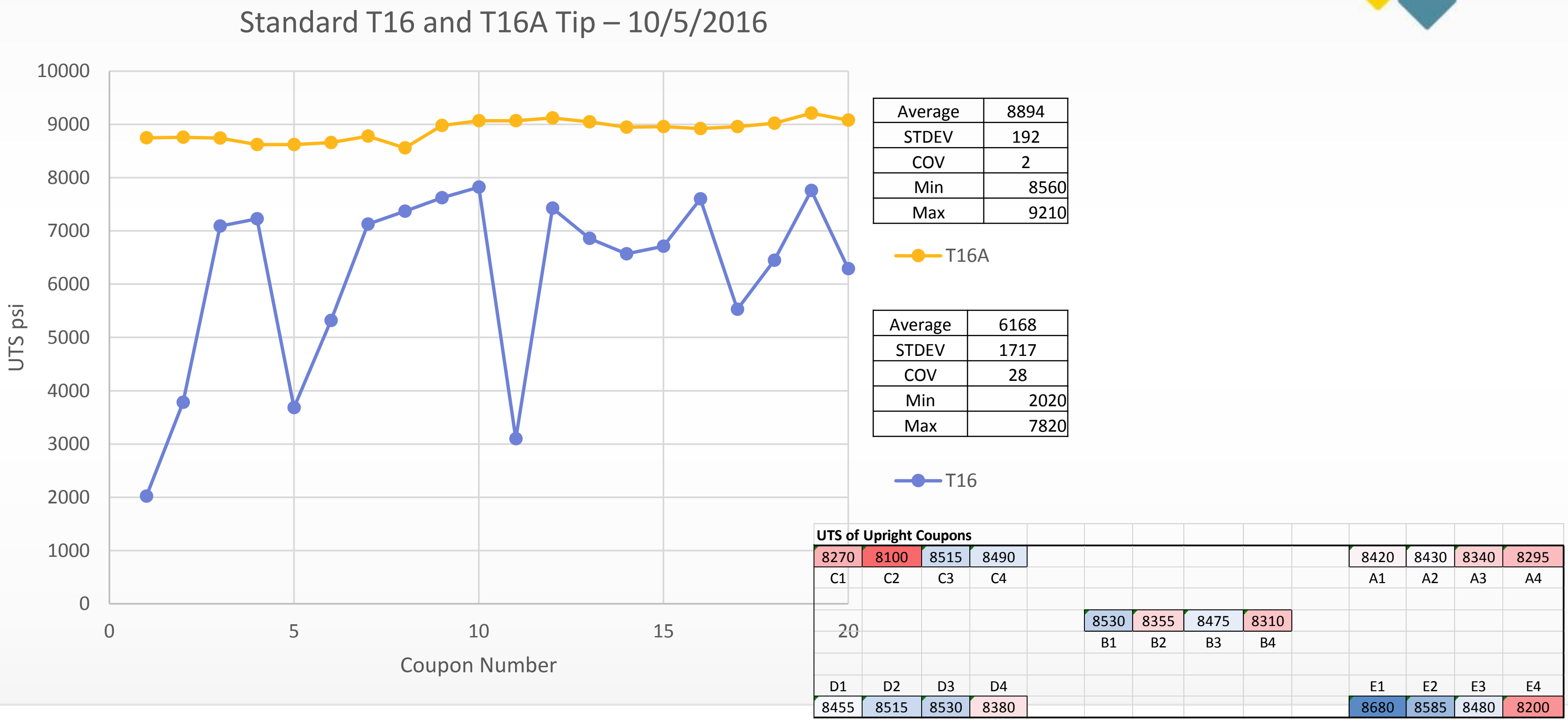


Abnormal Porosity

BR: Build Up related

PBR: Potential Build Up related

Strength data – Todays Standard T16 vs T16A



Average	8894
STDEV	192
COV	2
Min	8560
Max	9210

Average	6168
STDEV	1717
COV	28
Min	2020
Max	7820

UTS of Upright Coupons

8270	8100	8515	8490					8420	8430	8340	8295
C1	C2	C3	C4					A1	A2	A3	A4
				8530	8355	8475	8310				
				B1	B2	B3	B4				
D1	D2	D3	D4					E1	E2	E3	E4
8455	8515	8530	8380					8680	8585	8480	8200

Test Considerations

- Cannot print a coupon
  - Near net shape and final machining required
- Need to understand how build features will affect the coupon
  - Some print routines will provide a boundary and fill
  - What defines a material property vs a build feature - Holes
  - Need to capture process variability and not build features or variation in test
- Surface finish affects fatigue characteristics
  - Most other testing is not a significant item
- Need to understand the limits of the data produced to parts they represent
  - Limits on thicknesses?
- Post processing matters
  - Sequence and process needs exact definition.
  - Understand physical limits

Other Considerations

- Need to Emphasize Building Block Approach
  - Build features and material data may not correlate
  - Need feature based data – Like Design Handbook
- Not all build features and options are included in Qual
  - Material Data applies to a limited set of parameters
    - Equivalency needed for change to parameter or cross hatching routine

Going Forward

- Developing test methods and framework for AM material allowables is important
  - It is all about process and prescriptive specifications
- Not all AM materials and processes are ready for aerospace
- Need clear definition of material property vs design features
- Specification Limits, how they are generated and how they are used needs definition, development and discussion.
- Watch Polymer process and determine if framework can be pulled over to metallics
  - An Equivalency process is a good thing

Thank you...

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APPENDIX K—NAVAIR AM OVERVIEW

NAVAIR AM Overview

August 29, 2017

Presented To:

3rd Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured Parts

Presented By:

Dr. William Frazier and Ms. Liz McMichael, NAVAIR

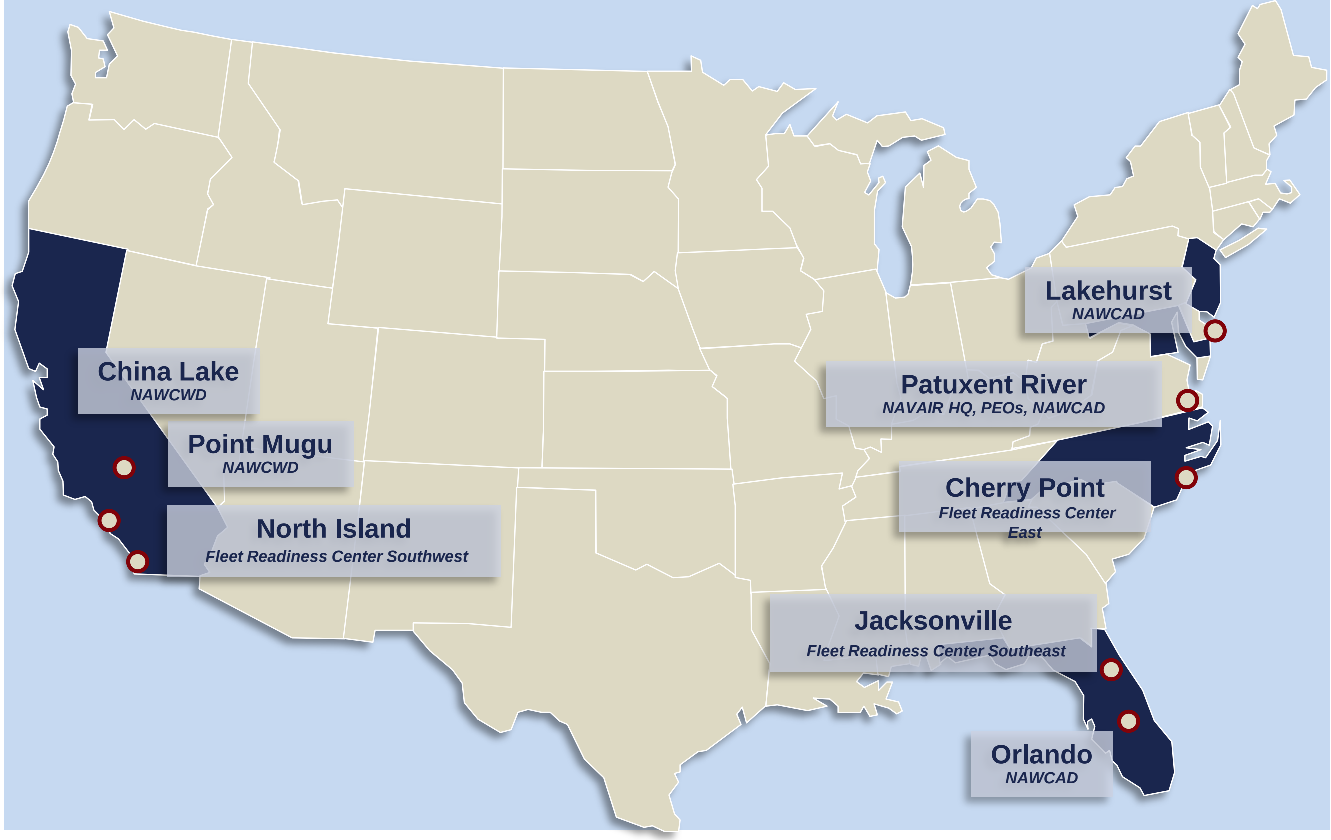
Acknowledgements:
Mr. Cifone, Deputy Assistant Commander for Research and Engineering

NAVAIR's Role in Naval Aviation

- Develop, acquire and support Navy and Marine Corps aircraft, weapons and related systems
- Increase Navy & USMC capability, readiness and affordability in a joint / coalition environment

NAVAIR Snapshot

Full Life-Cycle Management



27,298 Civilians	**1,654** Military	**8,875** Contractors

FY16 Workforce Numbers

Products

Tactical Aircraft

Air ASW, Assault & Special Mission

Unmanned Aircraft & Strike Weapons

Common Systems, Mission Systems, Training, ALRE

NAVAIR Products

Fixed Wing

A/C Launch & Recovery

Rotorcraft

Unmanned Air Systems

Weapons

Training Systems

Delivering Results

Tactical Aircraft

Unmanned Aircraft & Strike Weapons

Air Anti-Submarine Warfare (ASW), Assault & Special Mission

Actual FY16 Deliveries

136 New Aircraft

15,108 Missiles / Bombs

129 Unmanned Air Vehicles (UAV)

6 UAV Ground Systems

41 Training Devices

494 Aircraft Repairs

1,777 Engine Repairs

68,893 Component Repairs

4,506 Support Equipment Repairs

Test & Evaluation Ranges

Common Systems/Mission Systems/Training

Fleet Readiness Center Industrial Facilities

NAVAIR Airworthiness Authority

- NAVAIR has statutory authority for airworthiness approval for Navy and Marine Corps
  - Equivalent of FAA certification for civilian aircraft

Linking AM to NAVAIR Imperatives

Ready to Fight Tonight. Capabilities and Capacity to Win the Future.

1. Readiness

Parts on Demand

Distributed Supply Chain

Local Repair

2. Increased Speed to the Fleet

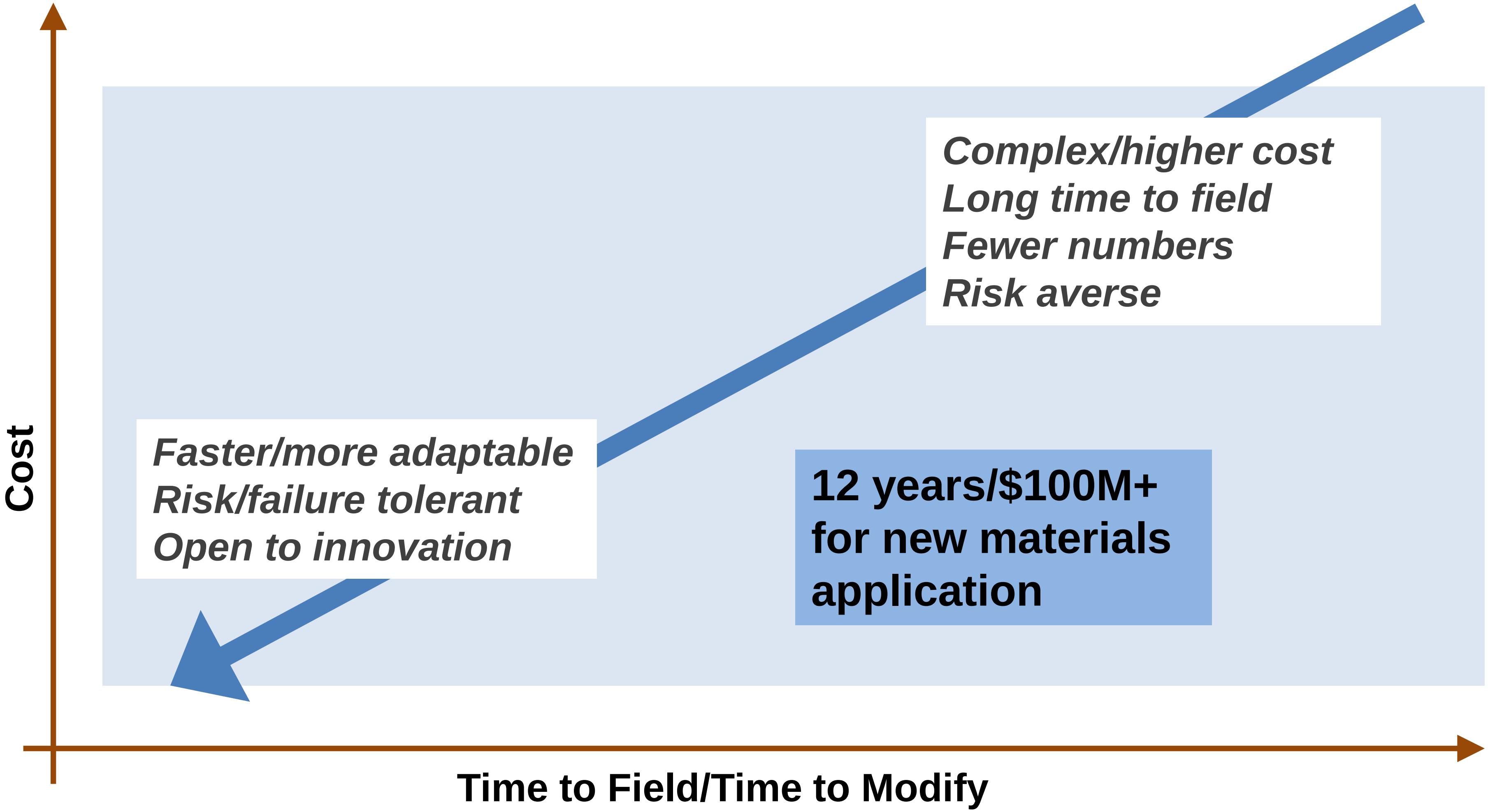
Small, Empowered Teams

Better Requirements Informed by Experimentation

Prototyping and Experimentation at all Levels

Understanding and Acceptance of Appropriate Risk

Turning the Tide



Complex/higher cost
Long time to field
Fewer numbers
Risk averse

Faster/more adaptable
Risk/failure tolerant
Open to innovation

12 years/$100M+ for new materials application

How do we reverse this trend?

Additive Manufacturing

Operationalize AM across solution space – Deliver high value AM capacity

NAVAIR AM Roadmap – Path Forward

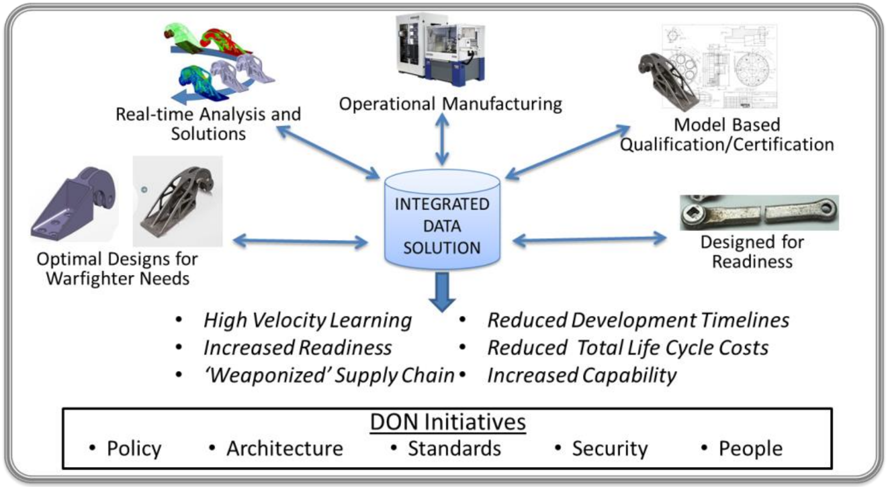
1. AM for Readiness and Sustainment
2. Enabling/Expanding Warfighter Capabilities
3. Enterprise Enablers
4. Digital Workforce


V-22 Flight Critical Part

NAVAIR/DON AM Standards


Warfighter Fabrication and Education (i.e. Fab Labs)

Digital Thread - Enterprise


Real-time Analysis and Solutions

Operational Manufacturing

Model Based Qualification/Certification

INTEGRATED DATA SOLUTION

Optimal Designs for Warfighter Needs

Designed for Readiness

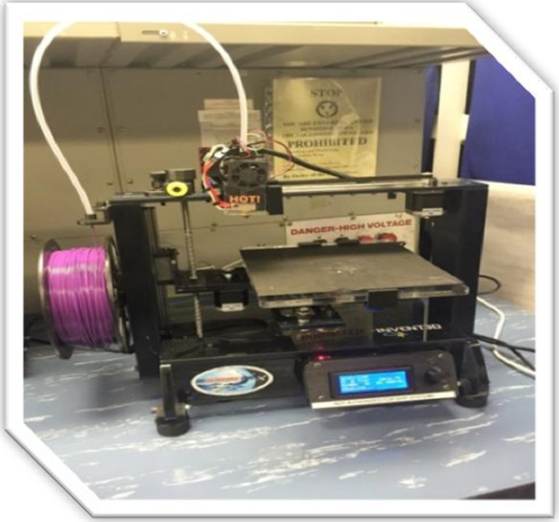
- *High Velocity Learning*
- *Increased Readiness*
- *'Weaponized' Supply Chain*
- *Reduced Development Timelines*
- *Reduced Total Life Cycle Costs*
- *Increased Capability*

DON Initiatives
- Policy
- Architecture
- Standards
- Security
- People

Complete, Secure, Authoritative Data Enables Advanced Manufacturing and Digital Supply Chain

Deliver AM Capabilities to Address Key Readiness Drivers

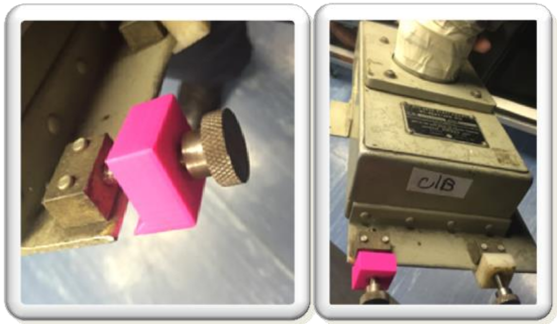
Fleet Success Stories



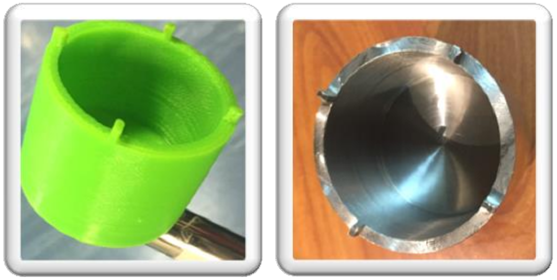
CVN-75 3-D Fabrication Lab

MH-60 Dipping Sonar Storage Cover

F/A-18 Nitrogen Purge Kit Fitting



Radar Test Bench Set Air Plenum Fixture Clamp



F/A-18C/D Signal Data Computer Spanner Tool

Hydra Radio “Tru-Clip”

Airworthiness and AM

Systems Engineering

Optimized and Customized Designs
Accelerated Development and Production

New Materials
Qual & Certification

Safety & Technical Risk

AIRWORTHINESS

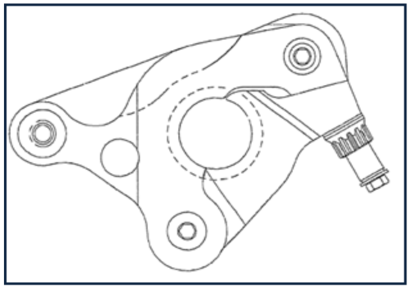
Training & Training Devices

AM and Workforce
Accelerated Training

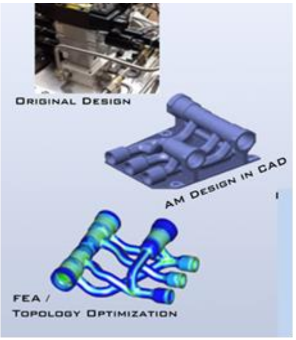
Continuous Airworthiness

Customization
Configuration Management

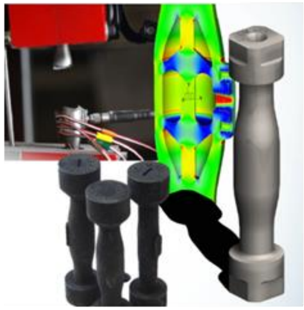
Revolutionize Airworthiness to reap the benefits of AM



On Demand Parts



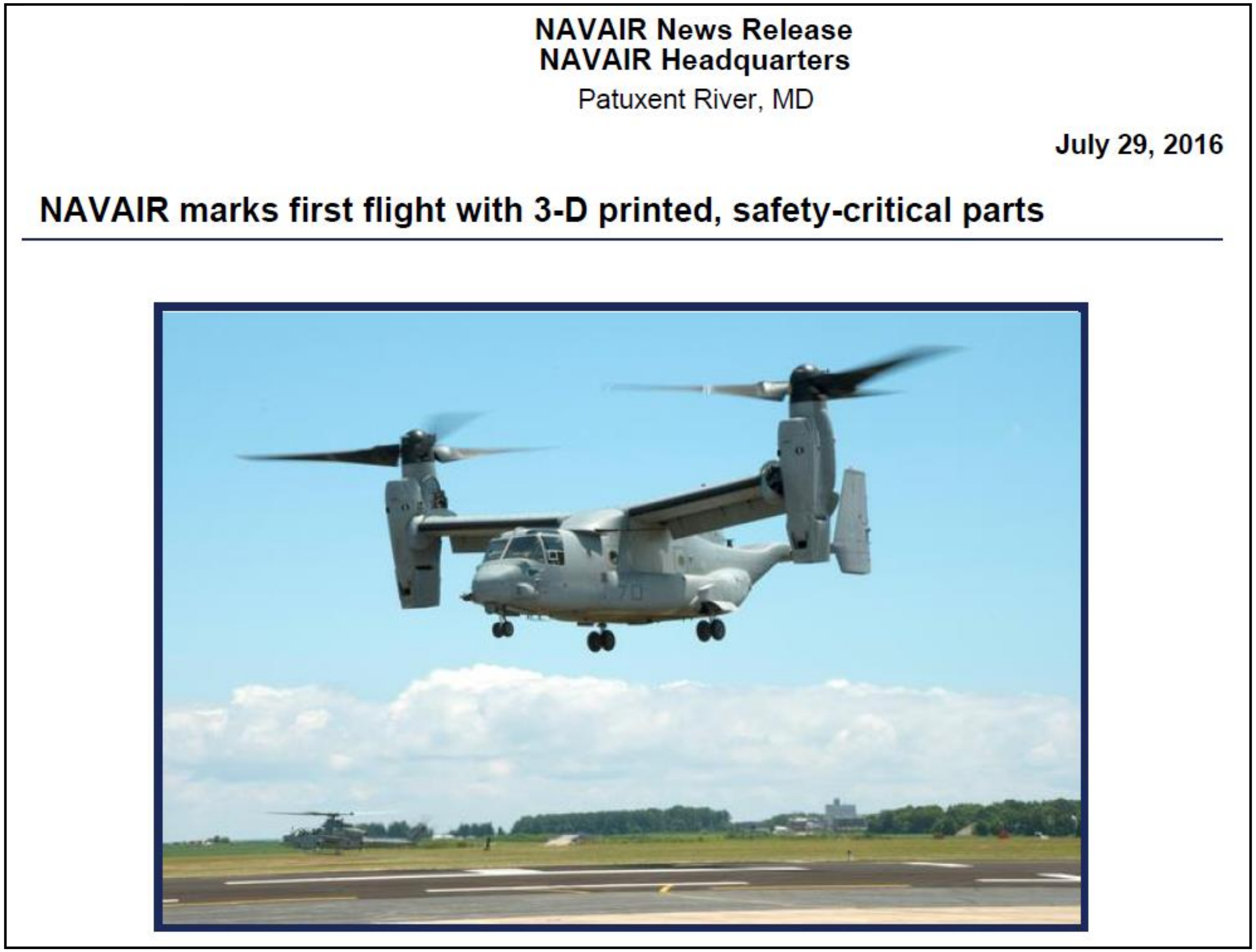
Optimized Design



Embedded Sensors

First Flight of a Safety-Critical AM Part

- Better fatigue life than forged part
- Qualified for full life
- Fleet introduction



NAVAIR News Release
NAVAIR Headquarters
Patuxent River, MD

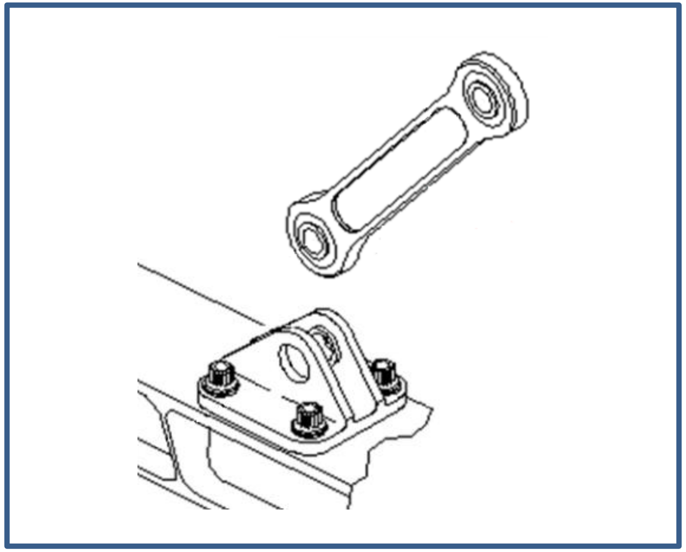
July 29, 2016

NAVAIR marks first flight with 3-D printed, safety-critical parts

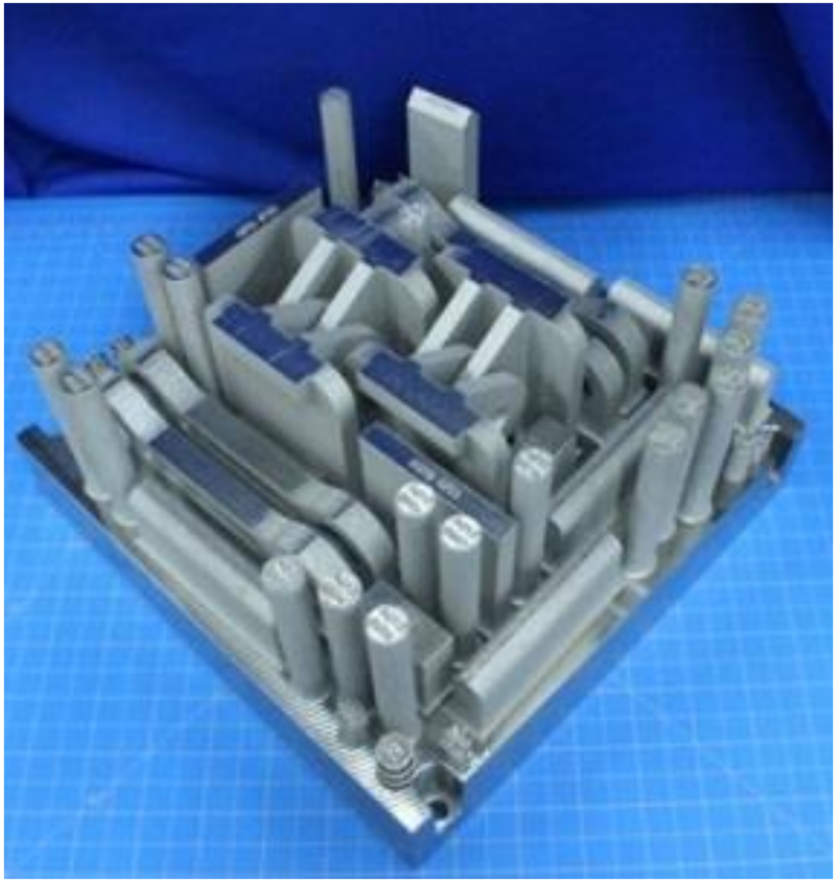
Ref: NAVAIR News Release, July 29, 2016

V-22 Flight Critical Part AM Build Design

V-22 Nacelle Link and Fitting



Parts & Coupons / Build



8 Parts	36 Test Coupons	20 Witness Coupons
• 4 Links	• 18 Z tensile/fatigue	• 5 Complex fit
• 4 Fittings	• 12 In-plane tensile/fatigue	• 2 Angle test
	• 4 C(T) fracture toughness	• 4 Density cylinder
	• 2 C(T) crack growth	• 1 Powder coffin
		• 1 Parameter grid

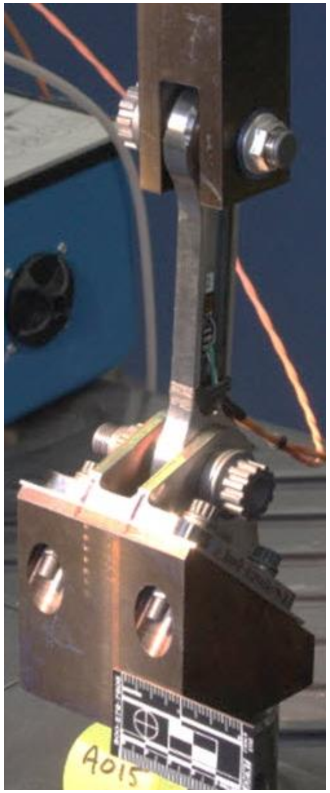
NAVAIR AM Process

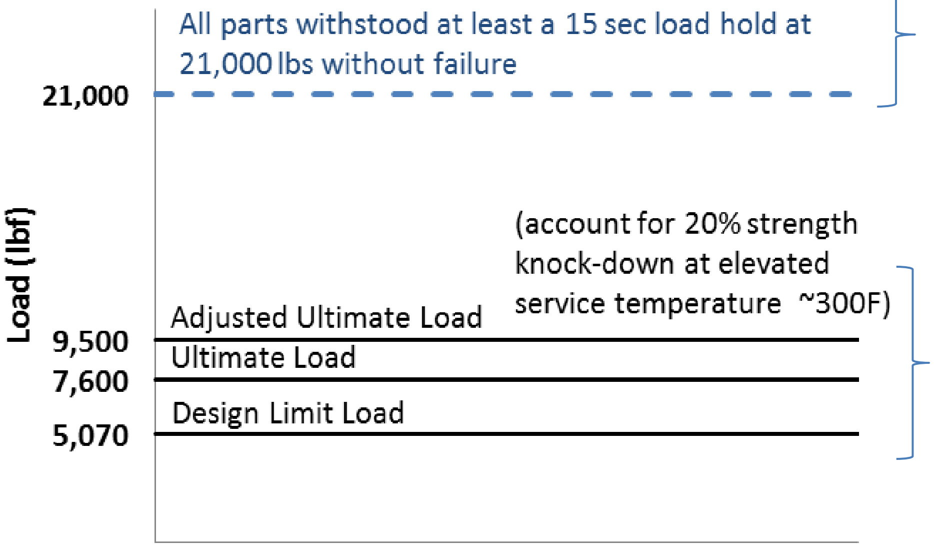
- Powder Characterization – Virgin vs Reused
- Printing Parameters – Machine Baseline
- Post Processing – HIP
- Witness Coupons – AM Build Process Stability
- Test Coupons – Tensile, Fatigue, Fracture Toughness
- Finish Machining
- Component Testing – Static and Fatigue

20 Months = Start to First Flight

Accelerated Development of Statistically Significant Data for Airworthiness

V-22 AM Component Static Test Results





All parts withstood at least a 15 sec load hold at 21,000 lbs without failure

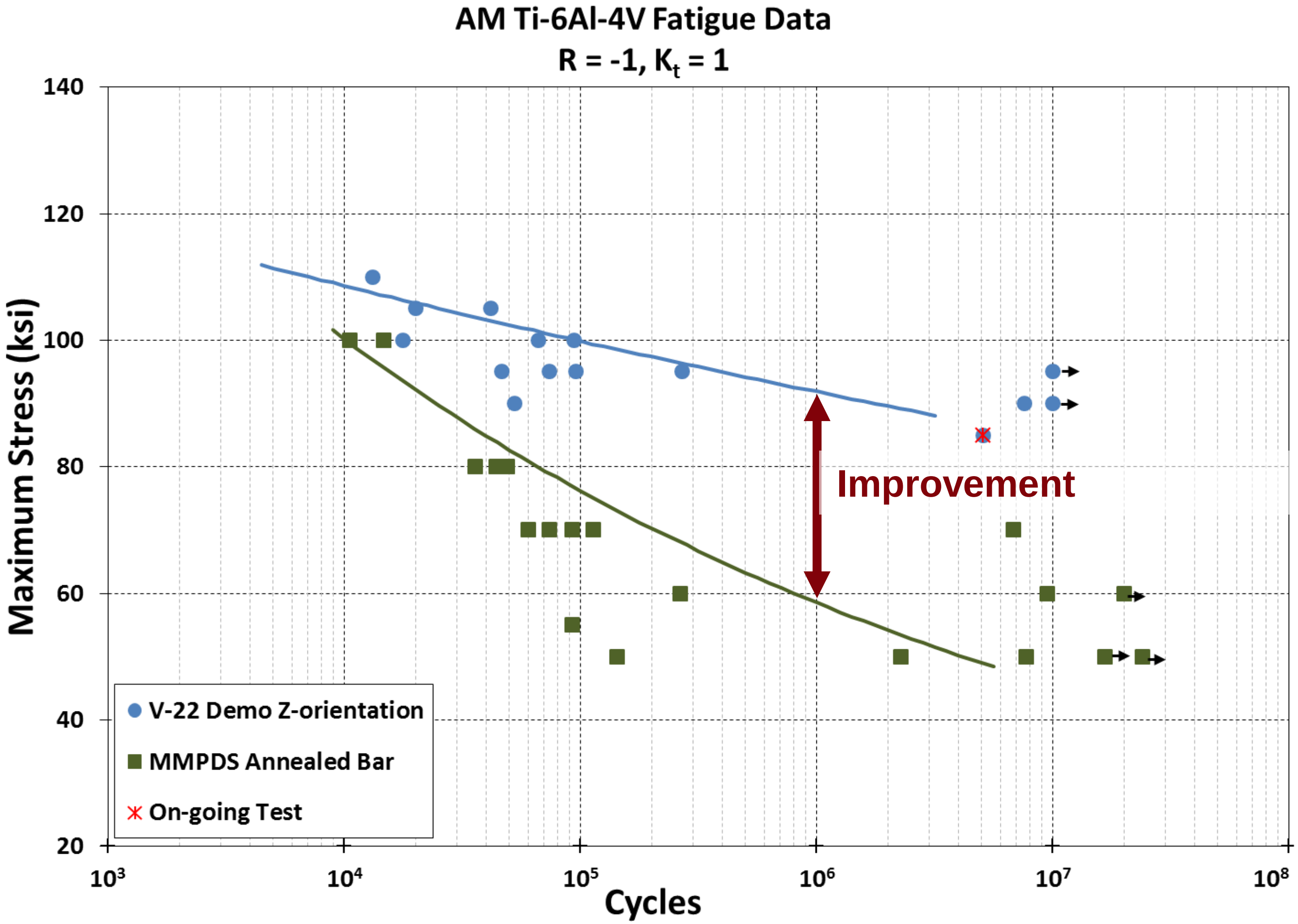
(account for 20% strength knock-down at elevated service temperature ~300F)

AM Part Performance (4 assemblies tested)

Part Requirements

Ti-64 Fatigue: AM Versus Wrought Bar

Fatigue behavior exceeds that of bar

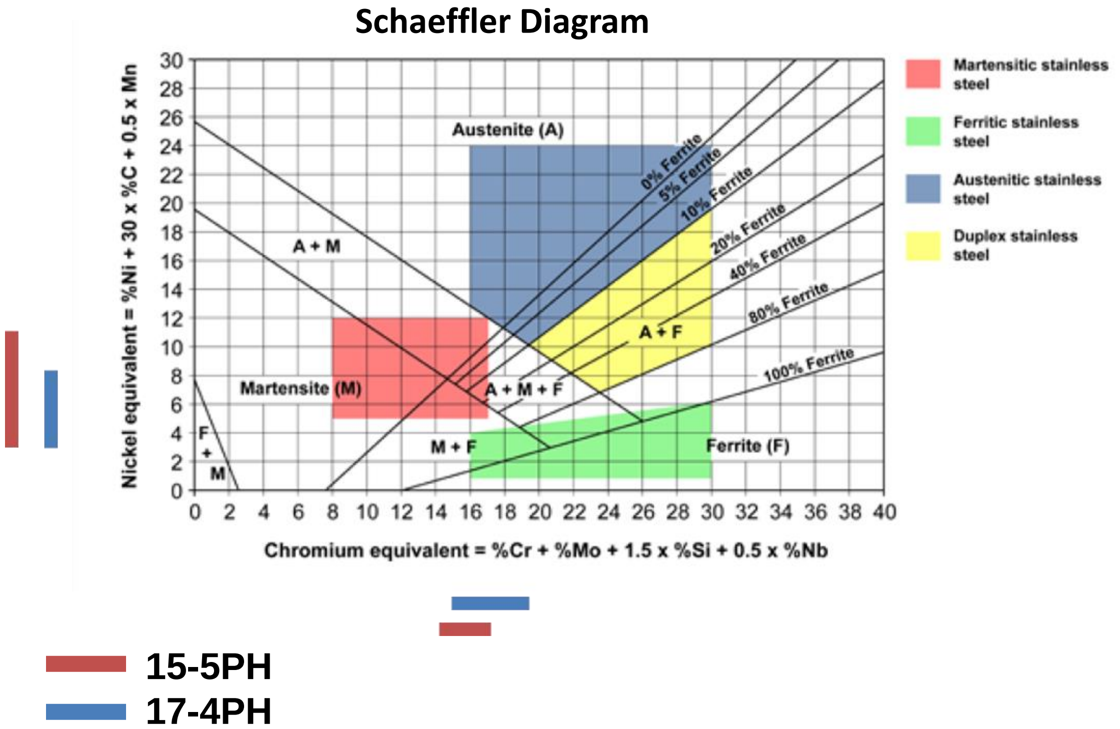


Ref: McMichael & Frazier, 2016 Sea Air and Space, May 2016

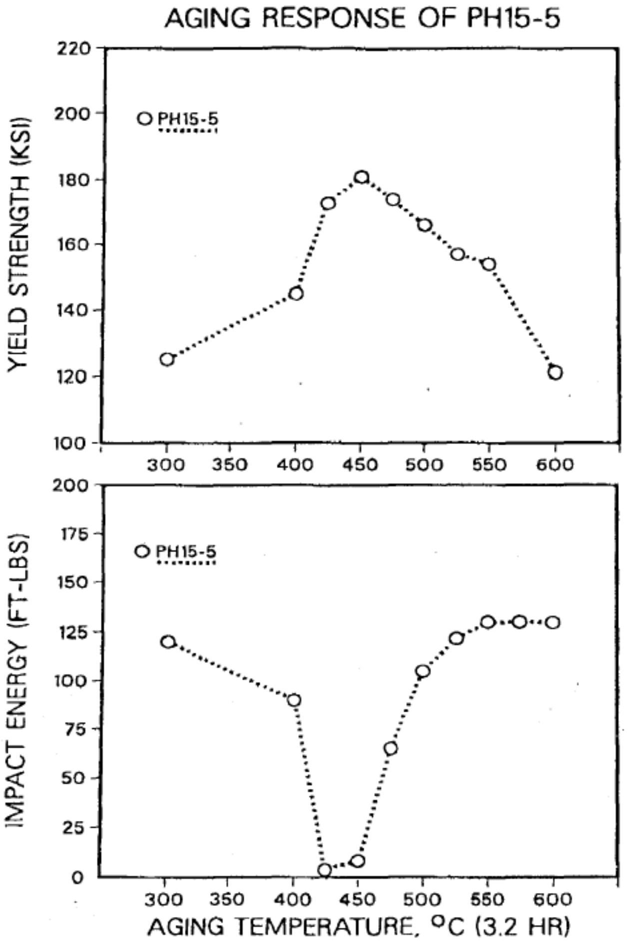
Precipitation Hardened Stainless Steel
(15-5PH & 17-4PH)

Element	17-4PH (wt%)	15-5PH (wt%)
C	0.07 max	0.07 max
Mn	1.00 max	1.00 max
P	0.040 max	0.040 max
S	0.030 max	0.030 max
Si	1.00 max	1.00 max
Cr	15.00-17.50	14.00-15.50
Ni	3.00-5.00	3.50-5.50
Cu	3.00-5.00	2.50-4.50
Nb, Ta	0.15-0.45	0.15-0.45

- **Both 15-5PH & 17-4PH alloys are corrosion resistant, high strength, precipitation hardening stainless steels.**
  - **Copper precipitates from the martensitic phase to strengthen the alloy.**

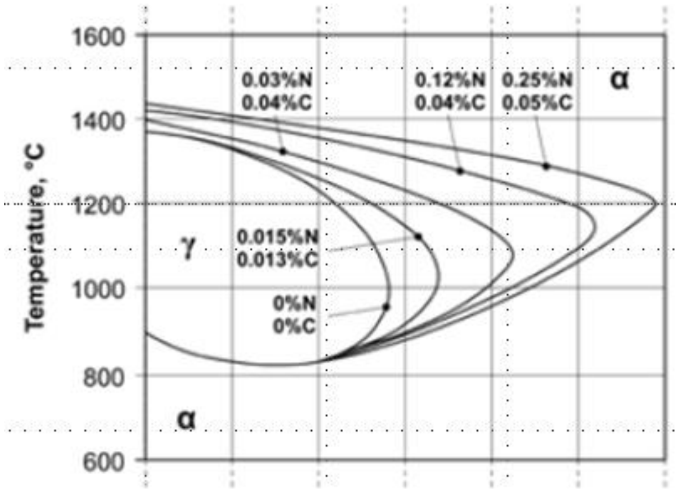


Thermal Processing Challenges



SAN_79 "Martensitic Stainless Steels,"
(Sandia National Laboratory Report, Circa 1979).

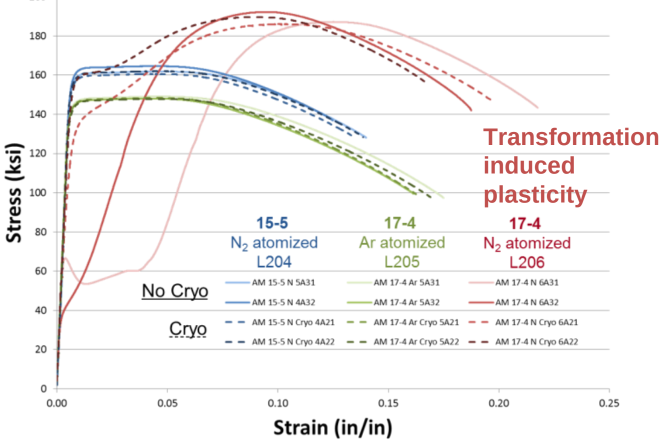
- **Nitrogen inhibits the ability to age harden 17-4PH but has little effect 15-5PH.**
- **Aging response critical to achieving optimal strength and toughness**



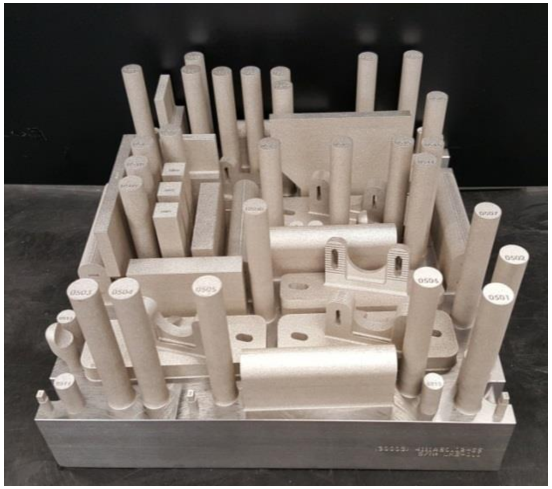
BON_14 Marco Boniardi and Andrea Casaroli, <u>Stainless Steels</u>, (Esine, Italy: Lucefin S.p.A., 2014).

AM Stainless Steel

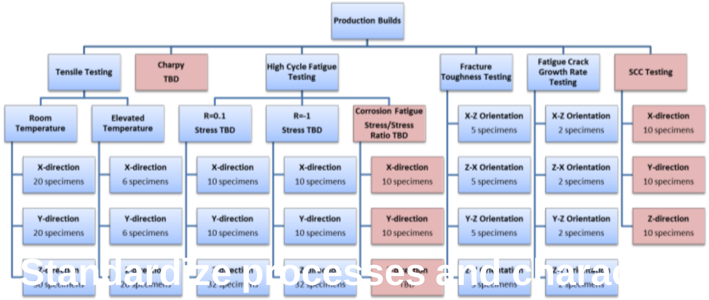
Yield strength 17-4PH made from N atomized powder is less than half that of 15-5PH or 17-4PH made using Ar atomized powder



15-5PH selected to AM legacy 17-4PH parts



H-1 IR Suppressor Support production build



Standardize processes and charac

- **Similar approach to Ti-6A-4V**
- **Additional testing for stainless steel**

Two Part Configurations

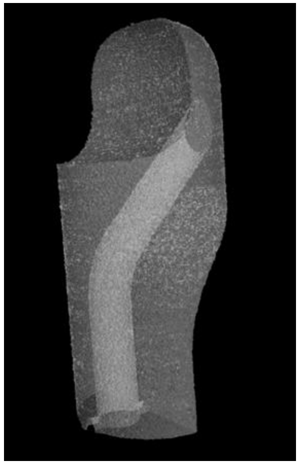
1. **Print 0.050" oversized and machine**

2. **Print near net shape**

Stainless Steel AM Development

To enable near net shape printed parts

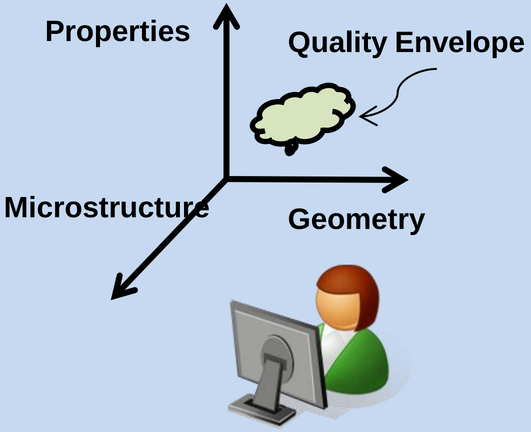
1. Optimize laser parameters to reduce near surface flaws
2. Employ “batch finishing” processes post-build
3. Characterize impact to fatigue performance



Coupon for process development

Model-based Qualification

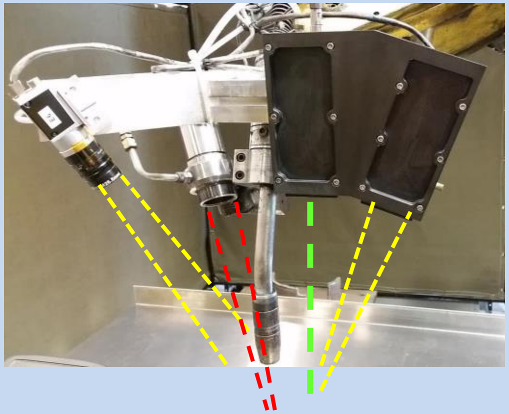
ICME Defines the Quality Envelope



Navy Integrated Computational Materials Engineering (ICME) Tools

+

Process Sensors & Controls



Navy Additive Manufacturing Capability, Equipment & Facilities

=

Quality Made Parts

Quality Ensured Parts

- **Navy**
- **OEMs**
- **Small Businesses**

The Future of Qualification/Certification

Ref: Frazier & McMichael, AM for Def. & Gov., Dec 8, 2015

Roadmap–AM Lines of Effort (LOE)

LOE 1: AM for Readiness and Sustainment

- Tooling & Repair
- Afloat/Expeditionary

LOE 2: Enabling/Expanding Warfighter Capability

- Custom Munitions
- Adaptive UXV
- Expeditionary AM

LOE 3: Enterprise Capability

- AM 3D Architecture–Digital Thread
- Supply Chain IT Integration
- Specifications and Standards

LOE 4: Digital Workforce

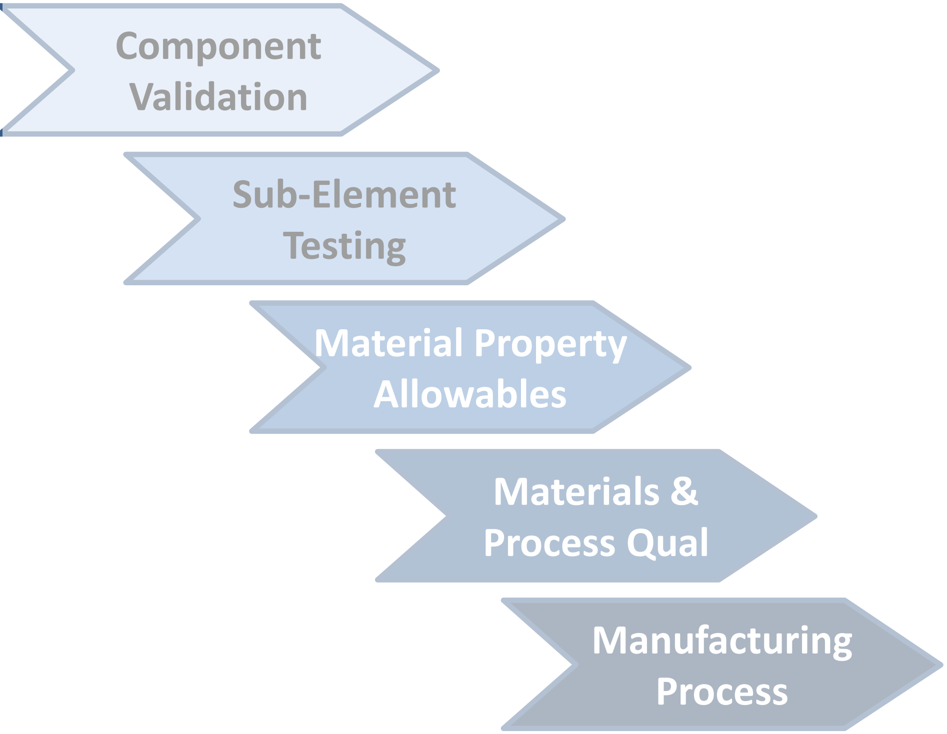
- FABLABs/MakerSpaces
- Innovation Hubs
- "AM Certified" Workforce

— Must address potential Cyber threat —

AM is Driving a Revolution

Current Process

- Linear Building Block Qualification Process
- Engineer Confidence based upon Statistically Substantiated Test Data



Component Validation

Sub-Element Testing

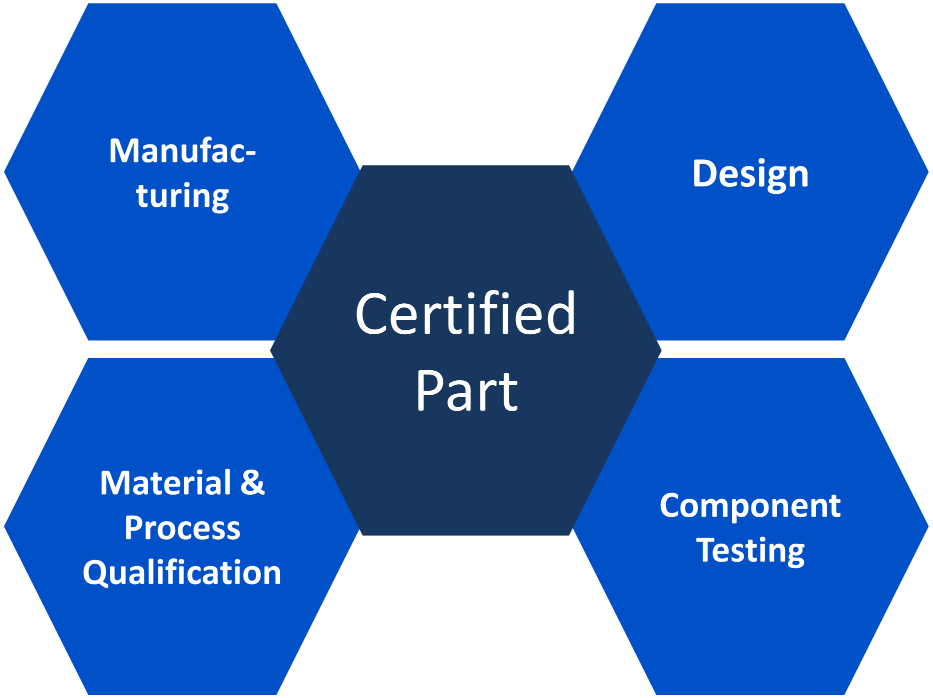
Material Property Allowables

Materials & Process Qual

Manufacturing Process

Vision State

- Concurrent Design, Manufacturing, Material & Process Qualification, and Component Testing
- Engineering Confidence based upon Validated Integrated Models and Simulation Tools.



Manufac-turing

Design

Certified Part

Material & Process Qualification

Component Testing

NAVAIR's AM Revolution

- NAVAIR is developing and qualifying flight critical AM parts to improve Readiness & Speed
- We have already fabricated and flown flight critical parts in a V-22
- We will collaborate with Industry and Academia to change the status quo

OUR WARFIGHTERS ARE DEPENDING ON US!!

Thank you

APPENDIX L—QUALIFICATION OF AN AM COMPONENT FOR FLIGHT

This presentation was considered proprietary and is not appended to the report

APPENDIX M—AM INFORMATICS AND COMPONENT/MATERIAL PEDIGREE

Pratt & Whitney
A United Technologies Company

Additive Manufacturing Informatics

Certification and Qualification Acceleration

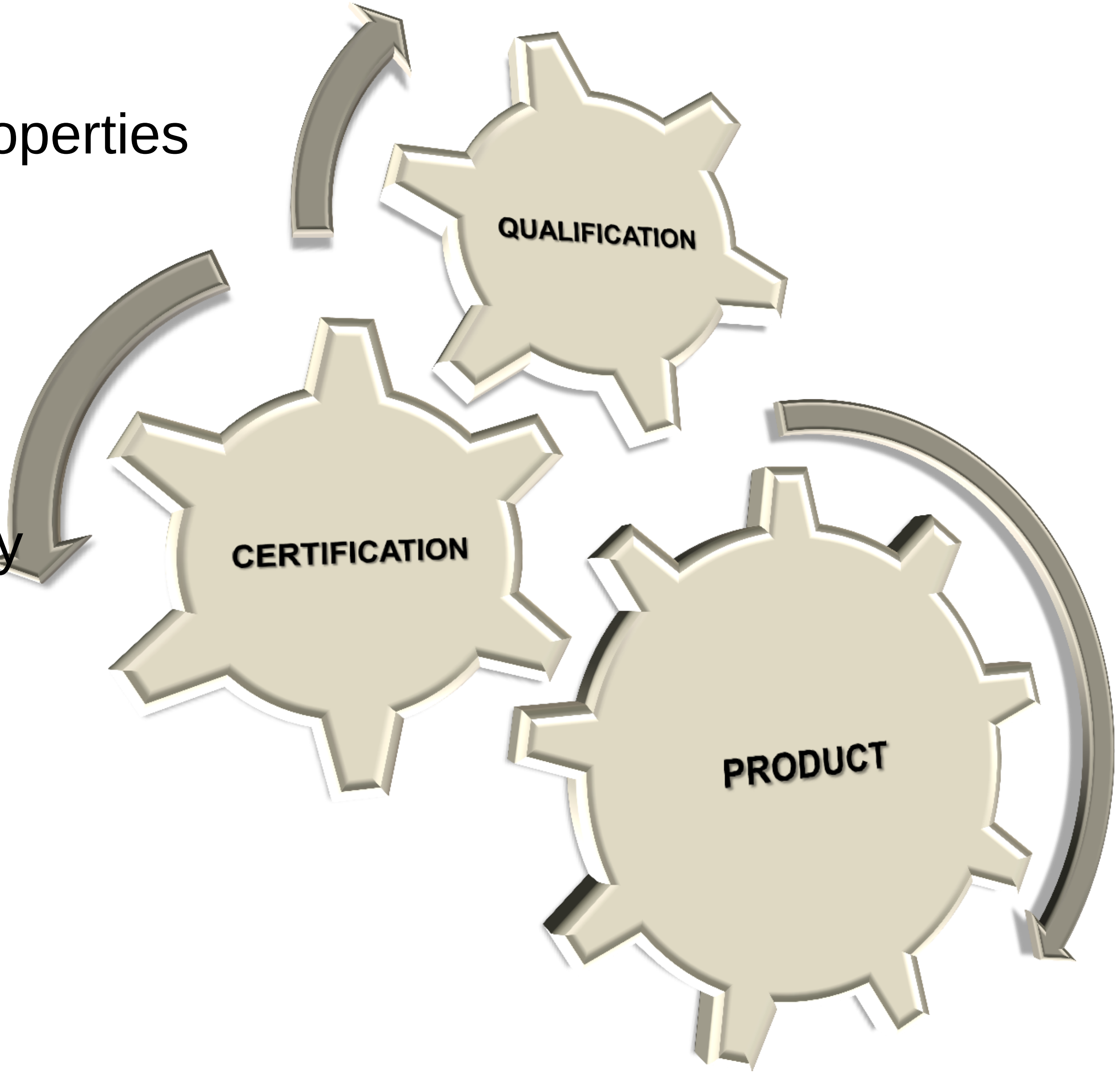
Amra Peles

The Third Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured (AM) Parts
Aug 29-31, Dayton, Ohio

ADDITIVE MANUFACTURING

Certification and Qualification Requirements

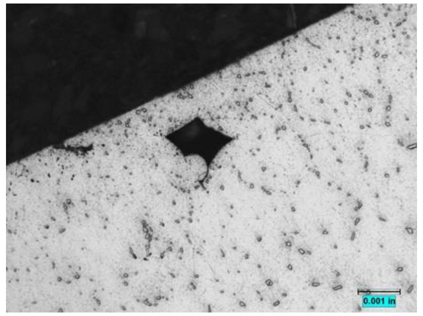
- Make reproducible parts with reliable material properties
- Make use of accepted certification methods
- Maintain constant high quality of parts
- Demonstrate parts meet specifications repeatedly



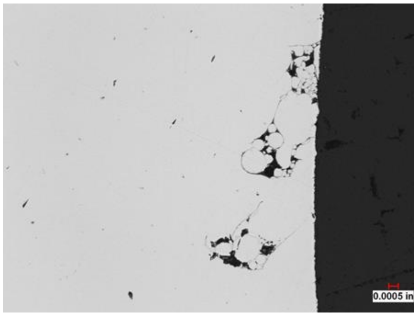
AM PART CERTIFICATION AND QUALIFICATION

Lesson Learned: Details Matter!

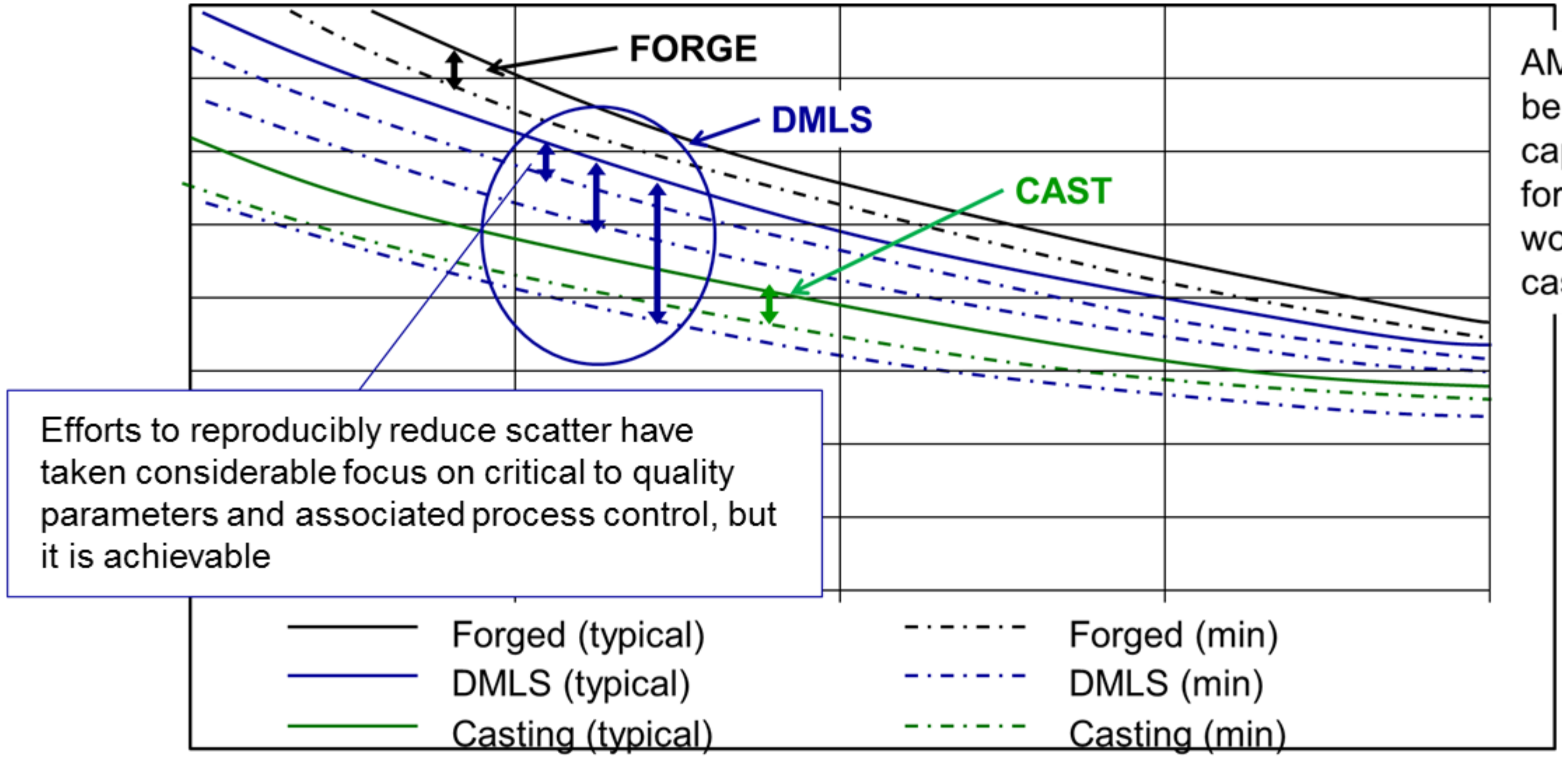
- Process defects
- Microstructure control
- Chemistry control
- Resultant property scatter
- Part-to-part / Batch-to-batch / Machine-to-machine variability
- Powder handling and re-use
- Geometry control
- Surface finish



Lack of fusion



Partially sintered powder



Efforts to reproducibly reduce scatter have taken considerable focus on critical to quality parameters and associated process control, but it is achievable

AM IN718 can be nearly as capable as forgings, or worse than a casting

No Technical Data Per the EAR or ITAR

AM PART CERTIFICATION AND QUALIFICATION

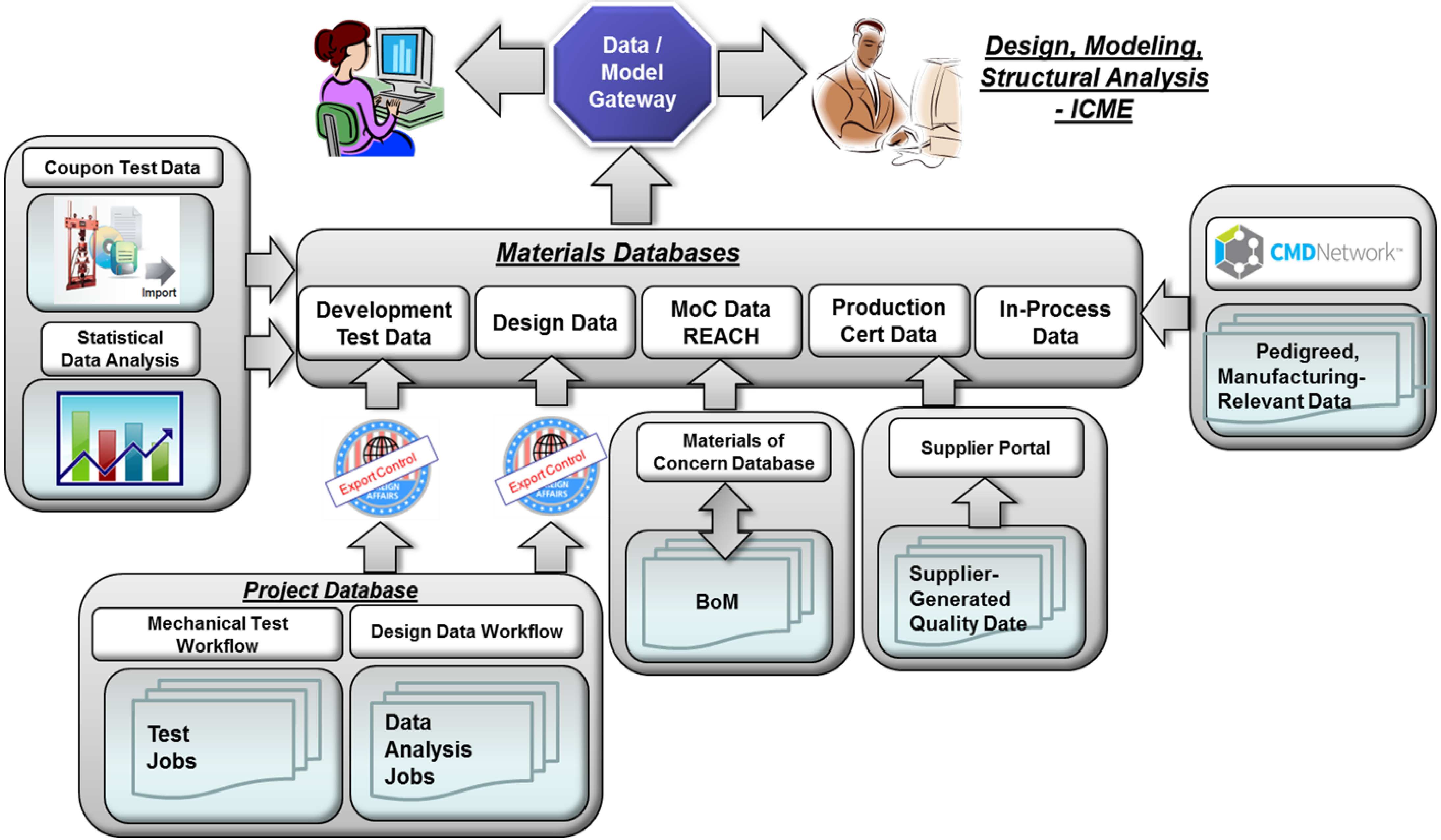
It can be done!

Electron beam Ti6-4: Synch ring bridge brackets

- Significant Conventional Machining from Incumbent Forging Process
- Optimize Utilization of Build Layout
- Good Ti6Al-4V Candidate
- Production in P&W Georgia Division
- Leveraged learning from more complex parts

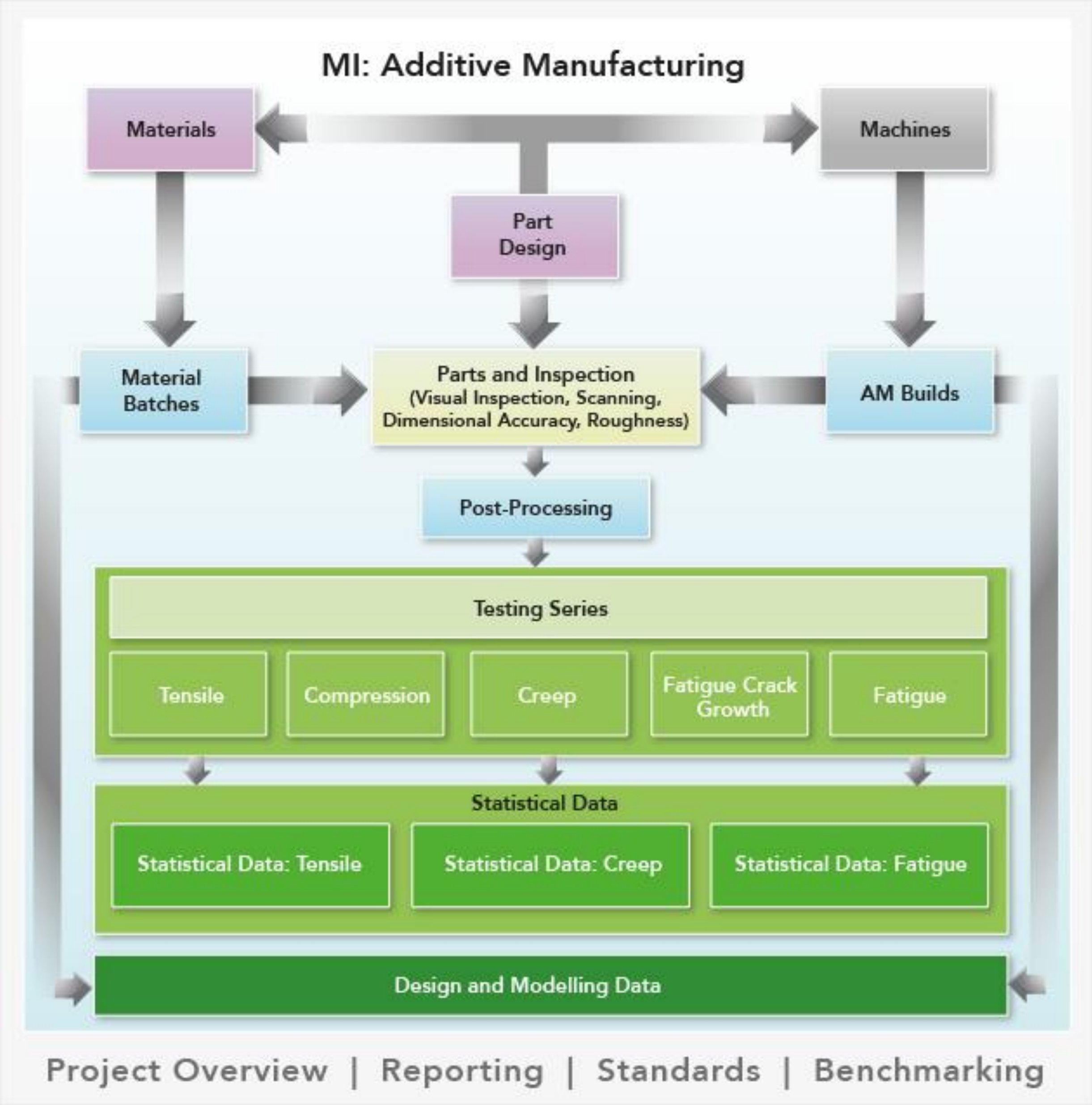
AM PART CERTIFICATION AND QUALIFICATION

Data Flow



DATA MANAGEMENT

Material and Process Pedigree Infrastructure Formalization (Schema)



Materials

• type • form • feed lot • compounding effects

Part geometry

• feature variability • overhangs • CAD tools • software versions

Processing

• build process parameters • build orientation • in process imaging • local conditions sensing • process controls

Post-processing

• surface roughness machining • near-net shape finishing • heat treating

Testing

• mechanical tests • materials characterization • non-destructive evaluation

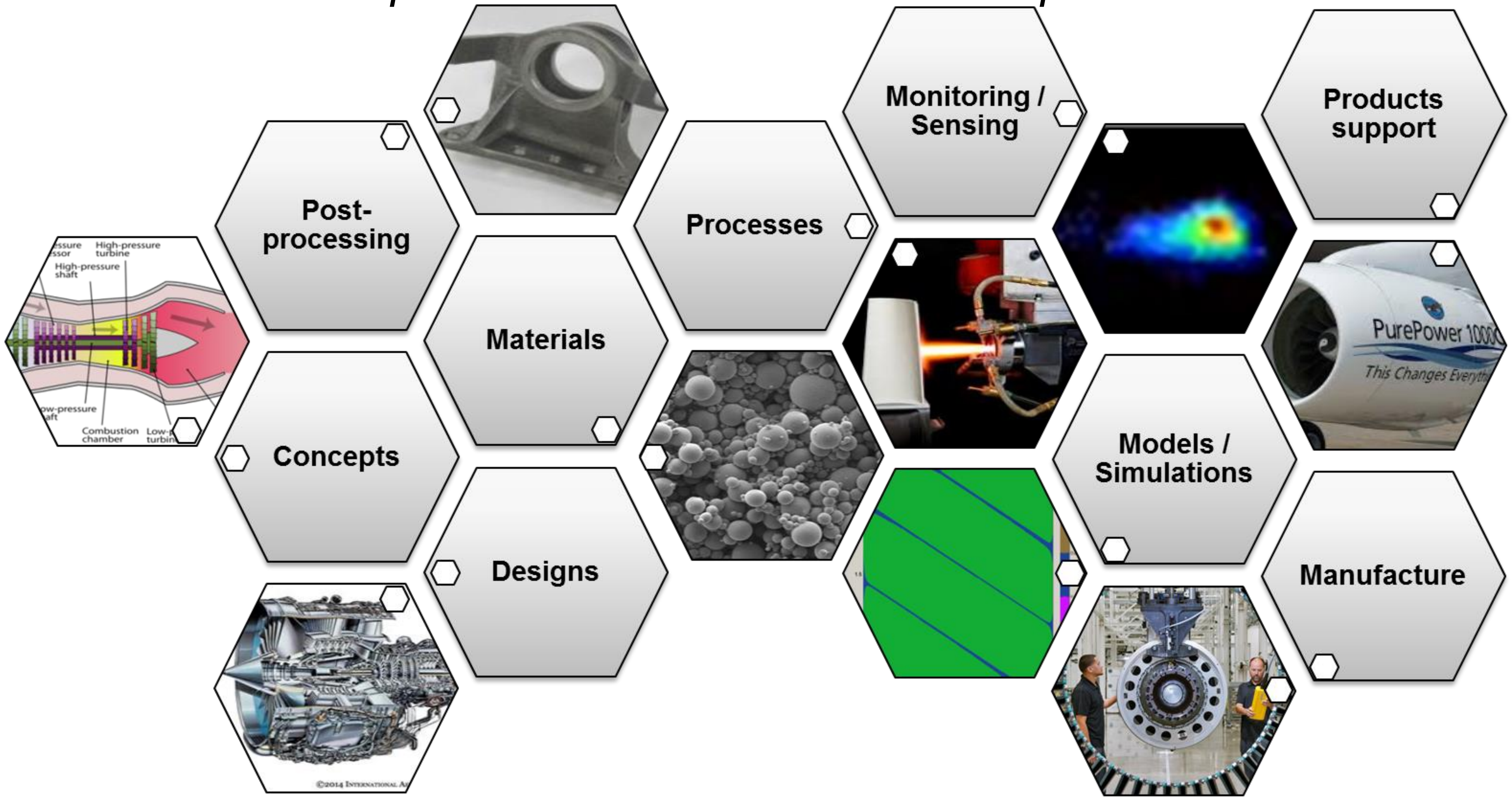
Designs and Models

• physics based • predictive • artificial intelligence

ADDITIVE MANUFACTURING INFORMATICS

Definition

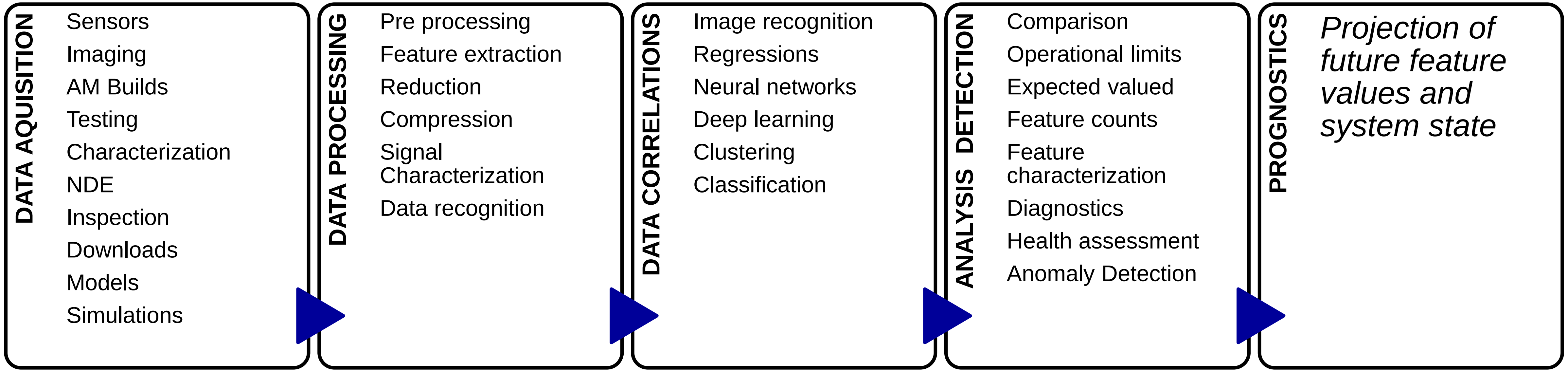
The management of AM data across its lifecycle with full maintenance of the complex relationship between the part design, material and individual processes used to create final part.



Digital Thread

ADDITIVE MANUFACTURING INFORMATICS

Strategy



DATA AQUISITION

- Sensors
- Imaging
- AM Builds
- Testing
- Characterization
- NDE
- Inspection
- Downloads
- Models
- Simulations

DATA PROCESSING

- Pre processing
- Feature extraction
- Reduction
- Compression
- Signal Characterization
- Data recognition

DATA CORRELATIONS

- Image recognition
- Regressions
- Neural networks
- Deep learning
- Clustering
- Classification

ANALYSIS DETECTION

- Comparison
- Operational limits
- Expected valued
- Feature counts
- Feature characterization
- Diagnostics
- Health assessment
- Anomaly Detection

PROGNOSTICS

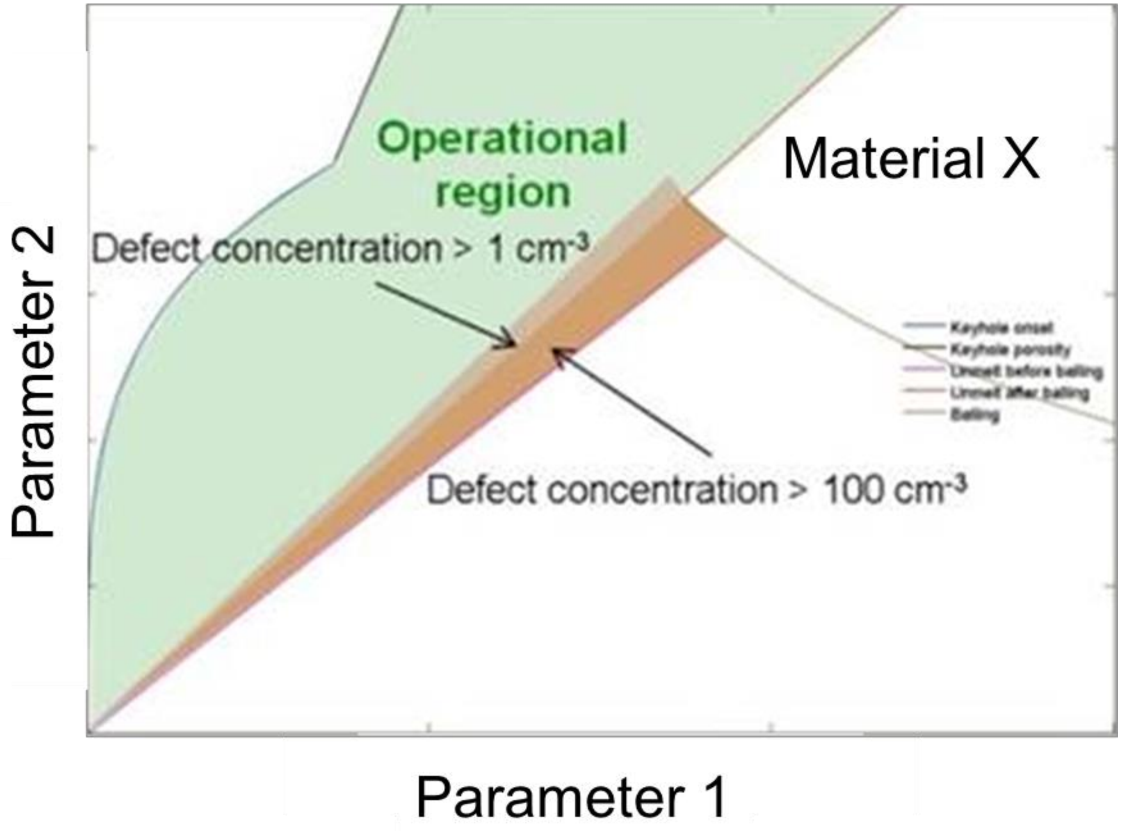
Projection of future feature values and system state

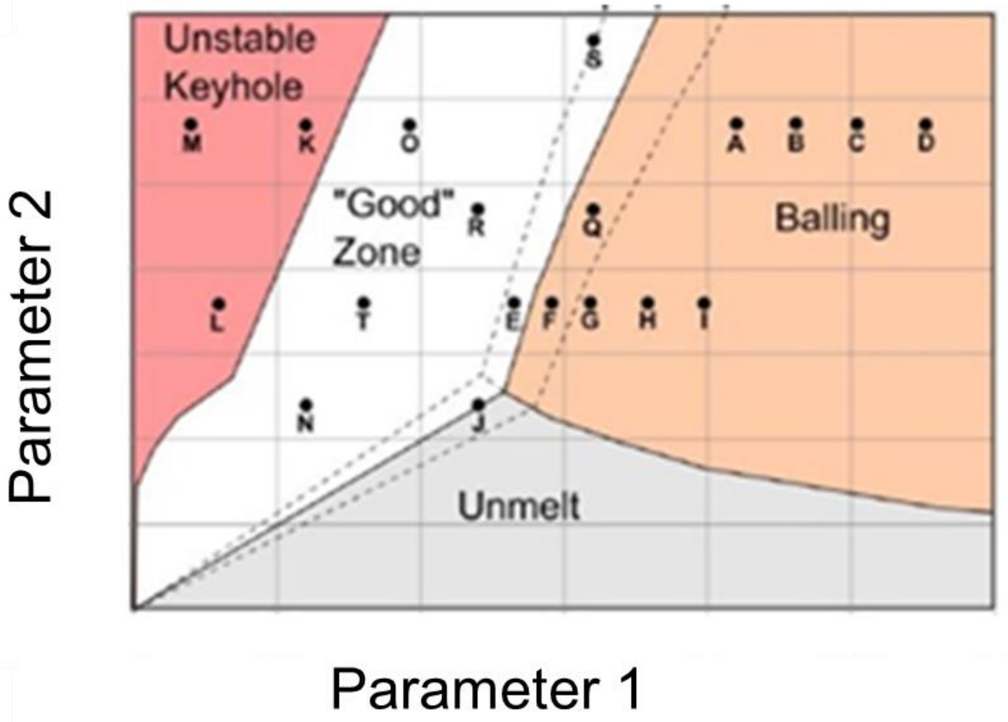
- Enable mining the relationships between part design, materials, and production processes to predict performance and validate those results against physical test results
- Enable visualizing directional and topological data and renderings from CAD models, in-process imaging, and simulation results
- Enable process and variation controls

MODELING INTEGRATION

Drive critical data generation

- Process definition
  - Physics based reasoning
  - Materials and process design space redefined
    - Defining window of build parameters and monitoring
- Product data
  - Specimen
  - Component

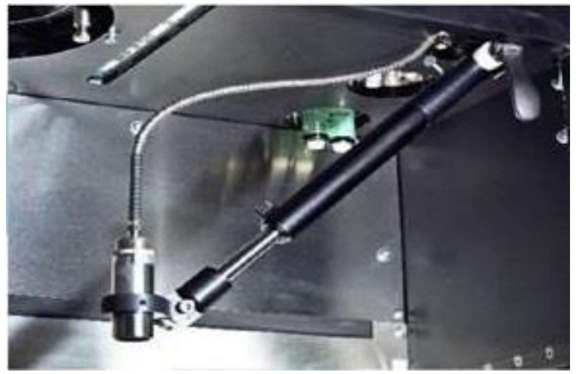




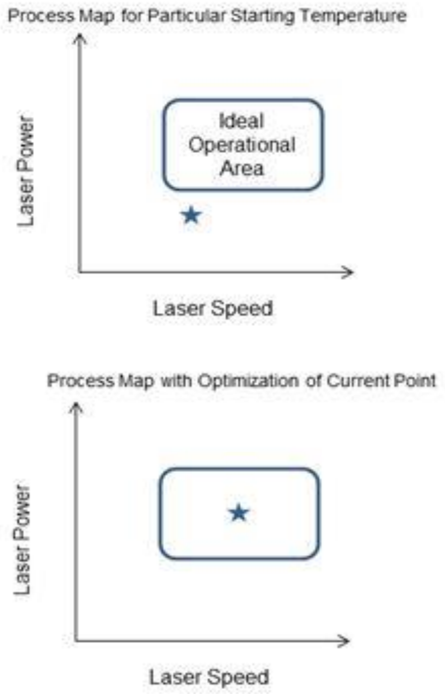
Guide for process control and process monitoring; focus on Critical-to-Quality parameters

PROCESS CONTROLS

Development of model-based feed-forward controls



Sensors*



Controls

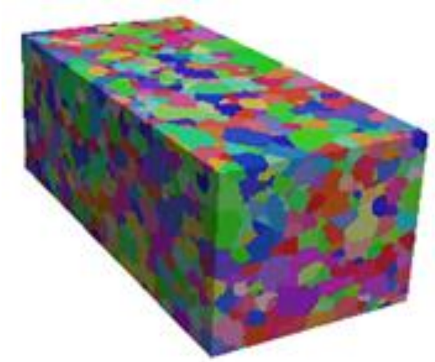
* Sigma Labs, Inc.

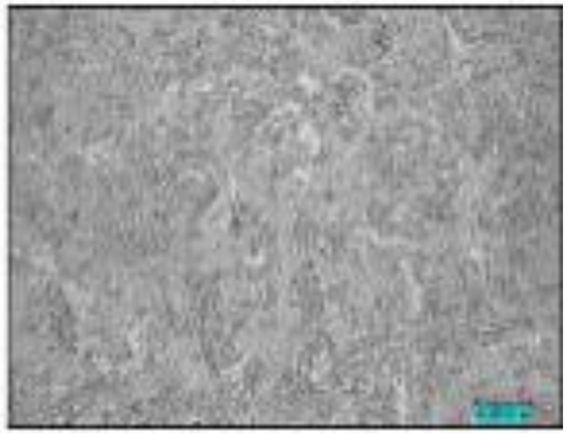
Enable feed-forward control and design for post-processing

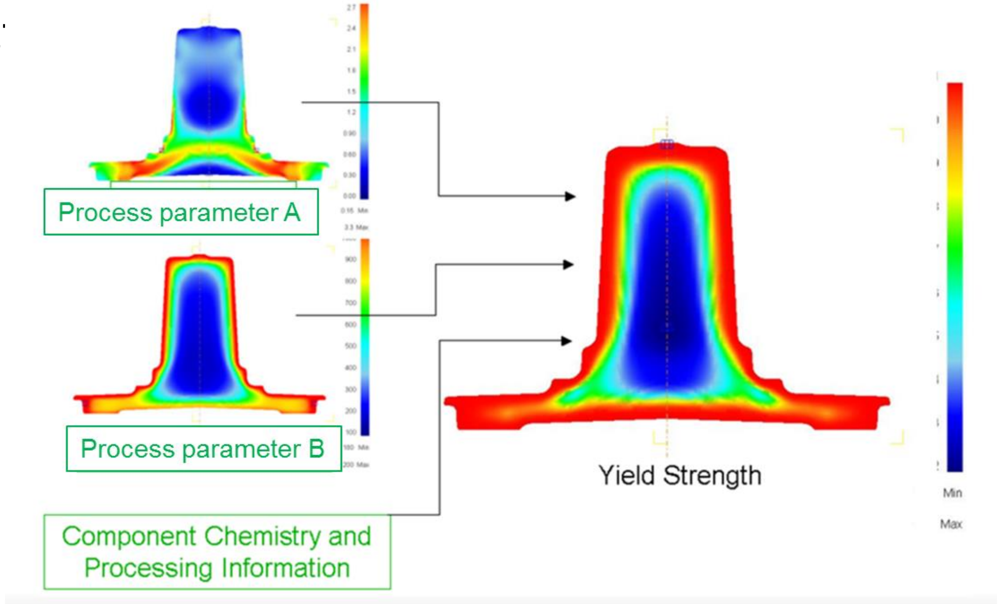
MATERIAL AND MATERIAL PROCESS OPTIMIZATION

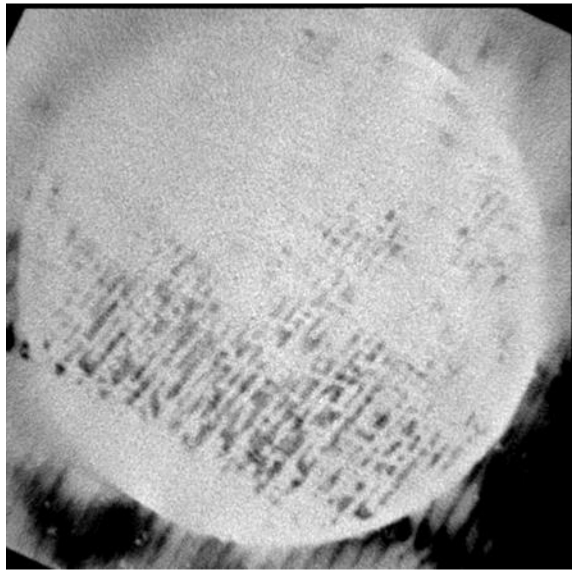
Correlate performance with material property and process parameters

Materials design allowable database –
Equivalency of test specimens and components through build-space unders

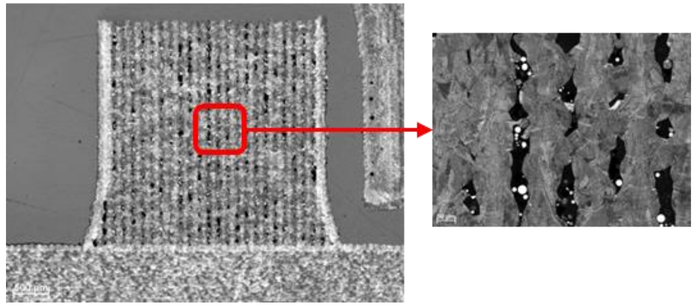








Example of horizontal lack of fusion due to large hatch spacing



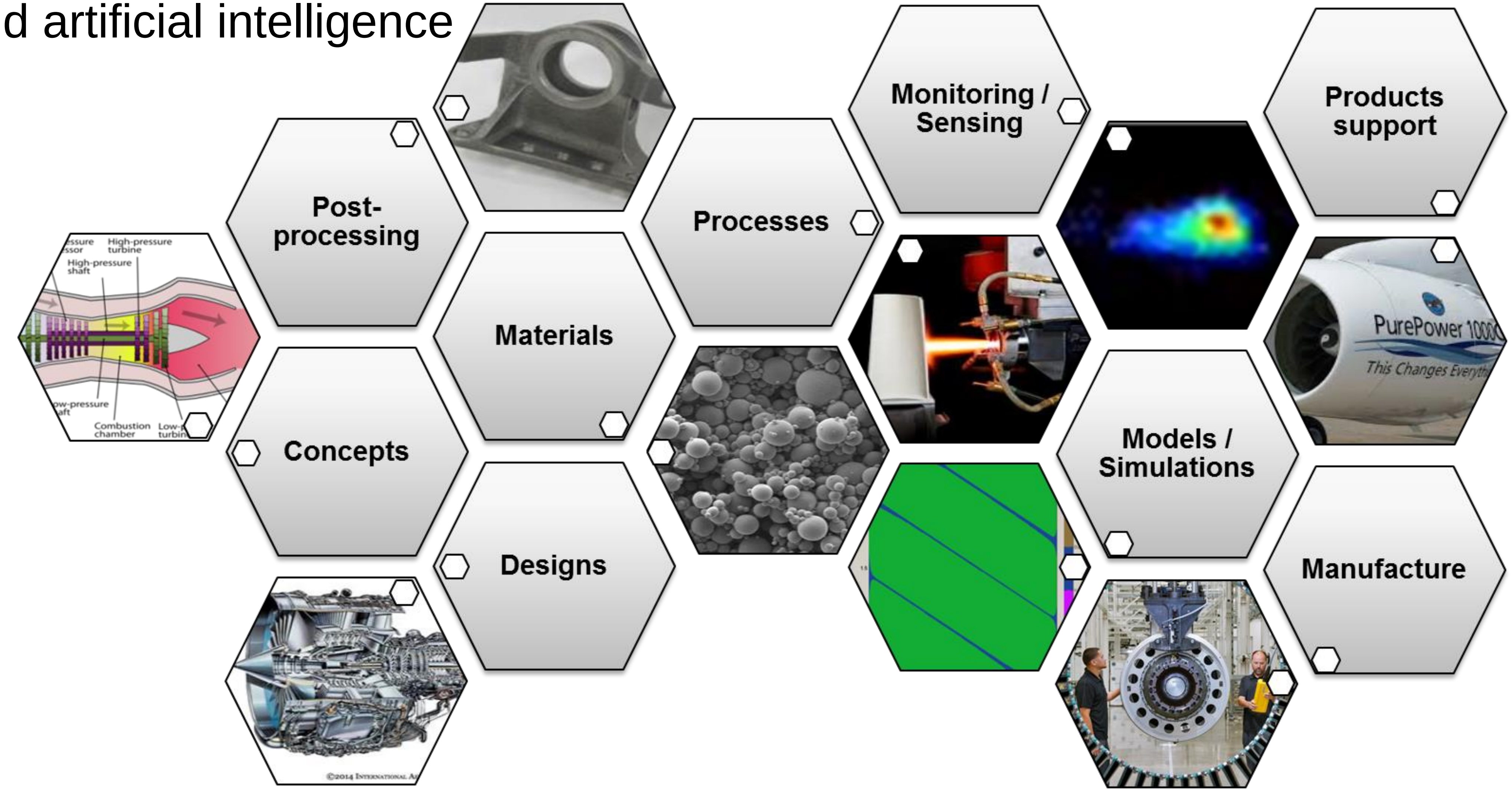
Optimizing material for performance

- Location-specific build understanding
- Tailored material and process to link to design allowables or for new, unique capabilities

SUMMARY

Additive manufacturing informatics

Technical and business decision making, accelerated certification and qualification supported by data, analytics, monitoring and artificial intelligence



Post-processing

Concepts

Materials

Designs

Processes

Monitoring / Sensing

Models / Simulations

Products support

Manufacture

THANK YOU

APPENDIX N—MMPDS PROGRESS ON DEVELOPING EQUIVALENCE CRITERIA AND SPEC MINIMAL VALUES FOR AM

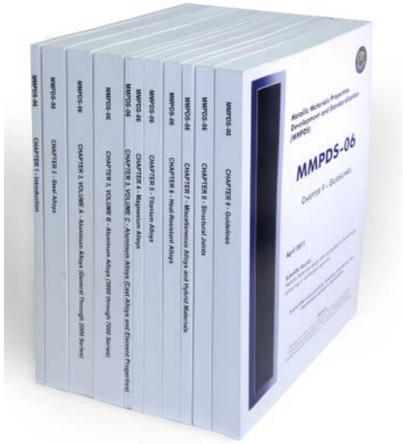
MMPDS Progress on Developing Equivalence Criteria & Support for SAE Spec Development

FAA-Air Force Workshop on Qualification/Certification of AM Parts

Doug Hall
Sr. Research Scientist
Program Manager - MMPDS
Battelle Memorial Institute
August 2017

Metallic Materials Properties Development and Standardization (MMPDS)

Formerly known as MIL-HDBK-5

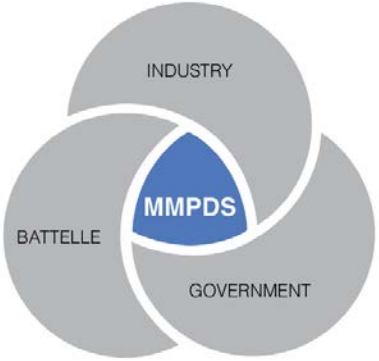


MMPDS Handbook is the primary source of statistically-based design allowable properties for metallic materials and fasteners used in many different commercial and military weapon systems around the world.

MMPDS is owned by the FAA and is licensed exclusively to Battelle.

- Collaborative effort with government, aerospace companies and metallic material producers. Twice yearly meetings for review and approval of statistical analyses and guidelines.

For more information visit www.mmpds.org



Approval Process for Aerospace Design Allowables

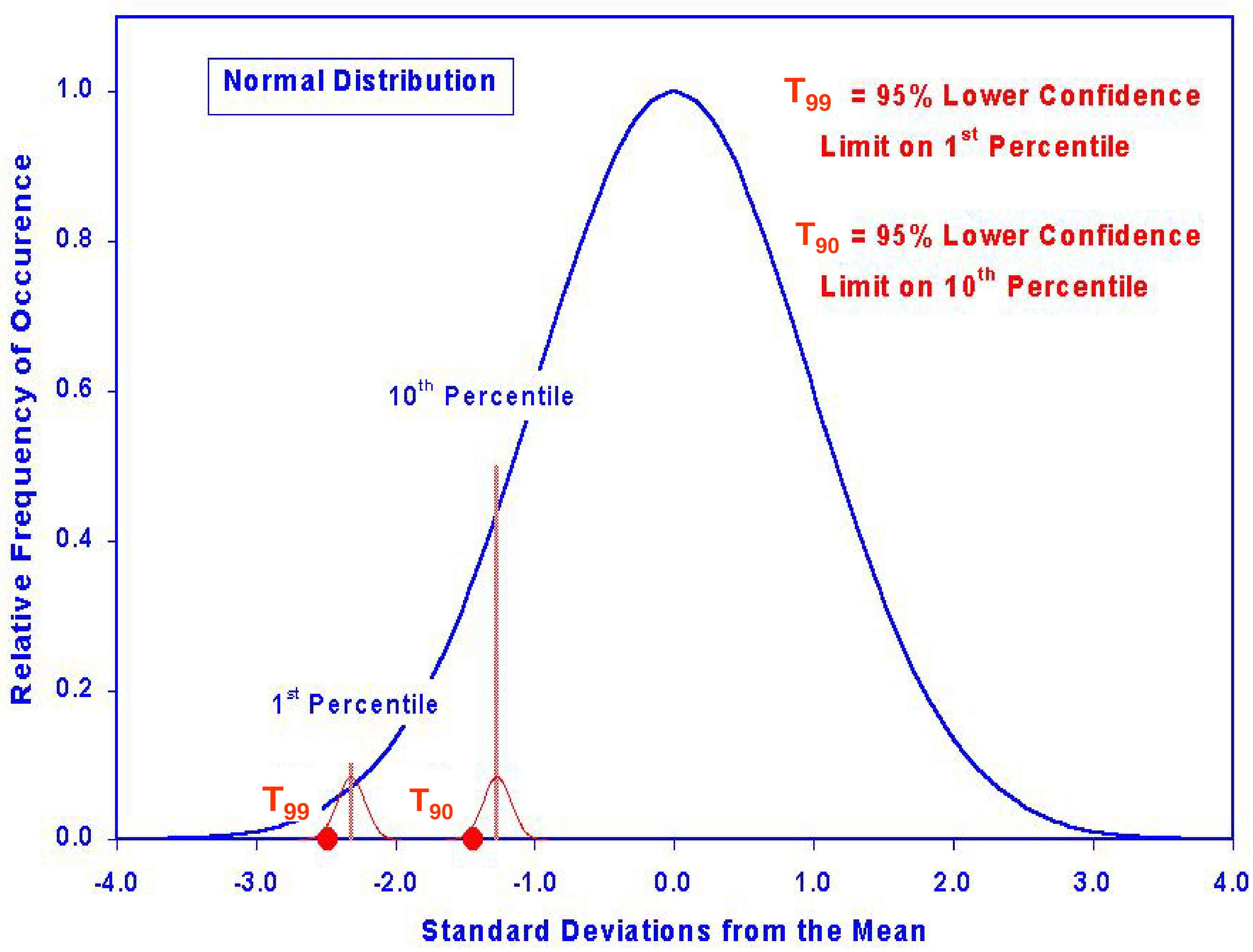
- Industry has two courses of action when pursuing FAA approval of all designs for aerospace metallic structures

Course of action #1:
FAA accepts "A-Basis" and "B-Basis" values published in the MMPDS Handbook (formerly the MIL-HDBK-5) as meeting the regulations of Federal Aviation Regulation (FAR) 25.613.

Or

Course of action #2:
Designers must submit sufficient data to allow the FAA to verify the design allowables used.

MMPDS A-Basis and B-Basis



A-Basis is the lower of the specification minimum or T_{99} value

B-Basis = T_{90}
It is not related to the specification minimum.

MMPDS Requirements

Public Specification

- Primarily AMS specifications – more data driven
- Few ASTM specifications - less restrictive

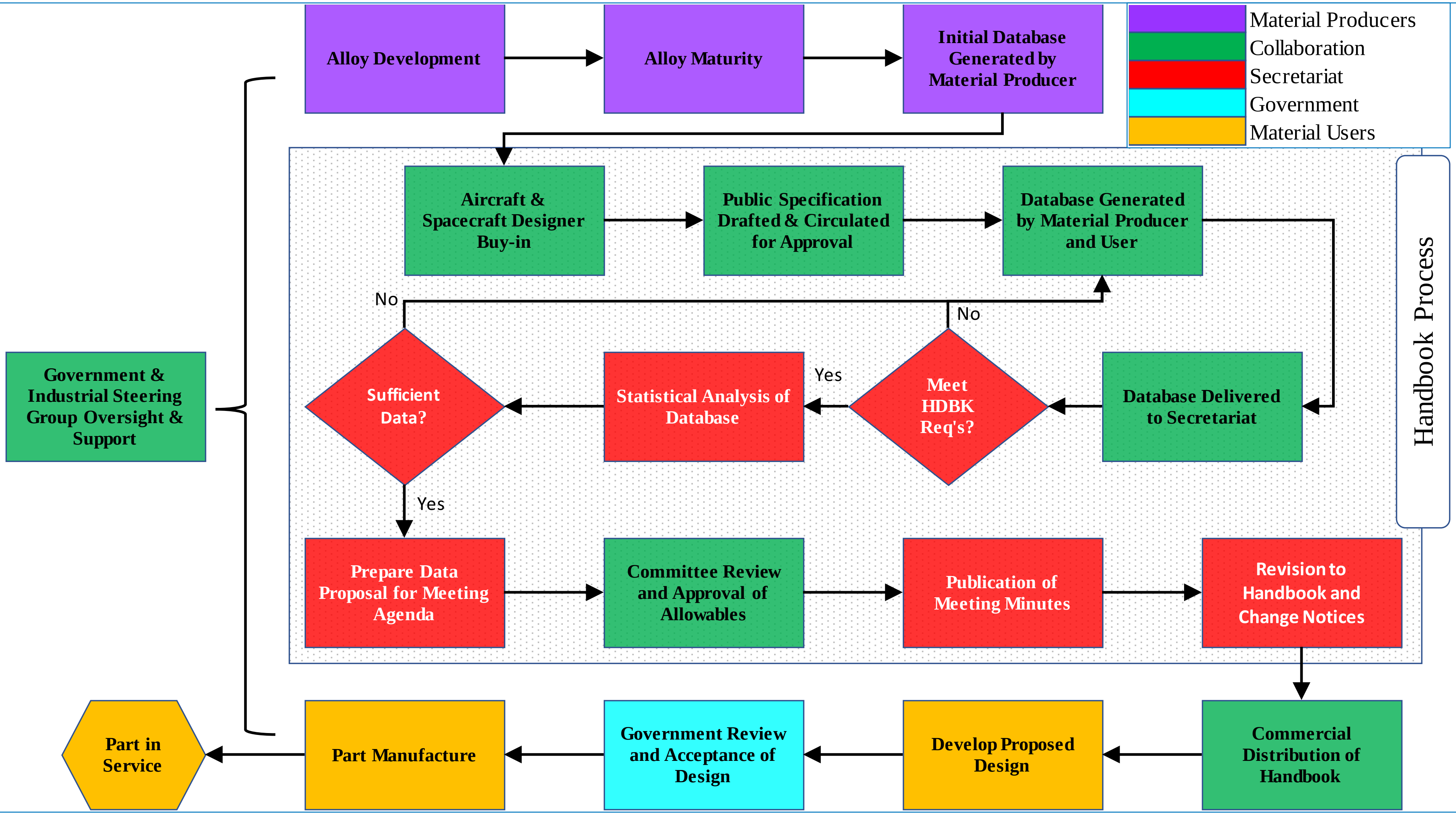
Property Tests

- Table 9.2.3 of MMPDS for test methods
- Table 9.2.4 of MMPDS for properties and sample size

Analysis and Review

- Per MMPDS Chapter 9
- Review by Industry and Government

GSG/ISG Review & Approval Process



🟪 Material Producers
🟩 Collaboration
🟥 Secretariat
🟦 Government
🟨 Material Users

Alloy Development

Alloy Maturity

Initial Database Generated by Material Producer

Aircraft & Spacecraft Designer Buy-in

Public Specification Drafted & Circulated for Approval

Database Generated by Material Producer and User

Database Delivered to Secretariat

Meet HDBK Req's?

No

Yes

Statistical Analysis of Database

Sufficient Data?

No

Yes

Prepare Data Proposal for Meeting Agenda

Committee Review and Approval of Allowables

Publication of Meeting Minutes

Revision to Handbook and Change Notices

Handbook Process

Commercial Distribution of Handbook

Develop Proposed Design

Government Review and Acceptance of Design

Part Manufacture

Part in Service

Government & Industrial Steering Group Oversight & Support

BATTELLE

MMPDS Benefits to Industry

- Use of statistically valid material and fastener allowables is a necessary part of the certification process
- A typical material properties test program for a single material costs $300K to 500K or more.
- Having a single, unimpeachable source for these properties:
  - Reduces the cost of aircraft products by reducing redundant testing
  - Reduces cost for Tier I companies approving Tier II material properties
  - Reduces cost for regulators approving Tier I certification packages
  - Levels the playing field for smaller aerospace companies to compete

AM is on the Horizon

OECD say 3D printing will replace traditional machining within 10 year…

3dprintingindustry.com

20 Likes • 8 Comments

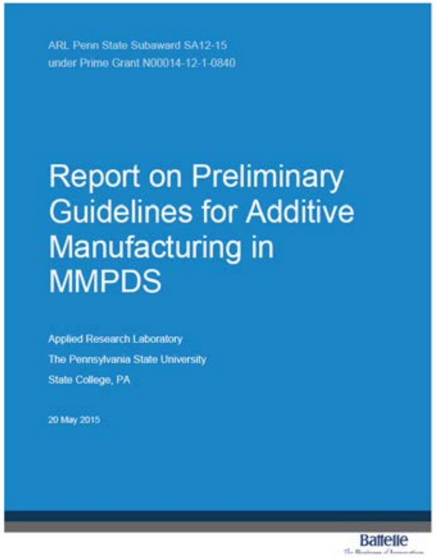
GSG 04-17 Evaluation of Requirements for Determination of Reliable Design Allowables for LAM Ti-6Al-4V

- AMS 4999[†] Laser Additively Manufactured Titanium
  - Wide range of conditions: 90 different parts, eight heat treatments & deposition thicknesses, two power levels, titanium powder oxygen content from 0.15 to 0.20%
  - 790 Tensile and yield strength tests (tested 9/98 thru 3/03)
  - Specification minimums exceeded if oxygen content ≥ 0.18%
  - Feasibility of developing A-/B-Basis design values were considered for MMPDS
  - Concern in the MMPDS community that properties might not be achieved on different machines or using other combinations of build parameters allowed by the specification.

[†] AMS 4999 released February 2, 2002

Emerging Technology Working Group

- Standing working group for 10+ years
- Refined focus on Additive started about 5 years ago
  - FAA support via Task 9 in our contract
  - Intense industry interest from material suppliers and Tier I & II users
- Identify material properties gaps – data and/or statistical tools
- Define minimum guidelines for consideration
- Develop tools and procedures applicable to process sensitive materials
- Drafted an outline for a new volume



ARL Penn State Subaward SA12-15
under Prime Grant N00014-12-1-0840

Report on Preliminary Guidelines for Additive Manufacturing in MMPDS

Applied Research Laboratory
The Pennsylvania State University
State College, PA

20 May 2015

Battelle

Recent Activity in Additive Manufacturing

- Agenda Item 11-40: Guidance on Emerging Technologies
- GSG directive - "Until the underlying infrastructure has matured, (i.e. material standards, testing standards, common terms such as heats and lots defined, etc.) and general design practices are available to industry, it is not possible to publish generic material properties for these unique material systems at this time"
- Agenda Item 16-20: Equivalence Testing Assuming a Change in Processing has Occurred.
- SAE AMS AM Subcommittee
  - Battelle & NIAR developing data submission guidelines for Additive Manufacturing for metals and polymers

11-40 Recommendations

- New guidelines and properties tables should published as a new volume of MMPDS
- Quantify the impact of major sources of variation for a material and the processing method
- Additional pedigree information will be needed to define processing, machine, machine type, etc.
- Table 9.2.3 and 9.2.4 list applicable test specifications and material property requirements.
- Equivalency algorithm tool beta version

Additive Metals – Gaps vs. MMPDS

Public Specification

- Public AMS specs are in the pipeline – LPBF IN 625
  - **Process Spec – AMS 7003**
  - **Feedstock Spec – AMS 7002**
  - **Powder Spec – AMS 7001**
  - **Part Spec – AMS 7000 – draft has min z-axis strength**

Property Tests

- Table 9.2.3 of MMPDS for test methods
- Table 9.2.4 of MMPDS for properties and **sample size**

Analysis and Review

- **Per MMPDS Chapter 9**
- **Undefined data analysis requirements**
- Review by Industry and Government

Equivalency

- Guidelines for determination of equivalency testing
  - CHM-17
    - Equivalence of means for B-Basis
    - H_0: Process is unchanged.
    - H_a : Process has Changed
  - MMPDS
    - Equivalence of A and B-Basis
    - H_0: Process has Changed.
    - H_a : Process is unchanged
  - Not unique to Additive
    - Demonstrate “equivalence” for alternative supplier, different machine, parts, new processing, new processing plant, etc.

Proposed for Equivalency Testing - Example

No. of Equivalence Tests	100				300			
	Number of Values Falling Below Acceptance Limits				Number of Values Falling Below Acceptance Limits			
	0	1	2	3	0	1	2	3
	Demonstrated Equivalance Below T90 Design Properties (in standard deviations)							
5	1.900	-	-	-	1.731	3.949	-	-
10	0.875	1.674	2.545	-	0.731	1.502	2.355	3.394
15	0.510	1.048	1.543	2.088	0.395	0.907	1.389	1.902
20	0.309	0.735	1.097	1.465	0.196	0.602	0.959	1.304
30	0.080	0.397	0.652	0.896	0.000	0.275	0.521	0.758
40	0.000	0.213	0.416	0.606	0.000	0.104	0.299	0.482
42	0.000	0.186	0.382	0.564	0.000	0.078	0.267	0.442
50	0.000	0.094	0.268	0.425	0.000	0.000	0.164	0.312
55	0.000	0.045	0.213	0.357	0.000	0.000	0.111	0.249
60	0.000	0.000	0.165	0.300	0.000	0.000	0.060	0.196
70	0.000	0.000	0.086	0.210	0.000	0.000	0.000	0.108
80	0.000	0.000	0.019	0.139	0.000	0.000	0.000	0.034
90	0.000	0.000	0.000	0.078	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.022	0.000	0.000	0.000	0.000

Baseline pop = 100
30 Tests
1 value falls below B

To calculate Est. B;
$B_{(est)} = B_{(p)} – (\sigma_{(p)} x AL)$

If it falls in green area (AL = 0) may be considered equivalent

Do more testing – now have 60 tests

No additional tests below B (only 1 below)

Equivalent !

Other Effort In Process

- More guidelines
  - Definitions of Heats, Lots, etc
  - Minimum number of Heats, Lots, Sample size (*propose same as for standard materials for B-basis? 10/10/100)*
  - Other variables?
  - Recommended standard test blanks designs
- Description of various processes
  - Limitations / cautions
  - Quality control recommendations
- Exploring AM opportunities

Input is greatly appreciated!!!

Potential Benefits of an AM MMPDS

- Use of statistically valid material and fastener allowables is a necessary part of the certification process
- A typical material properties test program for a single material costs 3x to 5x or more of a conventional alloy.
- Having a single, unimpeachable source for these properties:
  - Reduces the cost of aircraft products by reducing redundant testing
  - Reduces cost for Tier I companies approving Tier II material properties
  - Reduces cost for regulators approving Tier I certification packages
  - Levels the playing field for smaller aerospace companies to compete

AMS – Data Management Subcommittee

- Data guidelines defined definitions used
- Set test methods and minimum data requirements
- Require external review to confirm data is according to specs

AMS-AM Data Requirements

- **Table 2. Minimum Data Requirements for Lot Release Quality Control Specification Minimum per Machine Manufacturer (at least 3 serialized machines are required)**

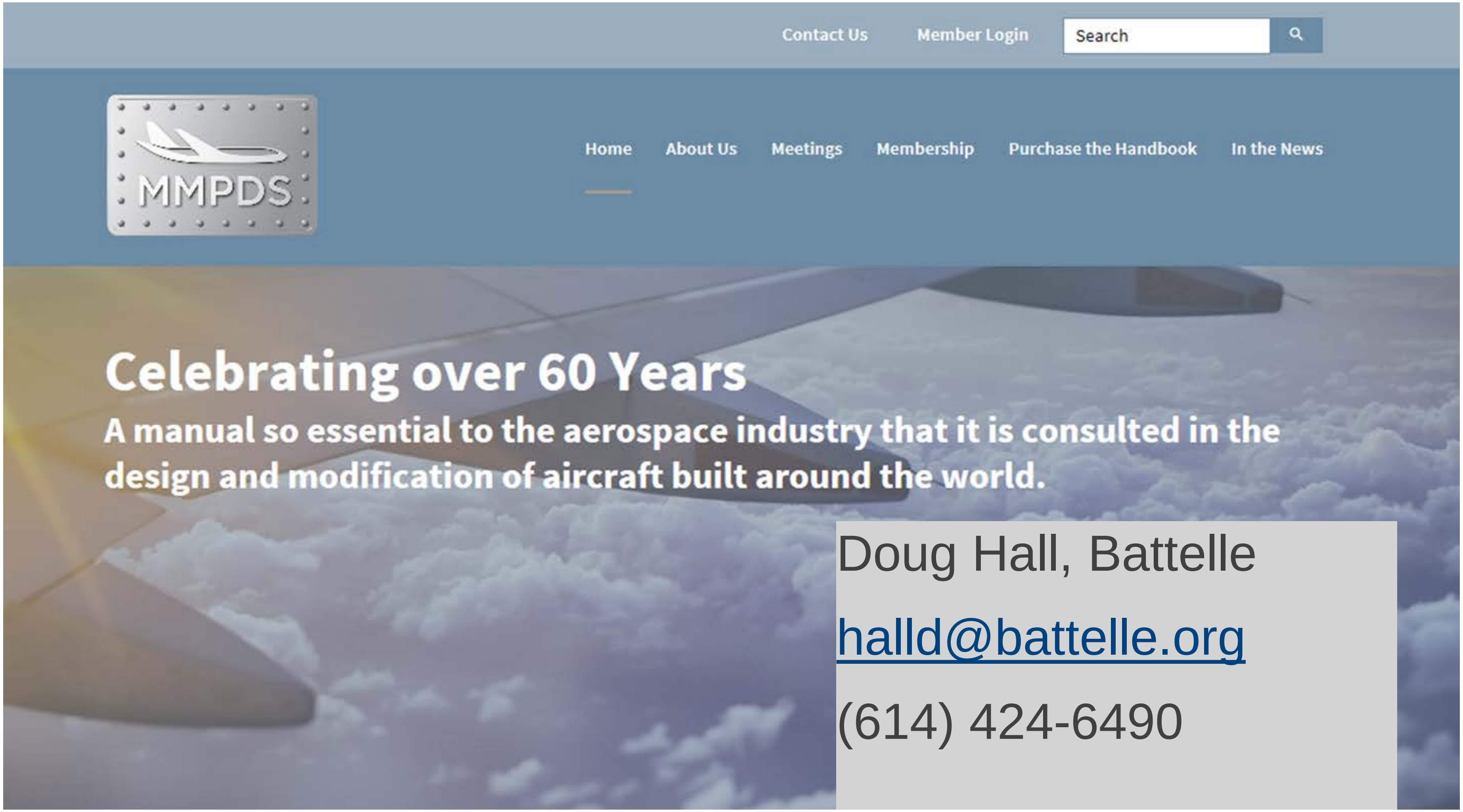
	Minimum Data Requirements per orientation			
# of Machines	Sample Size[1]	# Feedstock/ Powder Lots	# Heat Treat Lot	Format[2]
3	30	3	3	Excel®

1. Minimum number of coupons for each orientation/thickness as called out in the material specification.
2. Excel is preferred. For larger data sets, MMPDS data templates may be preferred. A request may be made at www.mmpds.org.

AMS-AM Specs for 625 LPBF

- **AMS7000** - Additive Manufacture of Aerospace Parts from Ni-base Super Alloy 625 via the Laser Powder Bed Process
- **AMS7001** - Ni Base 625 Super Alloy Powder for use in Laser Powder Bed Additive Manufacturing Machines
- **AMS7002** - Process Requirements for Production of Metal Powder Feedstock for use in Laser Powder Bed Additive Manufacturing of Aerospace parts
- **AMS7003** - Laser Powder Bed Fusion Process
- **Data have been analyzed by Battelle for AMS7000**

https://www.mmpds.org/



Celebrating over 60 Years

A manual so essential to the aerospace industry that it is consulted in the design and modification of aircraft built around the world.

Doug Hall, Battelle

halld@battelle.org

(614) 424-6490

BATTELLE

It can be done

800.201.2011 | solutions@battelle.org | www.battelle.org

APPENDIX O—PERSPECTIVES IN ADDITIVE LAYER MANUFACTURING AT ROLLS-ROYCE

Perspectives in Additive Layer Manufacturing at Rolls-Royce

Dayton, Ohio Aug. 30, 2017

Amit Chatterjee & N Mantle
(Global Materials Lead) (Head of ALM)

Trusted to deliver excellence

Rolls-Royce

Intelligent User
Intelligent Customer

The Importance of True Scale
Capability Demonstration
Ensuring Product Integrity

We insist on comprehensive demonstration

Target Products

Whole Engine & Flight Demo

Core Integration Vehicles

Component / Capability Technologies

And for Additive Manufacturing it is no different ...

Robust capability acquisition

Technology (TRL)

Research Partners & UTCs

Demonstrators

Engine Programmes

Research Partners & UTCs

Manufacturing Research Centres

Facility Investment

Manufacturing (MCRL)

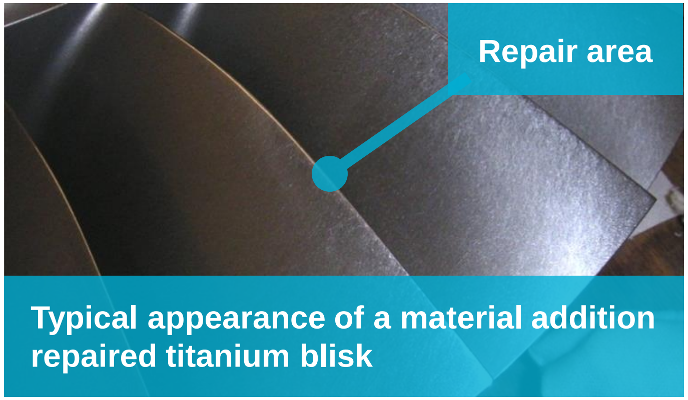
Vcom 16867

Background

Like our peers we've been using Additive/3D printing for 12+ yrs

We deploy ALM for the repair of parts including high integrity components

- **Enhancing their performance and extending their working life**



Typical appearance of a material addition repaired titanium blisk

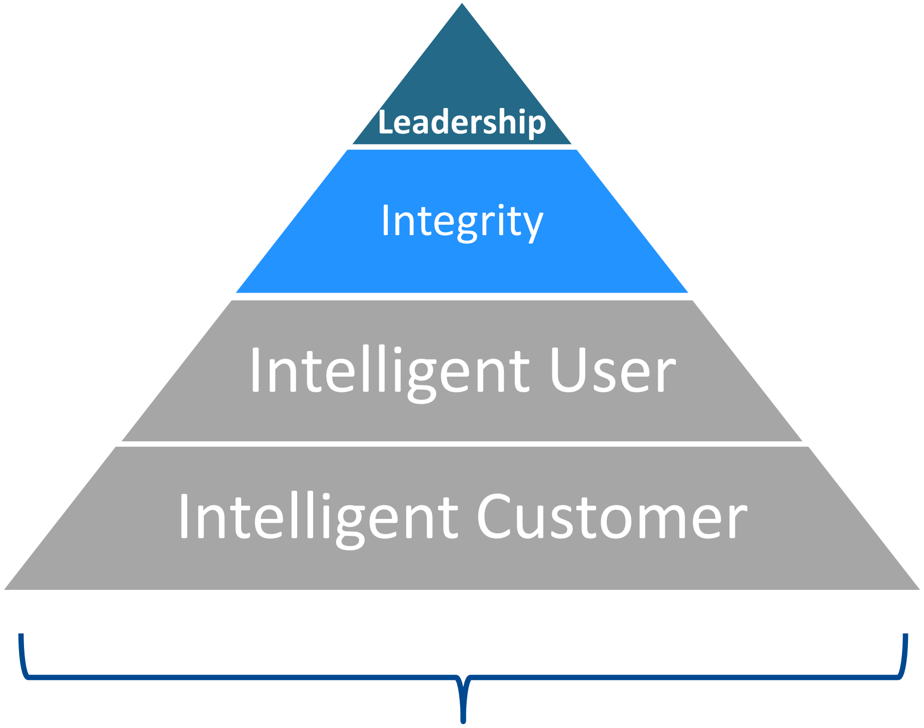
On our most recent Trent XWB-97 programme, we have developed and used industry leading ALM parts

The technology is used as standard in the development of advanced combustion systems

We continue this focus to exploit the full potential of ALM for the volume manufacture of gas turbine components

Our Approach

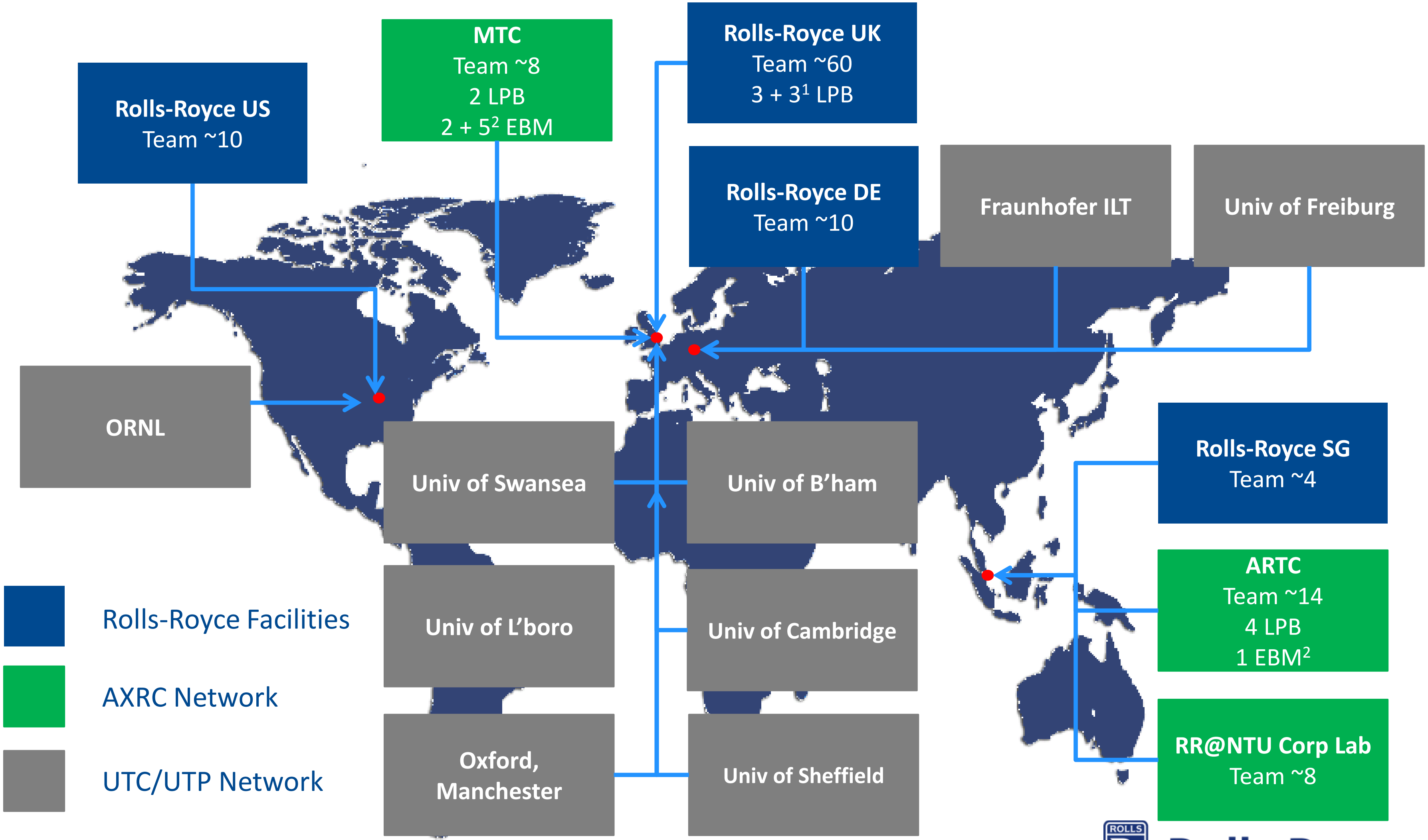
- Technology Theme Leadership
- Product Integrity
- Intelligent User
- Intelligent Customer



Licence to Operate

Global Aerospace Development Network

- Global team of >100 with access to ~20 machines



Rolls-Royce US
Team ~10

MTC
Team ~8
2 LPB
2 + 5[2] EBM

Rolls-Royce UK
Team ~60
3 + 3[1] LPB

Rolls-Royce DE
Team ~10

Fraunhofer ILT

Univ of Freiburg

ORNL

Univ of Swansea

Univ of B'ham

Univ of L'boro

Univ of Cambridge

Oxford, Manchester

Univ of Sheffield

Rolls-Royce SG
Team ~4

ARTC
Team ~14
4 LPB
1 EBM[2]

RR@NTU Corp Lab
Team ~8

🟦 Rolls-Royce Facilities

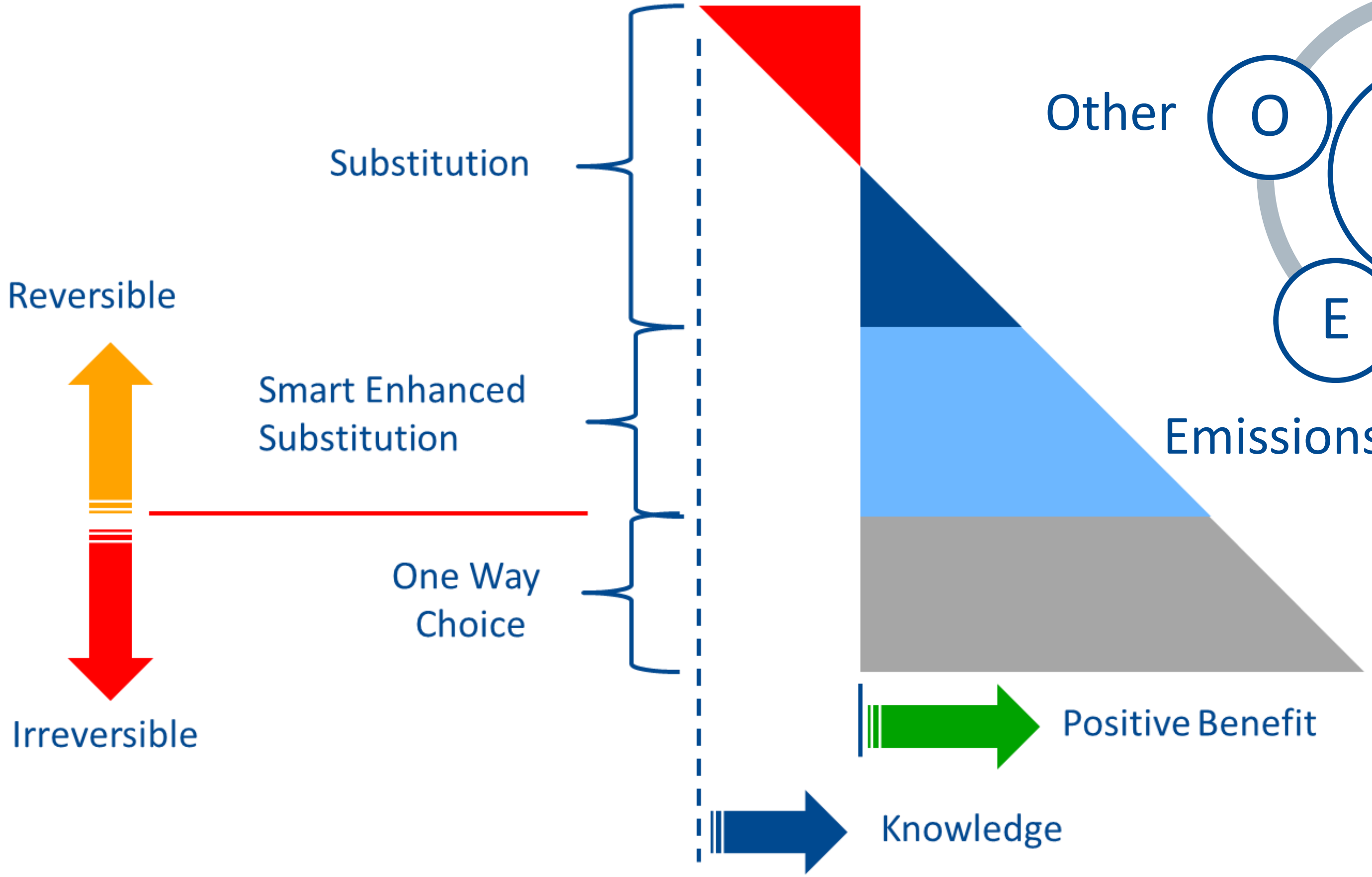
🟩 AXRC Network

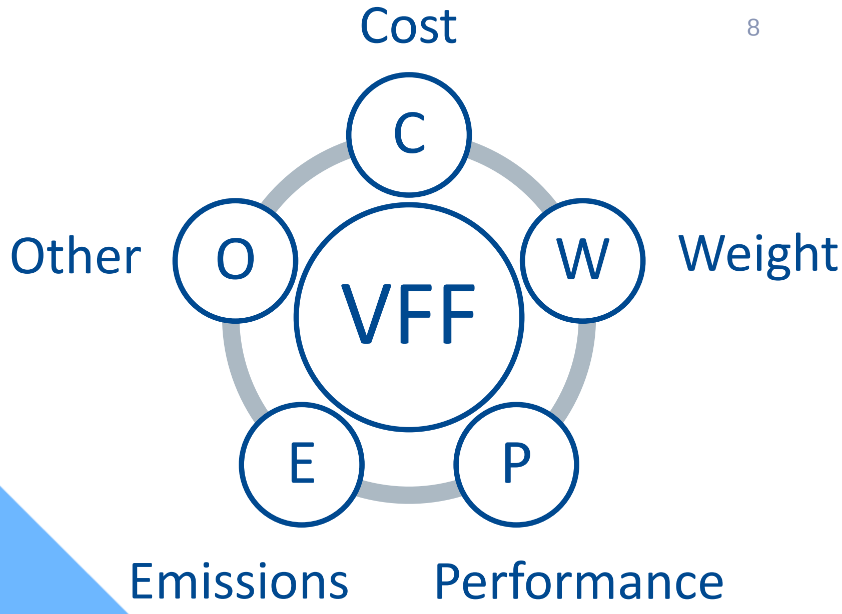
▨ UTC/UTP Network

[1] Installation January 2017
[2] Rolls-Royce owned

Rolls-Royce

ALM NPI - Value for Free





- **Maximum benefit from one way choice design for ALM – stepping stone enhanced substitutions are foreseen and required to manage risk**
- **VFF drivers differ with application**

Integrity & Assurance

Manufacturing

Consistency of Fabrication Methods

Materials

Suitability & Durability

Design

Materials Strength Properties & Materials Design Values

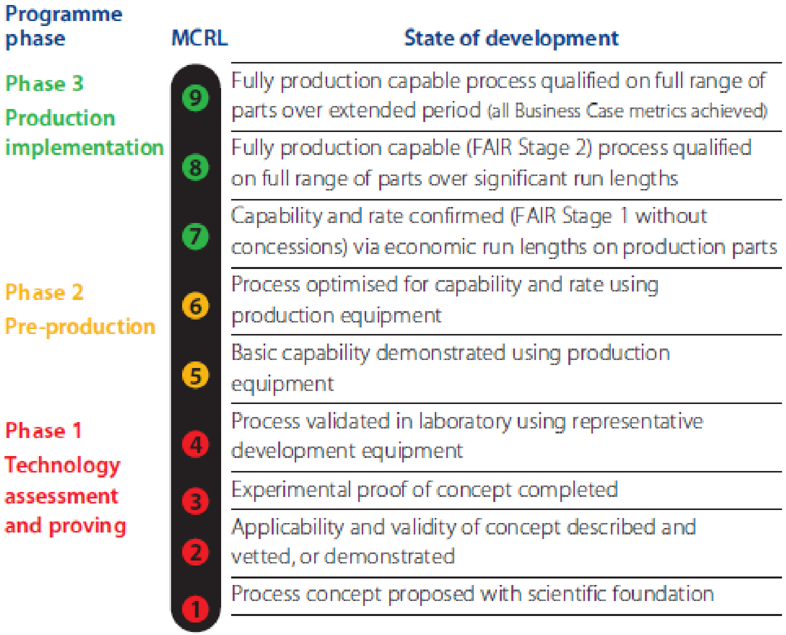
- **As an OEM we can and require to control all 3 to overcome barriers to deployment**

Manufacturing & Materials CA

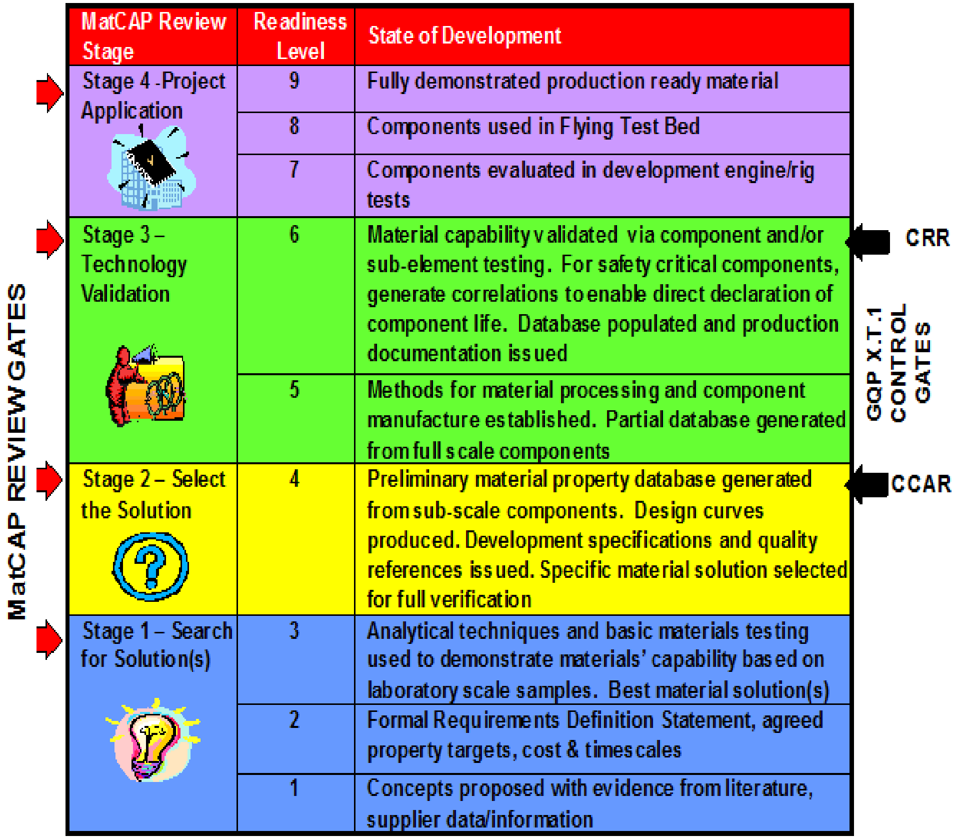
Established Materials Capability

&

Manufacturing Capability processes deployed



Programme phase	MCRL	State of development
Phase 3 Production implementation	9	Fully production capable process qualified on full range of parts over extended period (all Business Case metrics achieved)
	8	Fully production capable (FAIR Stage 2) process qualified on full range of parts over significant run lengths
	7	Capability and rate confirmed (FAIR Stage 1 without concessions) via economic run lengths on production parts
Phase 2 Pre-production	6	Process optimised for capability and rate using production equipment
	5	Basic capability demonstrated using production equipment
Phase 1 Technology assessment and proving	4	Process validated in laboratory using representative development equipment
	3	Experimental proof of concept completed
	2	Applicability and validity of concept described and vetted, or demonstrated
	1	Process concept proposed with scientific foundation



MatCAP REVIEW GATES

MatCAP Review Stage	Readiness Level	State of Development
Stage 4 -Project Application	9	Fully demonstrated production ready material
	8	Components used in Flying Test Bed
	7	Components evaluated in development engine/rig tests
Stage 3 – Technology Validation	6	Material capability validated via component and/or sub-element testing. For safety critical components, generate correlations to enable direct declaration of component life. Database populated and production documentation issued
	5	Methods for material processing and component manufacture established. Partial database generated from full scale components
Stage 2 – Select the Solution	4	Preliminary material property database generated from sub-scale components. Design curves produced. Development specifications and quality references issued. Specific material solution selected for full verification
Stage 1 – Search for Solution(s)	3	Analytical techniques and basic materials testing used to demonstrate materials' capability based on laboratory scale samples. Best material solution(s)
	2	Formal Requirements Definition Statement, agreed property targets, cost & timescales
	1	Concepts proposed with evidence from literature, supplier data/information

Repair & OEM component manufacturing

Specific Case Study Demonstrator EBM ESS vanes

Trent XWB-97 Front Bearing Housing

XWB97K Front Bearing Housing

ON THE CLIMB
AUSTRALIA PLOTS PATH TO AIR FORCE OF THE FUTURE
SHOW REPORT P20

TOXIC DEBATE

RULES REWRITE

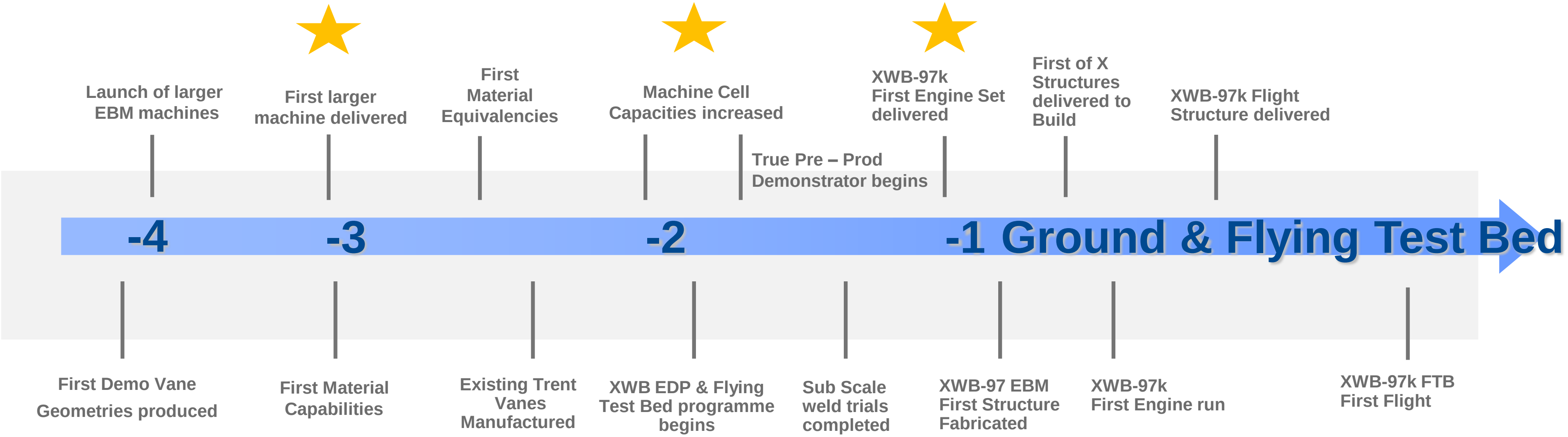
FLIGHT
INTERNATIONAL

COMMERCIAL ENGINES

THE POWER OF PRINT

Why Rolls-Royce is making its big move into ALM

Case Study Demonstrator - EBM Vanes



Launch of larger EBM machines

★ First larger machine delivered

First Material Equivalencies

★ Machine Cell Capacities increased

True Pre – Prod Demonstrator begins

★ XWB-97k First Engine Set delivered

First of X Structures delivered to Build

XWB-97k Flight Structure delivered

-4

-3

-2

-1 Ground & Flying Test Bed

First Demo Vane Geometries produced

First Material Capabilities

Existing Trent Vanes Manufactured

XWB EDP & Flying Test Bed programme begins

Sub Scale weld trials completed

XWB-97 EBM First Structure Fabricated

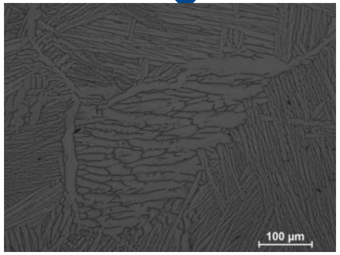
XWB-97k First Engine run

XWB-97k FTB First Flight

Clearly Setting Requirements

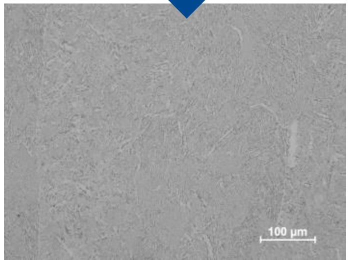
Single Casting

Individual Vanes



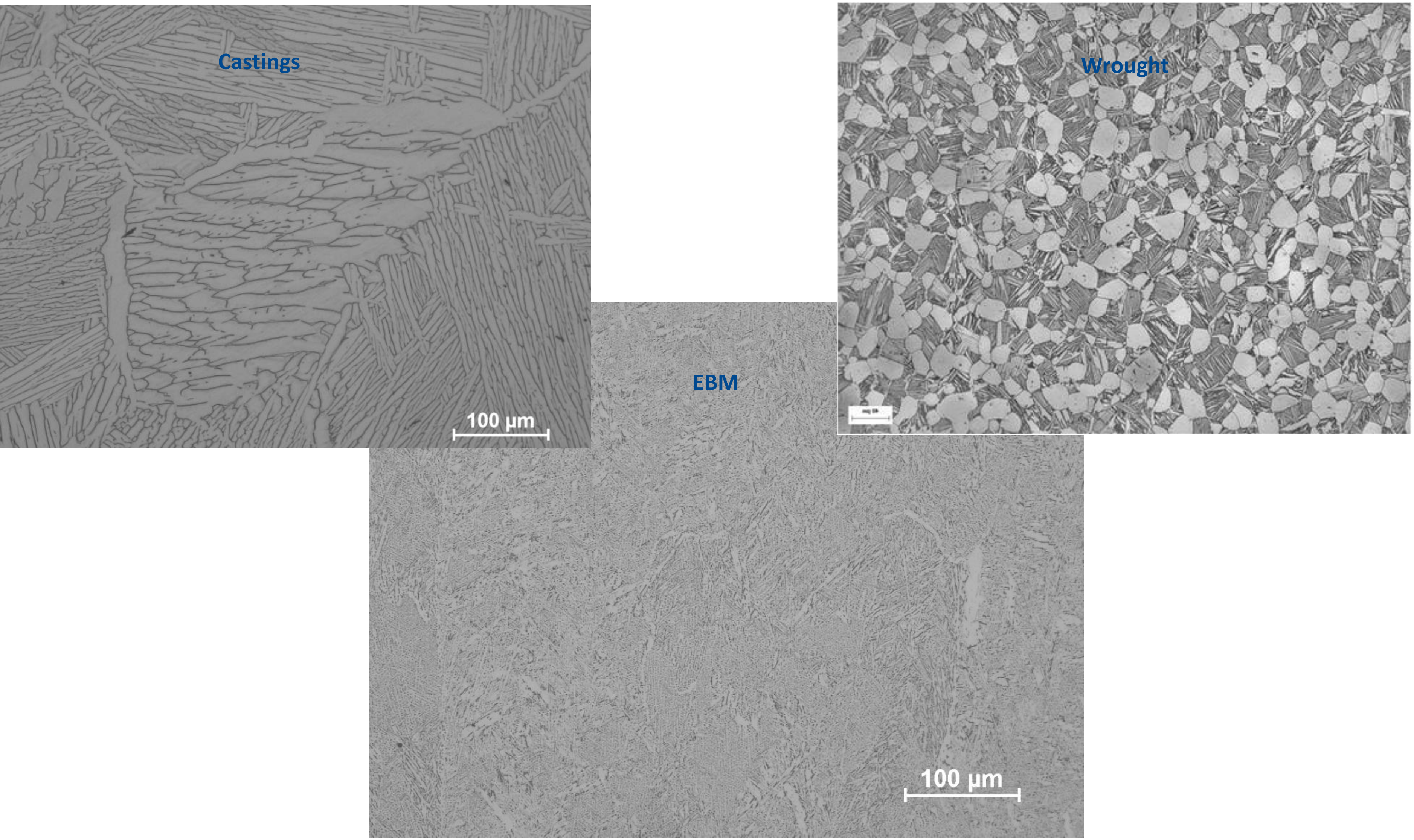
Very
coarse

Fine



- **Design requirements clear and understood**
  - **Required – equivalence in a true additive production environment**
  - **Required – equivalence across multiple machine cells**

Microstructures in Ti64



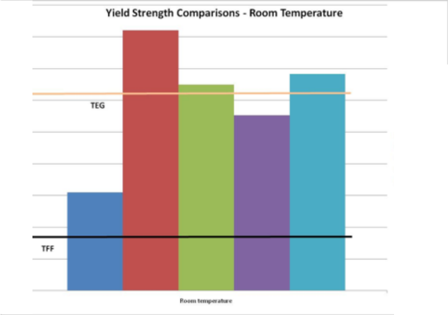
Different set of mechanical properties

Of course it started with Coupon Tests

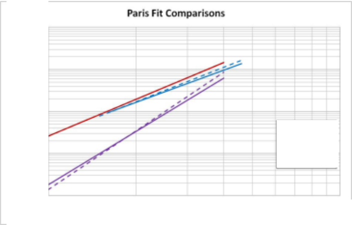
-5 to -3

Timeline

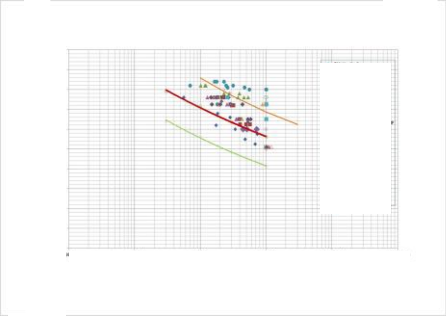
Tensile



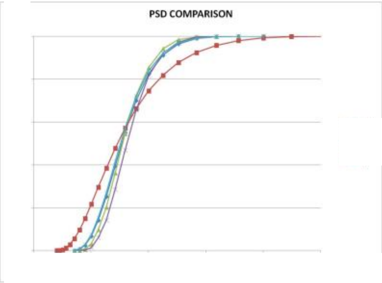
Crack Prop



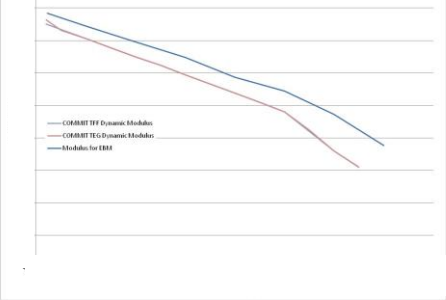
LCF



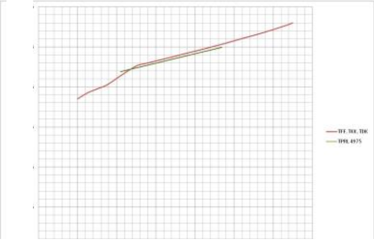
Powder PSD



Elastic Modulus



Thermal Expansion



- Multiple powder sources & methods
  - Extensive Powder characterization
- Testing of standard size test coupons e.g.
  - ~ 100 Fatigue, ~ 50 Tensile, ~ 25 Crack Propagation

Equivalence or better than casting data

Rolls-Royce

Then moved onto component geometries

-4 to -2

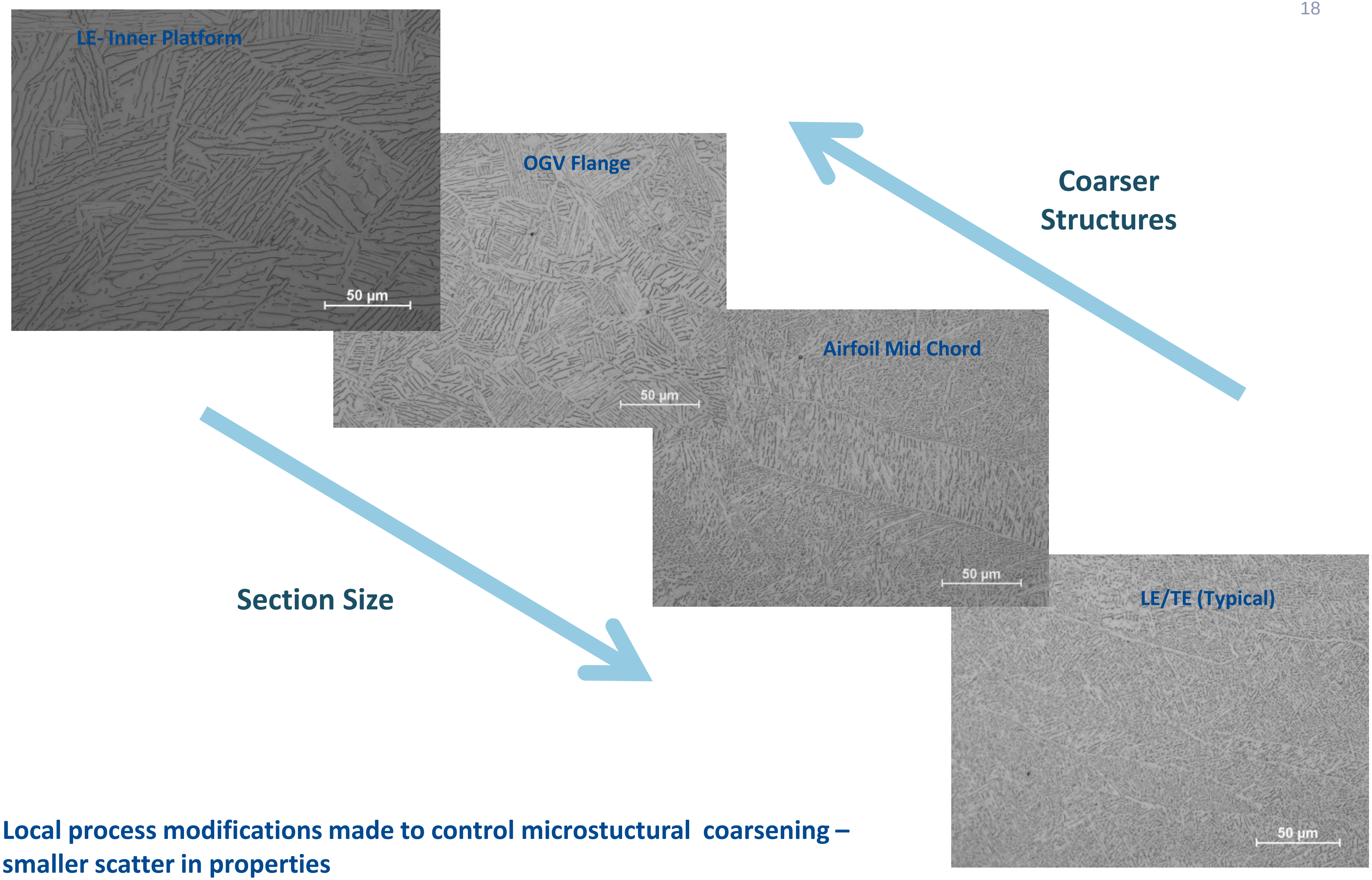
Timeline

- Multi Variant
- Machine Volume Restrictions
- Machine Volume Increased
- Build Orientations
- Geometry Effects
- Non Destructive Inspection Development

A robust method established

Rolls-Royce

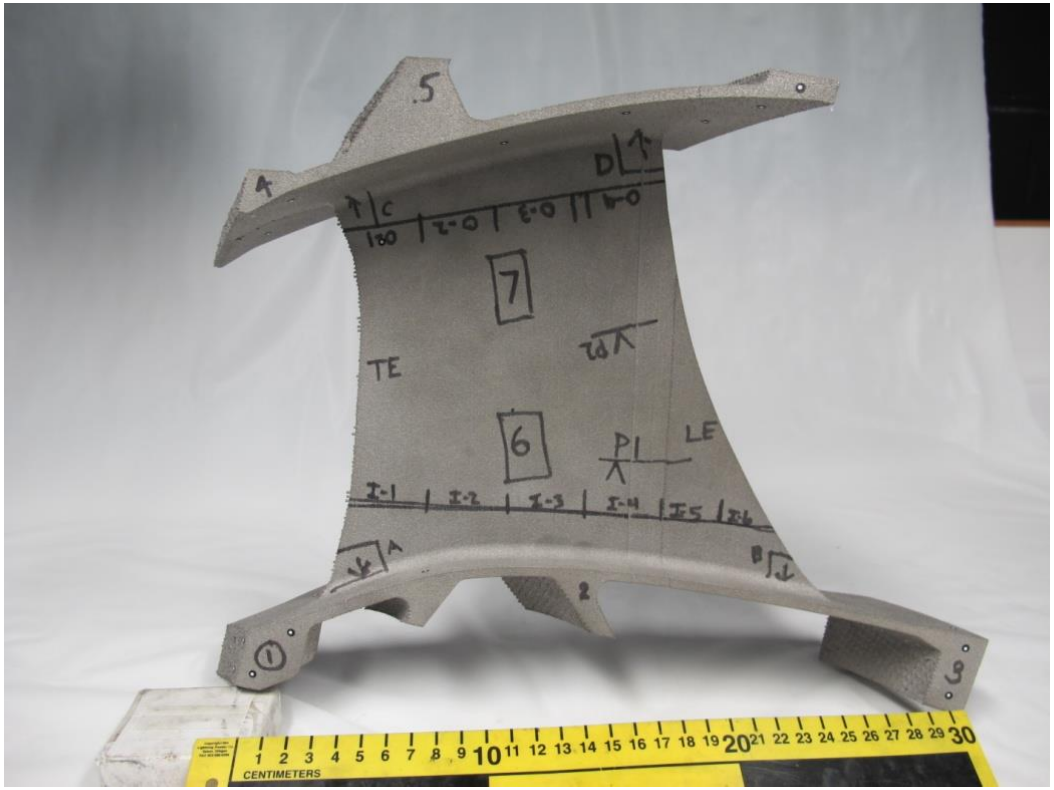
Microstructures



Local process modifications made to control microstuctural coarsening – smaller scatter in properties

Rolls-Royce

XWB Component Cut-Ups



- *Greater microstructural and property variability than observed in test specimens. Variations between thick, thin, downward sections etc. seen*
- *Design integrity confirmed and demonstrated*

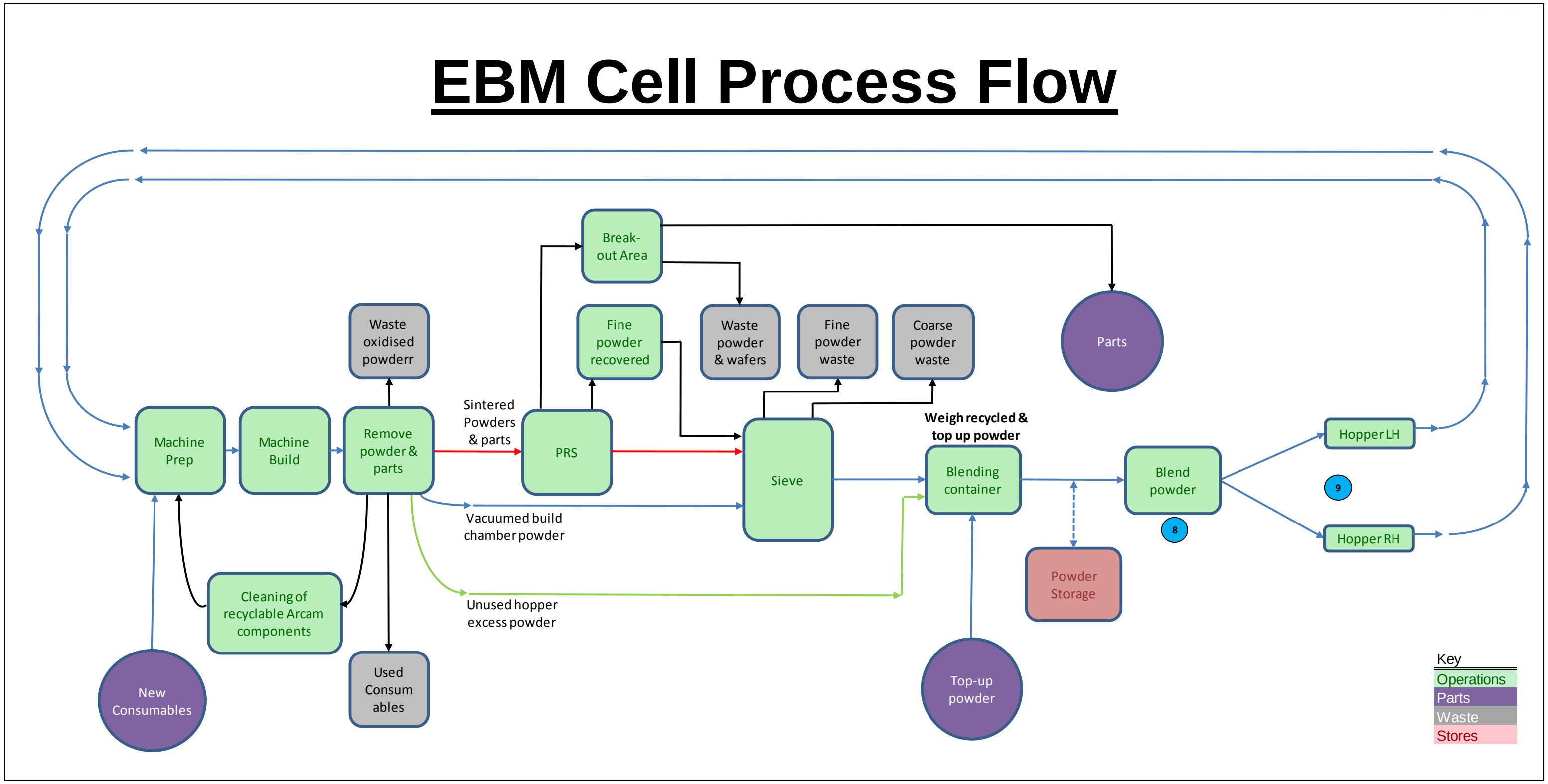
Validation
&
Demonstration

“What bad looks like is just as important”

True pre-production demonstrator

-2

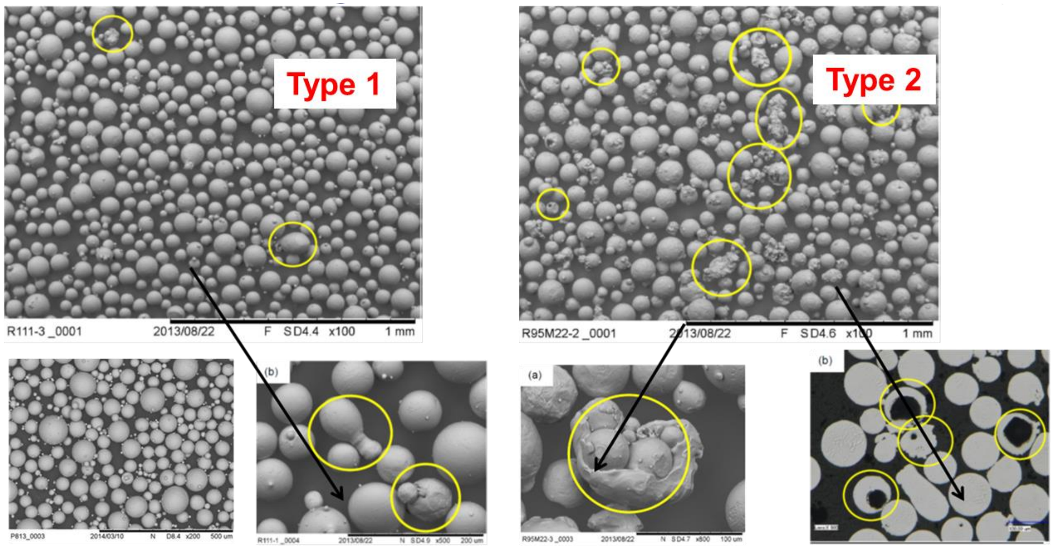
Timeline



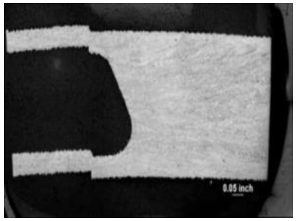
- Full 24-7 operation
- Understanding property sensitivity to powder management and abnormalities as a result of industrialised volumes
- Debits established
- Fixed Process and standards in place

Why establish a full scale pre-production demo?

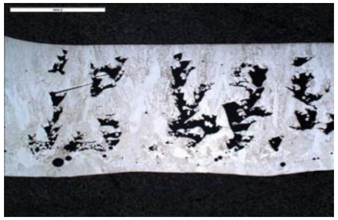
Control and thorough understanding of process variation is vital to maintaining product integrity – volume matters



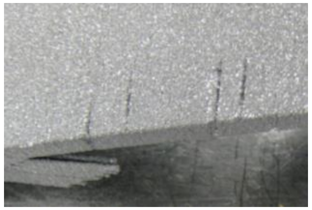
Early abnormality reduction and elimination



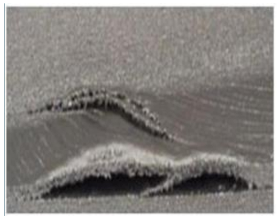
Layer Shifts



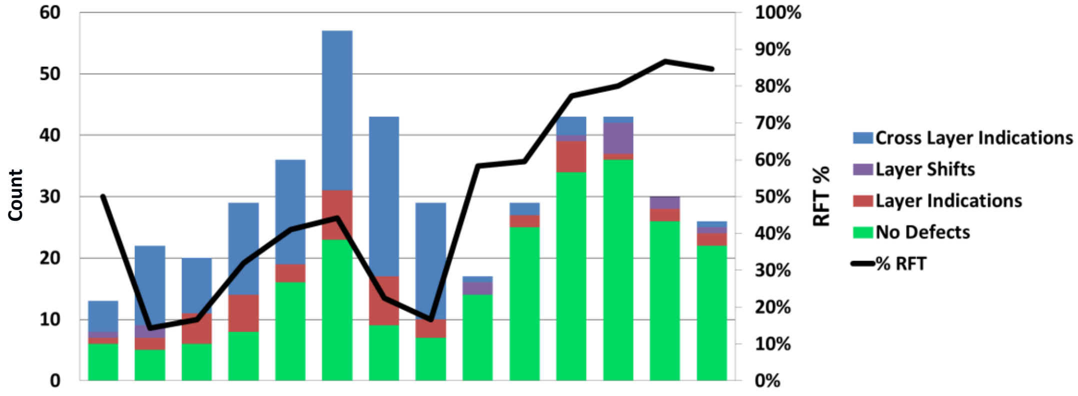
Cross Layer Defects:



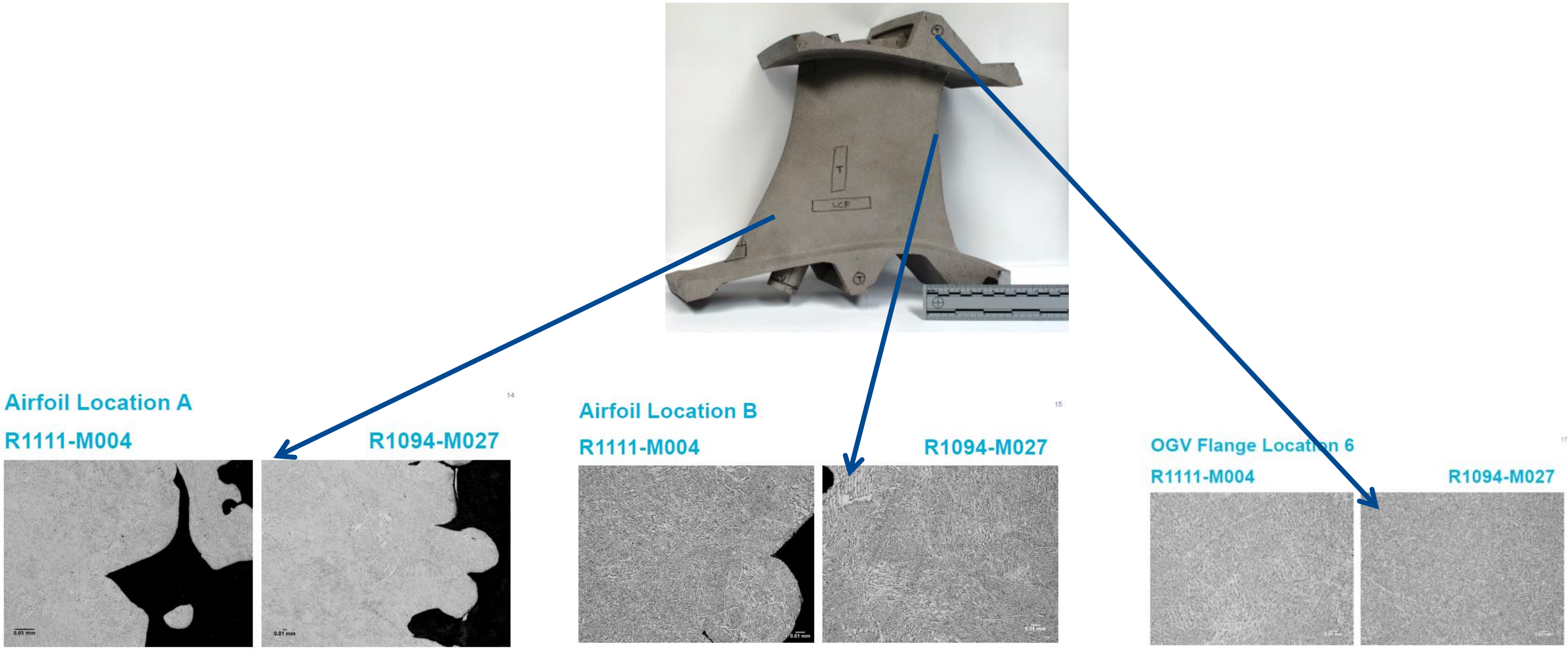
Layer Indications:



Layer Separation

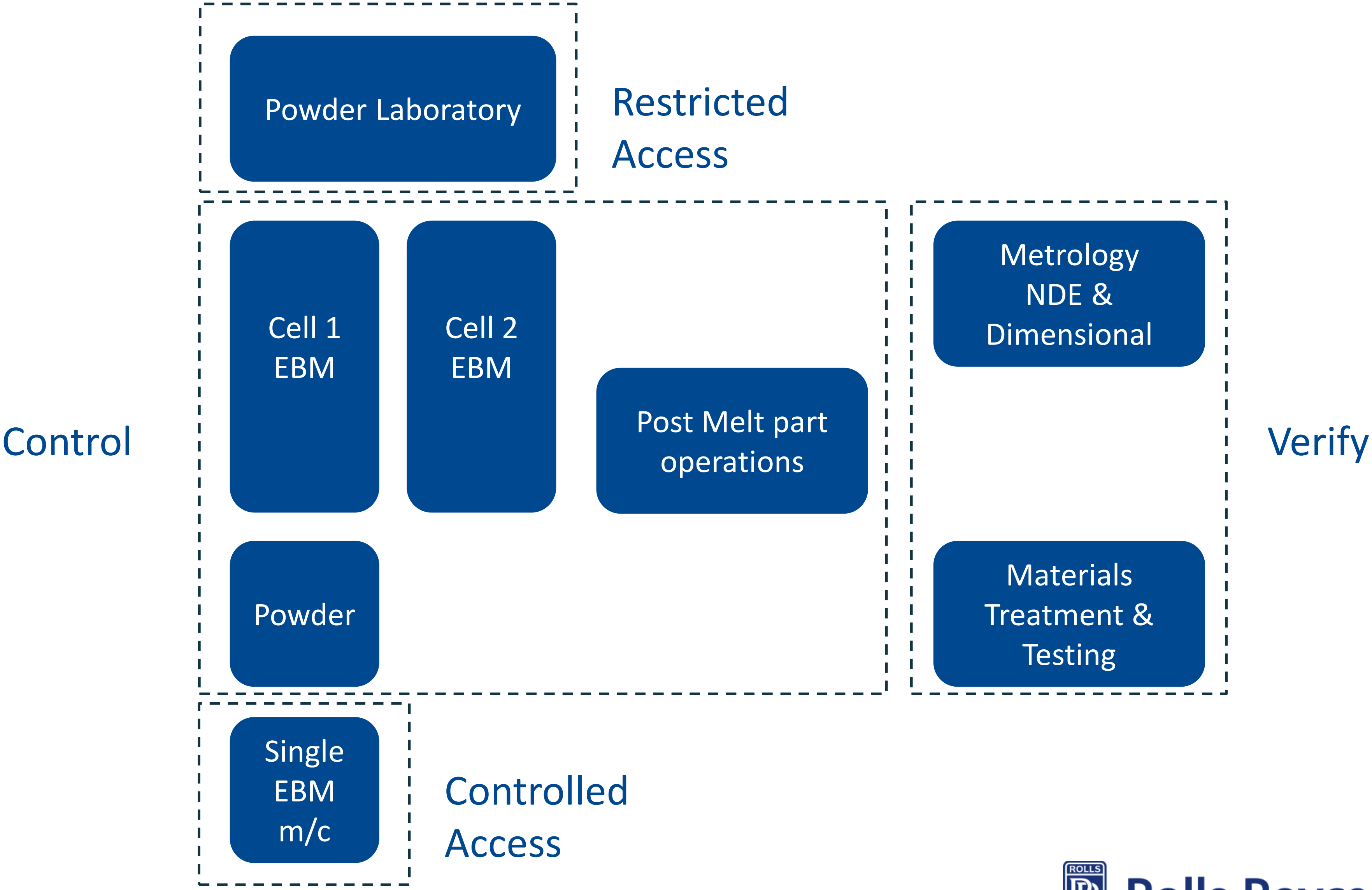


Build to Build and Intra M/c Variability Studied



Microstructural equivalence at identical locations demonstrated

Industrialisation – Under Control



Powder Laboratory

Restricted Access

Control

Cell 1 EBM

Cell 2 EBM

Post Melt part operations

Powder

Metrology NDE & Dimensional

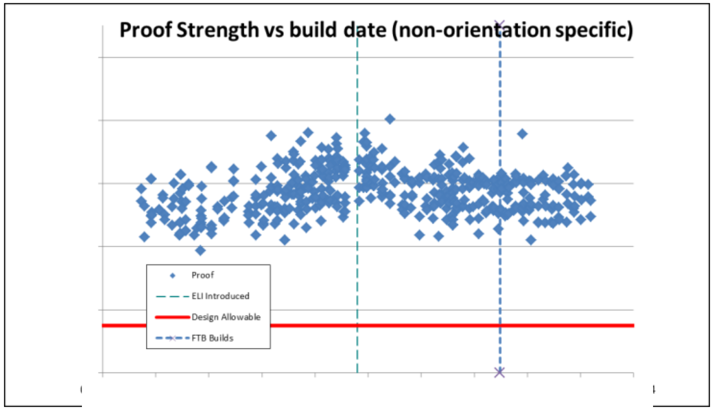
Materials Treatment & Testing

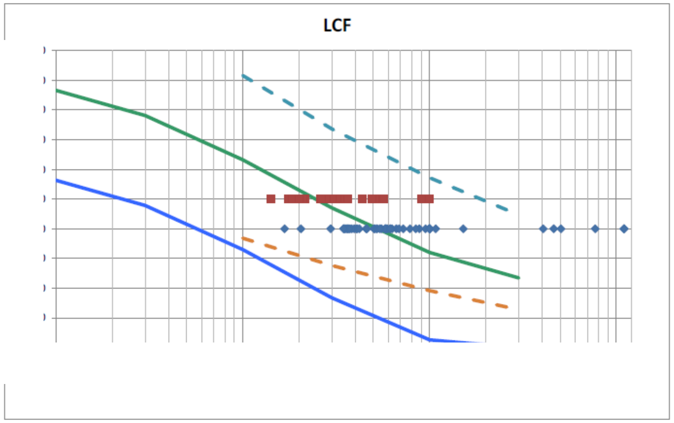
Verify

Single EBM m/c

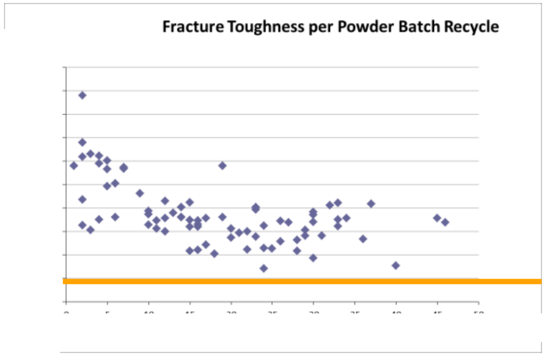
Controlled Access

Extended Testing on every build during Engine Development Program and Flying Test Bed Vane Manufacturing



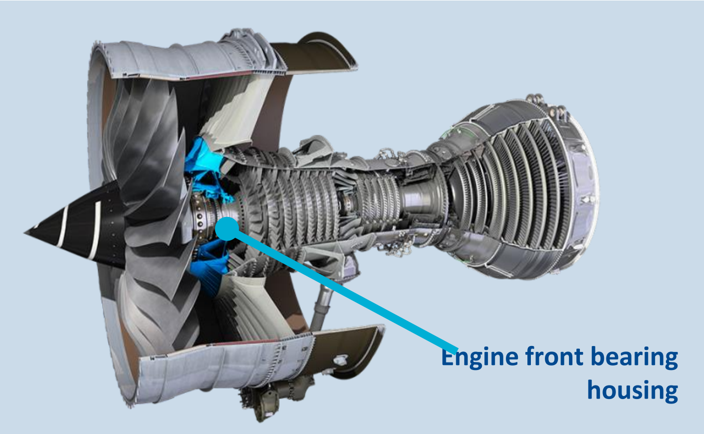


Over 400 tensile tests, 100 LCF and 50 fracture toughness tests



- ***All builds met requirements***
- ***Protecting product integrity while qualifying process changes***

XWB 97K EBM Front Bearing Housing



- Significant load bearing engine structure
  - **48 titanium printed aerofoils**
  - **1.5m diameter, 0.5m long**
- Successful ground testing in multiple Trent XWB-97 engines
- Demonstrated a 30% 'like for like' reduction in manufacturing lead time
- Faster and more cost-effective design iterations
- 100s of exacting aero quality parts made
- Tens of 1000s of hour of printing experience under full Rolls-Royce production conditions

- **Pioneered use of the world's largest EBM titanium 3D machines**

- Successfully Flight tested in late 2015
- A solid foundation for AM production development

Trusted to deliver excellence

APPENDIX P—QUALIFICATION AND CERTIFICATION OF ADDITIVE MANUFACTURED CRITICAL PARTS FOR UK MILITARY AVIATION

27 August 2017

Ministry of Defence

Qualification and certification of additive manufactured critical parts for UK military aviation

Rebecca Mangham, Senior Scientist – Materials (rrmangham@dstl.gov.uk)

Dr Matthew Lunt, Principal Scientist – Materials and Structures (MJLUNT@dstl.gov.uk)

Prof. Steve Reed, Dstl Fellow – Aircraft structural integrity (SCREED1@dstl.gov.uk)

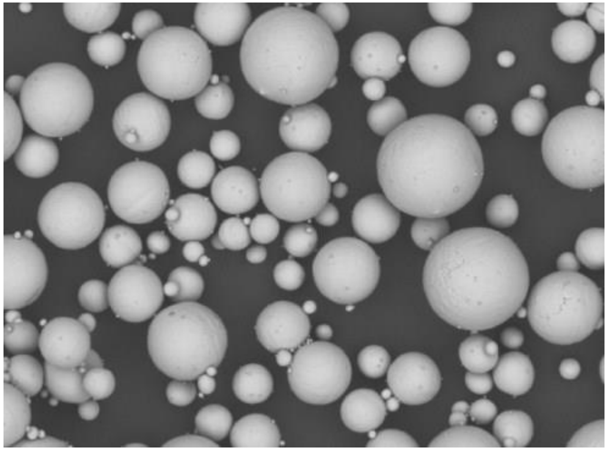
27 August 2017

UK OFFICIAL

DSTL/CP104061

Outline

- Introduction
  - Dstl
  - Novel technologies project
- Why AM?
- Challenges in qualification
- MASAAG guidance paper
  - Approach
  - Current regulations
  - AM Design and Build
  - Case studies



About [dstl]

Analysis

Systems

Weapons

C4ISR
Command, Control, Communication, Computers Intelligence, Surveillance And Reconnaissance

Human Capability

Counter-Terrorism (CT) and Security

CBR
Chemical, Biological And Radiological

Integrated Survivability

Cyber

- Delivers the UK MOD S&T programme
- An executive Agency of MOD
- Based at 3 main sites across the UK
- 4,500 employees - including civilians, scientists, military advisers and strategic partners

The qual. and cert. of novel technologies project

- Initiated to identify and support areas where qualification and certification could be a barrier to exploitation in air systems
- Later extended to also cover cyber vulnerabilities and their affect on airworthiness

Multi-Core Processors

Data-Driven Systems

Pilot Substitution Functions

Additive Manufacture

Mitigating Cyber - Threats and Vulnerabilities for Airworthiness

Why is AM of interest for military aviation?

UK military aviation challenges:

- Relatively small numbers of platforms
- Very long life – availability of spares
- Deliberately in harm's way
- Weight and volume constrained
- Need to reduce cost of development

Why is AM of interest for military aviation?

UK military aviation challenges:

- Relatively small numbers of platforms
- Very long life – availability of spares
- Deliberately in harm's way
- Weight and volume constrained
- Need to reduce cost of development

AM benefits:

- Ideal for small production runs:
  - Repair of parts, especially high value
  - One-off manufacture of parts (spares or prototypes)
- Different design/manufacturing constraints
  - Highly mass/volume-optimised structures

But…For critical applications AM is difficult to qualify and certify

- Large number of variables
- Many different machine or system types in use
- Intellectual property lies in the software and processes rather than hardware
- AM has the potential to be used for complex structures or legacy parts
- Often AM manufacturers are not hooked into qualification and certification frameworks

Qualification and Certification of AM in Military Aviation task

- Producing a Guidance Note for MASAAG
- Led by Dstl but delivered by a specially convened Working Group
  - MBDA, BAE Systems, Airbus, Rolls-Royce, GKN, Leonardo (AW), Lockheed Martin, SAFRAN Landing Systems, SME AM Businesses, Civil Aviation Authority, National Physical Laboratory, Health and Safety Laboratory, AM Bureaux, Academia, MOD (MAA, 1710 Naval Air Squadron), Dstl, TWI, High Value Manufacturing Catapult, QinetiQ
- Cite appropriate references from recognised authorities and peer reviewed journals (e.g. ASTM, ISO, etc.)
- Bring together others' activities (e.g. EASA, NadCap, SAE, etc.)

Our approach

1. Identify what our Regulatory Articles and Certification Standards already state for manufactured components.
2. Highlight where AM differs from other methods of manufacture.
   - Variables
   - Testing
   - Reporting
3. Provide case studies where the regulatory framework has been applied to AM components.

How are MOD airworthiness regulations applied?

Regulation

- e.g. The type airworthiness authority (TAA) **shall** ensure that Structural Integrity is established to demonstrate that the aircraft structure is airworthy to operate

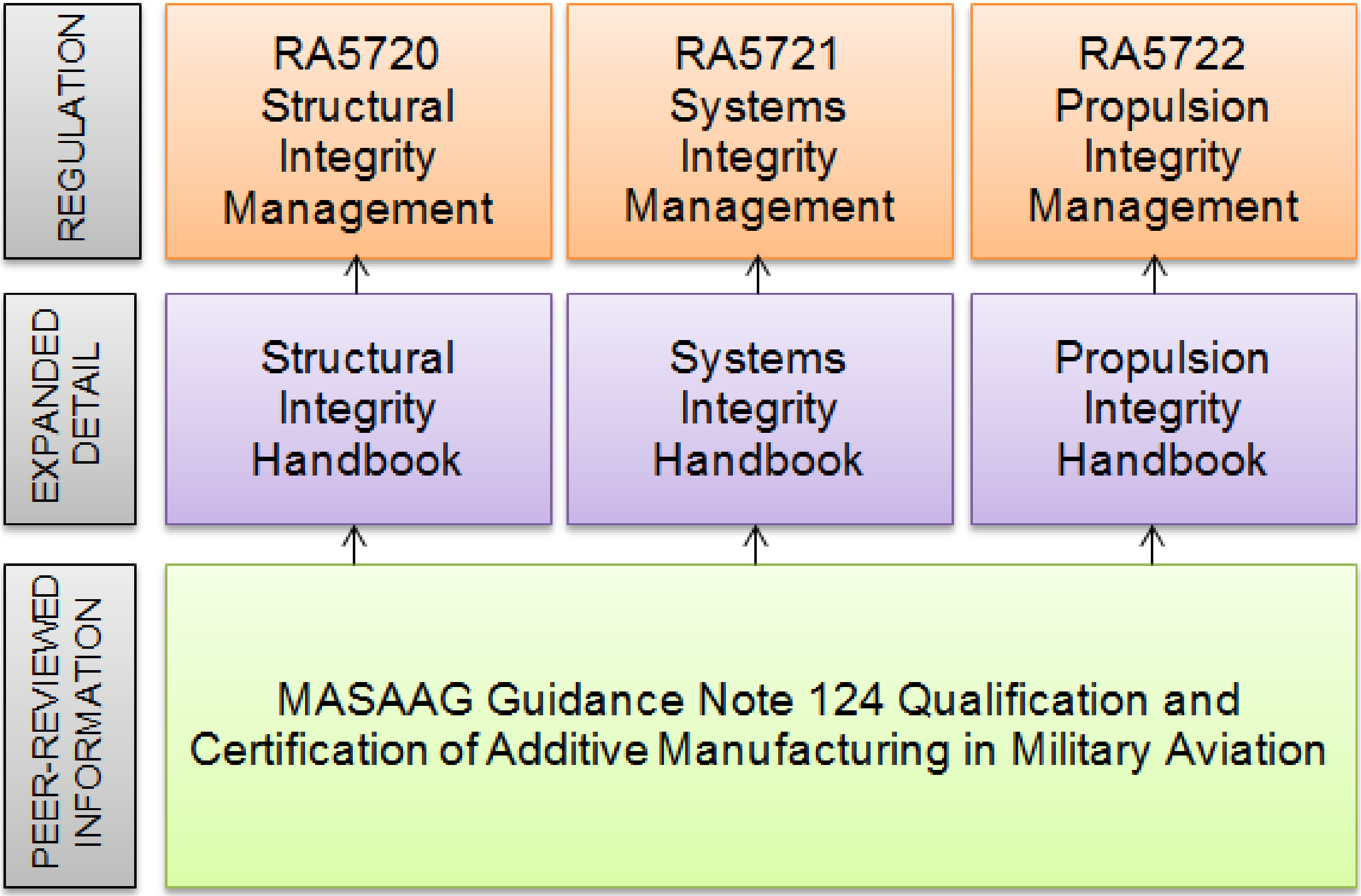
Compliance

- e.g. Appropriate static strength, fatigue strength and loads validation evidence, obtained during design, substantiation and certification of the aircraft, **should** be available to support the establishing of Structural Integrity

Guidance

- e.g. Much of the evidence required to establish Structural Integrity will be generated during the development phase in support of certification and registration of the aircraft. It is informed by: a. The structural design philosophy adopted for the certification basis as appropriate to the intended operation including shortfalls in the level of assurance, b. The structural verification and validation programme and the assumptions on which this is based. c. Structural hazards identified in the Hazard Log.

The MASAAG paper - scope



REGULATION

RA5720
Structural
Integrity
Management

RA5721
Systems
Integrity
Management

RA5722
Propulsion
Integrity
Management

EXPANDED DETAIL

Structural
Integrity
Handbook

Systems
Integrity
Handbook

Propulsion
Integrity
Handbook

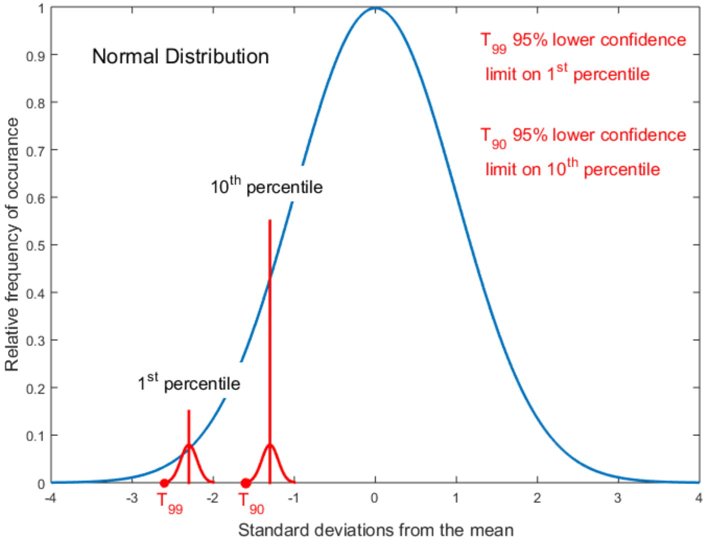
PEER-REVIEWED INFORMATION

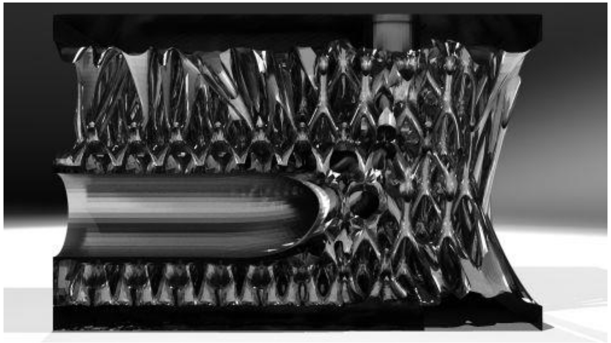
MASAAG Guidance Note 124 Qualification and Certification of Additive Manufacturing in Military Aviation

UK OFFICIAL

The MASAAG paper - scope

- Qualification and certification of:
  - Structures (Safe life)
  - Engines (LTFC, 2/3 disfunction)
- Types of parts:
  - Grade A (Structures)
  - Class/Group 1 (Engines)
- Metal AM techniques:
  - Laser powder bed
  - E-beam powder bed
  - Laser blown powder
  - Wire Arc

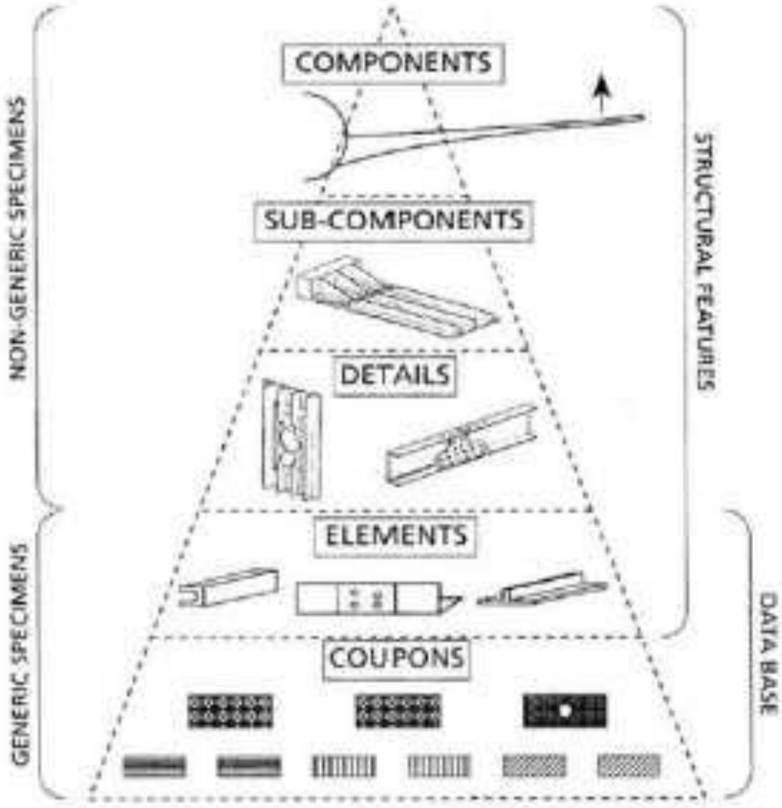




Courtesy MMSonline.com

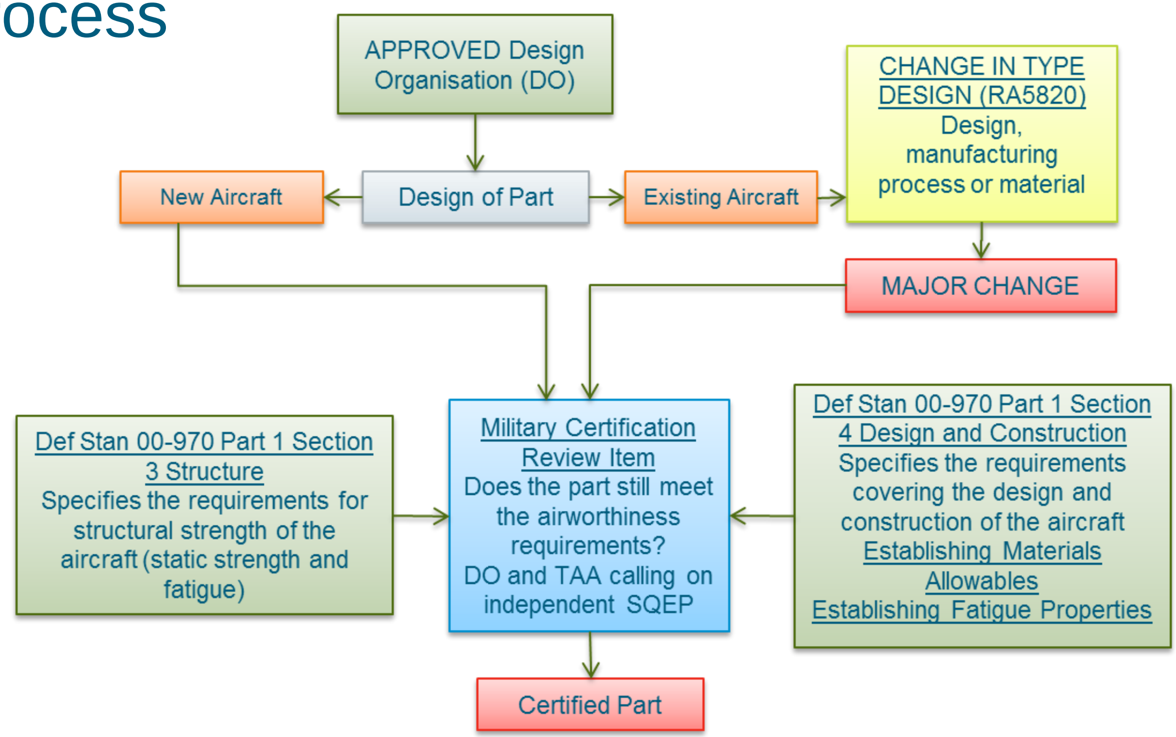
Guidance from other methods of manufacture

- High performance castings:
  1. Qualification of the process.
  2. Proof of the product.
  3. Monitoring of the process.
- Welding
  - Heat affected zones in repair
- Composites
  - Analogous to AM?
  - Building block approach



Recommendation 1

An AM part, whether for a new or existing aircraft, should go through a Military Certification Review Item-type process



APPROVED Design Organisation (DO)

Design of Part

New Aircraft

Existing Aircraft

CHANGE IN TYPE DESIGN (RA5820)
Design, manufacturing process or material

MAJOR CHANGE

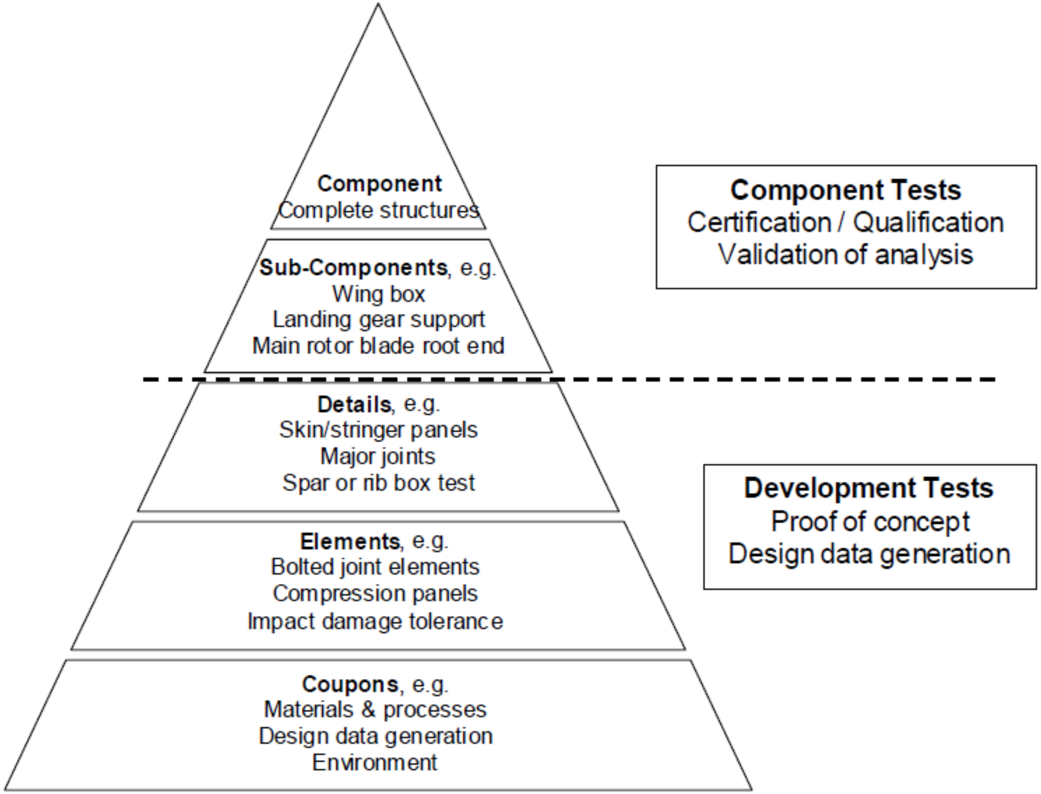
Def Stan 00-970 Part 1 Section 3 Structure
Specifies the requirements for structural strength of the aircraft (static strength and fatigue)

Military Certification Review Item
Does the part still meet the airworthiness requirements?
DO and TAA calling on independent SQEP

Def Stan 00-970 Part 1 Section 4 Design and Construction
Specifies the requirements covering the design and construction of the aircraft
Establishing Materials Allowables
Establishing Fatigue Properties

Certified Part

Recommendation 2



Component
Complete structures

Sub-Components, e.g.
Wing box
Landing gear support
Main rotor blade root end

Details, e.g.
Skin/stringer panels
Major joints
Spar or rib box test

Elements, e.g.
Bolted joint elements
Compression panels
Impact damage tolerance

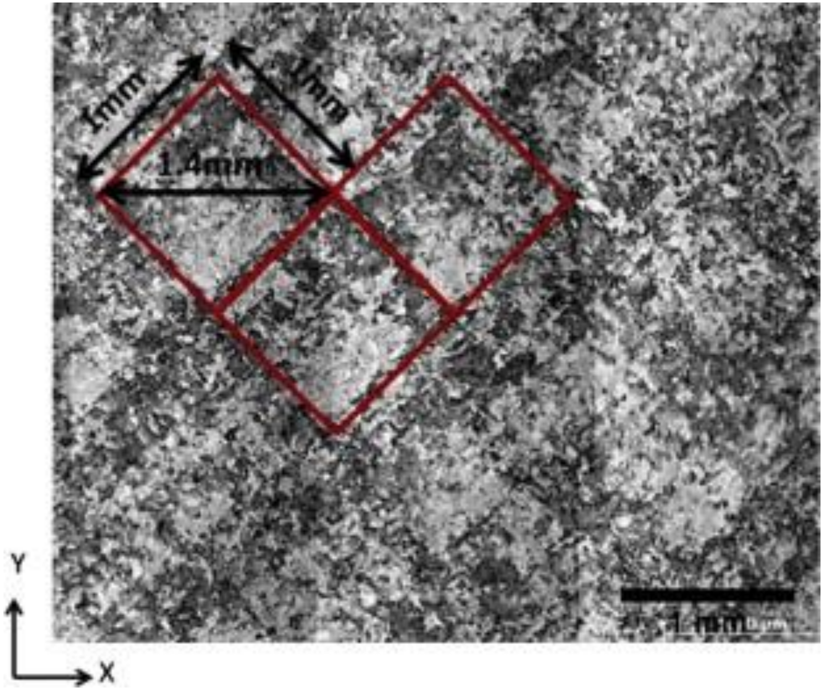
Coupons, e.g.
Materials & processes
Design data generation
Environment

Component Tests
Certification / Qualification
Validation of analysis

Development Tests
Proof of concept
Design data generation

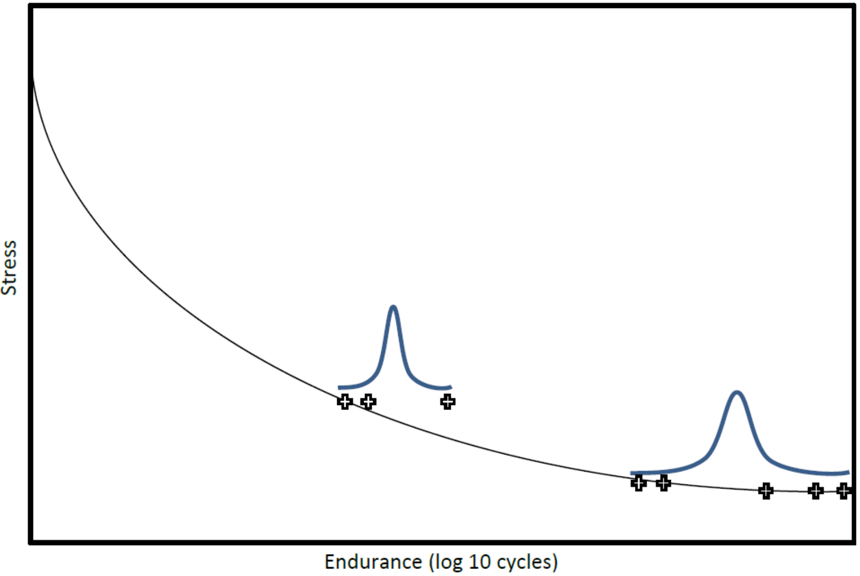
The philosophy of the testing pyramid should be adopted to provide a level of assurance that the sources of scatter have been captured in the design allowables and fatigue properties

Recommendation 3



For critical parts, until such time that AM is sufficiently mature, both the AM process AND the part should be qualified and certified as a way of establishing and guaranteeing variability

Recommendation 4



For the Safe-Life approach scatter factors for Safe S-N curves for AM parts should be rationally derived:

- They should be determined from tests of elements that are **representative** of structural features
- Customary statistical techniques should be applied to give the required probability of failure

AM Design and Build guidance

Introduction to AM processes

- Common defects
- An introduction to melting and solidification during AM

Part design

- Physical and mechanical properties
- Part geometry
- Design for anisotropy

Build design

- Machine Choice
- Facilities aspects
- Part configuration and build supports
- Scan strategy
- Build parameters / parameter set

Build key performance variables

- Feedstock
- Heat source
- Material pre-heating Environment
- In line measurement and control

Post processing techniques

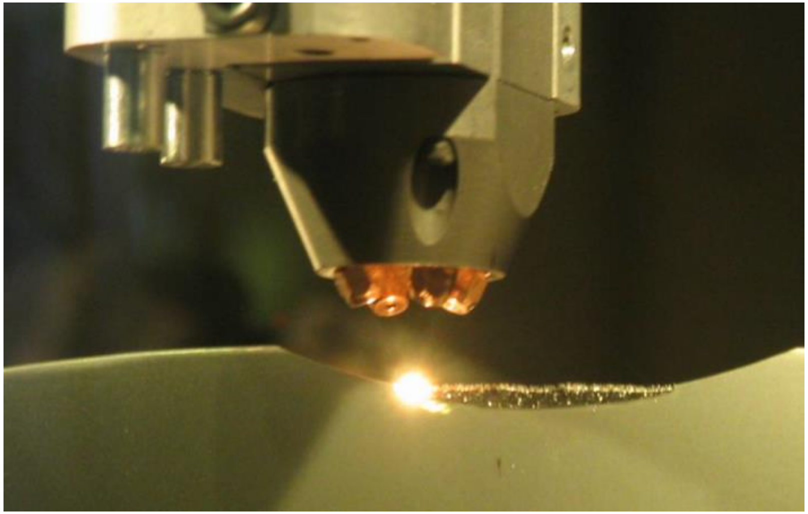
- Part removal from build plate
- Thermal post-processing
- Cold working
- Surface finishing

Component validation

- Witness, traveller and test specimens
- Inspection
- Destructive testing
- Non-destructive evaluation
- Residual Stress determination

Case studies

- Using case studies to represent the current technologies likely to be used for grade A parts:
  - Laser powder bed
  - E-beam powder bed
  - Laser blown powder
  - Wire Arc



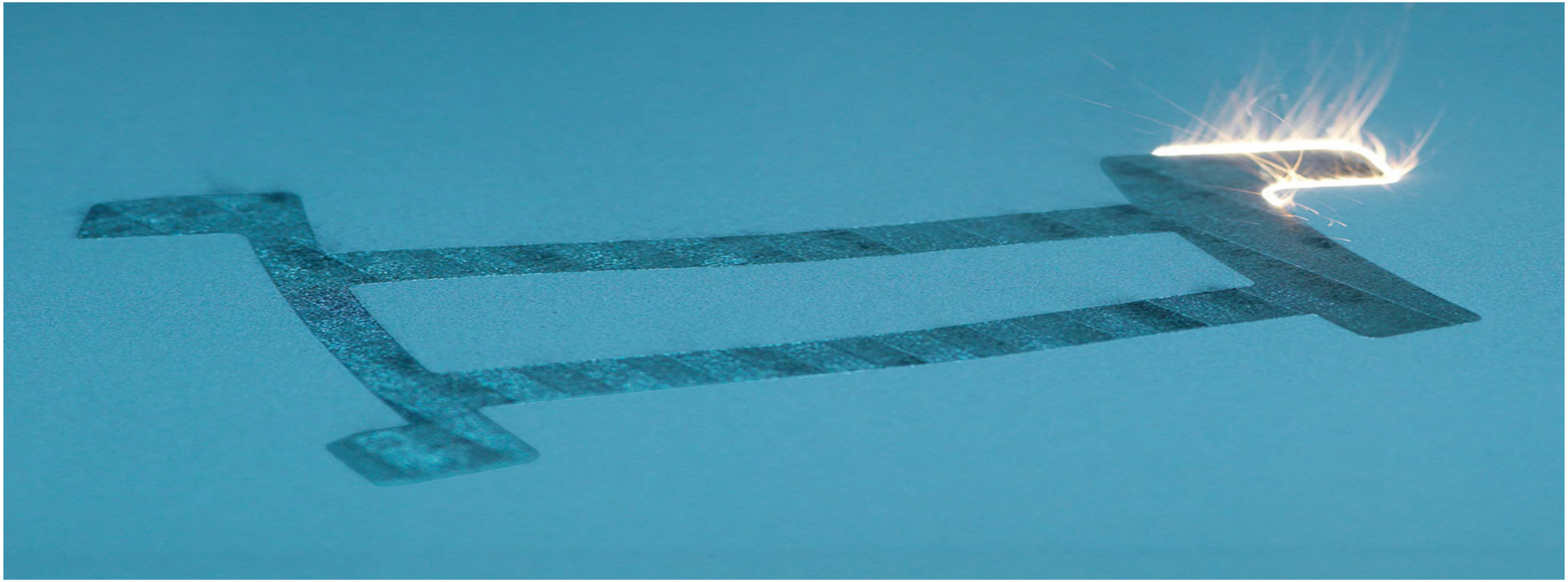
Summary

- UK MOD approach focussing on 3 key questions:
  1. What do our regulations already say in this area?
  2. How is AM different?
  3. What are industry doing already to qualify parts?
- Document progress on 3 questions:
  1. Complete, reviewed
  2. Complete, with our working group
  3. To be written, in the gift of our industry colleagues to provide

Any questions

27 August 2017

APPENDIX Q—ON-LINE PROCESS CONTROL TO ASSESS THE AS-BUILT COMPONENT QUALITY



On-line process control to assess as build SLM component quality

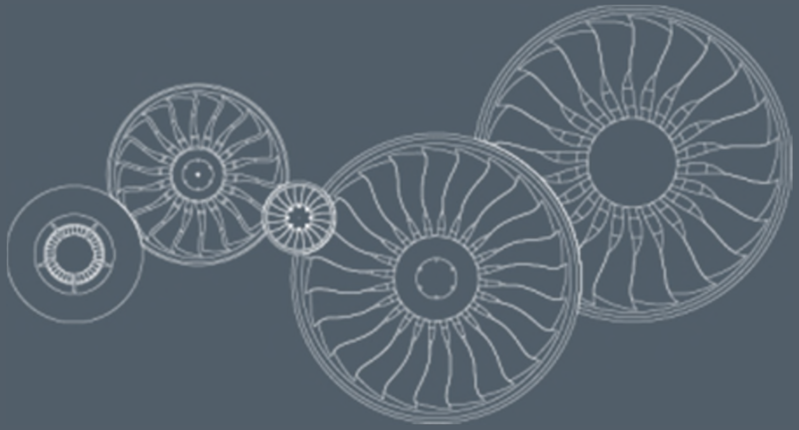
3rd FAA/USAF AM Workshop, Dayton

8/30/2017

Proprietary Notice

Agenda

1. Selective Laser Melting @ MTU
2. Quality Assurance Concept
3. On-line Monitoring by Optical Tomography
4. Quantification of Optical Tomography
5. Summary



Agenda

1. Selective Laser Melting @ MTU
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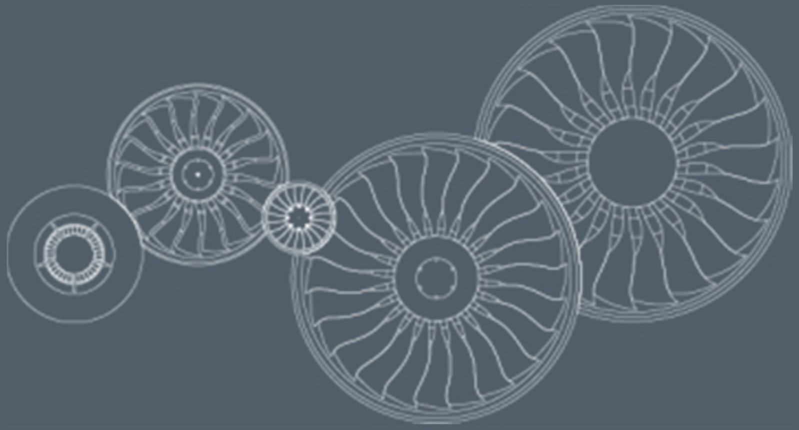


AM@MTU

History

1997
First studies
Rapid Prototyping

2007
First metal development parts

2010
First machine: Manufacturing of production toolings

2011
Start AM@MTU I

Production site established

2013
First series part for „PW1133G Boroscope boss“

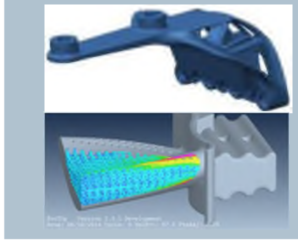
2015
Start AM@MTU II
Stepwise increase in capacity and applications

Continuous development of manufacturing expertise and range of applications

AM@MTU

Implementation Strategy

Phase 3: Center-of-Excellence



Optimization of part functionality, weight, and cost through “bionic design”

Phase 2: Industrialization

- Ramp-up capacities
- Cost effective manufacturing of raw parts
- Substitution of castings

Phase 1: Market Introduction

- Manufacturing of tooling
- Rig- and development hardware
- First Serial production part

Currently MTU is in the middle of Phase 2

AM@MTU

Facilities

Equipment

- 6 production M280 machines
- 2 technology M290 machines

→ **total of 8 machines**

Materials

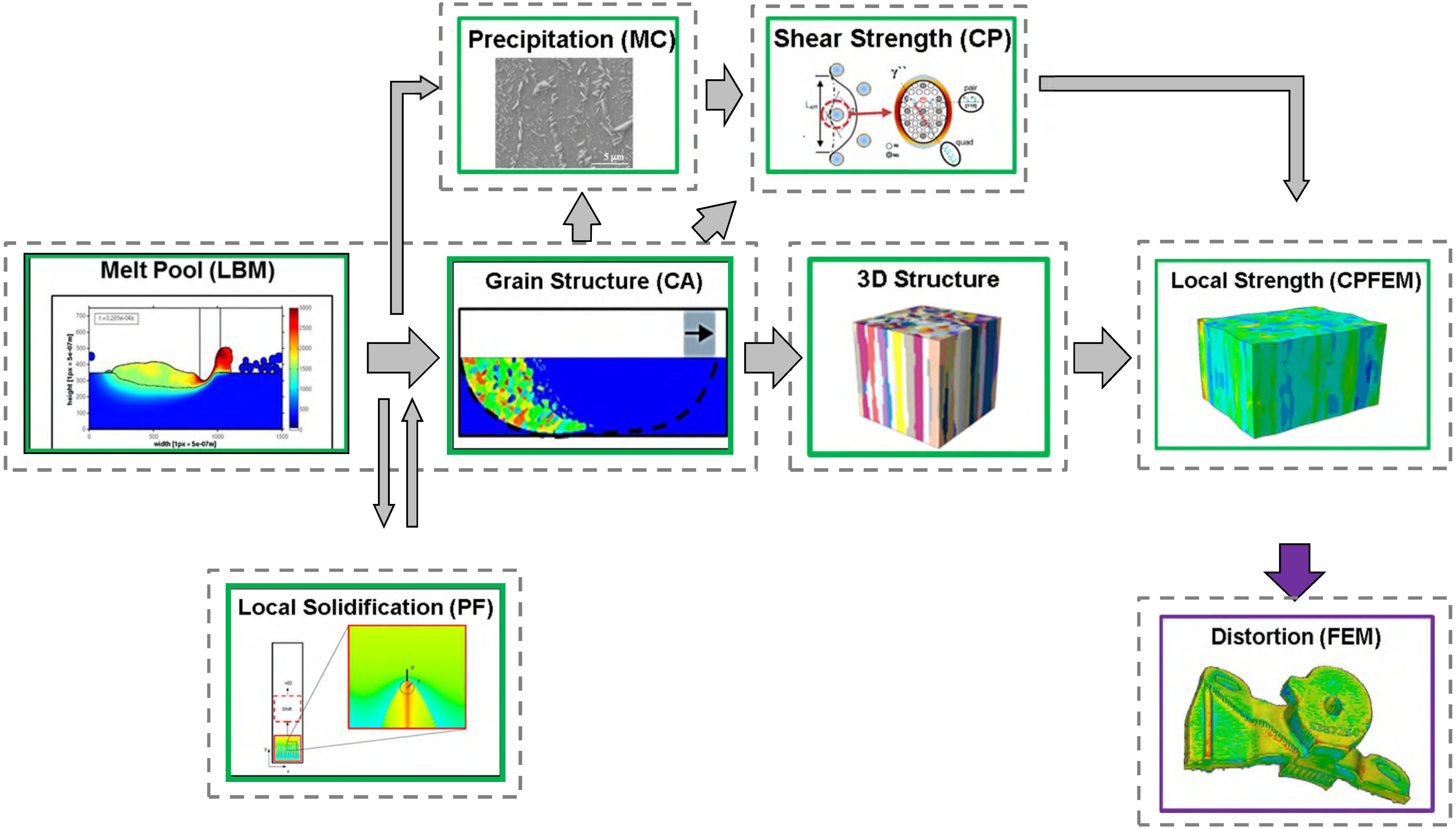
- **IN718**
- MAR-M509
- stainless steel 316L
- (Ti64)

Requirements for competitive facility:

- Necessity of identical quality and identical material data on all machines
- Increase of build-rate without change of material data
- Machine improvements at constant quality

AM@MTU

ICME for AM – simulation chain for material property prediction



Precipitation (MC)

Shear Strength (CP)

Melt Pool (LBM)

Grain Structure (CA)

3D Structure

Local Strength (CPFEM)

Local Solidification (PF)

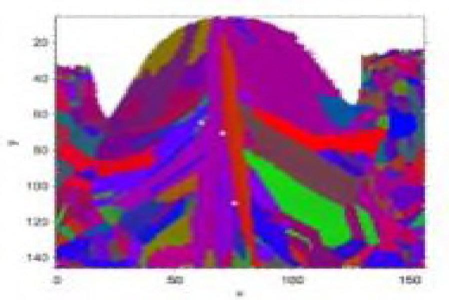
Distortion (FEM)

Assessment of process parameter combinations using melt pool simulations for fst. ‘quality envelope’

AM@MTU

Simulation as key element | Concept for Integrated Process Chain in Preparation

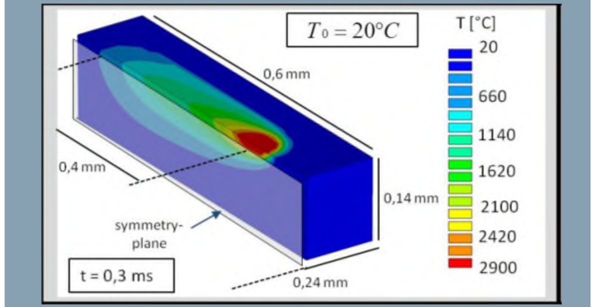
Material



- melt pool
- grain structure
- dendritic solidification
- precipitation hardening
- strength model

➔ dwell time/cooling rate

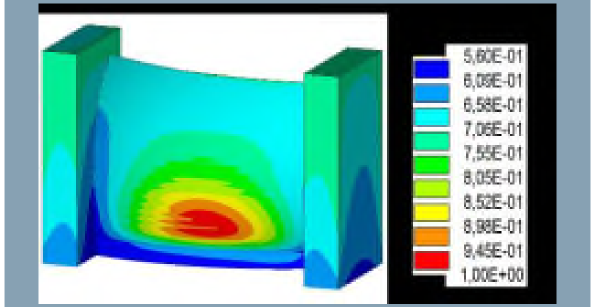
Thermal



- absorption model
- irradiation strategy
- energy per volume

➔ irradiation parameter

Distortion



Source: IWB

- distortion computation
- geometry refinement
- support optimization

➔ manufacturing model

Final objective: automated iterative simulation chain for computation of manufacturing model

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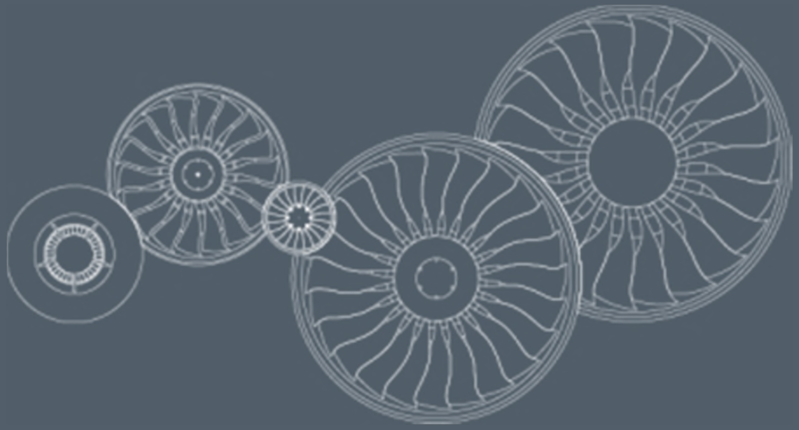
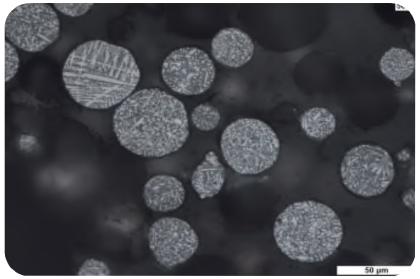


Quality Control

Concept




Raw Material / Powder	Production Line	Process	Part

Supplier

- Inspection certificate

MTU

- Incoming goods inspection
- Requalification of used powder

System Suitability Test

- Total productive maintenance
- Machine calibration
- Machine approval

Process Monitoring

- **Optical Tomography (MTU)**
- EOState:
  - Oxygen
  - Pressure
  - Z-Axis positioning
  - Collisions during recoating
  - Platform temperature

Component Testing/NDT

- Visual testing
- FPI
- X-Ray
- CMM / blue light
- Test bars
- Sacrifice parts

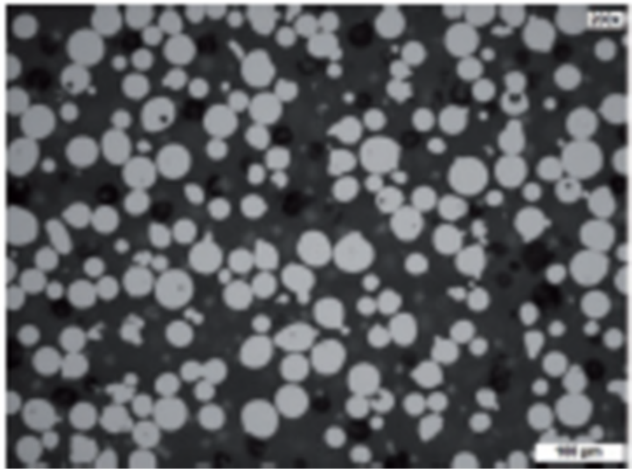
Quality control system has to cover full range of process chain

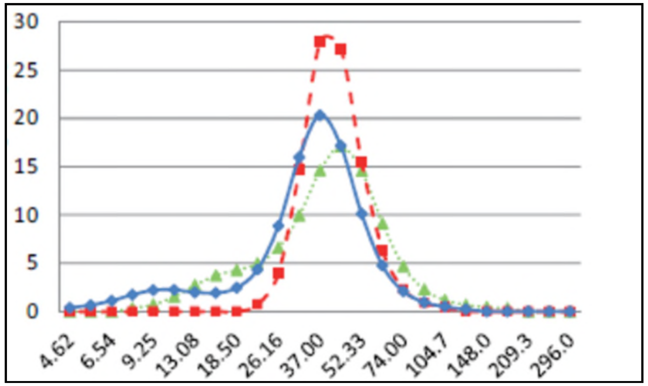
Quality Assurance of Powder

- Powder
  - \- Chemical composition
  - \- Particle size and distribution
  - \- Morphology
  - …

- Inspection certificate of supplier

- Requalification of used powder





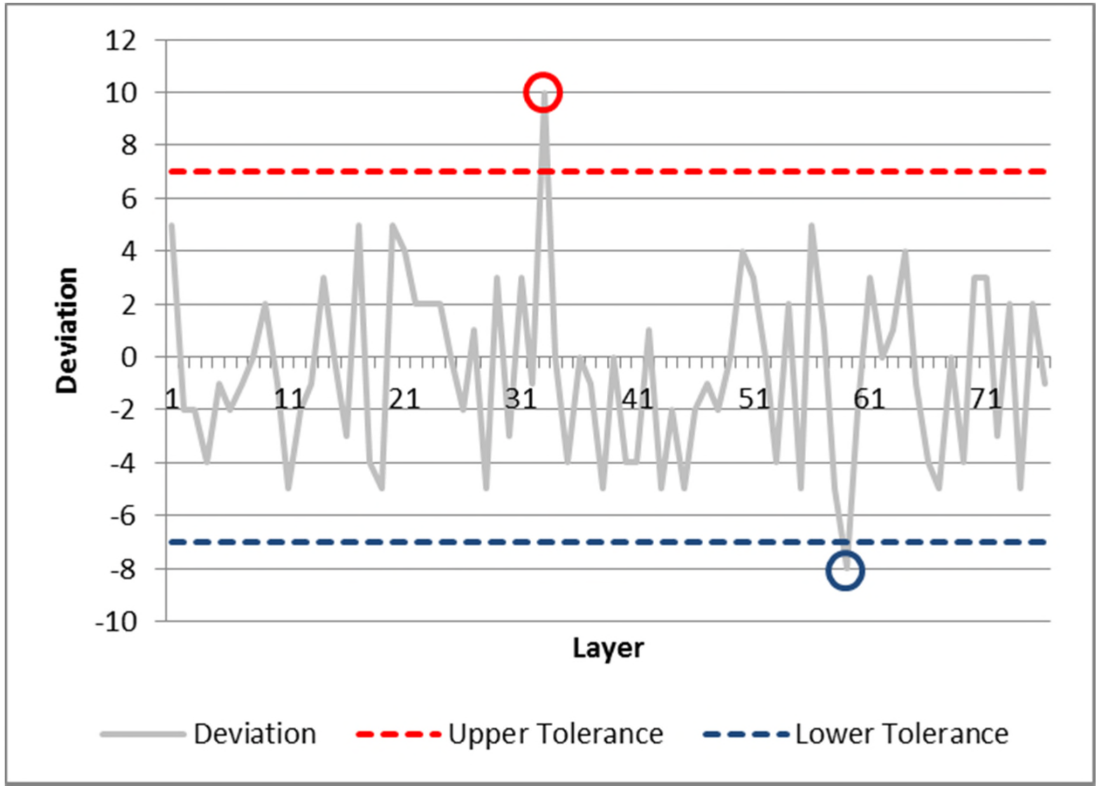
Particle Size Distribution

Quality Assurance of Production

- Total productive maintenance
- Machine calibration
- Machine approval

Quality Assurance of Process

- Platform position/shift
- Oxygen content
- Ar pressure
- Platform temperature
- Collision check



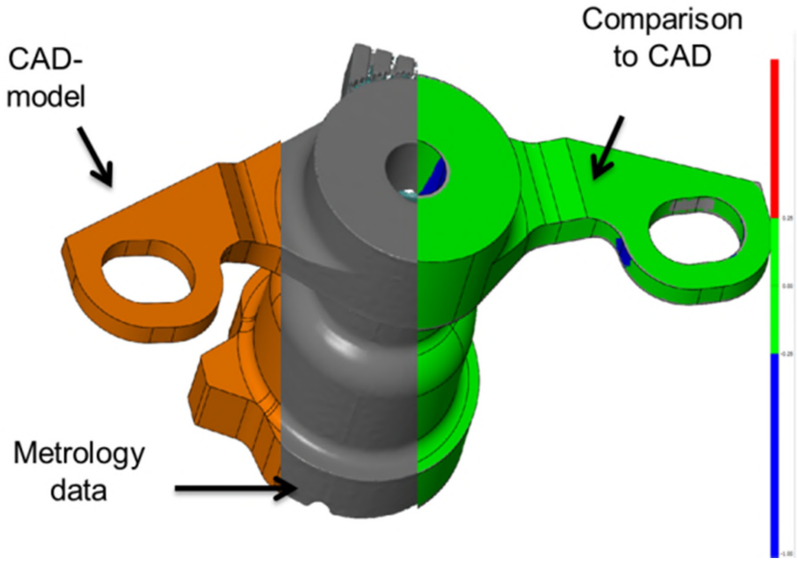
Layer thickness variations

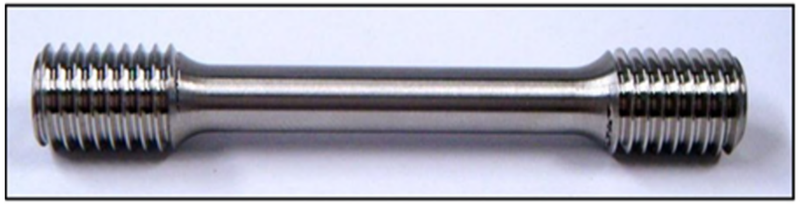
Quality Assurance of Part

- Metrology
  - White light scanning
  - Deviations from CAD-geometry

- NDT: X-CT, FPI, VT
  - Porosity
  - Surface cracks

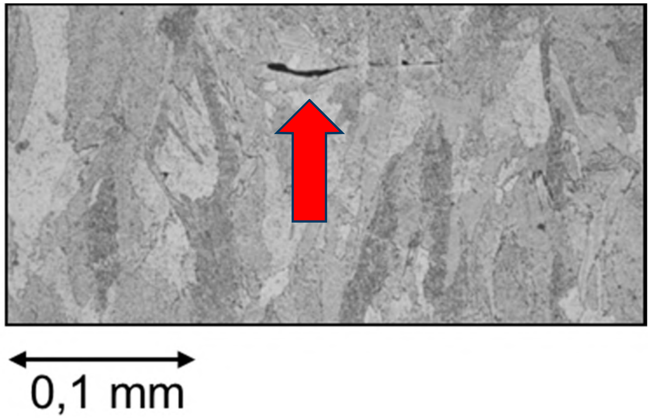
- Material Testing
  - Tensile strength
  - LCF / HCF
  - Sacrifice parts





Problem: Lack-of-Fusion Defect

- SLM-process deviations can lead to lack-of-fusion defects



Metallographic Cross Section

Internal defect	→	NO FPI
3D part geometry	→	NO UT
Part thickness	→	X-Ray difficult

Online Process Monitoring necessary!

Agenda

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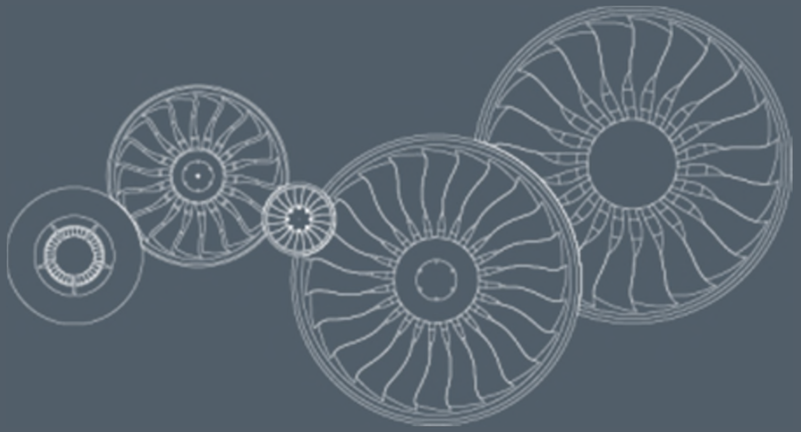
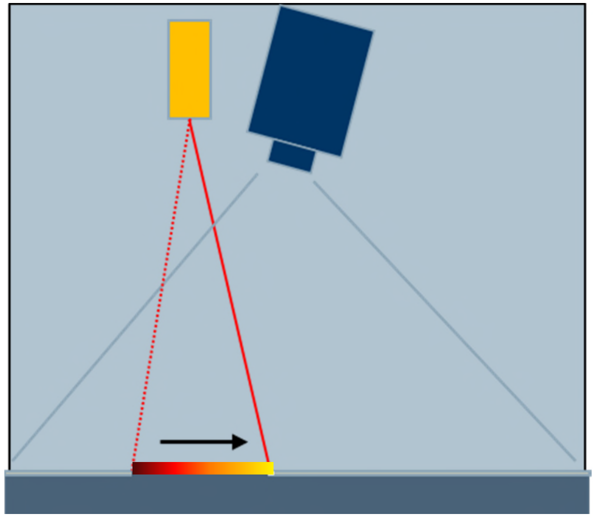


Principle of Optical Tomography

- Use high resolution CMOS camera
  (5 Megapixel)

- Make long time exposure of melt pool light
  (one image per layer)

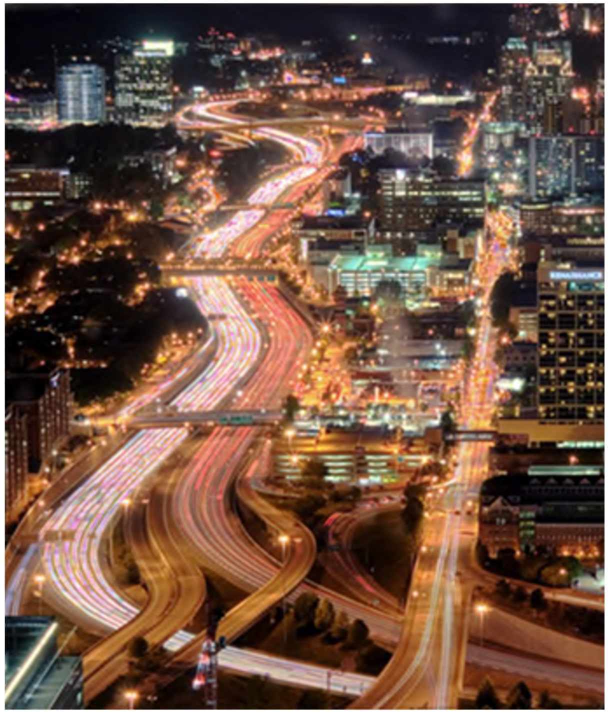


  - complete platform view
  - in the near infrared region
  - 900 - 940 nm filter

→ 0.1 x 0.1 mm² lateral resolution

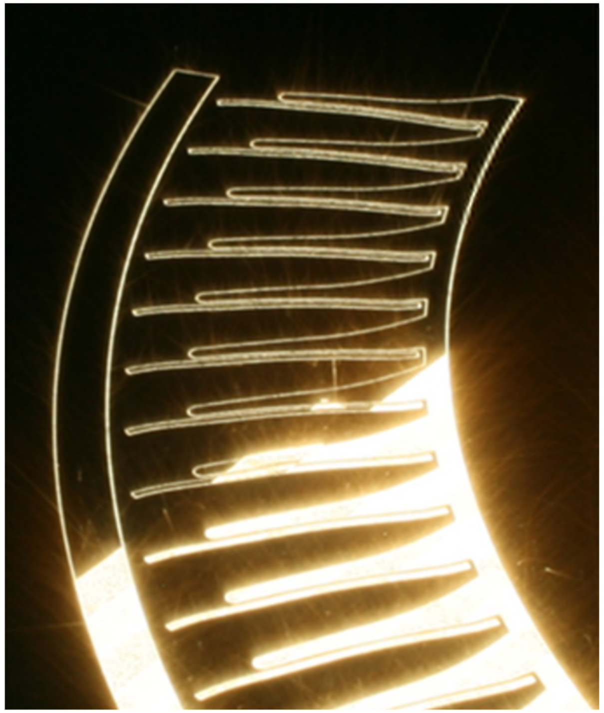
Result of Long Time Exposure

City at night



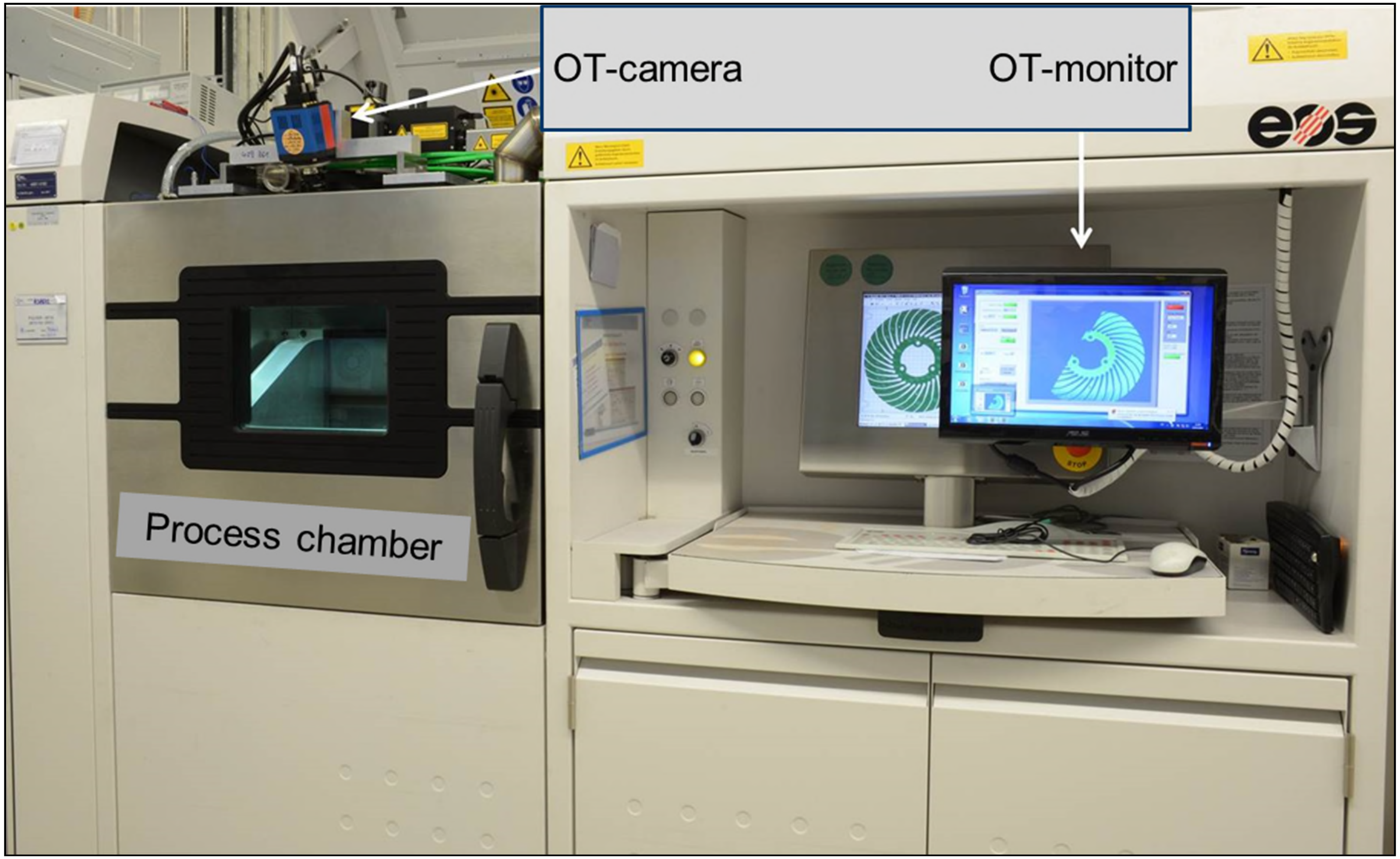
Brightness → Urban traffic density

SLM-process

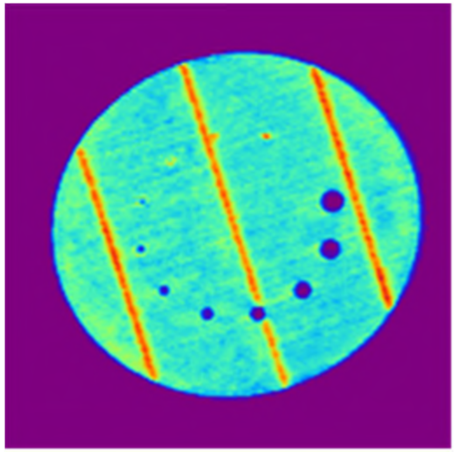


Brightness → Welding energy per unit length **!**

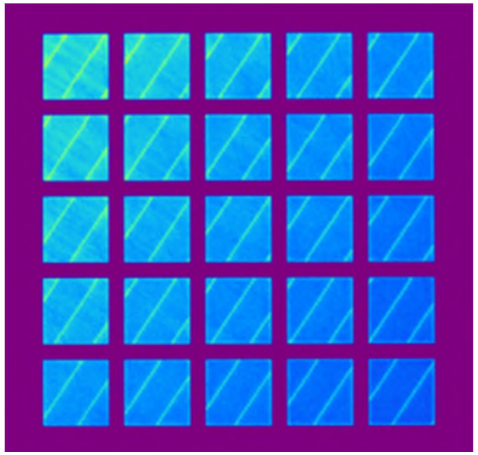
Realization of Optical Tomography



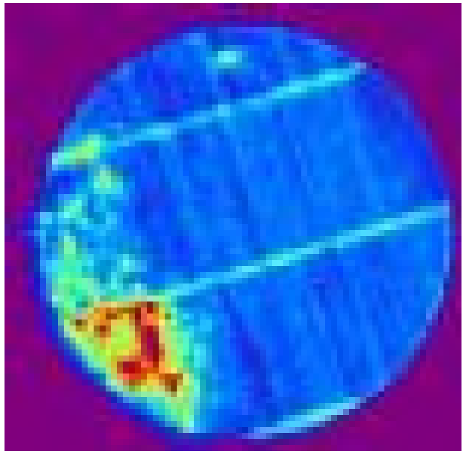
Features of Optical Tomography



Geometry & Metrics



Welding Parameters



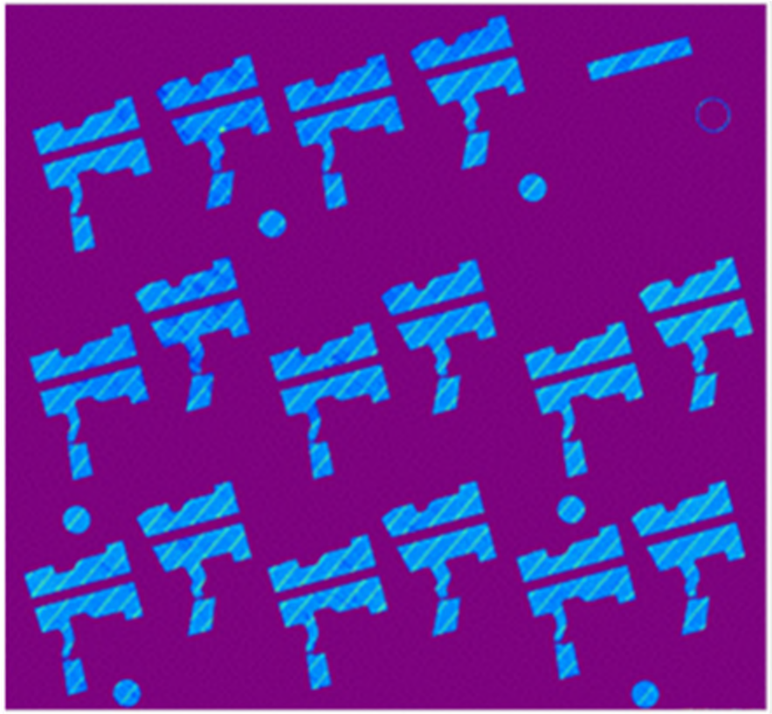
Process Deviations

- All of them with high lateral resolution (0.1 mm x 0.1 mm)
- Monitoring layer by layer without lack of data acquisition

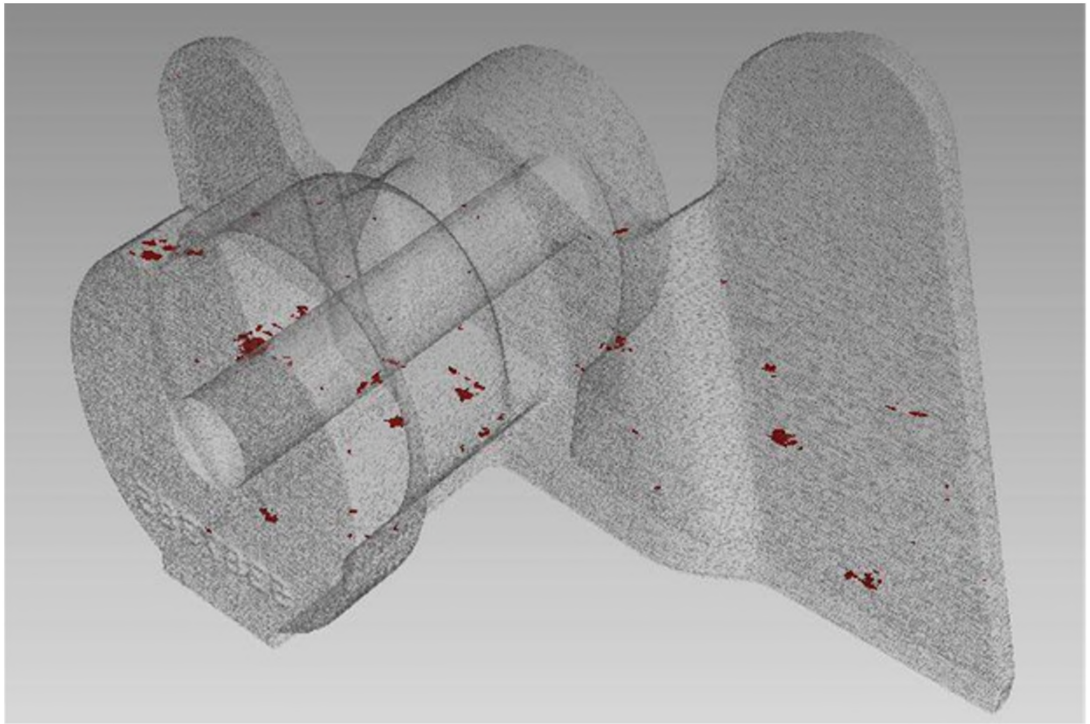
→ Optical 3D characterization of the complete SLM build job

Optical Tomography and Process Perturbation

From 2D OT image stack by X-ray rendering software



2D OT image of boroscope bosses



3D OT image of a boroscope boss
with indications due to process perturbation

Observations and lessons

What is and is not provided by OT

- Local recording of a measure for the introduced line energy
- Local recording of hotter or locations with a lower cooling rate (blobs)
- Local recording of turbulent smoke forming (hot spots)
- Correlation of smoke forming with fusion defect size
- No direct test of fusion defects
- No direct test of pores and cracks

What does this mean for the test of fusion defects?

- Fusion defects are due to different reasons:

- Smoke formation	(→ Hot Spots, correlation)
- Spits	(→ Blobs, correlation unclear)
- Material cumulation	(→ OT insensitive)
- …	

→ **Only in case of smoke formation the OT provides indication for fusion defects**

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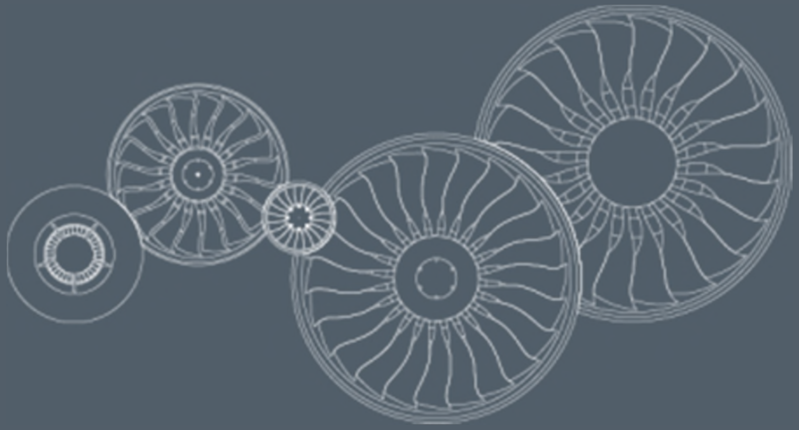
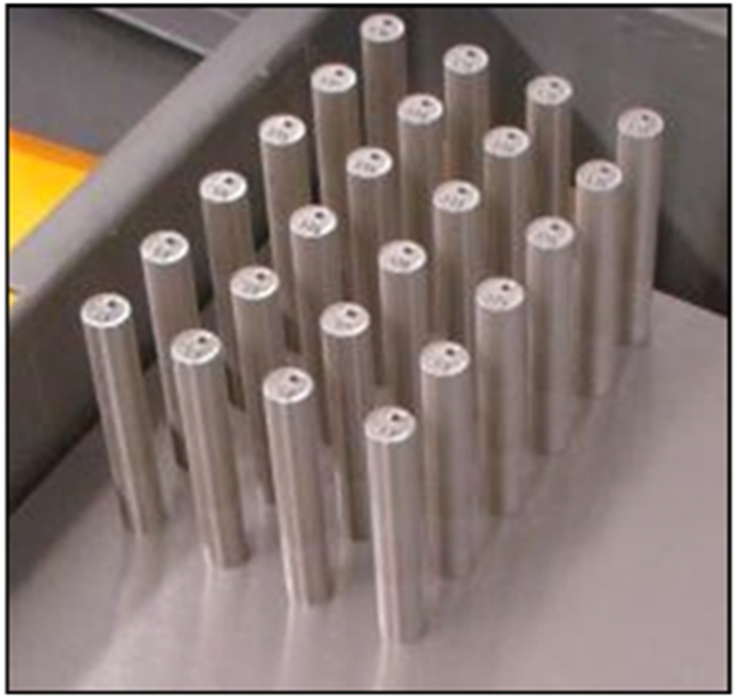


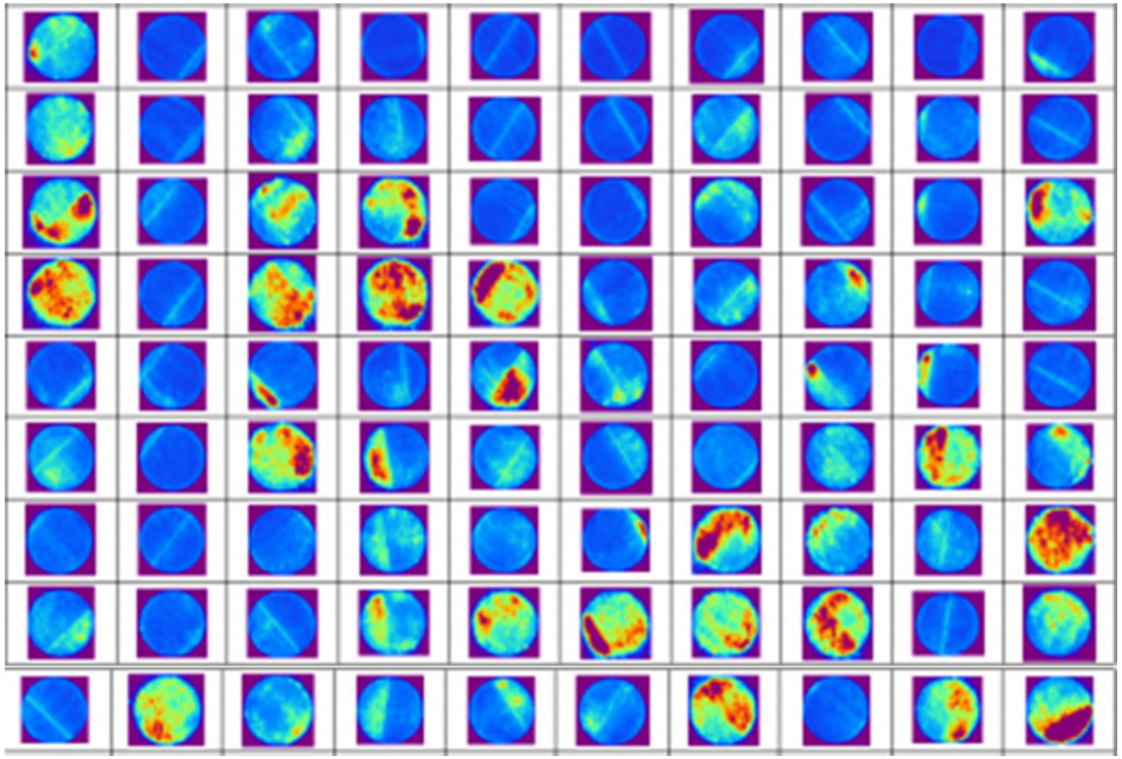
Build Jobs with Forced Process Perturbations

- Build jobs with 120 cylindrical specimens
- Each specimen with 10 localized process perturbations
- Process perturbation by Argon gas flow reduction

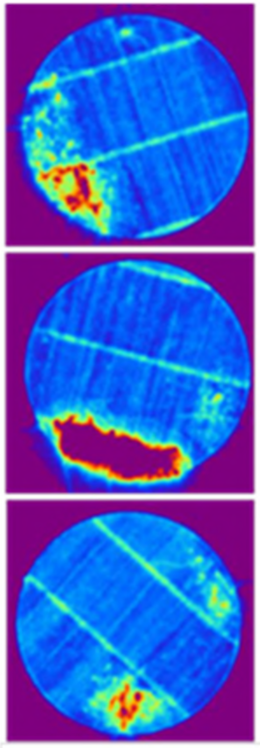
→ Production of lack of fusion defects



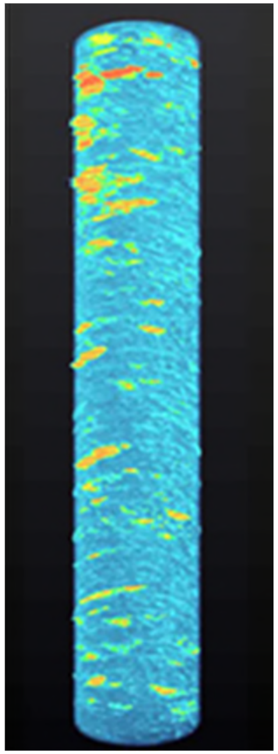
OT Images of Process Perturbations



Many different indications



Detail



3d-Image

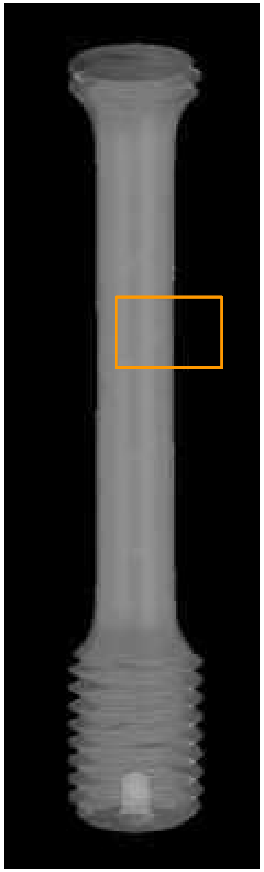
Conditioning of Specimens for X-Ray Tomography

- Preparation to tensile test specimens
- Controlled plastification:
  Lack of fusion defect → void (pat. pend.)
- Void detectable by X-ray tomography

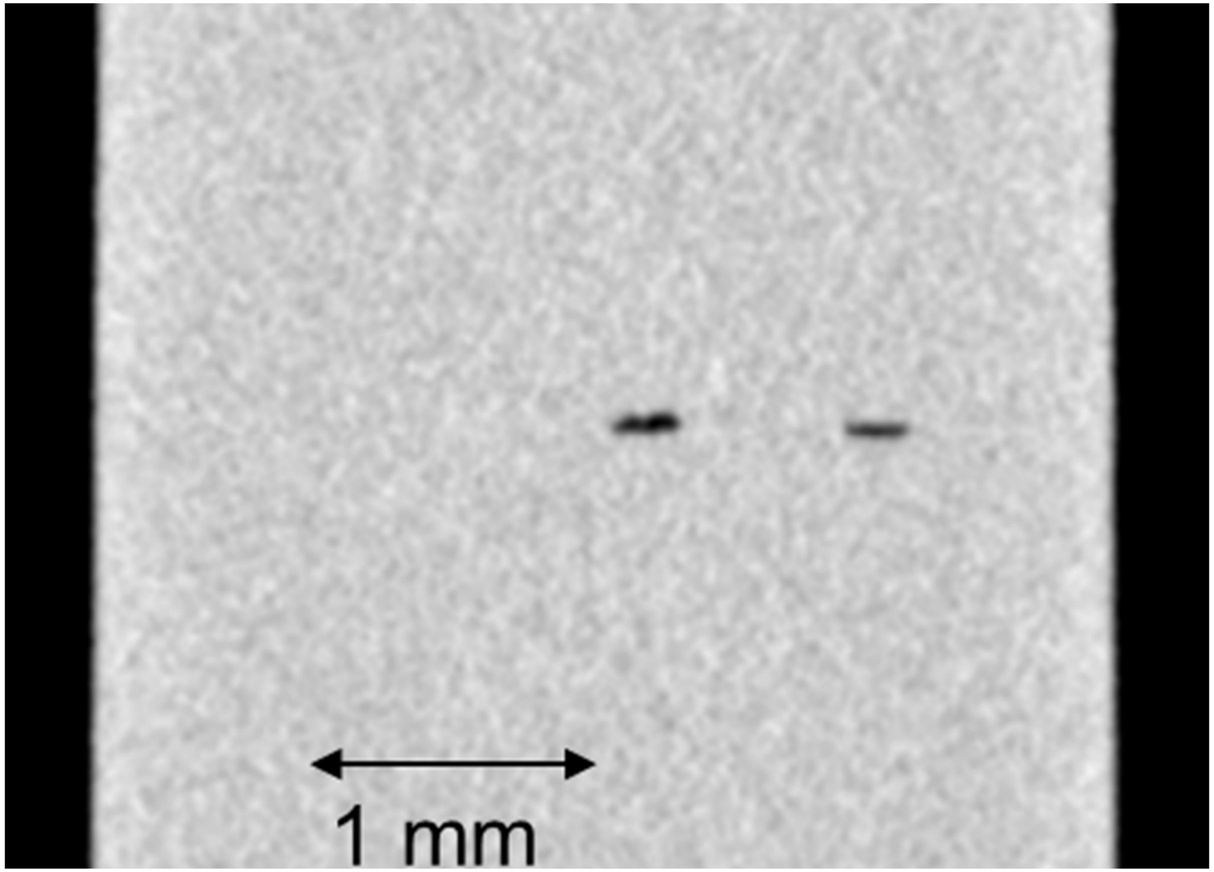
- X-CT system: GE v|tomex|s

  - up to 5 µm resolution possible

X-Ray Tomography Images



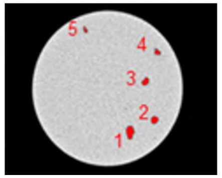
CT-Image



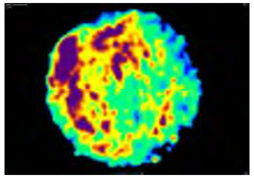
Lack of fusion becomes visible

Comparison of OT- and X-Ray Images

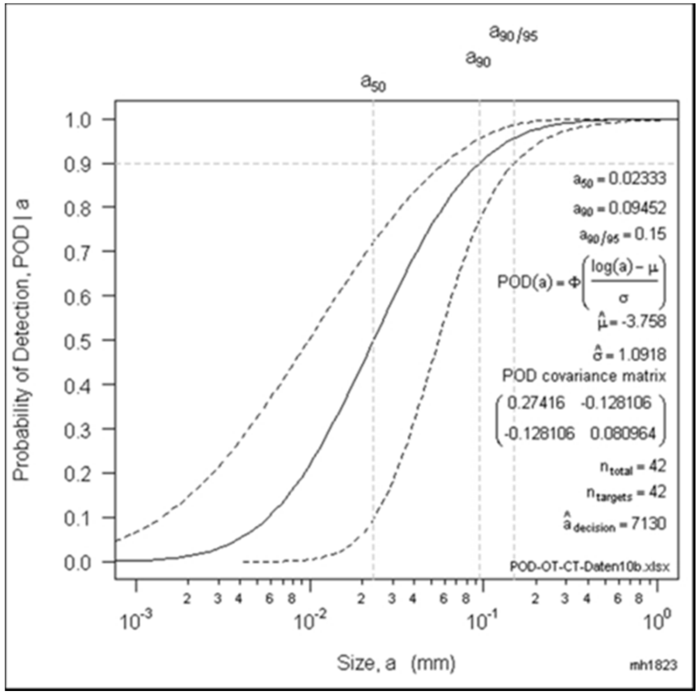
- 400 perturbated layers compared
- Algorithm developed using
  OT brightness values,
  size of indications and
  threshold value (signature)
- Signature correlates to defect size
  down to 50 µm
- POD-curves calculated



X-ray

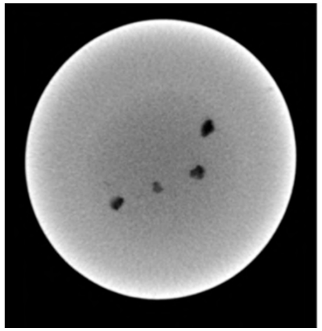


OT

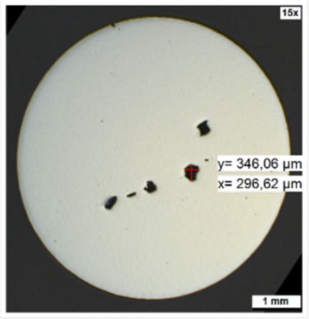


Validation of X-Ray Images

- X-ray image of perturbated layer



- Metallographic cross-section



→ All X-ray indications confirmed

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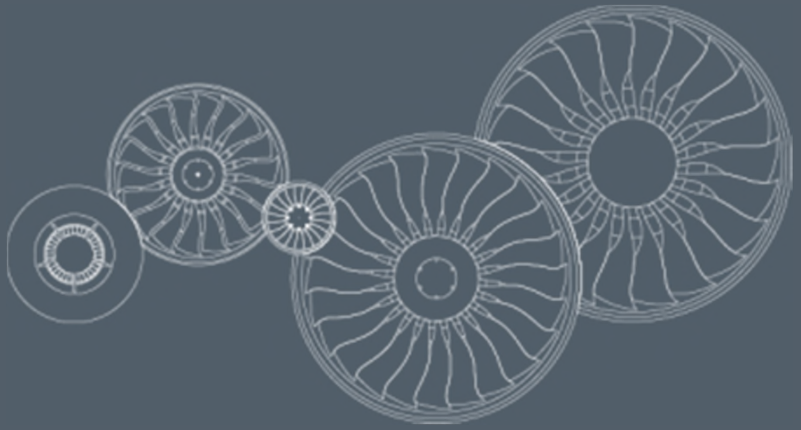
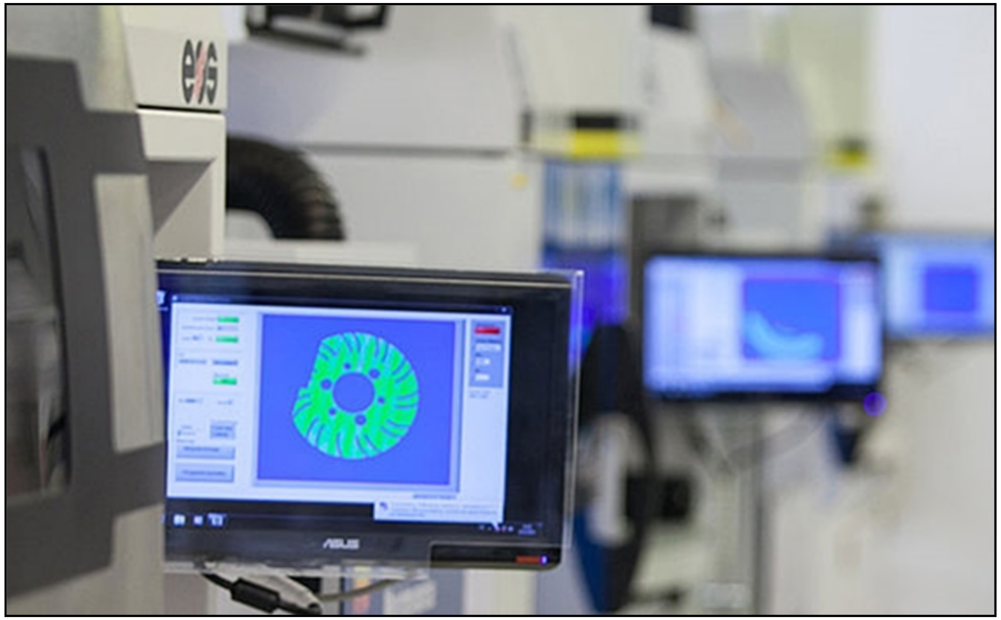


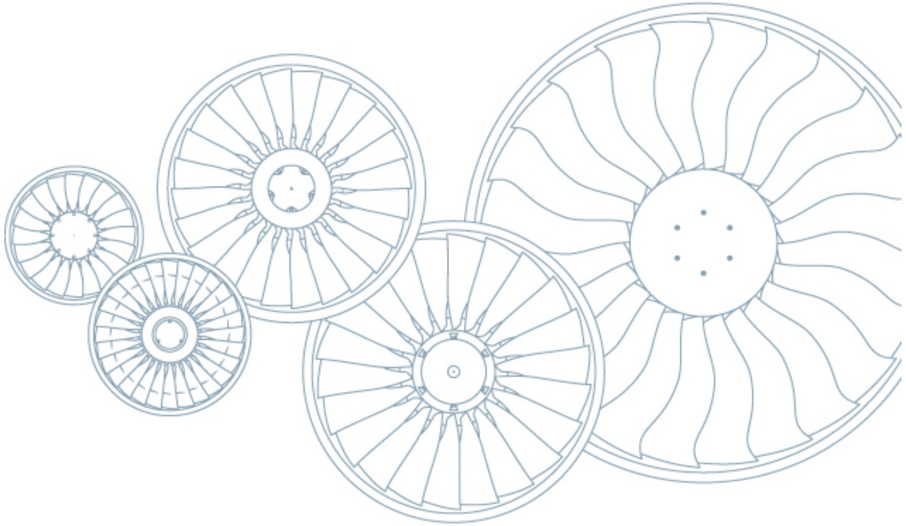
Summary

- Online-monitoring by optical tomography in use since 2014.
- Now: Testing on 150 µm defect size @ 90/95% POD is possible.
- But paradigm change for inspection is necessary.



- In the meantime further conventional testing methods are used like digital X-ray inspection and laser-thermography.

Thank You!
Questions?



APPENDIX R—IN-SITU MONITORING FOR ADDITIVE MANUFACTURING: IMPLICATIONS FOR THE DIGITAL MANUFACTURING AGE

SIGMA LABS

In-situ Monitoring for Additive Manufacturing: Implications for the Digital Manufacturing Age

Mark J. Cola, President & CTO

The Third Joint FAA – Air Force Workshop

on Qualification / Certification of Additively Manufactured (AM) Parts

August 30, 2017

Key Contributors

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Outline

Key Takeaways

Introduction to Sigma Labs

In-Process Monitoring and Materials Science

Motivations for In-Process Monitoring

Three Main Challenges for Metal AM

Use Case Examples

Summary

Key Takeaways

It’s all about the data…

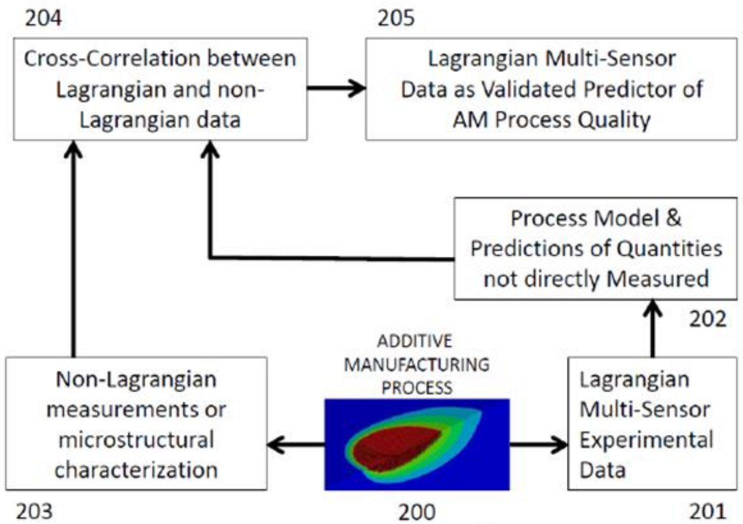
Sense – Sensors are becoming ubiquitous

What are you doing with the data?

Infer – Machine learning, extract relevance

Act – Real-time processing systems

Introduction to Sigma Labs Inc.



204

Cross-Correlation between Lagrangian and non-Lagrangian data

205

Lagrangian Multi-Sensor Data as Validated Predictor of AM Process Quality

Process Model & Predictions of Quantities not directly Measured

202

Non-Lagrangian measurements or microstructural characterization

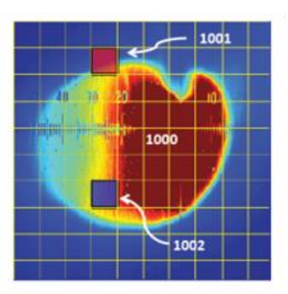
203

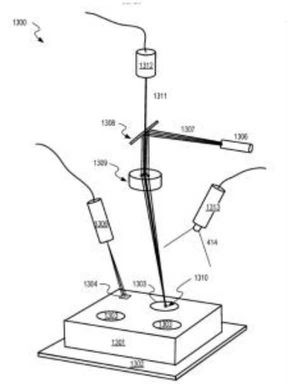
ADDITIVE MANUFACTURING PROCESS

200

Lagrangian Multi-Sensor Experimental Data

201





About Sigma

Founded in 2010, Sigma is located in Santa Fe, NM and is a software company that specializes in the development and commercialization of in-process monitoring solutions known as **PrintRite3D®** for 3D advanced manufacturing technologies.

Our people, processes and technologies are recognized leaders in disruptive technologies. Our products and services are engineered, manufactured, and qualified for use in highly demanding production environments for the aerospace & defense industries. Sigma's innovative approach to process control/quality assurance is a proactive, comprehensive and process-focused methodology that allows prediction with adequate confidence of product conformance to defined acceptance requirements.

Since inception in Sept 2010, Sigma has been able to establish credibility and acceptance within the aerospace & defense community and has become the go-to AM experts for in-process monitoring solutions. Sigma is ITAR Certified.

SIGMA LABS

Sigma's Products

Industry's Broadest Portfolio of "Best in Class" In-Process Monitoring software solutions with cutting edge machine learning algorthims. PrintRite3D® is the quality control solution that makes tomorrow's precision metal parts possible.

PRINTRITE3D® SENSORPAK™

Multi-sensors and affiliated hardware to collect real-time data on AM processes.

Comprises a set of off-axis and on-axis in-process sensors.

When coupled with PrintRite3D® INSPECT® or PrintRite3D® CONTOUR® modules, enables part quality assessment during manufacturing.

Capable of measuring the true in-process state variables associated with an additive manufacturing process.

PRINTRITE3D® INSPECT®

Software for in-process inspection of **METALLURGICAL PROPERTIES.**

Uses sensor data and establishes in-process metrics for each metal or alloy during the process.

Provides manufacturing engineers with part quality report based on rigorous statistical analysis of manufacturing process data.

Allows for interrogation of suspect part data and can be used for process improvement and optimization.

PRINTRITE3D® CONTOUR®

Under development

Software for in-process inspection of part **GEOMETRIC PROPERTIES.**

Layer-by-layer geometry measurement tool.

Provides manufacturing engineers with the capability of comparison of 'as-built' to original digital CAD model 'should be'.

Includes optics, mechanical system and data path to image two-dimensional melted powder.

PRINTRITE3D® ANALYTICS®

Under development

Software for manufacturing intelligence — **BIG DATA.**

Software and database that links all critical data over multiple builds, machines, and fabrication sites over time.

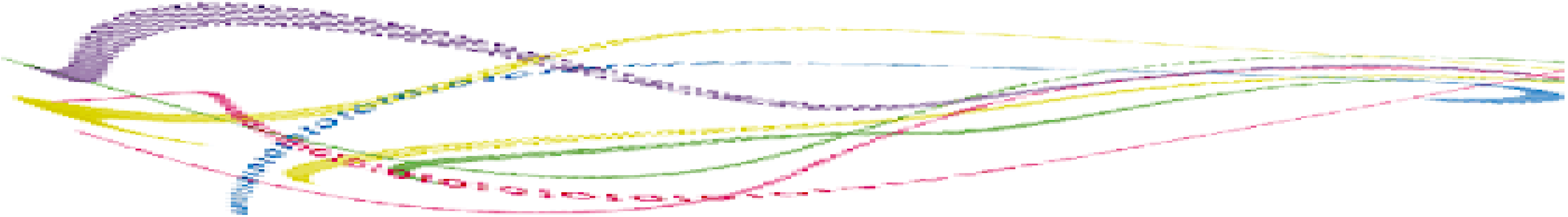
Provides management and seamless access to all in-process and post-process data over the entire product life cycle.

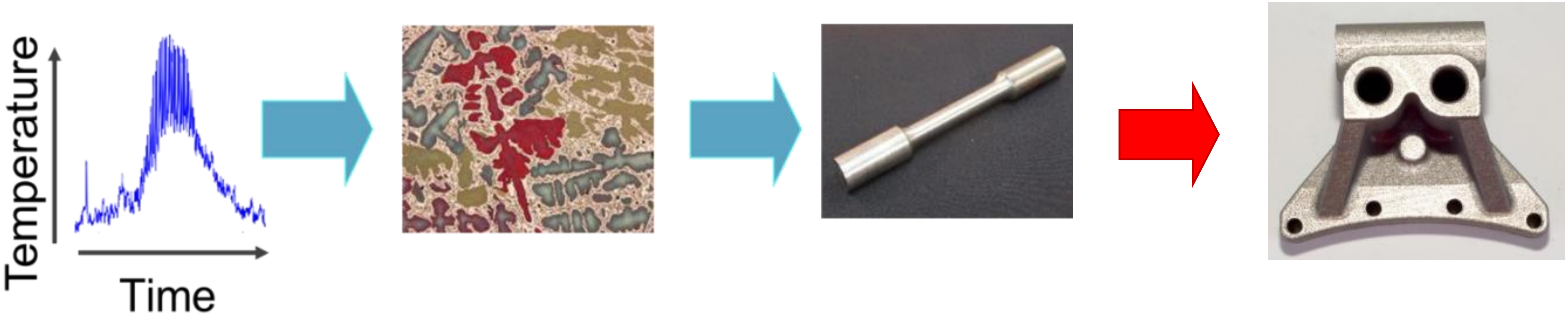
System Installations

PrintRite3D
INSPECT®

PrintRite3D
SENSORPAK®

In-Process Monitoring and Materials Science





Thermal History

Microstructure

Properties

Part Performance

Sigma’s Machine Learning Algorithms…are the Missing Link in the Digital Thread

Motivations for In-Process Monitoring

Why In-Process Monitoring for Additive Manufacturing?

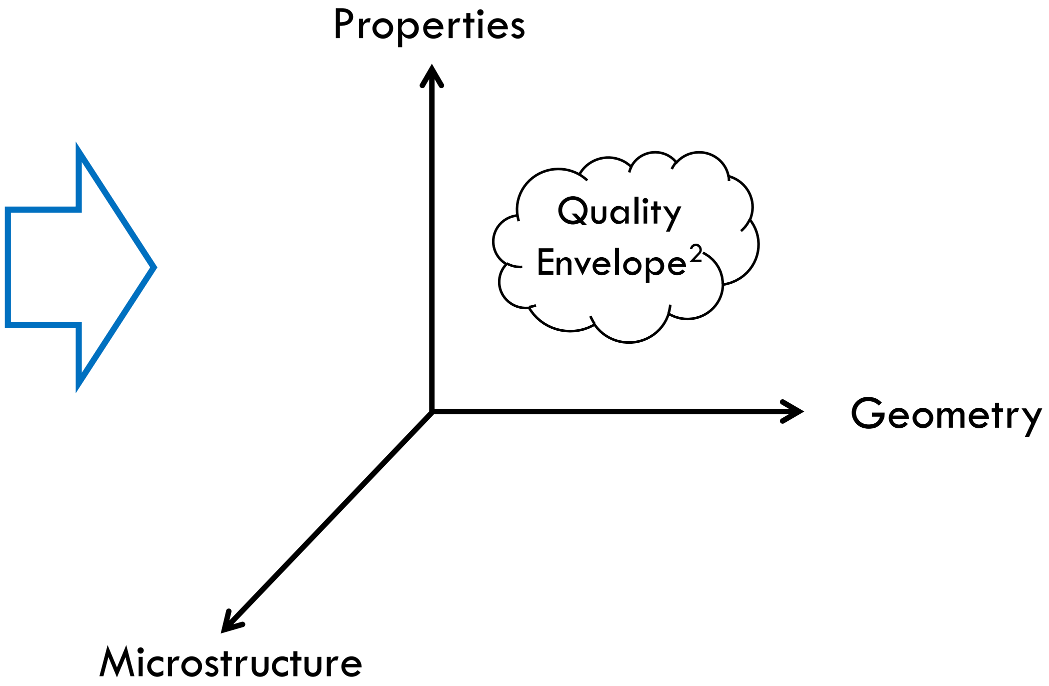
ISHIKAWA: *"The ideal state of quality control is when quality control no longer calls for inspection."*

DEMING: *"Final inspection is an admission that the process is out of control, the specification makes no sense, or both."*

Three Main Challenges for Metal AM

> *“One of the most serious hurdles to the broad adoption of additive manufacturing of metals is the qualification of additively manufactured parts.”* [1]

1. Quality (*Metallurgy*)
2. Shape (*Geometry*)
3. Productivity (*Big Data*)



Properties

Quality Envelope[2]

Geometry

Microstructure

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[1] *Rose Hansen, “Building the future: Modeling and uncertainty quantification for accelerated certification,” Science and Technology Review, January/February 2015*

[2] *W. Fraizer, NAVAIR AM Update, The Third Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured (AM) Parts, August 2017*

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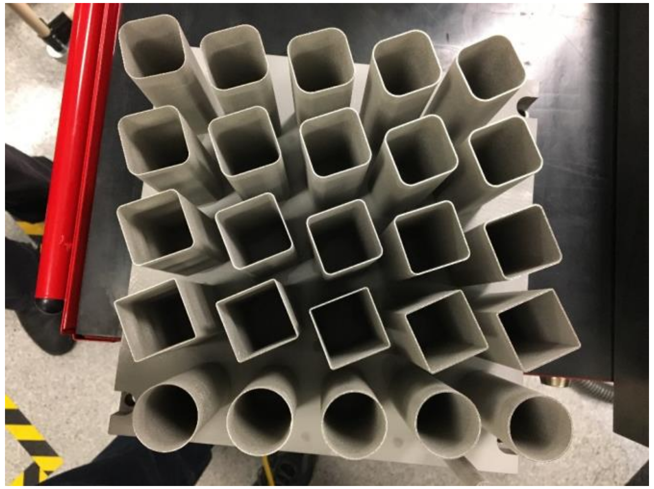
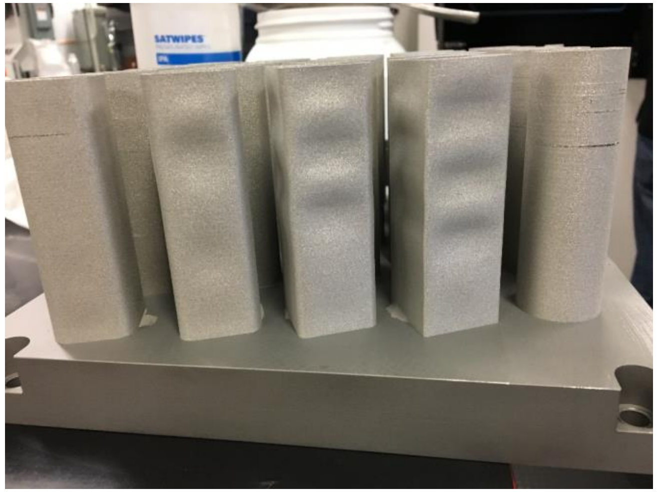
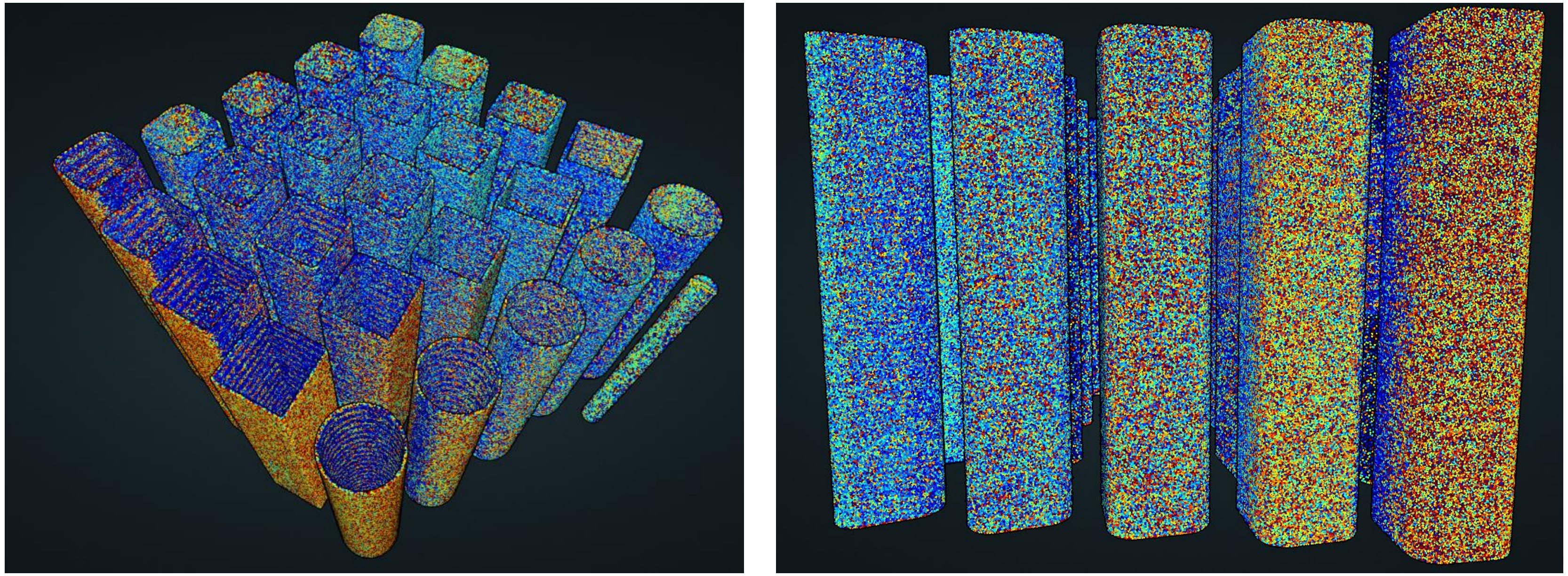
Use Case 1

Process Control Study





Evaluate Effect of Process Input Variations on Geometry / Ni-base Alloy



In-Process Feature Data

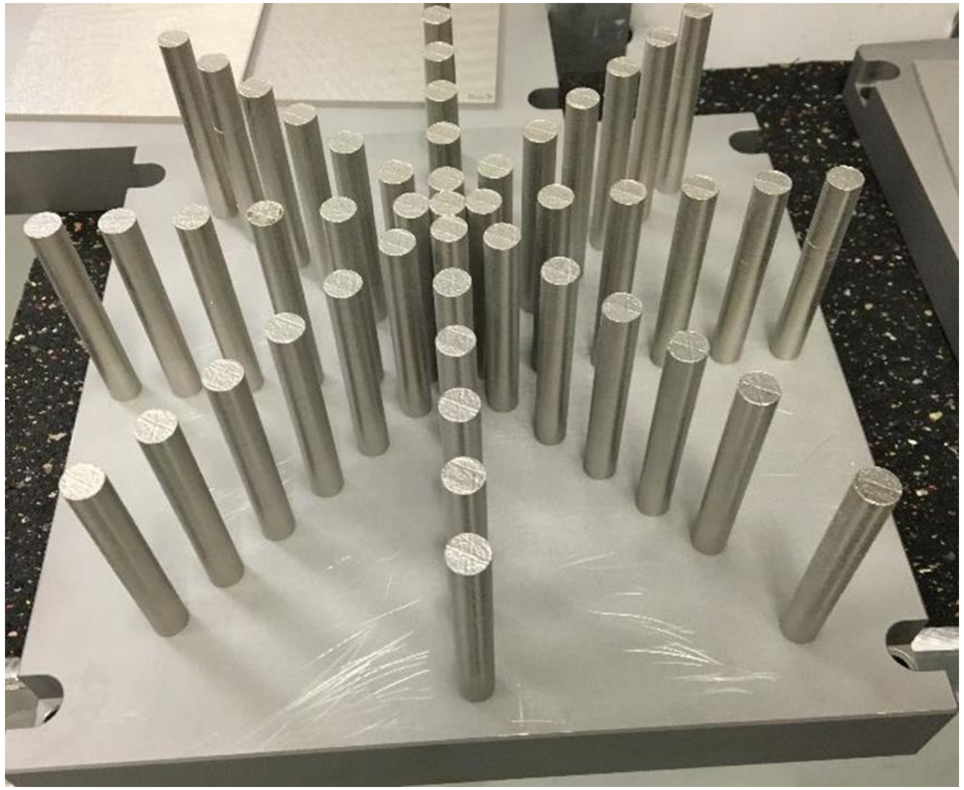
Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

Use Case 2

Process Control Study

Parameter Optimization / Ni-base Alloy

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8
Hatch Distance (mm):	0.12	0.14	0.14	0.14	0.14	0.14	0.14	0.12
Speed (mm/s):	1250	3780	880	1320	2200	2500	3000	1250
Power (W):	300	370	370	370	370	370	370	300
Beam Offset (mm):	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Stripe Width (mm):	100	100	100	100	100	100	100	100
Strip Overlap (mm)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
GED (J/mm^2)	2.000	0.699	3.003	2.002	1.201	1.057	0.881	2.000

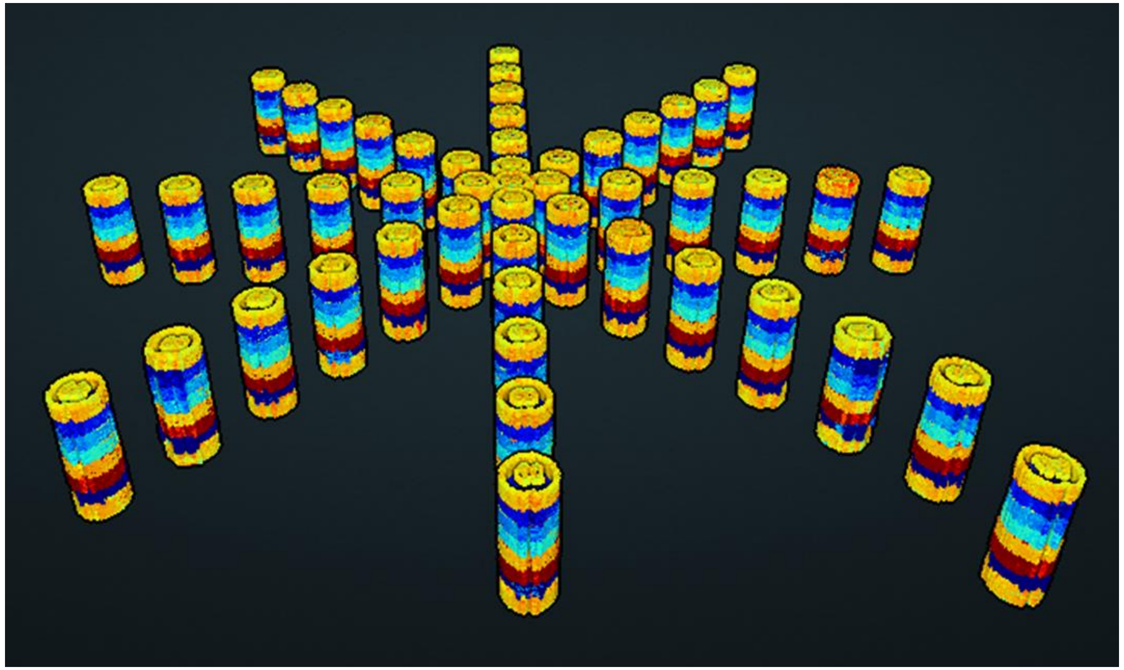


Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

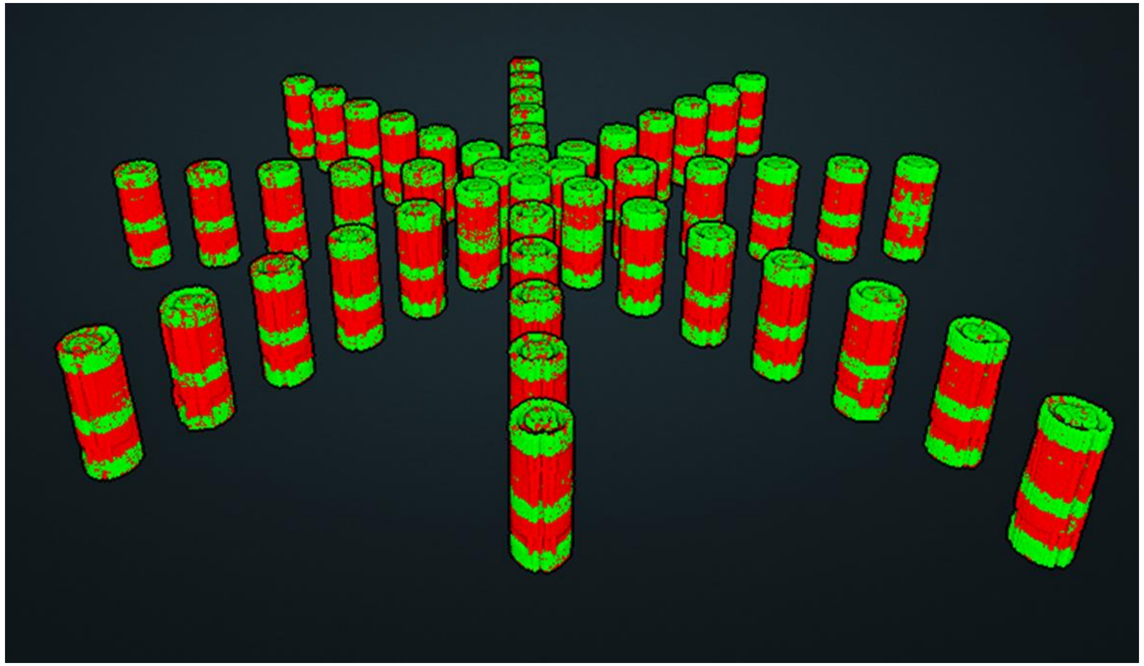
Use Case 2

Process Control Study

Parameter Optimization / Ni-base Alloy



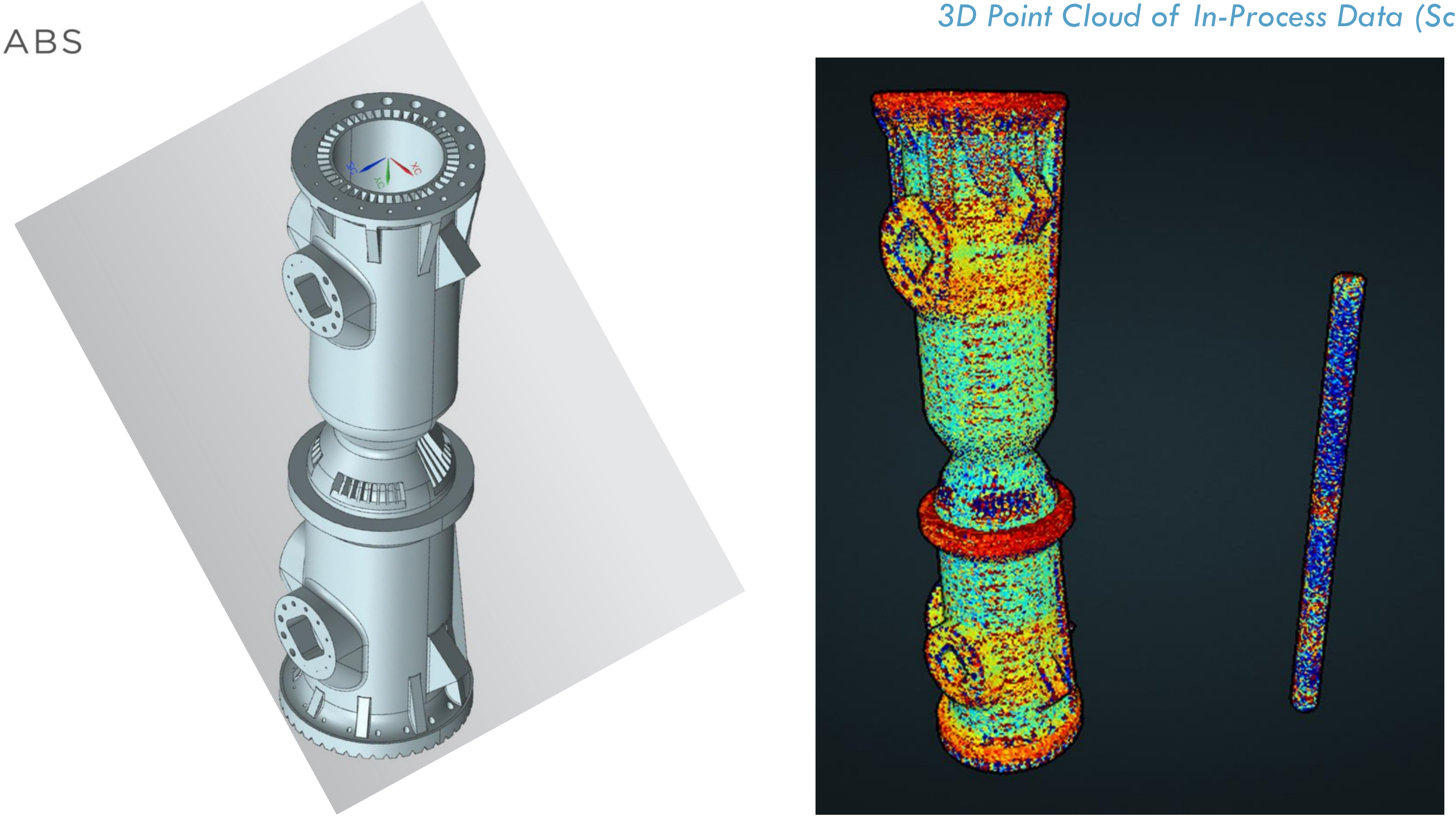
In-Process Feature Data



In-Process Quality Metric™ Data with Auto-Control Limit Feature

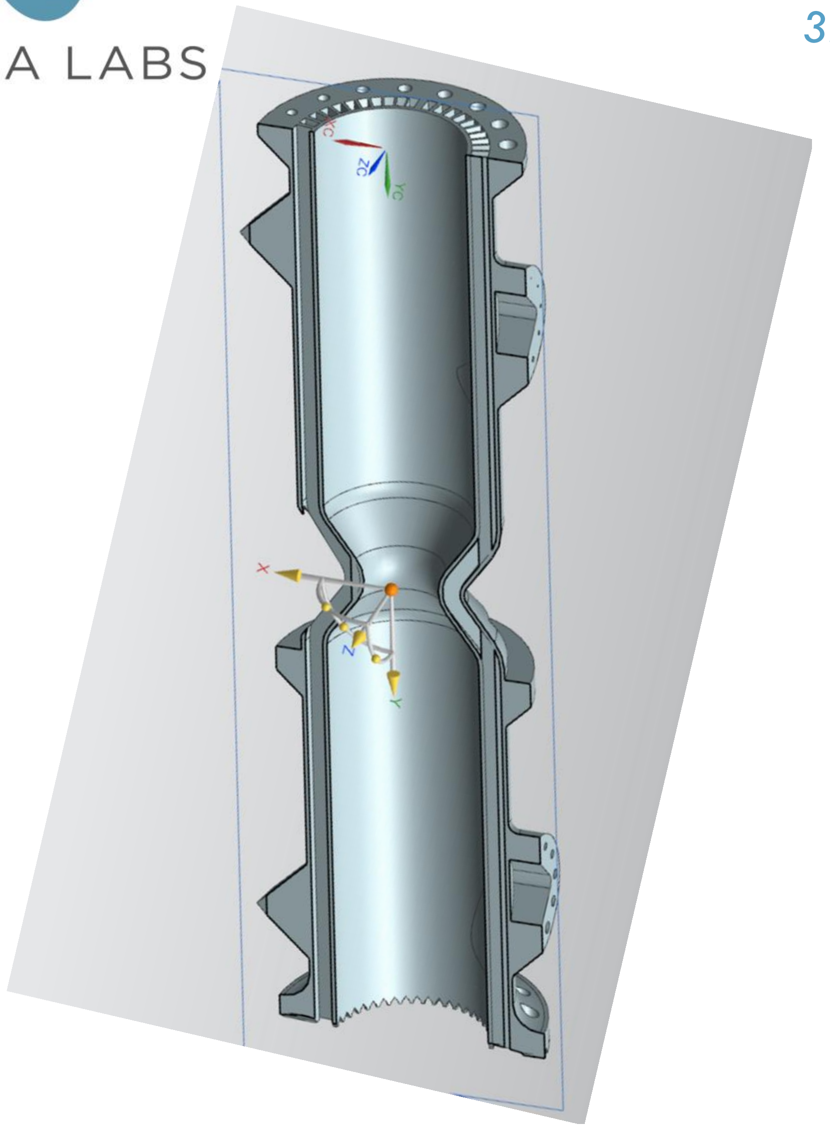
Use Case 3

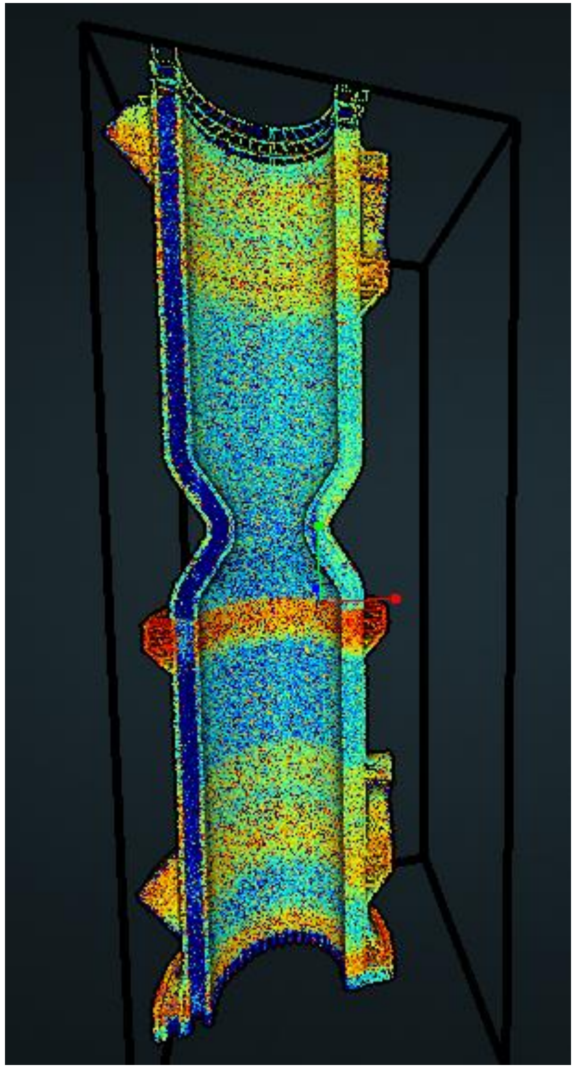
3D Point Cloud of In-Process Data (Scan Level)

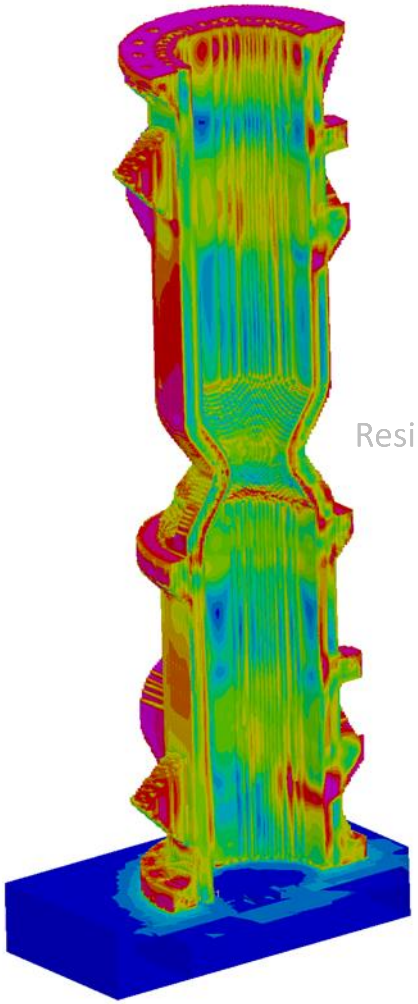


Use Case 3

3D Point Cloud of In-Process Data (Scan Level) Compared to Predictive Model





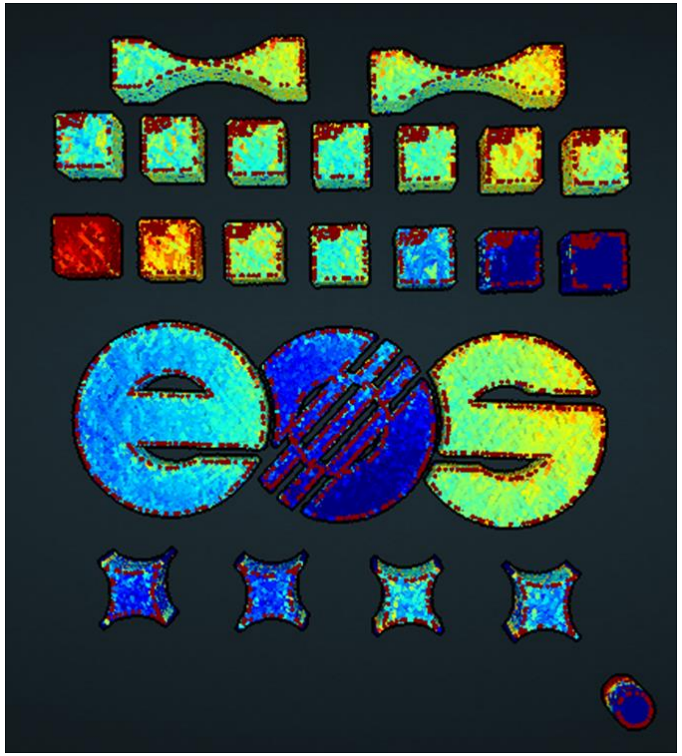


Residual Stress Model

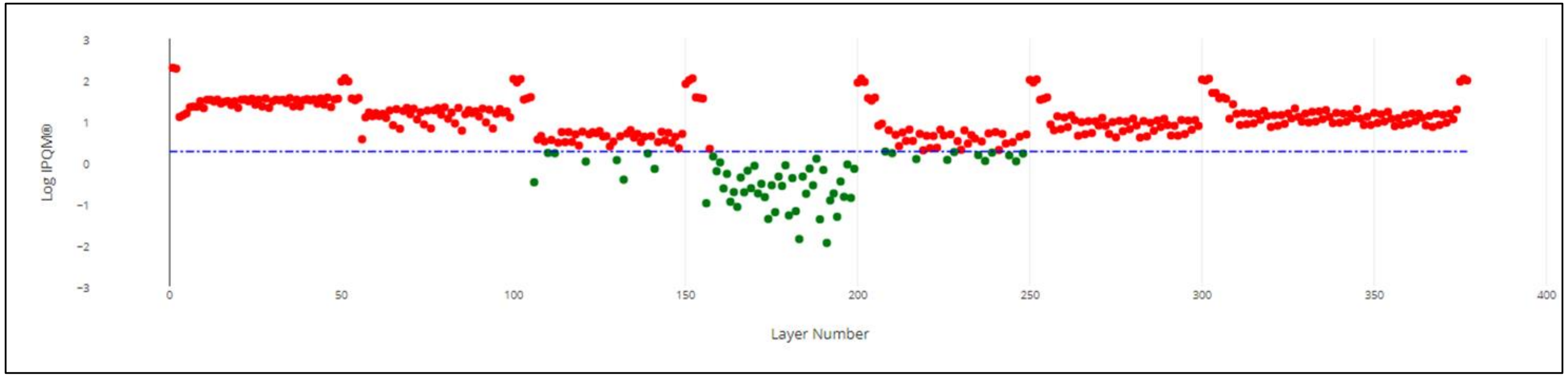
Use Case 4

3D Point Cloud of In-Process Data (Scan Level)

In-Process Feature Data



In-Process Quality Metric™ Data
with Auto-Control Limit Feature



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Key Takeaways

It's all about the data…

Sense – Sensors are becoming ubiquitous

What are you doing with the data?

Infer – Machine learning, extract relevance

Act – Real-time processing systems

Data-centric Programming…Less code, more math

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Thank You

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APPENDIX S—MEASUREMENT AND MODELING OF RESIDUAL STRESS IN STRUCTURAL COMPONENTS

Measurement and Modeling of Residual Stress in Structural Components

The Third Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured (AM) Parts

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Michael R. Hill
Founder and CEO, Hill Engineering, LLC
Professor, Mech & Aero Engg, UC Davis

Adrian T. DeWald
President, Hill Engineering, LLC

Outline

Prior work: Engineering Residual Stress in Aerospace Forgings

Recent Measurements of Residual Stress in AM Materials

Summary Remarks

Engineering Residual Stress in Aerospace Forgings

Michael R. Hill
Founder and CEO, Hill Engineering, LLC
Professor, Mech & Aero Engg, UC Davis

Dale L. Ball
Senior Fellow, Lockheed Martin Aeronautical

Mark A. James
John D. Watton
Alcoa Technical Center

Adrian T. DeWald
President, Hill Engineering, LLC

Funding from AFRL

88ABW-2016-3446 Distribution Statement A Approved for public release: distribution is unlimited.

Points for discussion

Structural design is advancing: more efficient = more demanding

- Materials have better resistance (materials, quality control)
- Engineering methods are improved (control, measurement, analysis)

Residual stress is an old problem

- Widely know to impact performance
  - Distortion
  - Long-term material behavior (fatigue and corrosion)

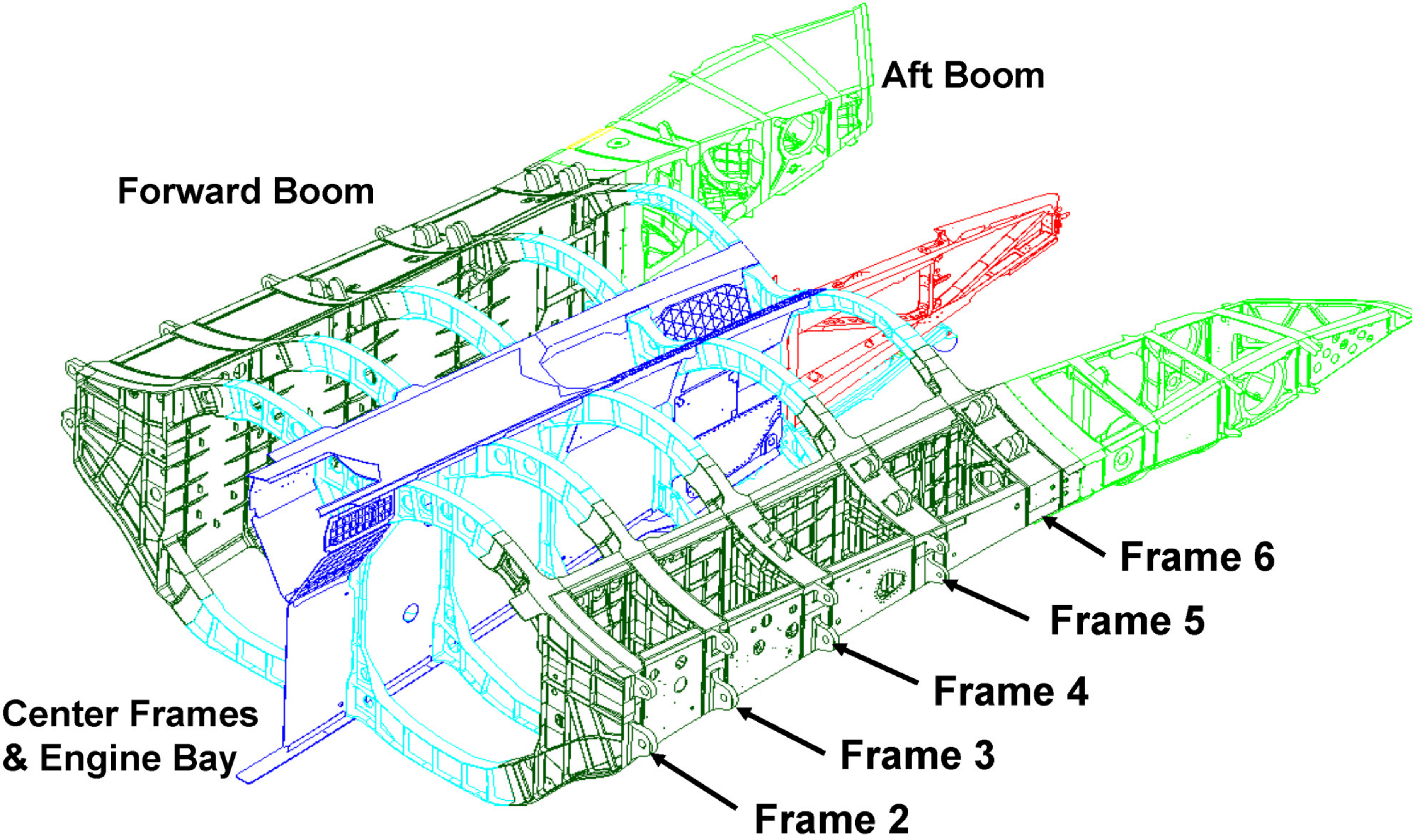
Methods used to account for residual stress in design

- Historically, we don’t (ignore it, avoid it, remove it)
- Gaining confidence in methods to handle residual stress up front in design analysis

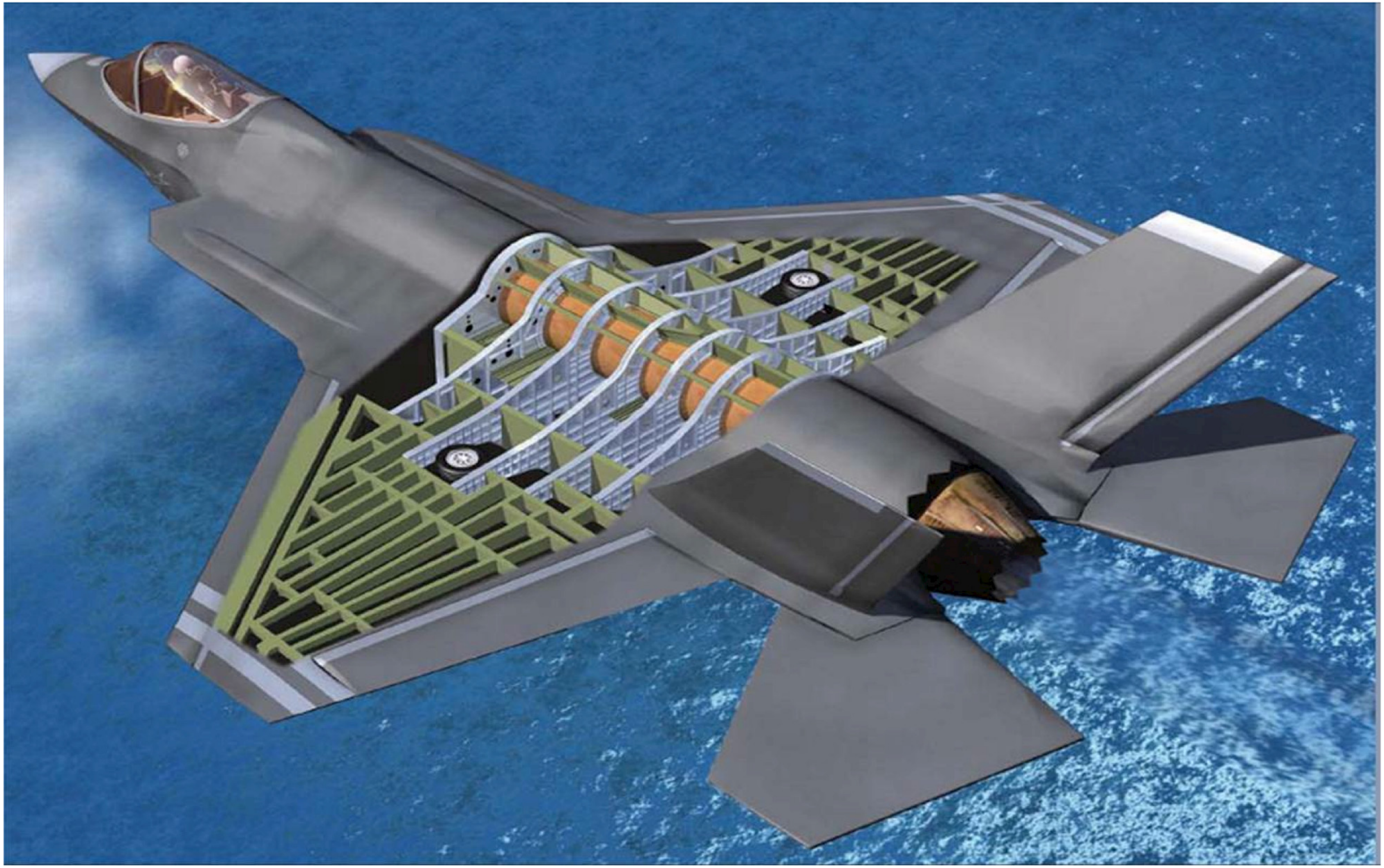
Residual stress engineering using model-based engineering: ICME (Integrated Computational Materials Engineering)

- Progress in airframe materials and supply-chain integration

Structural design: modern airframe, unitized sections



Structural design: modern airframe, unitized sections



Residual stress: ubiquitous (for better or worse)

Credit: Boeing

Residual stress = stress without load (mechanical, nor thermal)

Created by manufacture

- Forging
- Quenching
- Welding
- Cold deformation (drawing, rolling, bending)
- Peening, other surface treatments

May have significant effects

- Generally: compression helps, tension hurts
- Big issues:
  - Unanticipated part distortion
    - + At fab shop, or in depot
  - Unanticipated effects on subcritical cracking
    - + Fatigue, corrosion-fatigue, and SCC

Residual stress in design and manufacture

Historical design approach: residual stress is a known unknown

- Remove where possible (thermal or mechanical stress relief)
- Conservatively manage effects on degradation (fatigue, SCC, creep)
  - Conservative assumptions (i.e., tensile residual stress fields)
  - Inspect, repair, replace
  - Costs escalate with system age
- Important exception: compressive stress treatments (salvation)

Emerging design approach: residual stress part of specifications

- Know residual stresses in parts from validated models (requires measurements, and validation metrics)
- Include residual stress in materials and process engineering
  - Trade studies
  - Quality program
- Account for residual stress effects on performance

ICME principles at the root of the emerging design approach

- Integrate validated process model outputs with experimental observations in a holistic system to precisely assure material performance

Estimating residual stress - Models

Processes models can estimate residual stress

- Models are generally non-linear, and complex

Example: Forging of 70XX aluminum

- Thermal, elastic-plastic, and visco-plastic processes
  - Solution treat, quench, hold, cold work, age, cool
- Evolution of texture, strength-time-temperature
- Model as thermal, elasto-visco-plastic,
  with rate and temperature dependent stress-strain behavior

Models available for most metalworking processes

But … how ~~good~~ useful are model outputs

Process models can be applied to optimize manufacturing, design, maintenance

- Model validation is a big deal

Ref: PVPD Tutorial Series on Computational Weld Modeling, PVPD-72. Offered at the 2013 ASME PVP Conference, Paris, France. F.W. Brust, D.L. Rudland, M.R. Hill, and R. Dennis

Model validation is a key to ICME success

Validation means assessing a model's predictive capability by comparing calculations with experiments

- ASME V&V 10-2006: Guide for V&V in Computational Solid Mechanics

Experiment requirements based on the intended use of the model (ASME V&V 10-2006)

- Establish goals in planning the V&V program
- Proceed in hierarchical fashion from component to system level
- Validation specific to:
  - Particular computational model
  - Particular intended use

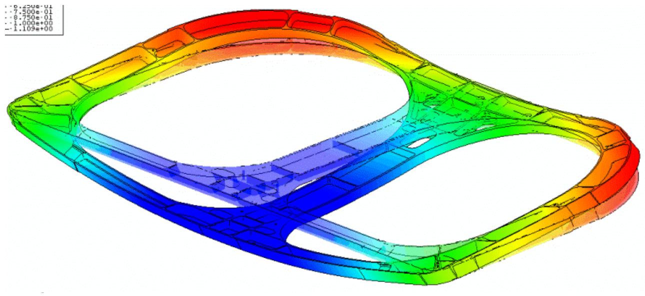
Simulation results and experimental data must have an assessment of uncertainty to be meaningful

- Developing useful uncertainty estimates requires focused effort

Model validation for RS: Examples to consider

Example 1: Knowledge of RS allows optimized machining process

- Goal: Predict shape-evolution of a part as it is being machined
- Validation Data: Dimensional data from controlled manufacturing trials



Example 2: RS-informed part lifing

- Goal: Predict useful life of specific components based on RS fields
- Validation Data: Crack growth data from component-level tests

Residual stress is not (usually) the end-goal

Residual stress is a means for correlating other phenomena

Most useful truth data generally not residual stress (more often distortion, crack growth, time to failure)

Making measurements: limitations

Measurements are obviously limited

- Models are seemingly unlimited …
  but, not useful without experimental validation

Residual stress is a rank 2 tensor field, that exists everywhere

- Realistically you can't measure $[\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{xz}, \tau_{yz}]$ throughout an entire part

Selecting good measurement locations and components is greatly helped by understanding what limited subset you want or need to measure

What you need depends on what you are using the measurements for

- Model validation
- Life prediction
- Distortion control
- …

Ref: M.B. Prime, "Residual Stress Measurement Methods: Making an Informed Choice," 2013 Residual Stress Summit, Idaho Falls, ID

Quality of residual stress data (model or measurement)

Judging the quality of residual stress data is difficult

- Models are non-linear and model inputs are uncertain
- Direct residual stress measurements are not possible
  - Always determined indirectly
  - Multiple techniques required to meet most needs (e.g., bulk and near-surface)
- Lack of truth data

Three approaches to assessing quality of measurement data

- Measurement repeatability – determines precision (but not accuracy)
- Cross-method validation – shows consistency (but not accuracy)
  - Best when methods use different physics (e.g., mechanical and diffraction)
- Phenomenological correlation – shows usefulness
  - Provides the most relevant truth data
  - Quantifies impact of residual stress
    - + e.g., on fatigue performance

Industry program on forging RS (MAI BA-11, 2011-15)

Metals Affordability Initiative

- DoD funded, industry-matched technology development programs
- Several have focused on residual stress technology (info on request)

Structural Designer Perspective (Dale Ball, 2010 RS Summit)

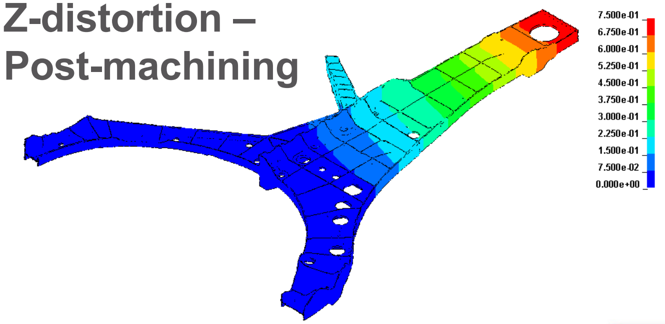
- Large single-piece forged bulkheads
  - 10-15% weight savings over conventional
- Residual stress issues:
  - Can cause distortion upon machining
    - Part rejection, costly rework
    - Assembly issues
    - Fit-up stress can cause early failure
  - Can confound fatigue crack growth rate data if not accounted for
  - Can cause premature cracking if not accounted for in design of finished parts

Large Forged Bulkhead (19.5 x 6.5 ft)

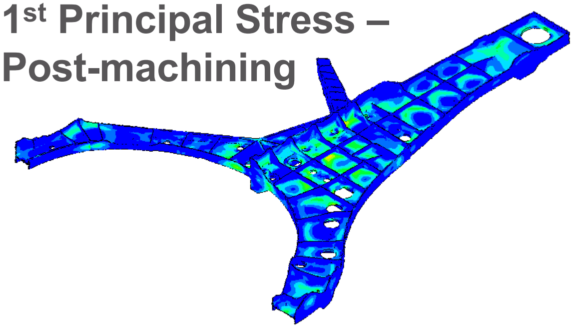
http://www.alcoa.com/

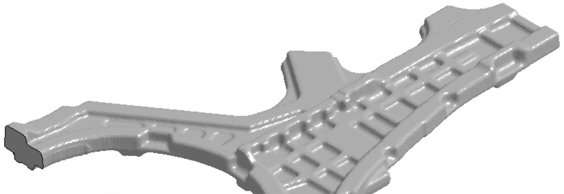
Alcoa model for aluminum forgings

Z-distortion – Post-machining



1st Principal Stress – Post-machining





Heat treat Al 7085 @ elevated temperature ~895ºF

Heat treatment

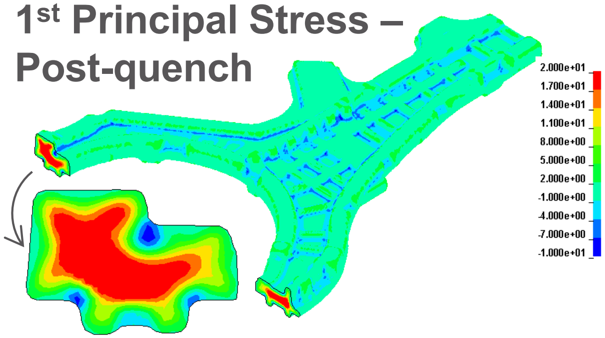
Rapid quench

Cold work stress relief

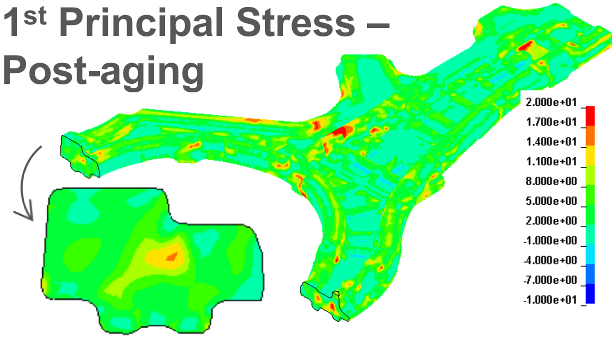
Artificial Aging

Machining

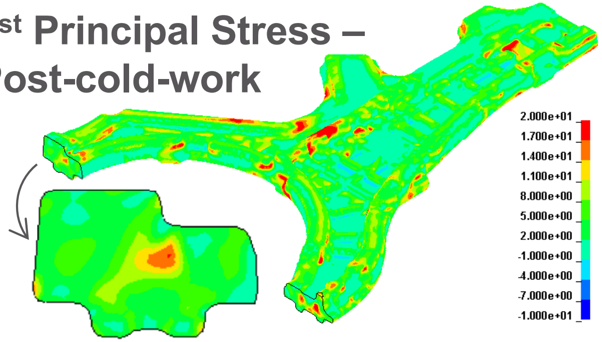
1st Principal Stress – Post-quench



1st Principal Stress – Post-aging



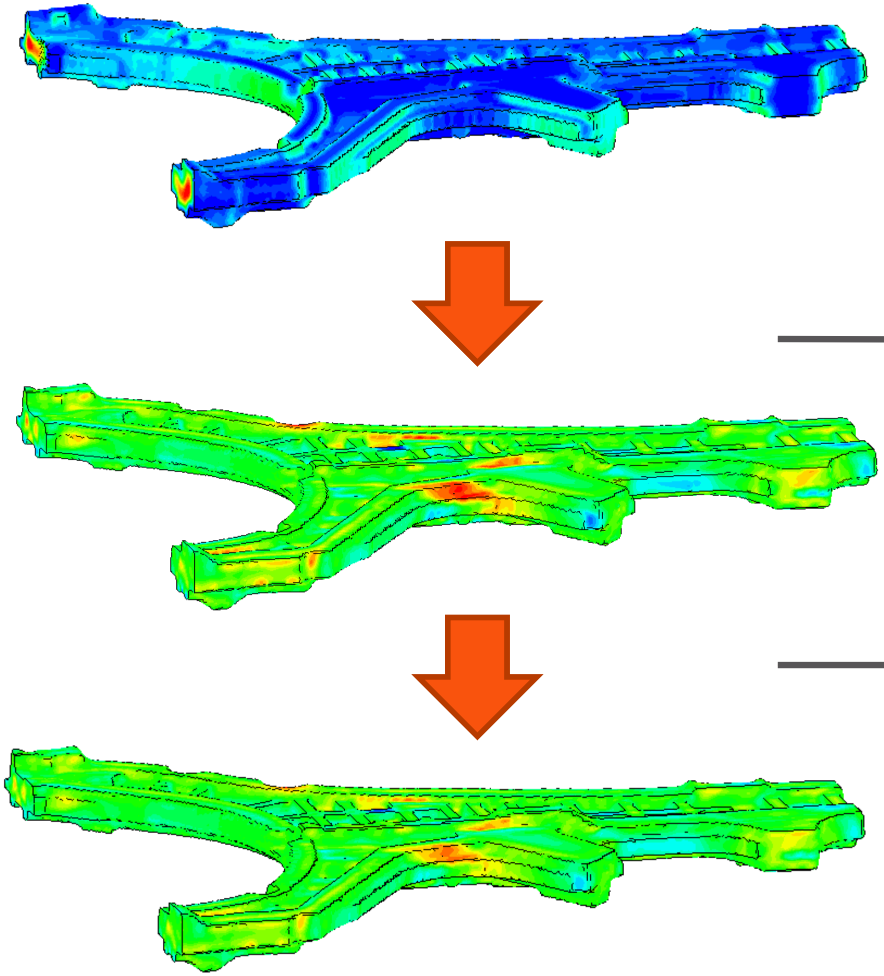
1st Principal Stress – Post-cold-work



Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

Public Release 88ABW-2015-5301

Alcoa model for aluminum forgings



Example bulkhead forging model

- Solution heat treat + Quench
- 497K solid hex constant stress elements
- Water quench from 895°F to 100°F
- Contours show XX stress: -37/38 ksi
- 11 CPU hours

- Cold-work stress relief
- Using 4 upper die segments
- Inline sequence on 35k ton press
- 506 CPU hours

- Post cold-work and post age cycle RS
- Contours show XX stress: -32/30 ksi

Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX
Public Release 88ABW-2015-5301

Residual stress measurement technique selection

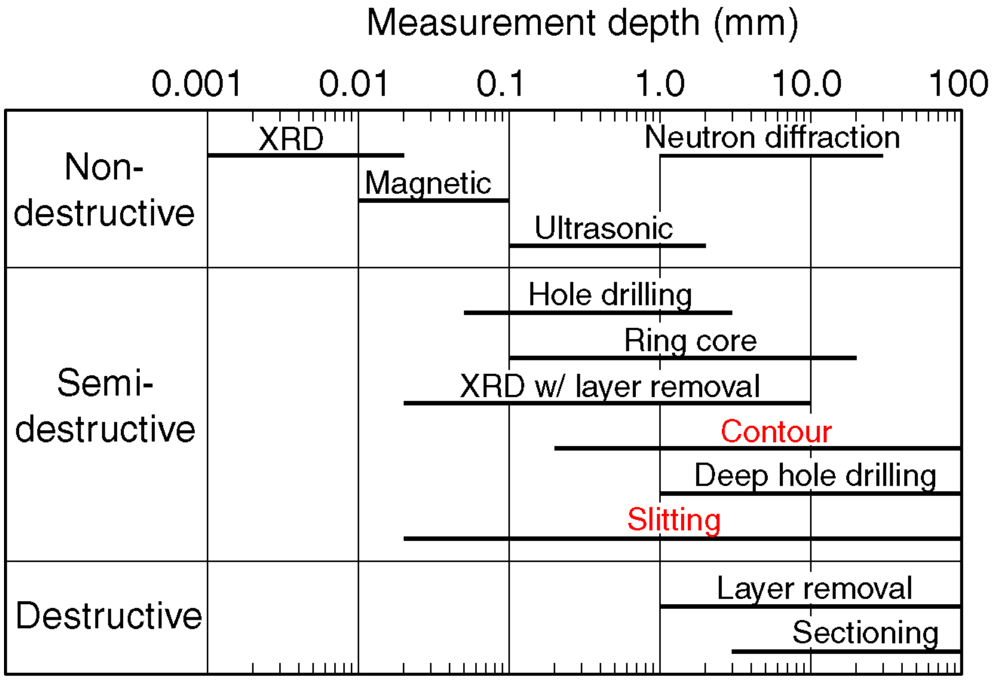
Variety of accepted RS measurement methods

- Each method has advantages and disadvantages

Select method based on needs of application:

- Stress field to be measured:
  - Depth of RS
  - Stress gradients, spatial variations
  - Number of RS components
- Body containing the stress
  - Geometry, size
  - Material property variations
  - Hazards
- Required accuracy, uncertainty
- Other factors to consider:
  - Destructiveness
  - Required equipment
  - Measurement time
  - Cost
  - Portability
  - Required expertise
  - Material handling

Three classes of technique:
- Diffraction (E beams)
- Mechanical (cut, deform)
- Other (physics-based)



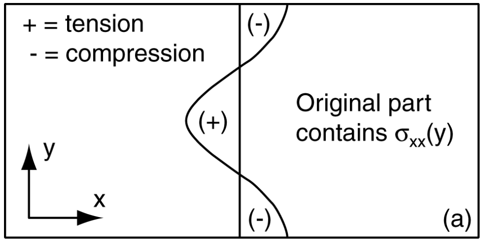
After: Prime, www.lanl.gov/residual/compare.shtml

Contour method

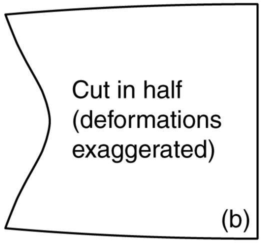
Contour method generates a 2D map of residual stress normal to a plane

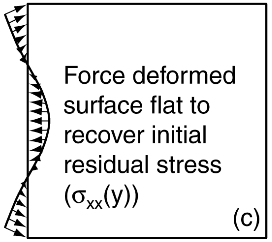
Contour method steps (illustrated for 2D body)

M. B. Prime, "Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut," JEMT, 123, 2001.

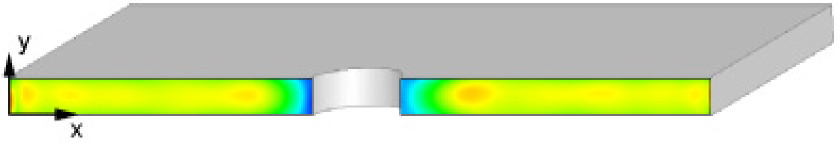


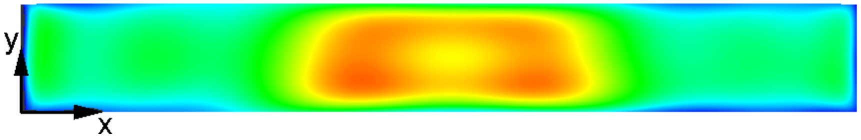
- Part contains unknown RS (a)
- Cut part in two: stress release ⇒ deformation (b)
- Measure deformation of cut surfaces
- Apply reverse of average deformation to finite element model of body (c)
- Map of RS normal to surface determined
- Same procedure holds for 3D





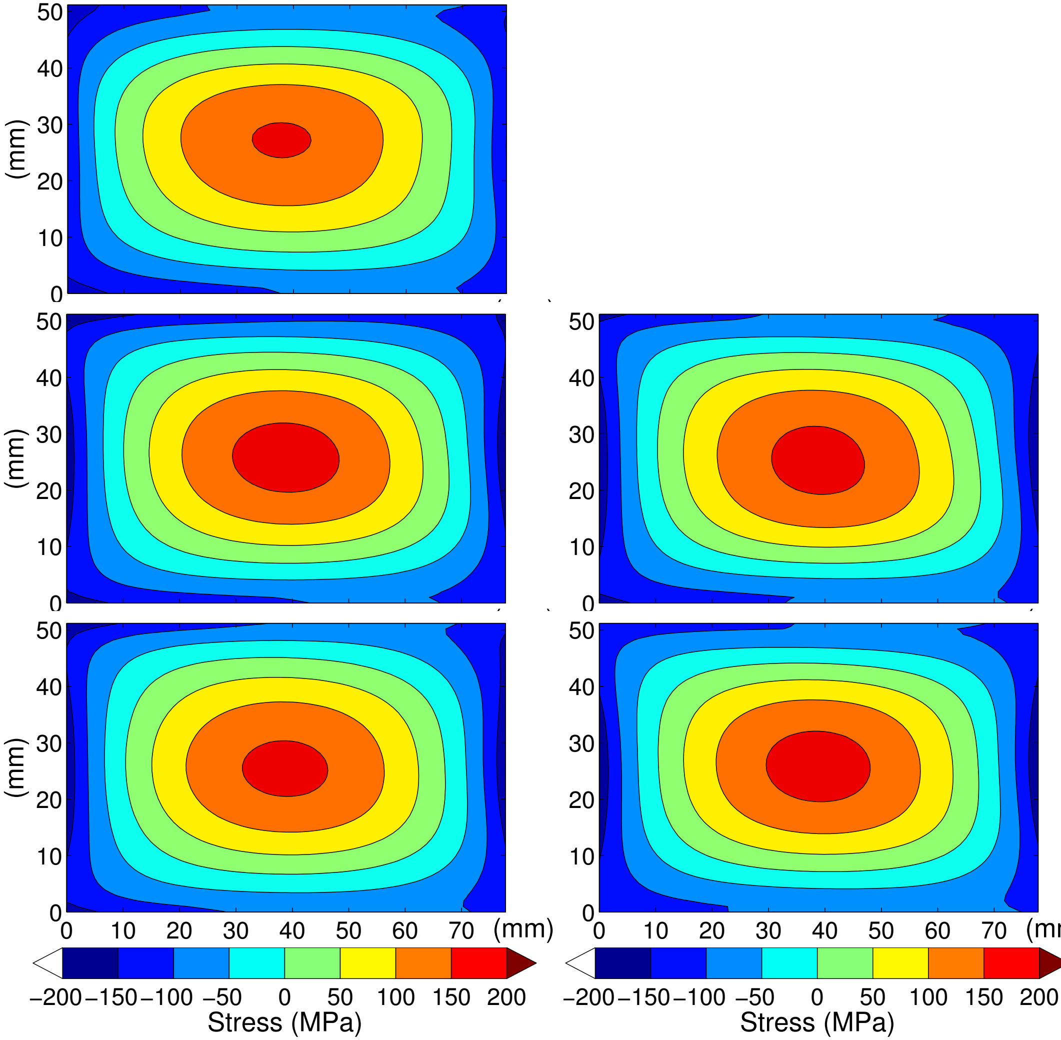
Cut → measure → FEM → 2D residual stress map

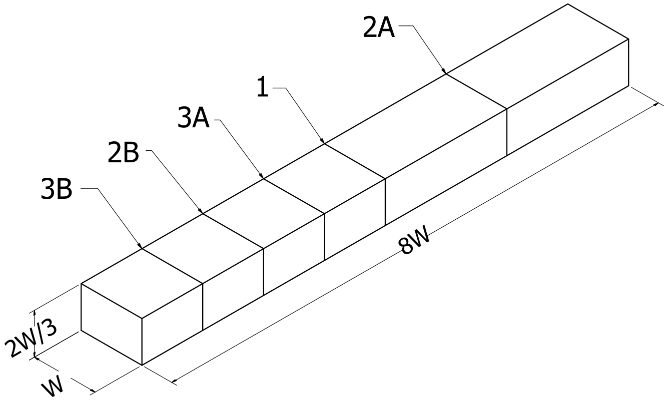




Measurement precision: repeatability in quenched bar

Contour method stress mapping





Cut 1

Cut 2A

Cut 2B

Cut 3A

Cut 3B

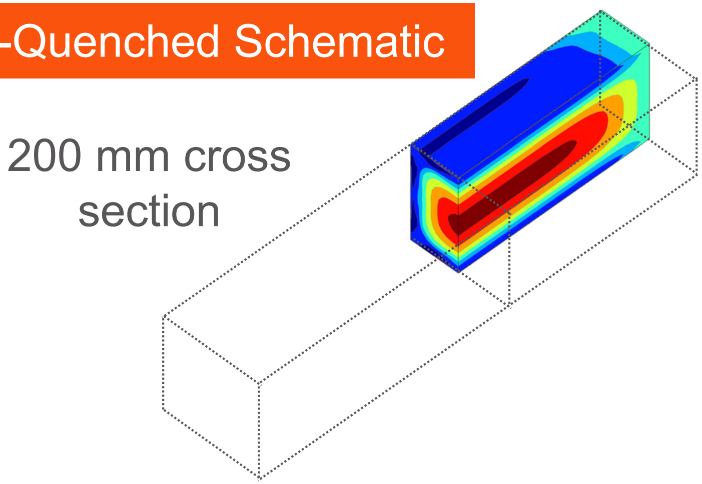
M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277

Cross-method validation in large hand forging

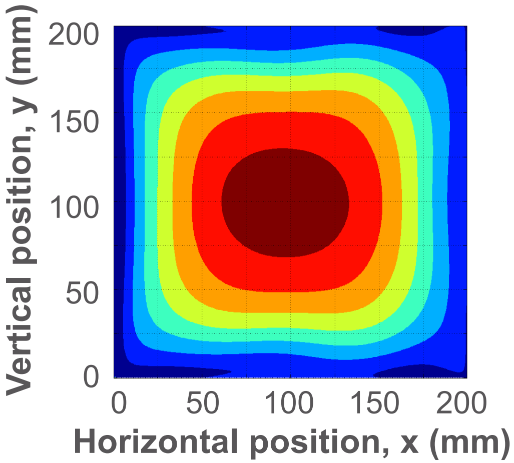
200 mm square-section quenched bar

Validation of Residual Stress Fields Determined from Material Process Models, M.R. Hill. A.T. DeWald, 2012, MS&T Symposium on ICME, Pittsburgh, PA

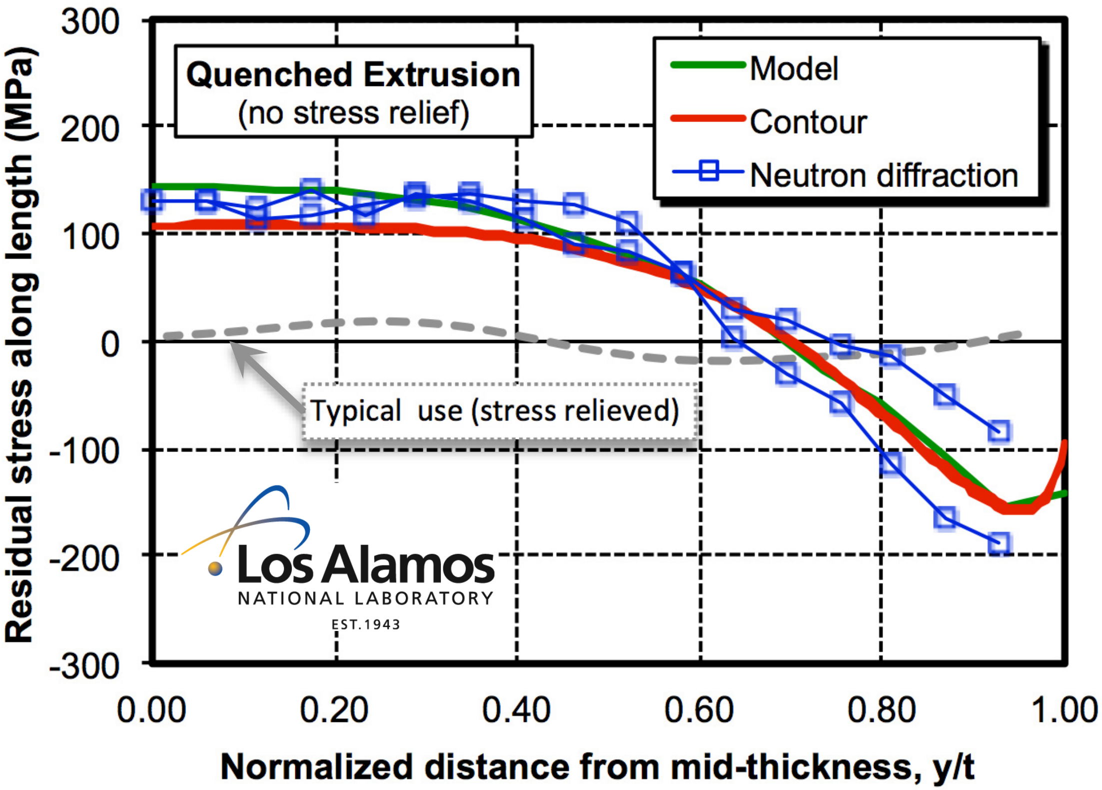
As-Quenched Schematic



Contour measurement



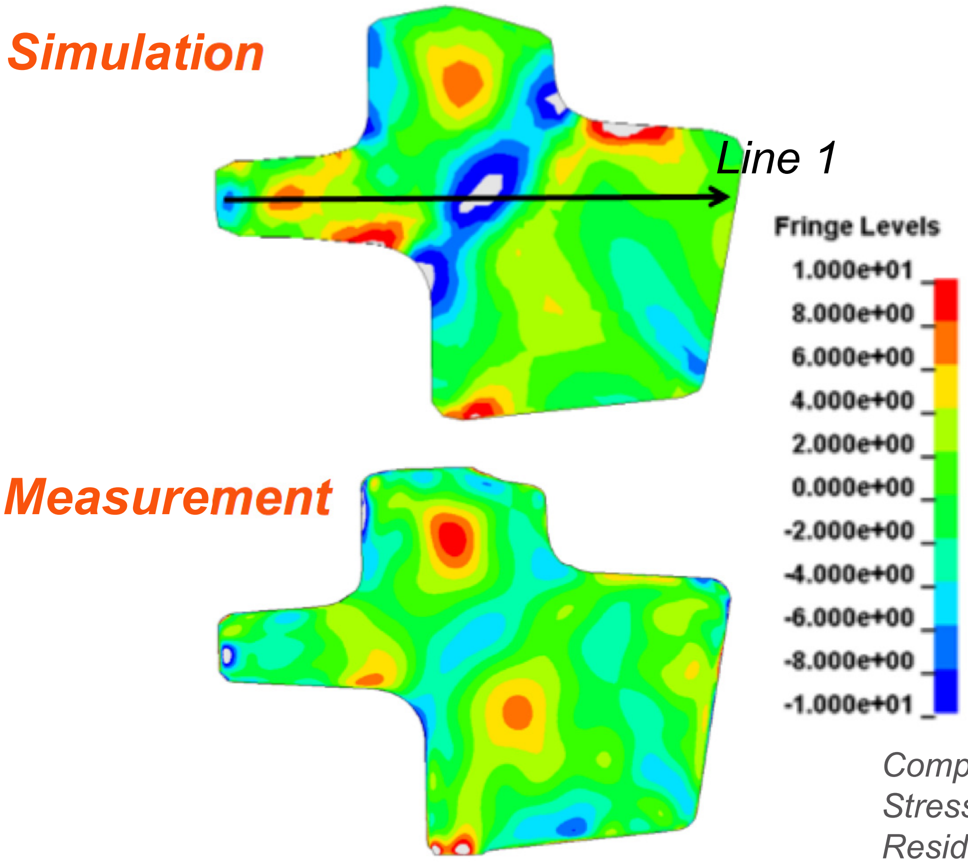
Validation: Quench model (Alcoa), Contour (HE), and Neutrons (LANL, UC Davis)

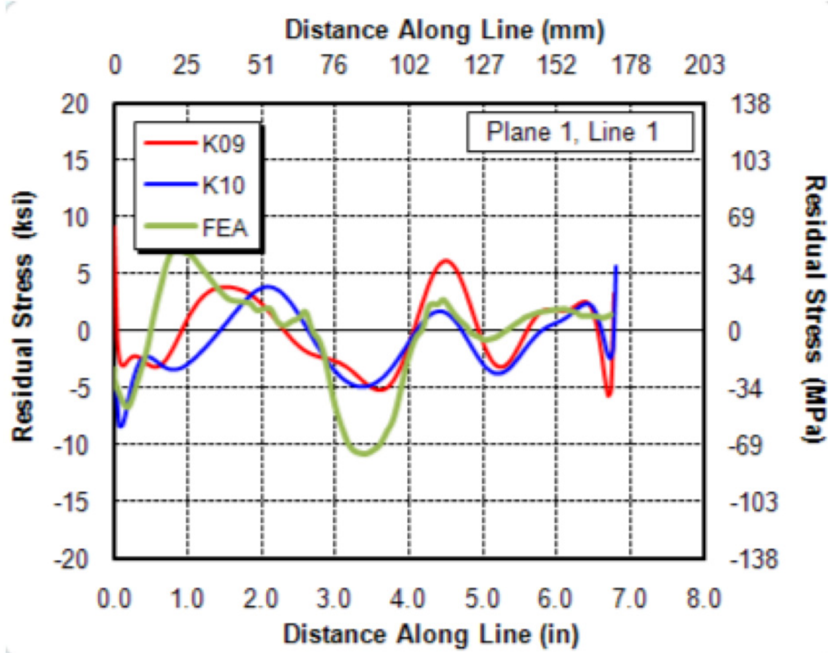


Model validation in aerospace die forging

Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Not shown, but important: measurement precision, model uncertainty



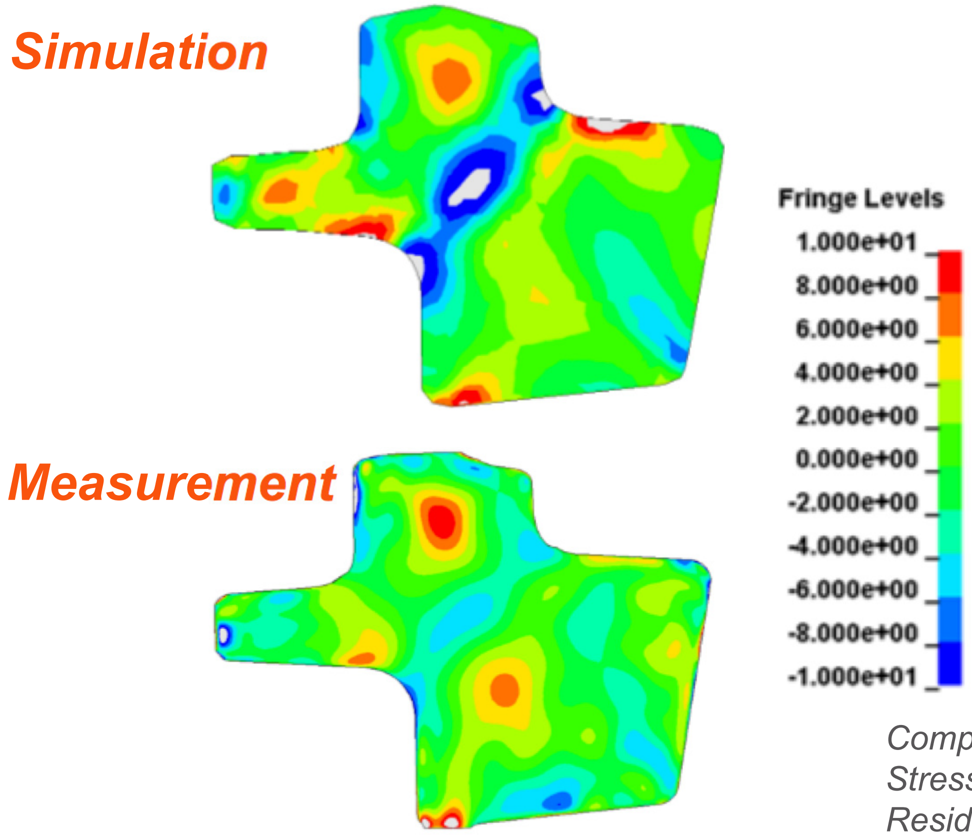


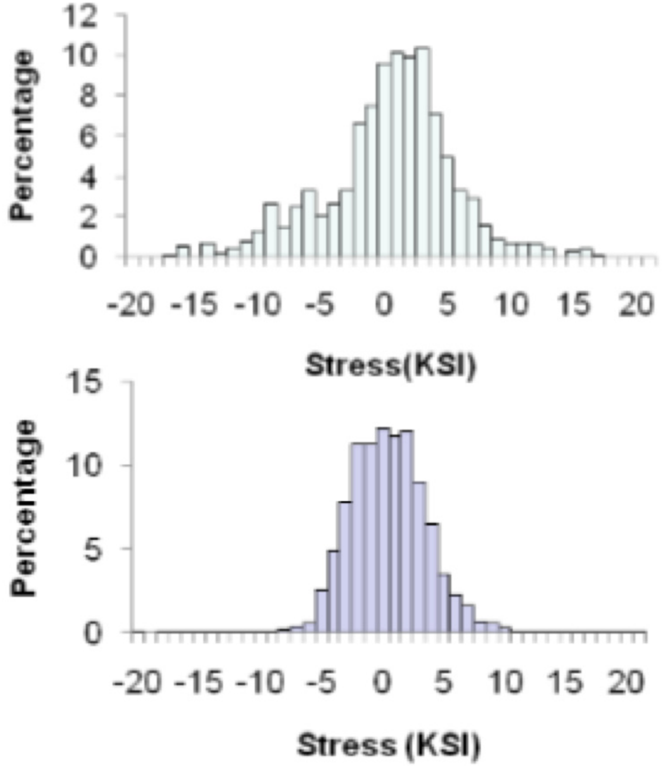
Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

Model validation in aerospace die forging

Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Measurements confirm ability of model to estimate residual stress levels and distribution



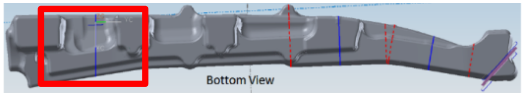


Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

Process consistency in aerospace die forging

Contour measurements in 6 forgings

(Mark James, Alcoa, 2012 Aeromat)



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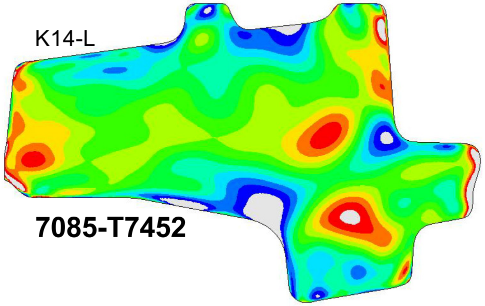
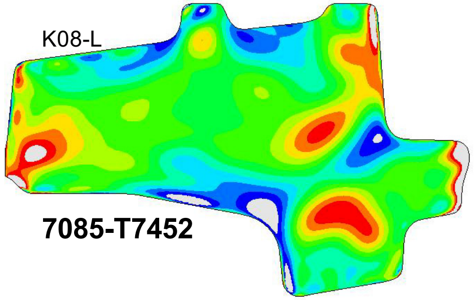
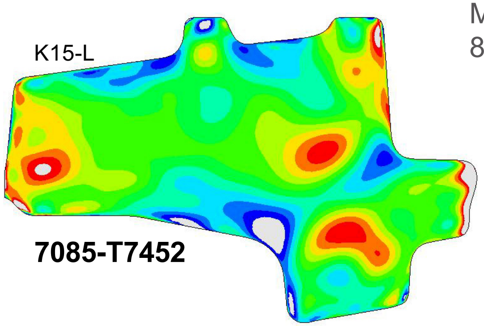
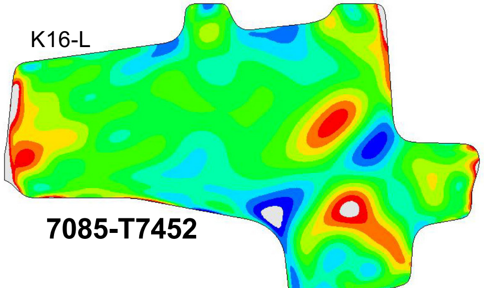
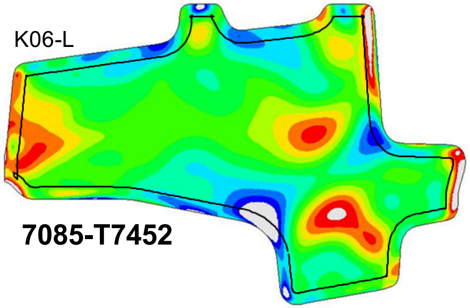
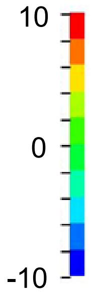


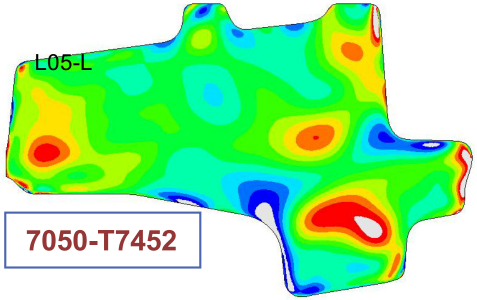


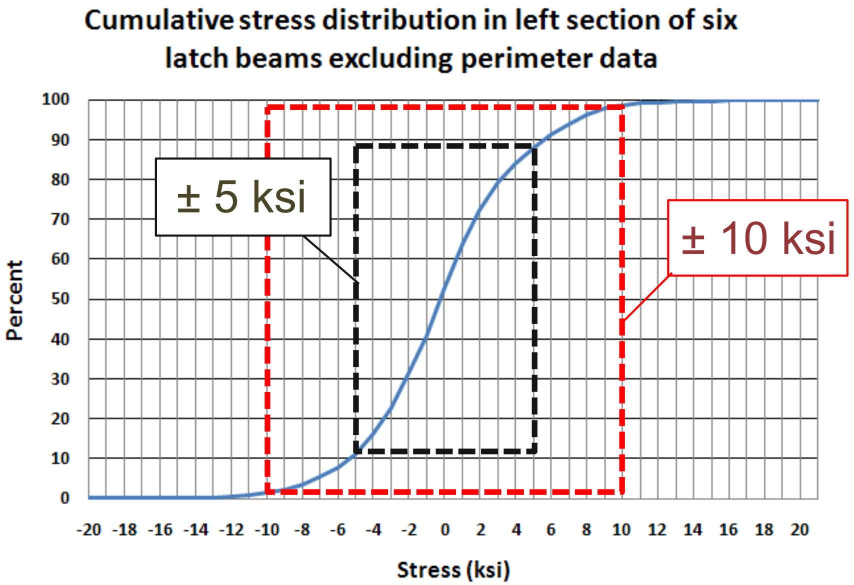








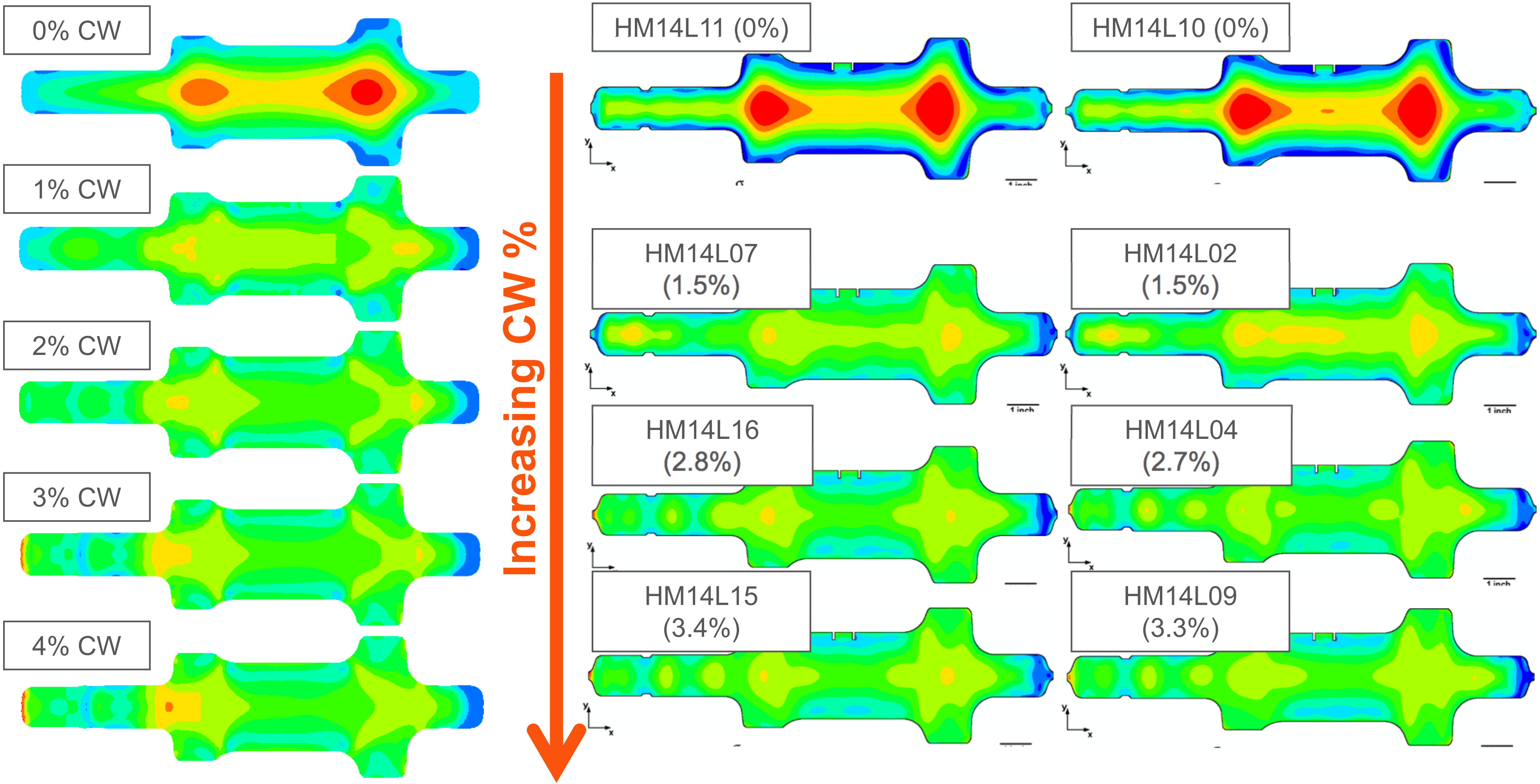




Cumulative stress distribution in left section of six latch beams excluding perimeter data

Validation of process sensitivity in aero die forging

Process model **Measurements**



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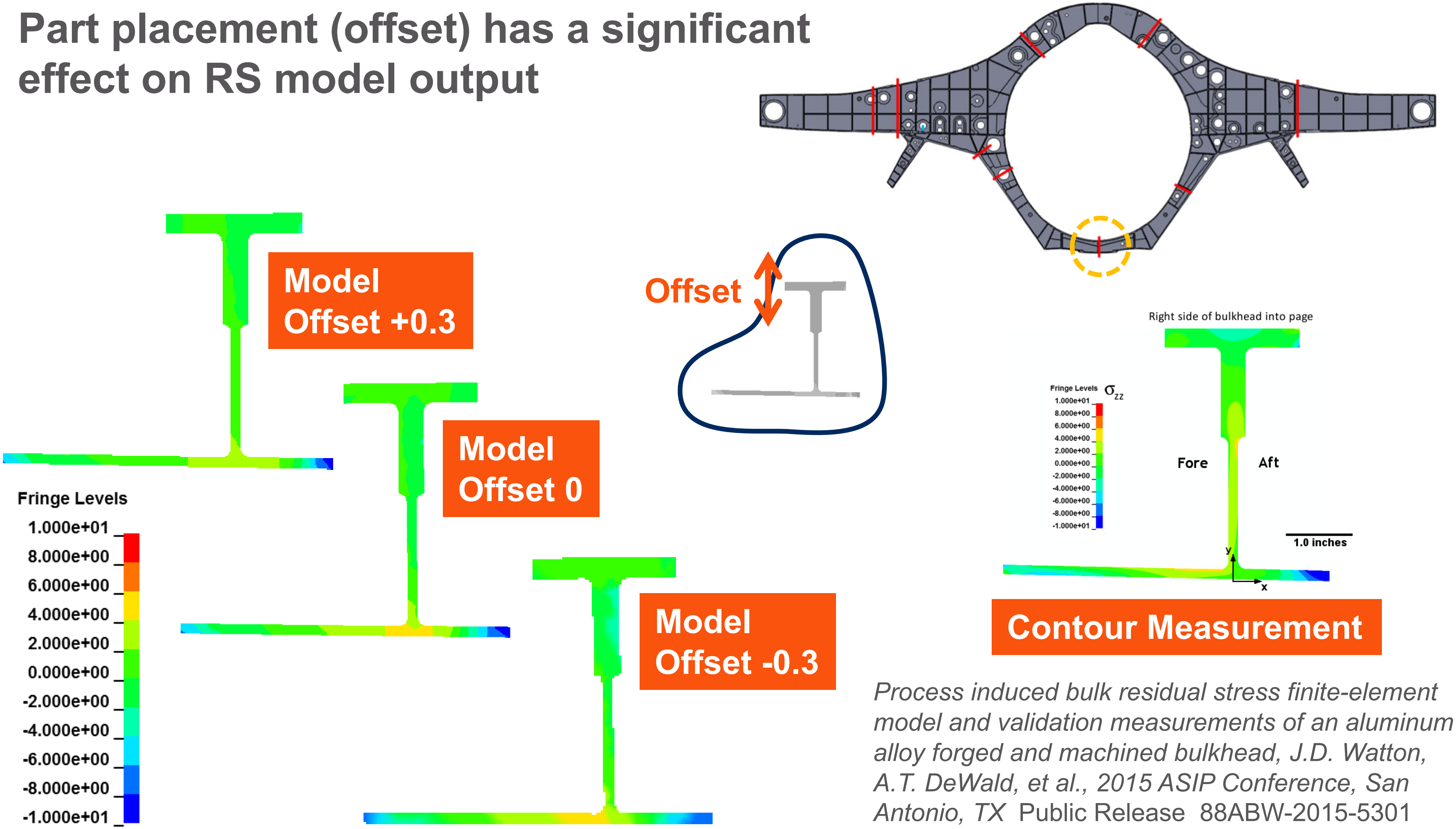
Validation of residual stress in machined parts

Part placement (offset) has a significant effect on RS model output

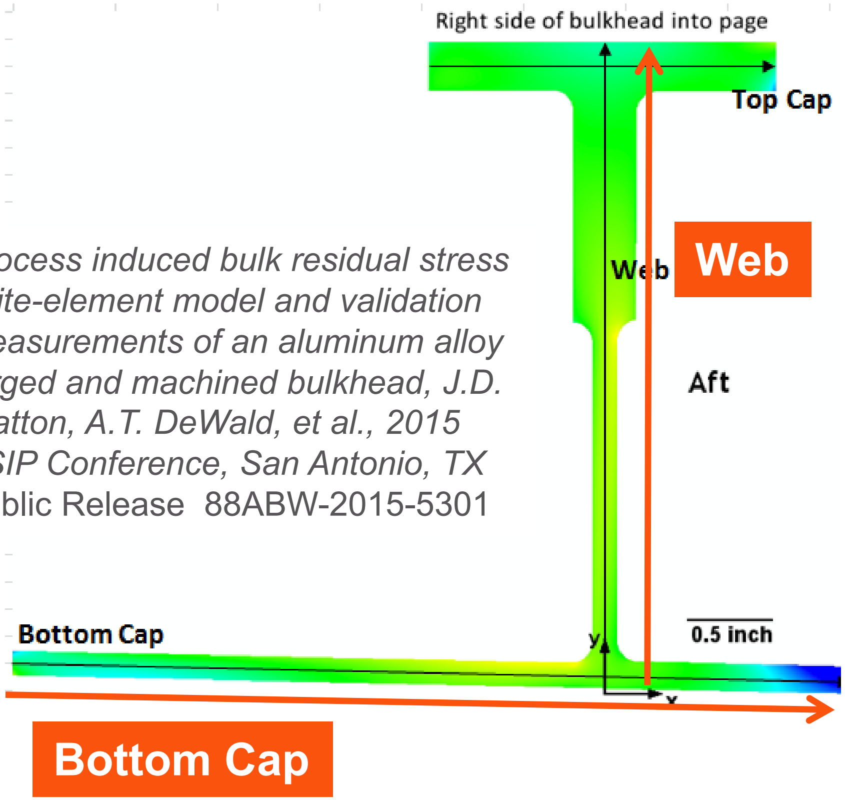


Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX Public Release 88ABW-2015-5301

Validation of residual stress in machined parts

Validation of residual stress in machined component

- Agreement within ±3 ksi



Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX
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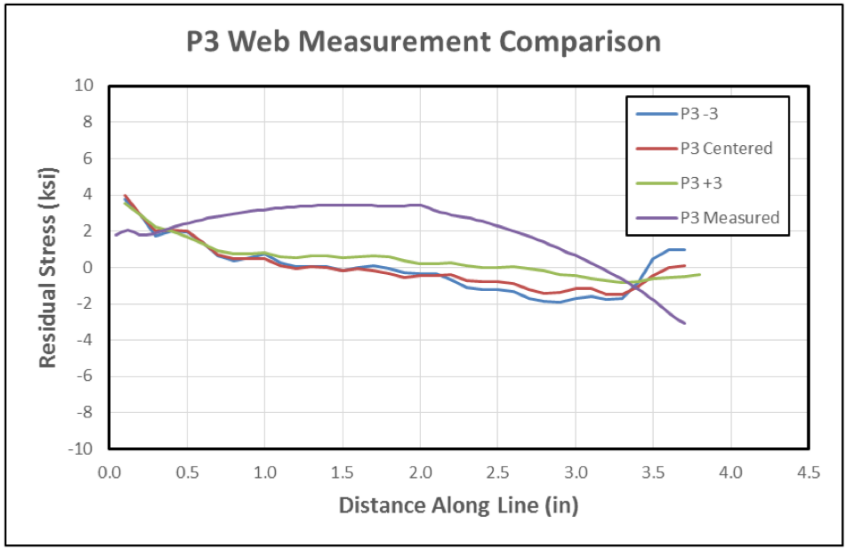
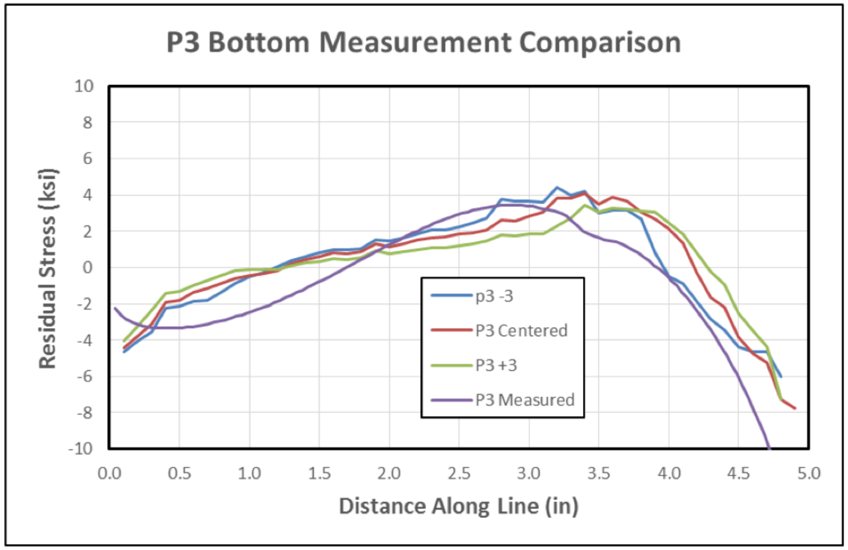
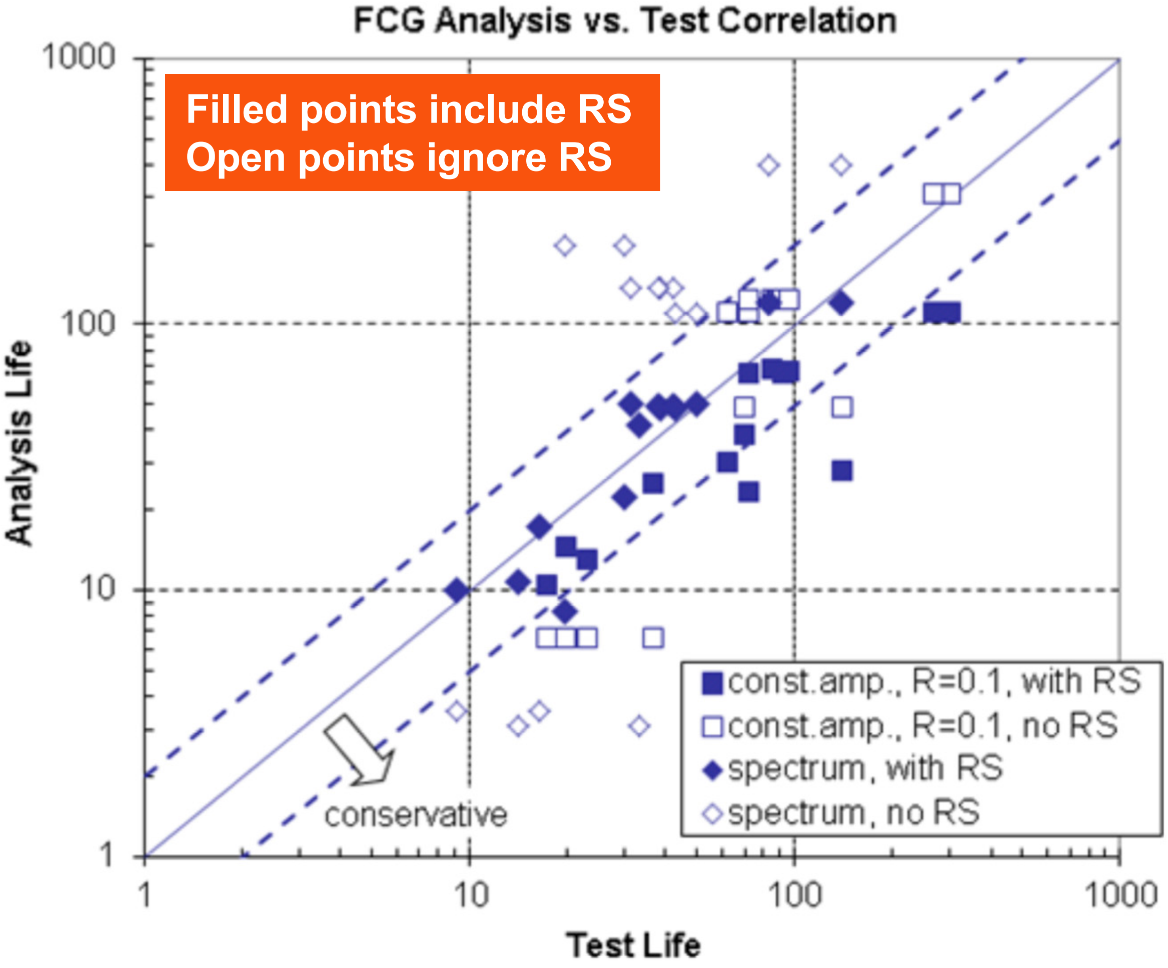


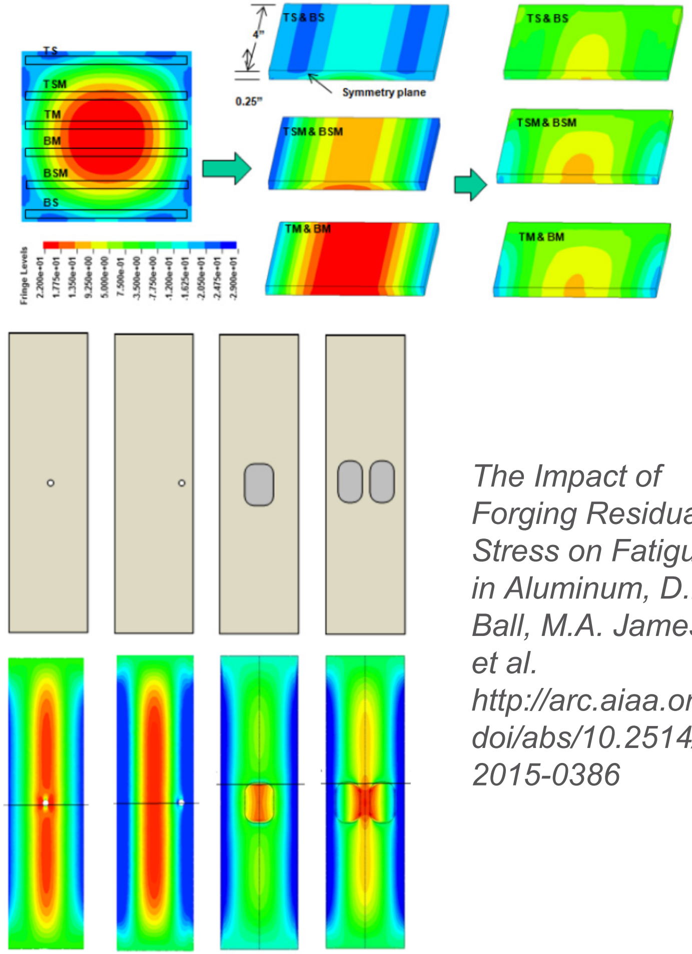


Validation of fatigue in parts removed from forgings

Fatigue crack growth tests: correlation of 6 unique coupon types in material with high residual stress



Filled points include RS
Open points ignore RS



The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Potential phases of engagement in model validation

1: Rejection

- “That seems wrong. You had better check your work.”
  … this occurs equally in those who model and those who measure

2: Fair consideration

- “That might be right, but I will stick with what I have.”
  … no time to deal with additional information

3: Coming around

- “Perhaps I need to consider adjusting my …”
  … methods … inputs … assumptions

4: Collaboration

- Best-practice engineering decisions reached based on results from validated models and well-executed measurements

Summary comments

The BA-11 program is breaking new ground for residual stress

- Validated process models will move residual stress from *known-unknown* to *known-known*
- Business case forecasts significant *cost-savings* from residual stress engineering
  - Operational cost savings from lower weight
  - Sustainment cost savings from better fatigue performance

Model validation is a crucial activity in residual stress engineering

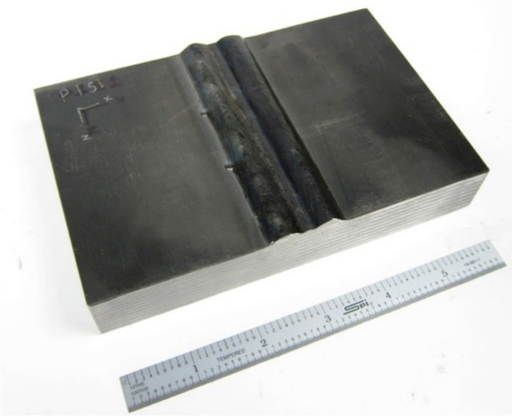
- Model – include process uncertainties
- Measurement – repeated measures provide uncertainty
- Both - reconcile unknown systematic biases
- ***Best truth data*** derived from material performance tests
  Fatigue crack initiation and growth

The team approach enables technological progress on key issues

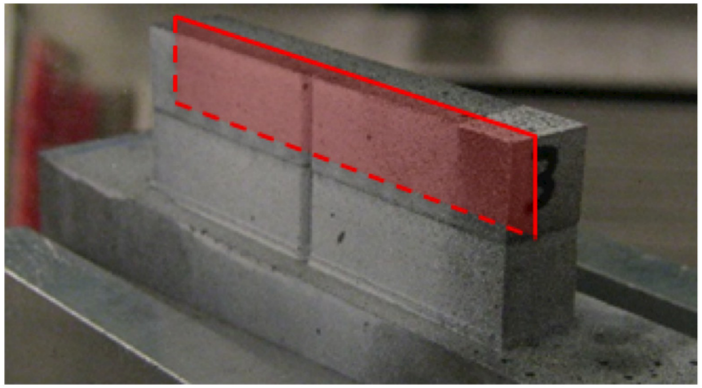
- Material supplier – raw materials, processing
- Manufacturer – processing, forging, machining, distortion, assembly
- Designer – failure processes, loading, environment
- Operator – maintenance, sustainment, life extension
- Regulator – safety, certification
- Technical experts

Recent AM Residual Stress Measurements

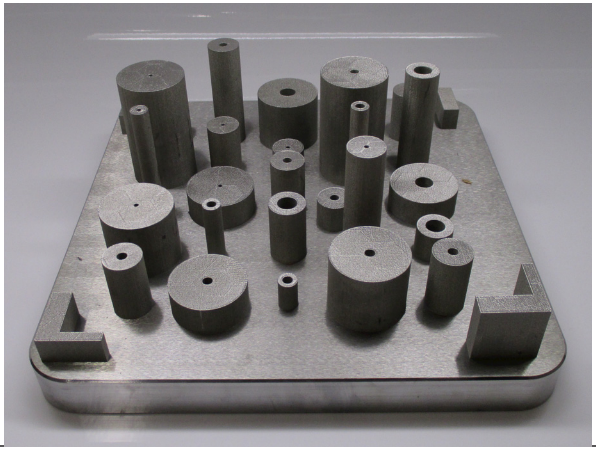
E-beam Wire (EBAM)



LENS



Powder Bed



AM residual stress measurements: EBAM, Ti6Al4V

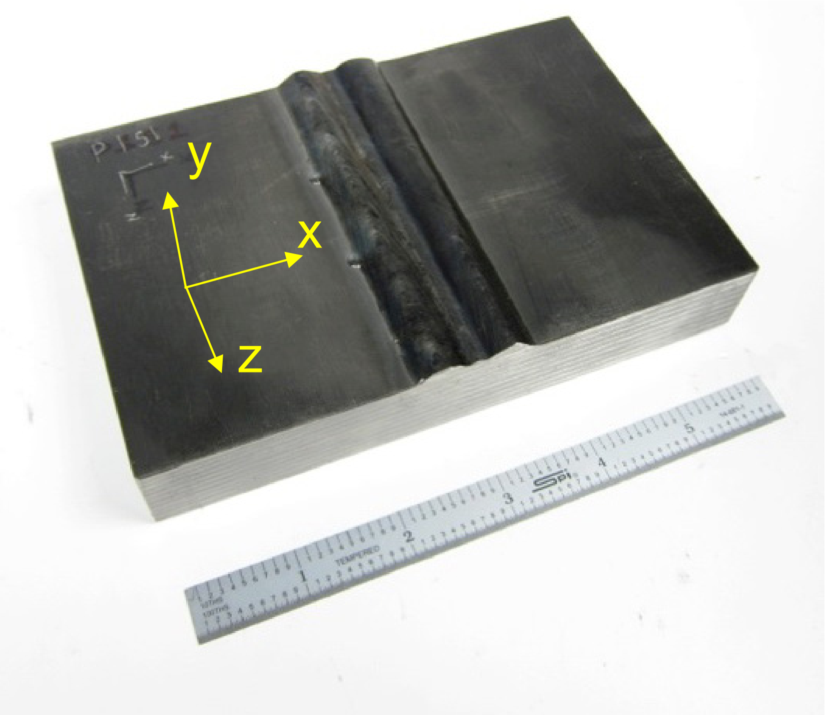
Deposit on Ti-6Al-4V plate

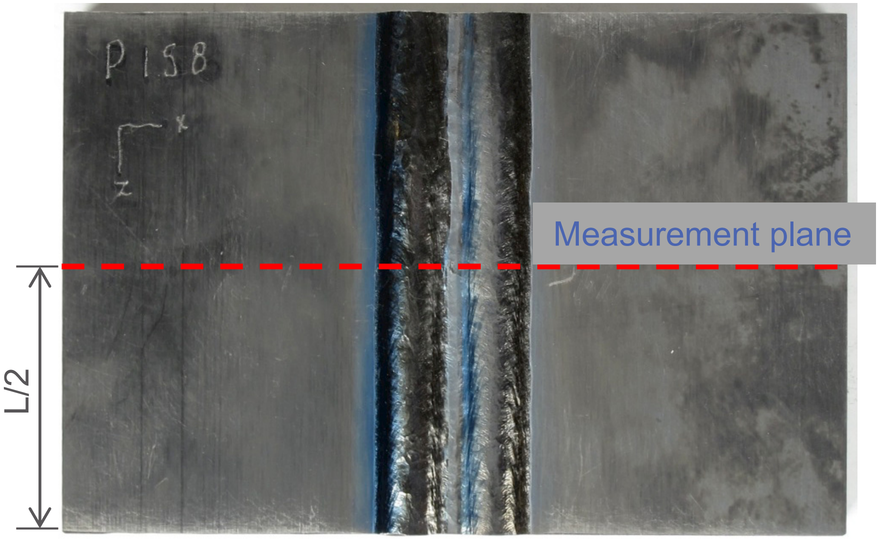
- Parent plate 48 inch long, 1 inch thick, 6 inch wide
- Electron-beam energy deposition, wire feed

2 sample types

- As-deposited
- Stress relieved

Contour measurements of axial stress

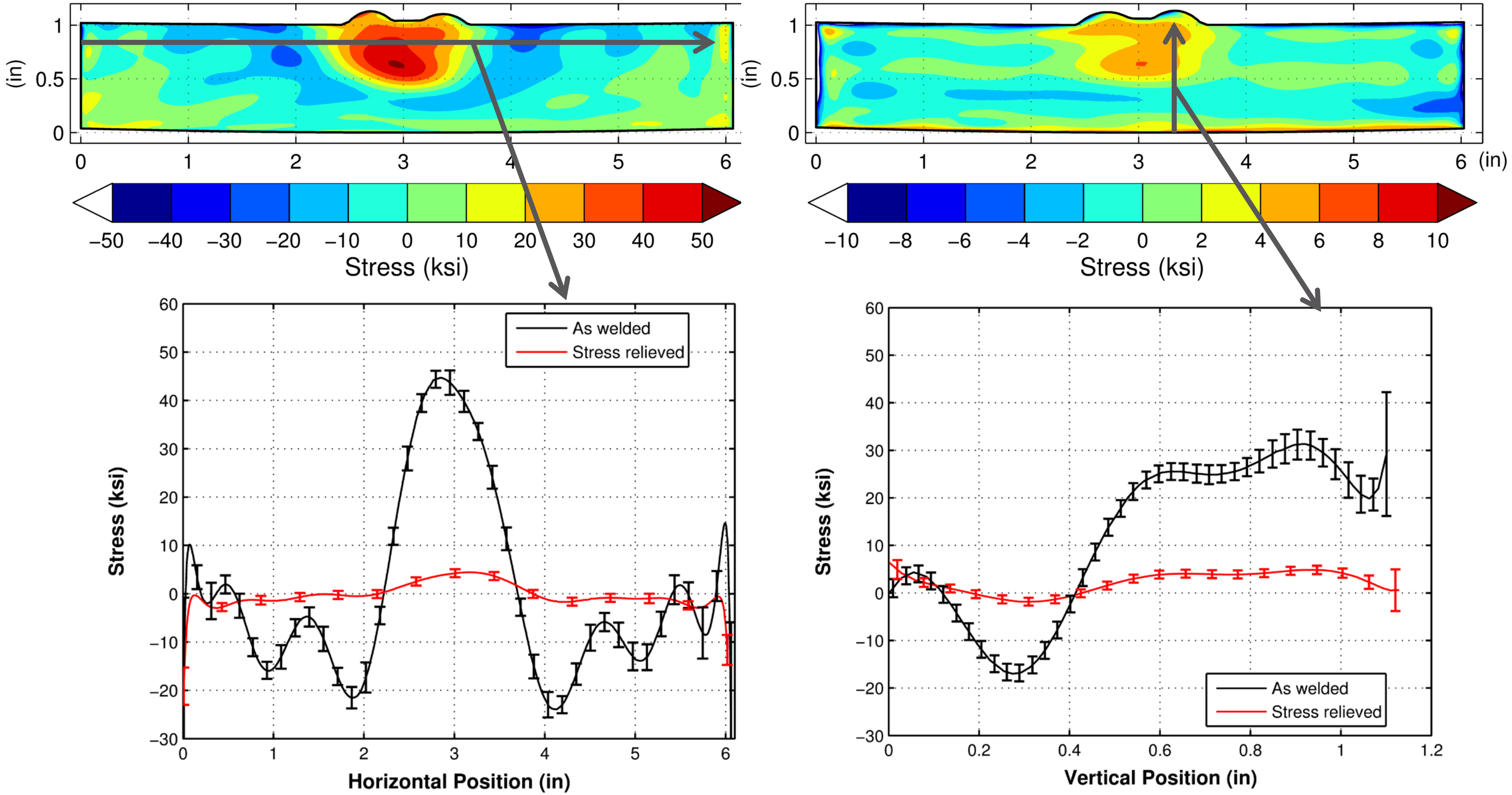




AM residual stress measurements: EBAM, Ti6Al4V

Comparison of as-deposited with stress relieved (note 5x color scale factor)

As-deposited **Stress relieved (1200° F)**



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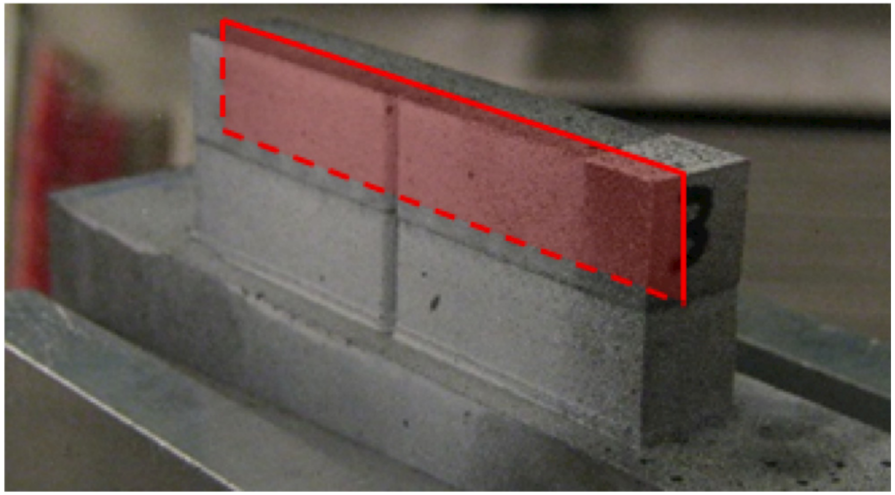
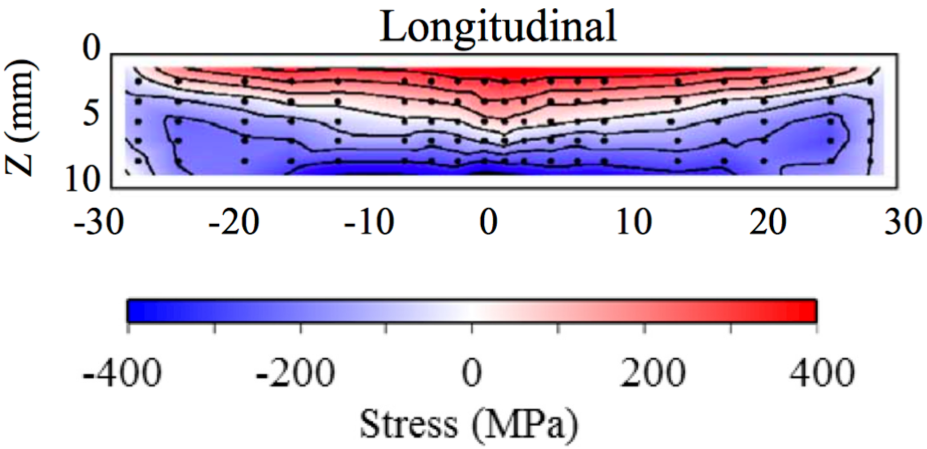
AM residual stress measurements: LENS, SS304L

Edge-notched beams 10 x 10 x 60 mm

Residual stress by neutron diffraction

- SMARTS instrument at LANL



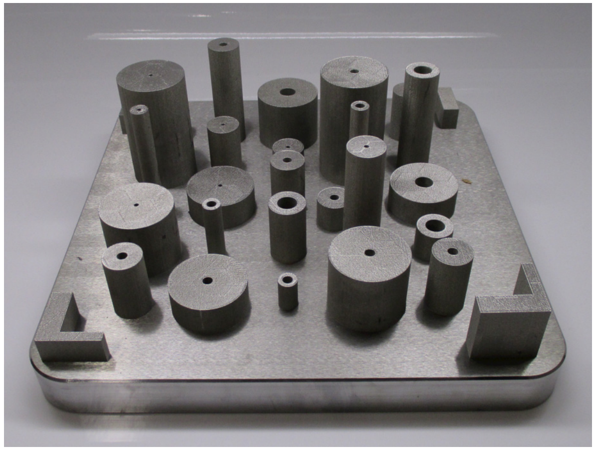


Brown, D. W., et al. (2016). "Neutron diffraction measurements of residual stress in additively manufactured stainless steel." Materials Science and Engineering: A **678**: 291-298.

AM residual stress measurements: PB, SS304L

Range of cylinders on plate

- Cut free from base plate

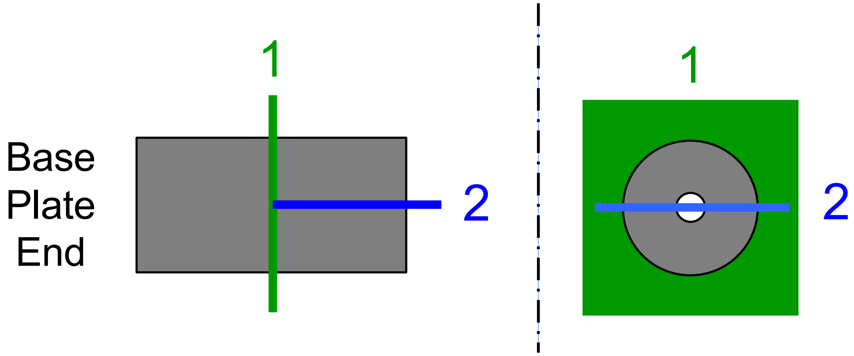


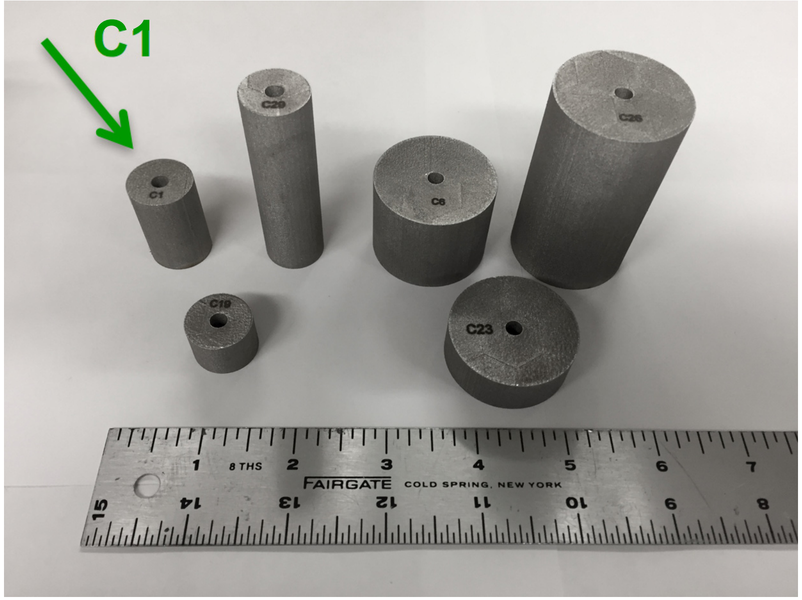
Example Measurements on C1

- Inside Diameter 4.9 mm (0.193”)
- Outside Diameter 19.2 mm (0.757”)
- Length 30.4 mm (1.198”)

Contour measurements

- Axial stress (1)
- Hoop stress (2)

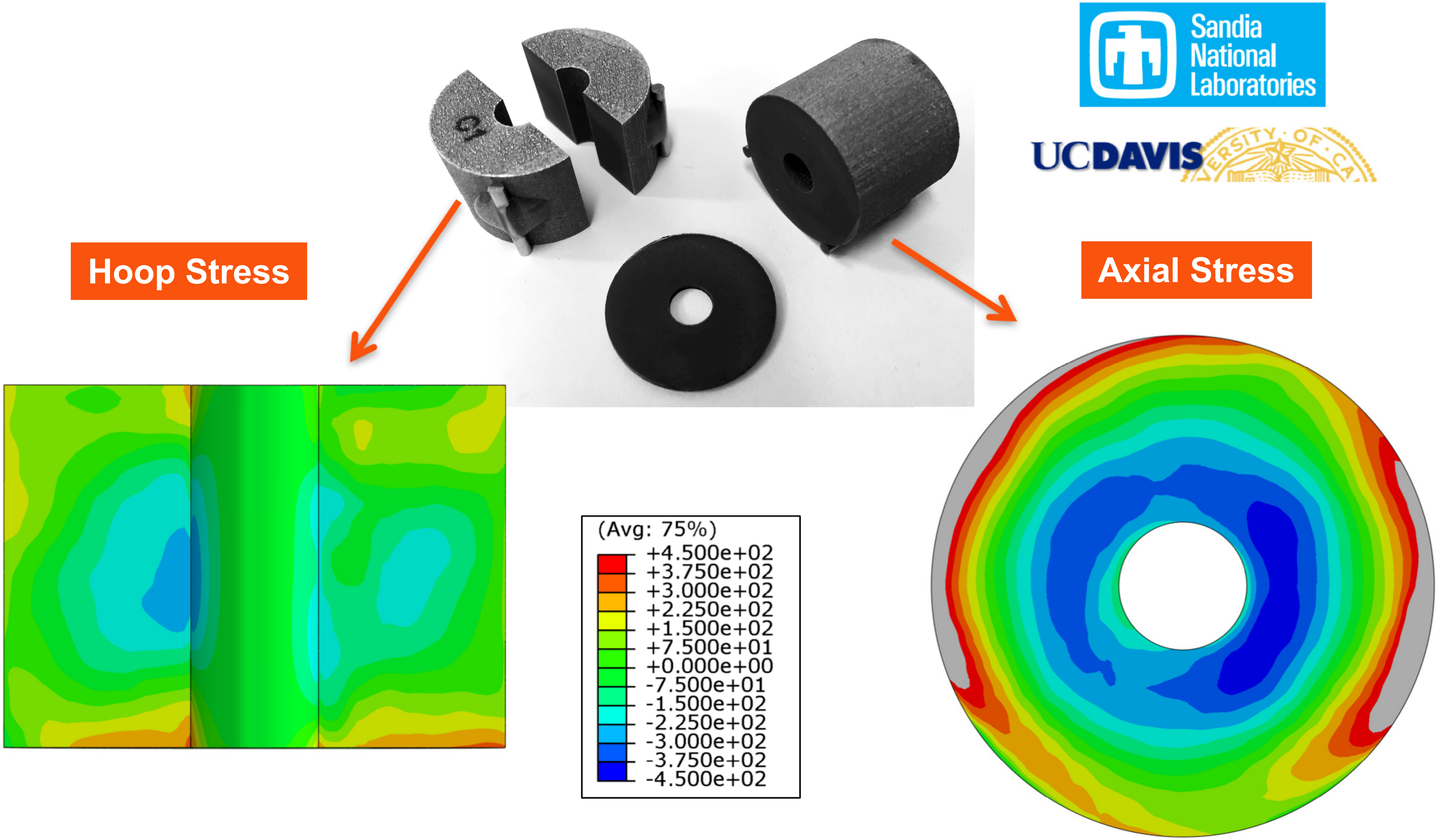




AM residual stress measurements: PB, SS304L

Sandia National Laboratories

UCDAVIS



Observations on RS in AM builds

Residual stresses are significant in AM builds

- Magnitudes 30% to 80% of as-built yield strength
- Spatial distributions similar to those in welds

Residual stress engineering opportunities

- Manage residual stress as a known known
  - Simplify development
  - Facilitate qualification
  - Manage transferability (coupon versus component)
- Manipulate residual stress fields for positive effect
  - Tension where not detrimental
  - Compression where beneficial
- Consider residual stress for quality assessment
  - High quality signal from process chain

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ENGINEERING
Predict. Test. Perform.

APPENDIX T—A CASE STUDY ON THE INCORPORATION OF BULK RESIDUAL STRESS IN AIRCRAFT COMPONENT DESIGN

FAA / AFRL Additive Manufacturing Workshop,
Dayton, OH

A Case Study on the Incorporation of Bulk Residual Stress In Aircraft Component Design

30 August, 2017

Dale L. Ball

LOCKHEED MARTIN
Aeronautics Company

A Case Study on the Incorporation of Bulk Residual Stress In Aircraft Component Design

PREFACE

The following is a brief review of several technology development and demonstration projects aimed at characterizing process induced bulk residual stresses in large aluminum forgings, and then explicitly including those stresses in the design analysis of the components machined from those forgings.

None of the work presented involved study of additively manufactured materials. Rather, the information is being provided as 'food for thought' as strategies are being developed for the management of residual stresses in AM materials for which post-deposition mechanical or thermal stress relief is not viable.

A Case Study on the Incorporation of Bulk Residual Stress In Aircraft Component Design

- INTRODUCTION
- RESIDUAL STRESS MODELING & MEASUREMENT (ICME)
- RESIDUAL STRESS INCORPORATION IN DESIGN (ICSE)
- CONCLUSIONS

Bulk Residual Stress in Component Design:

Introduction

- **Large aluminum forgings were adopted for use on F-35 during early SDD (2004):**
  - ***Structural unitization – single forged / machined part replaced multi-part design***
  - ***Significant weight savings – 10-15% over built-up plate design***
  - ***Significant manufacturing cost savings – 50% reduction in buy-to-fly ratio, reduced machining / assembly costs, reduced touch labor***

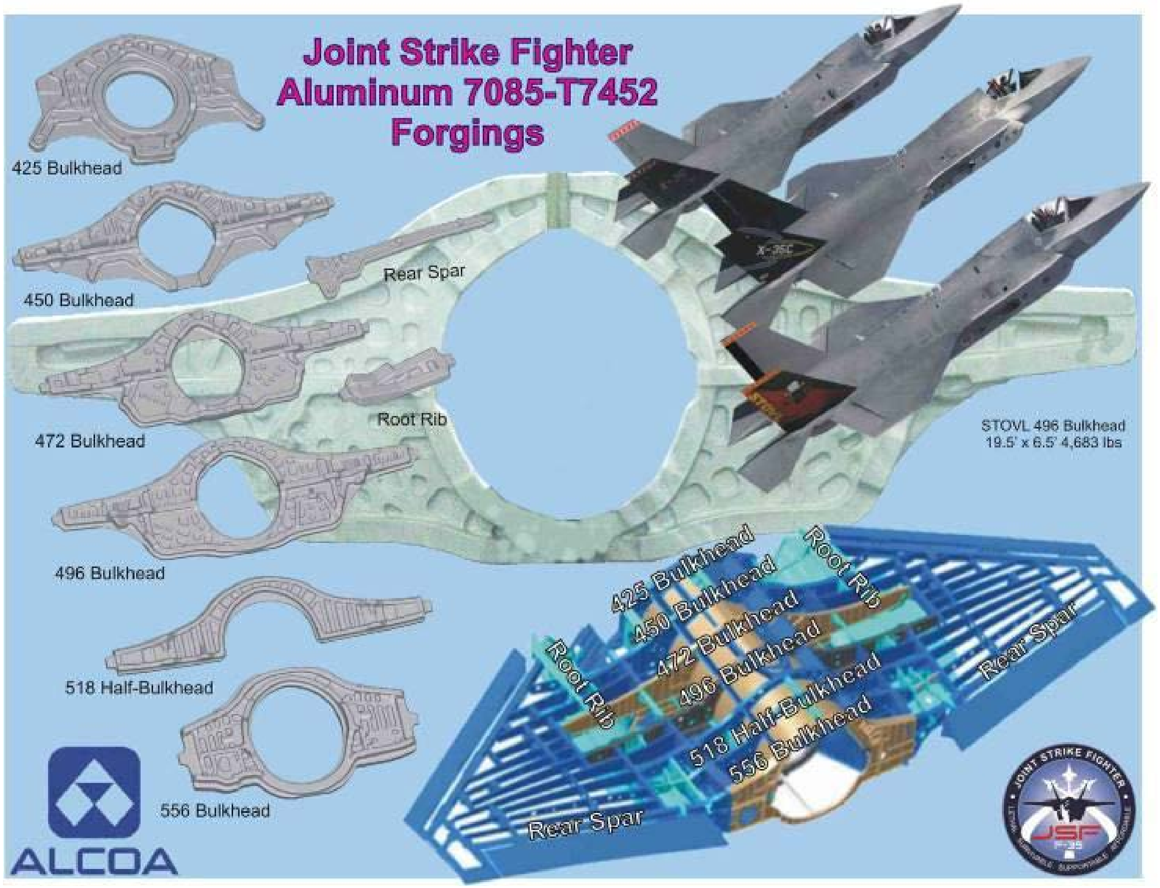
- **Successful transition required significant, long-term collaboration between LM Aero and Alcoa (now Arconic)**
  - ***Forging / machined part design – additional coverage for risk abatement***
  - ***7085 material characterization (mechanical properties)***
  - ***Forging residual stress characterization***

Bulk Residual Stress in Component Design:

Introduction

New Alcoa technologies were applied:

- **New forge alloy 7085-T7452**
- **Very large, monolithic die forgings**
- **Forgings designed for manufacturing**
- **CAD modeled "Signature Cold Work Process" (superior stress relief product)**



Forging Residual Stress Management:
Background

- All stakeholders recognized that
  - *forged aluminum parts contain residual stresses*
  - *presence of detrimental (tensile) residual stresses*
    - can confound material property data (esp. fatigue crack growth rate data) if not accounted for
    - may result in premature cracking if not accounted for in design
  - *effects of these would have to be addressed*

- The baseline design approach was to use mechanical properties with *implicit* (built-in) *residual stress*

- An updated design approach was developed, demonstrated and eventually adopted in which *bulk residual stresses are addressed explicitly*, rather than being accounted for through conservative material properties, test correlation factors, or other approximate means

Bulk Residual Stress in Component Design:

Introduction

- **The new design approach was made possible by recent advances in several fields:**
  - ***Experimental mechanics – development of the Adjusted Compliance Ratio (ACR) method for the extraction of confounding residual stress effects from fatigue crack growth rate (FCGR) data***
  - ***Integrated computational materials engineering (ICME) – development of the capability to predict forging process induced residual stresses***
  - ***Experimental mechanics – development of the contour method for the measurement of residual stresses***

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Bulk Residual Stress in Component Design:

Modeling & Measurement (ICME)

- **The general vision for integrated computational materials engineering (ICME) is to:**
  - ***develop computational tools for materials discovery, design, development, and sustainment***
  - ***develop experimental tools for discovery, characterization, validation and verification***
  - ***integrate these tools with information technologies, manufacturing-process simulations, and component design systems***

- **Realization of these capabilities will lead to:**
  - ***ability to develop and deliver optimized materials and manufacturing processes***
  - ***ability to provide improved product performance, manufacturability, and sustainability***
  - ***reduced cost***

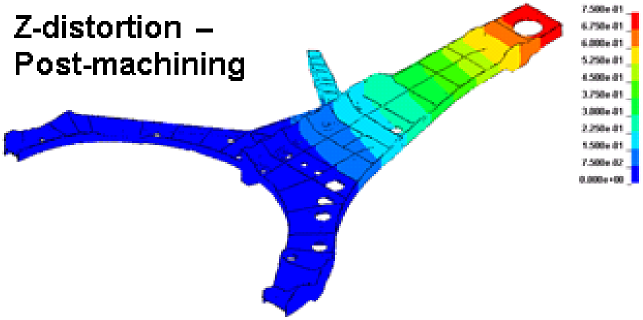
Bulk Residual Stress in Component Design:
Modeling & Measurement (ICME)

- **Alcoa Technical Center has developed forging-specific computational tools (ICME tools) for residual stress and machining distortion modeling**
- **The process model simulates five important processing steps:**
  1) ***Heat treatment: solution heat treatment temperature***
  2) ***Rapid quench: causes high tensile stresses in the core of the forging***
  3) ***Cold work stress relief: compression between dies at room temp***
  4) ***Artificial aging: relaxes bulk RS by creep***
  5) ***Machining: approximate bulk residual stress left in machined part by removal of all elements from the FE model that are not within the machined part profile***

Ref: Watton, et. al., USAF ASIP, December 2015

Bulk Residual Stress in Component Design:

Modeling & Measurement (ICME)



Z-distortion – Post-machining

Heat treat AL7085 @ elevated temperature ~895ºF

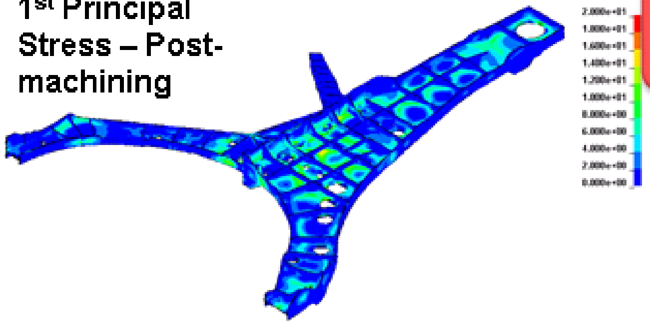
Heat treatment

Rapid quench

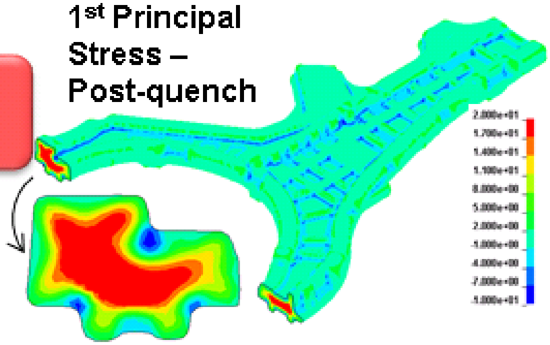
Cold work stress relief

Artificial Aging

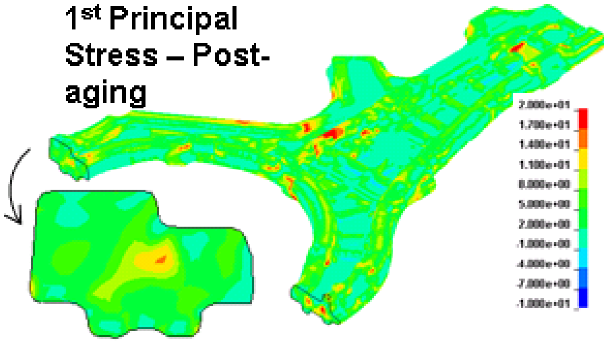
Machining



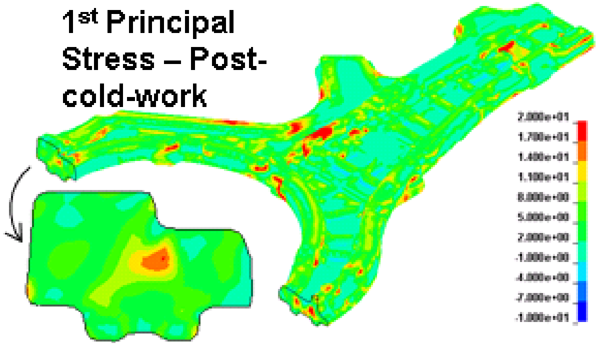
1st Principal Stress – Post-machining



1st Principal Stress – Post-quench



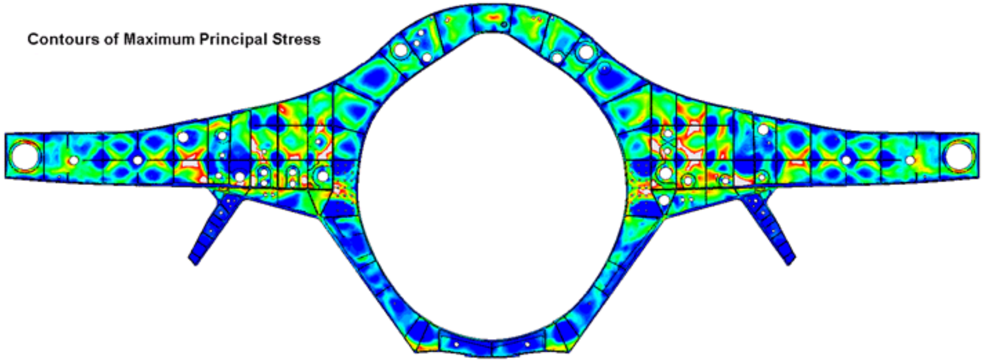
1st Principal Stress – Post-aging



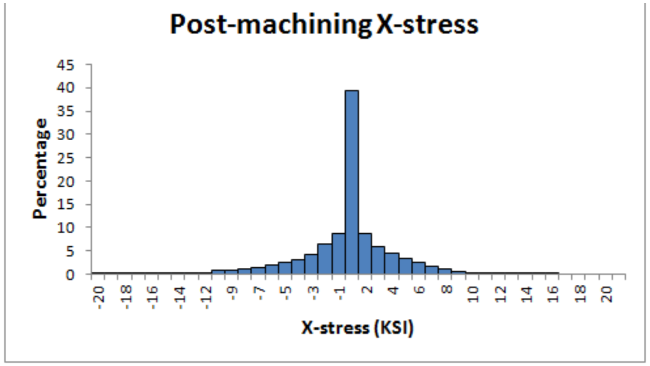
1st Principal Stress – Post-cold-work

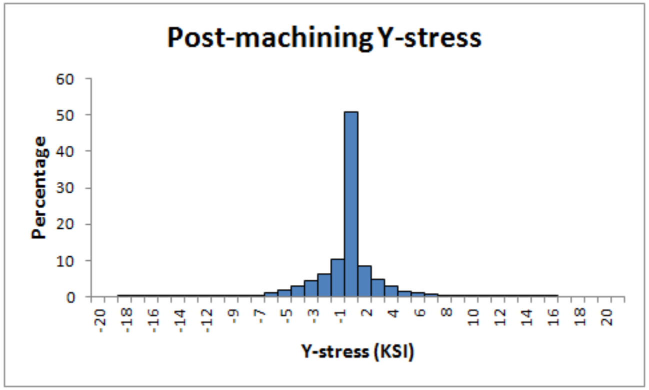
Ref: Watton, et. al., USAF ASIP, December 2015

Bulk Residual Stress in Component Design:
Modeling & Measurement (ICME)



- Alcoa has computed forging process induced residual stresses for finish machined parts in both production and test configurations
- FEA results (LSDyna) have been delivered to LM Aero – this has allowed structures team to interrogate all parts of the component deemed to be significant
  - *High residual stress*
  - *Significant spectrum loading*
  - *Combination of the two*

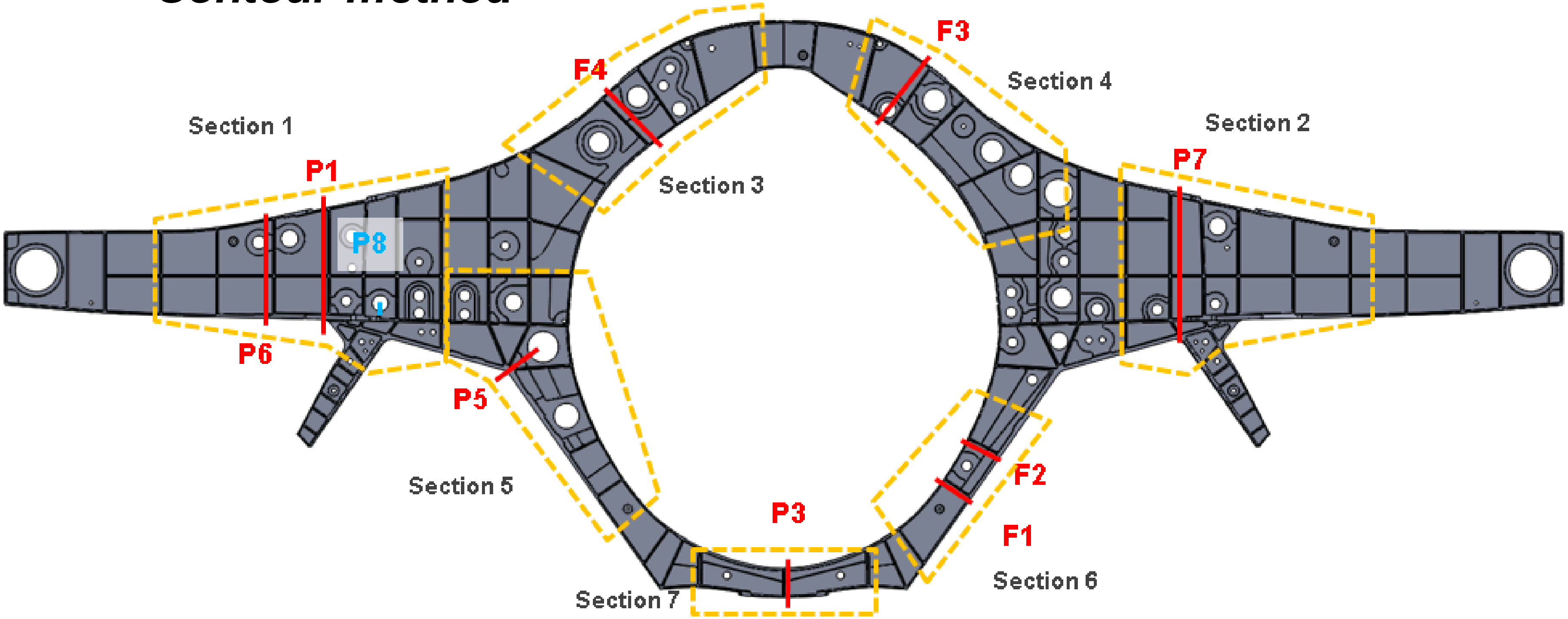




Bulk Residual Stress in Component Design:

Modeling & Measurement (ICME)

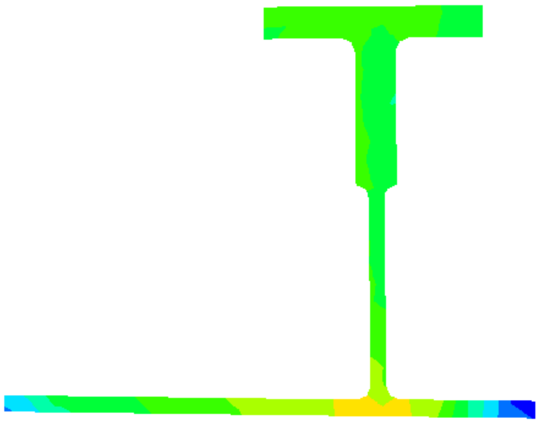
- **Hill Engineering and Alcoa have measured residual stresses at numerous locations in machined component**
  - ***Slitting method*** —
  - ***Contour method*** —



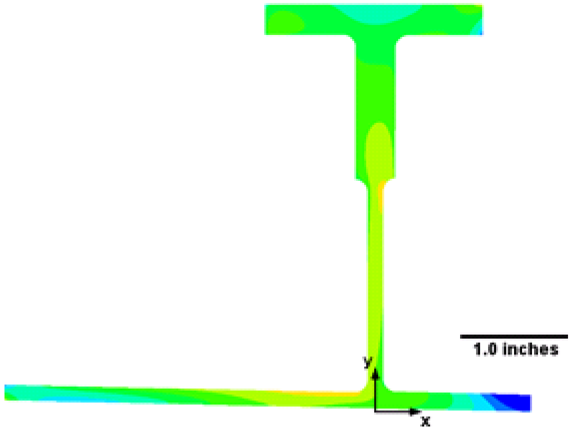
Bulk Residual Stress in Component Design:

Modeling & Measurement (ICME)

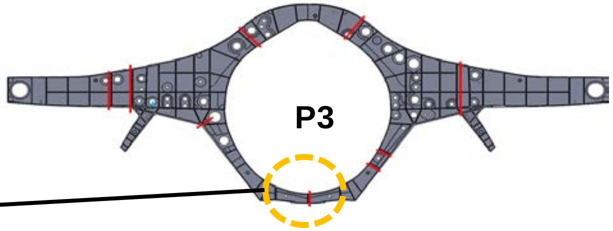
- Computed residual stresses have been compared to measured data at each measurement location
- Comparisons between 2D field data can be made in several ways
  - *Fringe plots of difference or ratio*
  - *Line plots*
- Qualitative agreement achieved
- Numerical differences will be quantified in planned, subsequent variability studies

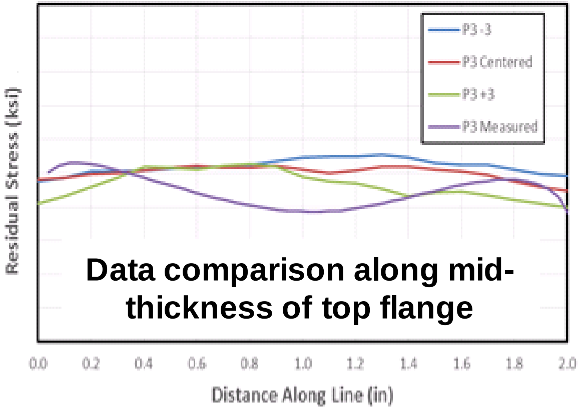


Modeled residual stress at location P3 (machined part from center)



Measured residual stress at location P3





Data comparison along mid-thickness of top flange

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Bulk Residual Stress in Component Design:

Incorporation in Design (ICSE)

- **It has been suggested recently that the ICME concept can and should be applied to structures development as well.**

- **By applying the ICME precepts to the structures domain we arrive at Integrated Computational Structures Engineering, or ICSE, which seeks to:**
  - ***develop computational tools for loads, strength and life analysis as required to support structural design, manufacture, test, and sustainment,***
  - ***develop experimental tools for characterization, validation and verification,***
  - ***integrate these tools with information technologies, manufacturing-process simulations, and component design systems.***

Bulk Residual Stress in Component Design:

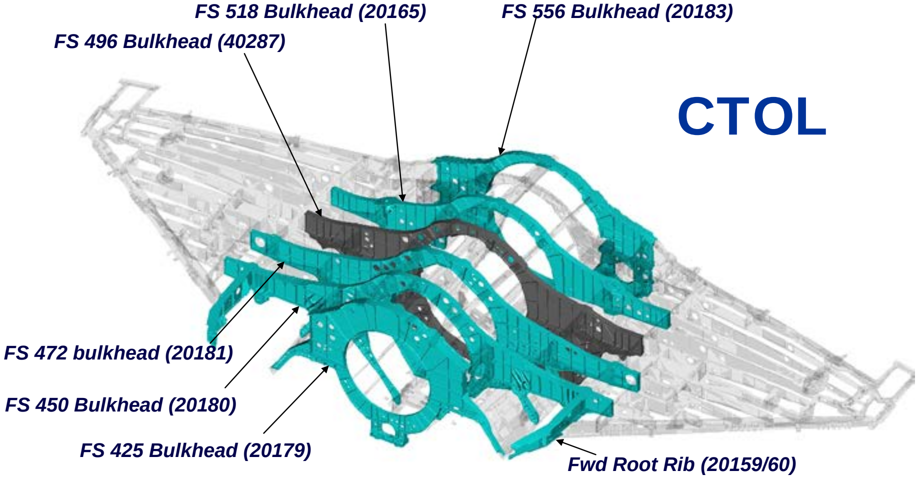
Incorporation in Design (ICSE)

- **At LM Aero, an integrated structural analysis tool set has been developed and demonstrated in which:**
  - ***A vehicle level finite element model is used for control point fatigue spectrum generation and automated bulk residual stress zone definition***
  - ***Control point specific fatigue crack initiation (FCI) and fatigue crack growth (FCG) lives and design allowable stresses are computed throughout the component:***
    - **first for the baseline design assumptions (typically no residual stress and conservative material properties),**
    - **then for the advanced design assumptions (explicit residual stress with intrinsic material properties)**
  - ***Point by point comparisons between the two approaches indicate where the baseline design may be too conservative (allowing weight reduction or avoidance) or the baseline design may be unconservative (allowing risk mitigation)***

Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

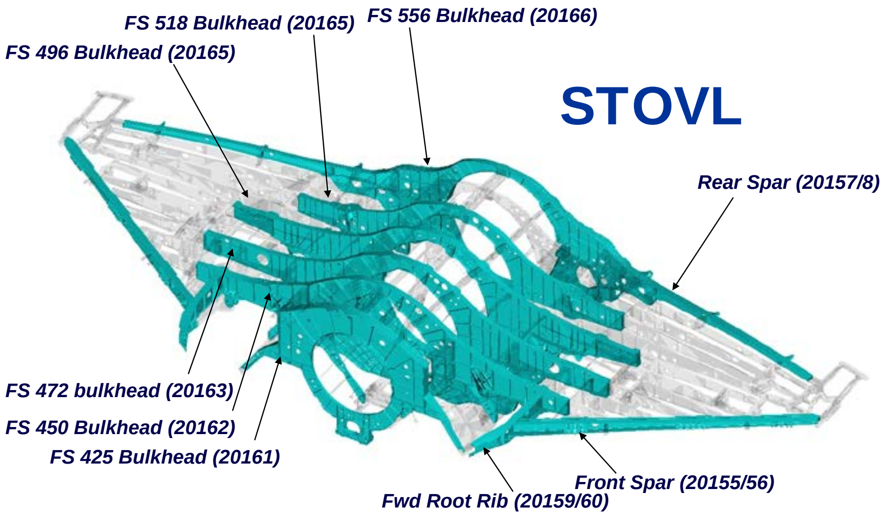
DESIGN, ANALYSIS OF SERIES OF FORGED BULKHEADS

- **4 to 6 bulkheads from each of three design variants, total of 15 bulkheads**
- **Approx 800 to 2000 control points (CPs) per bulkhead, total of 7000 CPs per variant**

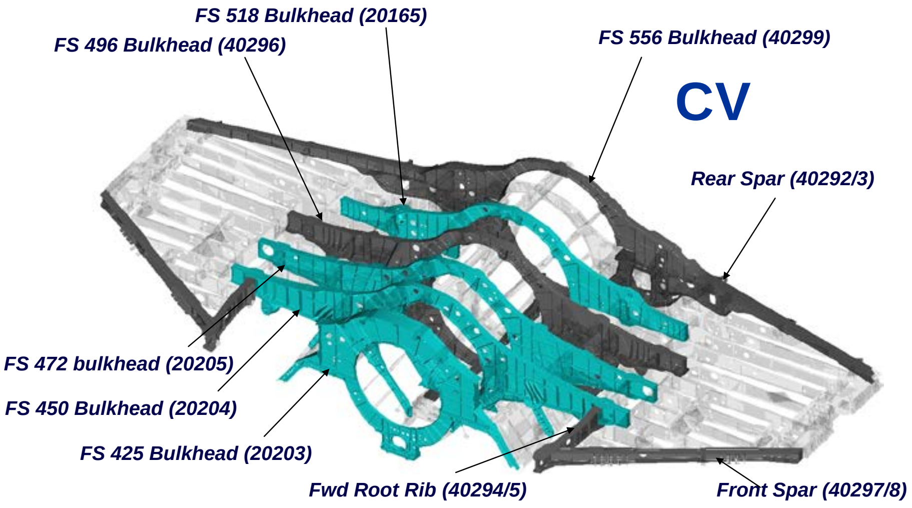


Highlighted Alcoa 7085-T7452 Forgings

Highlighted Alcoa Ti-6-4 Eli Forgings



All Highlighted Parts From Alcoa 7085-T7452 Forgings



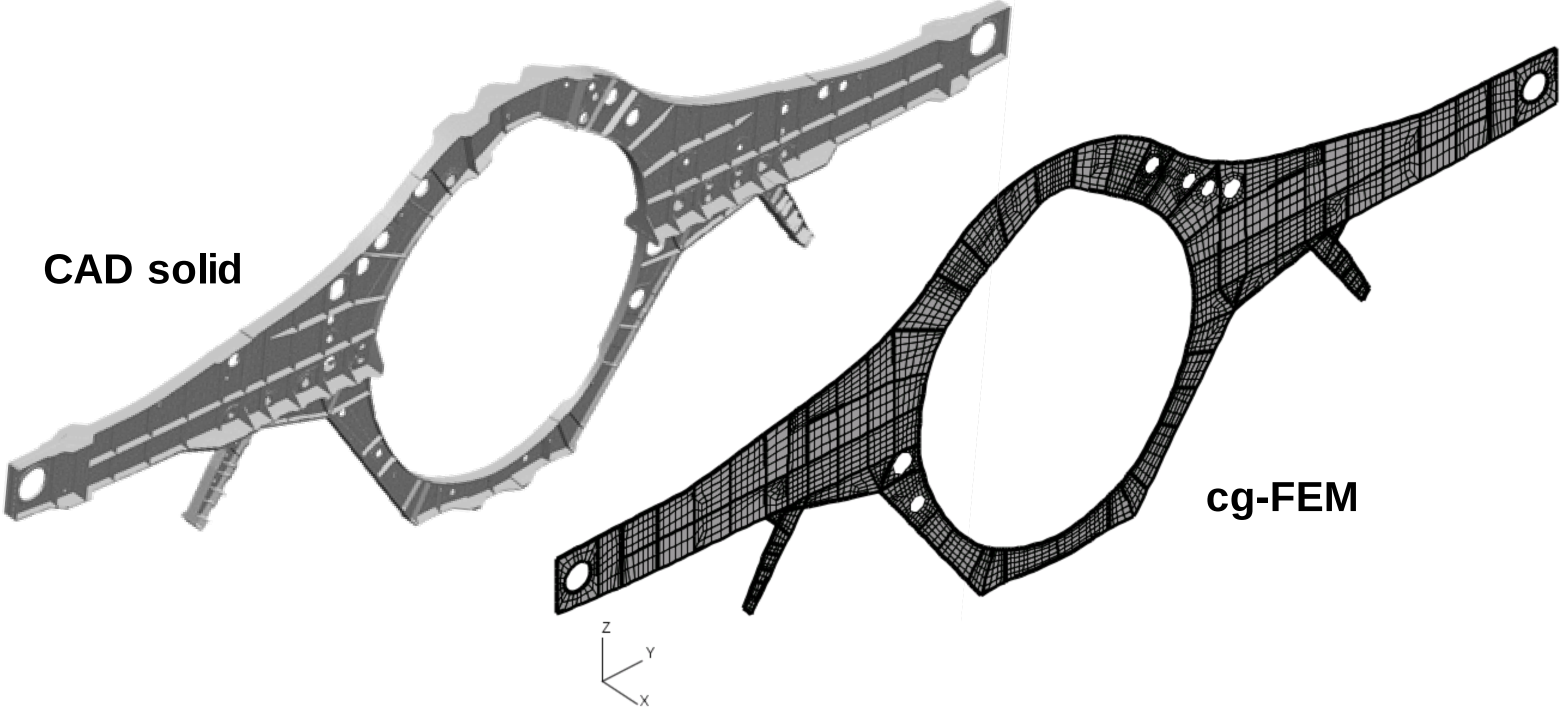
Highlighted Alcoa 7085-T7452 Forgings

Highlighted Alcoa Ti-6-4 Eli Forgings

Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

DESIGN, ANALYSIS OF SERIES OF FORGED BULKHEADS (cont'd)

- Coarse-grid-FEM is used for
  - *Residual stress zone definition*
  - *Location-specific (CP) spectrum generation*
  - *Location-, geometry-, and residual-stress-specific fatigue life and residual strength calculation*
  - *Design allowable stress and margin of safety calculation*

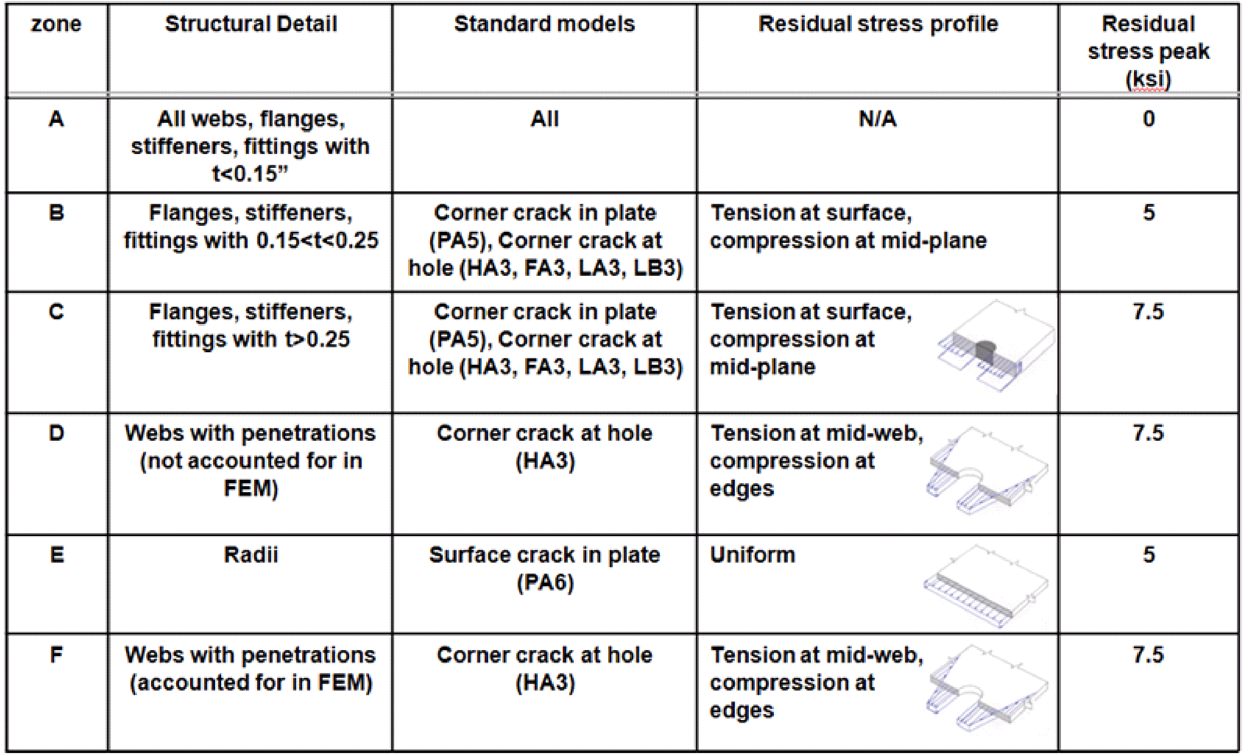


Bulk Residual Stress in Component Design:

Incorporation in Design (ICSE)

DESIGN, ANALYSIS OF SERIES OF FORGED BULKHEADS (cont'd)

- Elements in cg-FEM are automatically associated with one (or more) residual stress zone(s)
- Residual stress zone definitions:

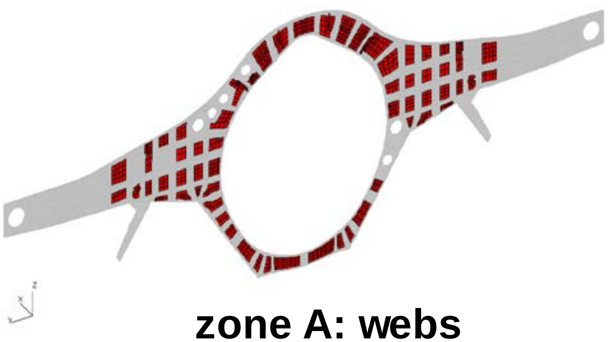


zone	Structural Detail	Standard models	Residual stress profile	Residual stress peak (ksi)
A	All webs, flanges, stiffeners, fittings with t<0.15"	All	N/A	0
B	Flanges, stiffeners, fittings with 0.15<t<0.25	Corner crack in plate (PA5), Corner crack at hole (HA3, FA3, LA3, LB3)	Tension at surface, compression at mid-plane	5
C	Flanges, stiffeners, fittings with t>0.25	Corner crack in plate (PA5), Corner crack at hole (HA3, FA3, LA3, LB3)	Tension at surface, compression at mid-plane	7.5
D	Webs with penetrations (not accounted for in FEM)	Corner crack at hole (HA3)	Tension at mid-web, compression at edges	7.5
E	Radii	Surface crack in plate (PA6)	Uniform	5
F	Webs with penetrations (accounted for in FEM)	Corner crack at hole (HA3)	Tension at mid-web, compression at edges	7.5

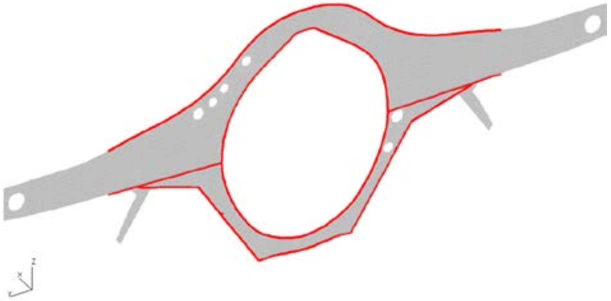
Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

DESIGN, ANALYSIS OF SERIES OF FORGED BULKHEADS (cont'd)

- Auto-zoning example, bulkhead A3

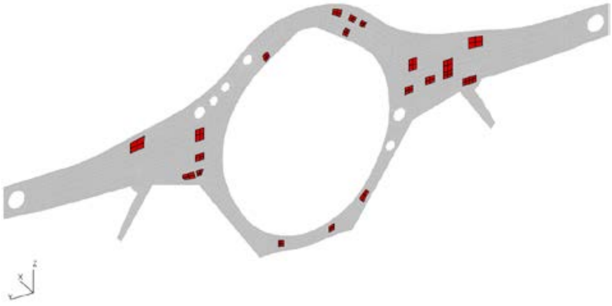


zone A: webs

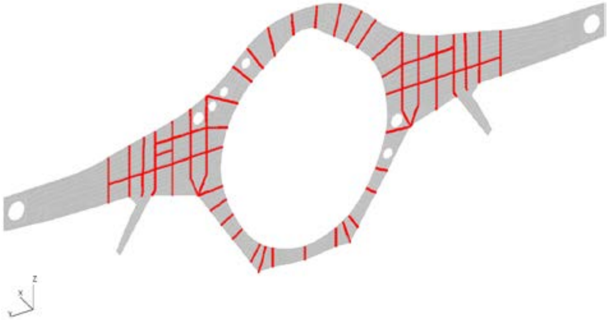


zone C: flanges with fastener holes

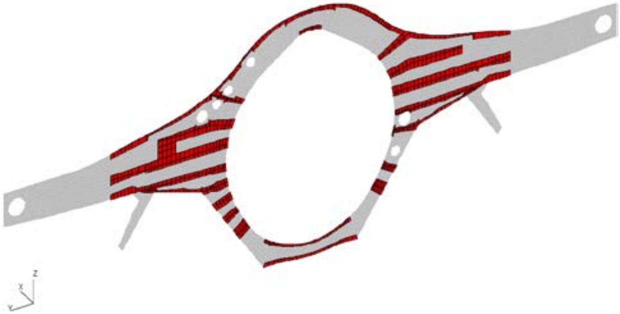
zone E: radii in webs adjacent to vertical flanges & stiffeners (mat-x)



zone D: webs with penetrations (penetrations not represented in AV-FEM)



zone C: stiffeners without fastener holes



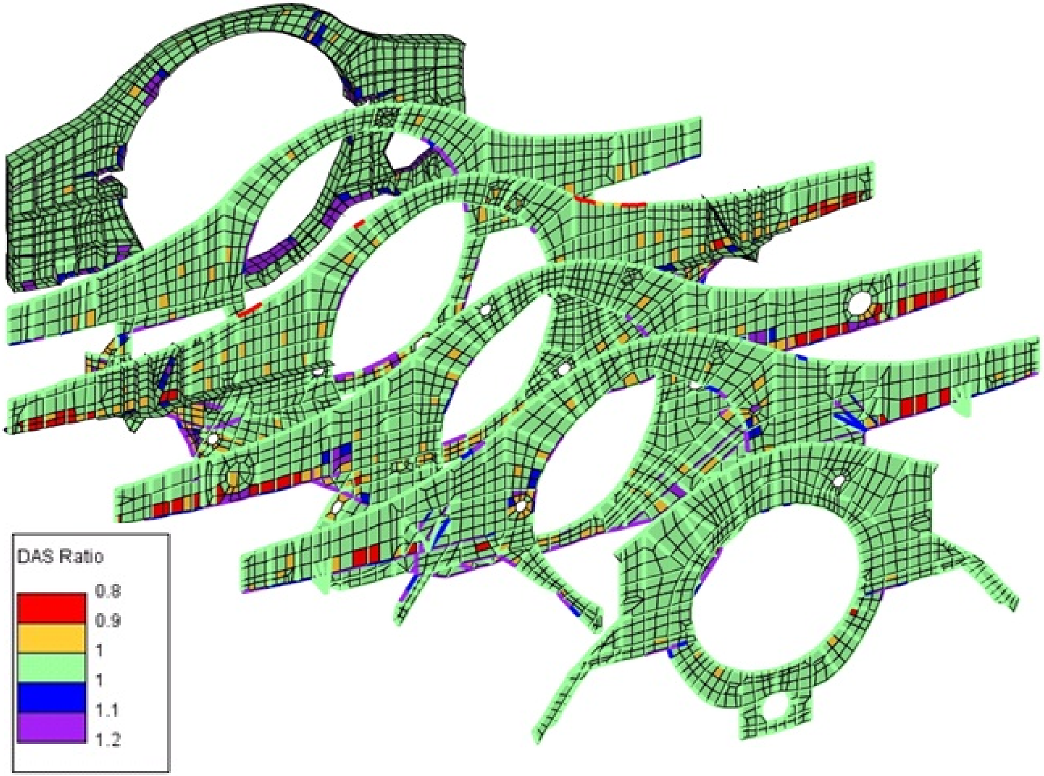
zone E: radii in webs adjacent to vertical flanges & stiffeners (mat-y)

Bulk Residual Stress in Component Design:

Incorporation in Design (ICSE)

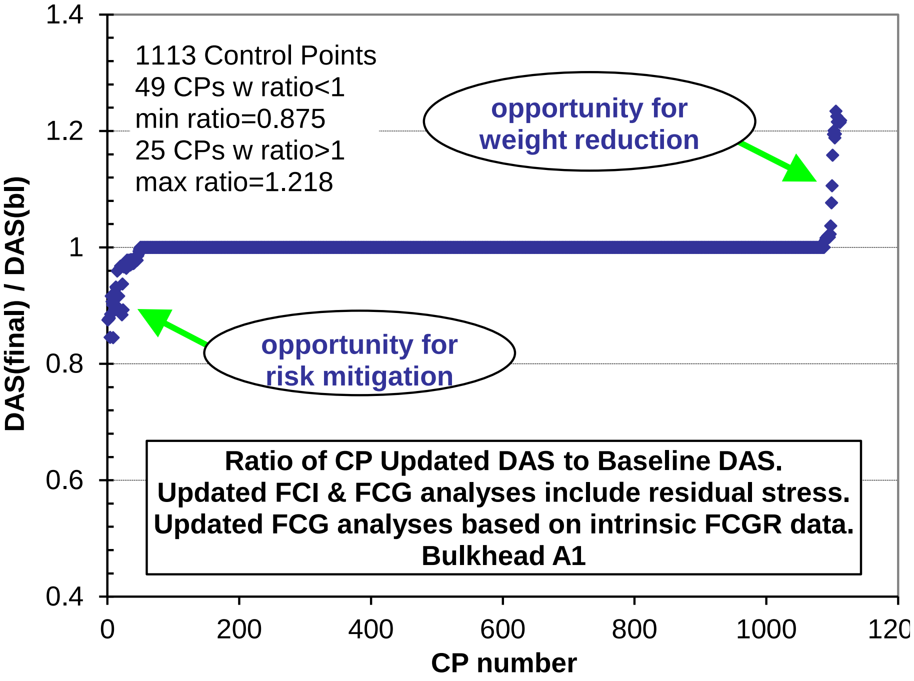
DESIGN, ANALYSIS OF SERIES OF FORGED BULKHEADS (cont'd)

- **Element specific fatigue spectrum auto generated at each CP**
- **Zone specific residual stress defined at each CP**
- **Generate design allowable stress (DAS) at each CP**
- **Baseline analysis –**
  - ***conservative material properties, implicit residual stress***
- **Updated analysis –**
  - ***intrinsic material properties, explicit residual stress where prescribed***
- **Compare updated vs baseline lives, allowables, etc. at each CP**
- **Identify locations for potential modification**

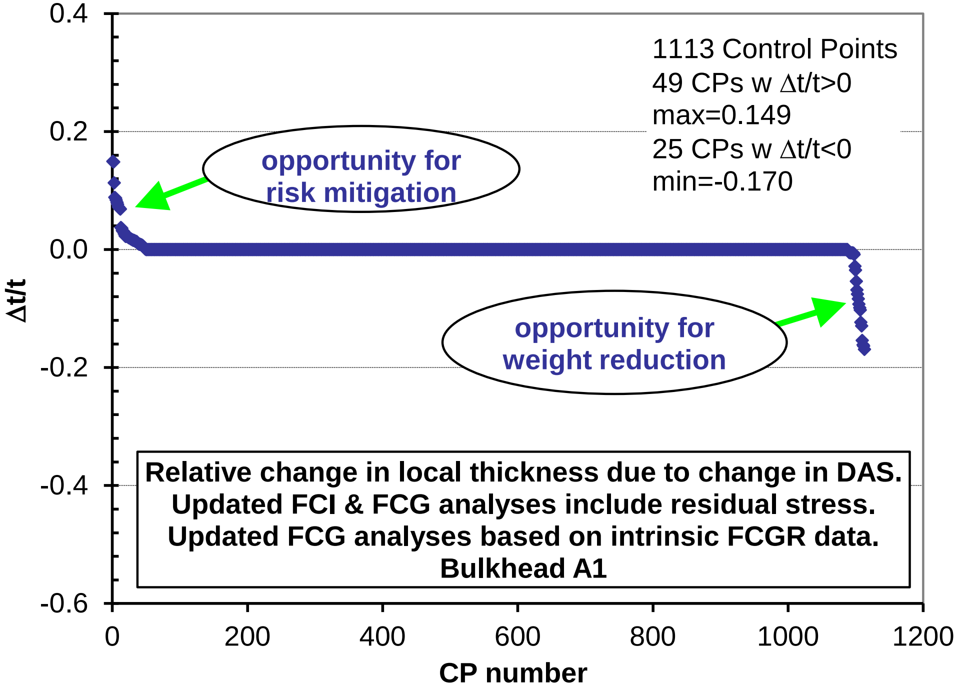


Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

- **Results for bulkhead A1:**
  - ***Ratio of DAS_{final} to DAS_{bl} shows decrease for 49 and increase for 25 out of 1113 CPs***
  - ***Indicates preliminary configuration is fairly well optimized for durability and damage tolerance with RS***



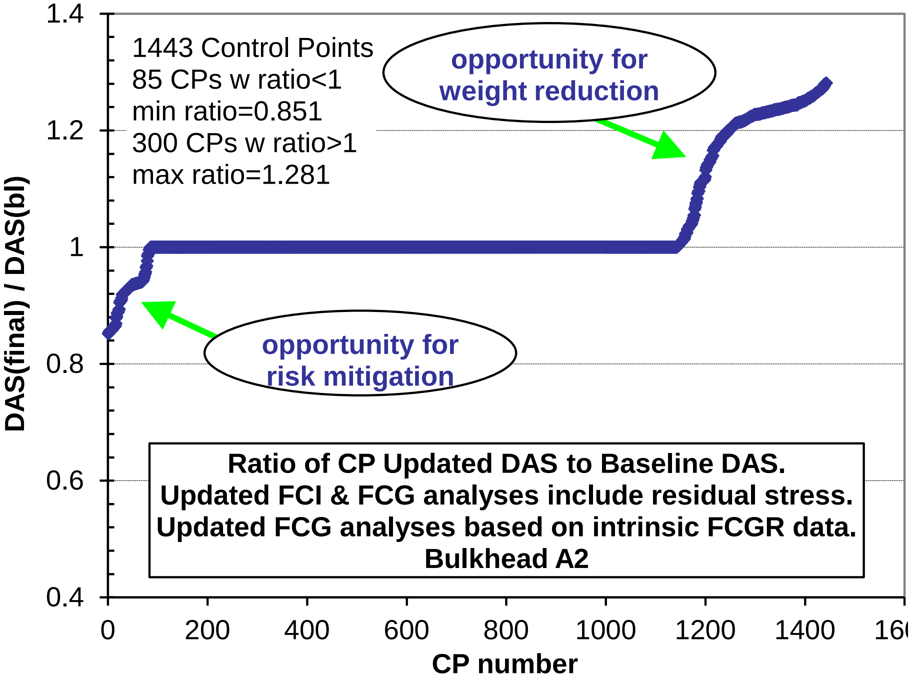
Ratio of CP Updated DAS to Baseline DAS.
Updated FCI & FCG analyses include residual stress.
Updated FCG analyses based on intrinsic FCGR data.
Bulkhead A1



Relative change in local thickness due to change in DAS.
Updated FCI & FCG analyses include residual stress.
Updated FCG analyses based on intrinsic FCGR data.
Bulkhead A1

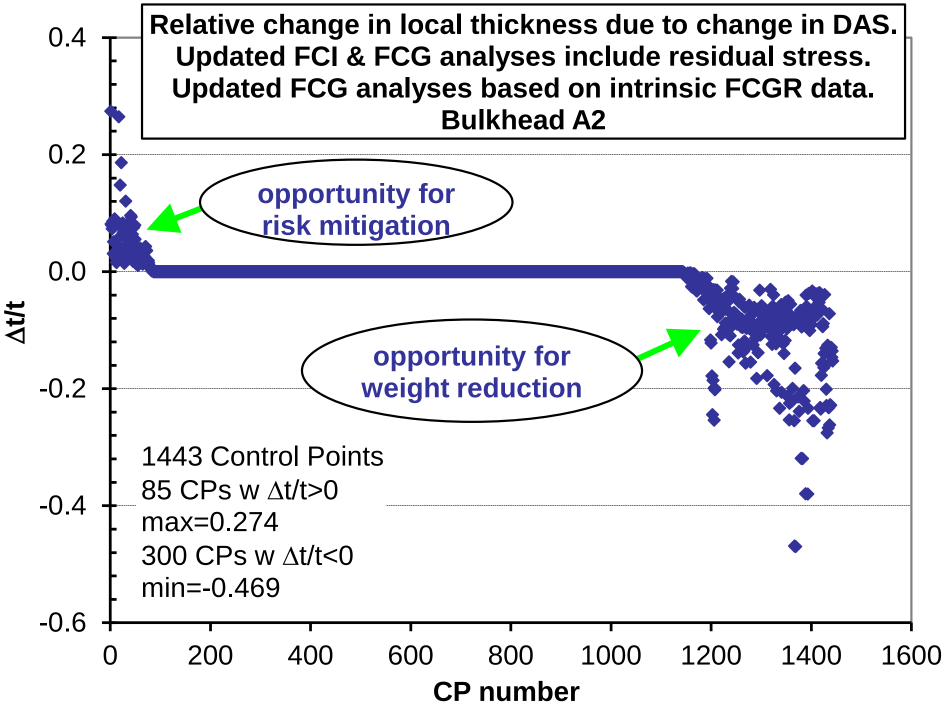
Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

- **Results for bulkhead A2:**
  - ***Ratio of DAS_{final} to DAS_{bl} shows decrease for 85 and increase for 300 out of 1443 CPs***
  - ***Indicates significant opportunity for optimization for durability and damage tolerance with RS***



1443 Control Points
85 CPs w ratio<1
min ratio=0.851
300 CPs w ratio>1
max ratio=1.281

Ratio of CP Updated DAS to Baseline DAS.
Updated FCI & FCG analyses include residual stress.
Updated FCG analyses based on intrinsic FCGR data.
Bulkhead A2

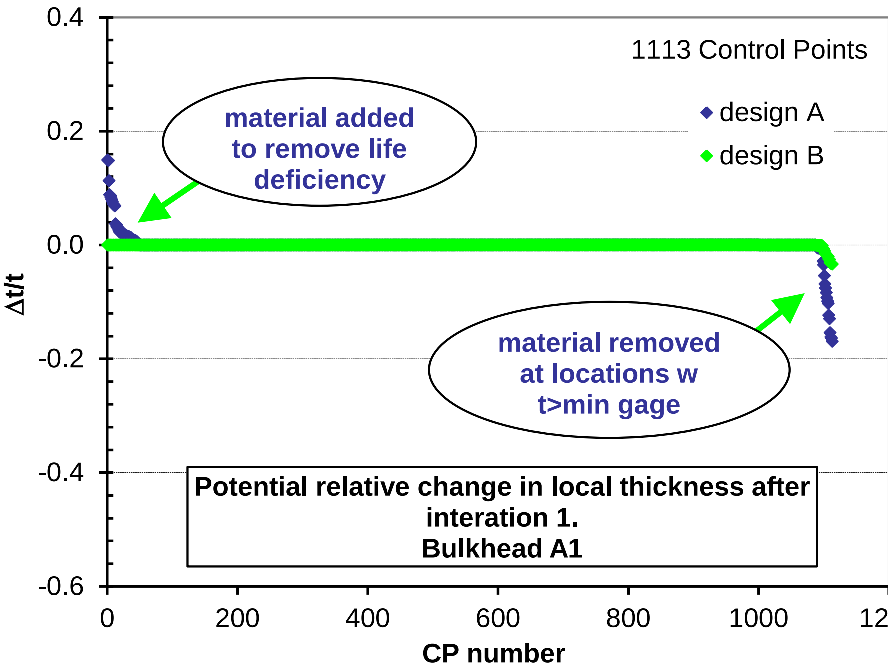


Relative change in local thickness due to change in DAS.
Updated FCI & FCG analyses include residual stress.
Updated FCG analyses based on intrinsic FCGR data.
Bulkhead A2

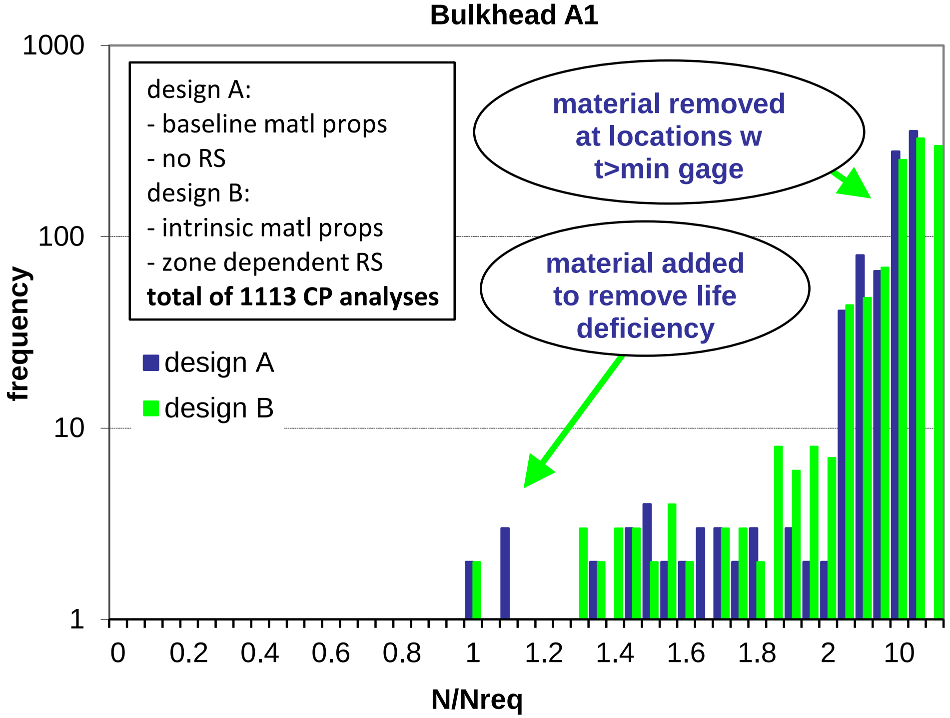
1443 Control Points
85 CPs w Δt/t>0
max=0.274
300 CPs w Δt/t<0
min=-0.469

Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

- **Design iteration for bulkhead A1:**
  - ***Thickness increase at 49 CPs, known life deficiencies removed***
  - ***Thickness decrease at 15 CPs (not all local potentials can be achieved due to other design constraints, especially min gage requirement)***
  - ***Net effect is improved DaDT performance and 3% reduction in weight***

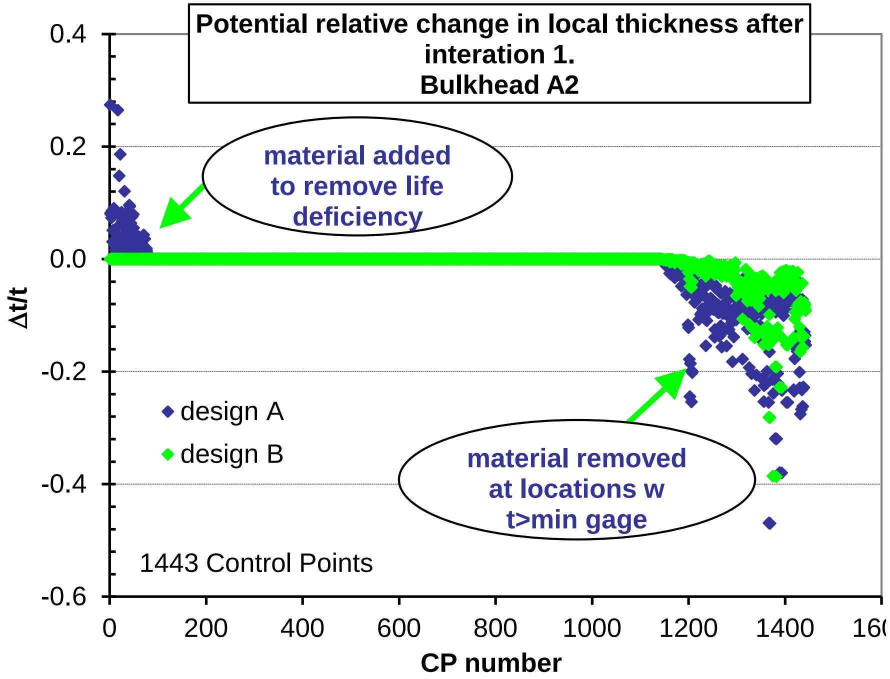


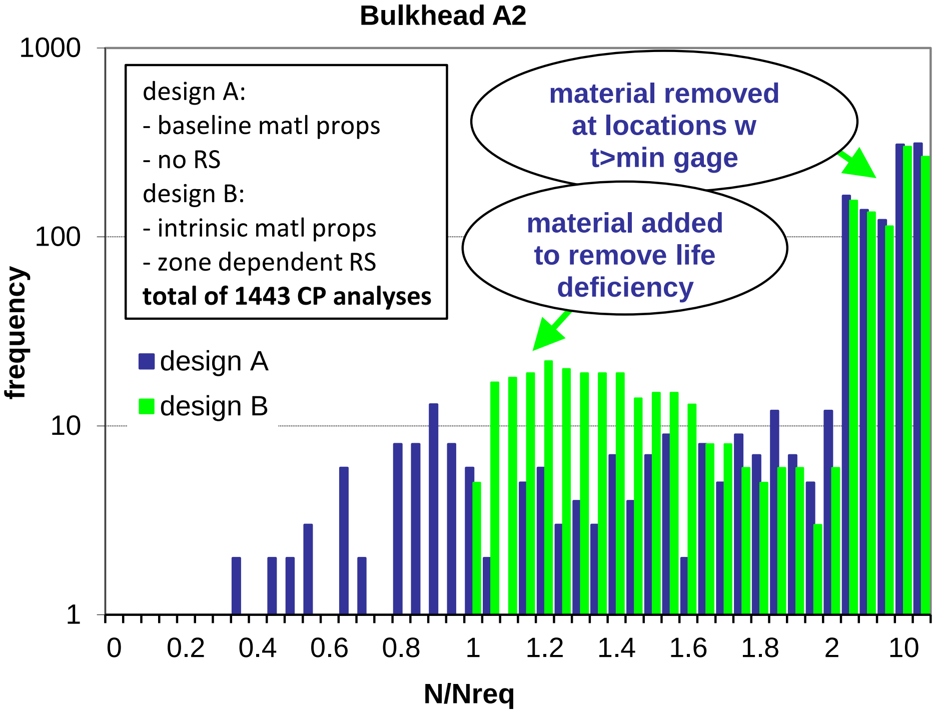
**Potential relative change in local thickness after interation 1.
Bulkhead A1**



Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

- **Design iteration for bulkhead A2:**
  - ***Thickness increase at 85 CPs, known life deficiencies removed***
  - ***Thickness decrease at 185 CPs (not all local potentials can be achieved due to other design constraints, especially min gage requirement)***
  - ***Net effect is improved DaDT performance and 5% reduction in weight***

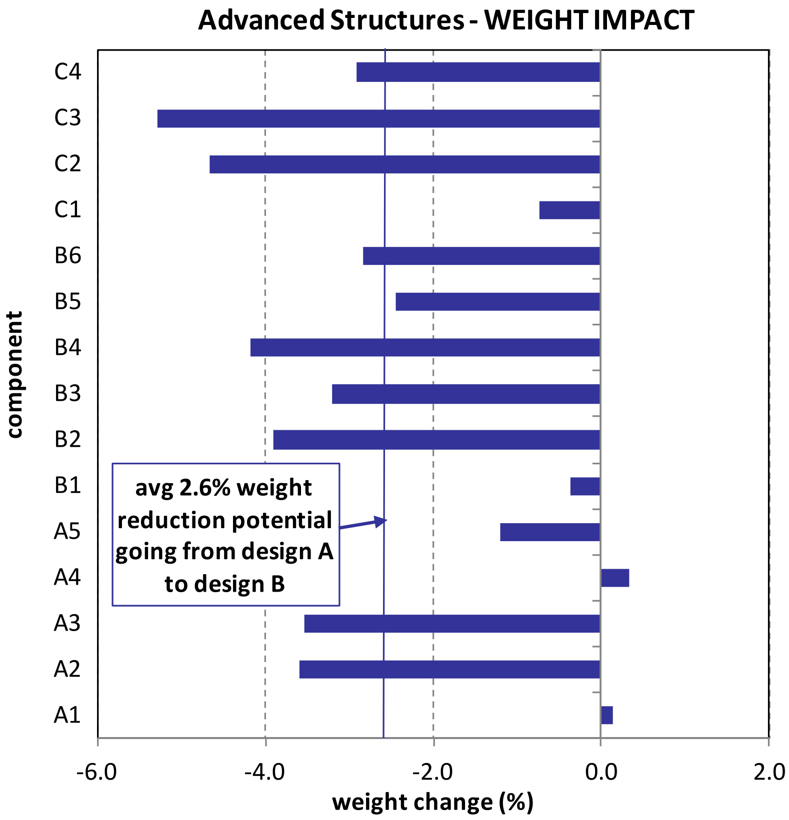


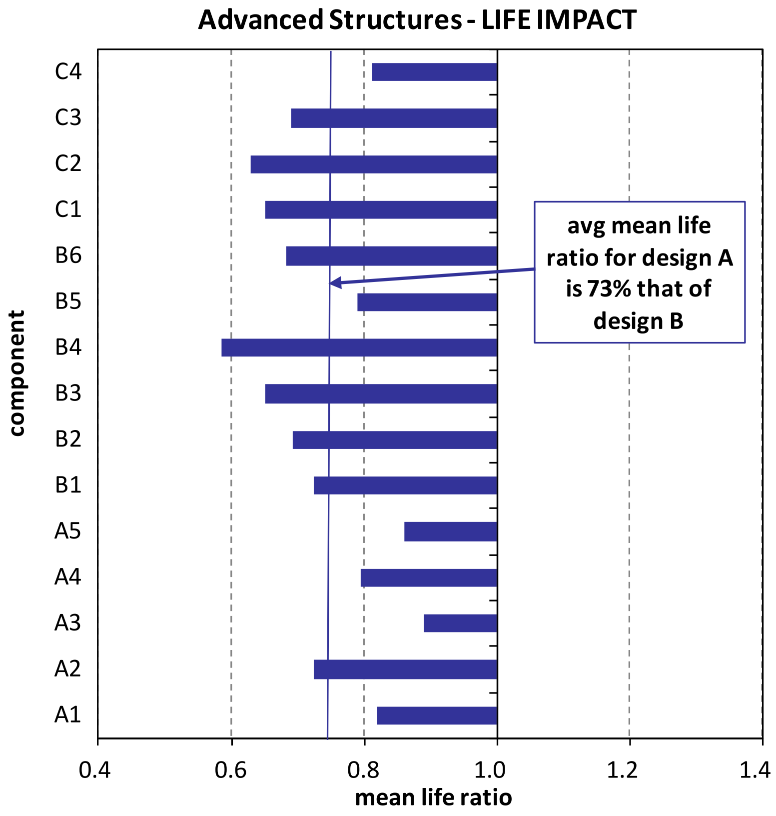


Bulk Residual Stress in Component Design:
Incorporation in Design (ICSE)

AGGREGATE DATA FOR EACH BULKHEAD –

- Estimate delta weight using element Δt/t data
- Calculate life ratios (final/baseline) on a per CP basis, then average for each bulkhead





A Case Study on the Incorporation of Bulk Residual Stress In Aircraft Component Design

- **INTRODUCTION**
- **RESIDUAL STRESS MODELING & MEASUREMENT (ICME)**
- **RESIDUAL STRESS INCORPORATION IN DESIGN (ICSE)**
- **CONCLUSIONS**

Bulk Residual Stress in Component Design:
Conclusions

- **Recent advances in the prediction and measurement of forging process induced residual stresses for large aluminum forgings are enabling an advanced design / analysis approach**
- **Approach calls for the explicit inclusion of forging process induced bulk residual stresses in the fatigue analyses used to design and certify a structure.**
- **It has been shown that the effects of tensile bulk residual stress on fatigue can be simulated with reasonable accuracy**
  - ***computed bulk residual stresses compare favorably with measured data***
  - ***accuracy of computed fatigue lives significantly improved when forging process induced residual stresses are addressed explicitly***

Bulk Residual Stress in Component Design:
Conclusions

- **It is expected that explicit inclusion of the appropriate product form bulk residual stresses during design calculations could accomplish two things:**
  - ***WEIGHT AVOIDANCE by the exclusion of residual stress effects from areas where no residual stresses exist, and***
  - ***ENHANCED STRUCTURAL INTEGRITY, resulting from proper sizing informed by the inclusion of detrimental tensile residual stresses in localized regions where they do exist.***
- **This advanced design / structural analysis approach has been adopted by the F-35 program which is currently using it for ongoing full scale durability test support analyses, as well as for current and future design / redesign / retrofit activities involving large aluminum forgings.**

Bulk Residual Stress in Component Design:
Conclusions

- **The long-term outlook for process induced bulk residual stresses is that:**

  The detrimental effects of tensile RS can be mitigated and/or managed during design by establishing and imposing appropriate requirements for their location, spatial distribution and magnitude, and for the inclusion of their effects during design structural analyses.

APPENDIX U—AMSC ROADMAP OVERVIEW

America Makes

The National Additive Manufacturing Innovation Institute

Additive Manufacturing Standards Collaborative (AMSC)
in partnership with ANSI

Rob Gorham

America Makes
Executive Director

The Partners

America Makes: nation's leading and collaborative partner in additive manufacturing and 3D printing technology research, discovery, creation, and innovation

ANSI: national coordinating body for voluntary standardization in the United States

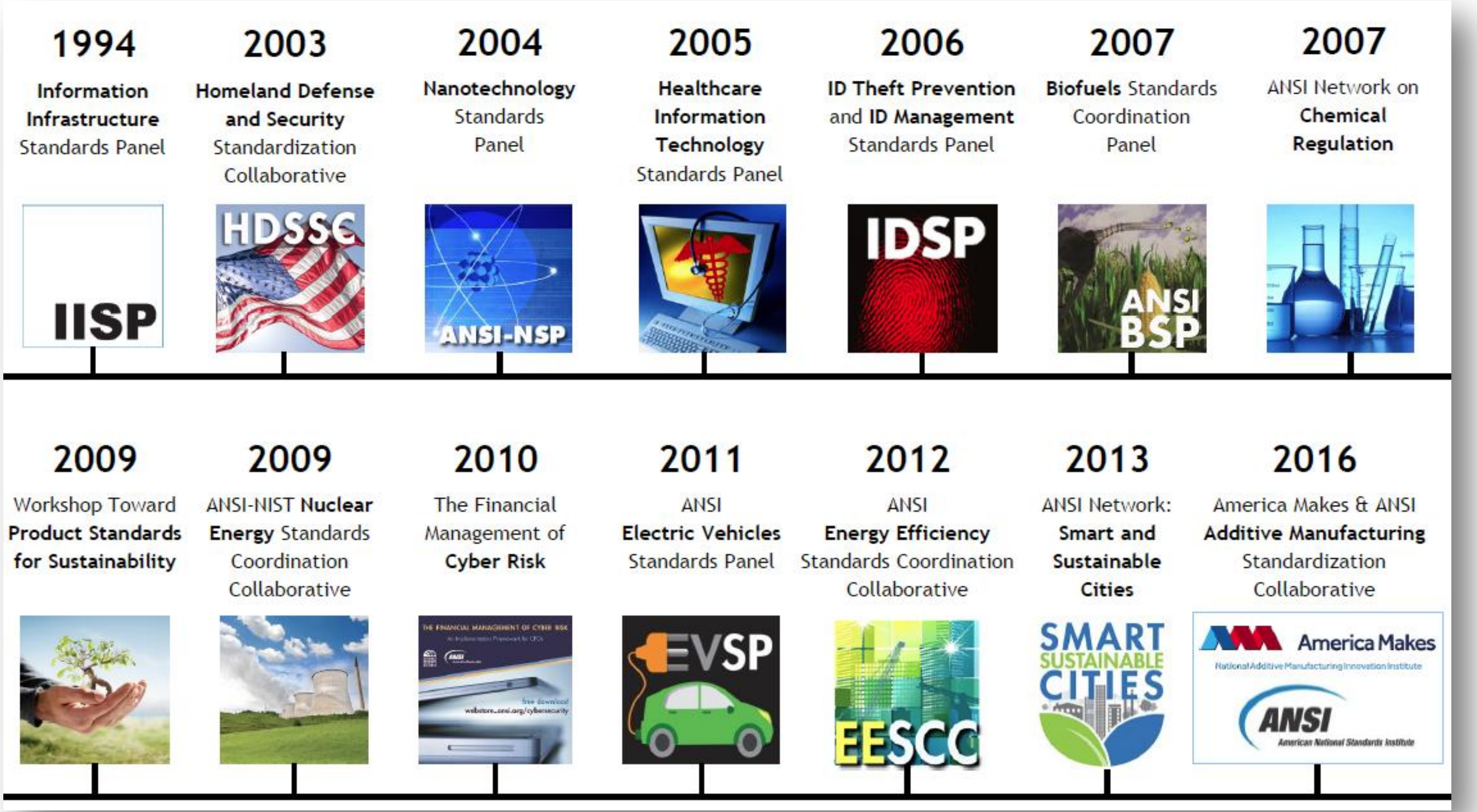
America Makes

Driven by

NCDMM
NATIONAL CENTER FOR DEFENSE MANUFACTURING AND MACHINING

ANSI
American National Standards Institute

Why ANSI?



1994
Information Infrastructure Standards Panel

2003
Homeland Defense and Security Standardization Collaborative

2004
Nanotechnology Standards Panel

2005
Healthcare Information Technology Standards Panel

2006
ID Theft Prevention and **ID Management** Standards Panel

2007
Biofuels Standards Coordination Panel

2007
ANSI Network on **Chemical Regulation**

2009
Workshop Toward **Product Standards for Sustainability**

2009
ANSI-NIST **Nuclear Energy** Standards Coordination Collaborative

2010
The Financial Management of **Cyber Risk**

2011
ANSI **Electric Vehicles** Standards Panel

2012
ANSI **Energy Efficiency** Standards Coordination Collaborative

2013
ANSI Network: **Smart and Sustainable Cities**

2016
America Makes & ANSI **Additive Manufacturing** Standardization Collaborative

The Drivers

- A number of standards developing organizations (SDOs) are engaged in standards-setting for various aspects of AM
- Coordination is needed to maintain a consistent, harmonized, and non-contradictory set of AM standards and specifications
- Before AMSC there was no process for identifying priorities and interdependencies in the development of AM standards and specs
- National Institute of Standards and Technology (NIST), U.S. Department of Defense (DoD), Federal Aviation Administration (FAA), several SDOs, were instrumental in formation of AMSC – formally launched in March 2016

AMSC Purpose and Objectives

- To coordinate and accelerate the development of industry-wide additive manufacturing standards and specifications, consistent with stakeholder needs, and thereby facilitate the growth of the additive manufacturing industry

- AMSC's charter does not include developing standards or specifications; rather, the hope is to help drive coordinated activity among SDOs

AMSC Participation

- Participation is open to additive manufacturing stakeholders that have operations in the U.S.
- Membership in America Makes and ANSI is not a prerequisite
- Members include:
  - Original Equipment Manufacturers (OEMs)
  - Feedstock Material Producers
  - User Stakeholders – Industry and Government
  - R&D Community – Academia and Government
  - SDOs
- More than 260 individuals from 150 public- and private-sector organizations involved
- Draws heavily from aerospace, defense and medical sectors

Examples of SDOs Involved

ASTM International

International Organization For Standardization

American Society of Mechanical Engineers

SAE International

Society of Automotive Engineers

American Welding Society

Institute of Electrical and Electronics Engineers

MITA MEDICAL IMAGING & TECHNOLOGY ALLIANCE A DIVISION OF NEMA

Association for the Advancement of Medical Instrumentation

IPC – Association Connecting Electronics Industries

Metal Powder Industries Federation

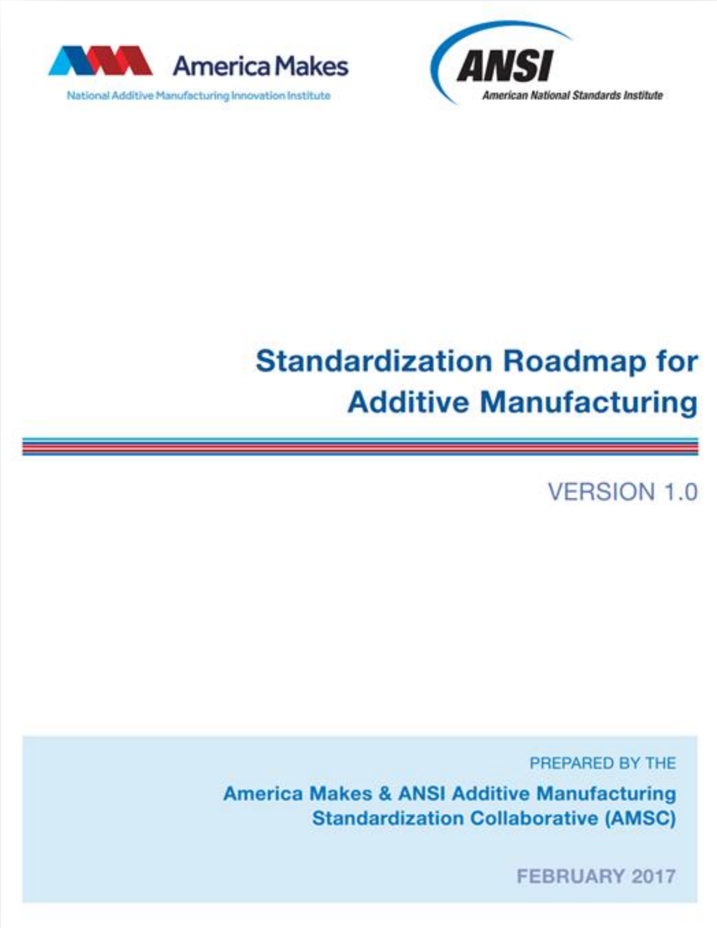
AMSC Deliverables

AMSC Standardization Roadmap for Additive Manufacturing, Version 1.0 (February 2017)

Identifies existing standards and specifications, as well as those in development, assesses gaps, and makes recommendations for priority areas where there is a perceived need for additional standardization

AMSC Standards Landscape:

A list of standards that are directly or peripherally related to the issues described in the roadmap



America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

Standardization Roadmap for Additive Manufacturing

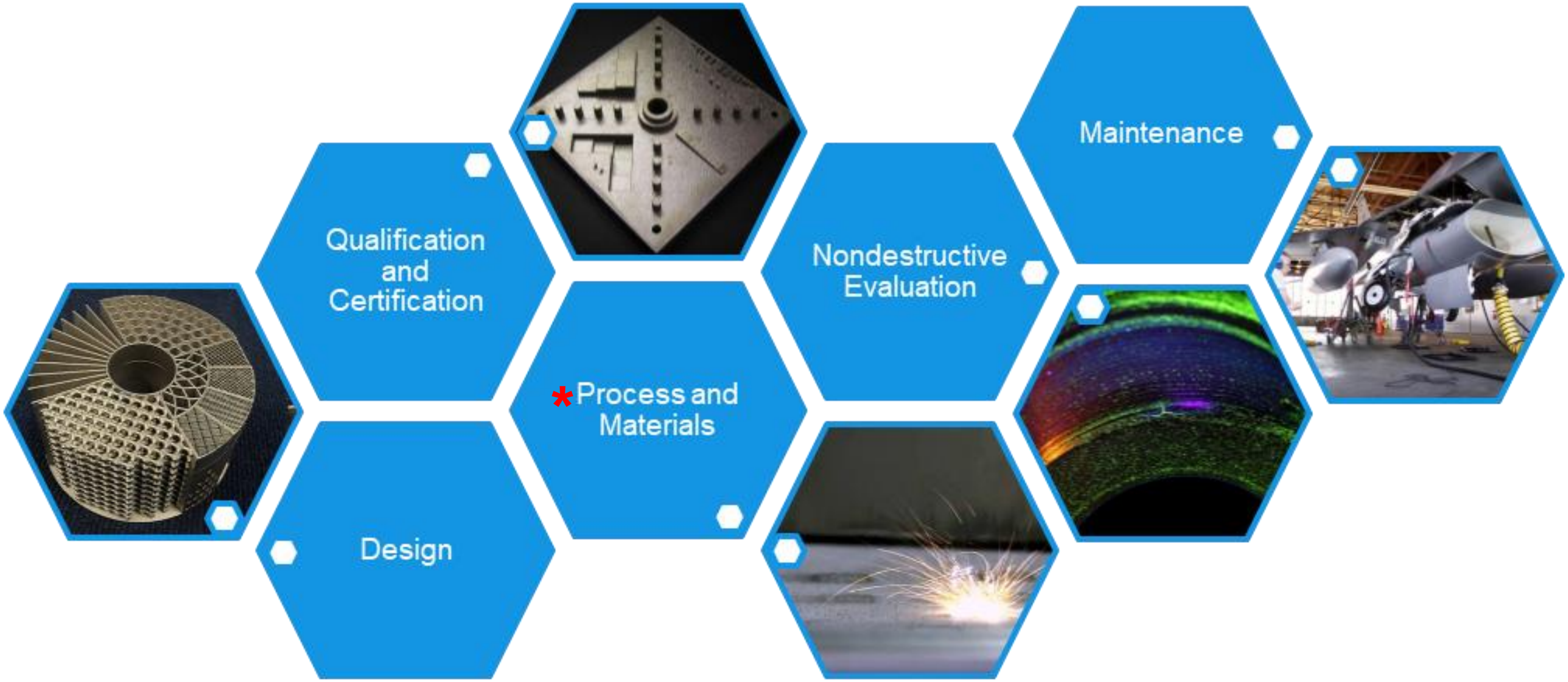
VERSION 1.0

PREPARED BY THE
America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

FEBRUARY 2017

Both available as downloads on www.ansi.org/amsc

AMSC Topical Areas



Qualification and Certification

Design

*Process and Materials

Nondestructive Evaluation

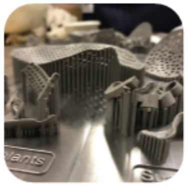
Maintenance

AMSC Topical Areas

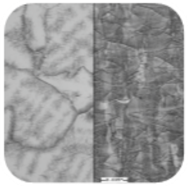
*Process and Materials

Precursor Materials

Process Control



Post-Processing



Finished Material Properties

The Approach to Topical Areas

- Describe the relevant subtopics and issues
- Identify published or in development standards and specs
- State any standards gap(s): "gap" means no published standard or specification exists that covers the particular issue in question
- Make a recommendation(s) how to fill the gap(s)
- Determine if additional R&D is needed
- Establish the priority for action (high, medium, or low)
- Identify an organization(s) that potentially can address the gap both for R&D and developing the standard

AMSC Gaps Breakdown

Section	High (0-2 years)	Medium (2-5 years)	Low (5+ years)	Total
Design	5	15	6	26
Precursor Materials	1	4	2	7
Process Control	4	8	5	17
Post-processing	0	4	2	6
Finished Material Properties	2	3	0	5
Qualification & Certification	5	6	4	15
Nondestructive Evaluation	2	3	0	5
Maintenance	0	8	0	8
Total	19	51	19	89

Note: 58 gaps require additional research and development (R&D)

Topical Area – Qualification & Certification

- Identified Guidance Documents
  - FDA Guidance on Technical Considerations for AM Devices
  - Lockheed Martin AM Supplier Quality Checklist
  - Aerospace Corp Mission Assurance Information Workshop
  - Composite Materials Handbook-17 (CMH-17) & Metallic Materials Properties Development and Standardization (MMPDS) Handbook
  - AWS D20
  - NASA Marshall Space Flight Center Draft Standard for Laser Powder Bed Fusion AM
  - ASME Y14.46
- User-Group/Industry Perspectives on Q&C
  - Perspectives from Aerospace, Defense, Medical Industries

19 High Priority Gaps

- D4: Application-Specific Design Guidelines
- D14: Designing to be Cleaned
- *D17: Contents of a TDP
- D18: New Dimensioning and ToleraRequirements
- D19: Organization Schema Requirement
- PM5: Feedstock Sampling
- PC2: Machine Calibration and Preventative Maintenance
- PC7: Recycle & Re-use of Materials
- PC9: Environmental Conditions: Effects ncing on Materials
- PC14: Environmental Health and Safety: Protection of Machine Operators

* Aerospace & Defense Gaps

19 High Priority Gaps **(contd.)**

- FMP3: Cleanliness of Medical AM Parts
- FMP4: Design Allowables (Material Properties)
- *QC1: Harmonization of AM Q&C Terminology
- *QC2: Qualification Standards by Part Categories
- *QC4: DoD Source (i.e., Vendor) Approval Process for AM Produced Parts
- QC9: Personnel Training for Image Data Set Processing
- QC10: Verification of 3D Model
- NDE1: Terminology for the Identification of AM Flaws Detectable by NDE Methods
- NDE3: Standard Guide for the Application of NDE to Objects Produced by AM Processes

* Aerospace & Defense Gaps

Gaps Relating to Q&C for Aerospace and Defense

- **D17: Contents of a Technical Data Package (High Priority)**
  - Develop a standard (or revise Mil-STD-31000) to describe all required portions of a TDP
  - ASME developing Y14.41.1 based on Appendix B of MIL-STD-31000A
  - Target for publication: early 2018

- **PC4: Machine Qualification**
  - Develop qualification standards for AM machines to pass in order to provide a level of confidence that these machines can produce parts with the required material properties
  - ASTM, SAE and AWS have relevant work in progress

Gaps Relating to Q&C for Aerospace and Defense

- **P1: Post-processing Qualification and Production Builds**
  - A standard should be issued that requires consistent post-processing to be applied for qualification and production builds.
  - Complete AWS D20.1

- **FMP1: Mechanical Properties**
  - Develop standards that identify the means to establish minimum mechanical properties (i.e., AM procedure qualification requirements) for metals made by a given AM system using a given set of AM parameters for a given AM build design, and for non-metals made by various processes

Gaps Relating to Q&C for Aerospace and Defense

- **QC1: Terminology (High Priority)**
  - Update quality management and other standards to harmonize definitions of qualification terms to encourage consistency across industry sectors
  - SDOs working to align definitions where possible

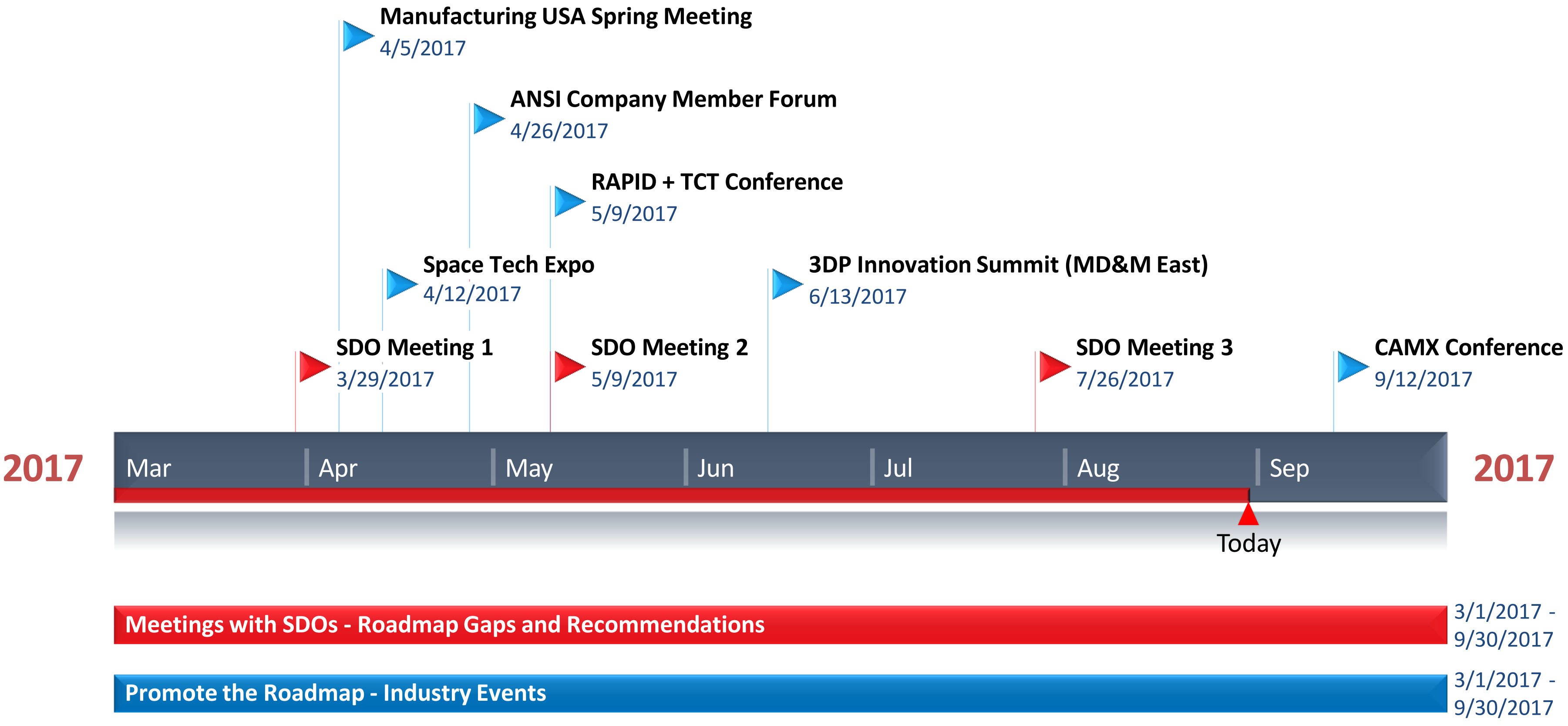
- **QC2: Qualification Standards by Part Categories (High Priority)**
  - Need a standard classification of parts, minimum qualification requirements, technology readiness level (TRL), and manufacturing readiness level (MRL) metrics for each part category that takes into consideration intended usage/environment
  - Could be a series of documents from each individual agency

Gaps Relating to Q&C for Aerospace and Defense

- **QC3: Harmonizing Q&C Terminology for Process Parameters**
  - Develop standardized terminology for process parameters for use across all AM equipment
  - ASTM, SAE and AWS have relevant work in progress

- **QC4: DoD Source (i.e. Vendor) Approval Process for AM Produced Parts (High Priority)**
  - Develop standards to assess required checks for levels of criticality and safety as part of the source approval process, starting with most mature technologies such as laser powder bed
  - 15 newly-proposed ASTM standards will help companies comply with new checklist for accreditation by National Aerospace and Defense Contractors Accreditation Program (NADCAP)

Activity Since Roadmap's Publication



Manufacturing USA Spring Meeting
4/5/2017

ANSI Company Member Forum
4/26/2017

RAPID + TCT Conference
5/9/2017

Space Tech Expo
4/12/2017

3DP Innovation Summit (MD&M East)
6/13/2017

SDO Meeting 1
3/29/2017

SDO Meeting 2
5/9/2017

SDO Meeting 3
7/26/2017

CAMX Conference
9/12/2017

Meetings with SDOs - Roadmap Gaps and Recommendations 3/1/2017 - 9/30/2017

Promote the Roadmap - Industry Events 3/1/2017 - 9/30/2017

Phase 2 Goals

- Discuss needs of other industries (e.g., automotive/heavy equipment, energy, industrial & commercial machinery)
- Expand discussion of other materials (e.g., polymers)
- Identify potentially overlooked gaps
- Provide an update on gaps already identified
- Phase 2 Kick-off meeting scheduled for Sep 7, 2017 at Philadelphia Navy Yard, Registration at: https://eseries.ansi.org/source/Events/Event.cfm?EVENT=AMSC_0917
- Target Date for Publication of Roadmap Version 2.0 end of June 2018

When America Makes America Works

America Makes

AmericaMakes.us @AmericaMakes /AmericaMakes

APPENDIX V—RECENT PROGRESS ON STANDARDIZATION OF ADDITIVE MANUFACTURING TECHNOLOGIES

ASTM INTERNATIONAL
Helping our world work better

Recent Progress on Standardization of Additive Manufacturing Technologies

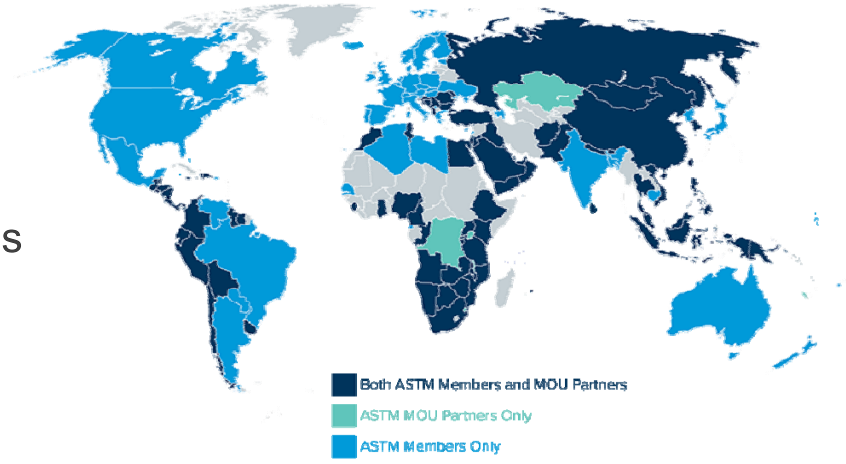
The 3rd Joint FAA – Air Force Workshop
on Qualification / Certification of AM Parts- Dayton,
OH, August 2017

Mohsen Seifi, PhD
Director, AM Programs, ASTM
Staff Research Associate, CWRU

About ASTM?

A Proven and Practical System

- Established in 1898
- 149 Committees & 12,500+ Standards
- 33,000 members
  - 8,000+ International Members from 135 countries
  - 5,100 ASTM standards used in 75 countries
- Accreditation:
  - American National Standards Institute (ANSI)
  - Standard Council of Canada (SCC)
- Process complies with WTO principles: Annex 4 of WTO/TBT Agreement



- Development and delivery of information made uncomplicated
- A common sense approach: **industry driven**
- Market relevant globally
- No project costs

149

main committees plus 2,017 subcommittees

Over a Century of Openness

How We Work

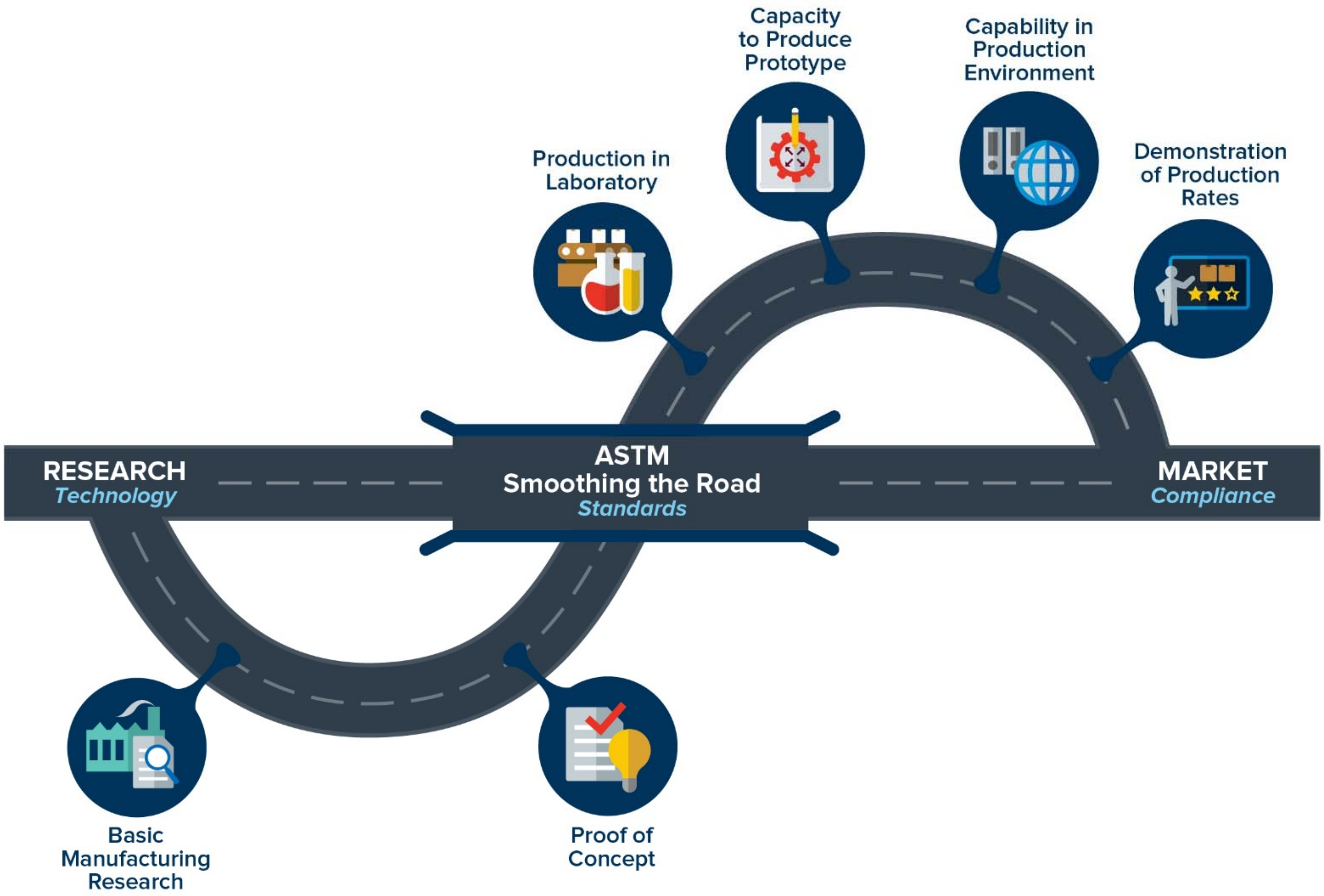
- **Provide Infrastructure and Tools**
  - Templates, Online balloting, Online collaboration areas, meetings support, managers, administrative support, editors, promotional support
- **Industry comes Together**
  - Exchange expertise and knowledge
  - Participating in a transparent process – open to anyone, anywhere

- Staff does not write standards, remain neutral
- Activities are Industry-driven

149

main committees
plus 2,020
subcommittees

ASTM Standards
Building the Bridge from Innovation to Market



Capacity to Produce Prototype

Capability in Production Environment

Production in Laboratory

Demonstration of Production Rates

RESEARCH
Technology

ASTM
Smoothing the Road
Standards

MARKET
Compliance

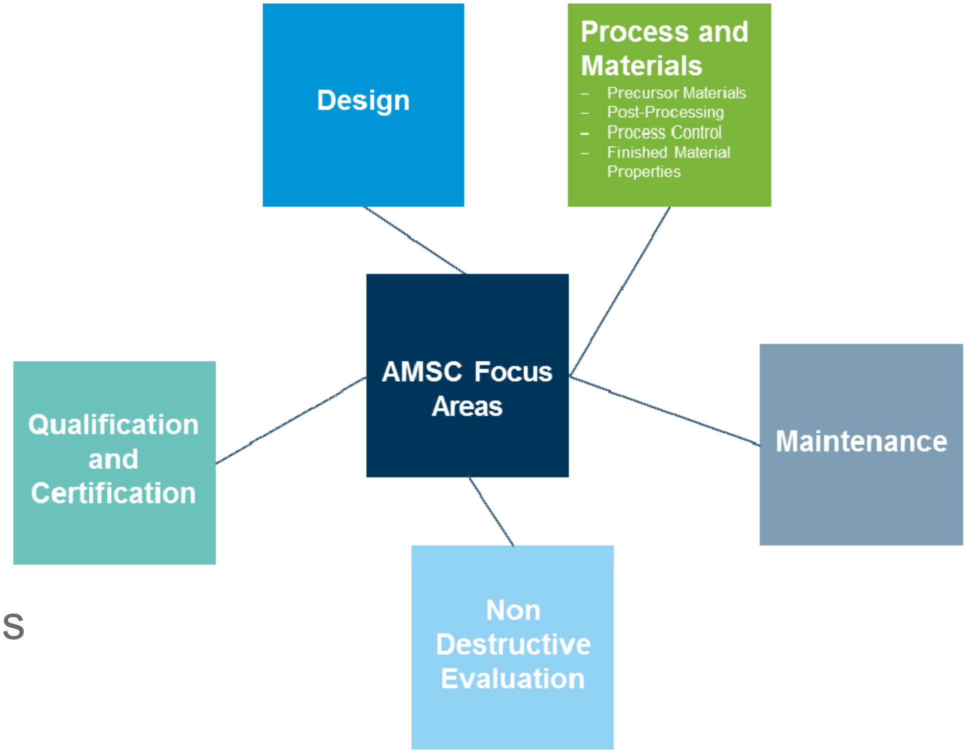
Basic Manufacturing Research

Proof of Concept

ASMC Roadmap Focus Areas

Of that total 89 gaps:

- 19 gaps/recommendations have been identified as high priority,
- 51 as medium priority,
- 19 as low priority.
- ASTM is positioned to address 82 gaps in conjunction with ISO.



Design

Process and Materials

- Precursor Materials
- Post-Processing
- Process Control
- Finished Material Properties

AMSC Focus Areas

Qualification and Certification

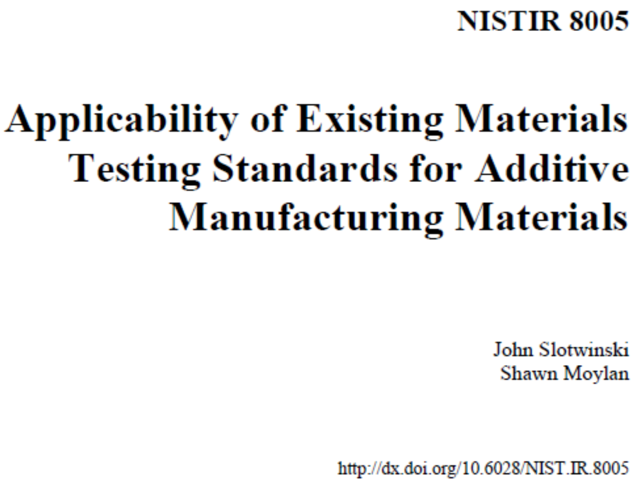
Maintenance

Non Destructive Evaluation

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

Two NIST reports investigated ASTM standards relevance to AM (ASTM E28, E08, B09, D20, ...)



NISTIR 8005

Applicability of Existing Materials Testing Standards for Additive Manufacturing Materials

John Slotwinski
Shawn Moylan

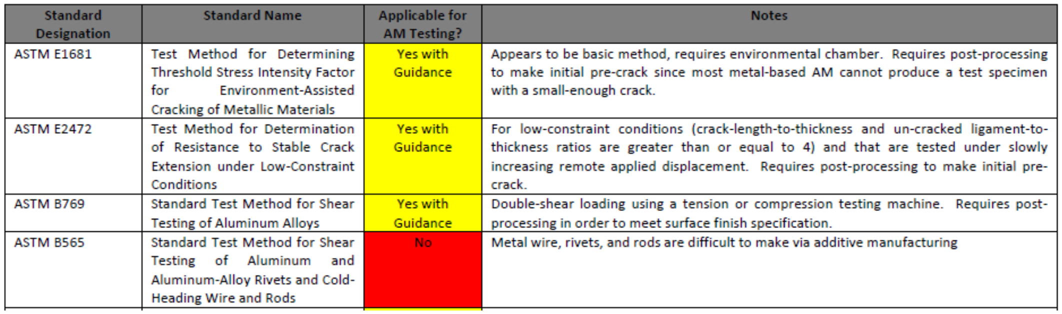
http://dx.doi.org/10.6028/NIST.IR.8005

National Institute of Standards and Technology
U.S. Department of Commerce

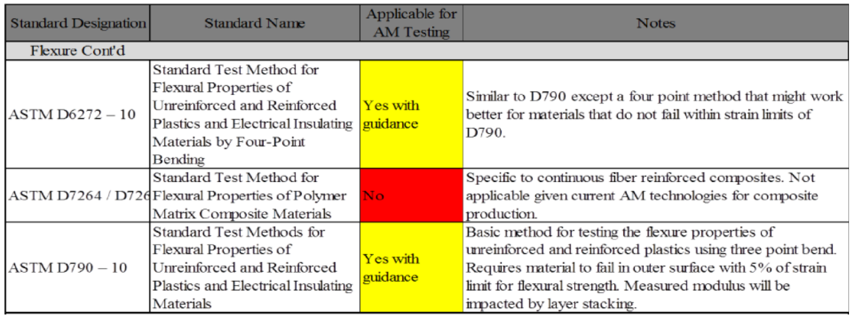
Materials Testing Standards for Additive Manufacturing of Polymer Materials:

State of the Art and Standards Applicability

Aaron M. Forster



Standard Designation	Standard Name	Applicable for AM Testing?	Notes
ASTM E1681	Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials	Yes with Guidance	Appears to be basic method, requires environmental chamber. Requires post-processing to make initial pre-crack since most metal-based AM cannot produce a test specimen with a small-enough crack.
ASTM E2472	Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions	Yes with Guidance	For low-constraint conditions (crack-length-to-thickness and un-cracked ligament-to-thickness ratios are greater than or equal to 4) and that are tested under slowly increasing remote applied displacement. Requires post-processing to make initial pre-crack.
ASTM B769	Standard Test Method for Shear Testing of Aluminum Alloys	Yes with Guidance	Double-shear loading using a tension or compression testing machine. Requires post-processing in order to meet surface finish specification.
ASTM B565	Standard Test Method for Shear Testing of Aluminum and Aluminum-Alloy Rivets and Cold-Heading Wire and Rods	No	Metal wire, rivets, and rods are difficult to make via additive manufacturing



Standard Designation	Standard Name	Applicable for AM Testing	Notes
Flexure Cont'd			
ASTM D6272 – 10	Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending	Yes with guidance	Similar to D790 except a four point method that might work better for materials that do not fail within strain limits of D790.
ASTM D7264 / D726	Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials	No	Specific to continuous fiber reinforced composites. Not applicable given current AM technologies for composite production.
ASTM D790 – 10	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	Yes with guidance	Basic method for testing the flexure properties of unreinforced and reinforced plastics using three point bend. Requires material to fail in outer surface with 5% of strain limit for flexural strength. Measured modulus will be impacted by layer stacking.

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Additive Manufacturing Sector:

Technical Committees relevant to AM

F42
Additive Manufacturing

Feedstock

Test Methods

Applications

A01
Steels

B09
Powders

E07
NDT

E08 — Fracture & Fatigue

E28 — Mechanical Testing

F07, F37, F38, F44, F47 — Aerospace

F04, E55 — Medical Devices, Pharmaceuticals

D20
Plastics

D30
Composites

E37 — Thermal Measurement

E57
3D Imaging

G01
Corrosion

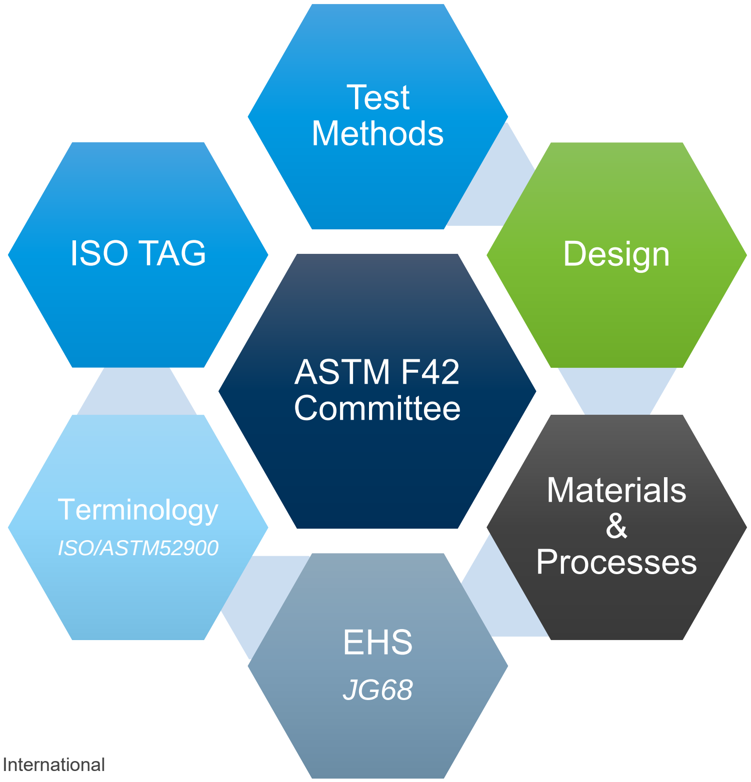
F25
Ship and Marine

ASTM F42 Fact Sheet 2017

Quick facts

Formed: 2009
Current Membership: 550+ members (Fastest growing TC across ASTM)
Standards: 15 approved, 30 in development
Meet twice a year, next meeting: Stockholm, Sept 18-21, 2017

Subcommittees and Focus Areas



ASTM F42 Committee

Test Methods

Design

Materials & Processes

EHS
JG68

Terminology
ISO/ASTM52900

ISO TAG

Global Representation:

(26 Countries Represented!)

Belgium
Canada
China
France
Germany
India
Italy
Japan
Singapore
Mexico
Netherlands
Norway
Pakistan
Singapore
Slovakia
South Africa
Spain
Sweden
Switzerland
Taiwan
United Kingdom
United States

PARTNERSHIPS:

- *MOU with SME*
- *Partnership in Standards Development (PSDO) & US TAG:* ISO TC 261
- *America Makes Membership + MOU* - Integration of R&D to standards
- *Partnership with 3MF* – File format standardization

Aerospace/Defense oriented stakeholders at F42 (subset): Industries/government

LOCKHEED MARTIN

AFRL

Federal Aviation Administration

Pratt & Whitney
A United Technologies Company

NAVAIR

Rolls-Royce

BOEING

AIRBUS

GE Aviation

United Technologies

TIMET

NORTHROP GRUMMAN

Gulfstream
A GENERAL DYNAMICS COMPANY

[dstl]

Honeywell

Parker

MITRE

LAI INTERNATIONAL

ARCONIC
Innovation, engineered.

IHI

AEROSPACE
Assuring Space Mission Success

Barnes
AEROSPACE
A business of BARNES GROUP INC

ATI

GKN AEROSPACE

NASA

WOODWARD

AEROJET ROCKETDYNE

INCODEMA 3D
ADDING TO THE FUTURE

CTC

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

NIST

MOOG

CalRAM
A Division of Precision Holdings

PennState
Applied Research Laboratory

Standardization Framework:
ASTM / ISO TC261 Develops AM Standards

AM Process and Equipment Standards
(e.g., Powder Bed Fusion, Material Extrusion, etc.)

General Standards
(e.g., AM terminology, test methods, safety, etc.)

Application Specific Standards
(Aerospace, Automotive, Medical, etc.)

Ultimate Objective:

Enabling Certification and Environmental, Health and Safety Compliance

Feedstock Material Standards
(e.g., metal powders, polymer filaments, etc.)

Finished AM Part Standards
(Post-processing methods, NDE, etc.)

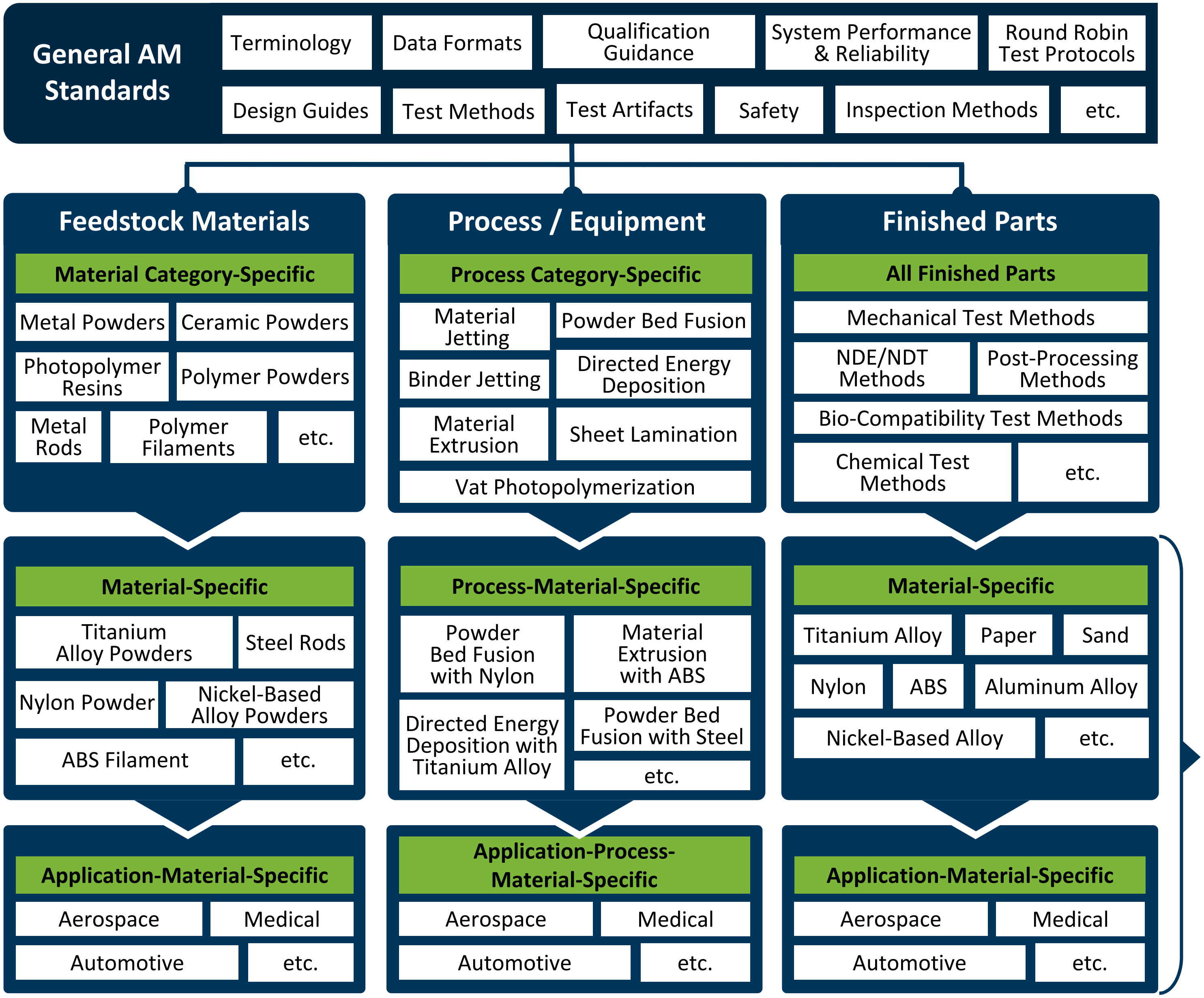
Great collaborative coordination to avoid duplication and contradiction:

ASTM INTERNATIONAL
Helping our world work better

International Organization for Standardization

James Thomas, ASTM President, and Rob Steele, ISO Secretary-General

Additive Manufacturing Standards Structure



General AM Standards

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

Feedstock Materials

Material Category-Specific

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

Material-Specific

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

Application-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

Process / Equipment

Process Category-Specific

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

Process-Material-Specific

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

Application-Process-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

Finished Parts

All Finished Parts

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

Material-Specific

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

Application-Material-Specific

- Aerospace
- Medical
- Automotive
- etc.

General Top-Level AM Standards

- General concepts
- Common requirements
- Generally applicable

Category AM Standards

Specific to material category or process category

Specialized AM Standards

Specific to material, process, or application

F42.01 Test Methods

Approved (3)

F2971 Practice for Reporting Data for Test Specimens Prepared by AM
F3122 Guide for Evaluating Mechanical Properties of Metal Materials Made via AM Processes

ISO/ASTM52921 Terminology for AM-Coordinate Systems and Test Methodologies

Under Development (4)

WK56649 / JG 60 - Practice for Intentionally Seeding Flaws in (AM) Parts
WK49229 / JG 61 - Orientation and Location Dependence Mechanical Testing for Metal AM
WK55297 / JG 52 - General Principles -- Standard Test Artefacts for AM
WK55610 / JG 63 - Characterization of Powder Flow Properties

Joint Groups (7)

JG59: NDT for AM
JG62: Guide for Conducting Round Robin Studies
JG66: Technical specification on metal powders

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Stakeholders

F42.04 Design

Approved (2)

ISO/ASTM52915 Specification for AM File Format (AMF) Version 1.2
ISO/ASTM 52910 Guide for Design for Additive Manufacturing

Under Development (4)

WK48549 Specification for AMF Support for Solid Modeling
WK54856 Principles of Design Rules
WK59167/JG57 Design Guideline for Laser-based PBF of Polymers
WK59131/JG57 Design Guideline for Laser-based PBF of Metals

Joint Groups (4)

JG54: Design Rules
JG67: Design of Functionally Graded Materials

195

Stakeholders

F42.05 Materials and Processes:

Covers Metals and Polymers

Approved (9)

Specs:

F2924 Specification for AM **Ti-6Al-4V** w/Powder Bed Fusion
F3001 Specification for AM **Ti-6Al-4V ELI** w/Powder Bed Fusion
F3184 Specification for AM **316 Steel Alloy** w/Powder Bed Fusion
F3055 Specifications for AM **IN718** w/Powder Bed Fusion
F3056 Specifications for AM **IN625** w/Powder Bed Fusion
F3091/F3091M Specification for Powder Bed Fusion of **Plastic Materials**

Guides:

F3049 Guide for **Characterizing Properties of Metal Powders** Used for AM Processes
F3187 Guide for **Directed Energy Deposition** of Metals
ISO/ASTM 52910 Guide for AM, General Principles, **Requirements for Purchased AM Parts**

Under Development (5)

WK51329 **Cobalt-28 Chromium-6 Molybdenum** Alloy with Powder Bed Fusion
WK53878 / JG 55 - **Material Extrusion** Based AM of Plastic Materials - Part 1: Feedstock materials
WK53423 **AlSi10Mg** with Powder Bed Fusion
WK58225 **Facility Requirements** for Metal Powder Bed Fusion
WK58240 Grippers of **Control Rod Drive Mechanism** (CRDM) of Nuclear Power Plants

Joint Groups (4)

JG56: Practice for Metal Powder Bed Fusion to Meet **Rigid Quality Requirements**
JG58: **Qualification, Quality Assurance and Post Processing** of PBF Metallic Parts
JG66: Technical Specification on **Metal Powders**

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Stakeholders

Supporting NADCAP Accreditation

F42.05 Material and Processes

Specifications and Practices

- WK58233 Specification for **Post Thermal Processing** of Metal Powder Bed Fusion Parts
- WK58222 Practice for **Metal Powder Reuse** in the Powder Bed Fusion Process
- WK58227 Practice for **Digital Data Workflow Control** for the Metal Powder Bed Fusion Process
- WK58234 Practice / Guide for **Storage of Build Cycle** Technical Data

Guides for Metal Powder Bed Fusion

- WK58219 Creating Feedstock Specifications
- WK58220 Specifying Gases and Nitrogen Generators
- WK58221 Receiving and Storing of Metal Powders
- WK58223 Machine Cleaning
- WK58224 Powder Disposal
- WK58226 IQ, OQ and PQ
- WK58228 Manufacturing Plan for Production Parts
- WK58229 Metallographic Porosity Evaluation of Test Specimens and Parts
- WK58230 Personnel Training Program
- WK58231 Maintenance Schedules and Maintaining Machines
- WK58232 Calibrating Machines and Subsystems

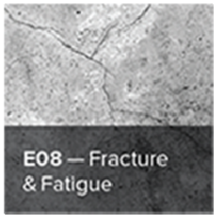
15

Drafts Under Development

More info: http://www.astmnewsroom.org/default.aspx?pageid=4264

ASTM Technical Committee Collaborative Effort

Example: F42, E08 and E07
(AM, Fatigue/Fracture, NDE)



Discussion areas:

- Understand Effect-of-Defect on Fatigue and Fracture Critical Properties
- Location and Orientation Dependence Microstructure and Fracture Critical Property Measurement
- Use NDE to understand scatter in design allowables database generation activities (process-structure-property correlation)
- Fabricate AM physical reference samples to demonstrate NDE capability for specific defect types
- Apply NDE to understand effect-of-defect, and establish acceptance limits for specific defect types and defect sizes
- Develop NDE-based qualification methods for aerospace application (screen out critical defects)
- Defect Detection and Inspection Techniques

ASTM Subcommittee E07.10 on Specialized NDT Methods
>100 pages document

Technical contacts:
Jess Waller (NASA)
Steve James (Aerojet)

Designation: X XXXX-XX

Work Item Number: 47031
Date: November 17, 2016

Standard Guide for Nondestructive Testing of As-built and Post-Processed Metal Additive Manufactured Parts Used in Aerospace Applications[1]

Technical contacts:
Jess Waller (NASA)
Steve James (Aerojet Rocketdyne)

CT, MET, PCRT, PT, RT, TT, and UT sections

In Ballot

- Defect type & part complexity determine NDE selection
- Process method determines defects determines NDE

Defect Classification/Source and Consequences:

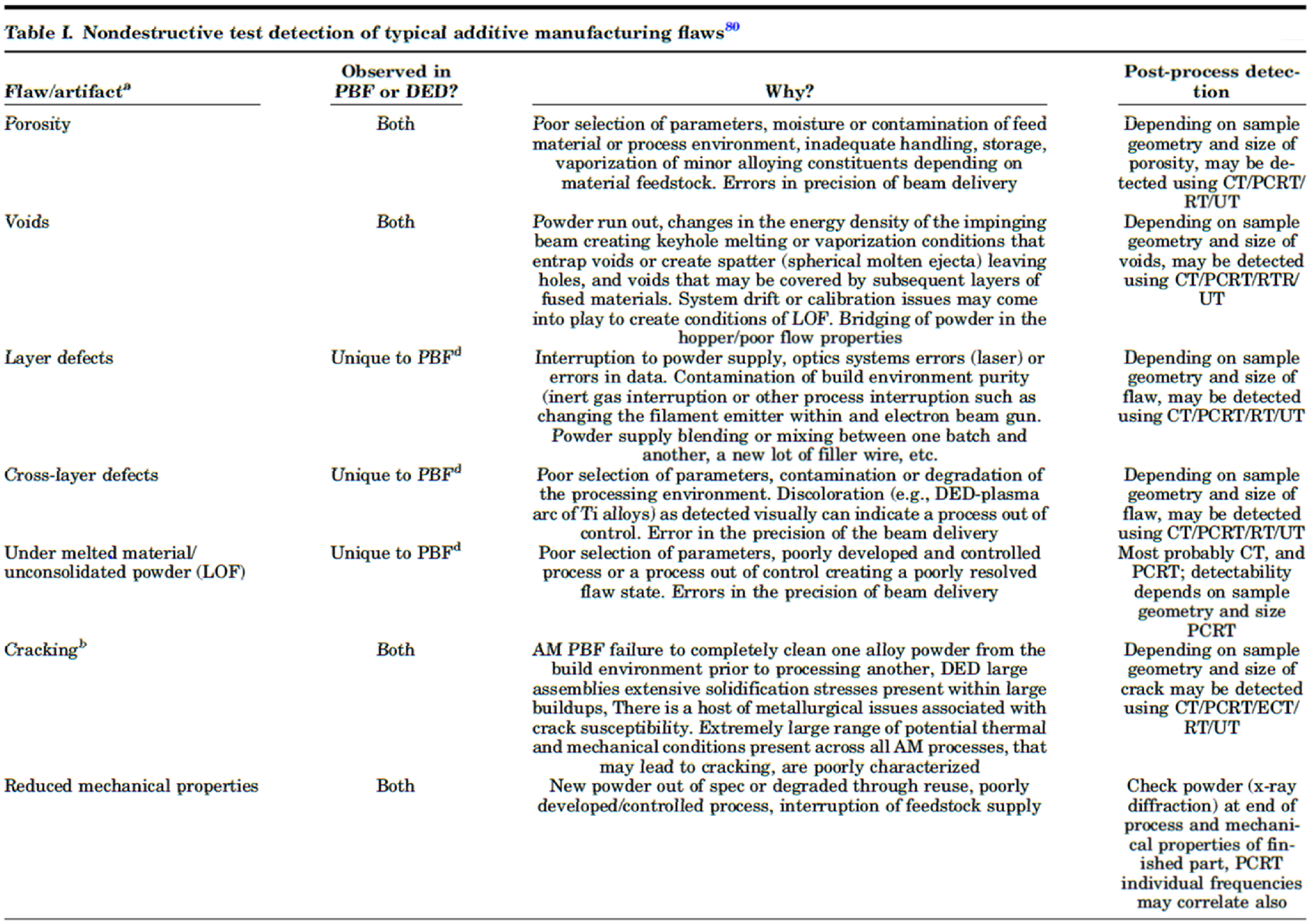


Table I. Nondestructive test detection of typical additive manufacturing flaws[80]

Flaw/artifact[a]	Observed in PBF or DED?	Why?	Post-process detection
Porosity	Both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery	Depending on sample geometry and size of porosity, may be detected using CT/PCRT/RT/UT
Voids	Both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper/poor flow properties	Depending on sample geometry and size of voids, may be detected using CT/PCRT/RTR/UT
Layer defects	Unique to PBF[d]	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption or other process interruption such as changing the filament emitter within and electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw, may be detected using CT/PCRT/RT/UT
Cross-layer defects	Unique to PBF[d]	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (e.g., DED-plasma arc of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery	Depending on sample geometry and size of flaw, may be detected using CT/PCRT/RT/UT
Under melted material/ unconsolidated powder (LOF)	Unique to PBF[d]	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery	Most probably CT, and PCRT; detectability depends on sample geometry and size PCRT
Cracking[b]	Both	AM PBF failure to completely clean one alloy powder from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups, There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present across all AM processes, that may lead to cracking, are poorly characterized	Depending on sample geometry and size of crack may be detected using CT/PCRT/ECT/RT/UT
Reduced mechanical properties	Both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply	Check powder (x-ray diffraction) at end of process and mechanical properties of finished part, PCRT individual frequencies may correlate also

ASTM WK47031 (Under ballot)

Use of Nondestructive Evaluation to Detect Defects of Interest

Designation: X XXXX-XX

Technical contacts:
Jess Waller (NASA)
Steve James (Aerojet Rocketdyne)

Work Item Number: 47031
Date: May 3, 2017

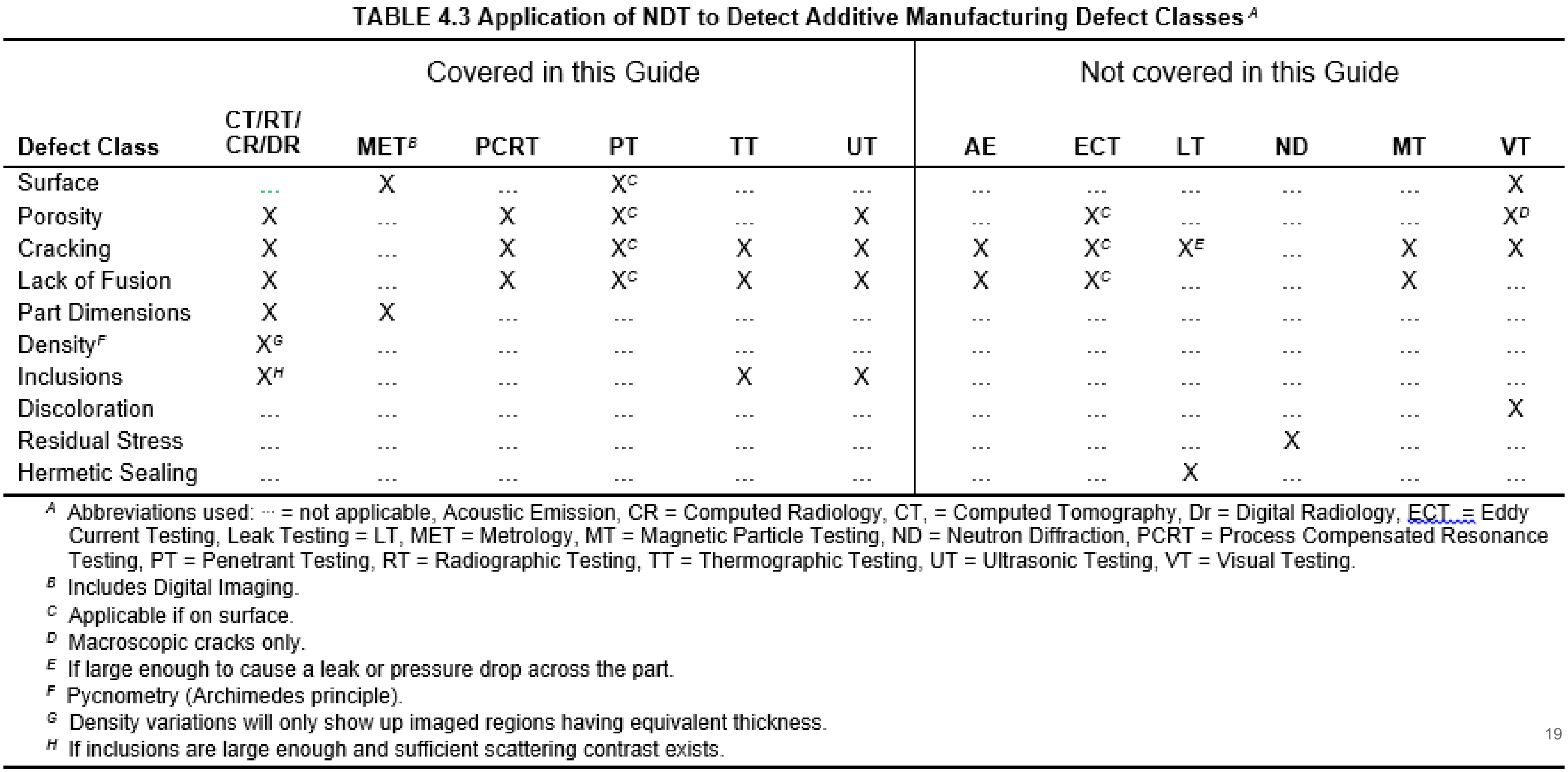


TABLE 4.3 Application of NDT to Detect Additive Manufacturing Defect Classes[A]

	Covered in this Guide						Not covered in this Guide					
Defect Class	CT/RT/ CR/DR	MET[B]	PCRT	PT	TT	UT	AE	ECT	LT	ND	MT	VT
Surface	...	X	...	X[C]	...	...	...	...	...	...	...	X
Porosity	X	...	X	X[C]	...	X	...	X[C]	...	...	...	X[D]
Cracking	X	...	X	X[C]	X	X	X	X[C]	X[E]	...	X	X
Lack of Fusion	X	...	X	X[C]	X	X	X	X[C]	...	...	X	...
Part Dimensions	X	X	...	...	...	...	...	...	...	...	...	...
Density[F]	X[G]	...	...	...	...	...	...	...	...	...	...	...
Inclusions	X[H]	...	...	...	X	X	...	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	...	...	...	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X	...	...	...

[A] Abbreviations used: ... = not applicable, Acoustic Emission, CR = Computed Radiology, CT, = Computed Tomography, Dr = Digital Radiology, ECT = Eddy Current Testing, Leak Testing = LT, MET = Metrology, MT = Magnetic Particle Testing, ND = Neutron Diffraction, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, VT = Visual Testing.

[B] Includes Digital Imaging.

[C] Applicable if on surface.

[D] Macroscopic cracks only.

[E] If large enough to cause a leak or pressure drop across the part.

[F] Pycnometry (Archimedes principle).

[G] Density variations will only show up imaged regions having equivalent thickness.

[H] If inclusions are large enough and sufficient scattering contrast exists.

ASTM E07.10 WK47031 Round Robin Testing Participants

CT/MET, MSFC/James Walker
*metal SLM parts, MSFC/Kristin Morgan
*ABS plastic parts, MSFC/Niki Werkheiser, Tracie Prater
CT, GSFC/Justin Jones
*EBF3 metal parts, LaRC/Karen Taminger

NASA

POD/fracture critical AM parts, ESA/Gerben Sinnema

ESA

AE, MRI/Ed Ginzel
CT/acoustic microscopy, Honeywell/Surendra Singh
UT/PT, Aerospace Rocketdyne/Steve James
CT/RT, USAF/John Brausch, Ken LaCivita
CT, Fraunhofer/Christian Kretzer
CT, GE Sensing GmbH/Thomas Mayer
CT, JAXA/Tabuchi Teruhiko, Kazuhiro Nakamura
PCRT, Vibrant Corporation/Eric Biedermann
PT, Met-L-Check/Mike White
NRUS, LANL/Marcel Remillieux

Commercial/Gov NDE

*Concept Laser/Marie Ebert
*DRDC/Shannon Farrell
†*Airbus/Amy Glover
†*UTC/John Middendorf, Wright State University/Greg Loughnane
†*CalRAM/Shane Collins

Commercial/Gov
AM Round Robin
Sample Suppliers

* delivered or committed to deliver samples
† E8 compliant sacrificial dogbone samples

Technical contacts:
Jess Waller (NASA)
Steve James (Aerojet Rocketdyne)

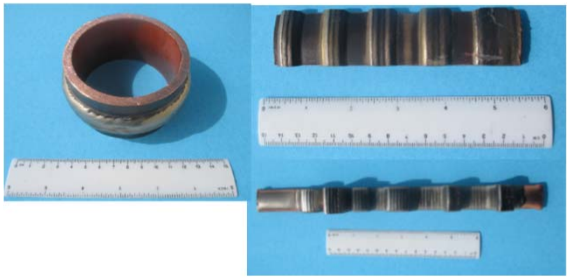
ASTM WK47031 Round Robin Testing (Leveraged)

Coordinated by Steve James (Aerojet Rocketdyne)

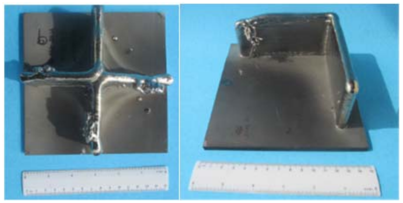
Technical contacts:
Jess Waller (NASA)
Steve James (Aerojet Rocketdyne)

Electron Beam Freeform Fabrication

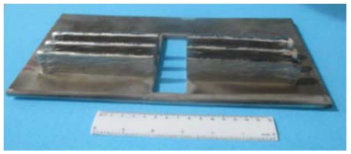
NASA LaRC
Inconel 625 on copper



Ti-6Al-4V (4)



SS 316

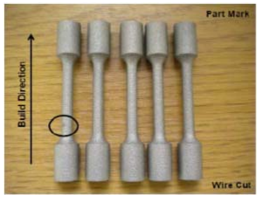


Al 2216

Laser-PBF

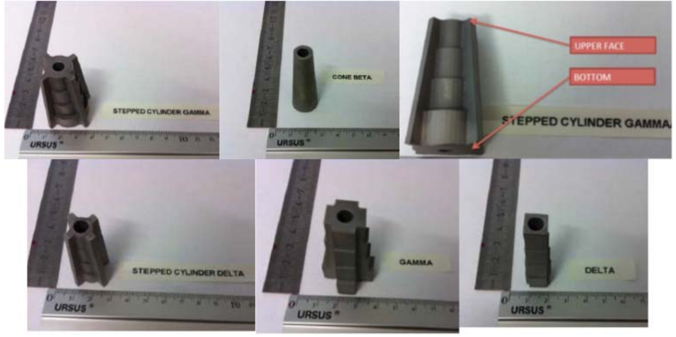
Georgia Univ.
Ti-6Al-4V bars

Airbus
Al-Si-10Mg dog bones



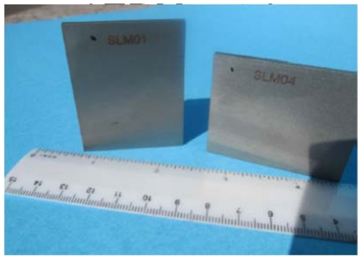
Concept Laser Inconel 718 inserts (6)
w/ different processing history

Concept Laser Inconel 718 prisms
for CT capability demonstration



Electron Beam-PBF

Met-L-Check
SS 316 PT/RT panels



Characterized to date by various NDE techniques (CT, RT, PT, PCRT, UT) to enrich the document

ASTM WK56649:

Practice for Intentionally Seeding Flaws in (AM) Parts

Technical contacts:
Steve James (Aerojet Rocketdyne)

1. Scope

- Best practice for the creation of flaws
- AM flaw types (identifies & illustrates)
- Detection methods

2. Reference Documents

3. Terminology

- During the development of the WK 56649 document terms related to the subject will be collected, defined, and later determined best venue for publication.
- flaw types

4. Summary of Practice

- The flaw classification approach
  - Volumetric
  - Linear
  - Planar

5. Flaw Introduction Methods

- Significant machine parameters for the creation of flaws

6. Applicable Flaw-Seeding Approach as a Function of Desired Flaw Type

7. Applicable Flaw-Seeding Approach as a Function of AM Process

8. Applicable Flaw-Seeding Approach as a Function of AM Material

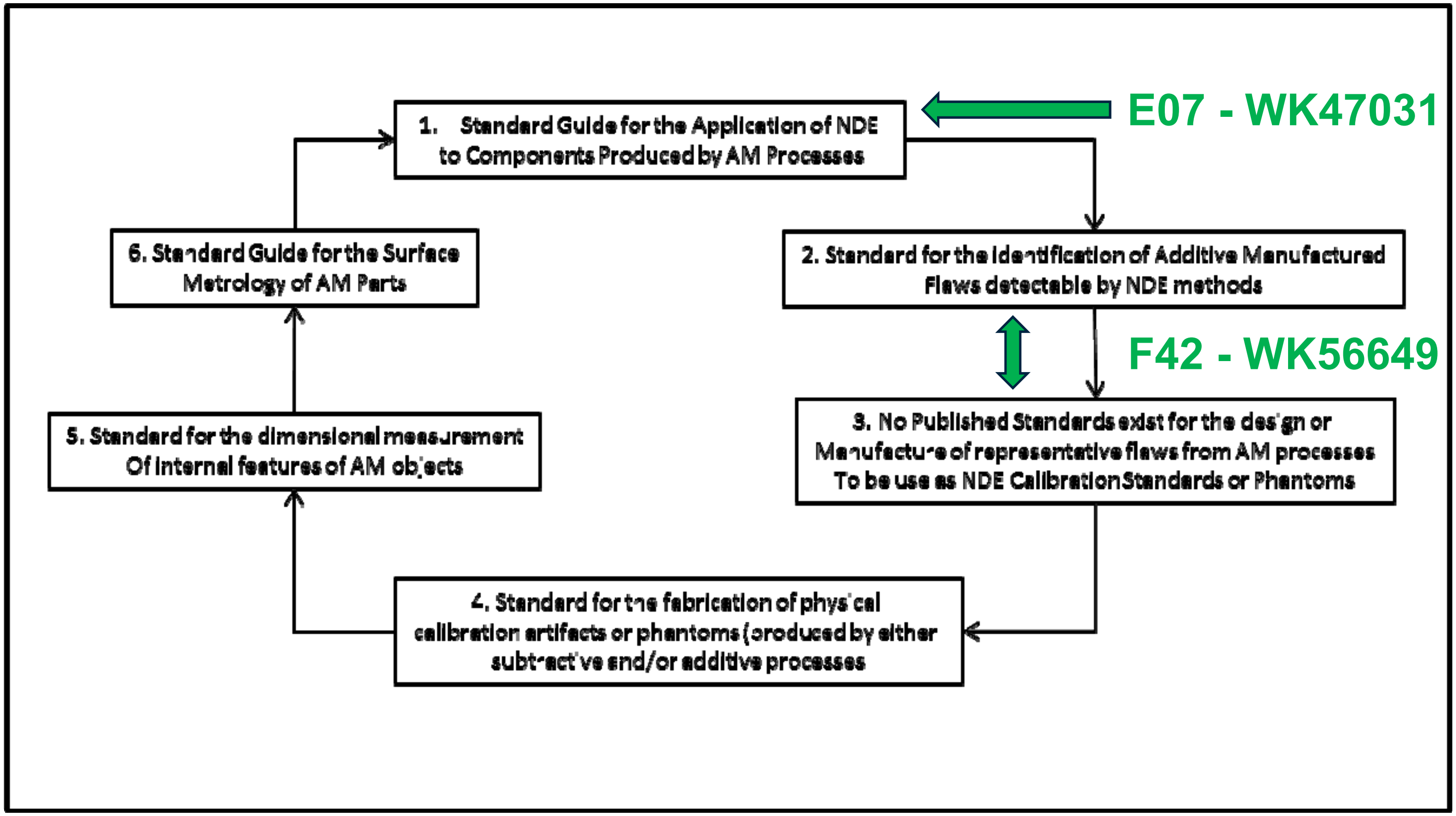
8. ANNEXs

- General AM Seeding Catalogue
- Acronyms

Draft is going under review and ballot

AMSC NDT of AM Standards Gaps Identified by NDE Working Group: 6 gaps

Standards in progress



1. Standard Guide for the Application of NDE to Components Produced by AM Processes

2. Standard for the Identification of Additive Manufactured Flaws detectable by NDE methods

3. No Published Standards exist for the design or Manufacture of representative flaws from AM processes To be use as NDE Calibration Standards or Phantoms

4. Standard for the fabrication of physical calibration artifacts or phantoms (produced by either subtractive and/or additive processes

5. Standard for the dimensional measurement Of internal features of AM objects

6. Standard Guide for the Surface Metrology of AM Parts

E07 - WK47031

F42 - WK56649

Current and future NDE of AM standards under development (ASTM)

Technical contacts: Jess Waller, Steve James

Draft: WK47031 POC: J. Waller

E07

Standard Guide for
Nondestructive Testing of As-Built and Post-Processed Metal Additive Manufactured Parts Used in Aerospace Applications

Balloting begun (CT, MET, PCRT, PT, RT, TT, and UT)

Draft: WK56649 POC: S. James

F42

Standard Guide for
Intentionally Seeding Flaws in Additively Manufactured Parts

Draft in Preparation

Draft: WKXXXX POC: S. Singh

E07

Standard Guide for
In-situ Monitoring During the Build of Metal Additive Manufactured Parts Used in Aerospace Applications

Motion to register as a formal work item approved by E07.10 (IR, LUT, VIS)

Draft: WKXXXX POC: TBD

E07

Standard Practice for
Dimensional Metrology of Surface and Internal Features in Additively Manufactured Parts

Future

Draft: WKXXXX POC: TBD

E07/F42?

Standard Practice for
the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability in Additively Manufactured Parts

Future, phys ref stds to demonstrate NDE capability

Case Western Reserve University

ASTM INTERNATIONAL
Helping our world work better

ASTM WK49229/JG61 at F42 in Collaboration with E08:

Guide for Measurement of Orientation and Location Dependent Mechanical Properties for Metal Additive Manufacturing

Required R&D and support!

America Makes
National Additive Manufacturing Innovation Institute

NAVAIR

Lockheed Martin

Federal Aviation Administration

United Technologies

Boeing

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Pratt & Whitney
A United Technologies Company

GE
Inspection Technologies

HZDR
Helmholtz Zentrum Dresden Rossendorf

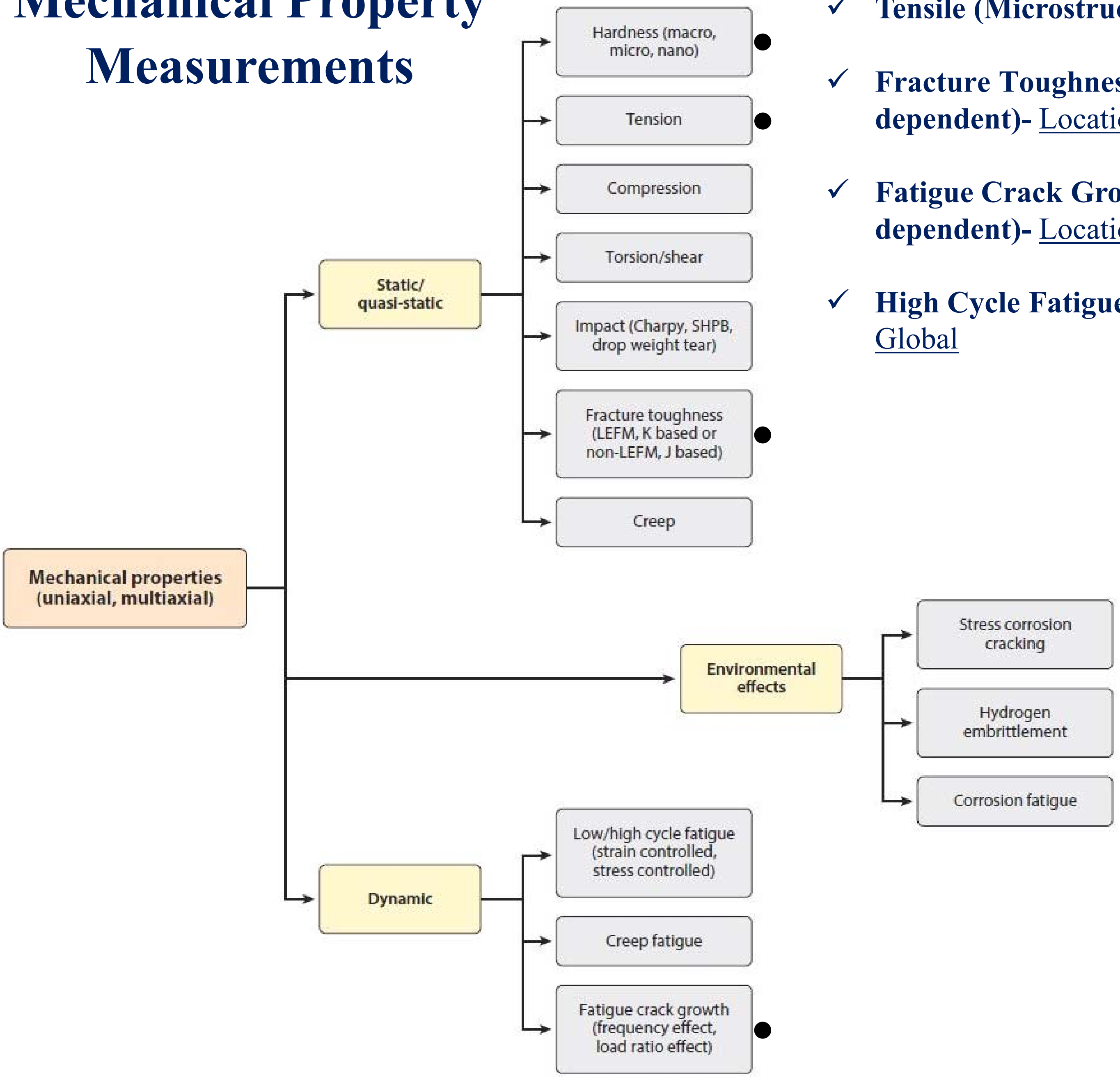
YXLON

SLM Solutions

COMTES FHT
Complete Technological Service - Forming, Heat Treatment

Nikon

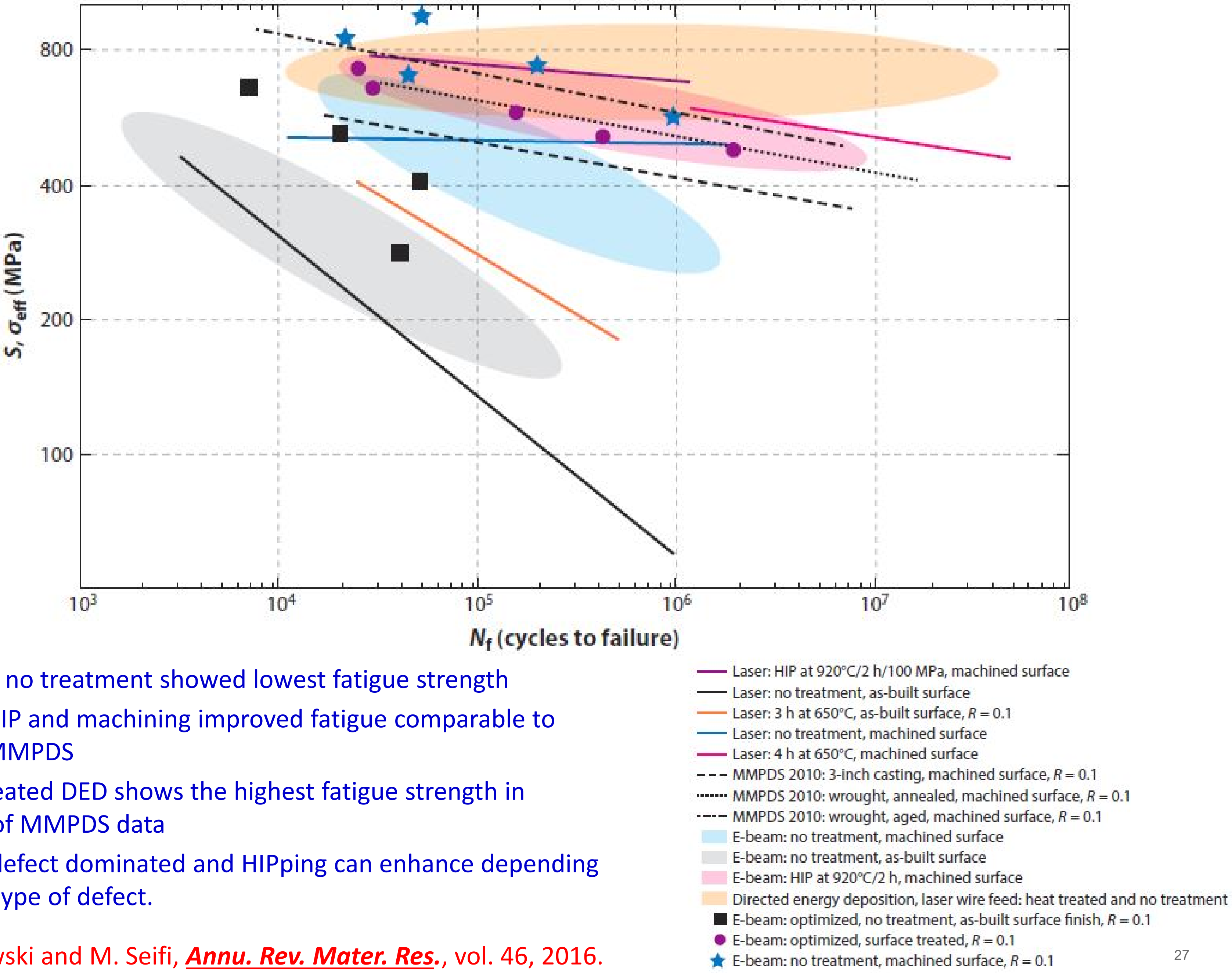
Mechanical Property Measurements



- ✓ **Tensile (Microstructure/Defect dominated)- Global**
- ✓ **Fracture Toughness (Highly Microstructure dependent)- Location specific**
- ✓ **Fatigue Crack Growth (Highly Microstructure dependent)- Location specific**
- ✓ **High Cycle Fatigue (Highly defect dominated)- Global**

J. J. Lewandowski and M. Seifi, ***Annu. Rev. Mater. Res.***, vol. 46, 2016.

High Cycle Fatigue for PBF Ti-6Al-4V

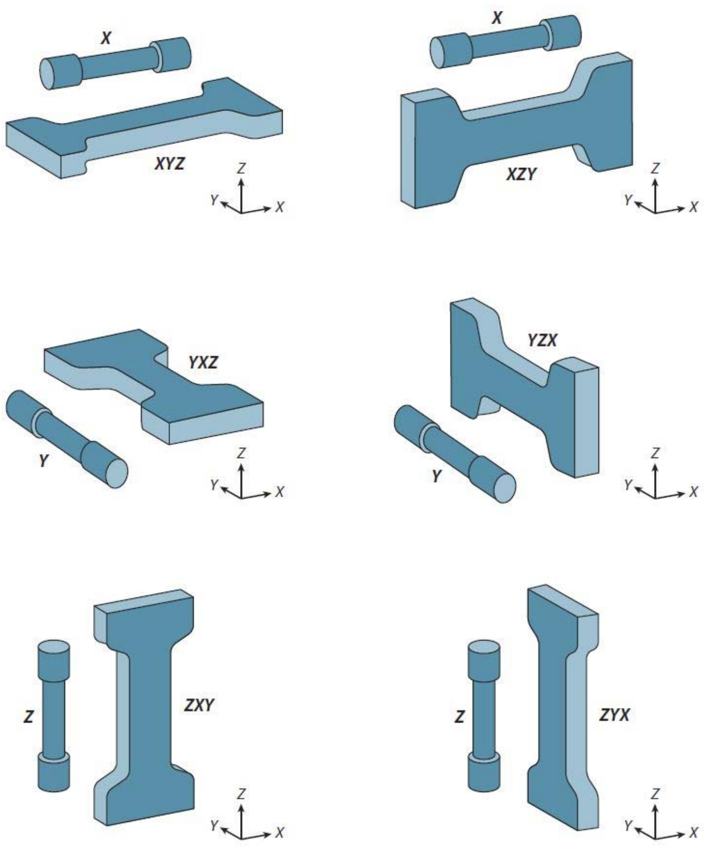


- As-built no treatment showed lowest fatigue strength
    - HIP and machining improved fatigue comparable to MMPDS
- Heat treated DED shows the highest fatigue strength in excess of MMPDS data
- Highly defect dominated and HIPping can enhance depending on the type of defect.

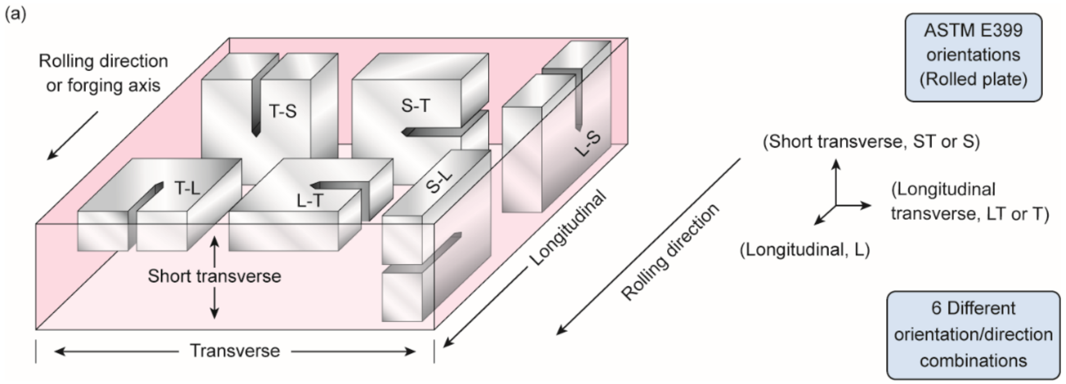
J. J. Lewandowski and M. Seifi, ***Annu. Rev. Mater. Res.***, vol. 46, 2016.

Mechanical Testing Protocols

ASTM WK49229, "Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing." ASTM International, 2015.

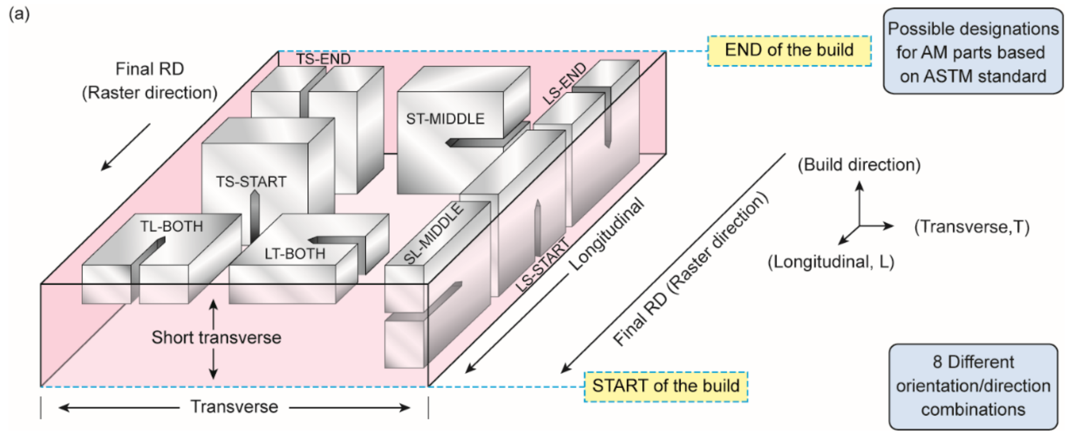


ISO / ASTM 52921. (2013).
Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies



ASTM E399 orientations (Rolled plate)

6 Different orientation/direction combinations



Possible designations for AM parts based on ASTM standard

8 Different orientation/direction combinations

Possible Designation Based on ASTM Standard for AM parts

J. J. Lewandowski and M. Seifi, ***Annu. Rev. Mater. Res.***, vol. 46, 2016.

Seifi, M., et. al (2015). **JOM**, 67(3), 597–607

Arcam A2X Processed Ti-6Al-4V: Fatigue and Damage Tolerance

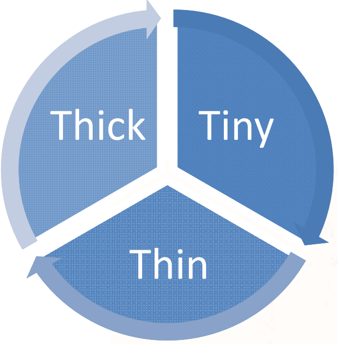
Size/geometry effect

Miniaturized samples: Cost effective

- 1st build- Default parameter setting
- 2nd build- Optimized parameter setting

Thick samples

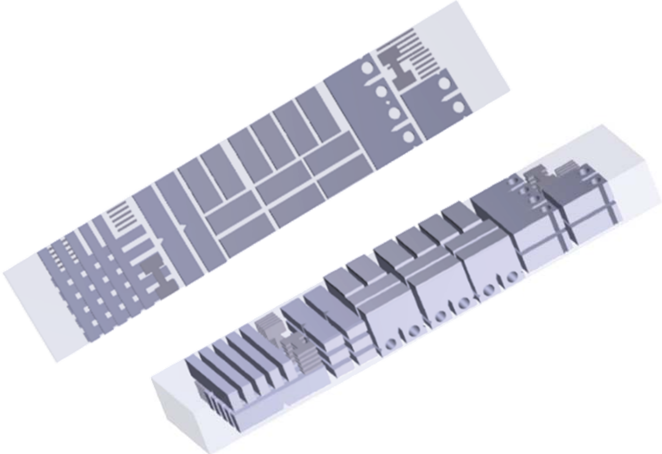
2.5 inch thick



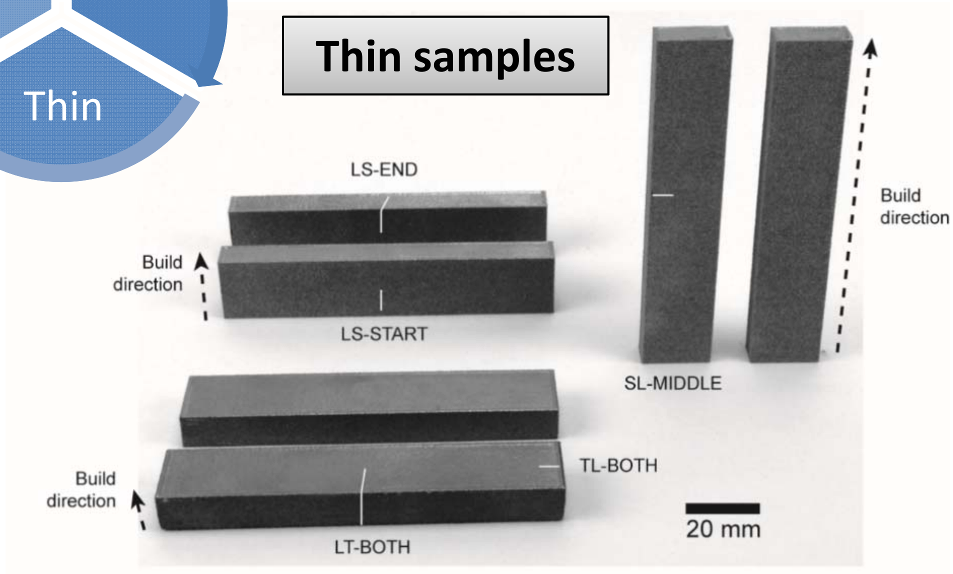
Thick

Tiny

Thin



Thin samples



Pratt & Whitney
A United Technologies Company

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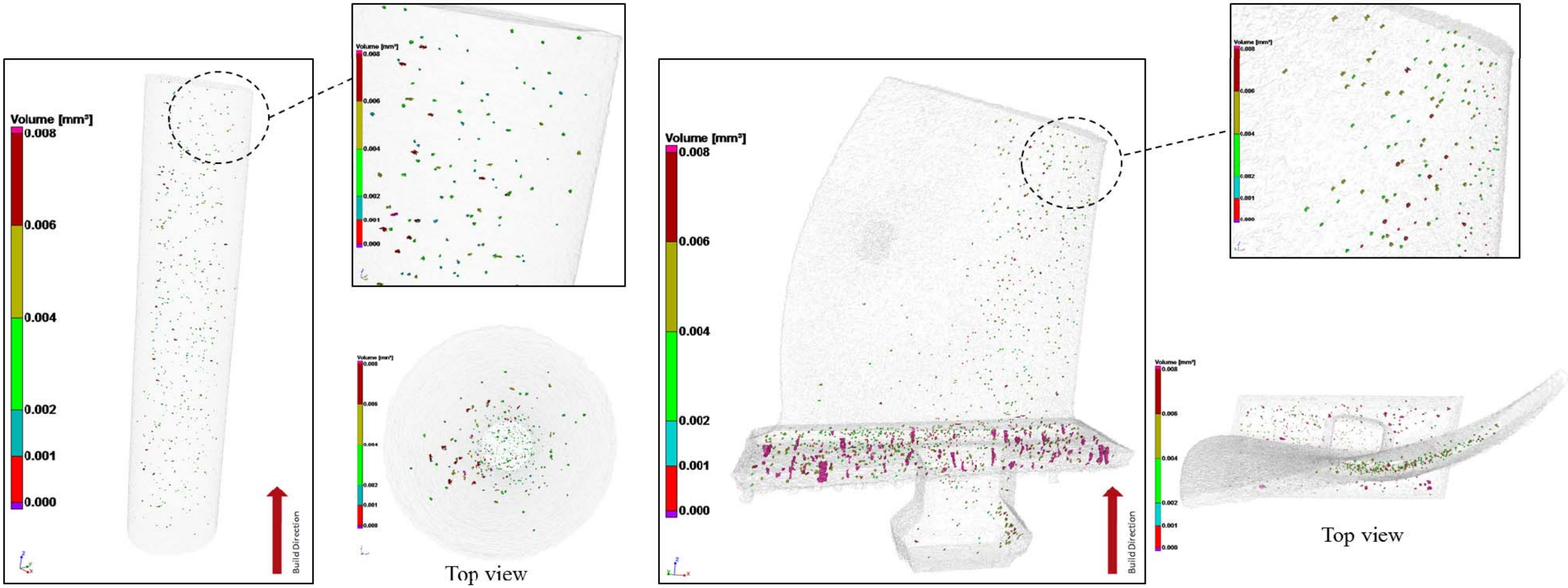
Case Western Reserve University
EST. 1826

Challenging transition from coupon to real component?



(Witness coupon) **Property Transition** **(Component)**

- XCT results conducted on a witness coupon and a component made at the same time demonstrating challenging property/characteristics transfer from witness coupon to the actual component.

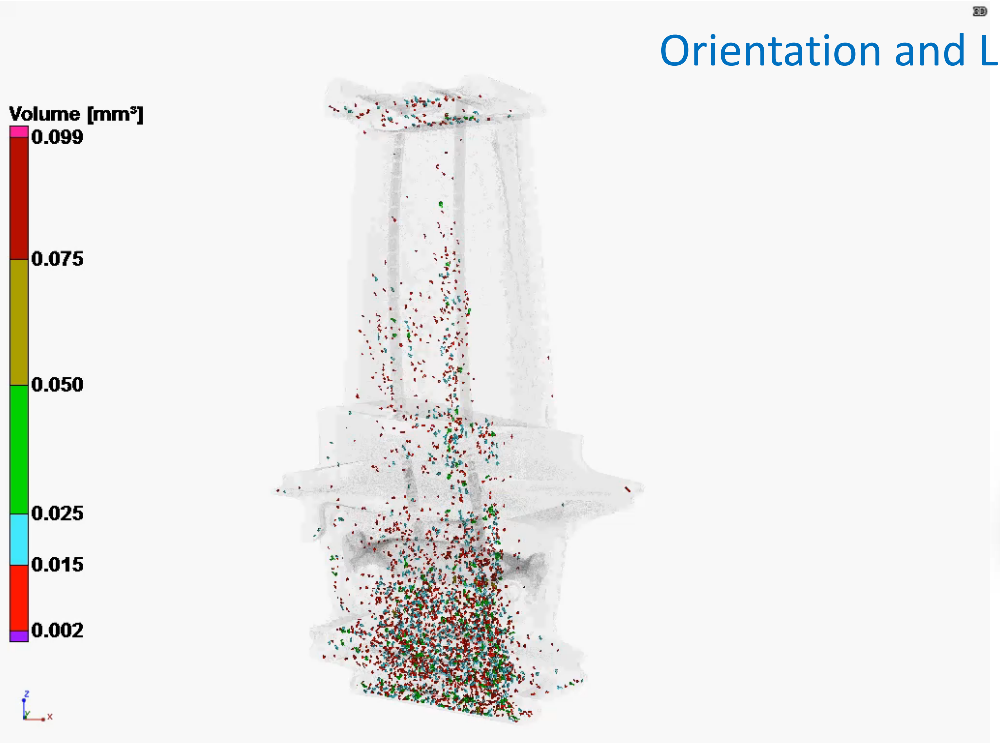
Seifi et. al, JOM,69(3):439–455, March 2017

Collaborative joint effort that includes contribution of colleagues at FAA, NASA and NIST

Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification

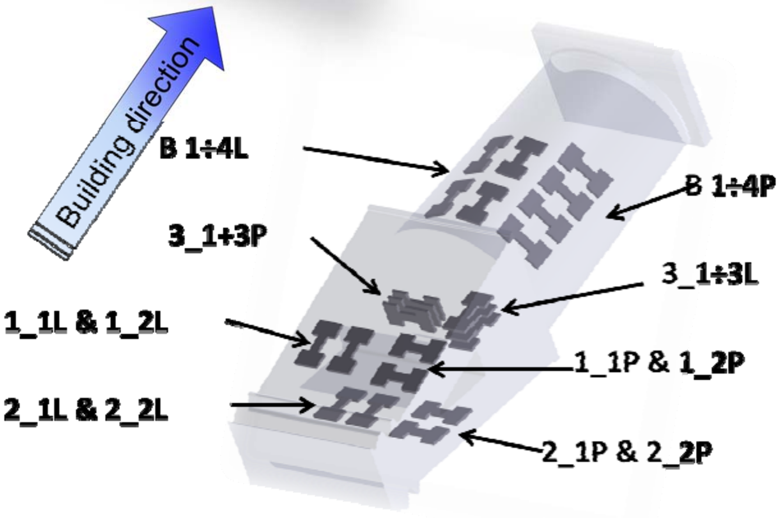
Mohsen Seifi, Michael Gorelik, Jess Waller, Nik Hrabe, Nima Shamsaei, Steve Daniewicz & John J. Lewandowski

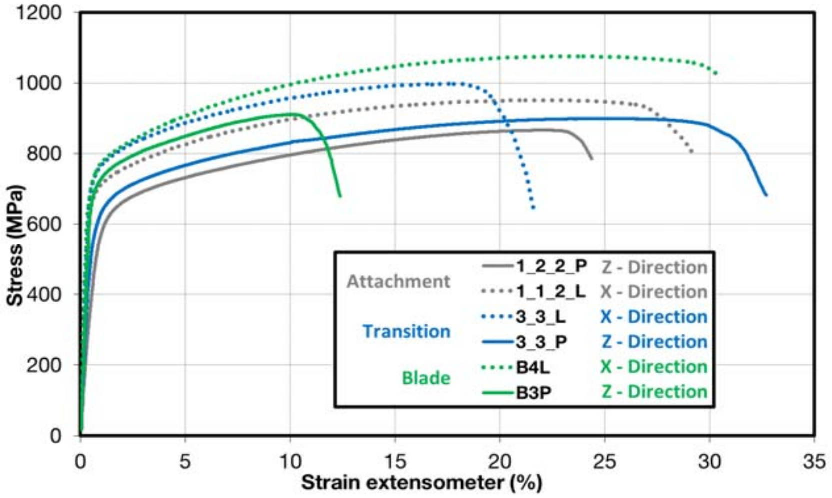
Orientation and Location Specific



SLM IN718

SLM SOLUTIONS





J. Dzugan, M. Seifi, and J. J. Lewandwoski et. Al "Miniaturized Mechanical Testing of Components Processed by Metal Additive Manufacturing" Fatigue Fract. Eng. Mater. Struct., In submission, 2017.

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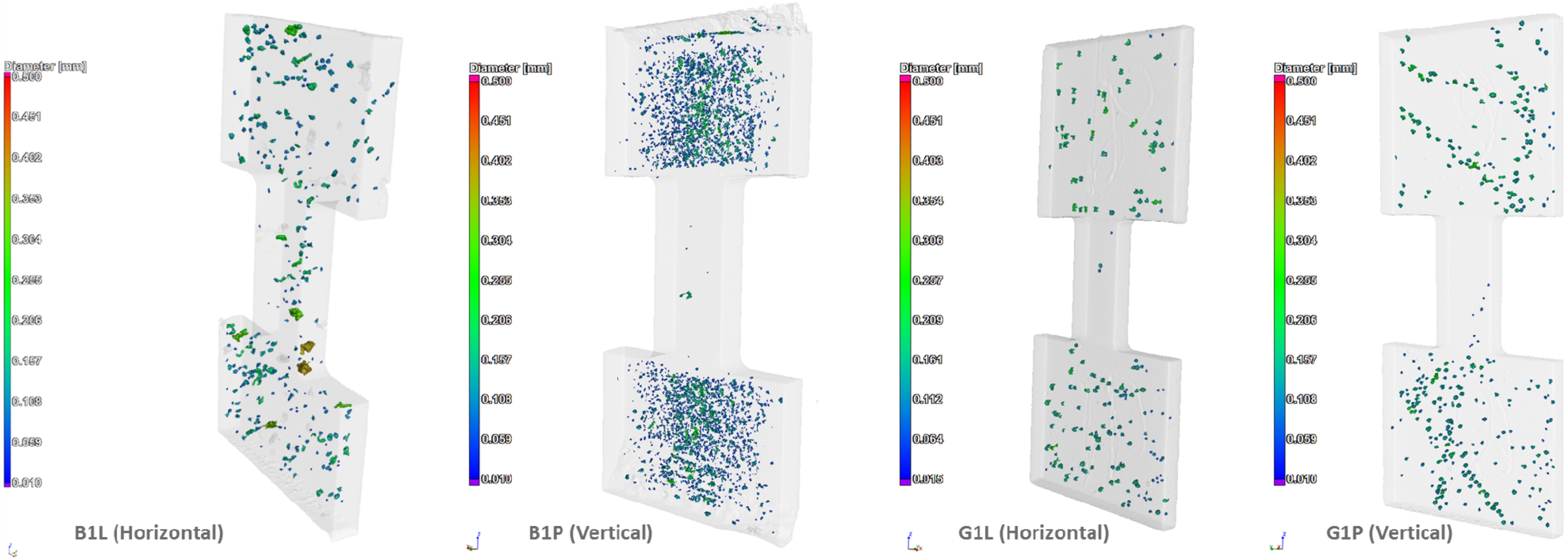
NAVAL AIR SYSTEMS COMMAND

Local characterization of defects, microstructure linkage: SLM IN718

ASTM WK49229, "Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing." ASTM International, 2015.

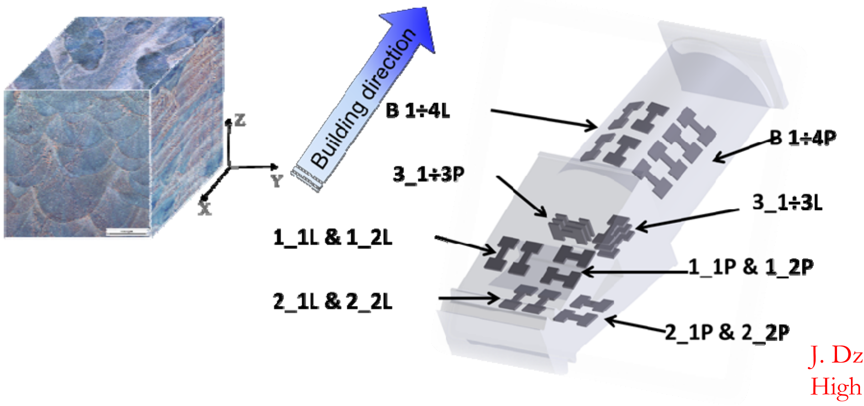


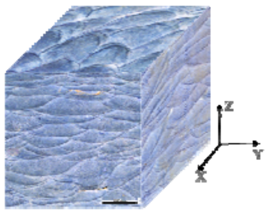
B1L (Horizontal)

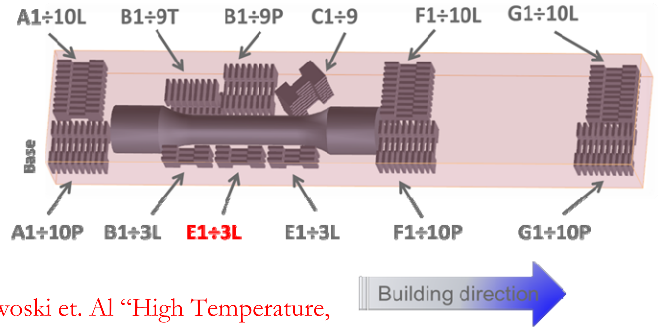
B1P (Vertical)

G1L (Horizontal)

G1P (Vertical)



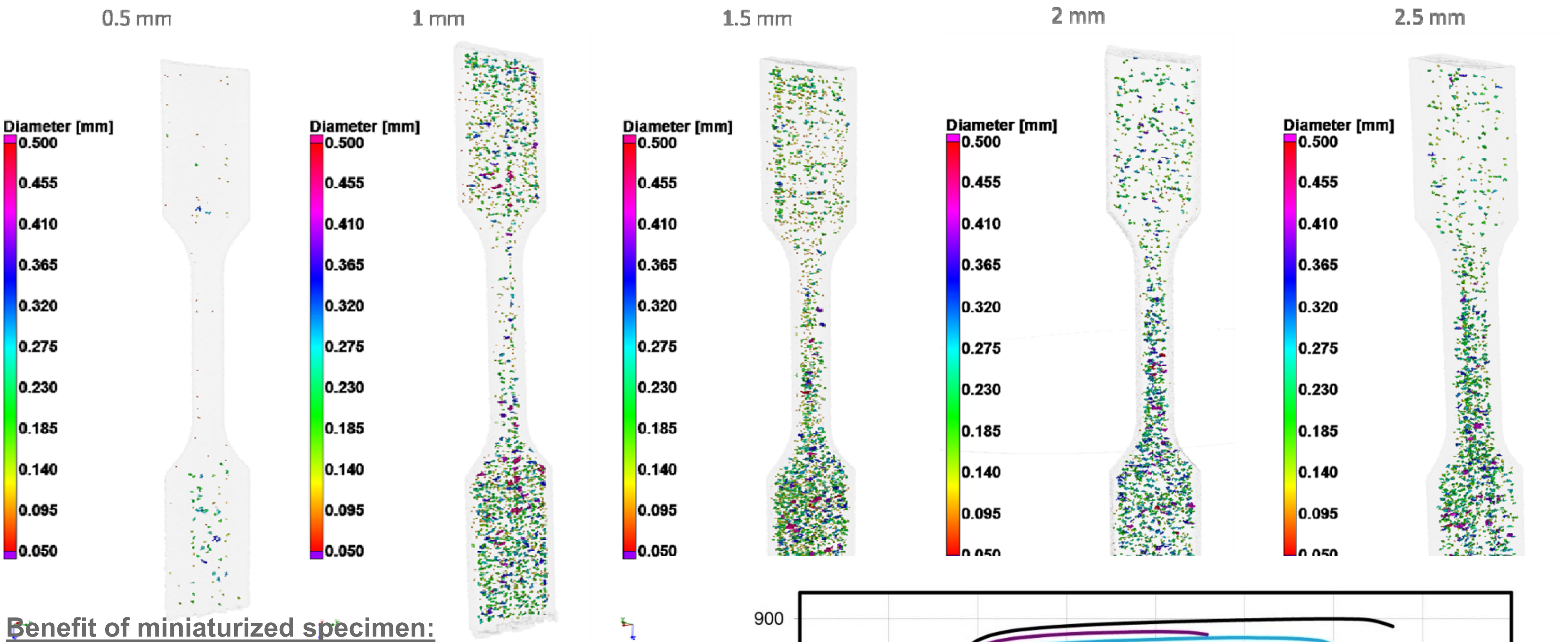




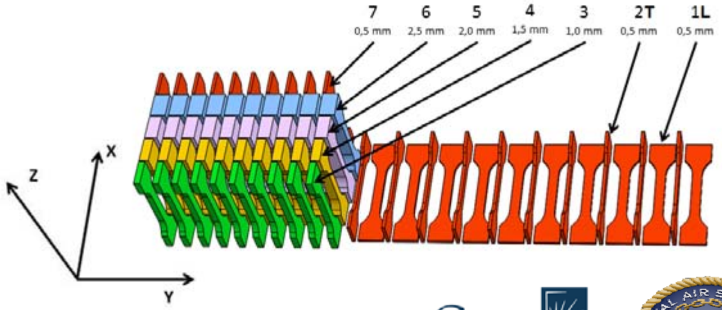
J. Dzugan, M. Seifi, and J. J. Lewandwoski et. Al "High Temperature, High Rate Fracture Behavior of SLM Processed IN 718 Using Miniaturized Specimens," Adv. Eng. Mater., In submission, 2017.

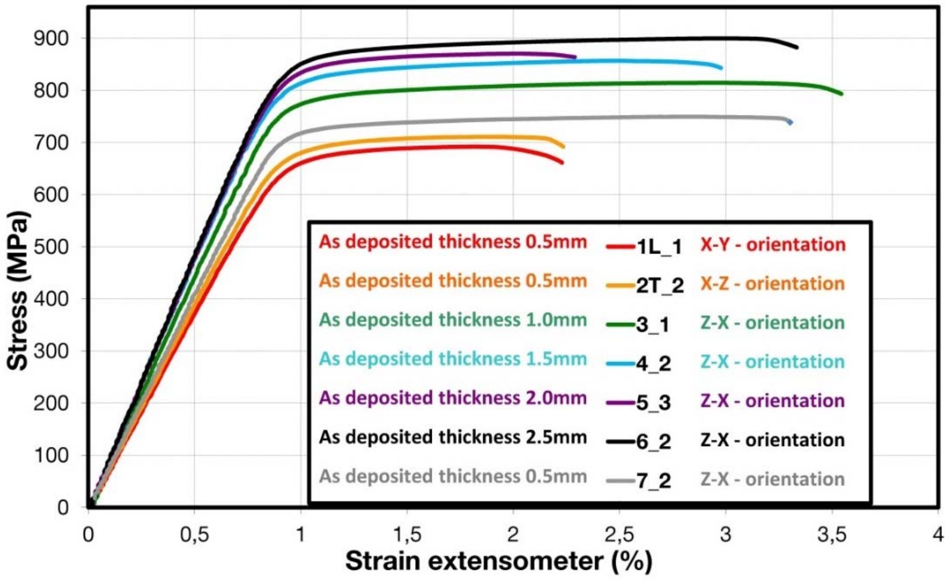
Thickness Effect on Defect Population

J. Dzugan, M. Seifi, and J. J. Lewandwoski et. Al “Effects of Thickness and Orientation on the Small Scale Fracture Behavior of Additively Manufactured Ti-6Al-4V,” *Material Characterization*, In submission, 2017.



Benefit of miniaturized specimen:
Achieve high resolution using XCT





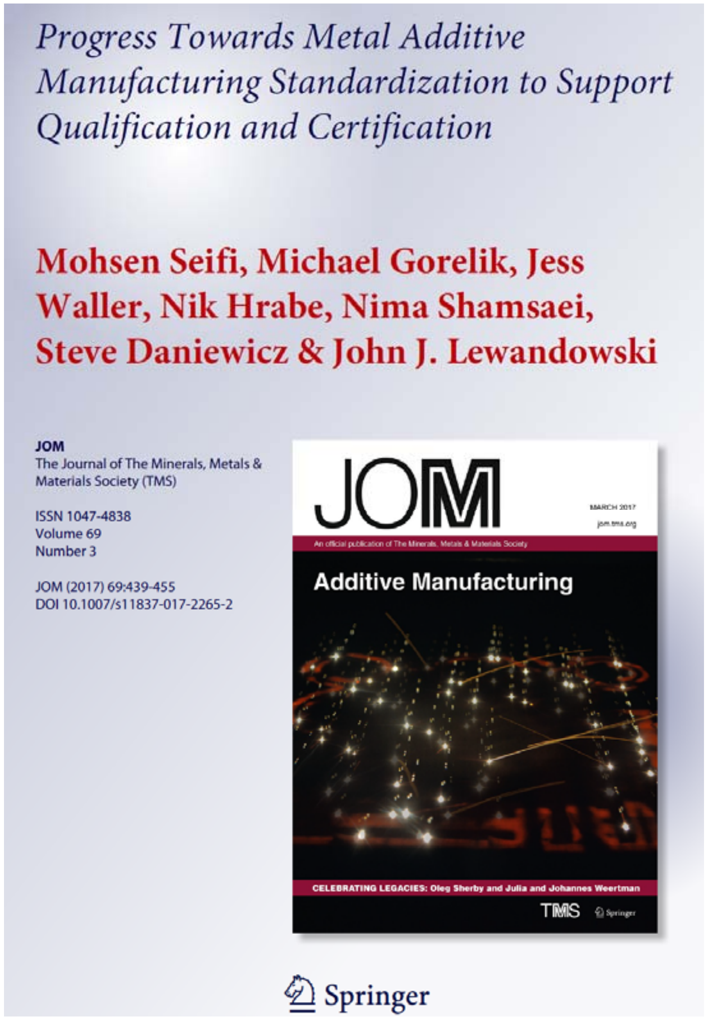
Symposium on Fatigue and Fracture of Additively Manufactured Materials and Components (**E08, F42, E07, NIST Sponsored**)

Topics to be addressed include:

- Applicability of existing fatigue and fracture test methods to AM materials
- Development of new fatigue and fracture test methods for AM materials
- Fatigue and fracture behavior of components fabricated using AM
- Residual stress effects
- Effects of process and design parameters on fatigue and fracture behavior
- Process optimization to improve fatigue performance of AM materials
- Nondestructive evaluation of components fabricated using AM
- High-speed, low-cost nondestructive evaluation techniques for AM

- **Dates:** November 15th - 16th, 2017
- **Location:** Hyatt Regency Atlanta, GA
- **Sponsored by:** E08 Fatigue and Fracture and NIST
- **Deadline for Abstract Submittal:** Past

Collaborative joint publication that includes contribution of colleagues at FAA, NASA and NIST



Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification

Mohsen Seifi, Michael Gorelik, Jess Waller, Nik Hrabe, Nima Shamsaei, Steve Daniewicz & John J. Lewandowski

JOM
The Journal of The Minerals, Metals & Materials Society (TMS)

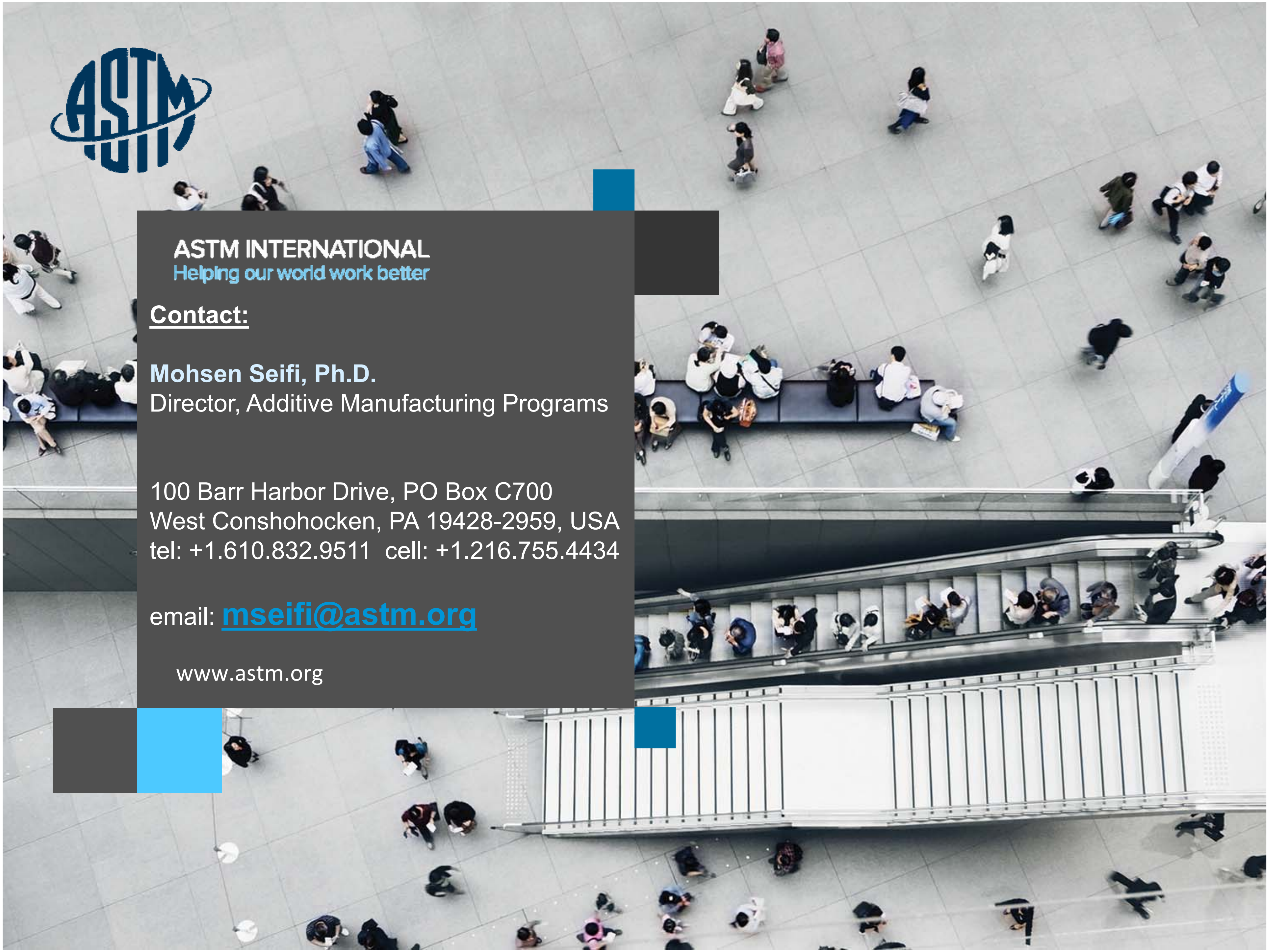
ISSN 1047-4838
Volume 69
Number 3

JOM (2017) 69:439-455
DOI 10.1007/s11837-017-2265-2

JOM
MARCH 2017
jom.tms.org
An official publication of The Minerals, Metals & Materials Society
Additive Manufacturing
CELEBRATING LEGACIES: Oleg Sherby and Julia and Johannes Weertman
TMS
Springer

Springer

http://link.springer.com/article/10.1007/s11837-017-2265-2



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Contact:

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Director, Additive Manufacturing Programs

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email: mseifi@astm.org

www.astm.org

APPENDIX W—SAE’S AMS-AM COMMITTEE ON STANDARDS DEVELOPMENT FOR AM – PROGRESS REPORT

SAE INTERNATIONAL

SAE'S AMS-AM COMMITTEE ON STANDARDS DEVELOPMENT FOR AM

PRESENTED AT:

2017 FAA-AFRL AM WORKSHOP @ UDRI, DAYTON OH

August 31, 2017

Dave Abbott, Chair

SAE AMS-AM COMMITTEE ON ADDITIVE MANUFACTURING

Additive Manufacturing Specifications – General

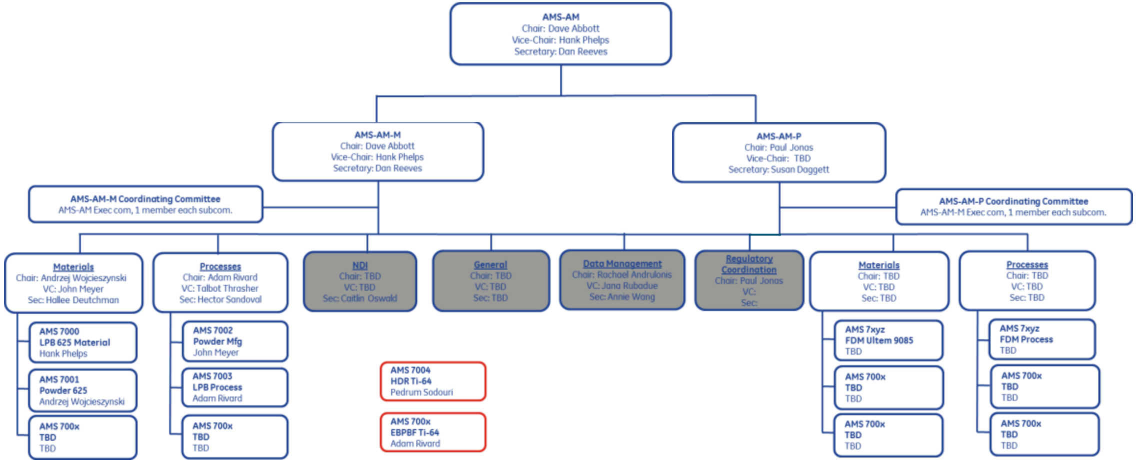
Several Standards Development Organizations (SDO's):

- **ASTM F42**
  - Formed 2010
  - Broad industry base including aerospace, medical, energy, automotive
  - Test methods, Design, Materials and Processes, EHS, Terminology
- **AWS D20**
  - Formed 2014
  - Process and operator qualification
  - Process specs.
- **AMSC**
  - America Makes & ANSI Additive Manufacturing Standardization Collaborative Standards development coordination between SDO's. Does not issue specs.
- **SAE AMS-AM**
  - Formed 2015 to provide specifications for the aerospace community.

SAE AMS-AM Committee

Scope:

To develop and maintain aerospace material and process specifications for additive manufacturing...



AMS-AM
Chair: Dave Abbott
Vice-Chair: Hank Phelps
Secretary: Dan Reeves

AMS-AM-M
Chair: Dave Abbott
Vice-Chair: Hank Phelps
Secretary: Dan Reeves

AMS-AM-M Coordinating Committee
AMS-AM Exec com, 1 member each subcom.

AMS-AM-P
Chair: Paul Jonas
Vice-Chair: TBD
Secretary: Susan Daggett

AMS-AM-P Coordinating Committee
AMS-AM-M Exec com, 1 member each subcom.

Materials
Chair: Andrzej Wojcieszynski
VC: John Meyer
Sec: Hallee Deutchman

AMS 7000
LPB 625 Material
Hank Phelps

AMS 7001
Powder 625
Andrzej Wojcieszynski

AMS 700x
TBD
TBD

Processes
Chair: Adam Rivard
VC: Talbot Thrasher
Sec: Hector Sandoval

AMS 7002
Powder Mfg
John Meyer

AMS 7003
LPB Process
Adam Rivard

AMS 700x
TBD
TBD

NDI
Chair: TBD
VC: TBD
Sec: Caitlin Oswald

General
Chair: TBD
VC: TBD
Sec: TBD

AMS 7004
HDR Ti-64
Pedrum Sodouri

AMS 700x
EBPBF Ti-64
Adam Rivard

Data Management
Chair: Rachael Andrulonis
VC: Jana Rubadue
Sec: Annie Wang

Regulatory Coordination
Chair: Paul Jonas
VC:
Sec:

Materials
Chair: TBD
VC: TBD
Sec: TBD

AMS 7xyz
FDM Ultem 9085
TBD

AMS 700x
TBD
TBD

AMS 700x
TBD
TBD

Processes
Chair: TBD
VC: TBD
Sec: TBD

AMS 7xyz
FDM Process
TBD

AMS 700x
TBD
TBD

AMS 700x
TBD
TBD

Formed in 2015

Currently:

- 180+ members
- 6 Subcommittees
- 6 specs and 4 guidance documents in development
- Recently expanded into polymers

AMSAM Committee Charter

Adopted May 5, 2016

Scope:

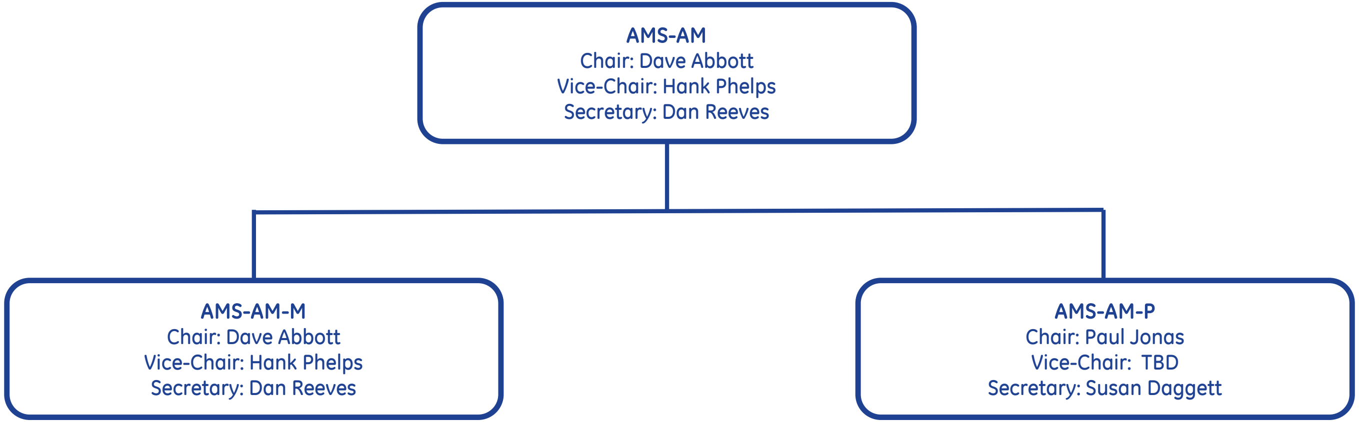
> **…to develop and maintain aerospace material and process specifications …for additive manufacturing, including precursor material, additive processes, system requirements and materials, pre-processing and post-processing, non-destructive testing and quality assurance.**
>
> **…the committee will collaborate with “other standards” organizations such as MMPDS, ASTM Committee F42 on Additive Manufacturing, AWS D20, Nadcap Welding Task Group, America Makes, CMH-17, and regulatory authorities such as FAA and EASA.**

AMSAM Committee Charter

Objectives:

- …develop Aerospace Material Specifications (AMS) for the procurement of additive precursor and manufactured materials … When applicable, ensure the material specification is tied to the appropriate shared material property database.
- Publish recommended practices and/or specifications for processing and fabrication of end products from AM materials.
- Provide a forum for the exchange of technical information related to additive manufacturing.
- Further the adaptation of industry sponsored material specifications through coordination with MMPDS, ASTM, AWS, Nadcap, other AMS committees and associated organizations.
- Coordinate requirements for publishing data in shared material property databases with MMPDS Emerging Technology Working Group for new metallic materials and CMH-17 for new composite materials.
- Establish a system to ensure material specifications are controlled and traceable.

AMS-AM Committee – Current Organization



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AMS-AM-M
Chair: Dave Abbott
Vice-Chair: Hank Phelps
Secretary: Dan Reeves

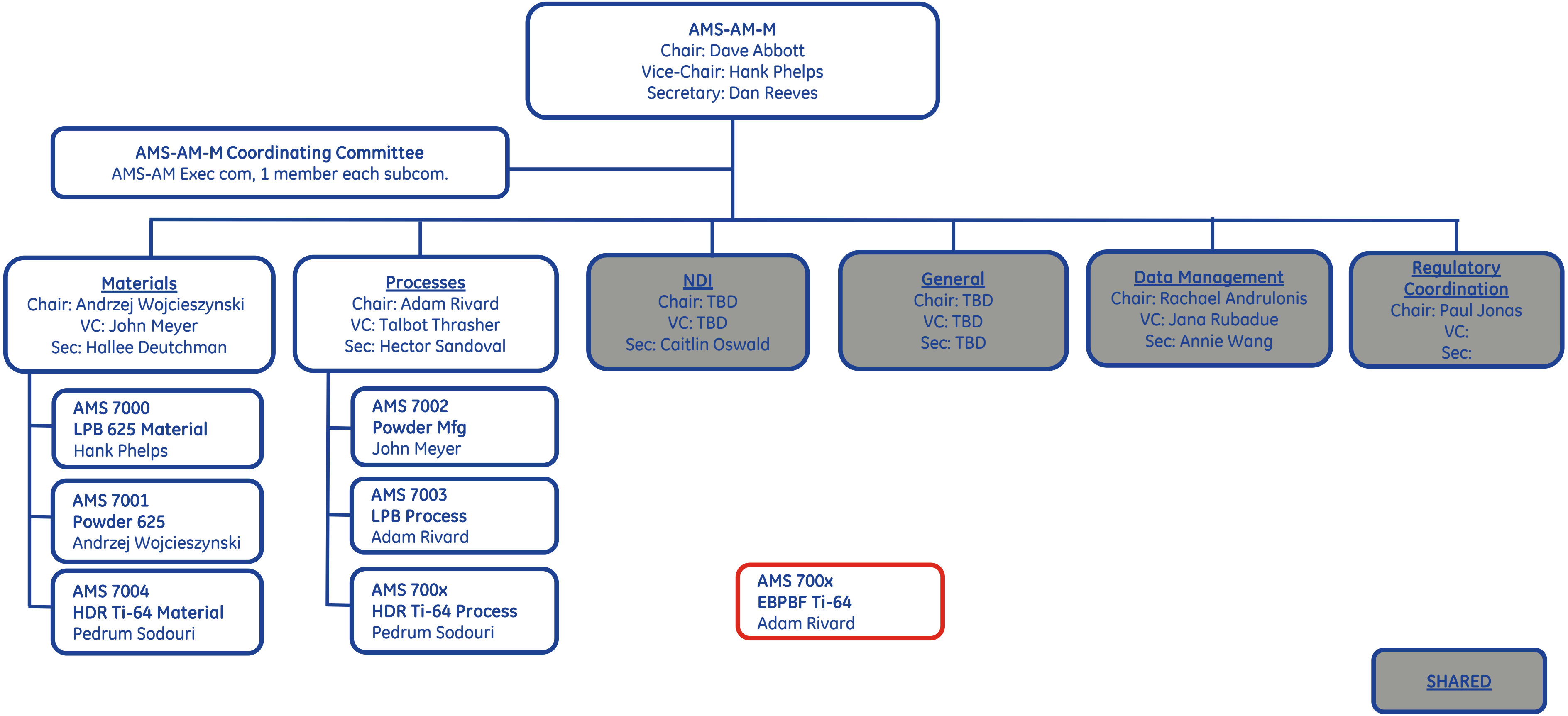
AMS-AM-P
Chair: Paul Jonas
Vice-Chair: TBD
Secretary: Susan Daggett

Metals Subcommittee

Polymer Subcommittee*

*Added polymer subcommittee Spring of 2017.

AMS-AM-M Subcommittee – Current Organization



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AMS-AM Exec com, 1 member each subcom.

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  LPB 625 Material
  Hank Phelps
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  Powder 625
  Andrzej Wojcieszynski
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  HDR Ti-64 Material
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NDI
Chair: TBD
VC: TBD
Sec: Caitlin Oswald

General
Chair: TBD
VC: TBD
Sec: TBD

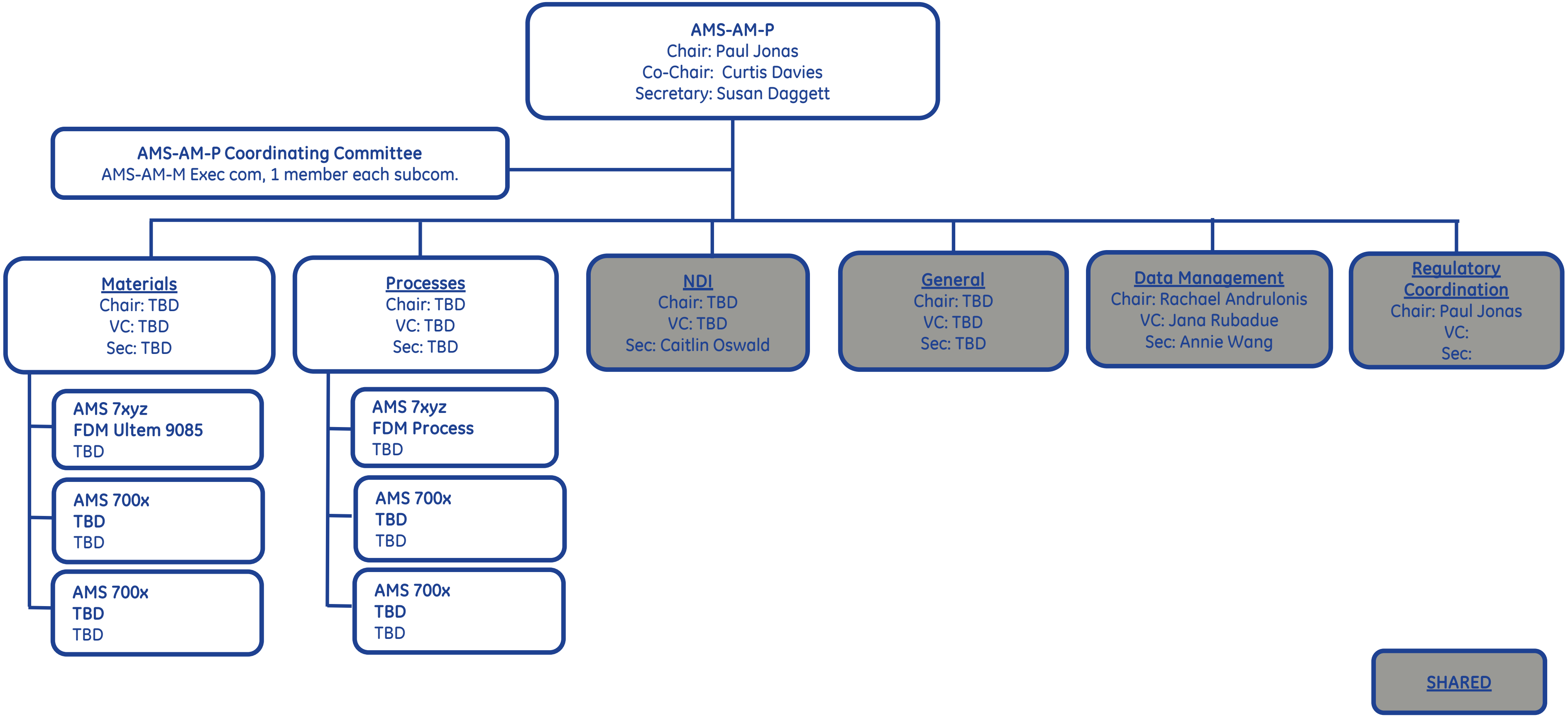
Data Management
Chair: Rachael Andrulonis
VC: Jana Rubadue
Sec: Annie Wang

Regulatory Coordination
Chair: Paul Jonas
VC:
Sec:

AMS 700x
EBPBF Ti-64
Adam Rivard

SHARED

AMS-AM-P Subcommittee – Current Organization



AMS-AM-P
Chair: Paul Jonas
Co-Chair: Curtis Davies
Secretary: Susan Daggett

AMS-AM-P Coordinating Committee
AMS-AM-M Exec com, 1 member each subcom.

Materials
Chair: TBD
VC: TBD
Sec: TBD

AMS 7xyz
FDM Ultem 9085
TBD

AMS 700x
TBD
TBD

AMS 700x
TBD
TBD

Processes
Chair: TBD
VC: TBD
Sec: TBD

AMS 7xyz
FDM Process
TBD

AMS 700x
TBD
TBD

AMS 700x
TBD
TBD

NDI
Chair: TBD
VC: TBD
Sec: Caitlin Oswald

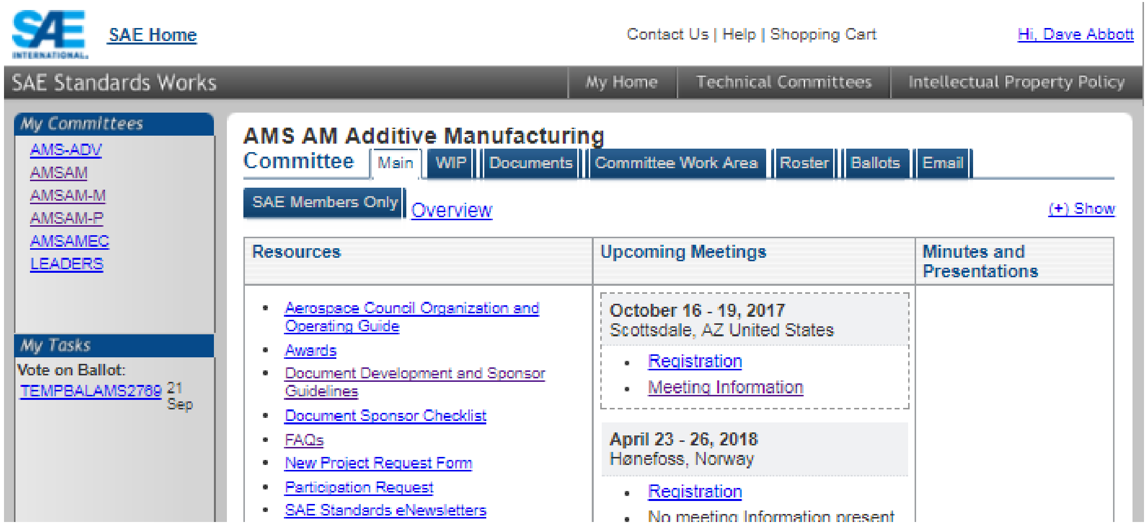
General
Chair: TBD
VC: TBD
Sec: TBD

Data Management
Chair: Rachael Andrulonis
VC: Jana Rubadue
Sec: Annie Wang

Regulatory Coordination
Chair: Paul Jonas
VC:
Sec:

SHARED

SAE AMS-AM Standards Works



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Hi, Dave Abbott

SAE Standards Works | My Home | Technical Committees | Intellectual Property Policy

My Committees

- AMS-ADV
- AMSAM
- AMSAM-M
- AMSAM-P
- AMSAMEC
- LEADERS

My Tasks

Vote on Ballot:
TEMPBALAMS2769 21 Sep

AMS AM Additive Manufacturing Committee

Main | WIP | Documents | Committee Work Area | Roster | Ballots | Email

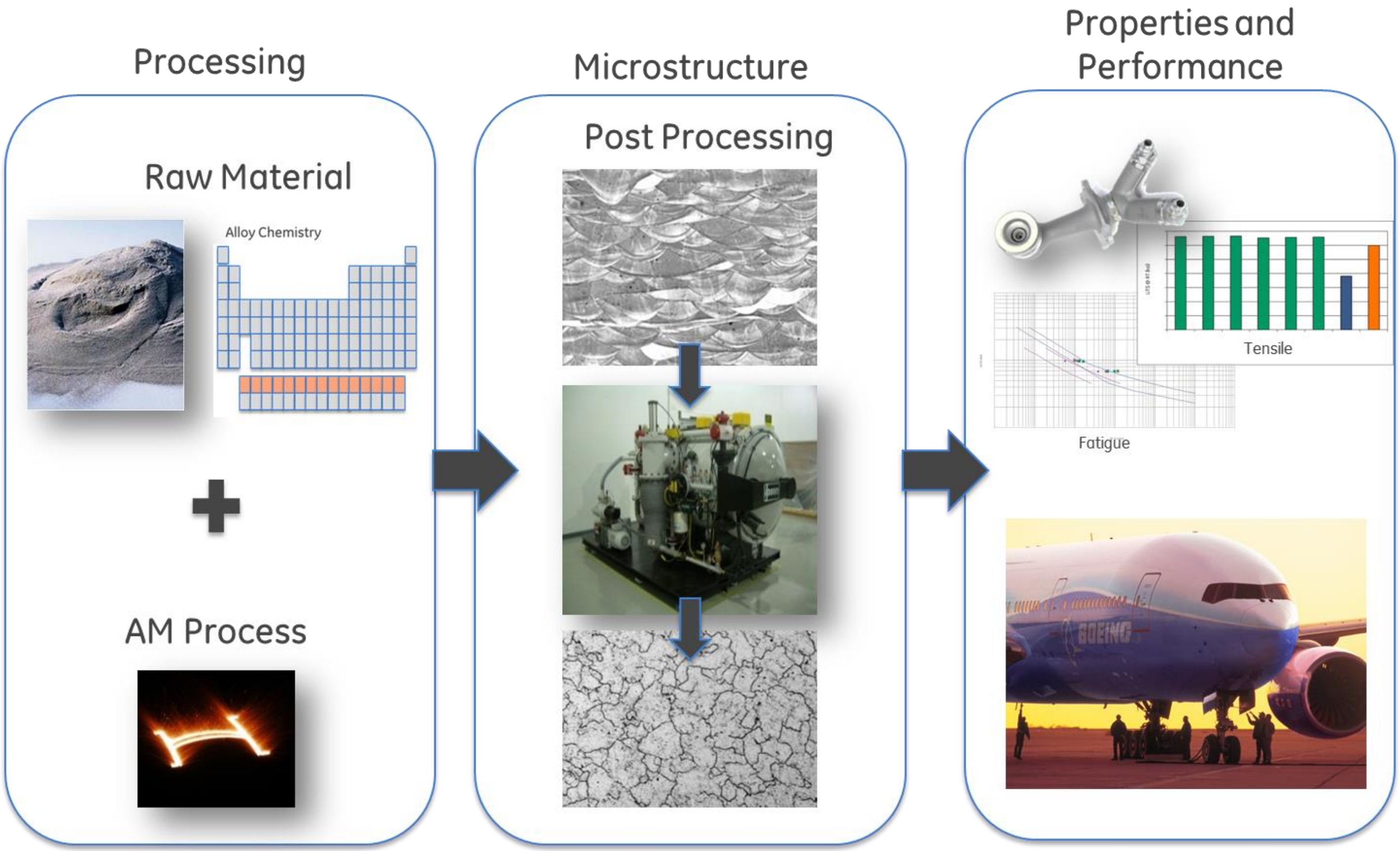
SAE Members Only | Overview | (+) Show

Resources	Upcoming Meetings	Minutes and Presentations
- Aerospace Council Organization and Operating Guide - Awards - Document Development and Sponsor Guidelines - Document Sponsor Checklist - FAQs - New Project Request Form - Participation Request - SAE Standards eNewsletters	**October 16 - 19, 2017** Scottsdale, AZ United States - Registration - Meeting Information **April 23 - 26, 2018** Hønefoss, Norway - Registration - No meeting Information present	

http://works.sae.org
Bookmark this site!

- All SAE technical committees use SAE standards works in the management of the committee.
- All useful documents, drafts, minutes, roster are accessed in Standards Works
- The site is secure owing to the nature of the material
- Committee processes – initiating documents, storing data, communicating, balloting, streamlined to allow fast and easy time-to-market

Additive Manufacturing Process Basics –



Processing

Raw Material

+

AM Process

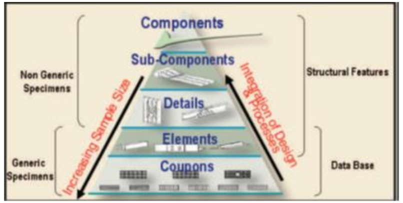
Microstructure

Post Processing

Properties and Performance

Control = Quality + Consistency

Increasing Degree of Complexity…

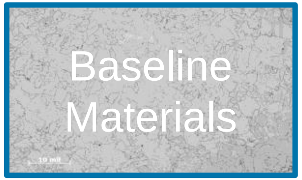


Advances in Composite Materials – Ecodesign and Analysis
Edited by Dr. Brahim Attaf

AM Materials

Commodity

- Recrystallization
- Equiaxed
- Homogeneous
- Isotropic

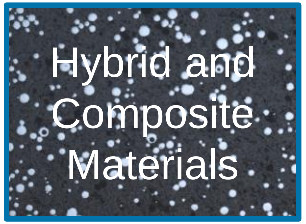


Tailored Microstructure

- Monolithic
- Continuous
- Some degree of anisotropy
- Some inhomogeneity

Composite

- Discrete phases
- Anisotropic
- inhomogeneous



AMS-AM Today → Future

Increasing Complexity

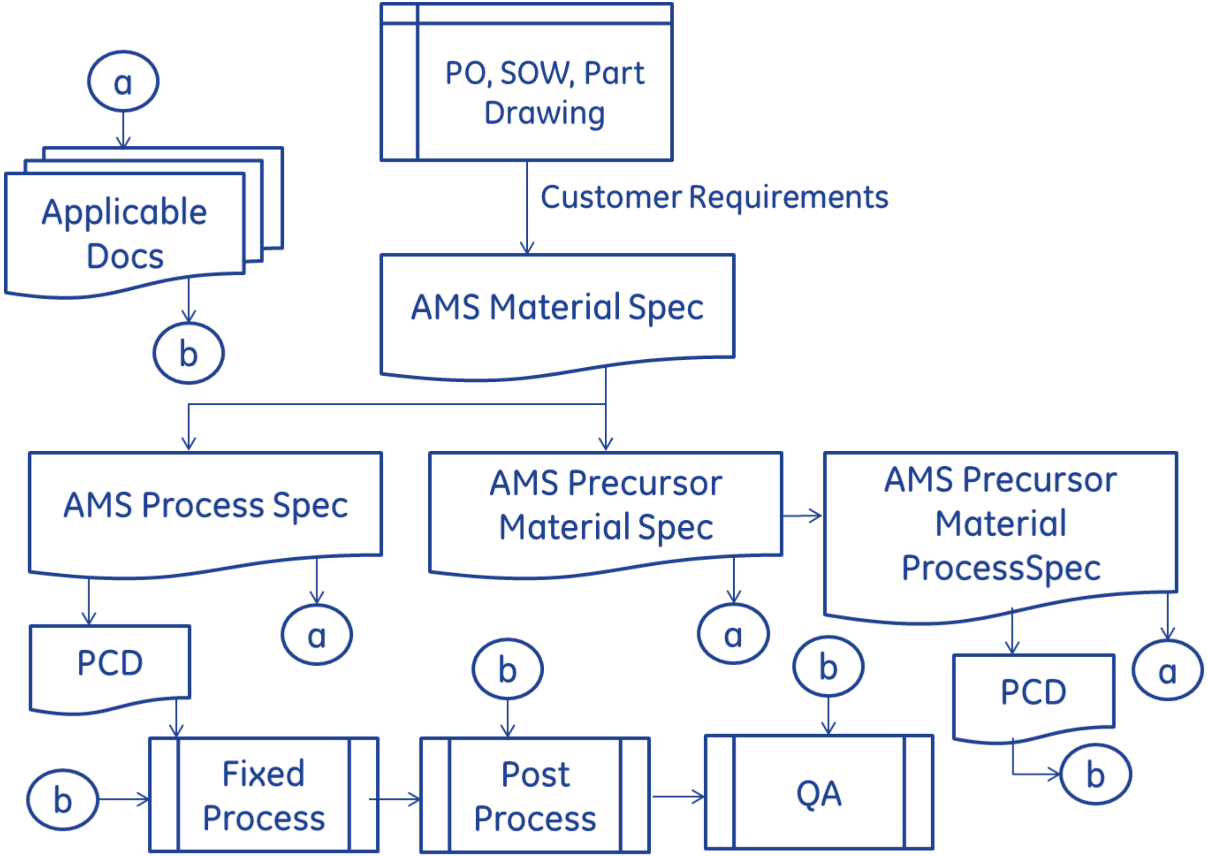
Keeping an Eye on the Future.

Specification Hierarchy

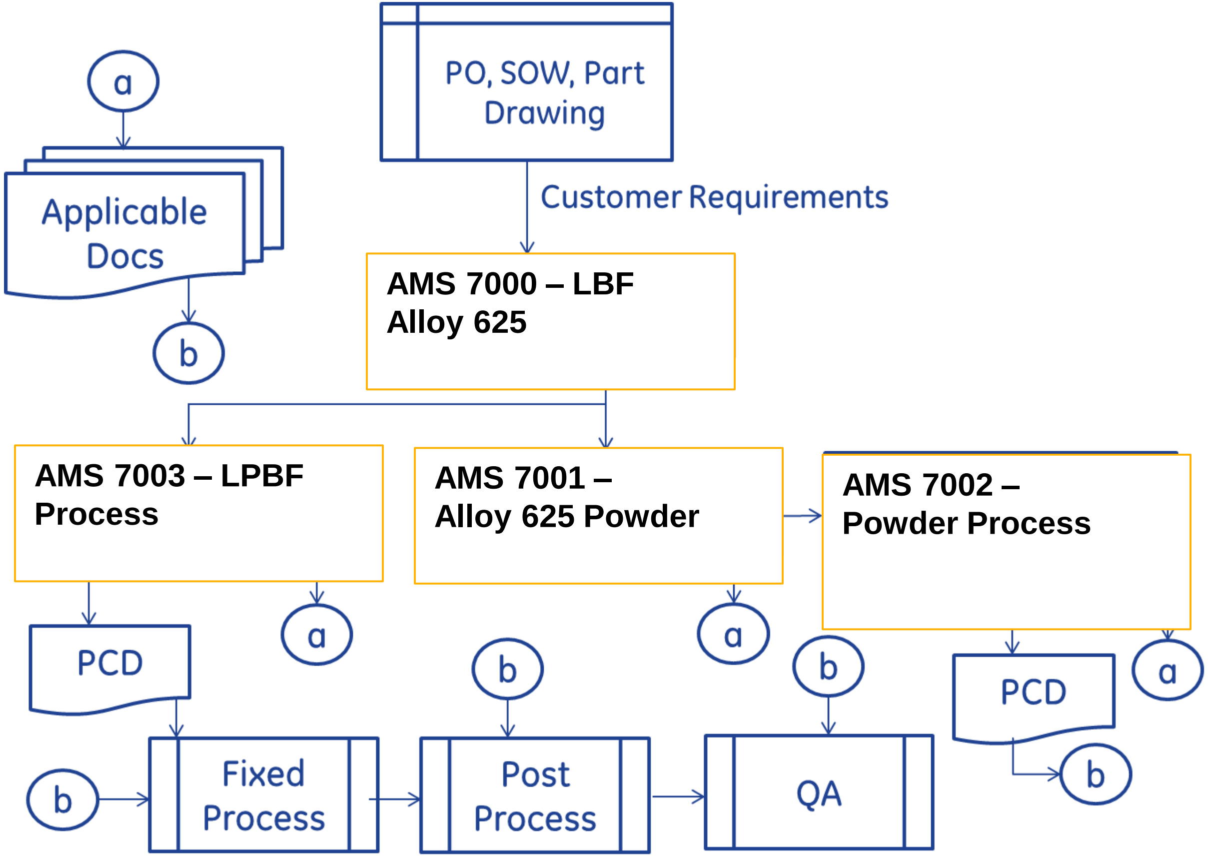
- **Material Specification … material requirements**
  - **Process Specification**
  - **Feedstock Material Specification**
    - **Feedstock Process Specification**

- **Hierarchical**
- **Defines requirements and establishes controls**
- **Performance-based and Pseudo-prescriptive (establish controls and provide substantiation)**

Flowchart – Specification Hierarchy



Specification Hierarchy Applied to First AMSAM Set of Specifications



Working Groups Update

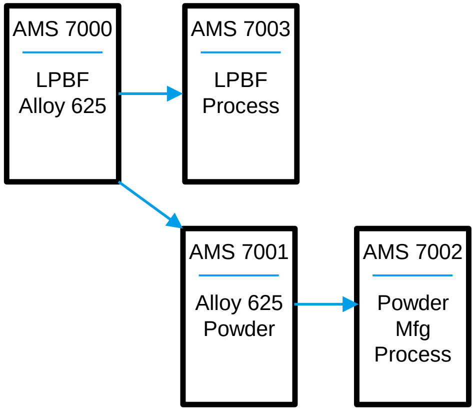
- Validating specifications via two working groups:

WG002 Specification Audit Working Group

- Evaluate specifications together as a single entity to check for completeness, conflicts, overlaps or any other issues.

WG003 Stress Test Working Group

- Simulate purchasing of a part made with material to AMS 7000 LPBF Alloy 625
- Two part geometries including 3D CAD models and drawing definition with notes tailored to AM.
- Currently creating purchasing documents (RFQ, SOW).

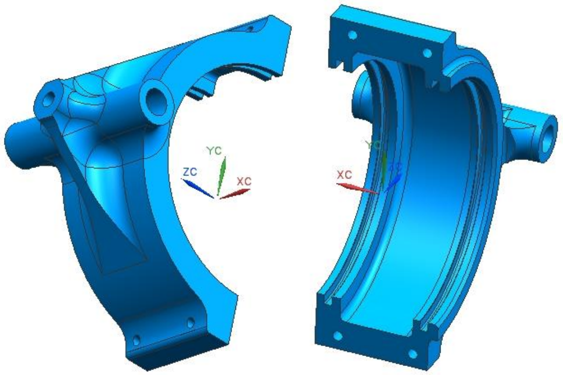


AMS 7000 — LPBF Alloy 625

AMS 7003 — LPBF Process

AMS 7001 — Alloy 625 Powder

AMS 7002 — Powder Mfg Process



Customization – Specification Minimums

- Specification Minimums:
  - Statistically-based methods
  - Conventional methodology.
  - Standard Number of Heat and Lot requirements.
    - May customize to better capture natural variation of process.
  - Heat and Lot definitions tailored to AM.
    - Leveraging ISO/ASTM 52900
    - Augmenting to SAE AMS requirements

Mechanical Property	**Statistical Basis**	**Minimum Data Requirements per orientation**			**Format**^{2}
		Sample Size^1	**No. of Heats (chemistries)**	**No. of Lots**	
Tensile Yield or Ultimate Strength, or Compression Yield Strength	Specification minimum	30	3	3	Excel (may use MMPDS tensile data template)
Elongation	Specification minimum	30	3	3	Same template as tensile data
Reduction in Area	Specification minimum	30	3	3	
Plane-Strain Fracture Toughness^3	Specification minimum	30	3	3	Excel (may use MMPDS fracture template)

1. For additively manufactured products, minimum per as-built thickness range. Exception when there is a significant thickness effect and regression analysis may be used per MMPDS guidelines. A reasonable number of samples should be used to span the thickness range. Small sample sizes must meet guidelines for uniformity across thickness range as detailed in SAE guidelines noted above and MMPDS. True uniformity is not required. Contact www.mmpds.org with questions.
2. For MMPDS data templates, contact www.mmpds.org.
3. See AMS statistical guidelines for aluminum materials regarding use of K_q.

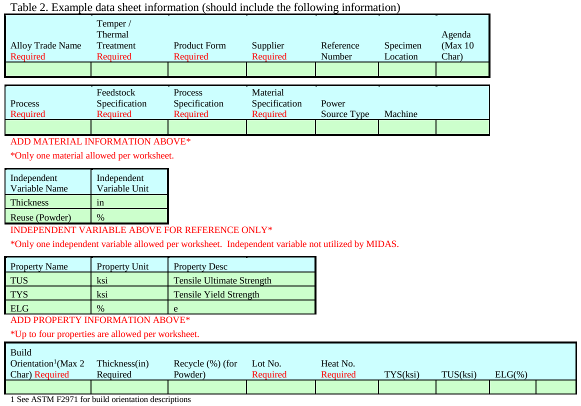


Table 2. Example data sheet information (should include the following information)

Alloy Trade Name Required	Temper / Thermal Treatment Required	Product Form Required	Supplier Required	Reference Number	Specimen Location	Agenda (Max 10 Char)

Process Required	Feedstock Specification Required	Process Specification Required	Material Specification Required	Power Source Type	Machine	

ADD MATERIAL INFORMATION ABOVE*

*Only one material allowed per worksheet.

Independent Variable Name	Independent Variable Unit
Thickness	in
Reuse (Powder)	%

INDEPENDENT VARIABLE ABOVE FOR REFERENCE ONLY*

*Only one independent variable allowed per worksheet. Independent variable not utilized by MIDAS.

Property Name	Property Unit	Property Desc
TUS	ksi	Tensile Ultimate Strength
TYS	ksi	Tensile Yield Strength
ELG	%	e

ADD PROPERTY INFORMATION ABOVE*

*Up to four properties are allowed per worksheet.

Build Orientation[1](Max 2 Char) Required	Thickness(in) Required	Recycle (%) (for Powder)	Lot No. Required	Heat No. Required	TYS(ksi)	TUS(ksi)	ELG(%)	

1 See ASTM F2971 for build orientation descriptions

Benefits of AM Industry Consensus Specifications

- **Puts in place the appropriate requirements and controls to ensure consistency and quality in the final product**
- **Enables public material property database with verifiable pedigree**
- **Foundational for regulatory acceptance and certification processes**
- **Ensures a level playing field for existing and future participants in the AM industry**

2017 Fall Meeting

- October 16-19, 2017
- Wild Horse Pass Hotel & Casino, Chandler, AZ
- Sponsor: LAI International Inc
- Planned Activities
  - 28-day ballot results LPBF-625 specifications
  - Includes Polymer Subcommittee face-to-face meeting
  - New specifications
    - *EBM and PTAW of titanium alloys*

QUESTIONS?

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APPENDIX X—PROPOSED COLLABORATION APPROACH TO PROCESS AND MATERIALS CHARACTERIZATION EFFORTS

Brian A. Hann
August 30, 2017
2017 FAA CSTA/AFRL Workshop for Additive Manufacturing

PROPOSED COLLABORATION APPROACH TO PROCESS AND MATERIALS CHARACTERIZATION EFFORTS

Honeywell
THE POWER OF **CONNECTED**

Materials Characterization Acceleration

- **Problem Statement**: Aerospace customers require material strength properties to be based on enough tests of material meeting approved specifications to establish design values on a statistical basis. Design values in MMPDS (for metallic materials) and the statistical methods outlined therein (for materials not detailed MMPDS) are generally recognized by our customers and regulators. These efforts typically require **500+ tests** to characterize a new material and **18+ months**.
  - Not atypical to exceed $1M per materials
- **Proposed Approach:** Identify customer / supplier / non-competitor to partner in process development, specification development, and design allowable generation.

Opportunity to reduce individual cost by >50% and schedule by >33%

Serial Approach to Process Development and Data Generation

Phase 1 - Build Parameter Development

- Optimize powder size / distribution – Includes down-select of atomization gas / build environment
- Minimize cracking / porosity
- Emphasis on robust parameter development
- Draft powder specification

Phase 2 – Post-build Process Development

- Stress-relief
- HIP
- Heat treatment (Solution and Age)
- NDT Method Development
- Draft Materials Specification

Phase 3 – Design Data Builds, considering:

- Machined and as-built surfaces
- Orientation effects
- Representative build volume
- Representative post-build thermal processing

Phase 4 – Scalability to Part / Data Analysis

- Cut from part testing
- Fractography (to identify failure modes)
- Statistical Analysis / Modeling

Phase 5 – Release Allowables for Design

- Finalize Specifications
- Approve Suppliers
- Pursue opportunities for production

Phase 6 – Substantiation

- Allowables serve as basis for fixed process substantiation, new machine qualification, or new supplier qualification

Example Test Matrix

			Powder Lot										
		Test	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Total
			HON			**Partner A**			**Partner B**			**HON**	
Tensile	1	Tension Yield, Ultimate, Elongation (room temp)	12	12	12	12	12	12	12	12	12	12	120
	2	Effect of temperature on Tensile properties	4	4	4		4		4		4		24
	3	Effect of wall thickness of tensile properties	4			4		4		4		4	20
	4	Effect of thermal exposure (hardness + tensile)		4			4		4		4		16
	5	Effect of notch on tensile properties	6			6			6				18
	6	Effect of welding on tensile properties		2	2		2	2		2	2		12
	7	Effect of brazing on tensile properties	3			3			3			3	12
Physical	8	Thermal Conductivity	2			2			2				6
	9	CTE	2			2			2				6
	10	Elastic Modulus	2			2			2				6
	11	Shear Modulus	2			2			2				6
	12	Density	1			1			1				3
Fatigue	13	Low Cycle Fatigue (smooth bar)	12	12	12	12	12	12	12	12	12	12	120
	14	Low Cycle Fatigue, impact of surface treatment		4			4			4			12
	15	Low Cycle Fatigue, Impact of surface finish (as-built)			4			4			4		12
	16	Effect of notch on LCF	2	2	2	2	2	2	2	2	2	2 spares	20
	17	High Cycle Fatigue (smooth bar)	6	6	6	6	6	6	6	6	6	6 spares	60
	18	High Cycle Fatigue, impact of surface finish (as-built)	4			4			4				12
Corrosion	19	Environmental Testing		4			4			4			12
FCGR	20	Fracture Toughness			2			2			2		6
	21	Crack growth	2			2			2				6
		Total Test Bars	64	50	44	60	50	44	64	46	48	31	509

Advantages

- Significantly reduced cost and schedule
- Captures sources of variation
  - Powder supplier to powder supplier
  - Powder lot to powder lot
  - Machine manufacturer to machine manufacturer
  - Machine to machine
  - Build to build
  - Within build
  - Powder re-use
  - Post-build processing
- Increased awareness of other equipment
- Provides opportunity to share with SDO’s (for industry-standard materials)

Expectation is that customers accept this approach

QUESTIONS?

Honeywell
THE POWER OF **CONNECTED**

APPENDIX Y—AM RESEARCH AT THE FRAUNHOFER AND RWTH AACHEN UNIVERSITY

AM Research at the Fraunhofer ILT and RWTH Aachen University

FAA – USAF workshop on Qualification and Certification of Additively Manufactured parts

30 August 2017, Dayton

M.Sc. Robin J. Day

Fraunhofer ILT

DAP Digital Additive Production

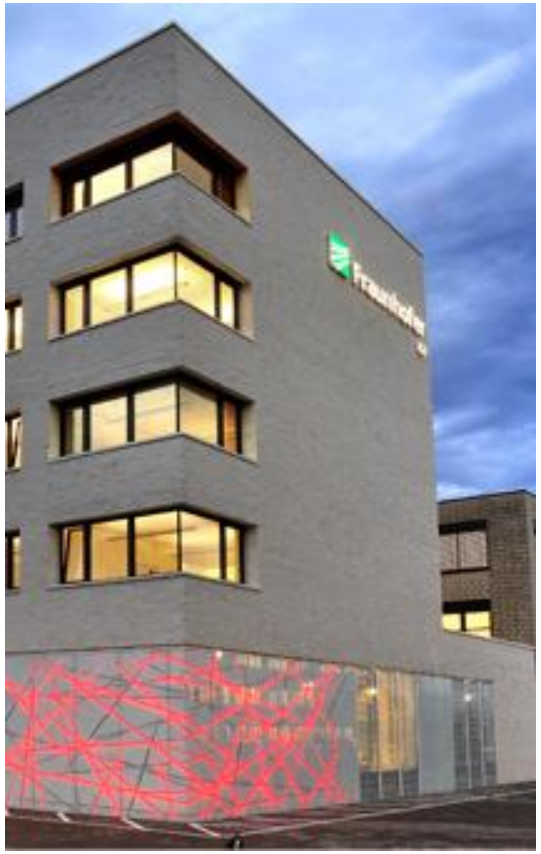
RWTH AACHEN UNIVERSITY

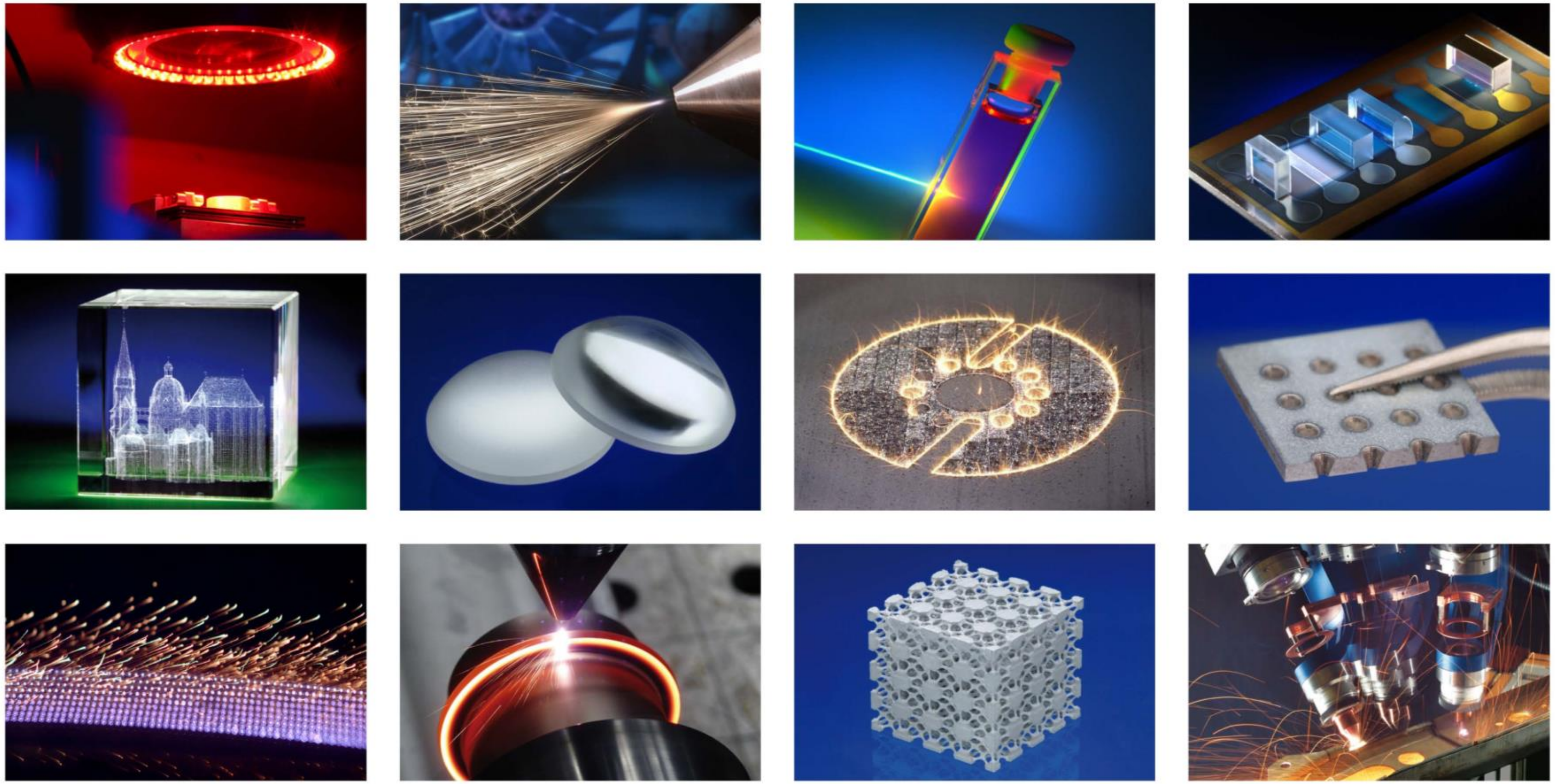
Agenda

Introduction

Fraunhofer ILT

Tailor-made Solutions





Innovation Management

Mission Statement

Knowledge Management

Strategy Plan

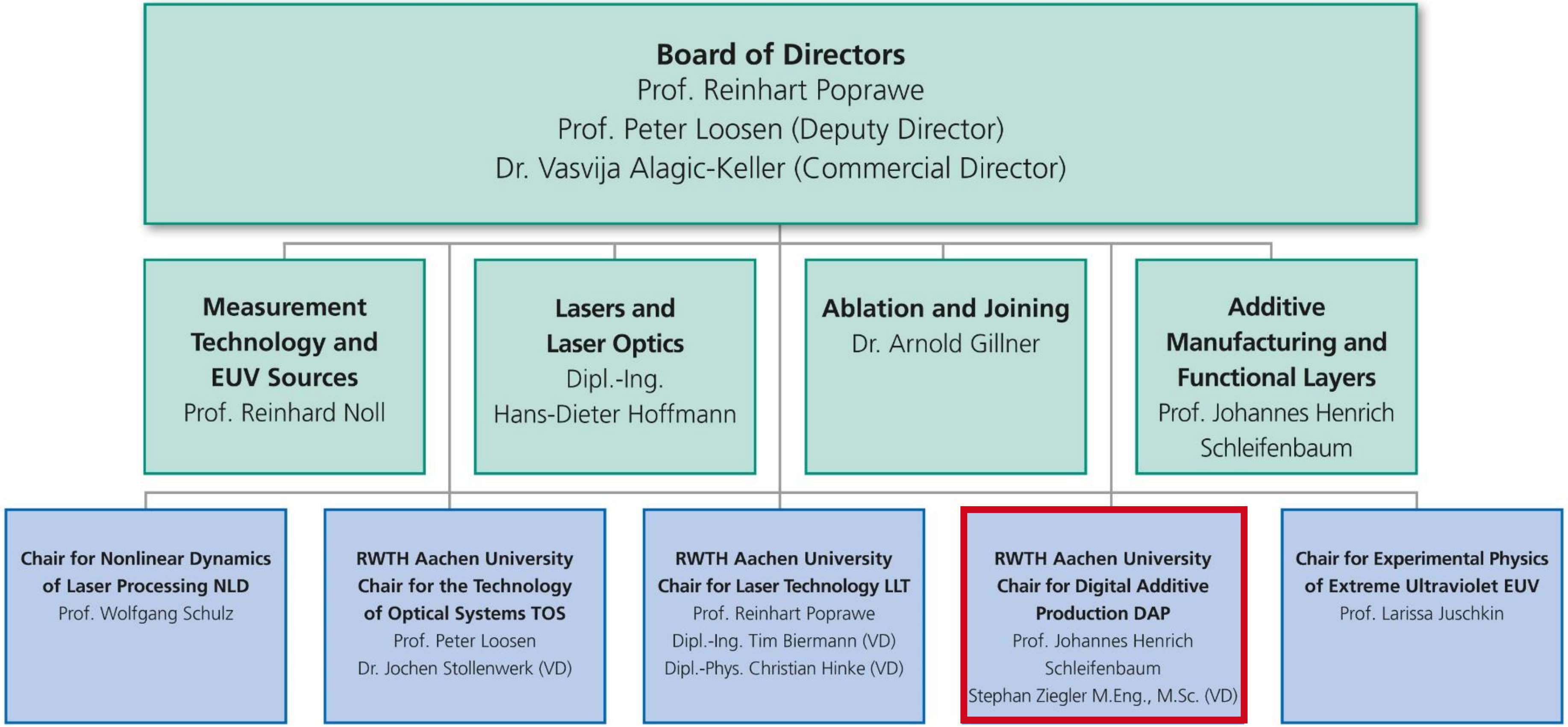
Core Areas / Business Areas
Technology / Product
Roadmaps

Methods / Professional Competence

Quality Management System

DIN ISO 9001

Fraunhofer ILT and RWTH Aachen University



Board of Directors
Prof. Reinhart Poprawe
Prof. Peter Loosen (Deputy Director)
Dr. Vasvija Alagic-Keller (Commercial Director)

Measurement Technology and EUV Sources
Prof. Reinhard Noll

Lasers and Laser Optics
Dipl.-Ing.
Hans-Dieter Hoffmann

Ablation and Joining
Dr. Arnold Gillner

Additive Manufacturing and Functional Layers
Prof. Johannes Henrich Schleifenbaum

Chair for Nonlinear Dynamics of Laser Processing NLD
Prof. Wolfgang Schulz

RWTH Aachen University Chair for the Technology of Optical Systems TOS
Prof. Peter Loosen
Dr. Jochen Stollenwerk (VD)

RWTH Aachen University Chair for Laser Technology LLT
Prof. Reinhart Poprawe
Dipl.-Ing. Tim Biermann (VD)
Dipl.-Phys. Christian Hinke (VD)

RWTH Aachen University Chair for Digital Additive Production DAP
Prof. Johannes Henrich Schleifenbaum
Stephan Ziegler M.Eng., M.Sc. (VD)

Chair for Experimental Physics of Extreme Ultraviolet EUV
Prof. Larissa Juschkin

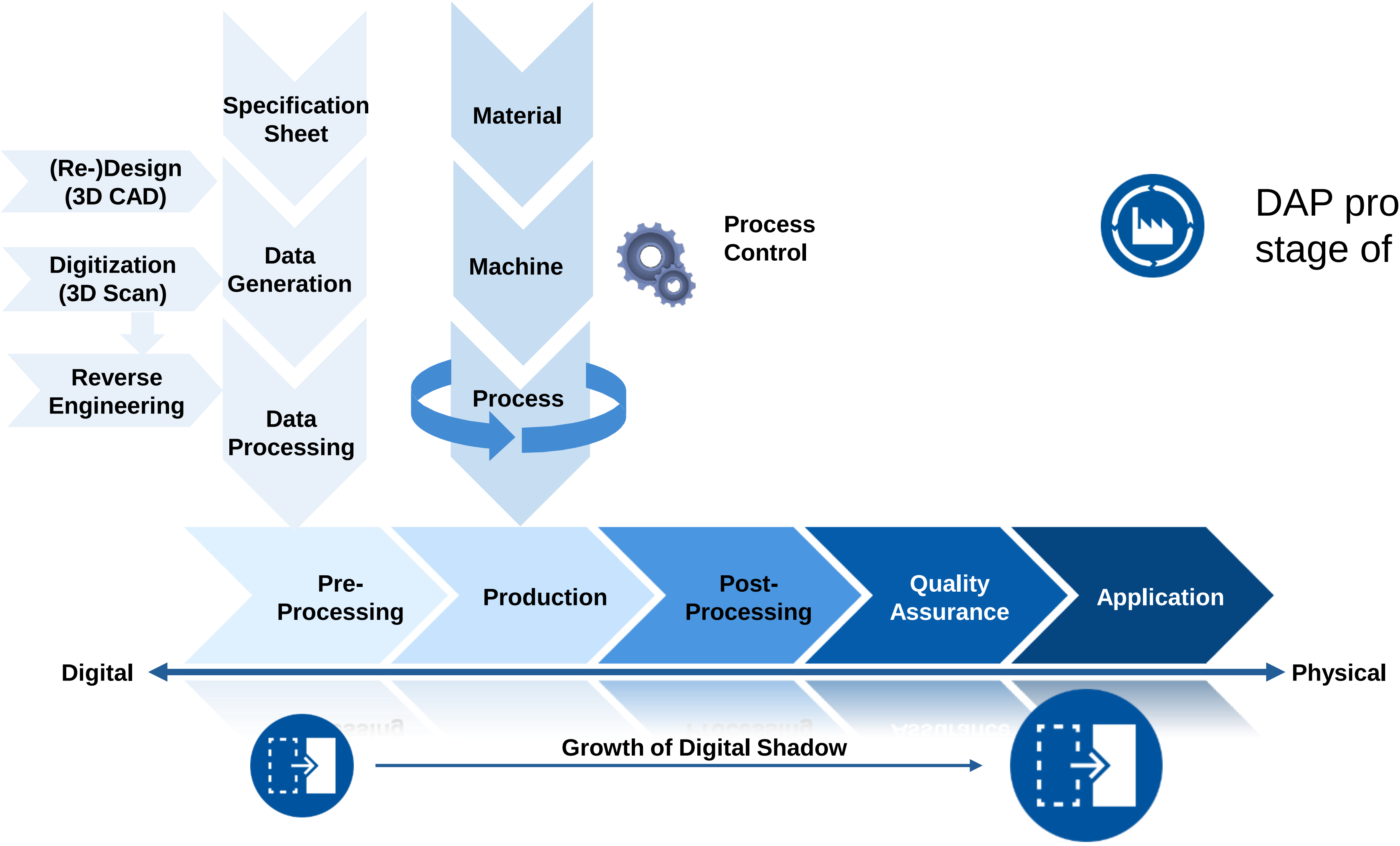
RWTH Aachen University - Digital Additive Production DAP

Industrial Application

Digital Twin / Software

Consulting / Education

RWTH Aachen University - Digital Additive Production DAP



(Re-)Design (3D CAD)

Digitization (3D Scan)

Reverse Engineering

Specification Sheet

Data Generation

Data Processing

Material

Machine

Process

Process Control

Pre-Processing

Production

Post-Processing

Quality Assurance

Application

Digital

Physical

Growth of Digital Shadow

DAP provides support at every stage of the AM process chain.

RWTH Aachen University - Digital Additive Production DAP
Available SLM systems

EOS
M270
$P_L \leq 200$ W

Realizer
SLM 50
$P_L \leq 120$ W

EOS
Formiga P110
$P_L \leq 30$ W (CO2)

EOS
M290
$P_L \leq 400$ W

Aconity
ONE
$P_L \leq 400$ W

Trumpf
TrumaForm
$P_L \leq 1000$ W

Concept
X-Line2000
$P_{L1} \leq 1000$ W
$P_{L2} \leq 1000$ W

Aconity
MIDI & MINI
$P_L \leq 1000$ W
$P_L \leq 400$ W

Laboranlagen – Eigenentwicklungen:

5x ILT Machines
$P_L \leq 200$ W
$P_L \leq 400$ W
$P_L \leq 500$ W
$P_L \leq 600$ W (CO_2)
$P_L \leq$ 5x 200 W

Concept
M1
$P_L \leq 400$ W (1500 W)

SLM Solutions
280 HL Twin
$P_{L1} \leq 400$ W
$P_{L2} \leq 400$ W

RWTH Aachen University - Digital Additive Production DAP
Process parameters available for almost any metal powder

Steel

- 1.2083
- 1.2343
- **1.2344**
- **1.2709**
- **1.4404**
- **1.4540**
- **1.4542**

Aluminium

- **AlSi9Cu3**
- **AlSi12**
- **AlSi7Mg**
- **AlSi10Mg**
- **AlMgSc**

Super Alloys

- **Hastelloy X**
- **IN625**
- **IN718**
- IN738
- IN738LC
- **IN939**
- MAR M247
- MAR M509
- René142

Titanium

- **Ti6Al4V**
- **Ti Grade 2**

Magnesium

- AZ91
- WE43

Copper

- CuCrZr (K150)
- CuNiSi (K220)
- CuNiCo (K265)

CoCr Alloys

- **CoCr (ASTM F75)**
- **CoCrMP1**
- **CoCrSP2**

R&D

- 1.7131 (16MnCr5)
- Hartmetalle (WC-Co)
- Al-CNT
- Mg-Ca-Zn
- PLA-CC (Polymer)
- Ti-/Fe-Aluminide
- …

Research Activities

Research Activities

Digital Additive Production

Excellence Cluster

ICTM

CDPP

FRI-FDM

Ford

Lattice Structure

VDMA

Digital Material

DPP

Kärcher

Research Activities

Digital Additive Production

Excellence Cluster

ICTM

CDPP

FRI-FDM

Ford

Lattice Structure

VDMA

Digital Material

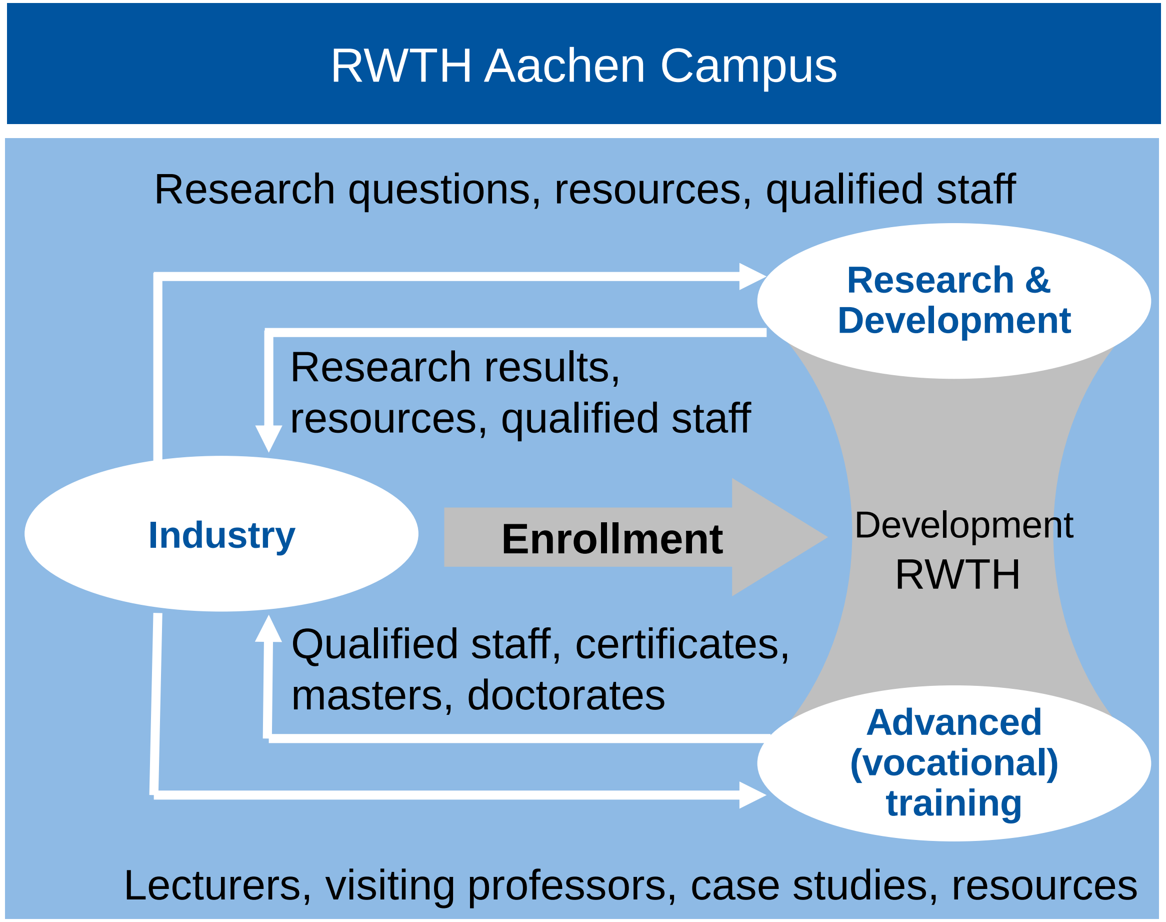
DPP

Kärcher

Digital Photonic Production

DPP

Cooperation between Industry und RWTH



RWTH Aachen Campus

Research questions, resources, qualified staff

Research & Development

Research results, resources, qualified staff

Industry

Enrollment

Development RWTH

Qualified staff, certificates, masters, doctorates

Advanced (vocational) training

Lecturers, visiting professors, case studies, resources

Symbiosis of Science and Industry

- Holistic and systemic research
- Demand-oriented integration of skills and disciplines
- Consolidation of cooperation
- Attractive service offerings
- Clear assignment of roles and responsibilities
- Access to resources and technology
- Use of synergies effects and economies of scale

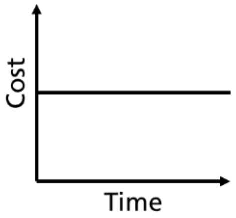
DPP

Machine Transferability

Approaches

Transferability

Creating experience

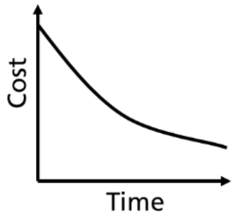


- Standardized qualification build job
- Machine characterization
- Part quality classification

- Short term: fixed qualification of single machines

Creating knowledge

- Process understanding
- Standardized machine requirements
- Standardized, knowledge-based machine tuning
- Machine classification with reduced qualification

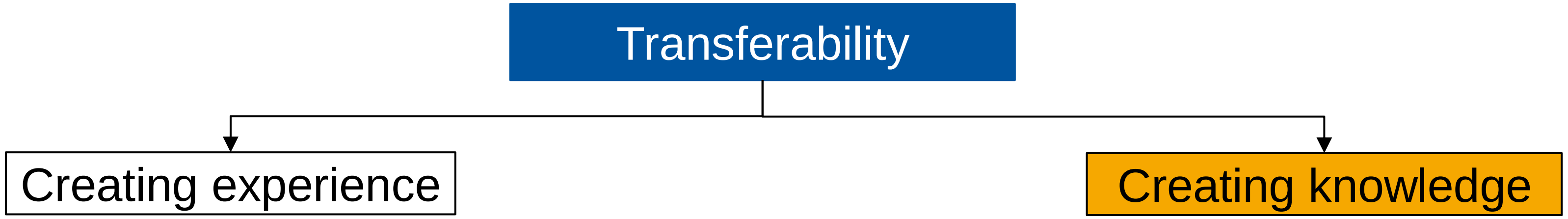


- Mid term: Adapted qualification of machine types

Machine Transferability

DPP

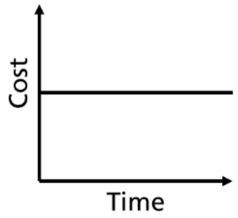
Approaches



Transferability

Creating experience

Creating knowledge



- Standardized qualification build job
- Machine characterization
- Part quality classification

- Process understanding
- Standardized machine requirements
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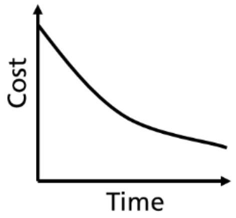


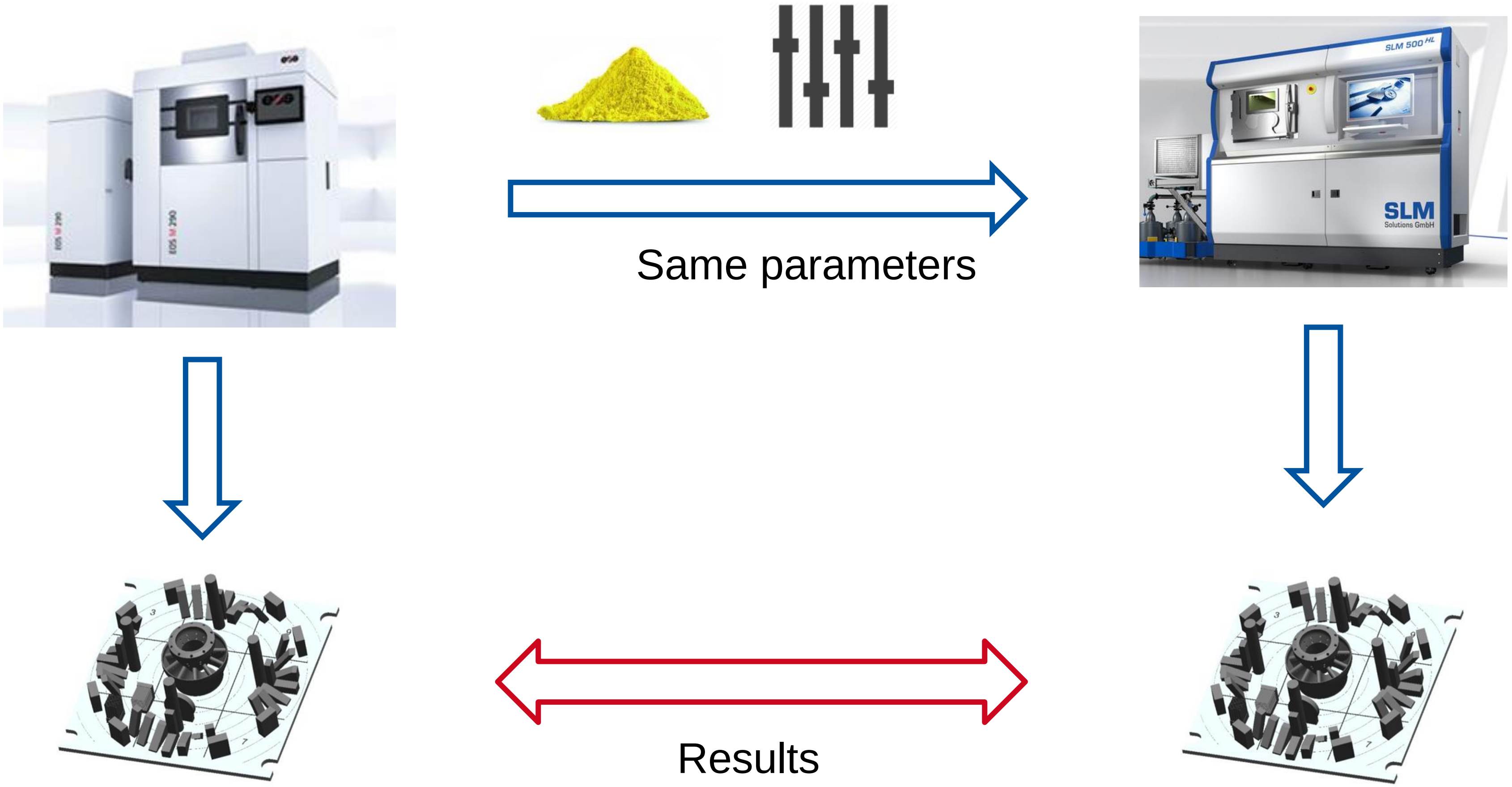
➢ Short term: fixed qualification of single machines

➢ Mid term: Adapted qualification of machine types

Machine Transferability

DPP

Creating Knowledge



Same parameters

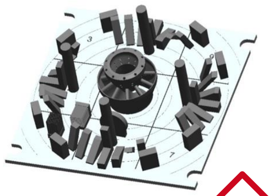
Results

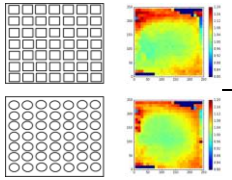
- Same environment produces same parts
- Comparison of results between to machines

Machine Transferability

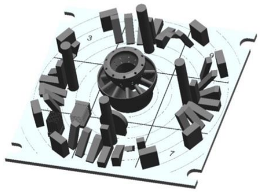
DPP

Machine 1





Δ Results



Machine 2

Beam Properties → e.g. Scanspeed

Shield Gas → e.g. Turbulence

Layer Preparation → e.g. Double Coating

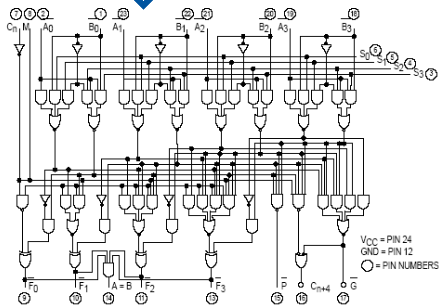
Machine Quality

Part Quality

Density

Roughness

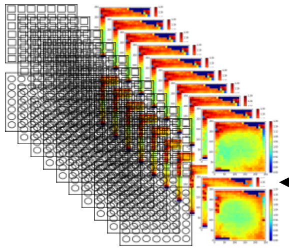
Strength

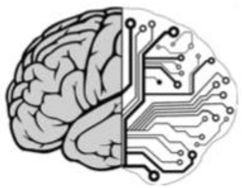


- Explain ΔResults by understanding the cause effect correlation between machine and part quality

Machine Transferability

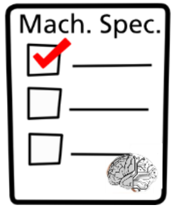
DPP

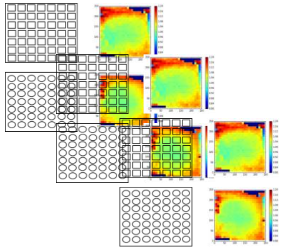


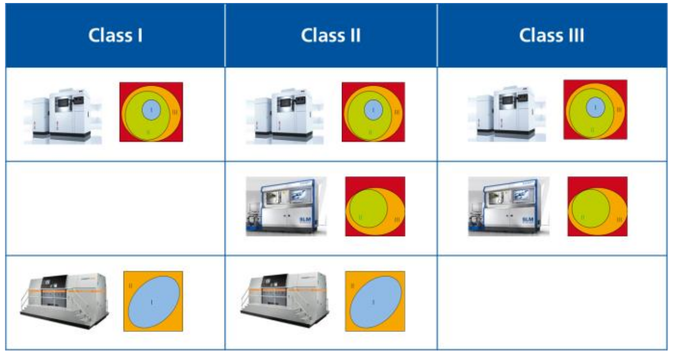


Knowledge Based

Tune to







Class I	Class II	Class III

- Reduce qualification jobs

- Tune machine to certain properties and quality

- Create machine specification for machine acceptance

Future Challenges and Trends

Challenges and Trends

Introduction of AM Processes into Production

1. Specialized personal required
   - There is no specific “AM-engineer” available
   - Almost no practical training in LMD / SLM available
   - Application of AM requires change of mind in the head of designers and engineers

2. Lack of documented (and free of IP) accessible knowledge
   - On-going process which is addressed by universities, research institutes and organized collaborations like ICTM

3. Lack of standards for powder, process and part qualification
   - Strong focus in current R&D projects and responsible standardization associations (DIN, CEN, ISO…)

Challenges and Trends

Technical Perspective

4. Increase of productivity to reduce part costs
   - Increase fraction of value-adding process steps (100 % laser on time)
   - Parallelization of scanning process (multi spot systems)
   - Application or part specific machine concepts

5. Process robustness and transferability of process parameters

6. Suitable QM systems to reduce required effort for inspection
   - Increase understanding of important and unimportant boundary conditions which SLM systems need to provide
   - Process monitoring systems are being developed at the moment and are already partially available

Challenges and Trends

Technical Perspective

7. Availability of materials with suitable high temperature capabilities
   - ➢ Improved processing strategies
     - ▪ Preheating
     - ▪ Local adaptation of solidification conditions …
   - ➢ Modification of chemical compositions
   - ➢ New materials specifically developed for AM processes

8. Surface roughness of complex geometries with inaccessible surfaces
   - ➢ New process strategies and finishing methods
     - ▪ Pulsed lasers during manufacturing
     - ▪ Electropolishing as post-processing …
   - ➢ Improve understanding of the impact of internal surface roughness on part properties

Photonics Cluster

Stakeholder

Research Building CDPP	Fraunhofer ILT und IPT	Industry Building DPP

Forschungscampus Digital Photonic Production

RWTH AACHEN UNIVERSITY

RWTH-I³ (planned)

present	5	RWTH Chairs
future	10	RWTH Chairs

Fraunhofer ILT

Fraunhofer IPT

20 Partners from Industry

TRUMPF, BMW, INNOLITE TAILORED MOLDS AND OPTICS, MTU Aero Engines, AMPHOS, SIEMENS, PHILIPS

Photonics Cluster

Concept and Buildings

Research Building CDPP

Fraunhofer ILT und IPT

Industry Building DPP

Forschungscampus Digital Photonic Production

DFG-Collaborative Research Centres

DFG-Research Groups

DFG-Cluster of Excellence

DFG-Projects

BMBF-Collaborative Research

European Projects

Fraunhofer Strategic Research

Fraunhofer Leistungszentrum

AiF-Projects

Bilateral Research Contracts

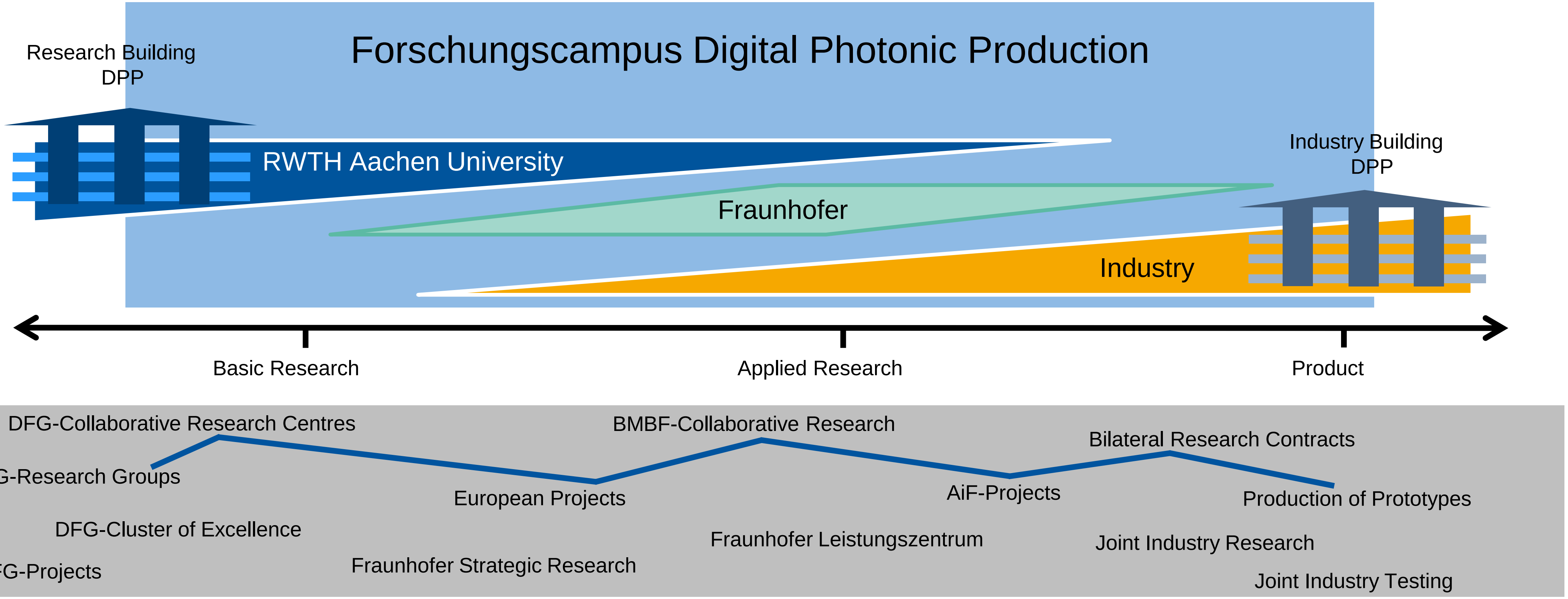
Production of Prototypes

Joint Industry Research

Joint Industry Testing

Photonics Cluster

Concept and Structure



Forschungscampus Digital Photonic Production

Research Building
DPP

RWTH Aachen University

Fraunhofer

Industry Building
DPP

Industry

Basic Research

Applied Research

Product

DFG-Collaborative Research Centres

BMBF-Collaborative Research

Bilateral Research Contracts

DFG-Research Groups

European Projects

AiF-Projects

Production of Prototypes

DFG-Cluster of Excellence

Fraunhofer Leistungszentrum

Joint Industry Research

DFG-Projects

Fraunhofer Strategic Research

Joint Industry Testing

Photonics Cluster

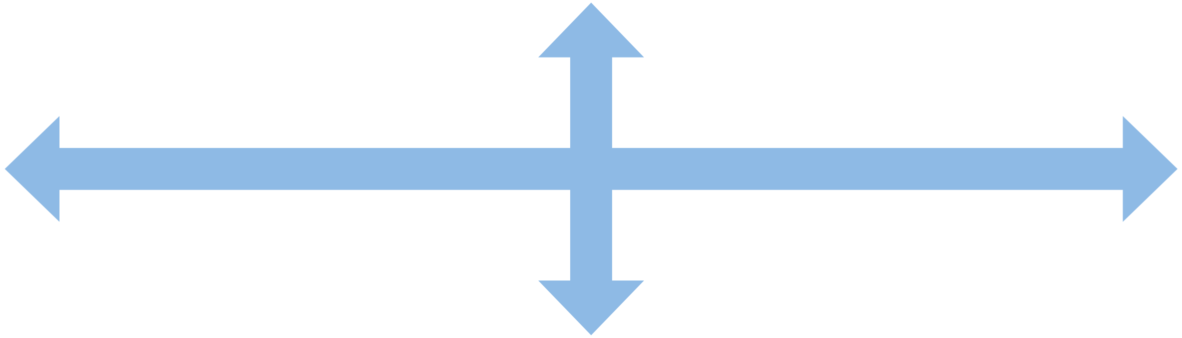
Vast network, outstanding know-how, excellent solutions.

LLT Chair for Laser Technology

DAP Digital Additive Production

RWTH AACHEN UNIVERSITY

TOS Lehrstuhl für Technologie Optischer Systeme

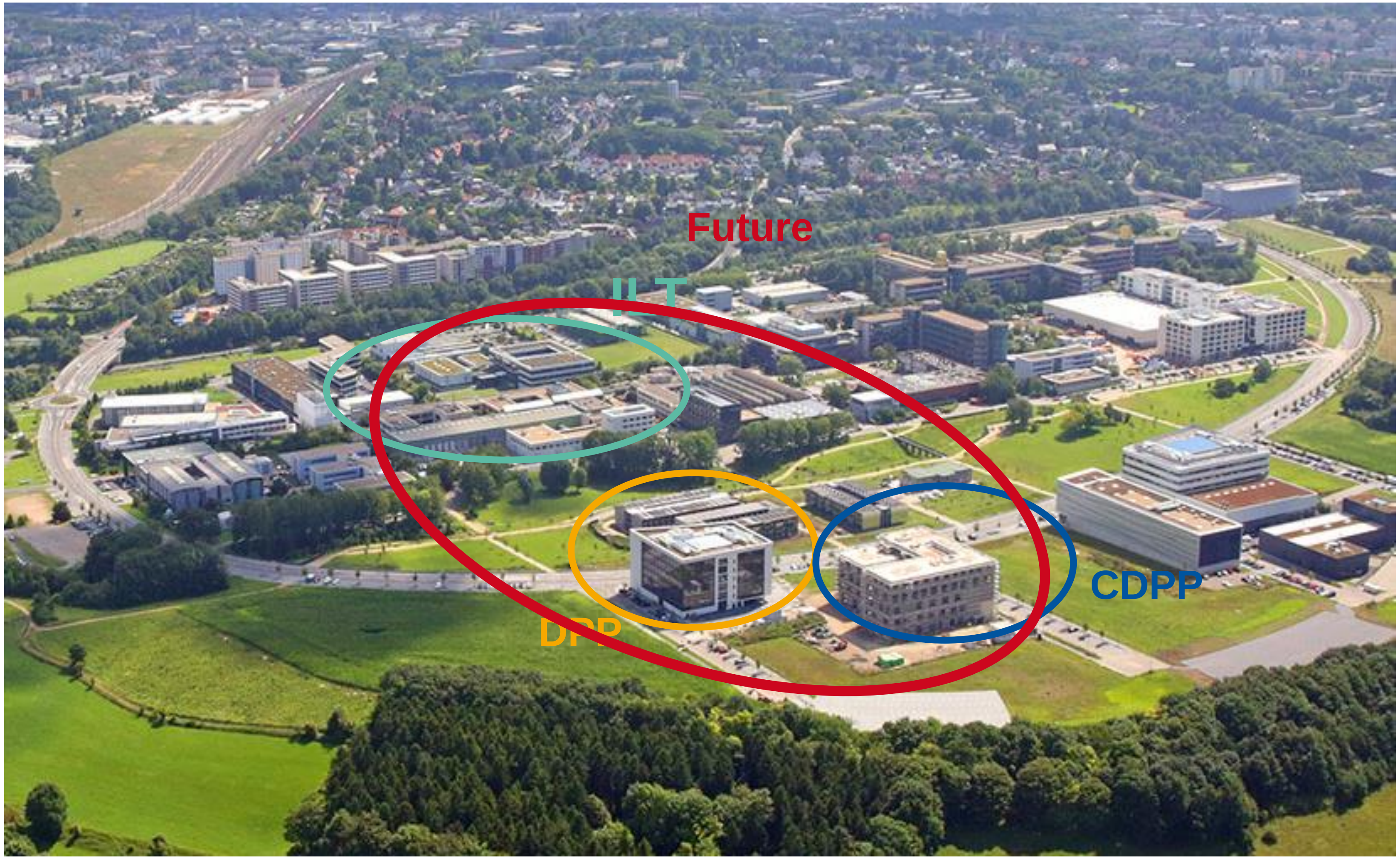


Center Digital Photonic Production CDPP

Digital Photonic Production DPP

Fraunhofer ILT

Photonics Cluster



Now it's your turn

Questions, Inputs, Feedback

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Univ.-Prof. Dr.-Ing. Dipl.Wirt.-Ing.
Johannes Henrich Schleifenbaum

APPENDIX Z—OVERVIEW OF NRC ADDITIVE MANUFACTURING ACTIVITIES AND TECHNOLOGY DEVELOPMENT

NRC·CNRC

National Research Council of Canada

Overview of Additive Manufacturing Activities

2017-08-29

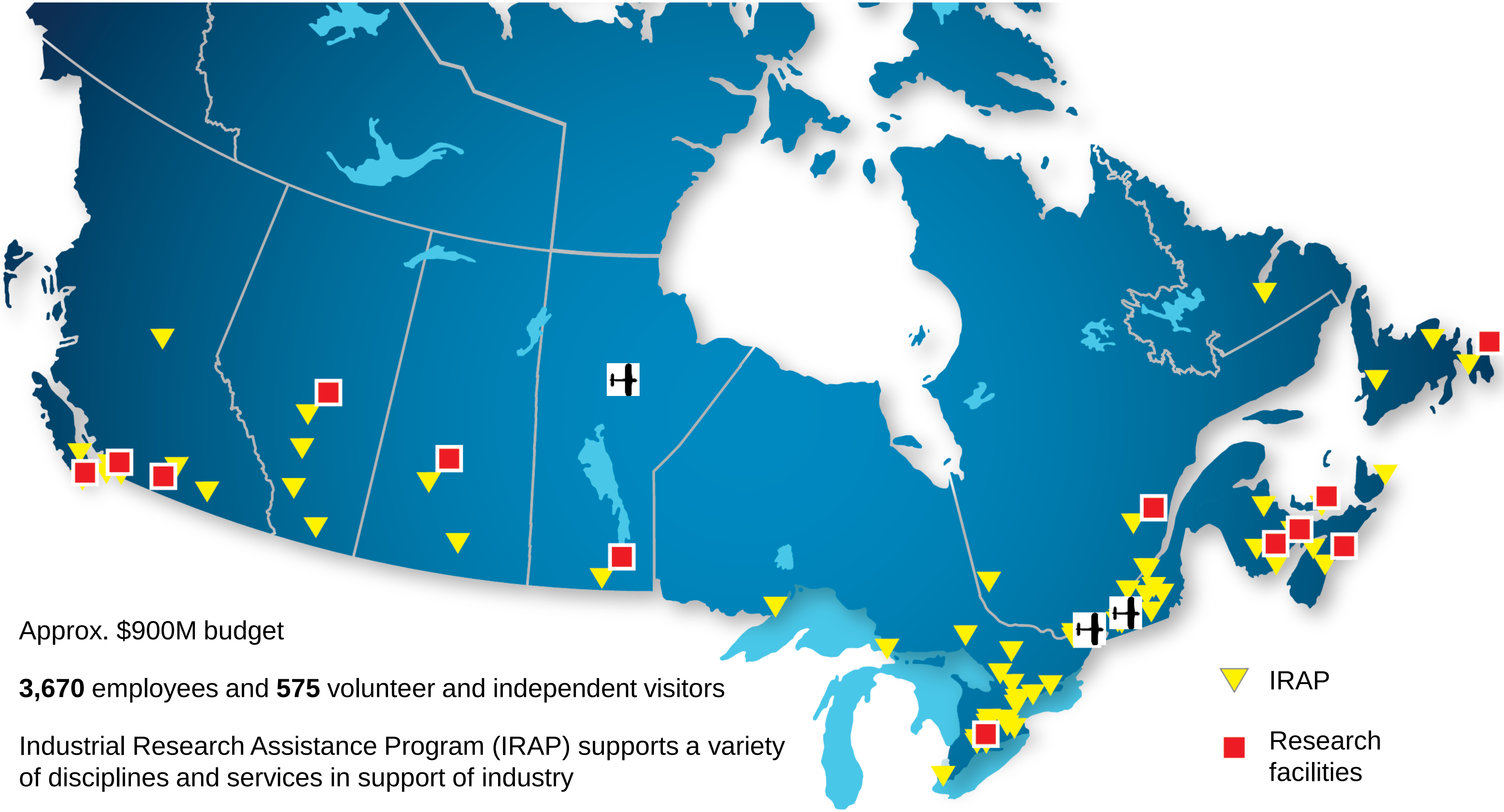
Robert Amos, Min Liao

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Who is NRC?



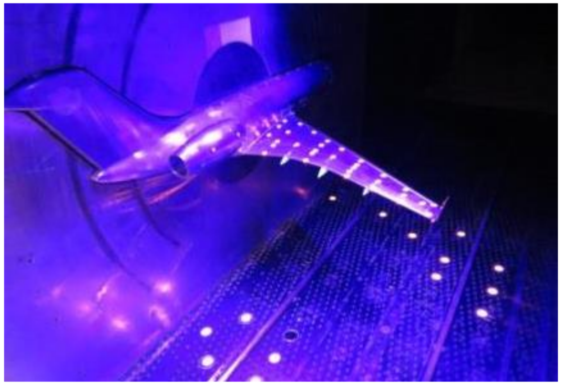
- Approx. $900M budget
- **3,670** employees and **575** volunteer and independent visitors
- Industrial Research Assistance Program (IRAP) supports a variety of disciplines and services in support of industry
- Research facilities provide strategic research & development and technical services to national and international clients

▼ IRAP

🟥 Research facilities

✈ Aerospace research facilities

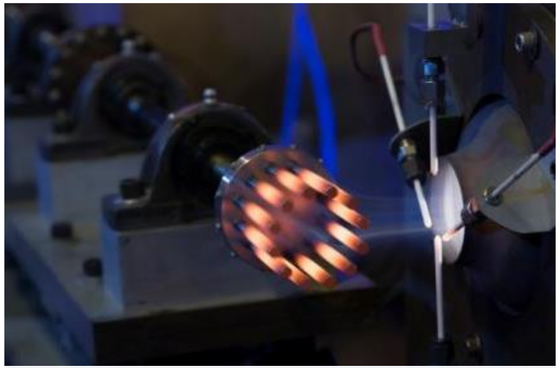
Aerospace Competencies – 330 Technical Experts



Aerodynamics

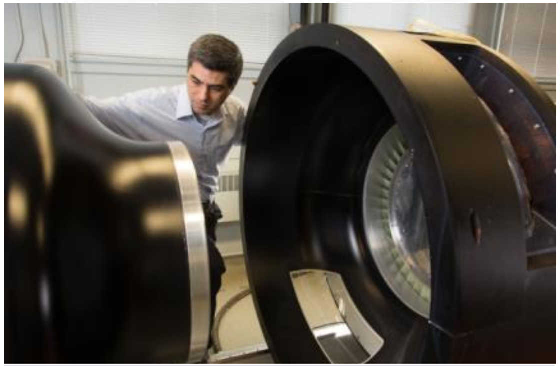
Manufacturing

Flight Research



Structures and Materials

Gas Turbine Engines



Technical Services

Facilities – $500M Research Infrastructure + HPC

Aerodynamics

Structures, Materials and Manufacturing

Flight Research

Gas Turbines

Challenges: Design, Processing, Materials and Performance

Key challenges associated with AM - Processes and Materials are Part Specific

Challenges:

1. ***Design –*** energy consumption over the whole lifecycle
2. ***Thermal conditions – couple energy source (EB/laser) with feed (powder/wire):*** no feedback from the welder
3. ***Thermal gradients*** **–** microstructural and residual stresses
4. ***Microstructral heterogeneity –*** solidification structure with crystal orientation and anisotropy
5. ***Heterogeneous mechanical properties –*** Lower than forging, slightly better than casting

Increase in Process Knowledge using AM Modeling

Lessons learnt:

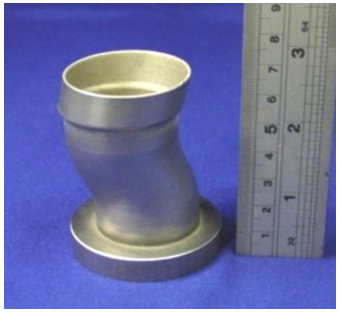
1. ***Using design freedom*** is paradigm shift for engineers; “expensive” lightweight material are viable: reduce energy, weight, emissions (lifecycle)
2. ***Process optimization*** is critical to automated manufacturing success (controlling energy input)
3. ***In-situ intermediate heat treatment –*** Beam oscillation in situ with EB system can be applied to heat treat and mitigate cracking.
4. ***Microstructure*** is related to process parameters, build/layup trajectory/strategy and location → varying precipitation kinetics → levels of locked residual stresses → discontinuities (defects?) → inline NDI
5. ***Mechanical performance*** some material have static and dynamic properties inferior to traditional wrought and machined forms → scatter in mechanical performance → secondary processes (HIP) or hybrid processes required

Technology Advancement Goals/Activities

National Research Council Canada
Conseil national de recherches Canada

Goal: Precision Metallic Parts via Laser AM Reduction of post processing

- Improving Surface Finish
- In Situ Heat Treatments
  - Dwell Times, Oscillating Melt Pool
- Adding details to existing structure
- Process Control Aiming To Achieve Wrought Values



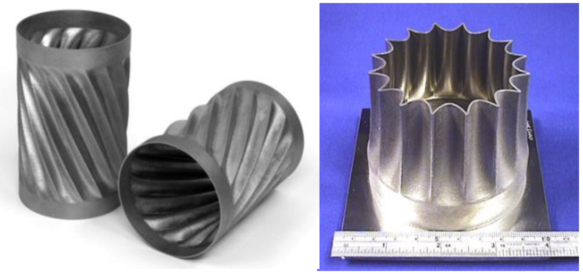
Demonstration piece & LC system built for Airbus

Building airfoils on turbine disc to form a "blisk".

NRC In-House System

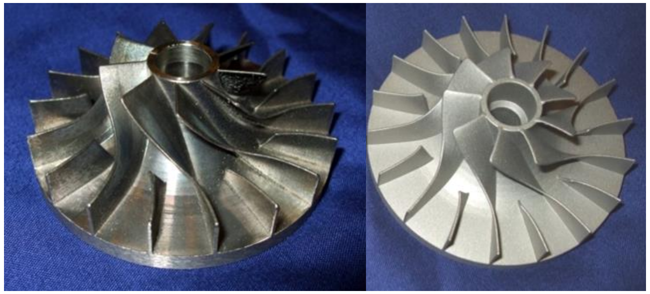
Build Success

- Surface finish: up to 1-2 μm
- Dimensional accuracy up to +/-0.075 mm
- Strength comparable to Wrought Materials



Conditions		σ_y (MPa)	σ_{UTS} (MPa)	Elongation (%)
As-consolidated IN-625	Horizontal	518	794	31
	Vertical	477	744	48
Cast IN-625		350	710	48
Wrought IN-625		490	855	50

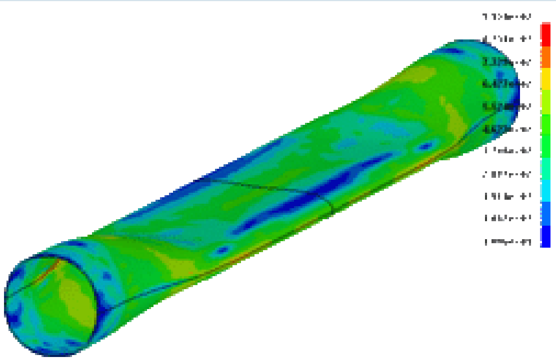
Material Conditions		σ_y (MPa)	σ_{UTS} (MPa)	δ (%)	Hv_{200}
LC IN-718 Vertical	As-consolidated	432±5	802±21	39±5	257
	HT	1085±19	1238±12	21±2	445
Wrought IN-718 - HT		1036	1240	12	-
IN-718 Sheet - HT		1050	1280	22	420



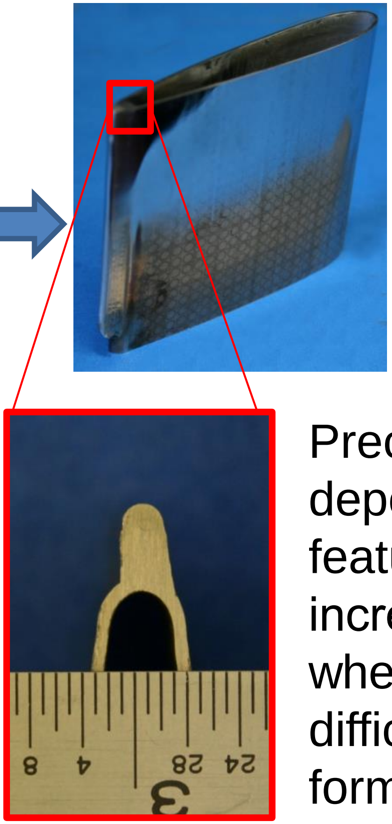
As-consolidated

After sand blasting

Goal: Advancing Hybrid Manufacturing (Fine Deposition)



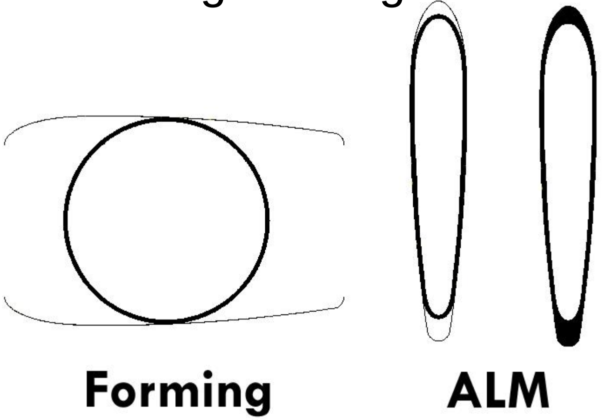
Precision forming (FEM) to meet high tolerance whilst minimizing waste generation



Combined Gains
Low buy to fly
Just in time production
Tailored performance
Low material waste

Precise EB additive deposition to build features giving increased “thickness” where needed that is difficult to attain with forming

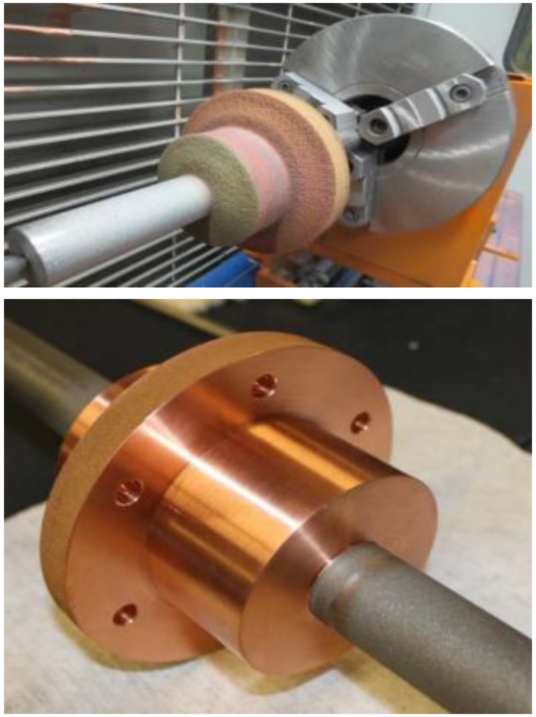
High tolerance inner geometry formed to avoid local fine cracks (thermal stresses)



Additive layer manufacture to integrate features at high productivity rates and minimal material loss

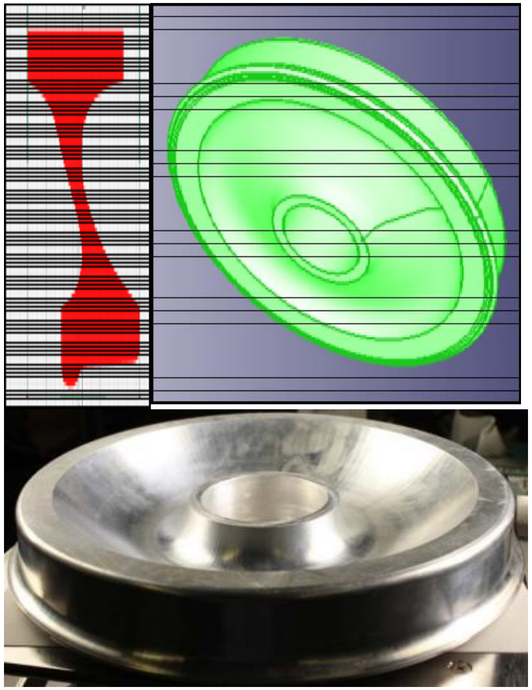
Goal: Advance Additive Manufacturing Implementation of Cold Spray

(Cold Spray Additive Manufacturing Consortium)



High Volume deposition rates

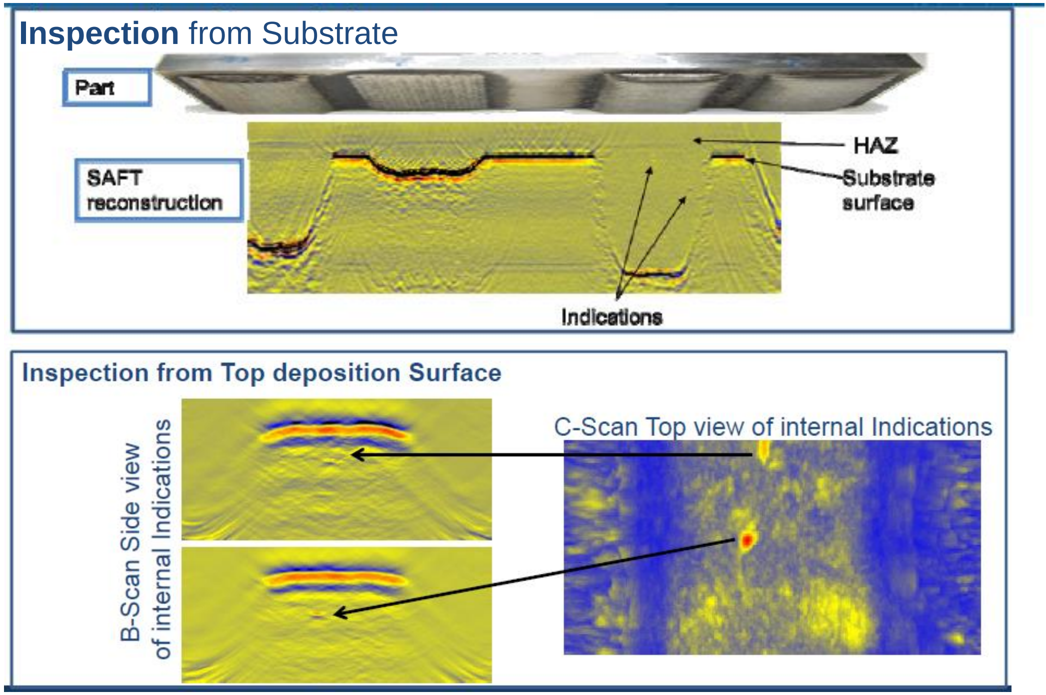
~100 Time Laser



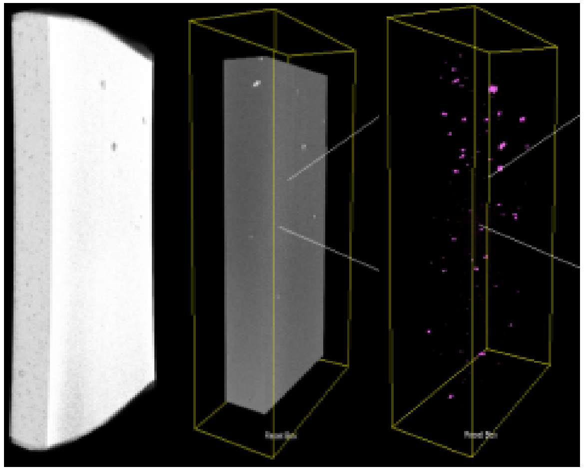
- Prototype of aluminum Rail wheel

Goal: Advance the state of the art for NDE

- Laser Ultrasonic (In situ)
    - Images to the left
- CT/ MicroCT
- Eddy Current
- Thermal
- X-Ray Diffraction
- Intelligent Systems



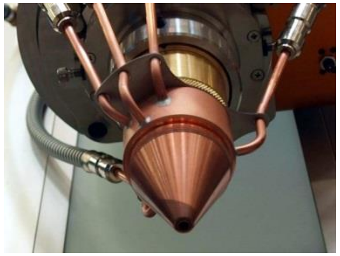
Laser Ultrasonic



Goal: Additive Manufacturing and Repair in Open Environment

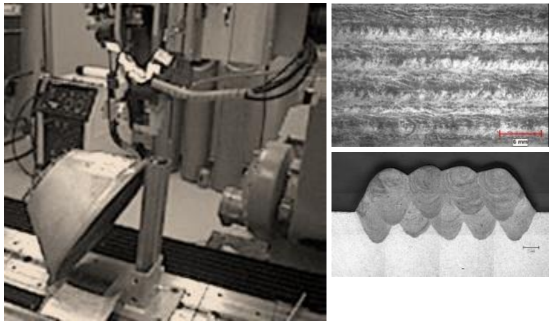
Industrial cells for additive manufacturing and repair using
(1) a 3 kW TRUMPF fibered diode laser CNC system and
(2) a 5.2 kW IPG fiber laser robotic system .

Both integrated with powder/wire feeding capability and localized shielding/gas protection for technology demonstration on large-scale industrial size components (unbound part size). Diode laser with reduced sensitivity for back reflection from Al alloys.



No cracking or porosity at interface or in the interlayers of the deposit

Laser deposition with powder feeding



Laser repair of Mg sand cast component - process development to technology demonstration with robotic laser system

Scrapped high pressure turbine rotor

Build/repair of IN718 with laser system – process development and optimization (high mechanical properties at elevated temperatures in service) to demonstrate repair of heavily damaged turbine rotors

Repair Development Road Map (MRO Program)

Future 2 – 5+ years

Process development

- Material
- Dual Material powders
- Application Process Development
- Technology Identification

Repair Specific Considerations

- Heat treat
- Surface Preps
- Post-Treatment Localized Heat treats.
- Testing Proof of Concept

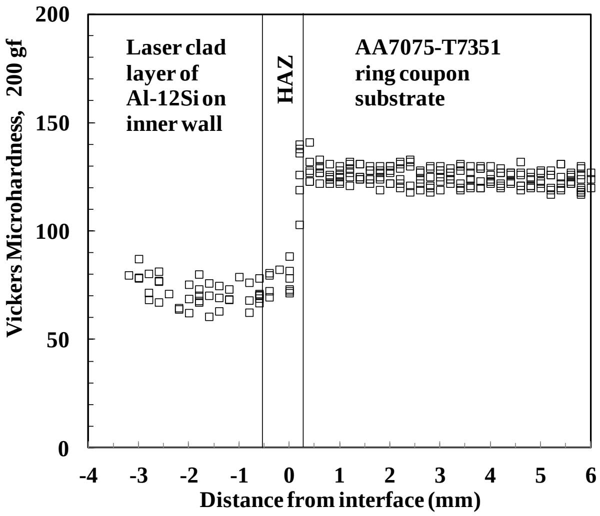
Explore Through Technology Demonstration

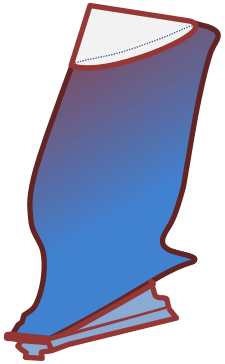
General standardization

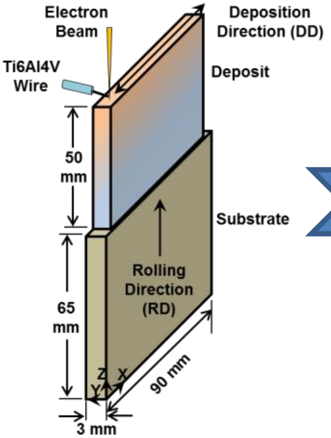
- Functional Concept Groups
- Standardized Procedures
- Part Clearance Approach

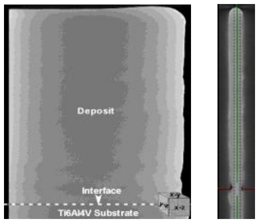
Repair Demonstration Projects

Repair Concept S61 Lug

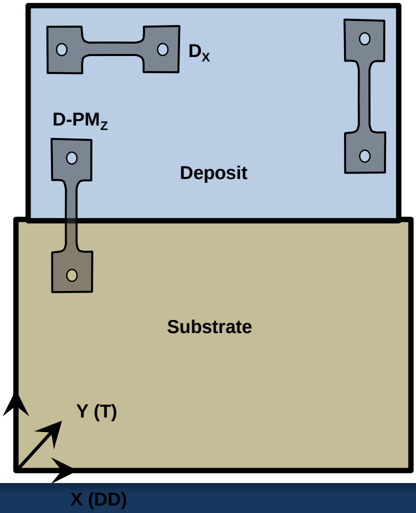




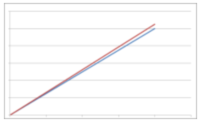




Correct Parameters and control, virtually residual stress free.



Wrought Values As Deposited

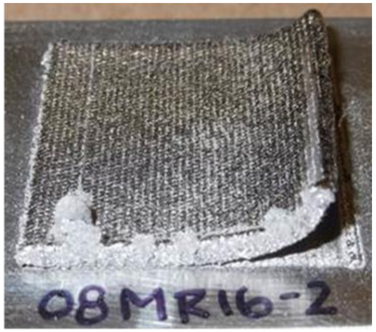


Repair Experimental Investigations

Mixed Materials

- Titanium deposited on 7075

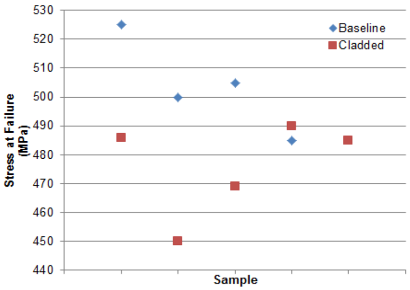
5 layers



12 Layer

- Residual Stress Sufficient to tear 7075
  - Different hatching to be explored

- Al-MMC on 7075



- Interesting Failure mode
  - Always had curvature

Observations and Lessons

- The strength Ti-6Si-4V (wire based) seems to be more sensitive to process parameter and geometry than post processing
    - Post processing can be reduced with sufficient process development
- Require additional considerations
    - Surface prep
    - Geometry models
    - Localized heat treat

Burloak Technologies
a division of SAMUEL

NATO
OTAN

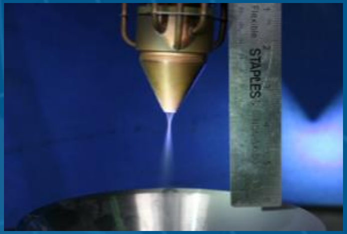
ArcamEBM
A GE Additive Company

RENISHAW

THE TECHNICAL COOPERATION PROGRAM
TTCP

QETE / CETQ

NRC·CNRC Canada
NRC Industrial Research Assistance Program



Certification

RCAF AM Certification Process Development

Objective
Develop and demonstrate additive manufacturing (AM) certification process for an aircraft structural application; the project aims to study the effects of input parameters on:

(1) the defects through advanced non-destructive techniques (NDT),

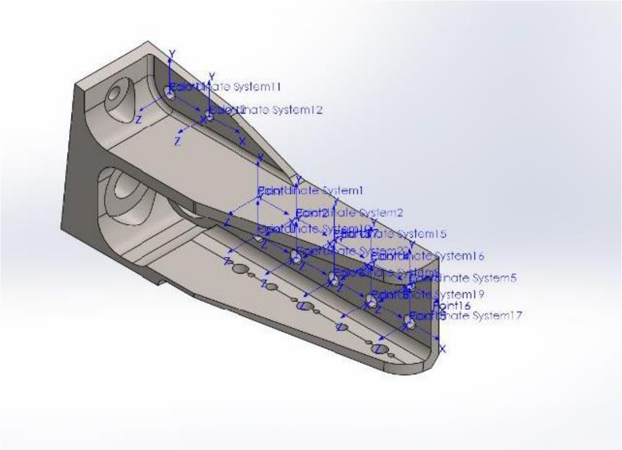
(2) geometrical characteristics through advanced 3D optical measuring systems,

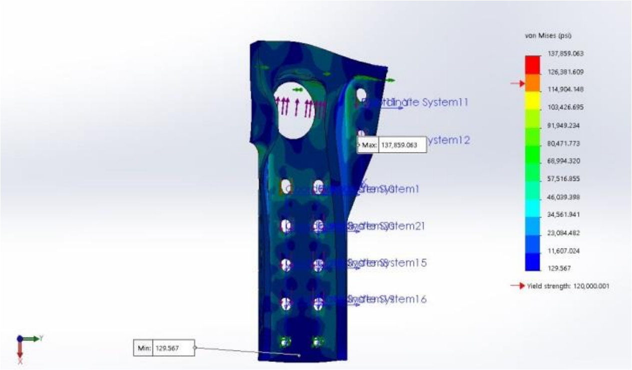
(3) microstructural constituents through microscopy,

(4) residual stresses through testing and modeling,

(5) mechanical properties through static and fatigue testing, and

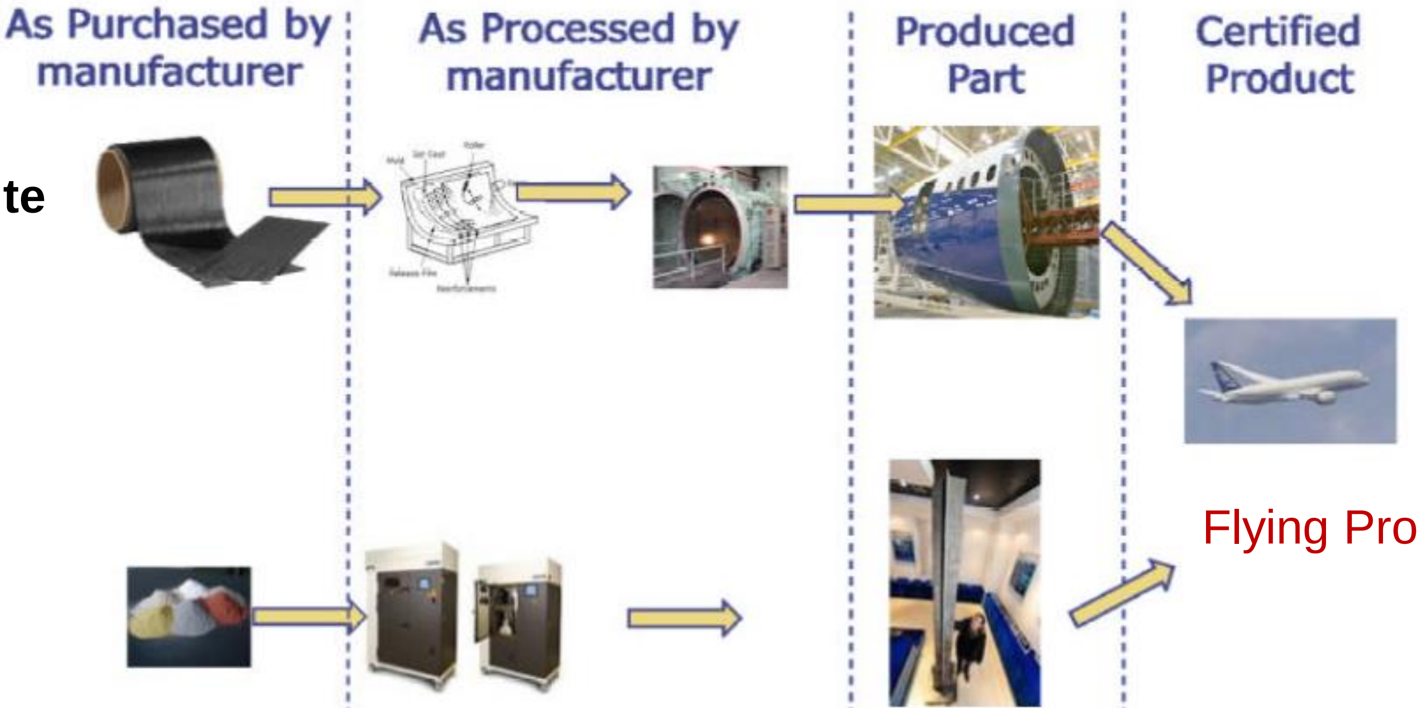
(6) fatigue life prediction including safe-life and damage tolerant.





Similarity to Composites

Composites and metallic AM materials have similar production requirements



Composite

AM

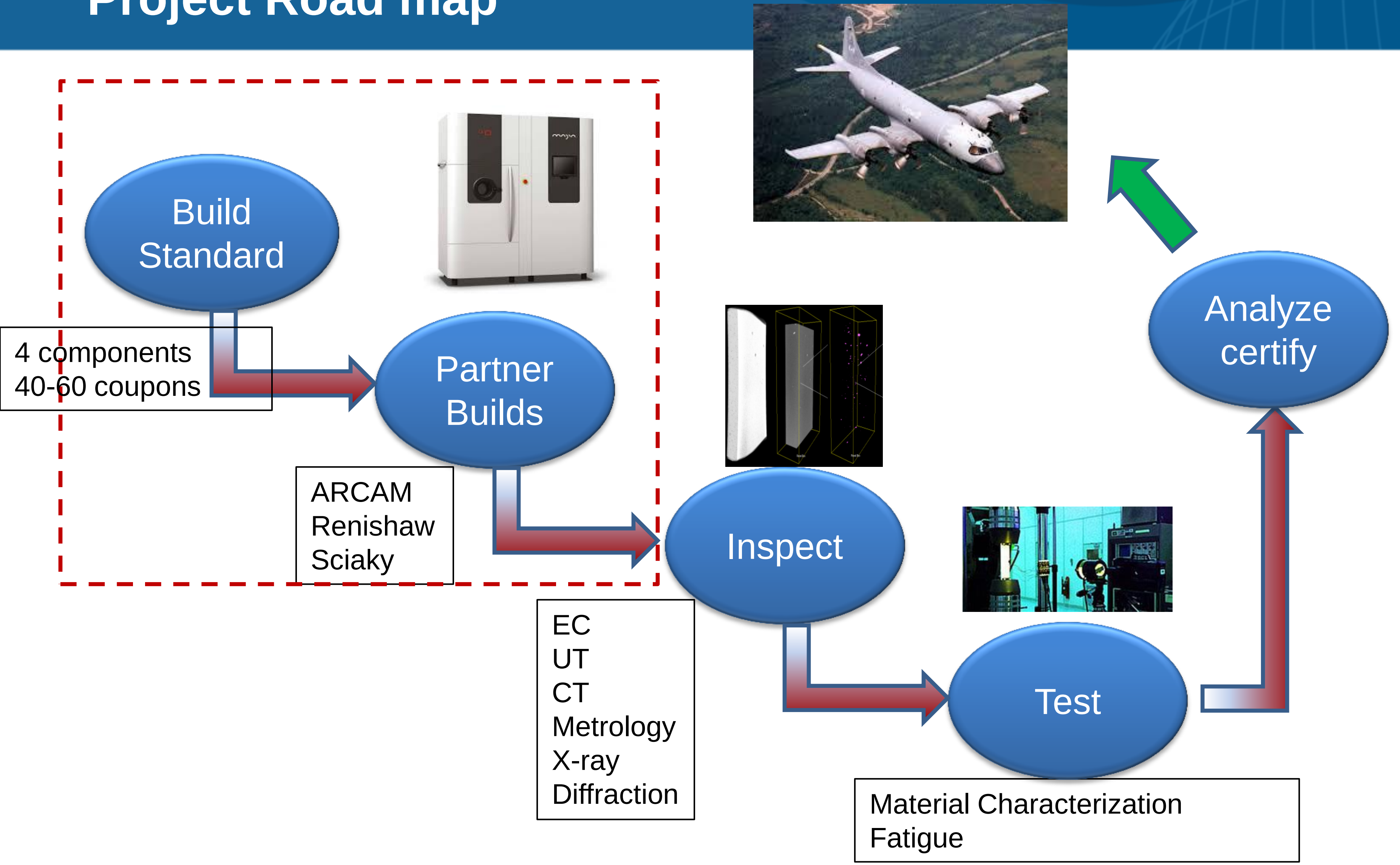
Flying Product

Powders/Wire

Machine Vendors
Production Centers

Production

Project Road map



Build Standard

4 components
40-60 coupons

Partner Builds

ARCAM
Renishaw
Sciaky

Inspect

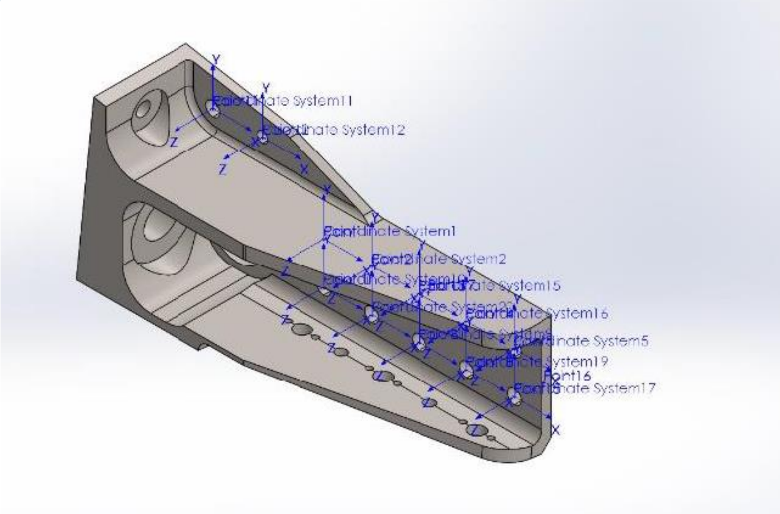
EC
UT
CT
Metrology
X-ray
Diffraction

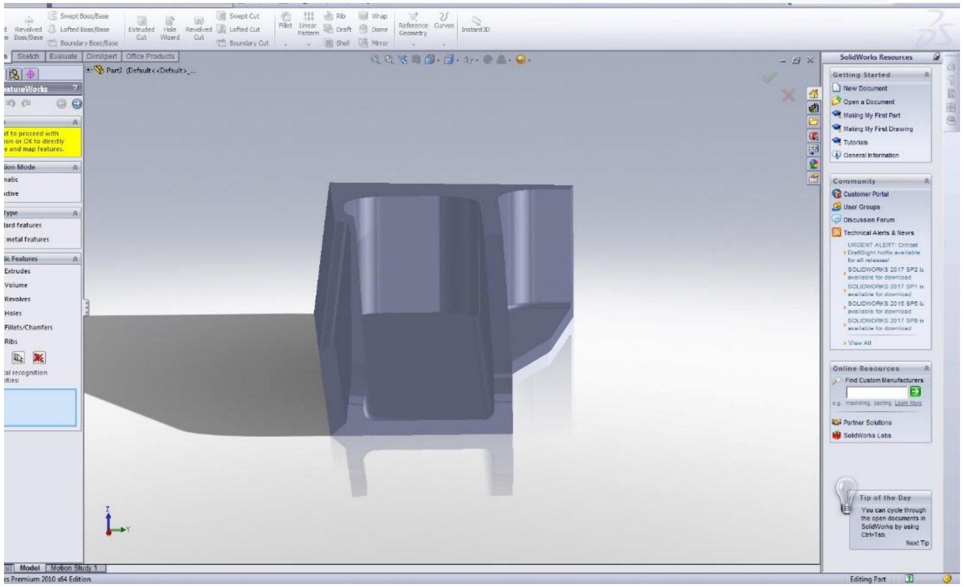
Test

Material Characterization
Fatigue

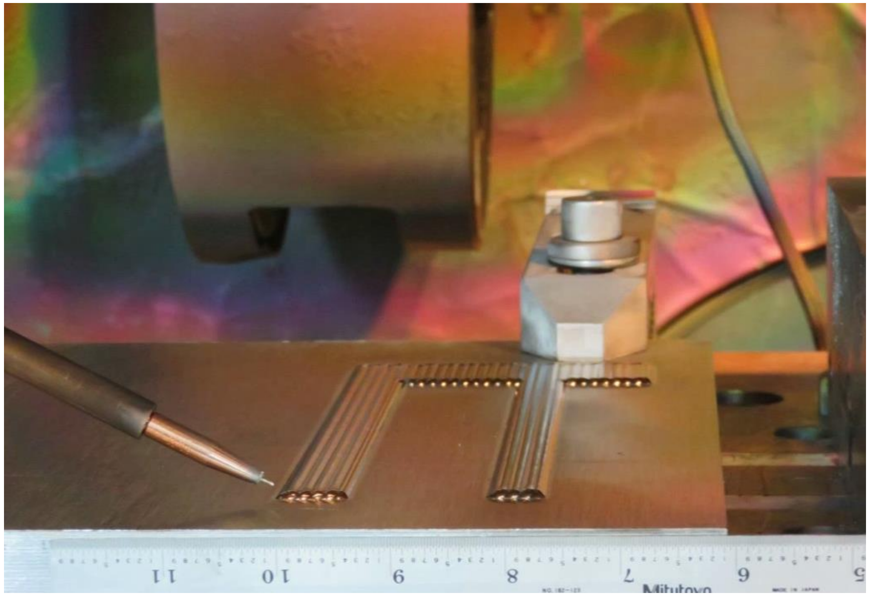
Analyze certify

Electron Beam Additive Manufacturing of Ti6Al4V





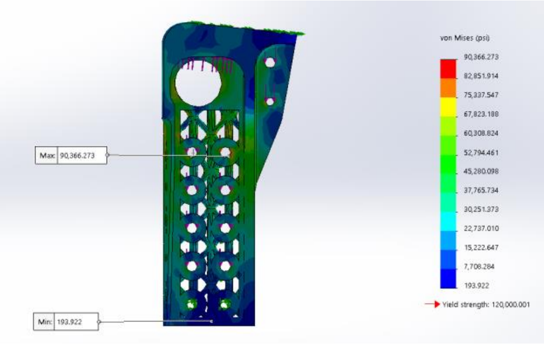
Tip of the Day: You can cycle through the open documents in SolidWorks by using Ctrl+Tab.

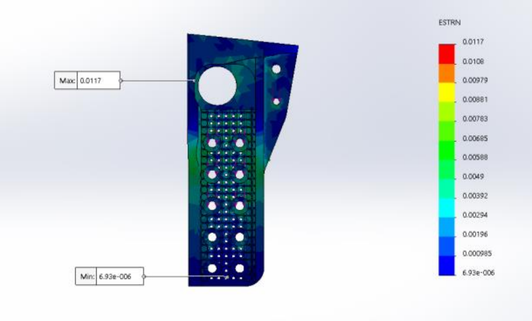


- Reverse engineering of part
- CAD STL file
- Stress Analysis
- Design for Manufacturing with EB AM
- EB AM Ti6Al4V process development

Part Optimization – Load Optimization

- Flexibility of AM Permits interesting possibilities for Unique features
- Development of Localized Fatigue Concentrations are possible
    - Engineers and designers need to aware.





NRC Future activities and Way Forward

- Continue with application and technology development
  - Investigating a touch-free ‘development’ center

- New Material development and characterization
  - Working toward AM specific materials
  - Blended Materials and Powders

- NDE development
  - In situ inspection/monitoring of build process

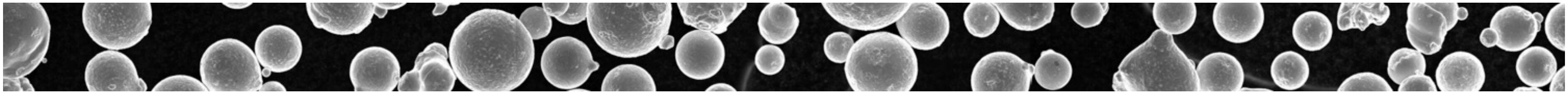
- Melt Pool Control through feed back in situ sensing

Thank You Very Much!

APPENDIX AA—POWDER FEEDSTOCK AS A PROCESS VARIABLE FOR SLM 718 HARDWARE

The Third Joint FAA – Air Force Workshop on Qualification / Certification of Additively Manufactured (AM Parts) held at University of Dayton - River Campus

Powder Feedstock as a Process Variable for SLM 718 Hardware



National Aeronautics and Space Administration

Chantal Sudbrack (Task Lead), David Ellis, Brad Lerch, Timothy Smith, Ivan Locci and Aaron Thompson

NASA John H. Glenn Research Center at Lewis Field, Cleveland Ohio

Richard Boothe, Will Tilson, Ken Cooper, Kristin Morgan (Project POC)

NASA George C. Marshall Space Flight Center, Huntsville Alabama

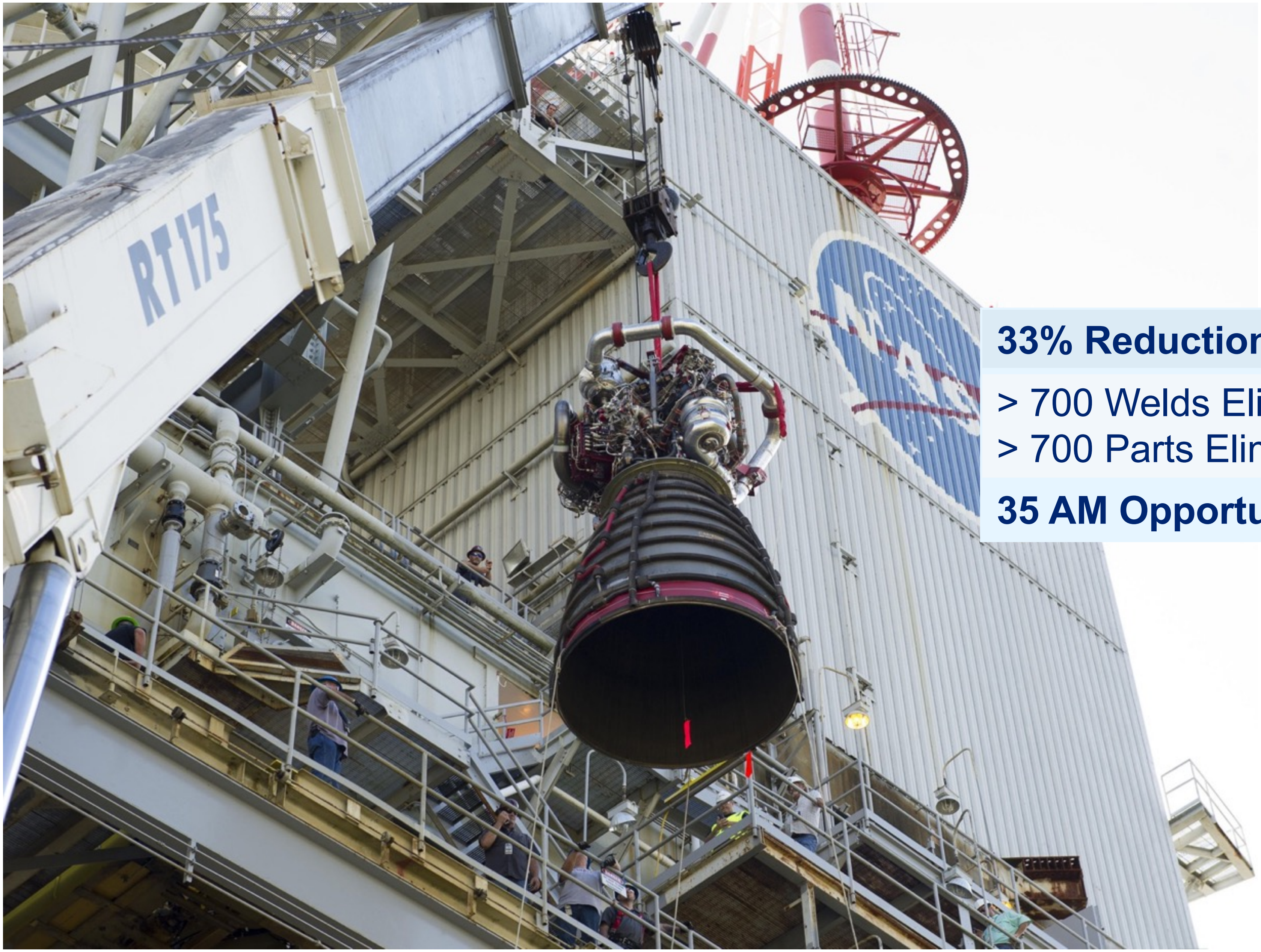
Jonathan Tylka

NASA White Sands Test Facility, Las Cruces, New Mexico

August 31, 2017

Acknowledgements: *NASA HEOMD / Space Launch System Liquid Engine Office / Additive Manufacturing Structural Integrity Initiative (AMSII) Project, MSFC Advanced Manufacturing and Heat Treat Facilities, GRC Analytical Sciences Group, GRC Mechanical Testing Facility, Robert Carter (GRC), Brian West (MSFC), Doug Wells (MSFC), Interns – Alejandro Hinojos (OSU), Paul Chao (CMU), Ben Richards (NU)*

Space Launch System RS-25 Affordability Strategy



33% Reduction in Cost

> 700 Welds Eliminated
> 700 Parts Eliminated

35 AM Opportunities

AM Qualification and Certification at NASA

Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

SpaceX's AM SuperDraco Engine

Program partners in crewed space flight programs (Commercial Crew, SLS and Orion) are actively developing **AM parts scheduled to fly crew as early as 2018.**

NASA cannot wait for national Standard Development Organizations to issue AM standards.

- In response to request by CCP, MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- Final revision currently in work; target release date of Dec 2016.
- **Standard methodology adopted by CCP, SLS, and Orion**.
- Continuing to watch progress of standards organizations and other certifying Agencies.
- Goal is to incorporate AM requirements at an appropriate level in Agency standards and/or specifications.

POC: Doug Wells

National Aeronautics and
Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard
for Additively Manufactured
Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Target release date:
September 2017

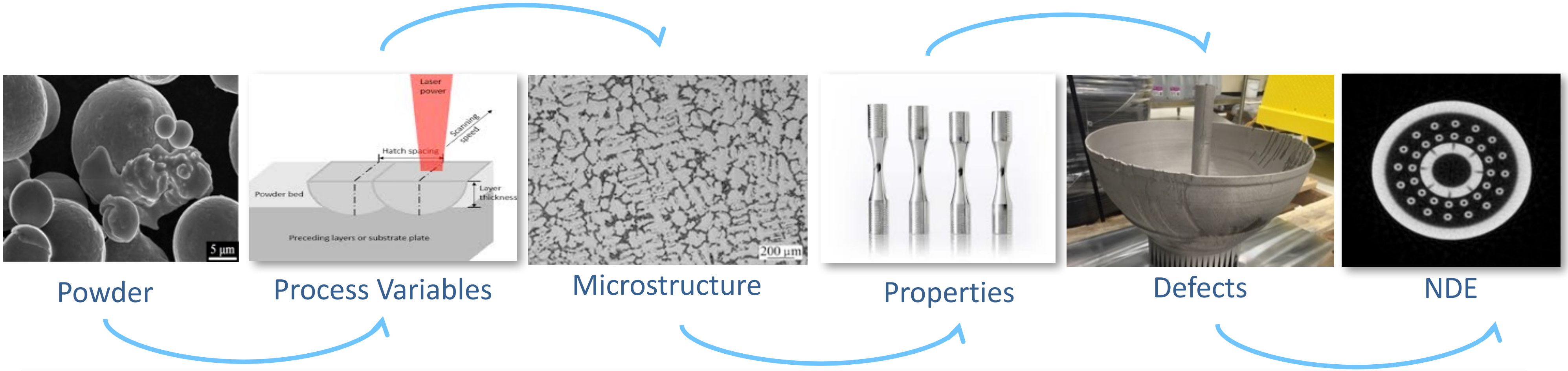
AMSII – Mitigating SLM risk to NASA Programs

Additive Manufacturing Structural Integrity Initiative proposed in April 2015

1. To bridge fundamental knowledge gaps of SLM Alloy 718 and processes
2. To provide data to inform MSFC standard and specification development

SLS Liquid Engine Office funded a subset of the AMSII activities from FY16 to FY18

- Powder Feedstock and Recyclability Limits (GRC-led) → "Powder Task"
- SLM Microstructure and Properties (MSFC-led)
  - Machine Repeatability
  - Machine-to-Machine Variability
- Characteristic Defect Structures (LaRC-led)
- NDE & Rogue Defect Detection (cooperation w/NASA NDE Working Group)



kristin.l.morgan@nasa.gov

Task Motivation

- Data on powder feedstock variability in open literature are limited & inadequate
- Support **NASA standard and RS-25** for safety-critical SLM 718 hardware by examining feedstock relationships to processing, homogeneity, durability & performance
  - ➢ *In what ways does 718 feedstock vary across the industry?*
  - ➢ *How does its variability influence microstructure, flowability, spreading, build quality, and performance?*
  - ➢ *Is it possible to identify control limits and tolerances?*

Major Objectives

- Obtain comprehensive industry **lot-to-lot comparison** to understand and identify the feedstock controls important to SLM Alloy 718 hardware
- Comparison used to down select 5 unique powder lots for a larger-scale (300 lbs each) investigation to include reuse / recyclability study and more expansive mechanical testing

718 Study: Powder Feedstock Lot-to-Lot Variability

Recent effort: First powder ordered April 2016, builds completed January 2017,heat treatment completed April 2017

Focus here: 11 powders from 8 vendors in two common SLM size ranges

- *In what ways does 718 feedstock vary across the industry?*
  - Visual comparison of powders and their particle size distributions
  - ICP / LECO bulk powder chemistry measurements
  - Particle shape and surface roughness (Morphologi)
- *How does its variability influence microstructure, flowability, spreading, build quality, and performance?*
  - Flow behavior and FT4 rheology measurements
  - Build quality and microstructure – surface roughness, porosity, grain structure
  - Performance – Tensile and High Cycle Fatigue (HCF) results
- *Is it possible to identify control limits and tolerances?*

Approach

Procure as many off-the-shelf 718 powders in 50 lb lots as possible for a comprehensive lot-to-lot comparison

- **Six ~15-45 µm standard SLM cut**
- **Five ~10-45 µm standard SLM cut**

		Alloy 718 Powders	GRC ID	Vendor Specified Powder Cut (µm)	Vacuum Melt Production	Gas
Reseller Vendor A	1	Vendor 1, Powder 1	A1	15-45	Gas Atomized (GA)	Ar
	2	Vendor 1, Powder 2	A2	10-45	GA	Ar
	3	Vendor 1, Powder 3	A3	10-45	GA	Ar
Direct Suppliers	4	Vendor 2, Powder 1	B1	15-45	Rotary Atomized (thermal spray)	Ar
	5	Vendor 3, Powder 1	C1	15-45	GA	N
	6	Vendor 4, Powder 1	D1	16-45	GA	Ar
	7	Vendor 5, Powder 1	E1	10-45	GA	N
	8	Vendor 6, Powder 1	F1	15-45	GA	Ar
	9	Vendor 7, Powder 2	G2	11-45	GA	Ar
	10	Vendor 7, Powder 3	G3	16-45	GA	Ar
	11	Vendor 8, Powder 1	H1	10-45	GA	Ar

Powder Analysis
Chemistry
Morphology
Porosity, Dendrites, Inclusions
Shape Factors, Particle Size Distribution (PSD)
Particle Size Distribution (PSD)
Packing Density
Flow measurements
Rheological properties

Eight other comparisons

Omitted: Undersized 0-22 µm G1 powder (no build), Oversized 45-90 µm G4 powder (1 build)

Stay tuned: 2nd lots from D, E, F vendors (3 builds) & Once Reused of these lots (3 builds)

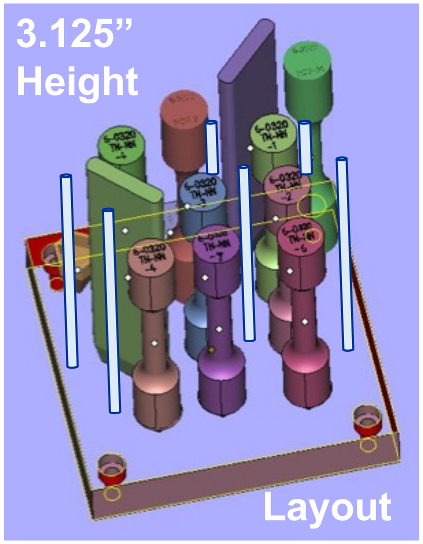
Processing Details

NASA MSFC Concept Laser M1 machine:

- Customized 718 parameters for RS-25 projects
- Layer thickness: 30 µm
- Continuous scan strategy plus contours

Small box configuration requires start /stop to refill piston with powder

18 builds over 3 months



Taper Ends for Easy Snap Off

- **Two microstructure bars**
  - **Green-state bar** → inherent to the process
  - **Fully heat treated (FHT) bar** → post process response
- **Screen tensile and high cycle fatigue at room temperature with FHT test bars**
  - **As-Fabricated vs. Low Stress-Ground Surface**
- Six FHT flammability rods

Visible refill lines

Green-state “met” bar

MSFC Build → ***10 – 16 weeks*** → ***To GRC***

Full Heat Treatment

Stress Relief at MSFC

Hot Isostatic Pressing in 4 cycles at Outside Vendor

Solution and Aged to AMS 5664E in batches at MSFC

Machine

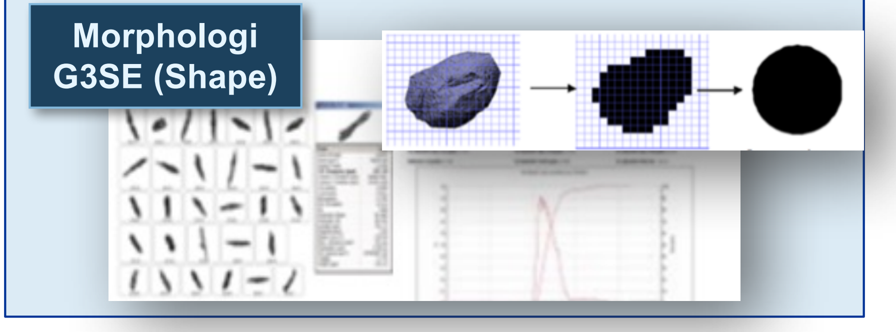
718 Study: Powder Feedstock Lot-to-Lot Variability

➢ ***In what ways does 718 feedstock vary across the industry?***

- Visual comparison of powders and their particle size distributions
- ICP / LECO bulk powder chemistry measurements
- Particle shape and surface roughness (Morphologi)

Malvern Morphologi G3SE
Optical projections of N >20,000
individual particles for each run,
2 run average

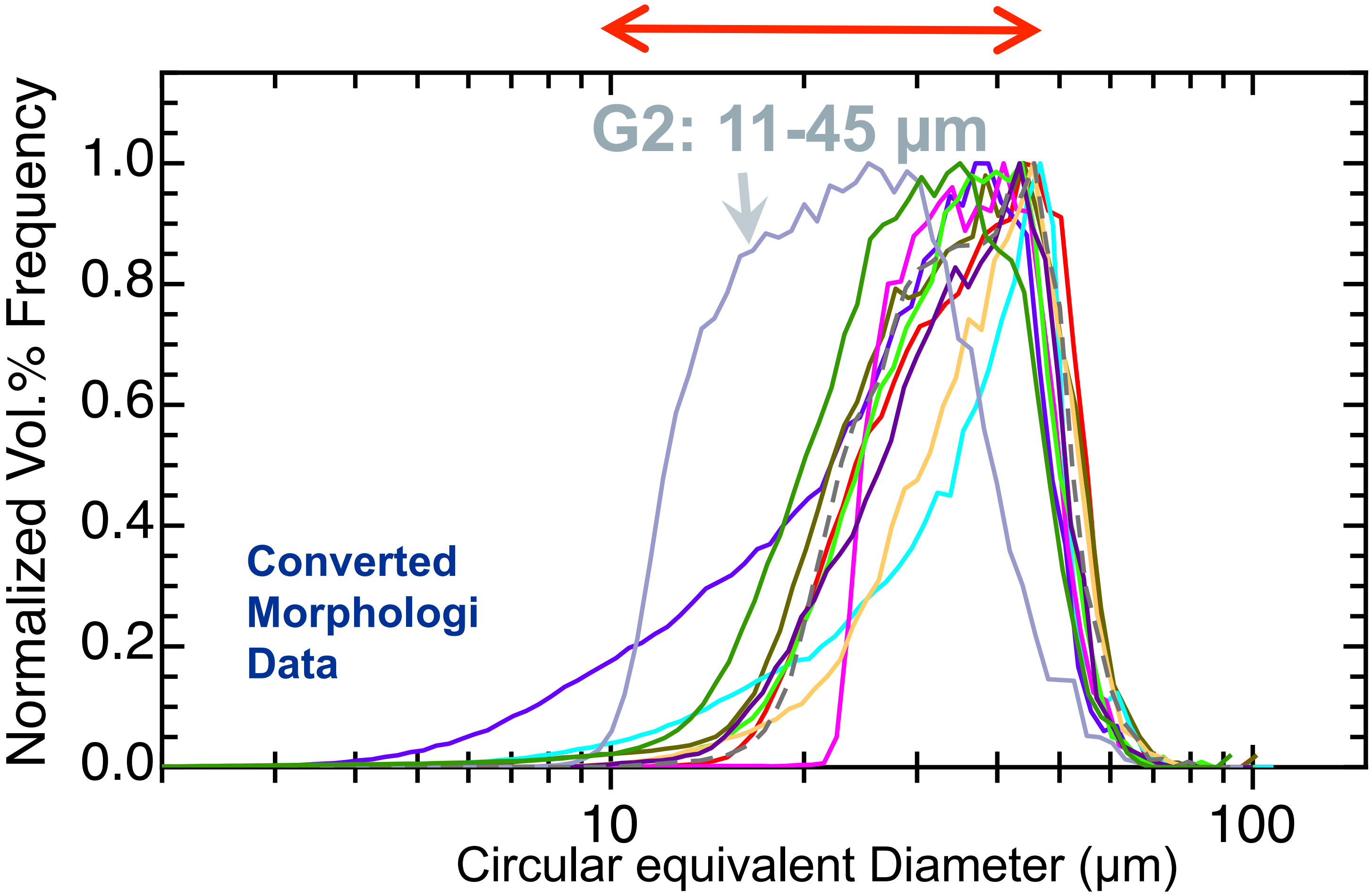
Count basis PSDs
Shape factors: circularity, convexity, aspect ratio



Powder cuts meet SLM size range but the two size classes are mostly not well separated

Some vendors provide better size fidelity to their product labelling

All these <u>volume basis</u> PSDs appear unimodal

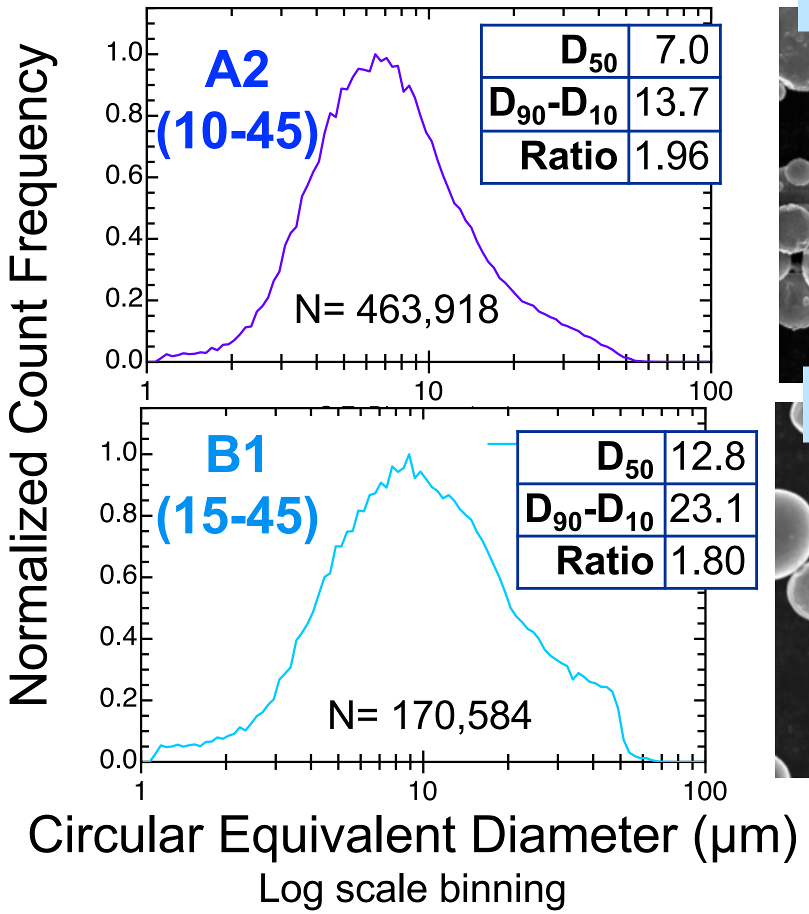


<u>Count basis</u> is more sensitive to fines. How do distributions differ?

Count basis PSDs divide into three groups

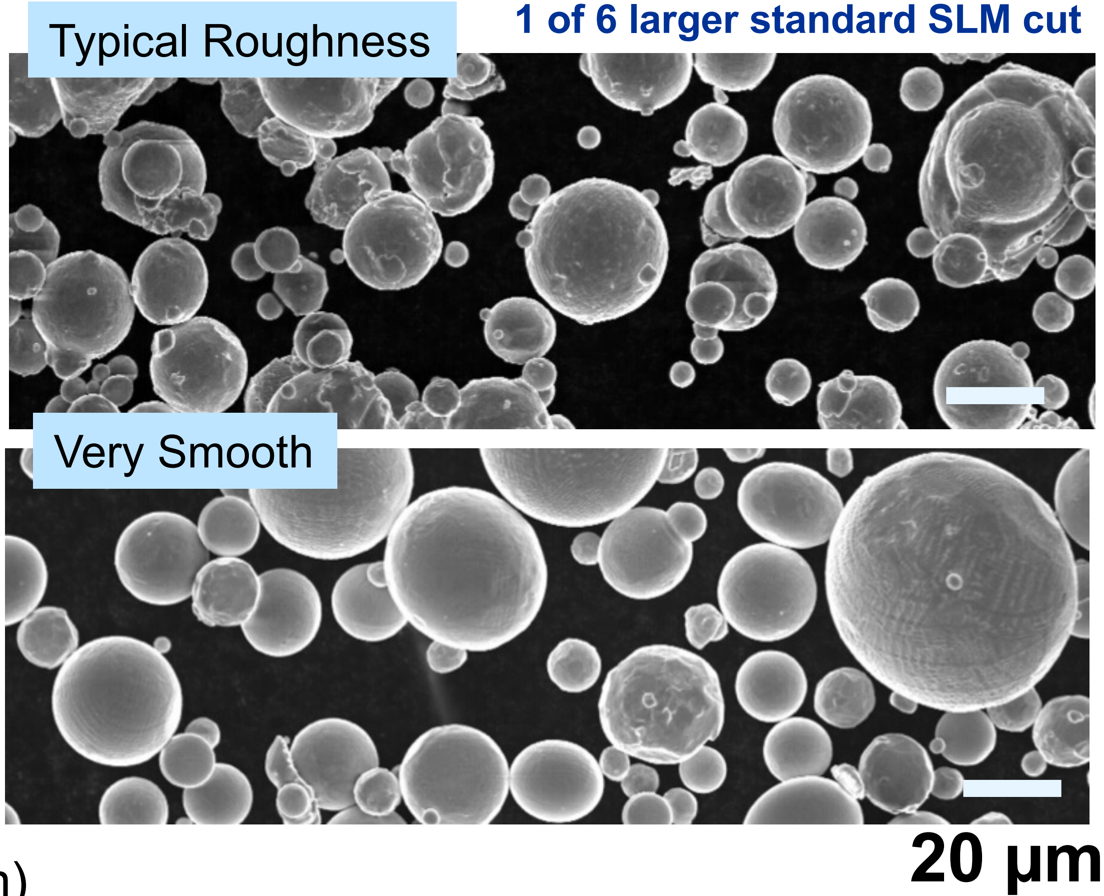
Group 1"Undersized" : PSDs are unimodal & widely distributed

1 of 5 smaller standard SLM cut
1 of 6 larger standard SLM cut



D_{50}	7.0
D_{90}-D_{10}	13.7
Ratio	1.96

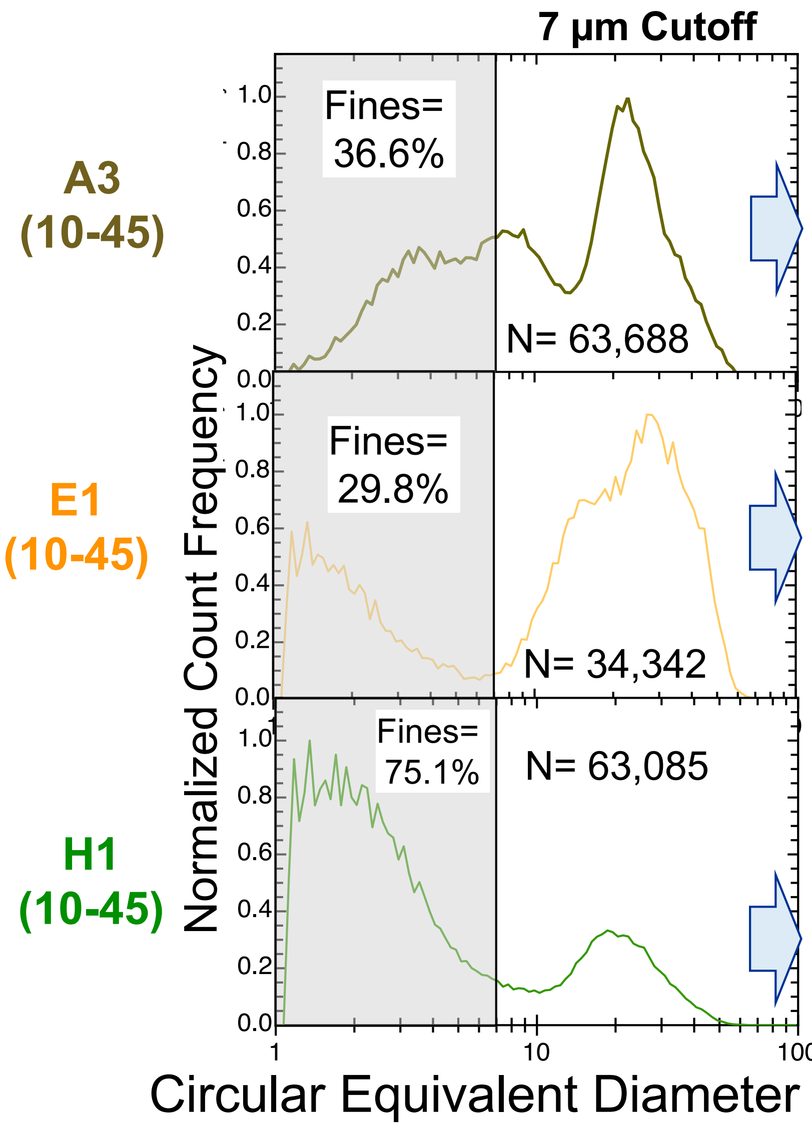
D_{50}	12.8
D_{90}-D_{10}	23.1
Ratio	1.80



A comparative tool is the scaled width, Ratio= $D_{50}/(D_{90}-D_{10})$

Distinct distributions with morphology differences

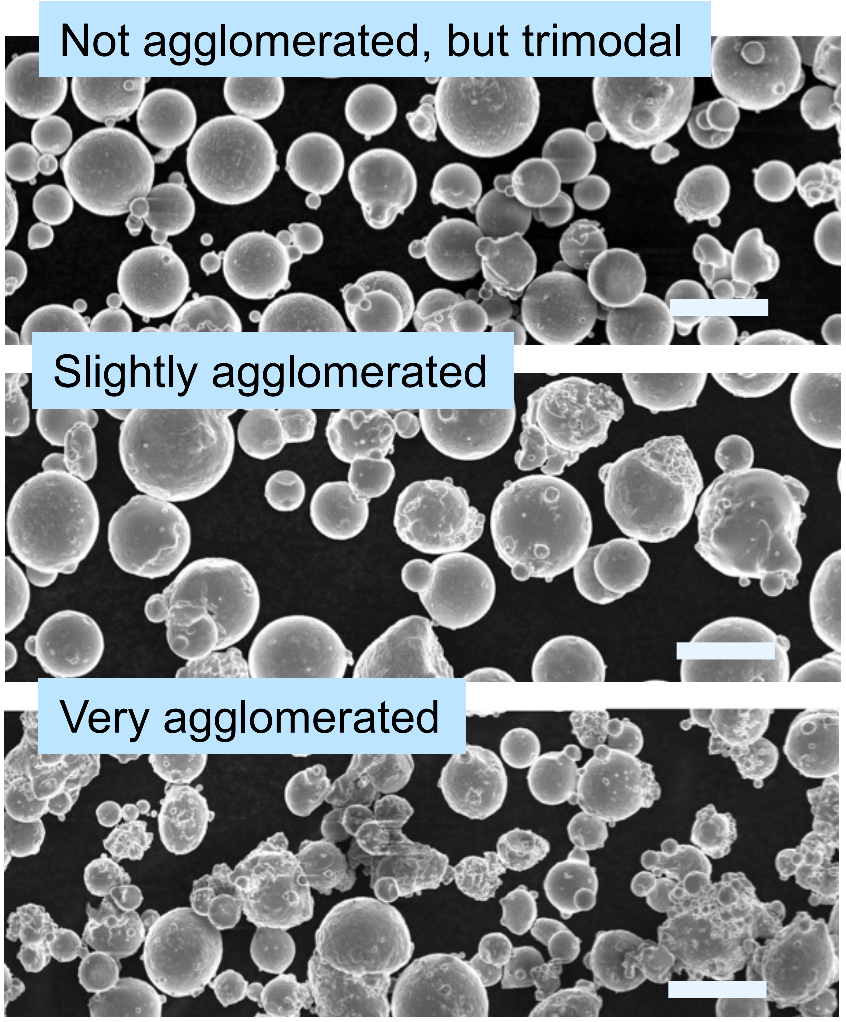
Group 2“Mixed” : PSDs are bimodal or trimodal



D_{50}	20.2
D_{90}-D_{10}	26.9
Ratio	1.33

D_{50}	23.9
D_{90}-D_{10}	29.8
Ratio	1.25

D_{50}	18.7
D_{90}-D_{10}	22.9
Ratio	1.22



3 of 5 smaller standard SLM cut **40 µm**

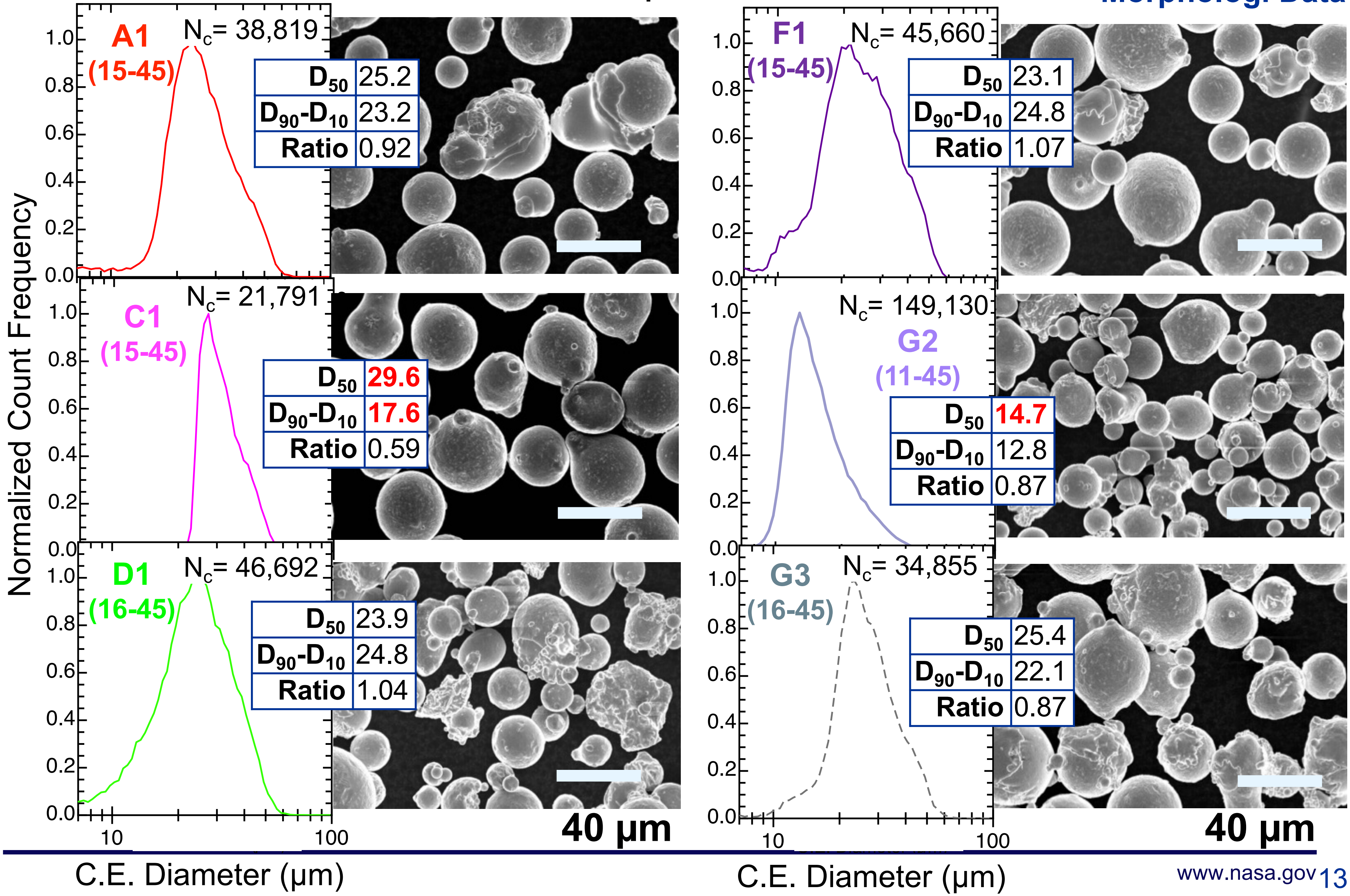
Group 3 "Normal": Unimodal PSDs with few satellites

5 of 6 larger and 1 of 5 smaller standard SLM cuts

7 µm Cutoff

7 µm Cutoff

Morphologi Data



A1 (15-45)

D_{50}	25.2
D_{90}-D_{10}	23.2
Ratio	0.92

C1 (15-45)

D_{50}	29.6
D_{90}-D_{10}	17.6
Ratio	0.59

D1 (16-45)

D_{50}	23.9
D_{90}-D_{10}	24.8
Ratio	1.04

F1 (15-45)

D_{50}	23.1
D_{90}-D_{10}	24.8
Ratio	1.07

G2 (11-45)

D_{50}	14.7
D_{90}-D_{10}	12.8
Ratio	0.87

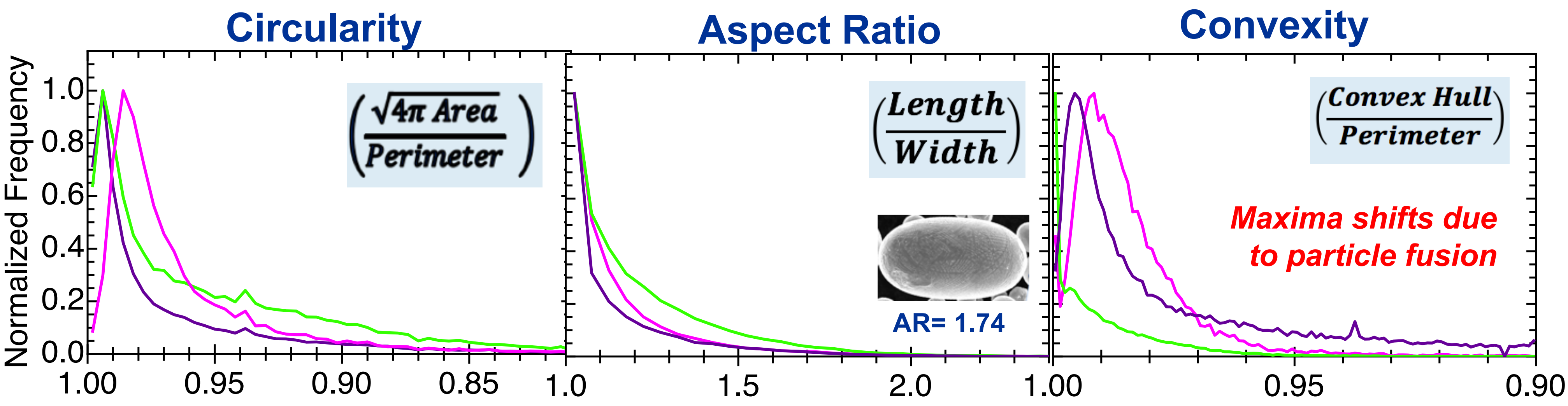
G3 (16-45)

D_{50}	25.4
D_{90}-D_{10}	22.1
Ratio	0.87

Powders appear highly regular and spherical

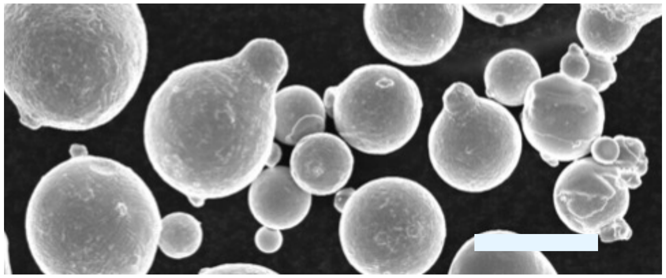
Slight differences in the shapes:
Tails or shifts in maxima within shape factor distributions

Circularity = Aspect Ratio = Convexity = 1 for a perfect sphere silhouette

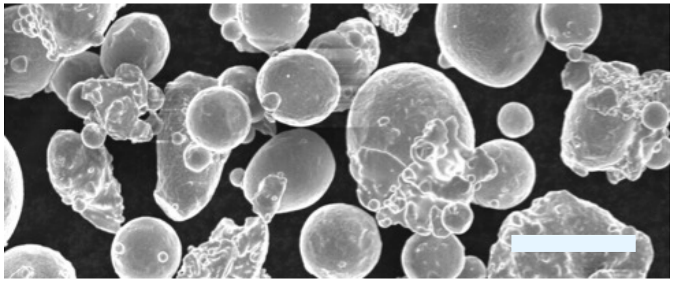


Maxima shifts due to particle fusion

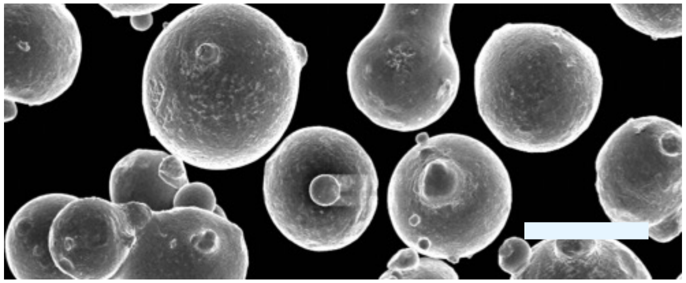
Typical



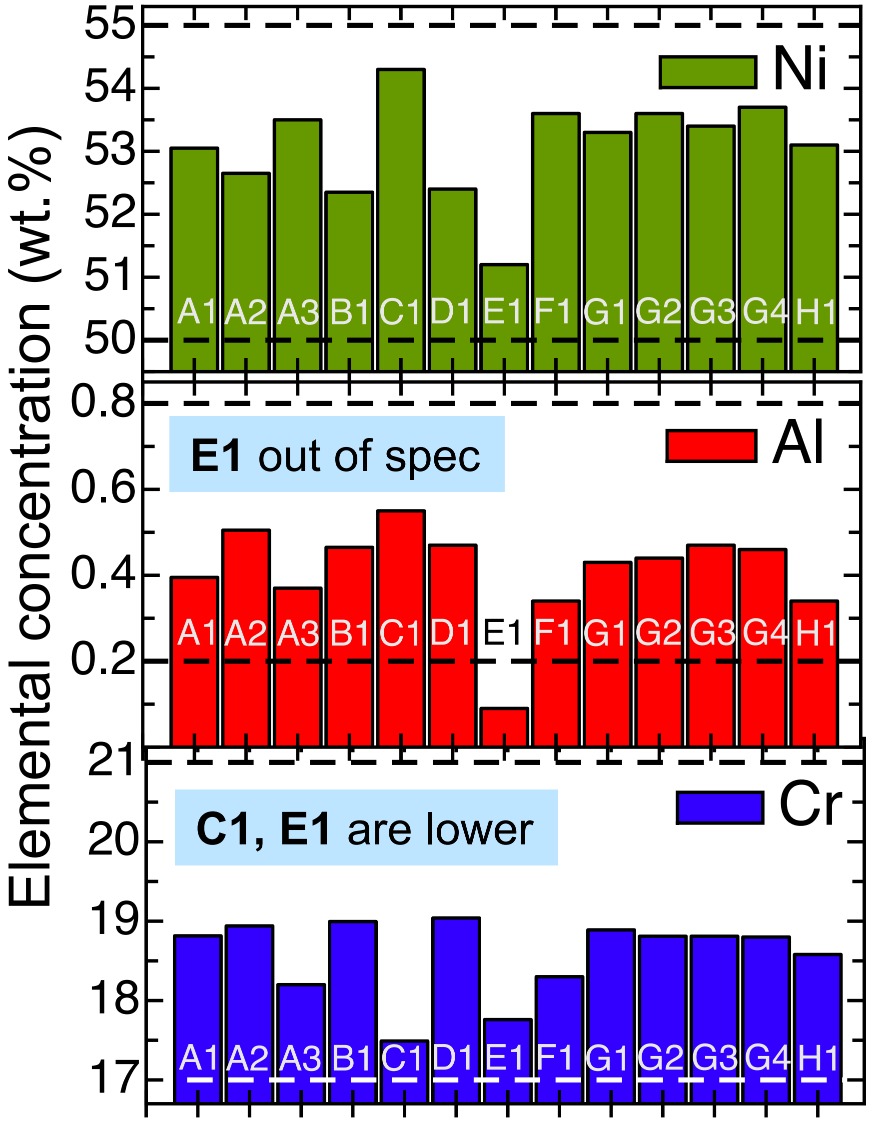
Agglomerated D1

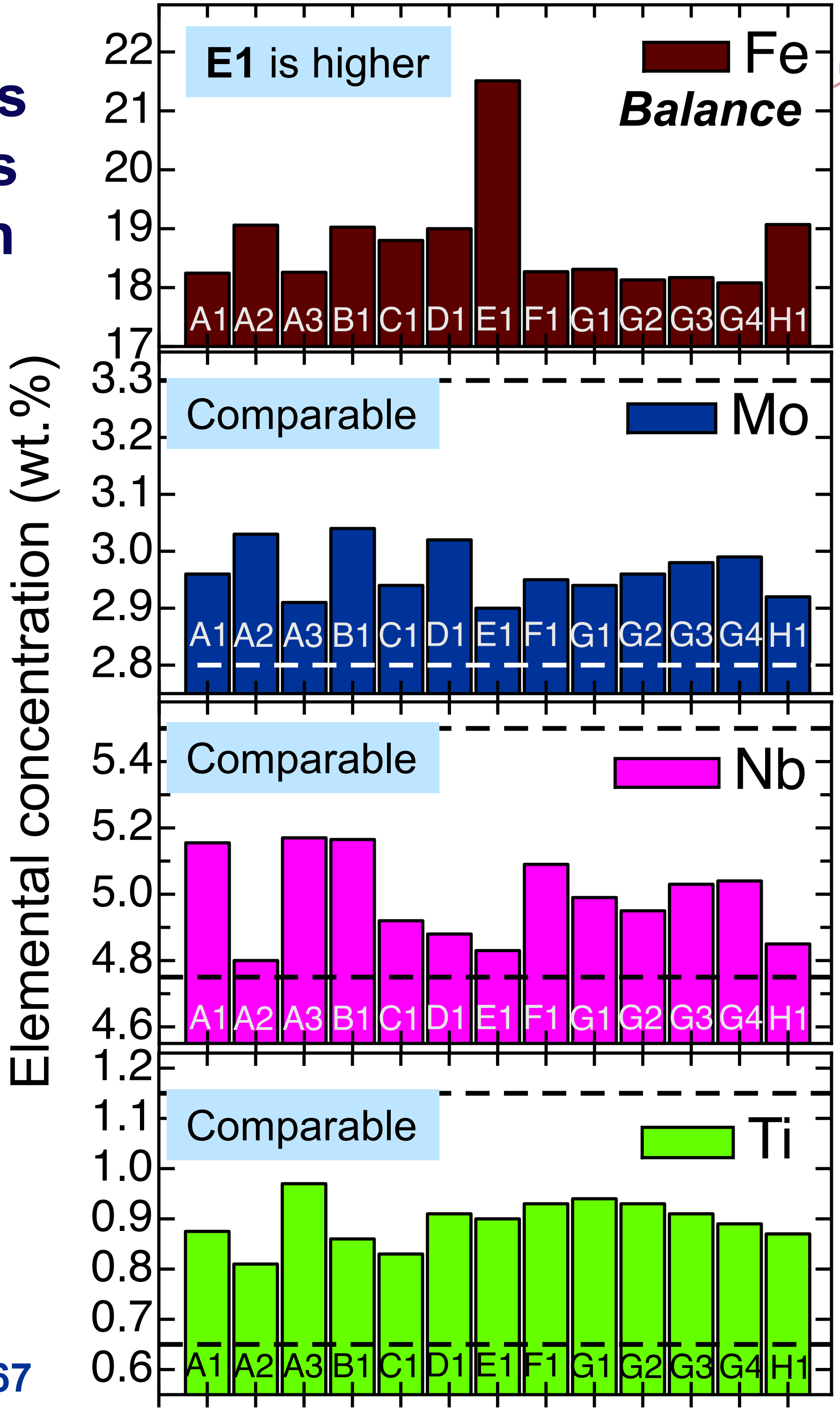


Larger diameter C1



Chemistry: Major components have consistencies & outliers within Alloy 718 specification

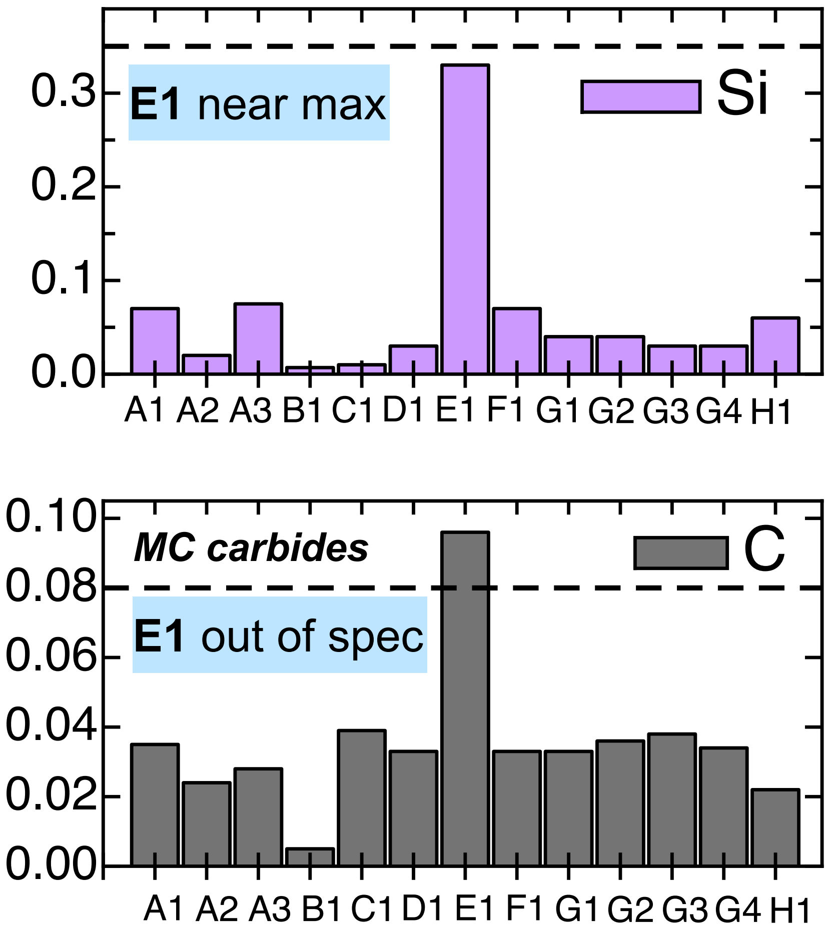




2 ICP-AES run average compared to ASTM 367

Chemistry: High content of minor component & trace impurity could lead to segregation, inclusions, & weldability issues

Elemental concentration (wt.%)

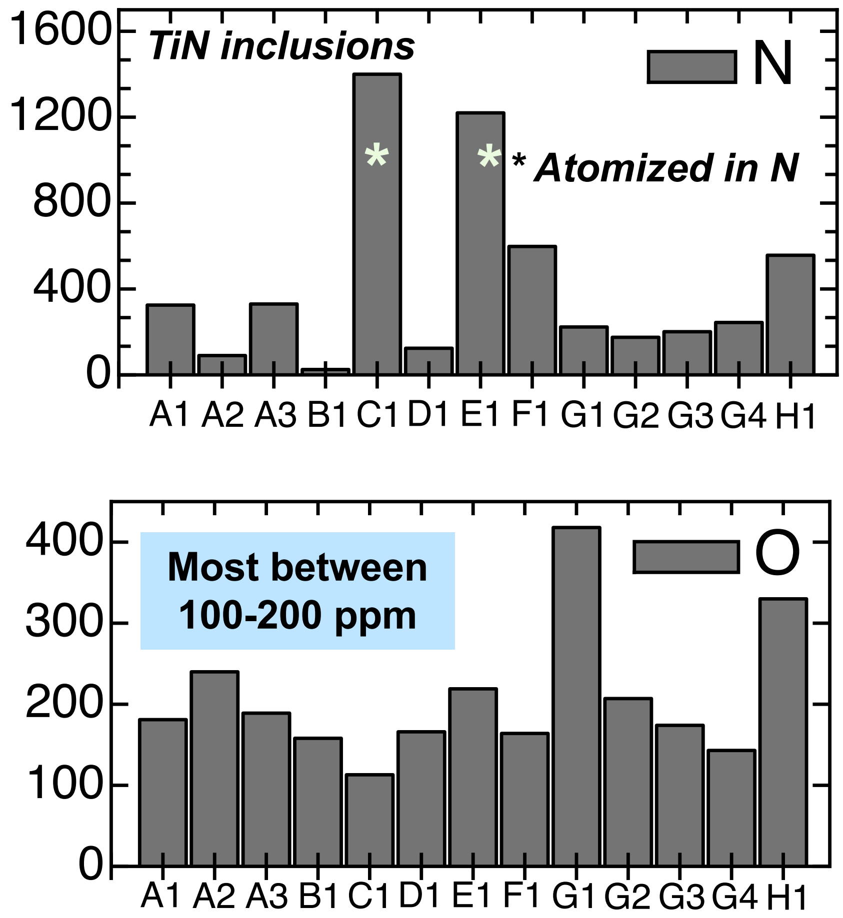


E1 near max

MC carbides

E1 out of spec

Elemental concentration (ppm wt.%)



TiN inclusions

** Atomized in N*

Most between 100-200 ppm

2 run average compared to ASTM 367

718 Study: Powder Feedstock Lot-to-Lot Variability

- ***How does feedstock variability influence microstructure, flowability, spreading, build quality, and performance?***
  - Flow behavior and FT4 rheology measurements
  - Build quality and microstructure – surface roughness, porosity, grain structure
  - Performance – Tensile and High Cycle Fatigue (HCF) results

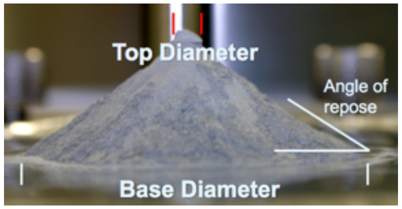
Freeman Technology FT4 Rheometer

Testing done under contract to LPW Technology Ltd., Pittsburgh, PA

Images reproduced with kind permission of Freeman Technology http://www.freemantech.co.uk/

- Several quality rheometers on the market
- Rheometers measure a variety of static and dynamic powder properties relevant to additive manufacturing machine builds
- FT4 testing is nearly totally automated
- Confined flow, unconfined flow, shear flow

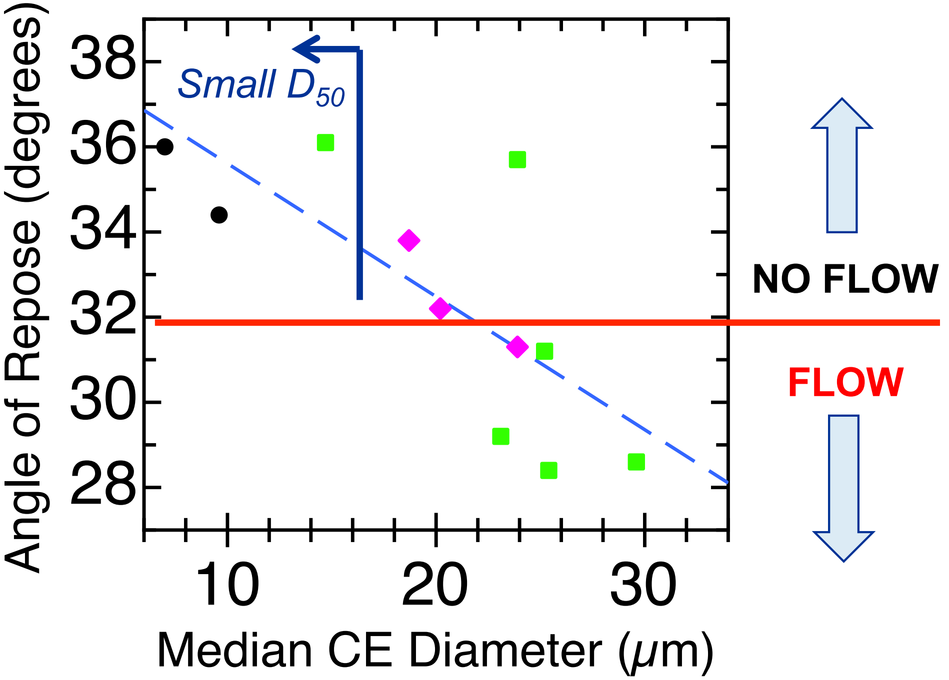
Carney flow influenced by particle diameter, morphology & how particles are distributed



Flow improves with increasing diameter

Powder Lot ID by Group	D_{50} (µm)	Percentage of Fines (%)	Avg Carney Flow Time / 50 g (sec)	Angle of Repose (deg)
Undersized (Group 1)				
A2 (10-45)	7.0	–	No Flow	36.0
B1 (15-45)	9.6	–	No Flow	34.4
Mixed (Group 2)				
H1 (10-45)	18.7	75.1	No Flow	33.8
A3 (10-45)	20.2	36.6	No Flow	32.2
E1 (10-45)	23.9	29.8	3.49	31.3
Normal (Group 3)				
G2 (11-45)	14.7	1.1	No Flow	36.1
D1 (16-45)	23.9	10.8	No Flow	35.7
A1 (15-45)	25.2	10.4	4.10	31.2
F1 (15-45)	23.1	14.5	3.03	29.2
C1 (15-45)	29.6	19.9	3.08	28.6
G3 (16-45)	25.4	7.0	3.37	28.4

Flowed when angle of repose < 32°

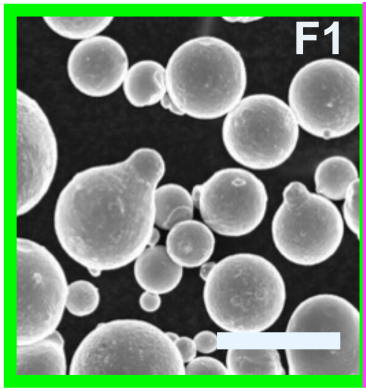


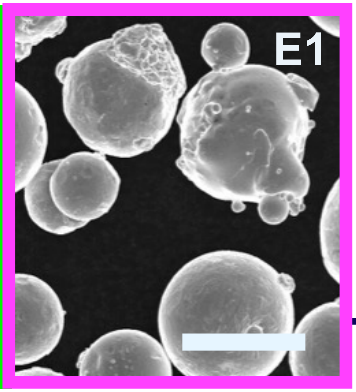
FLOW: Smooth & few satellites

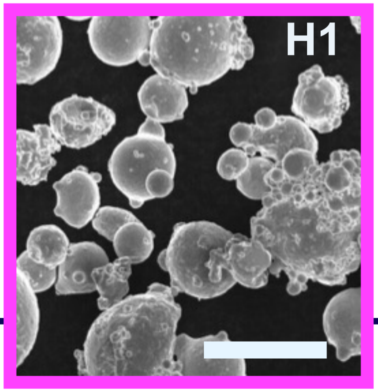
NO FLOW: I. Small Diameters

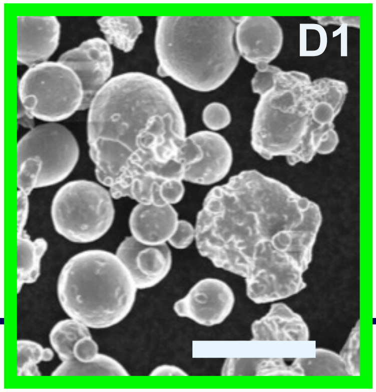
II. Agglomerated & bumpy

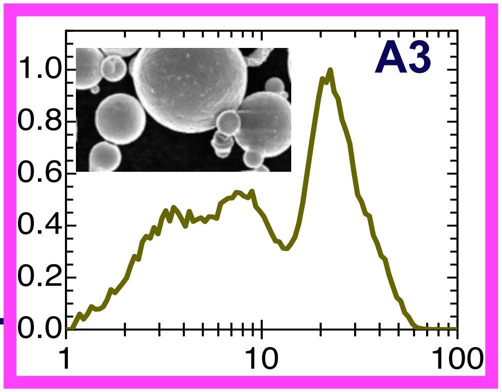
III. Atypical trimodal PSD









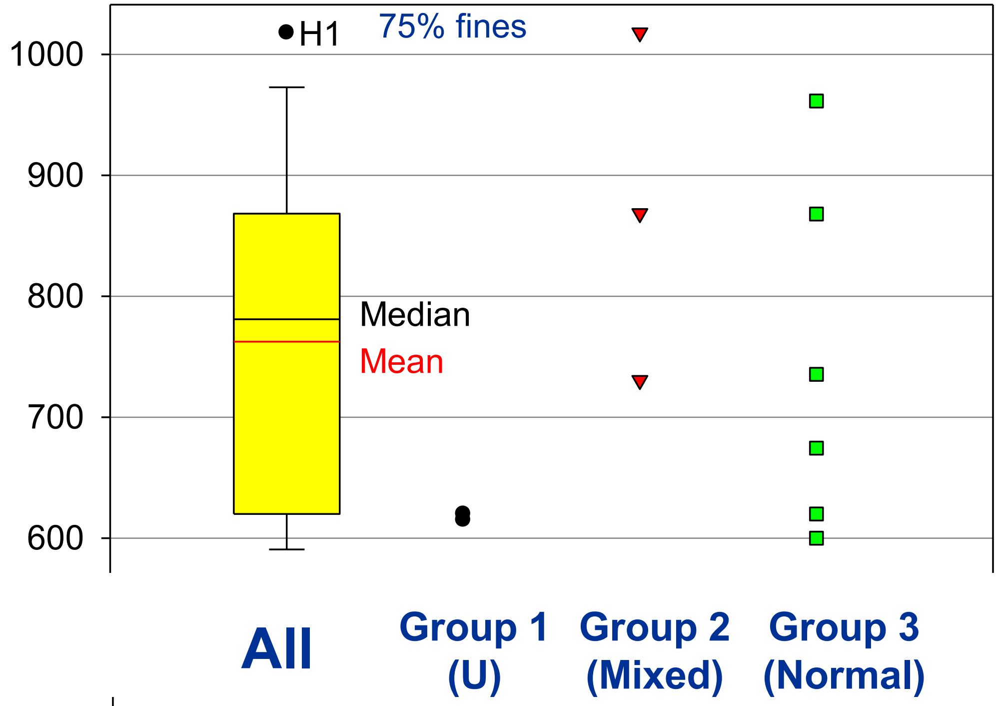


Rheology: Study of flow and deformation under applied forces

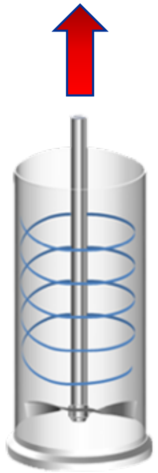
Basic Flow Energy (mJ)

Confined flow test

- Forced flow in a confined capacity (e.g. feed lines)
- Low air content or heavier powder will increase difficulty to move

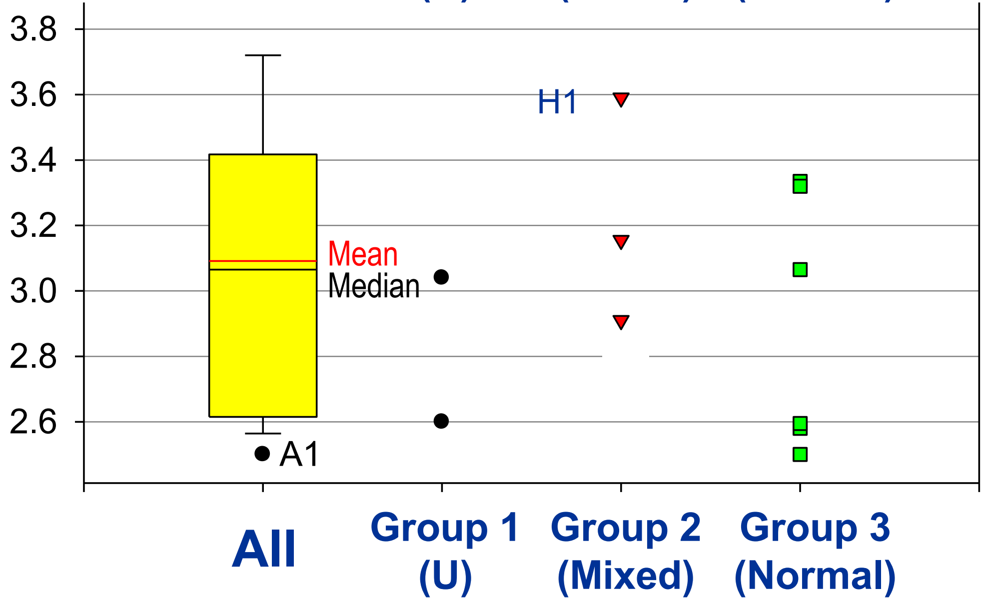


Specific Energy (mJ/g)



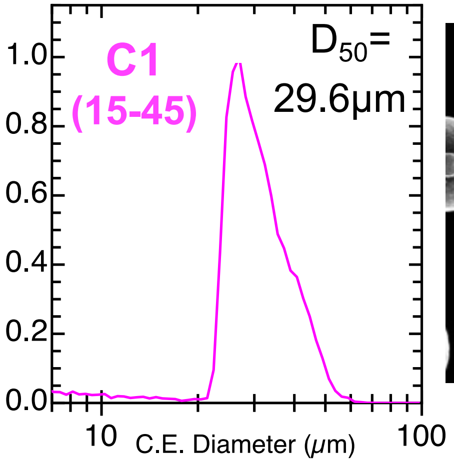
Unconfined flow test

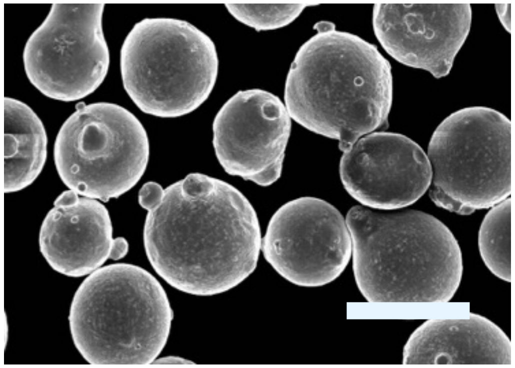
- Low stress, free flow of the powder in all directions
- Powder assemblies with high cohesivity should have higher specific energy



FT4 rheometer measurements

C1 powder has an unusually high flow function



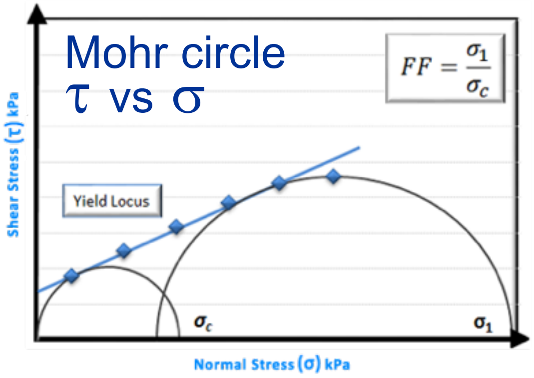


Shear cell

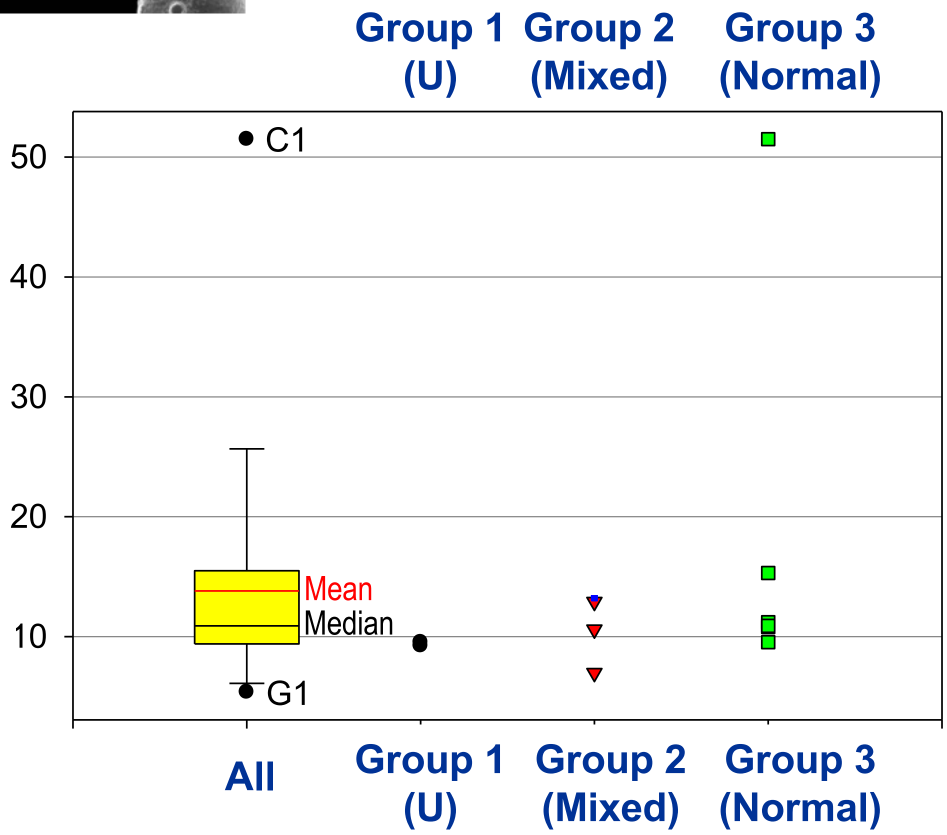
©Freeman Technology

Flow Function

Shear flow measurement



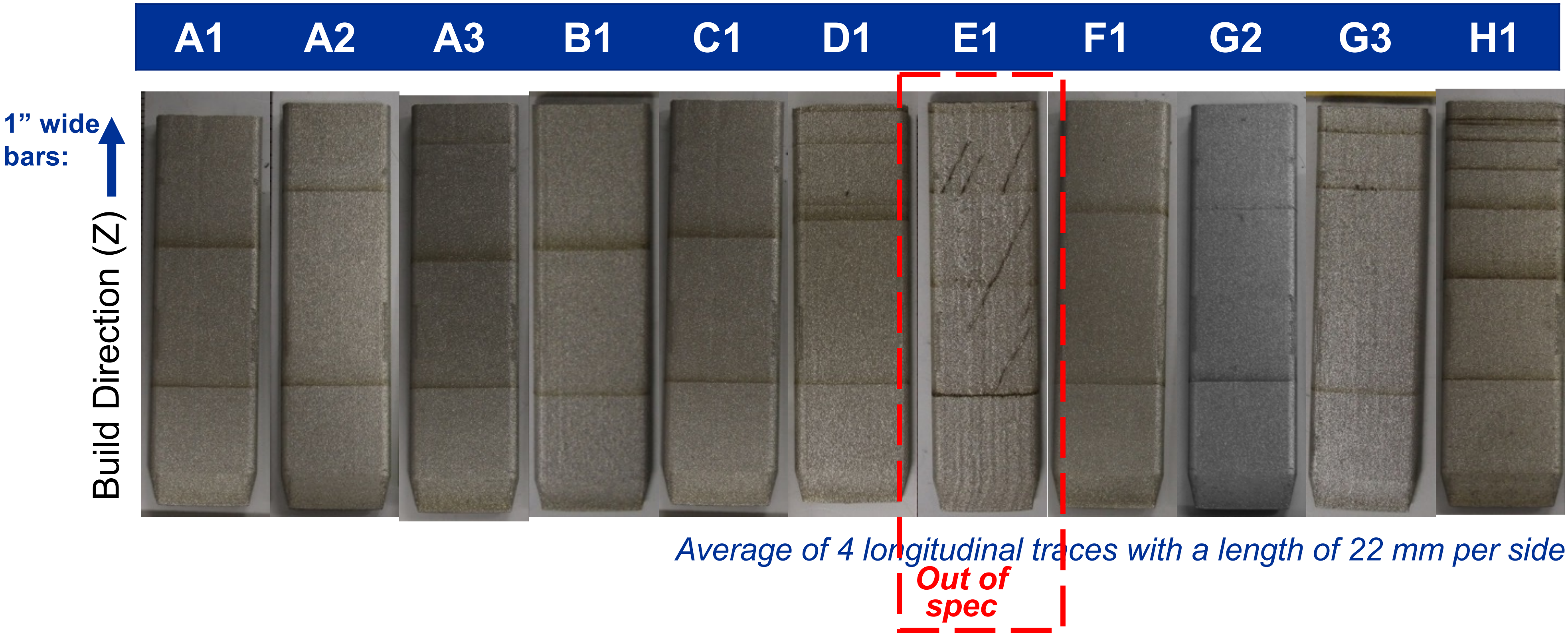
- Major Principle Stress (σ_1) to Unconfined Yield Strength (σ_c)
- Higher values indicate better flowability, non-cohesive powders



Impact of Feedstock Variability on Build Quality

Green State Met Bars

Traceable measurements on the Alicona InfiniteFocus Microscope



Average of 4 longitudinal traces with a length of 22 mm per side

Roughness is not proportional to mean particle diameter

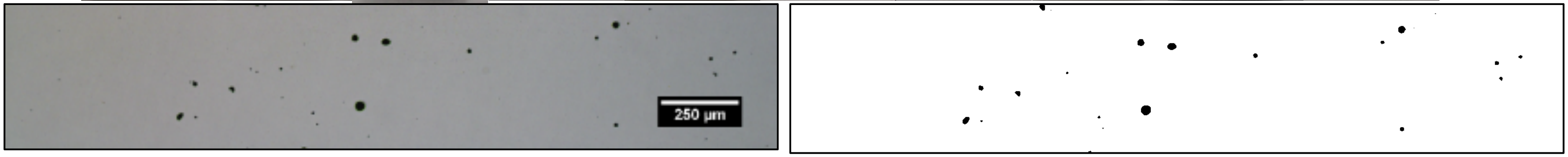
D_{50} (µm)	25.2	7.0	20.2	12.8	29.6	23.9	23.9	23.1	14.7	25.4	18.7
RMS roughness	7.13 ± 0.08 µm	9.8 ± 0.6 µm	8.22 ± 0.11 µm	9.9 ± 0.9 µm	8.6 ± 1.0 µm	9.2 ± 0.7 µm	9.66 ± 0.17 µm	7.68 ± 0.08 µm	7.6 ± 0.7 µm	10.4 ± 1.5 µm	12.0 ± 0.7 µm

Impact of Feedstock Variability on Build Quality

Green State Met Bars *Threshold image analysis of 5 areas in 1 cm x 1 cm XZ piece from mid-section*

1” wide bars:

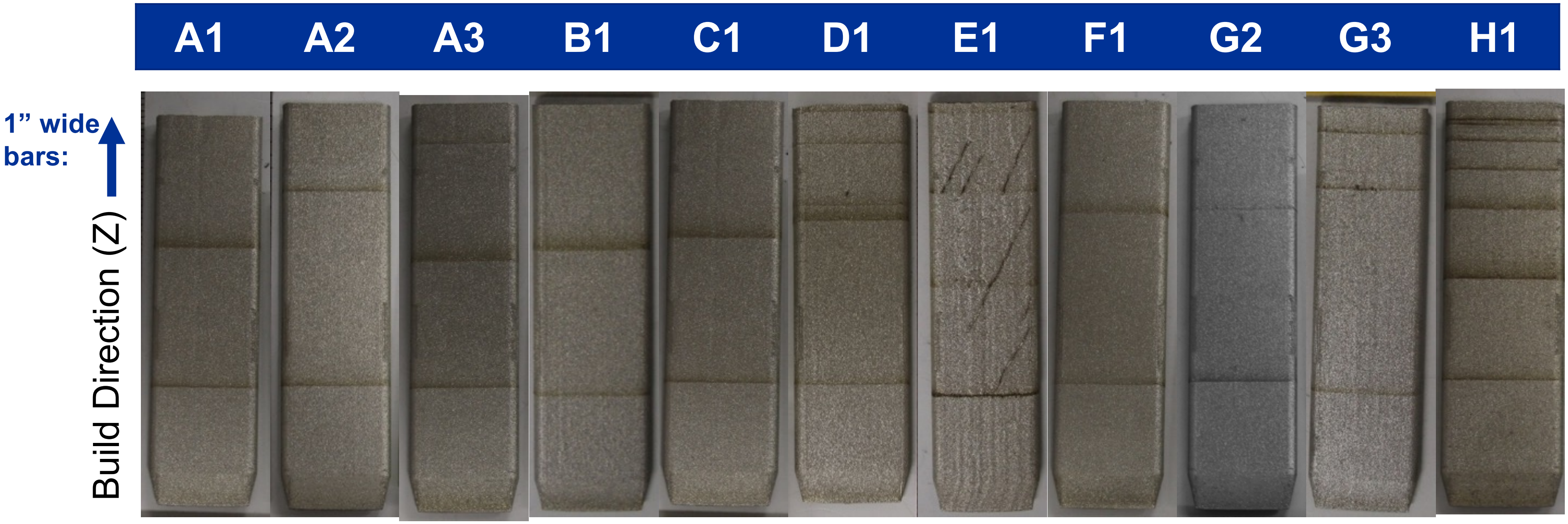
Build Direction (Z)



	A1	A2	A3	B1	C1	D1	E1	F1	G2	G3	H1
Green Porosity	0.19 ± 0.09 %	0.69 ± 0.23 %	0.19 ± 0.15 %	0.18 ± 0.09 %	0.14 ± 0.07 %	0.10 ± 0.07 %	0.46 ± 0.32 %	0.15 ± 0.09 %	0.14 ± 0.09 %	0.14 ± 0.07 %	0.19 ± 0.11 %
Green Pore Size	12.2 ± 3.0 µm	22 ± 4 µm	12 ± 3 µm	11.5 ± 2.3 µm	10.9 ± 2.3 µm	9.6 ± 2.6 µm	14.4 ± 3.0 µm	9.5 ± 2.0 µm	9.3 ± 1.8 µm	10.0 ± 1.9 µm	8.3 ± 1.5 µm
FHT Porosity											
FHT Pore Size											

Impact of Feedstock Variability on Build Quality

Green State Met Bars *Threshold image analysis of 5 areas in 1 cm x 1 cm XZ piece from mid-section*



Optimized SLM parameters produces low porosity → excellent build quality that is further improved with HIP

	A1	A2	A3	B1	C1	D1	E1	F1	G2	G3	H1
Green Porosity	0.19 ± 0.09 %	0.69 ± 0.23 %	0.19 ± 0.15 %	0.18 ± 0.09 %	0.14 ± 0.07 %	0.10 ± 0.07 %	0.46 ± 0.32 %	0.15 ± 0.09 %	0.14 ± 0.09 %	0.14 ± 0.07 %	0.19 ± 0.11 %
Green Pore Size	12.2 ± 3.0 µm	22 ± 4 µm	12 ± 3 µm	11.5 ± 2.3 µm	10.9 ± 2.3 µm	9.6 ± 2.6 µm	14.4 ± 3.0 µm	9.5 ± 2.0 µm	9.3 ± 1.8 µm	10.0 ± 1.9 µm	8.3 ± 1.5 µm
FHT Porosity	< 0.02 %	< 0.02 %	< 0.02 %	< 0.02 %	0.04 ± 0.02 %	< 0.02 %	< 0.02 %	< 0.02 %	0.28 ± 0.20 % *	< 0.02 %	0.06 ± 0.04 %
FHT Pore Size	3.3 ± 0.4 µm	3.3 ± 0.3 µm	3.5 ± 0.6 µm	3.4 ± 0.4 µm	3.1 ± 0.6 µm	5.1 ± 1.2 µm	3.3 ± 0.4 µm	3.3 ± 0.5 µm	3.0 ± 0.3 µm	4.5 ± 1.4 µm	4.3 ± 0.6 µm

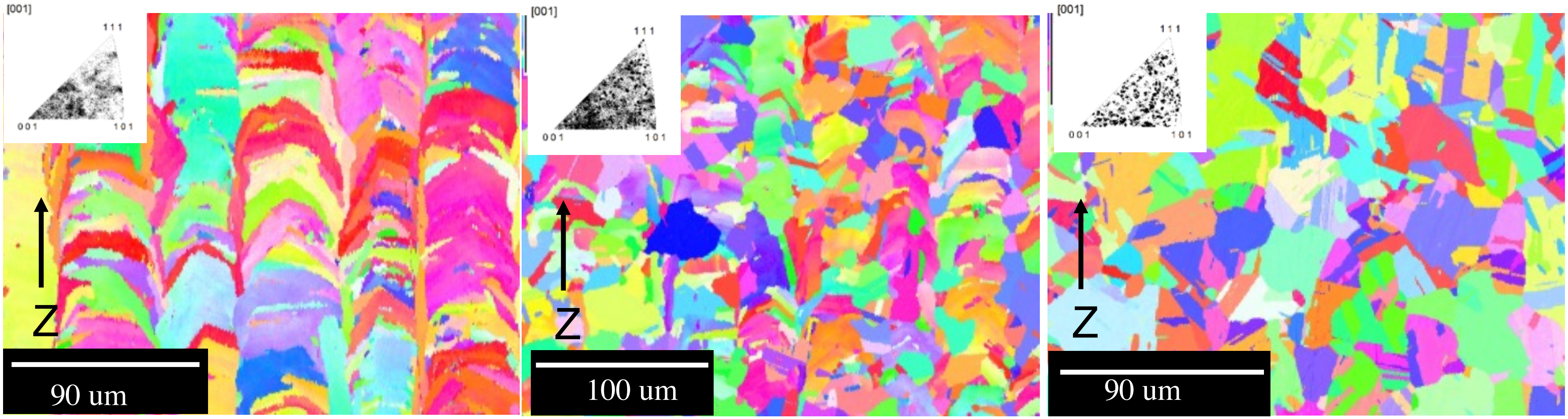
* Recheck

Three grain structure regimes observed after heat treat

Retained SLM structure for lots atomized in nitrogen

Partially Recrystallized for H1 lot

Fully Recrystallized Grain sizes 50 -90 µm



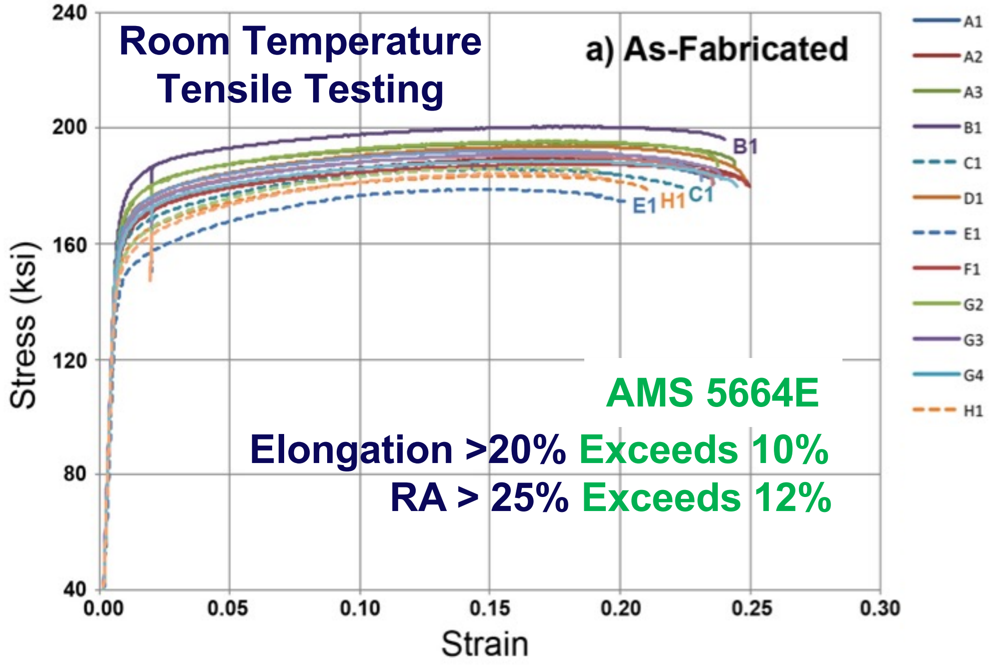
Recommend Ar-atomization and N content < 400 ppm for homogeneous grain distribution

Linear intercept	A1	A2	A3	B1	C1 (N GA)	D1	E1 (N GA)	F1	G2	G3	H1
Mean grain diameter (± 95% CI)	70 ± 5 µm	57 ± 4 µm	74 ± 12 µm	68 ± 9 µm	36 ± 5 µm	53 ± 4 µm	21.5 ± 1.3 µm	89 ± 12 µm	63 ± 6 µm	71 ± 6 µm	40.9 ± 2.3 µm
N content ppm	325	90	331	25	1395	122	1220	607	176	199	562

Nitrides pin grain boundaries in both N-atomized powders, retains smaller (001)-oriented grain sizes from fabrication.

EBSD maps and pole figures

Heat Treated SLM 718 meets or exceeds minimum requirements for lots within chemistry specification

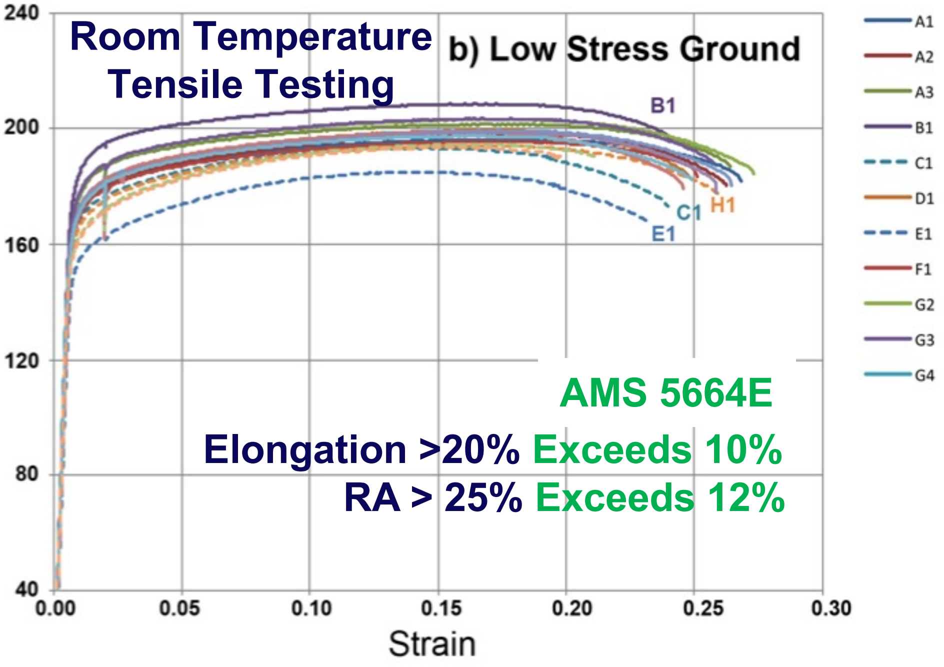

Room Temperature Tensile Testing

a) As-Fabricated

AMS 5664E

Elongation >20% Exceeds 10%

RA > 25% Exceeds 12%


Room Temperature Tensile Testing

b) Low Stress Ground

AMS 5664E

Elongation >20% Exceeds 10%

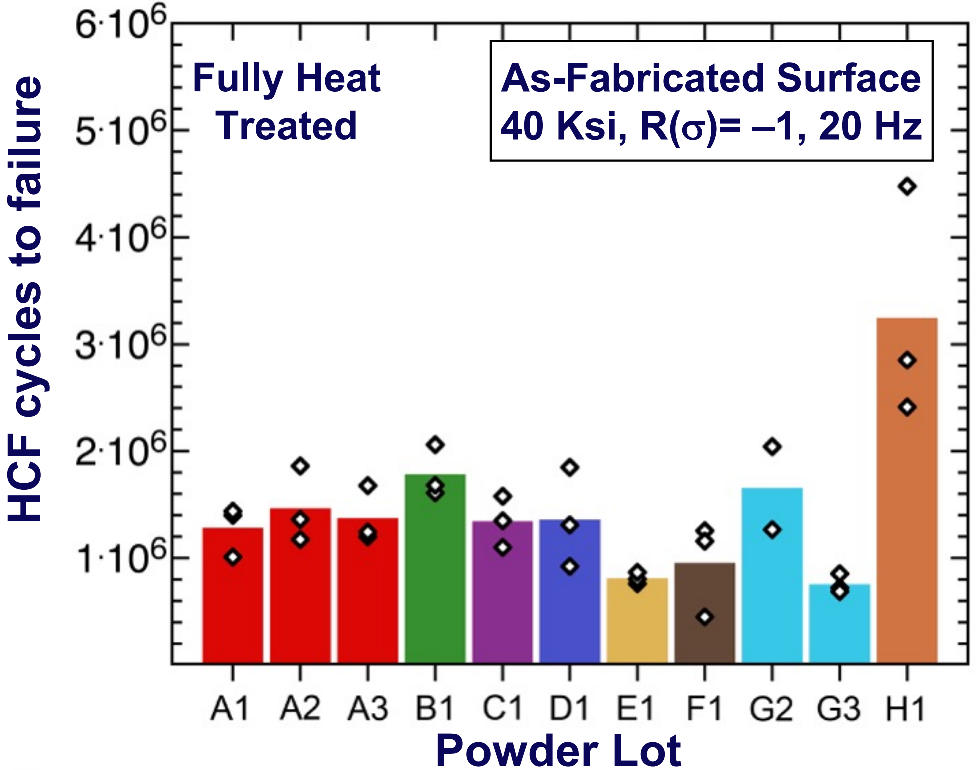
RA > 25% Exceeds 12%

As-fabricated	UTS (ksi)	0.2% YS Offset (ksi)
AMS 5664E	180.0	150.0
B1 (Low C)	200.5	171.1
Rest (H1 >>G2)	183.5-195.5	151.6-165.4
E1 (Off Spec)	178.8	144.9

Low Stress Ground	UTS (ksi)	0.2% YS Offset (ksi)
AMS 5664E	180.0	150.0
B1 (Low C)	208.8	179.3
Rest (H1 >>G3)	193.4-203.6	160.8-165.4
E1 (Off Spec)	185.0	150.6

Screening study: *AF condition appears mostly invariant to powder, while LSG condition varies with powder lot due to microstructure*

Room Temp. HCF testing (Load Control)

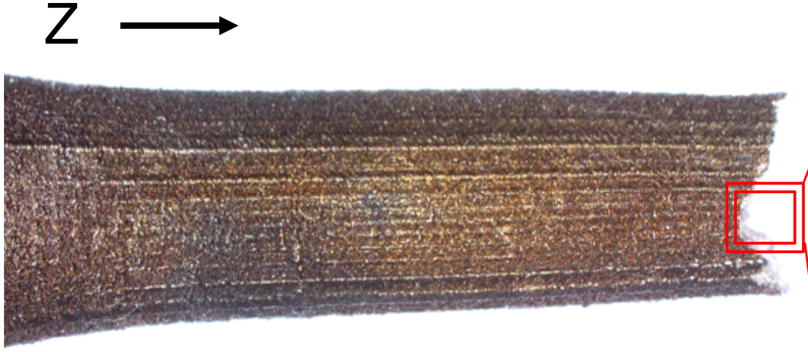


As-Fabricated (AF)

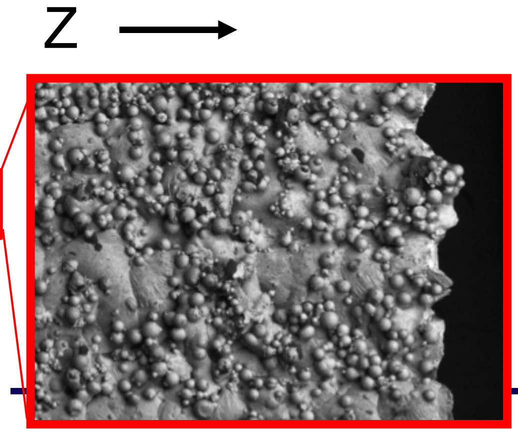
- Only H1 AF HCF is statistically different → 75% fines contribute to fused surface

As-Fabricated and Low Stress Ground

- Failure modes are being examined
- Single initiation points that are mostly near or at the surface, where crack propagates transgranularly
- Limited crack initiations from embedded defects (unmelted particles, inclusions, etc.)



Surface of failed AF test bar is slightly oxidized and ridged



Fracture surface

Concluding remarks

- Powders evaluated are distinct and lead to distinct flow behavior:
  - Outliers in both major and minor additions within specification plus one off-specification powder
  - Wide variation in modality and shape of particle size distributions on a number basis that is not as pronounced on volume basis typical to laser spectral methods
  - Our screening showed larger standard cut (15-45 µm) less likely to have a high percentage of fines; may be vendor dependent
  - Differences in agglomeration and fusion captured by shape factor distributions
  - Able to correlate some aspects of rheological properties with distribution characteristics of the powders
- Optimized SL M parameters for 718 yielded high quality builds with low porosity and acceptable tensile properties across many distinct powder lots; however, nitrogen content needs to be controlled to produce equiaxed grain distribution
- **Lot-to-lot comparison** of powder feedstock variability gave some initial guidance to control limits for 718 SLM hardware
  - Recommend: Atomization in Ar and < 400 ppm N content

chantal.k.sudbrack@nasa.gov

Future Work

Target: NASA Technical Report, March 2018 https://www.sti.nasa.gov/

In progress:

- Detailed green state and heat treated microstructure and defect evaluation
- Failure mode evaluation of HCF tests in screening study
- Flammability testing

Primary and secondary correlation analysis with rich data set to link to control limits

Also next: Reuse & recyclability study

Looking ahead to expanded study with much more exhaustive property evaluation:

- ***Extremes**: Very smooth vs. highly agglomerated*
- ***Typical**: Particle size effect*
- ***Key chemistry differences***

Thank you for your attention! Questions?

chantal.k.sudbrack@nasa.gov

APPENDIX BB—LASER POWDER BED FUSION PROCESS CONTROL FOR FLIGHT CRITICAL PARTS

Laser Powder Bed Fusion Process Control

For Flight Critical Parts

Dr Paul Guerrier
Moog Inc.
East Aurora, NY

This document, including all enclosed slides, consists of general capabilities information that is not defined as controlled technical data under ITAR Part 120.10 or EAR Part 772.

Overview

- Laser Powder Bed Fusion Process Control For Flight Critical Parts

- Company Introduction
- Overview of Moog's AM Capabilities
- Moog's AM Experience So far
- Part Quality & Process Sensitivity
  - Primary effects
  - Secondary effects
  - Tertiary effects
- Moog's Proposed Route to Qualification & Certification
- Making Use of a Digital Workflow
- Summary
- Questions

Moog Inc.

- Founded in 1951 by Bill Moog
- Medium-size, multinational
  - $2.5B sales in FY'16E
  - 100+ locations in 28 countries
  - Over 11,000 employees
- Traded on the New York Stock Exchange (MOG-A)
- People-oriented environment with emphasis on individual responsibility
- Reputation for high quality and technical excellence

Argentina
Australia
Brazil
Canada
China
Costa Rica
Finland
France
Germany
India
Ireland
Italy
Japan
Lithuania
Luxembourg
Netherlands
Norway
Philippines
Russia
Singapore
South Africa
South Korea
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

Moog Internal AMC Facilities

2 Renishaw AM250 & 1 Renishaw AM500M LPBF Machines

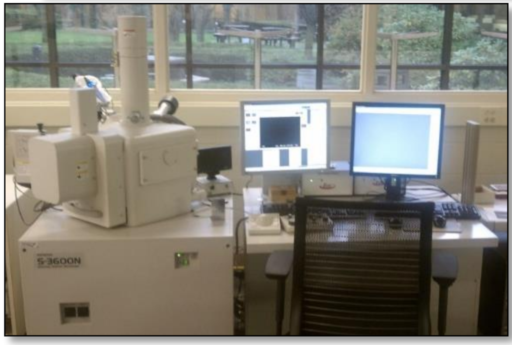
Wide Throat Wire EDM

Stress Relieve Oven

Personal Protection Equipment

Ultrasonic Cleaner and Grit Blast

Materials and Process Engineering

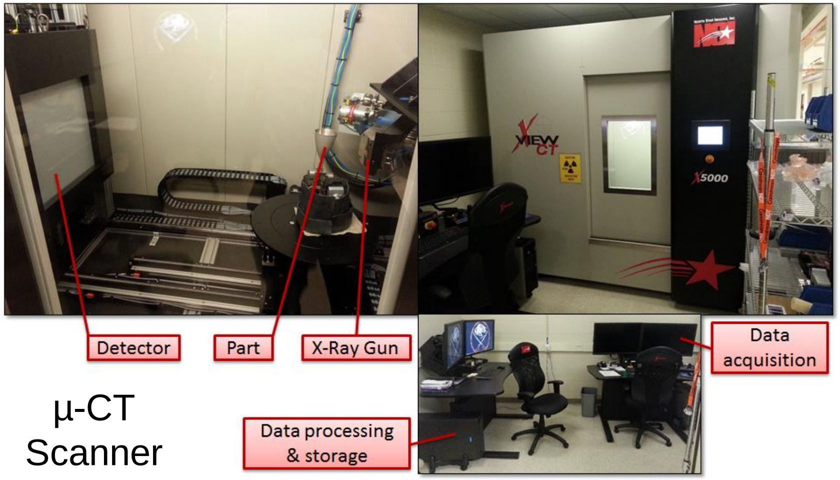


SEM

Auger

Fluid Sampling Lab

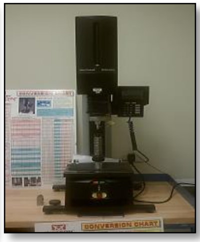
Auto Polisher



μ-CT
Scanner

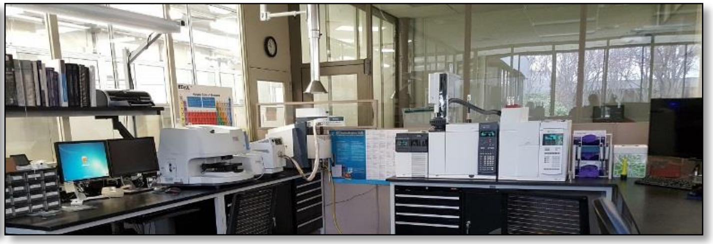
Mechanical Testers

Common Area Microscopes



Hardness
Tester

Bore Scope



FTIR & GC/MS

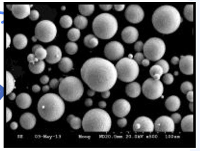
Moog Livonia Additive Manufacturing Production

- 17 Laser Powder Bed Fusion machines
- Facility moving to East Aurora, NY

- Wide Range of Metals
  - 15-5, 17-4 & 316 Stainless Steels
  - Cobalt Chrome
  - Inconel 625 & 718
  - Aluminum (AlSi10Mg)
  - Titanium (Ti64)
  - Maraging Steel (MS1)
  - Hastalloy-X
  - Copper

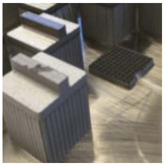
AM is more than just the AM Machine:

Includes: Specification, Sieving, reuse, handling, filling, removal



Powder Management

Build Stresses



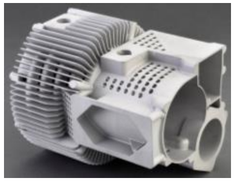
Supports

Recoater direction

Build Plate Design

Build Direction

Data Control and Verification



AM Design freedom/ constraints

Machining allowances

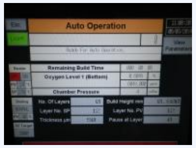
AM Design rules 2.0

DESIGN MANUAL FOR ADDITIVE MANUFACTURING

(FOR METAL PARTS TO BE MANUFACTURED USING LASER POWDER BED FUSION)

MRE40633

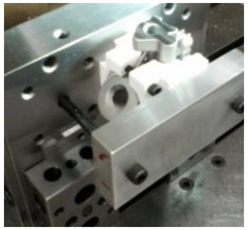
AM part Selection (Suitability criteria/ assessment)



AM Machine Parameters

AM Machine Control strategies

Build Verification



Finish Machining

3D scanning

Honing

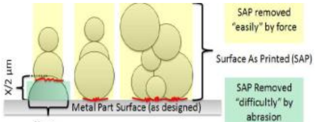
CT scan

AM part Costing

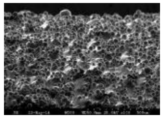
Polishing

Stress relieve

EDM



SAP Level I/II removal



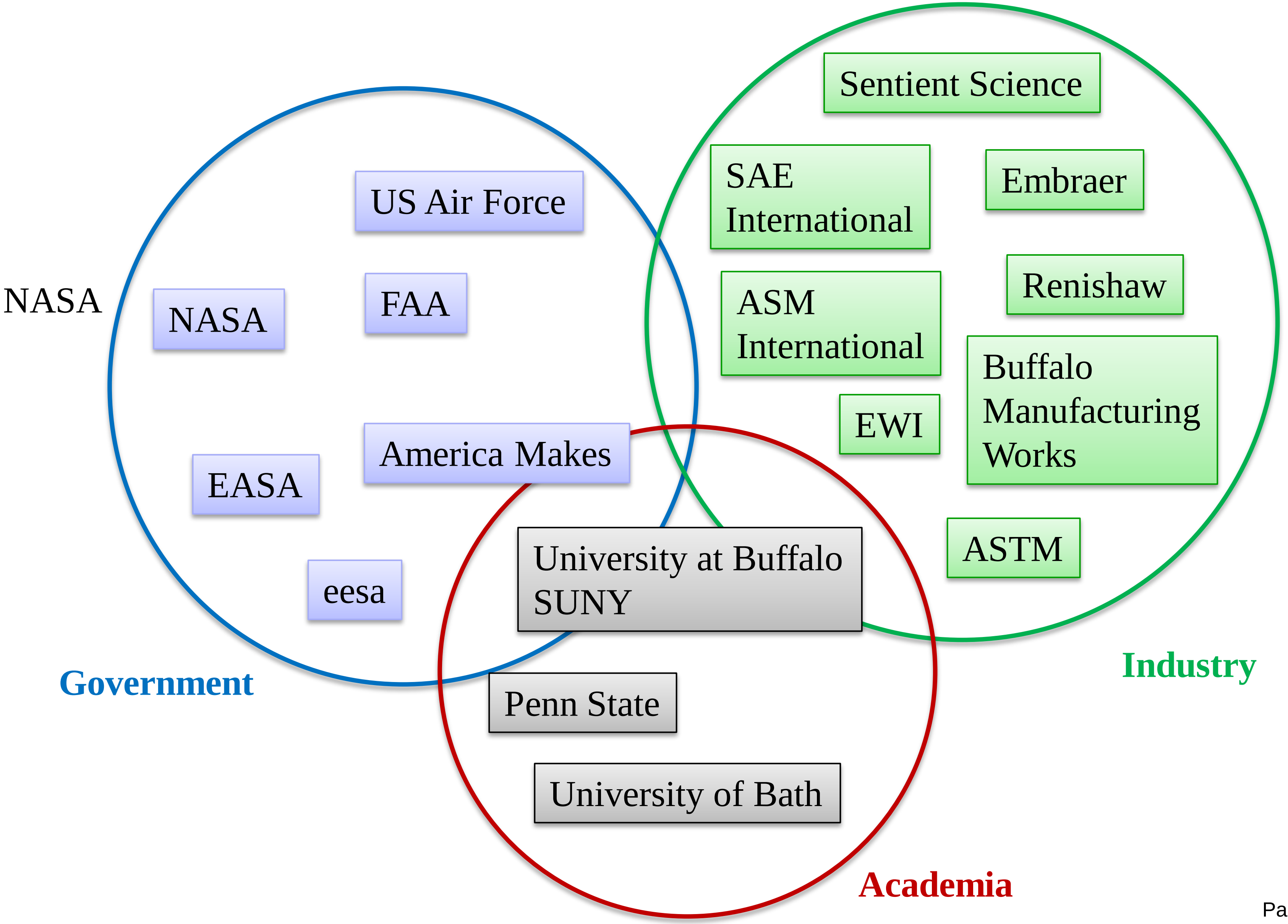
Contamination Control

Heat Treat

AM Enabled Personnel & Training at Moog

- Metal AM Training Course developed and delivered
- Circa 100 AM enabled engineers & business development colleagues
- 4+ years prior to owning and operating a metal AM LPBF machine in house on design and development for the process
- 3+ years with equipment

Research & Development Associations



NASA

US Air Force

NASA

FAA

EASA

America Makes

eesa

Sentient Science

SAE International

Embraer

ASM International

Renishaw

EWI

Buffalo Manufacturing Works

ASTM

University at Buffalo SUNY

Penn State

University of Bath

Government

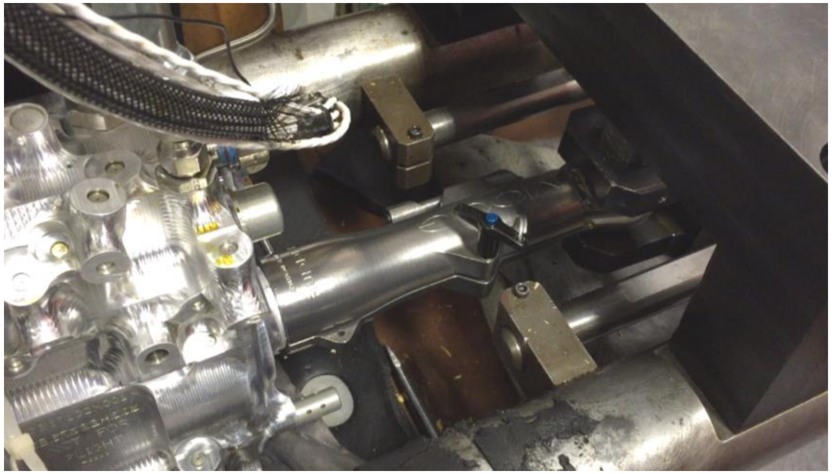
Industry

Academia

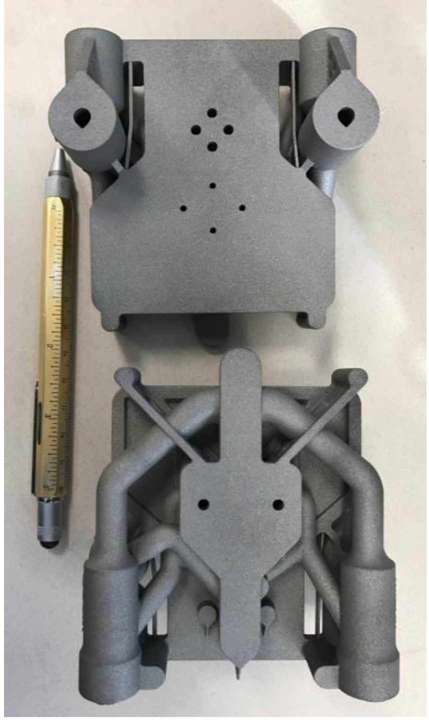
Production Hardware

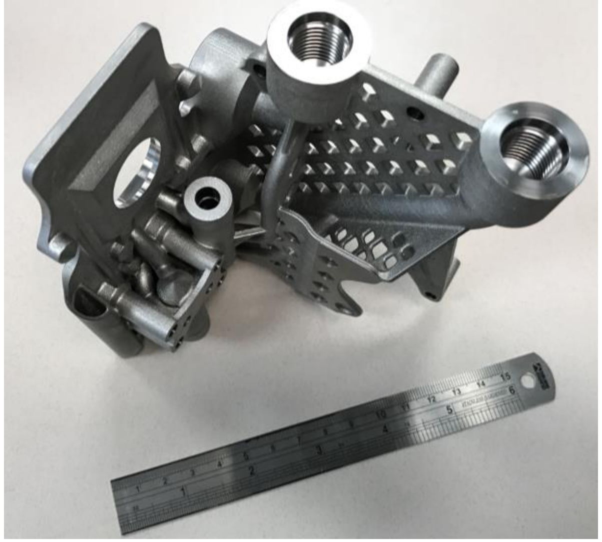
Hydraulic Locking Collars – Ground Equipment

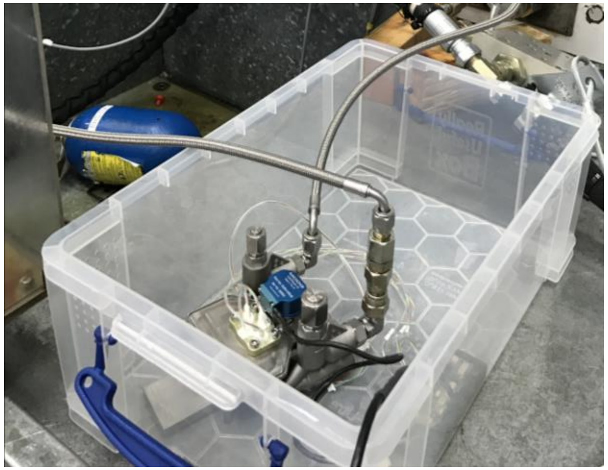
Locking Collar Under Test



Robotics Actuation

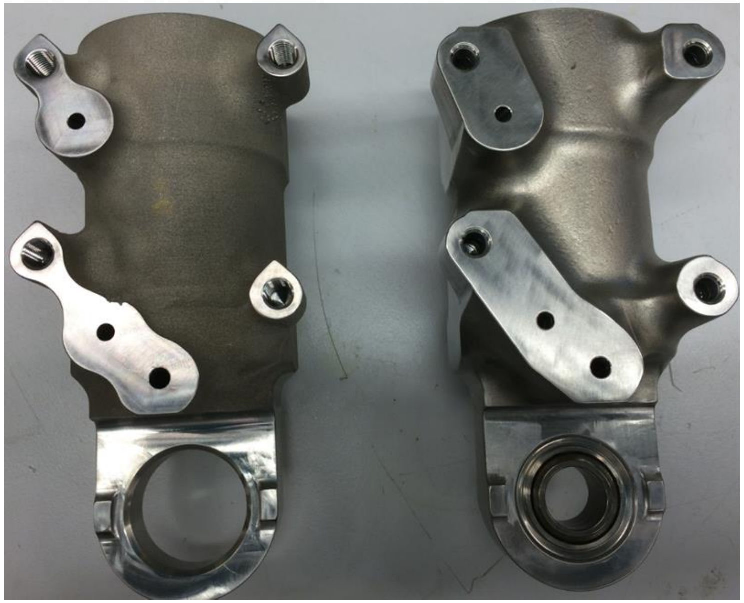


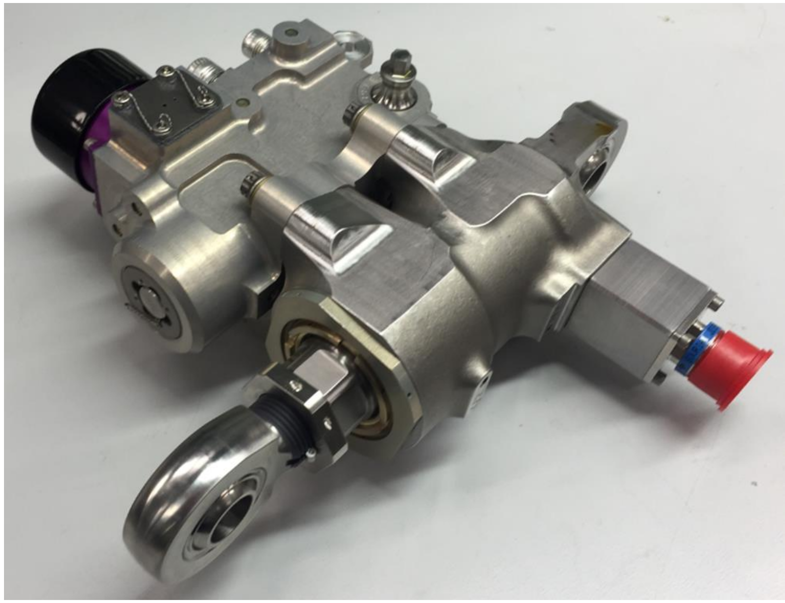




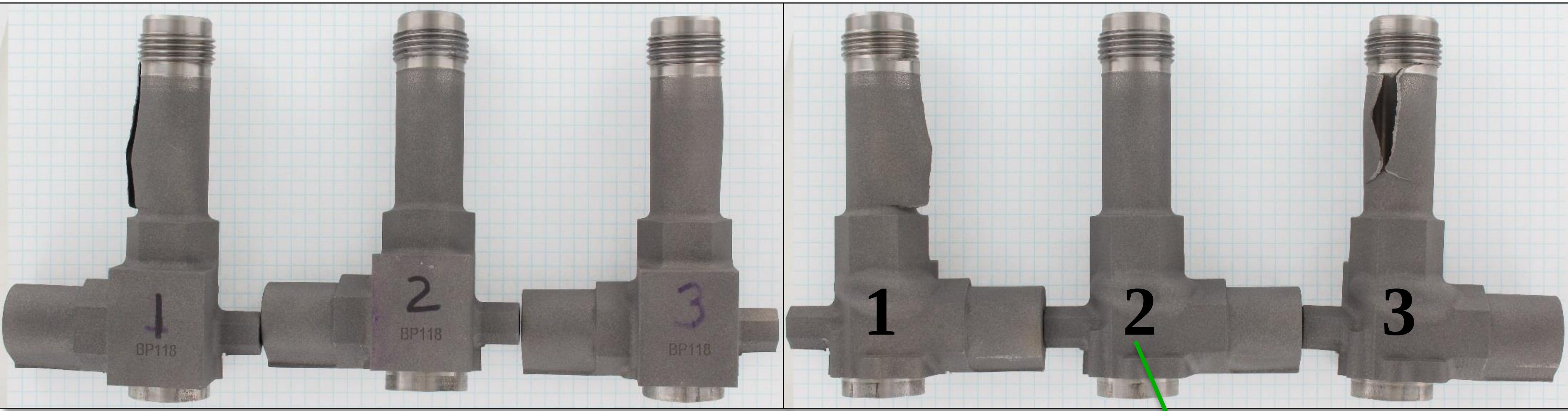
Embraer E2 Outboard Spoiler Cylinder Demo

- Proof of concept demonstration
  - 15-5PH stainless steel cylinder was AM printed on Renishaw AM250
  - Non-flight demonstration actuator now assembled using AM cylinder shown
  - Actuator has been Acceptance Tested and will be subject to limited endurance and fatigue testing

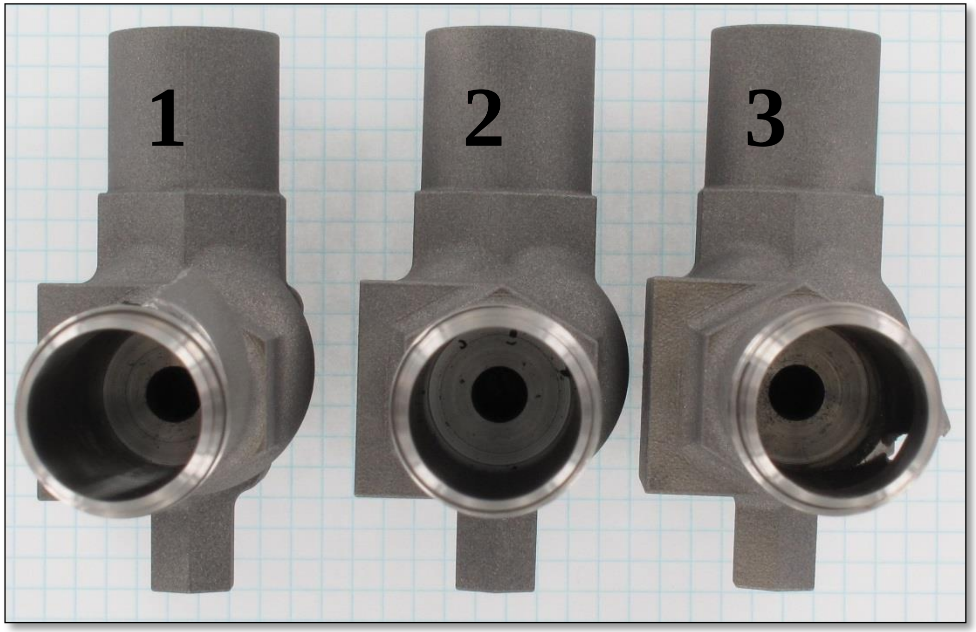




Propulsion Valve

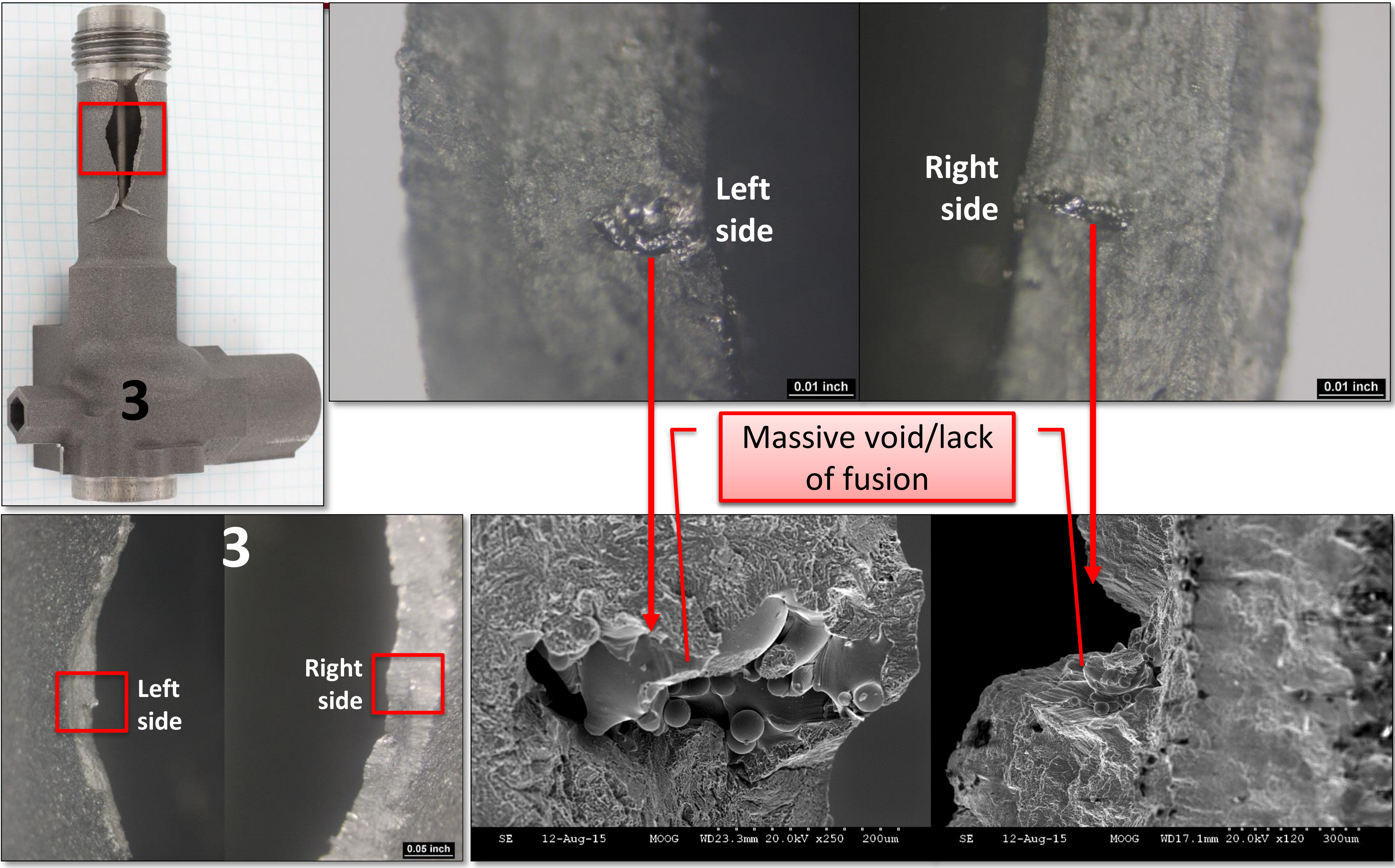


Test Pressure
20,000 psi



Burst Test Specimen 2 did not burst even with 0.05" wall

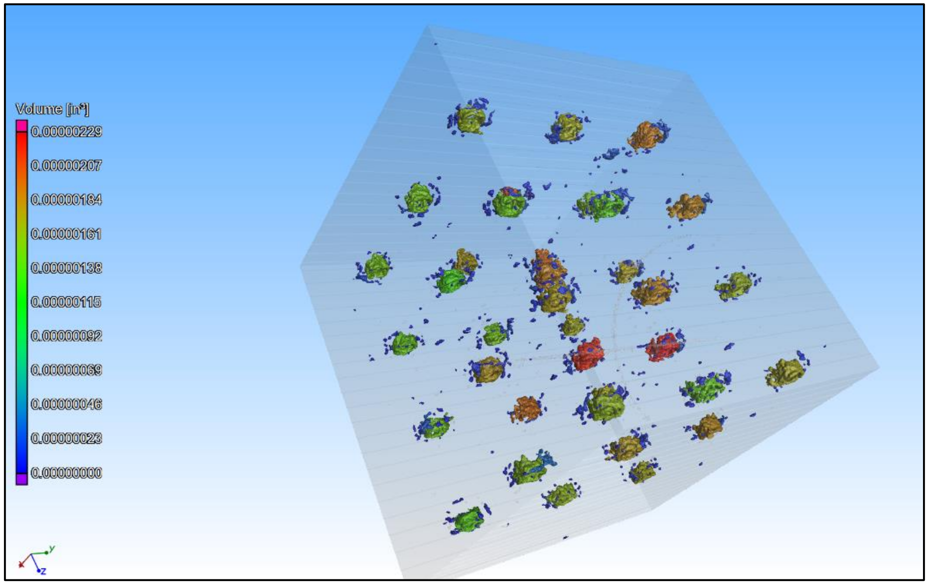
Burst Test Sample 3

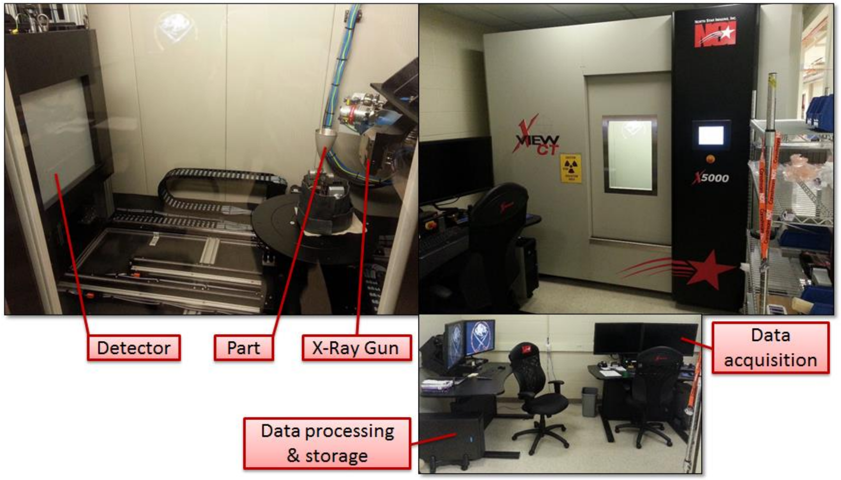


Massive void/lack of fusion

Part Inspection Via X-ray CT – Learning So far

- On site X-ray CT installed at Moog
- Inspection of AM parts will be part of production for critical applications
- X-Ray CT reliably detected small defects and porosity in the range of .00X” for small parts





Helicopter “Flight Control” Drag Links

UAV

Helicopter “Flight Control” Drag Links

- The Moog OPV was flown with an “Experimental Airworthiness Certificate” from the FAA for a standard Robinson R44 Helicopter with a [full authority] autopilot for product R&D purposes.
- The aircraft was restricted to flight over a small area near Griffiss Airport in Central NY State.
- The aircraft was always flown manned with a pilot on board and in command, the autopilot [OPV system] was switched on for autonomous flight in the test area.
- Operation outside the designated flight test area required that the system be mechanically disconnected from the flight controls (for ferrying the aircraft to and from Moog Griffiss Airport).

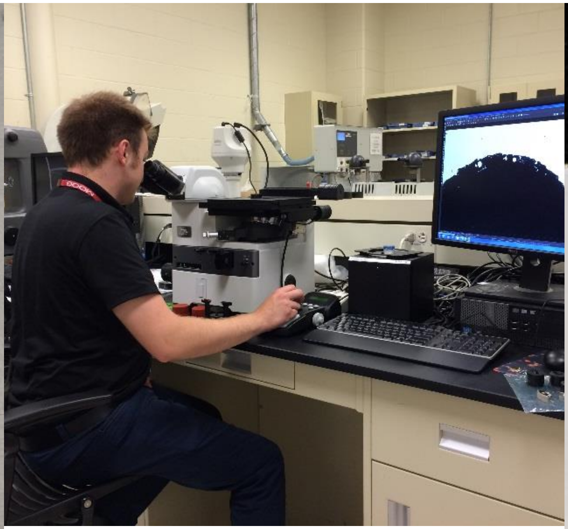
Part Quality & Process Sensitivity

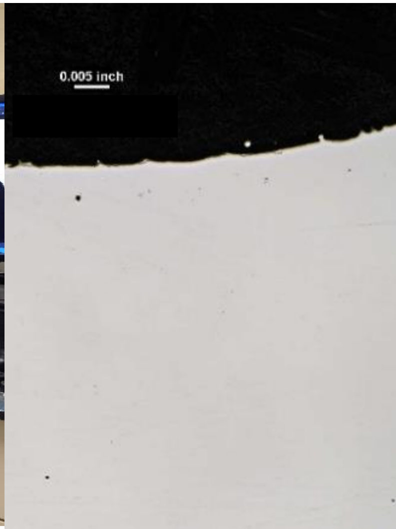
- Primary Effects
  - Part geometry & support structure
  - Raw material: composition
  - LPBF Equipment: calibration, accuracy, machine control software, tool path creation software, **laser parameters**
  - AM Part: residual stress, heat treatment & finishing processes
- Secondary Effects
  - LPBF Equipment: **inert gas flow**
  - Raw material: re-use, moisture content & detailed chemistry
  - Build plate layout
- Tertiary Effects
  - TBD

AM Parameter Optimization

- AM Equipment Commissioned & Calibrated
- Benchmark Standard Parameter Part Quality
- Understand Which Parameters to Change & Why
- Modify Parameters & Improve Part Quality
- Document Process & Maintain

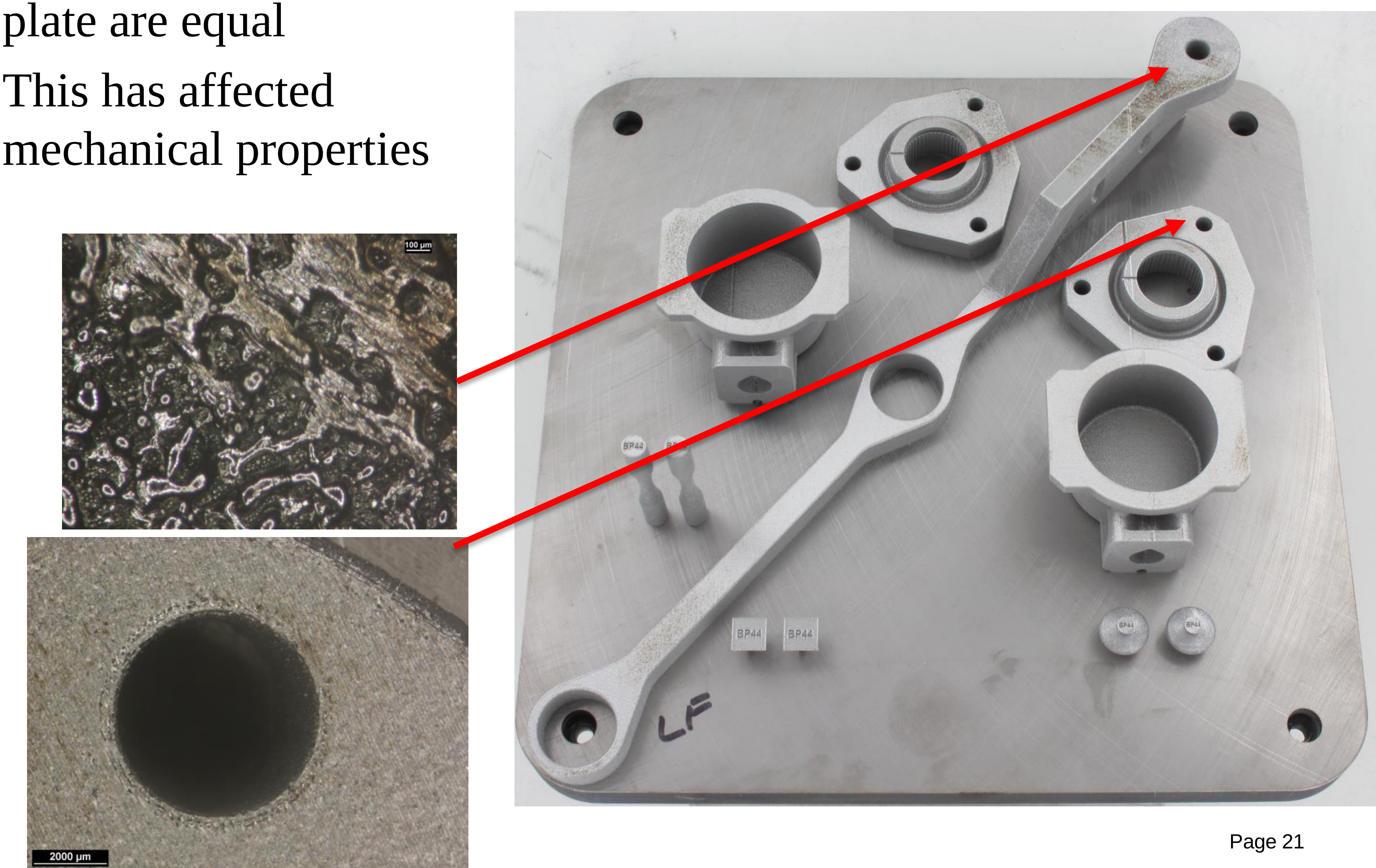
Make Coupons
Inspect
Adjust Parameters
Make Sample Parts
Inspect/Confirm
Make Parts





Inert Gas Flow Effects

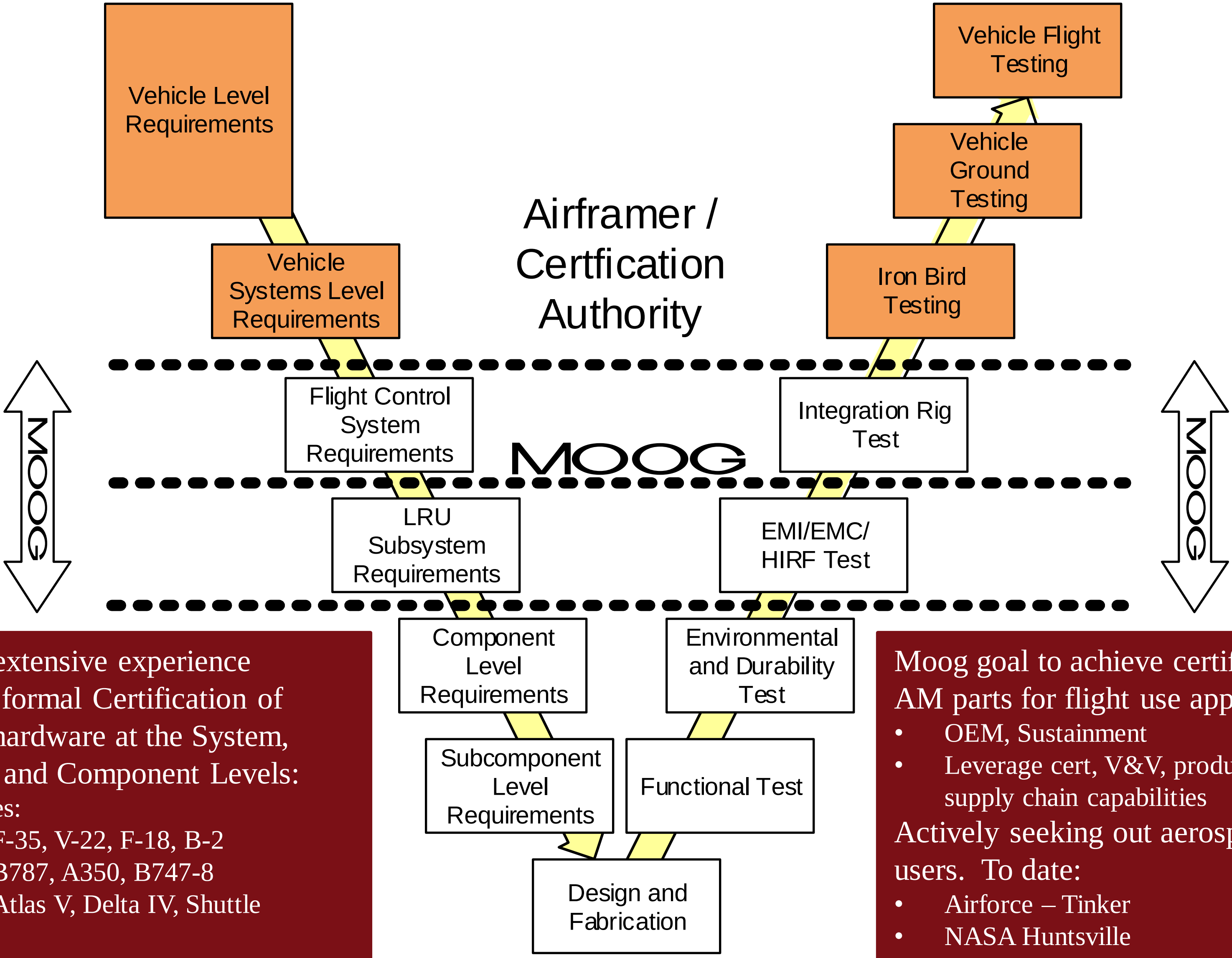
- Not all areas of build plate are equal
- This has affected mechanical properties



Qualification & Certification

- Qualification & Certification of parts for AM

Moog Certification Experience



Vehicle Level Requirements

Vehicle Systems Level Requirements

Flight Control System Requirements

LRU Subsystem Requirements

Component Level Requirements

Subcomponent Level Requirements

Design and Fabrication

Functional Test

Environmental and Durability Test

EMI/EMC/ HIRF Test

Integration Rig Test

Iron Bird Testing

Vehicle Ground Testing

Vehicle Flight Testing

Airframer / Certfication Authority

MOOG

Moog has extensive experience supporting formal Certification of aerospace hardware at the System, Subsystem and Component Levels:

- Examples:
  - F-35, V-22, F-18, B-2
  - B787, A350, B747-8
  - Atlas V, Delta IV, Shuttle

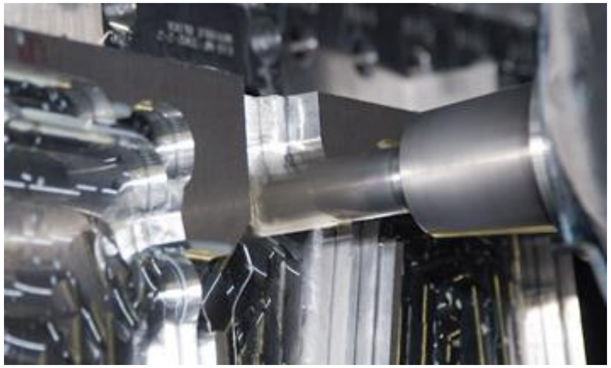
Moog goal to achieve certification of AM parts for flight use applications

- OEM, Sustainment
- Leverage cert, V&V, production and supply chain capabilities

Actively seeking out aerospace lead users. To date:

- Airforce – Tinker
- NASA Huntsville
- Embraer

Additive Manufacturing vs Traditional Fabrication

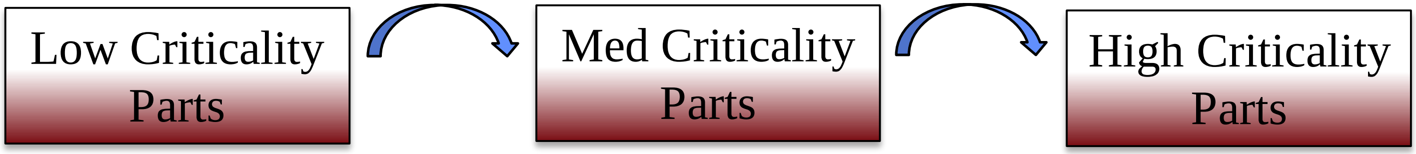


- Traditional (subtractive) fabrication process removes portions of preexisting material during part fabrication
  - Industry holds a long history and understanding of the effects of machining, heat treat, casting and forging processes on material properties (includes damage tolerance and fatigue)
- Additive Manufacturing (AM) process creates the material and the part at the same time
  - AM describe a range of processes, (laser, e-beam, powder bed, wire feed, etc.)
    - Sources of variation need to be identified and controlled for repeatable parts

Civil Airworthiness Requirements: Relevant FARs

- Suitability – Part XX.603 (ex. 14 CFR 25.603, Materials)
- Producibility – Part XX.605 (ex. 14 CFR 25.605, Fabrication Methods)
- Characterized Mechanical and Physical Properties, Predictability of Performance – Part XX.613 (ex. 25.613 Material strength properties and material design values)
  - Follow practices conceptually similar to MIL-HDBK-17 for composite structures, or AWS D1.1 for weldments

- This path combined with a *risk managed approach* to technology insertion will be followed in the short term. This will support technology introduction, while standards are developed and real experience (flight hours) is gained
  - Work from lower criticality uses to moderate and finally high criticality application


Low Criticality Parts

Med Criticality Parts

High Criticality Parts

Moog Process Coverage Compliance Matrix

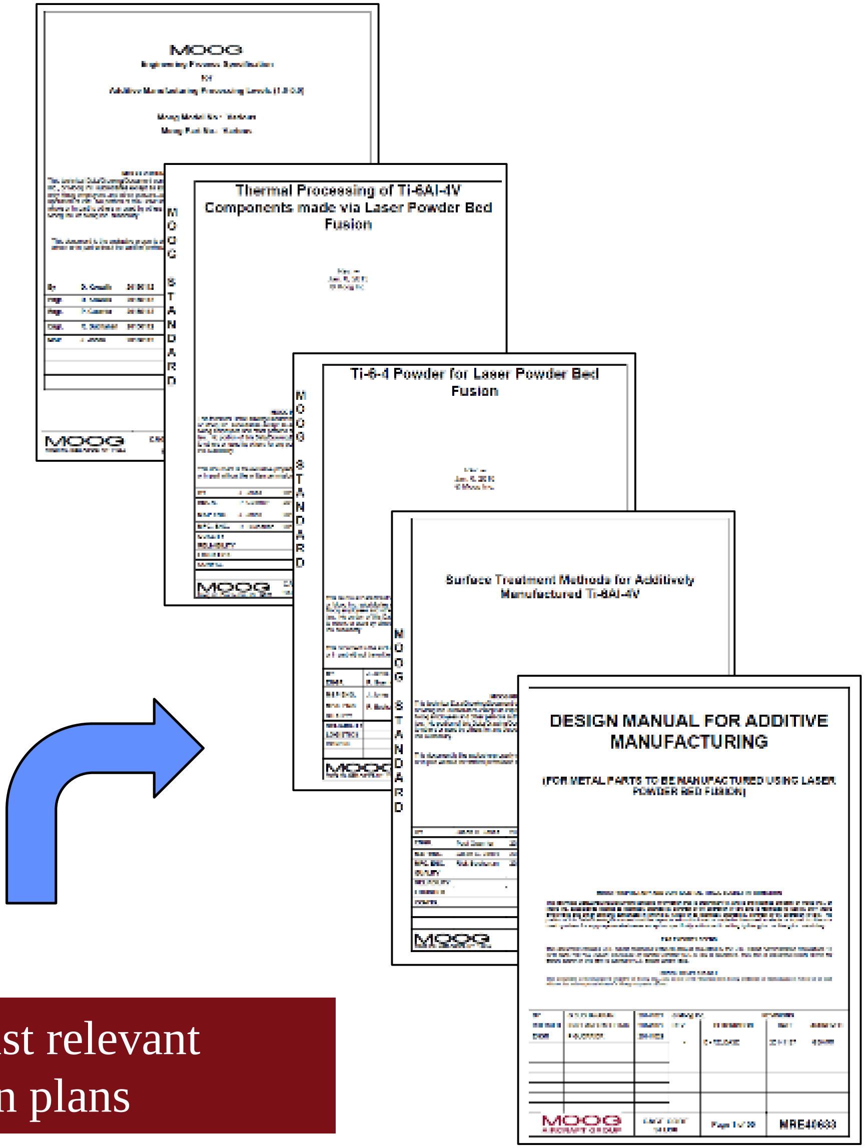
Common **Industry Understanding or Acceptance of:**	**Al 2014 Cast** *(common airframe alloy)*	**AM Alloy** *(airframe or engine alloy)*
Material and process specs	Yes	No / WIP
Design allowables - Effect of Environment - Knock down factor	Yes	No / WIP
Capable NDI methods - Effect of surface finish	Yes	No / WIP
Characterization of material defect / anomalies types	Yes	No / WIP
Key manufacturing process control parameters and acceptable ranges	Yes	No / WIP
Effect of process parameters on microstructure and mechanical properties - Heat Treat - Hipping	yes	No / WIP
Qualification / certification criteria	Yes	No / WIP

MOOG Standards
EMS45279:Ti, EMS45710:15-5, EMS52093: F357
MRE43676:Ti MRE46017:15-5 MREXXXX: F357 in work
EPS47032
MRE48189
EPS42894 EPS50785
MRE43676:Ti MRE46017:15-5
Point Certified Design/Process (2)

1. Table courtesy Jim Kabbara (FAA AM National Team Lead) taken from presentation by Chinh Vuong (FAA), presented to SAE Aerospace Standards Summit July 7, 2015
2. Near term plan – until appropriate standards are sufficiently mature

Certification: Full Cycle Process Control Documentation

- MRE40633
  - **Design** of AM components
- EPS42894
  - **Process Control** for LPBF AM
- EMS45279
  - Moog AM **Powder** specification for Ti 64
- EPS43680
  - **Thermal Processing** for AM Ti64
- EPS46237
  - **Thermal Processing** for 15-5PH
- EPS44249
  - **Surface Finish** Treatments, **FOD** removal
- MRE43676
  - **Material Properties** for AM Ti 64
- MRE46017
  - 15-5PH Material Allowable
- EPS47032
  - **NDI** of AM Parts
- EPS50785
  - Inspection of Additively Manufactured Coupons



MOOG

Thermal Processing of Ti-6Al-4V Components made via Laser Powder Bed Fusion

Ti-6-4 Powder for Laser Powder Bed Fusion

Surface Treatment Methods for Additively Manufactured Ti-6Al-4V

DESIGN MANUAL FOR ADDITIVE MANUFACTURING

(FOR METAL PARTS TO BE MANUFACTURED USING LASER POWDER BED FUSION)

MRE40633

Lessons learned result in Problem Reports against relevant process documents: closed loop corrective action plans

Digital Workflow

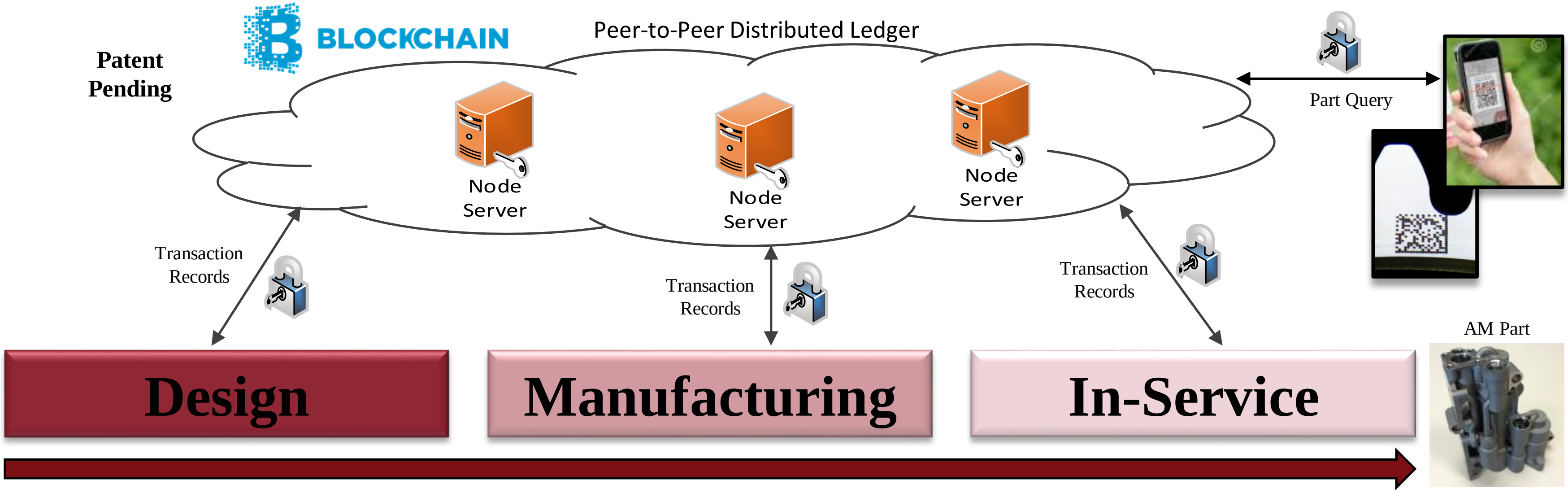
- Today
  - Parts typically have CAD electronic models
  - Manufacturing information is a mix of analogue & digital
  - Supporting evidence is often scanned PDF “paperwork”
  - Value is placed on knowing the provenance of the part of assembly
- Tomorrow
  - A continuous thread of digital data from CAD model via machine tool G-code to finished part
  - Supporting evidence stored in stand alone databases
  - Cyber attack resilience
- Future
  - Distributed network of databases with embedded trust

Belikovetsky et al. (2016), dr0wned - Cyber-Physical Attack with Additive Manufacturing, arXiv:1609.00133

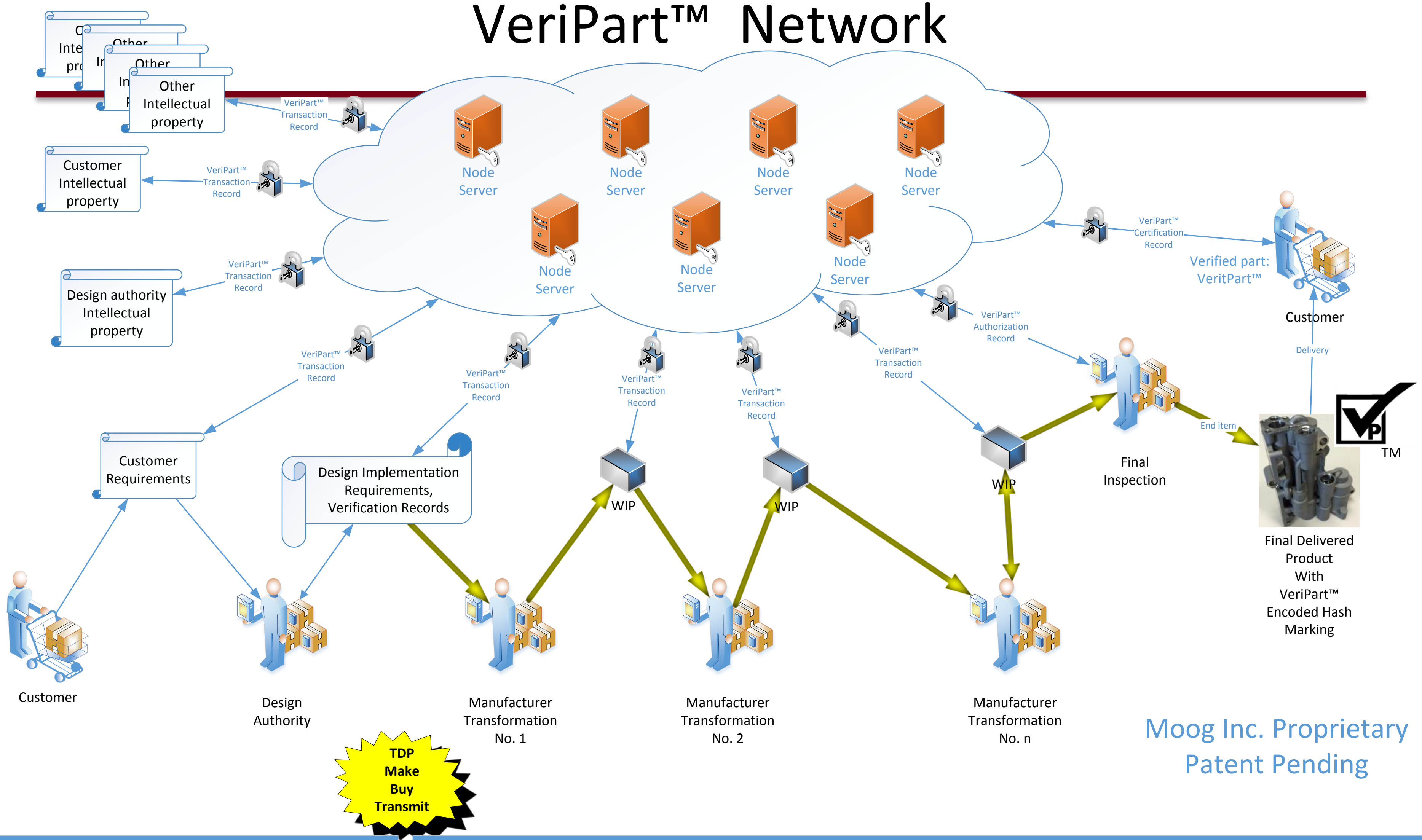
Moog VeriPart®: Secure, Authentic Parts for Distributed Supply Chain

- With industry and gov't partners, Moog has been developing a technology solution for digital enabled parts supporting up to the most critical, regulated applications. This solution provides:
  - **Provenance** with **Traceability** on a **per part** basis
    - History of a part through the design-manufacture-use cycle per part (digital twin)
  - **Secure** data transport
  - Digital rights management, **licensable** transactions
  - **Authenticity** of printed goods, assemblies
- Leverages blockchain shared distributed ledger technology
  - A shared database providing provenance and authenticity on a per part basis
    - Blockchain technology employed by Bitcoin cryptocurrency

Patent Pending



VeriPart™ Network



Other Intellectual property

Customer Intellectual property

Design authority Intellectual property

VeriPart™ Transaction Record

Node Server

Verified part: VeritPart™

VeriPart™ Certification Record

VeriPart™ Authorization Record

Customer

Delivery

Customer Requirements

Design Implementation Requirements, Verification Records

WIP

Final Inspection

End item

TM

Final Delivered Product With VeriPart™ Encoded Hash Marking

Customer

Design Authority

Manufacturer Transformation No. 1

Manufacturer Transformation No. 2

Manufacturer Transformation No. n

TDP Make Buy Transmit

Moog Inc. Proprietary
Patent Pending

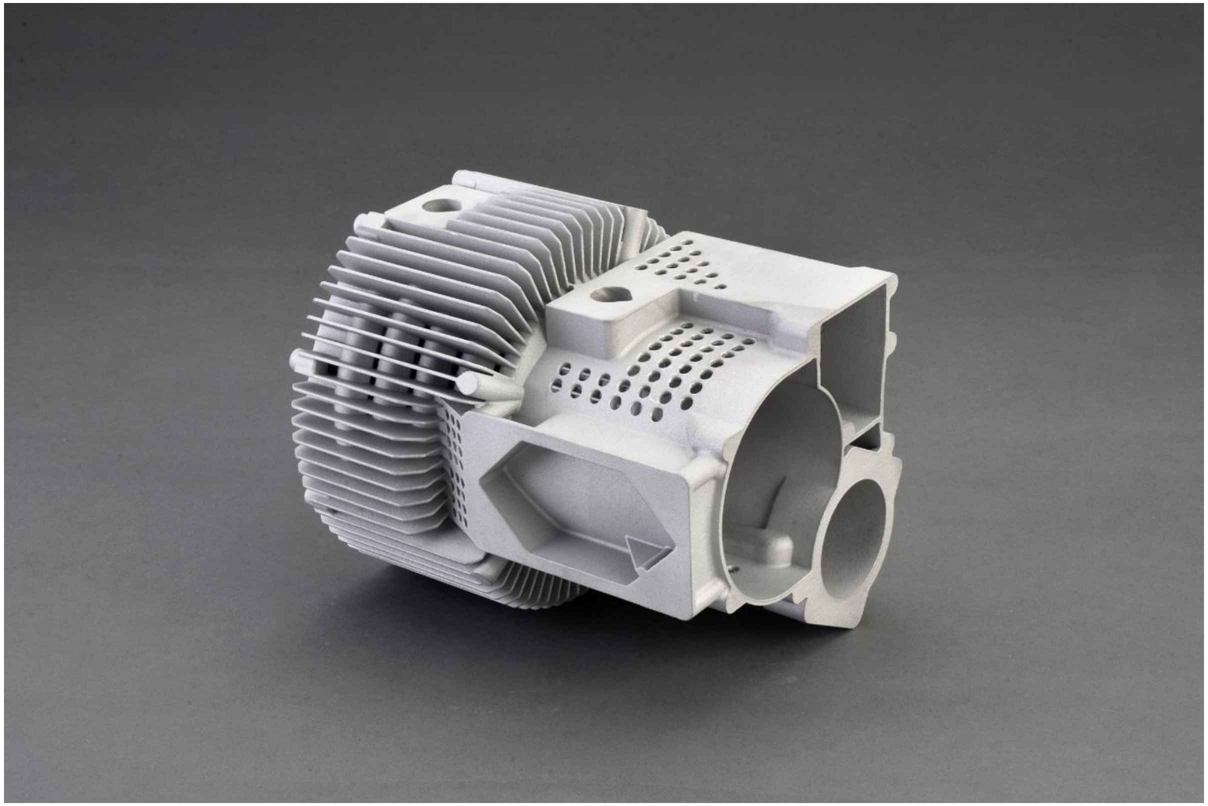
Digital space	Physical space
Master ledger	Individual side ledgers

Summary

- Laser Powder Bed Fusion Parts for Flight Critical Applications
  - Part quality is process sensitive
  - Presently Industry Standards are emerging
  - Moog are determining process limits and writing/updating process specifications
  - Moog are determining material allowables
  - Flight parts are possible with sufficient process controls in place
- Data & AM Adoption
  - A risk managed approach is being taken
  - Managing: design data, in process data, production Acceptance Test Data & part provenance (e.g. via VeriPart®) has the potential to be transformational

Patent Pending

Questions



APPENDIX CC—ADDITIVE MANUFACTURING QUALIFICATION FOR LIQUID ROCKET ENGINE APPLICATIONS

Additive Manufacturing Qualification for Liquid Rocket Engine Applications

August 31, 2017

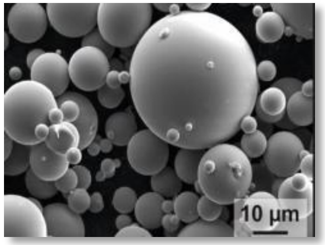
Nick Mule, Program Manager

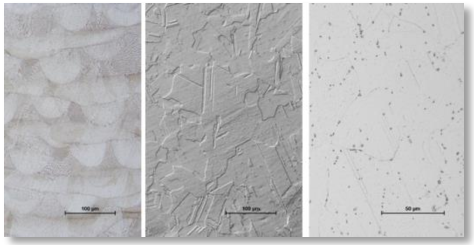
Additive Manufacturing
Aerojet Rocketdyne

Distribution Statement A: Approved for Public Release

Agenda

- **Additive Manufacturing (AM) Applications in Liquid Rocket Engines**
- **Qualification of Additive Manufacturing Process for Rocket Engines**
- **Recent Testing Progress of Additive Manufactured Rocket Engine Parts**
- **Emerging Process Monitoring Methods for AM**





Defining the process by which additive manufacturing is qualified for rocket engines

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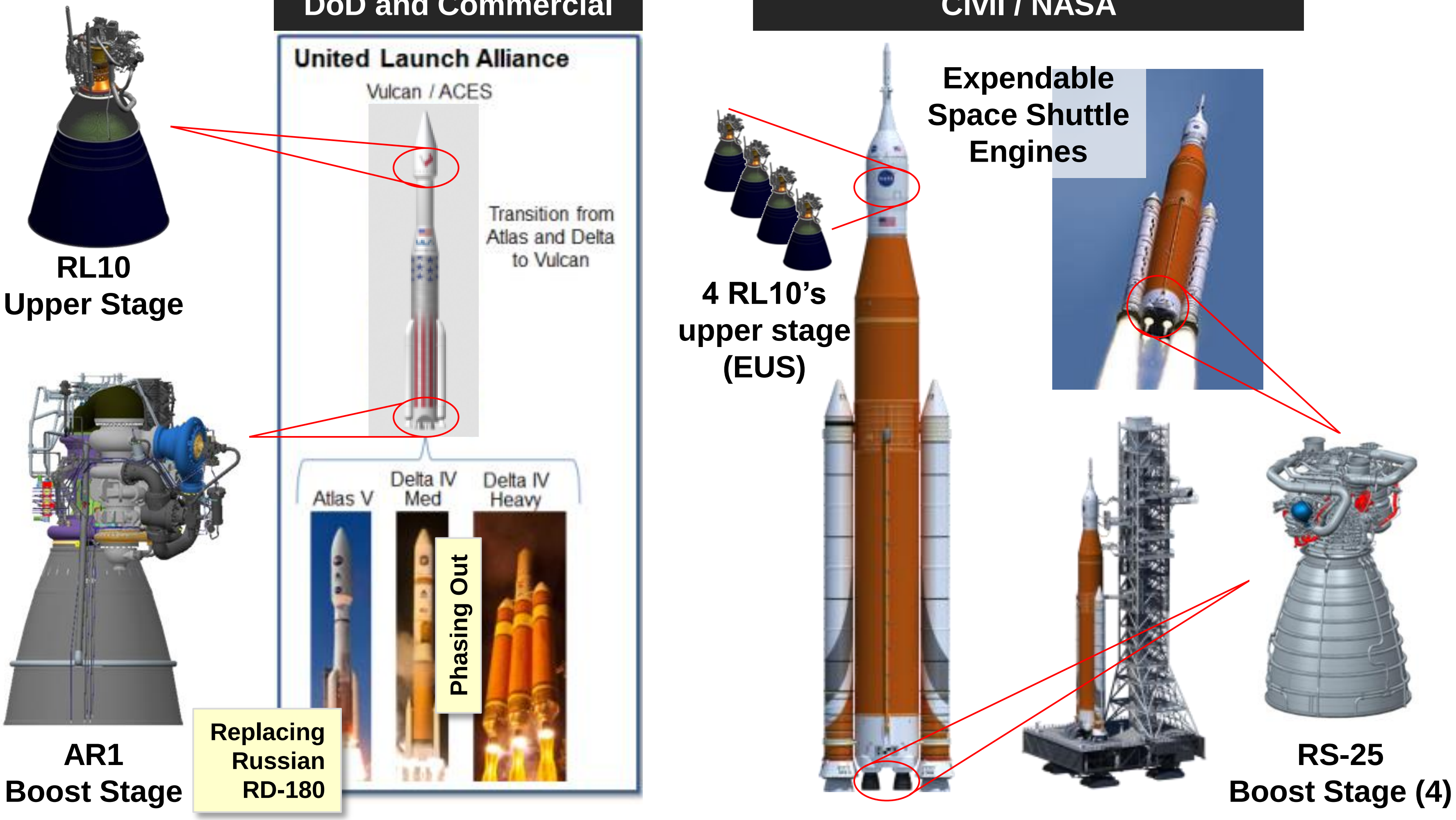
Liquid Rocket Engine Landscape

DoD and Commercial

Civil / NASA

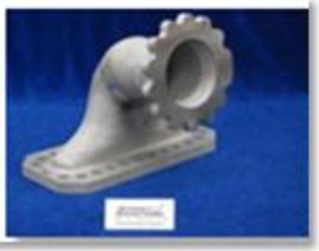


Competitive market focused on affordability – scale up of AM needed

Additive Manufacturing in Rocket Engines

- **Additive Manufacturing (AM) benefits:**
  - Reduced development time
  - Reduced part lead time
  - Complex designs enabled
  - Selective Laser Melting (SLM):
    - Fine feature detail
    - Removal of loose powder
    - Low rate production
- **Targeted parts in rocket engines:**
  - Injectors
  - Thrust chambers
  - Valve housings
  - Turbomachinery hardware
  - Plumbing, ducts integral flanges



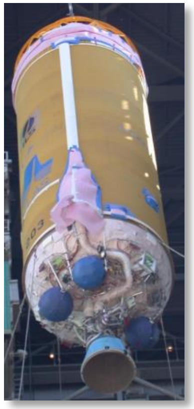


- ➢ **Nickel**
- ➢ **Copper**
- ➢ **Aluminum**


Selective Laser Melting (SLM) process has transformed rocket engine manufacturing

Rocket Engine Programs with AM

- **RL10 Upper Stage**
  - Main injector
  - Thrust chamber
  - Propellant inlets
  - Oxidizer control valve
  - Turbopump housings



- **AR1 Booster Engine**
  - Preburner injector
  - Main injector
  - Ball shaft
  - Heat exchanger

- **Orion Crew Capsule**
  - Nozzle extensions

- **RS-25 (NASA SLS)**
  - Pogo Base, Shell, Baffle
  - Rigid ducts
  - Ball shaft

- **MPS 120 Satellite**
  - Propellant tank / piston

- **Bantam**
  - Main injector
  - Thrust chamber
  - Nozzle
  - Turbopumps

- **Others…**
  - In development…

Aerojet Rocketdyne application of additive manufacturing has broad use

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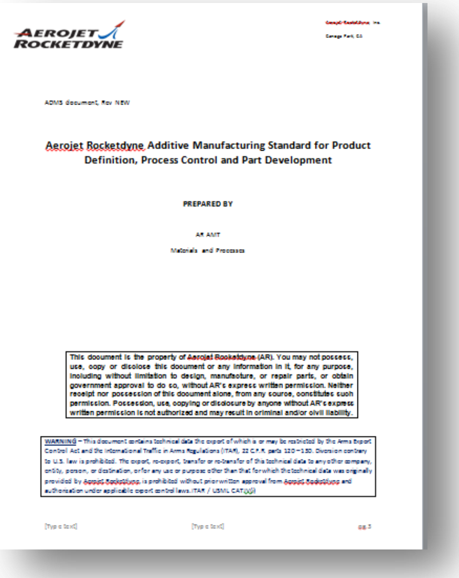
Qualification of AM Parts for Rocket Engines

Aerojet Rocketdyne Developed AM Standard

- **Applicability**
  - Powder bed Fusion Only (SLM)
  - Parts destined for component level test, engine test, certification and flight
- **Purpose**
  - Establish requirements for engine programs
  - Establish key processing variables that require control and documentation … <u>for production</u>
- **Required for all AR programs with AM hardware**
  - Specific program tailoring permitted
  - Risk based
  - Customer input solicited



Aerojet Rocketdyne, Inc.
Canoga Park, CA

ADMS document, Rev NEW

Aerojet Rocketdyne Additive Manufacturing Standard for Product Definition, Process Control and Part Development

PREPARED BY

AR AMT

Materials and Processes

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AM Standard to define requirements for use on rocket engine programs

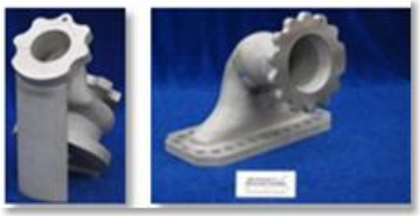
AM Standard Requirements

Alloy

- **Powder and Processing Specs**
  - – Specific to alloy and process
- **Material Properties**
  - – Cover temperature and environment range
- **Qualified Metallurgical Process (QMP)**
  - – Specific to machine
  - – Certify a process and alloy as acceptable and shall be required for fabrication of production hardware

Part Specific

- **Process Verification Unit (PVU)**
  - – Manufacturing Test Demonstrators (MTD's)
    - Development part with purpose to validate a locked process for production
  - – PVU Report
    - Documents the lessons learned from MTD's and establishes the locked process for production initiation
    - Includes Metallurgical Cut Up evaluation of parts

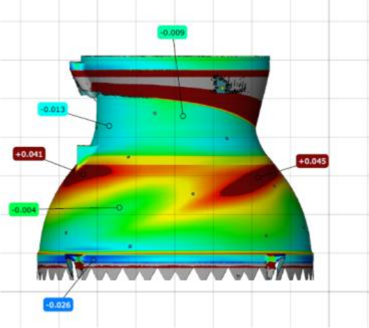


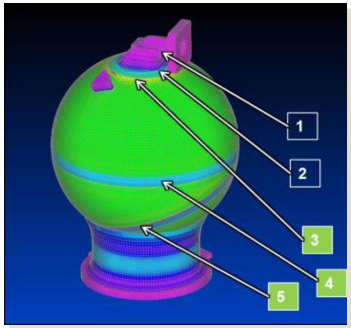
Elements of AM Standard required for flight qualification of rocket engine hardware

Example : RS-25 Engine Qualification

- **Manufacturing Technology Demonstrators (MTD)**
  - **Develop the TRL of the alloy/machine/part combination**
  - **Build Process Verification**
    - Build supports and producibility of the part
    - Meets dimensional requirements
  - **Metallurgical Process Verification**
    - Porosity, microstructure and mechanical properties
    - Verify key part dimensions (i.e. wall thicknesses)
  - **Functional Evaluation**
    - Part-specific function evaluation may include:
      - Flow testing
      - Proof (cyclic) and burst testing

RS-25 Pogo Assembly

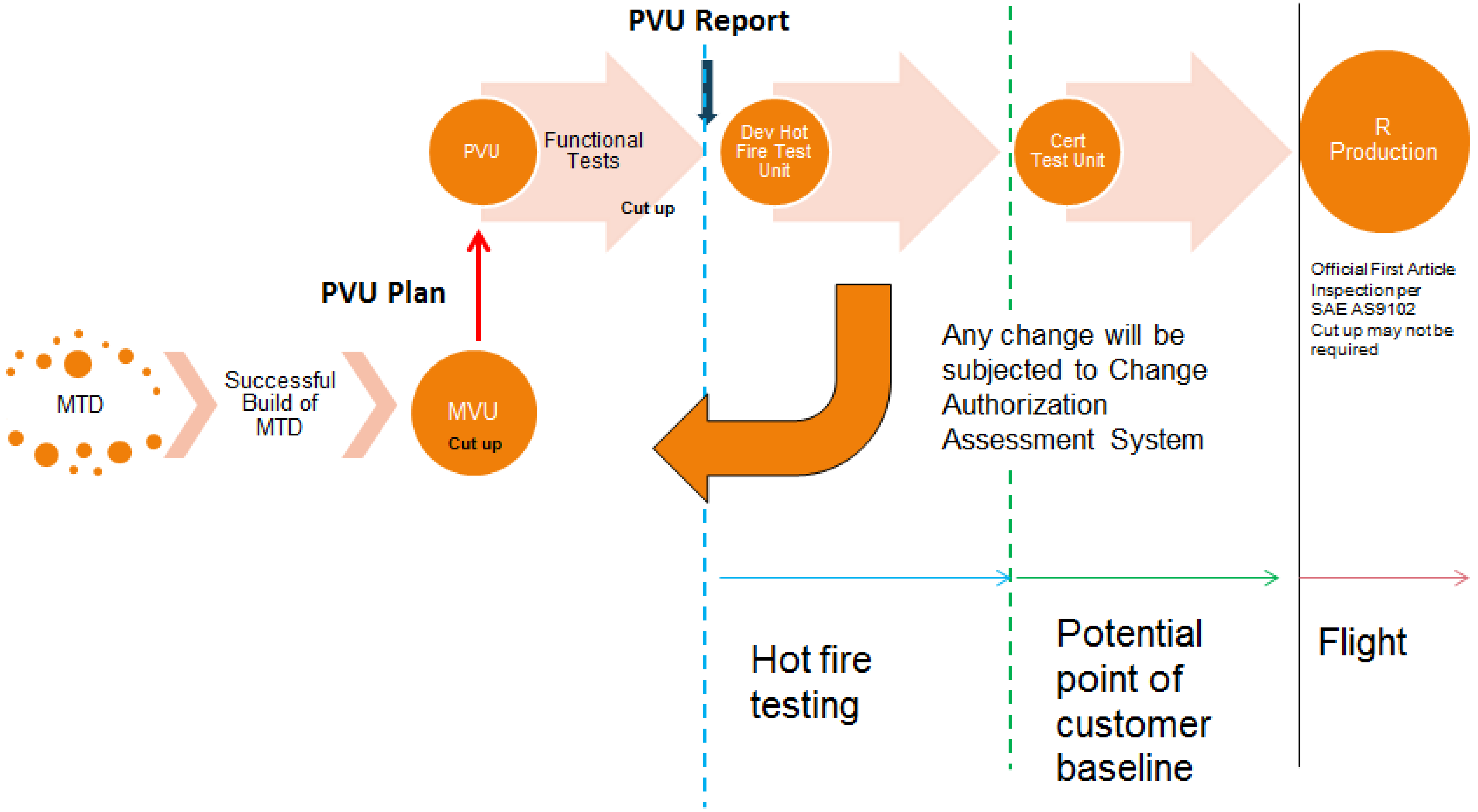




- Proof (multiple cycles)
- Increase pressure to burst

Lessons learned in early part builds enable rapid development cycle at low risk

Example : RS-25 Engine Qualification



Example of SLM Part Cert process for RS-25

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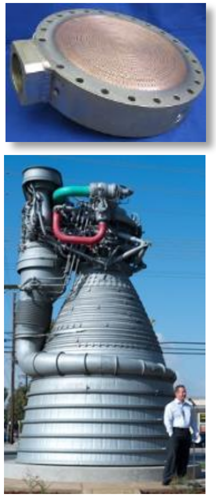
Testing and Qualification of AM Parts

- **F-1A**
  - Preburner injector
  - Heritage 1960's design
  - SLM trial in 2010
  - Successful hot fire test
  - *Learned what AM can do (and cannot do)*

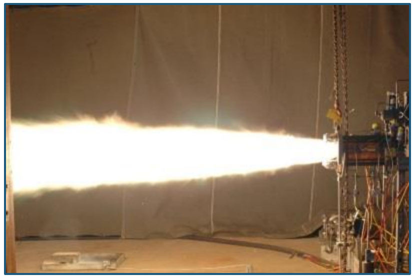


F1 Engine Preburner Injector

SLM F-1A Preburner Injector

F-1A Preburner Injector Test at NASA-MSFC

- **AR1**
  - Single element injector
    - Successful test
  - Preburner injector
    - Successful test
  - *Rapid engine development*



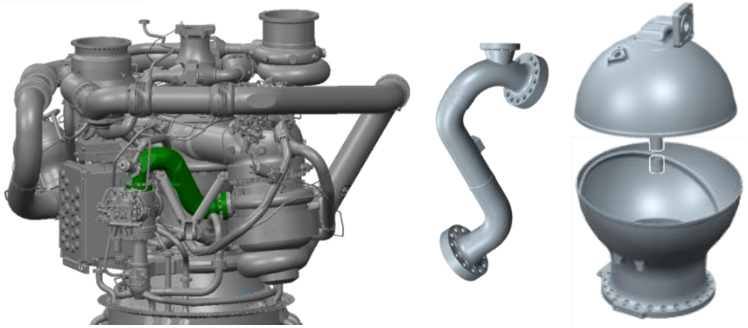
Single Element Test

Staged Combustion Test at NASA-SSC

Learned what AM can enable and applied to new engine development program

Testing and Qualification of AM Parts

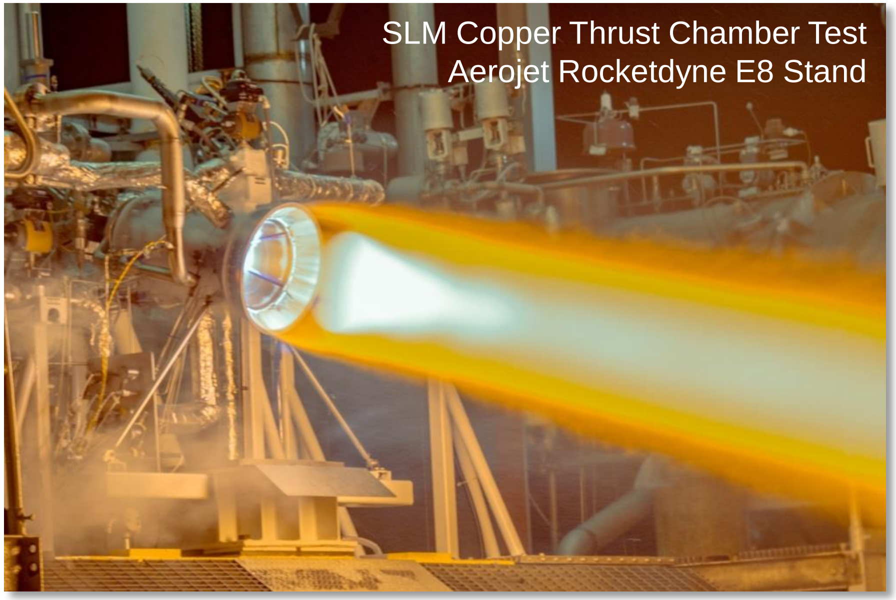
- **Bantam**
  - SLM Inco 625 thrust chamber assembly
  - Tested at NASA-MSFC
  - 800 to 1,000 psia chamber pressure
  - *Low cost commercial upper stage*
- **Orion Crew Module**
  - Reaction Control Thruster Nozzles
  - SLM Inco 625
  - *First AM parts slated for flight*
- **RS-25**
  - Identify legacy parts that can be AM
  - Develop low cost, robust demonstrations
  - *Making NASA SLS more affordable*



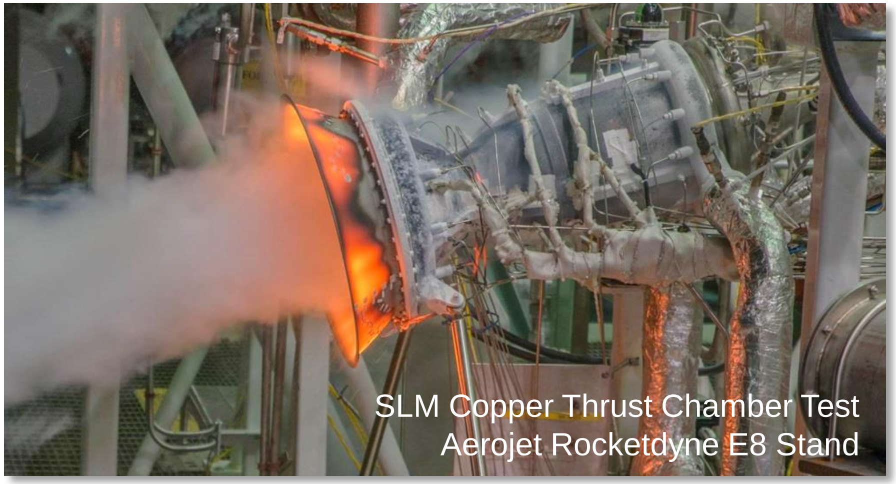
System level testing for new and legacy engine parts with AM

Testing and Qualification of AM Parts

- **RL10**
  - Main Injector (not shown)
  - Copper Thrust Chamber Assembly (TCA)
    - Full scale RL10 size
    - Demonstrated RL10 operational requirements
  - *High performance heat exchanger*



SLM Copper Thrust Chamber Test
Aerojet Rocketdyne E8 Stand



SLM Copper Thrust Chamber Test
Aerojet Rocketdyne E8 Stand

Full scale parts functionally validated in system level testing

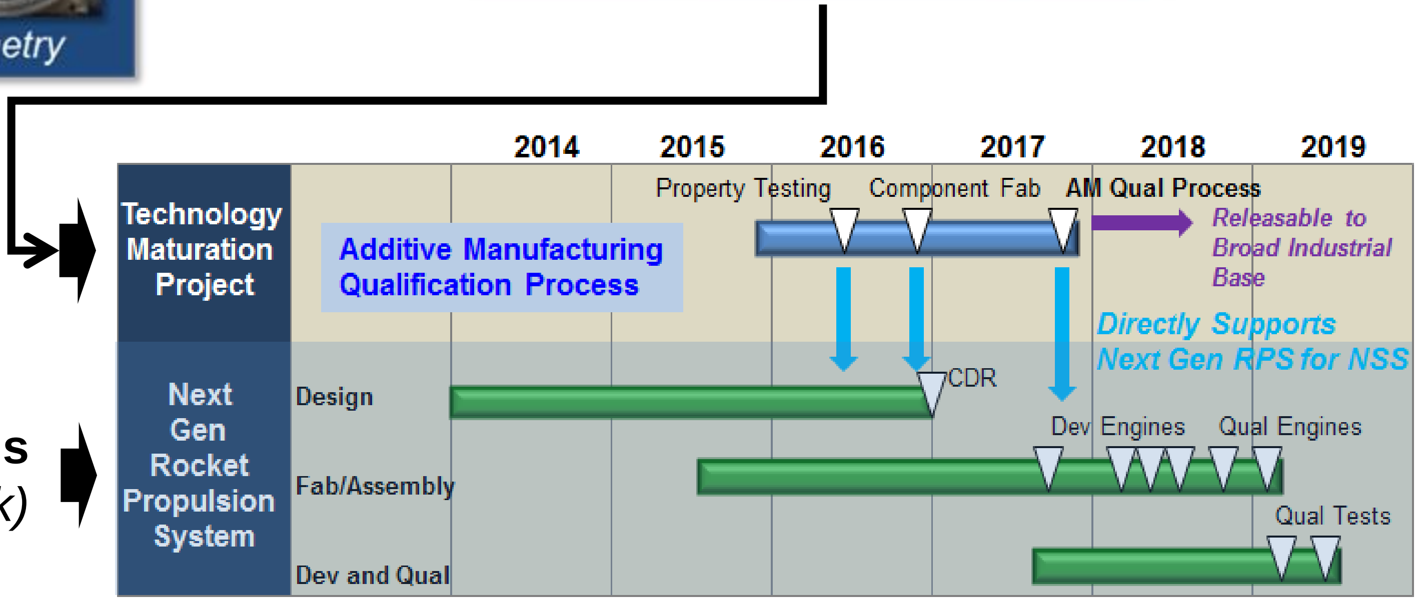
Additive Manufacturing Qualification Process (AMQP)

Can make these today…

Complex internal geometry

This process will improve confidence in part quality

To enable this
(with lower risk)



Developing new methodology to qualify AM parts with improved confidence in quality

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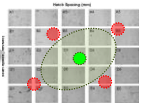
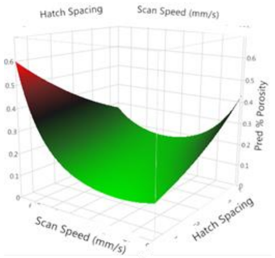
Developed AMQP Process

Statistical Analysis and Integration



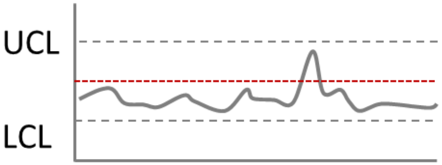
Process Sensitivity

Acceptable SLM Process Operating "Window"



Process Data

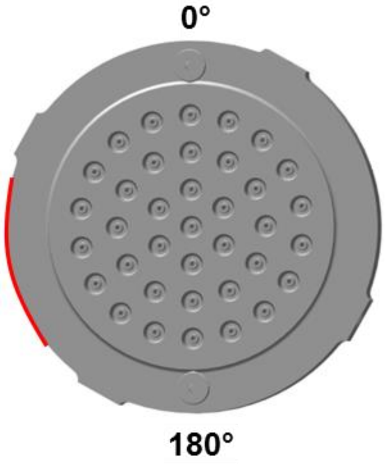
Sensor Data Acceptance Criteria Developed Around Operating "Window"



Component Application

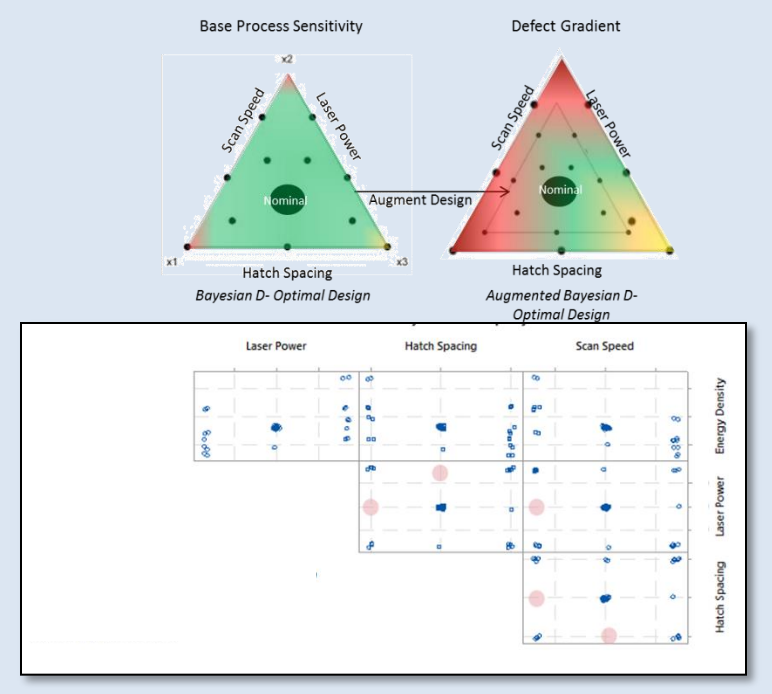
Analysis Methodology for Predicting Functional Performance Variation

Integrated Quality Assurance Approach



Designs of Experiments for Process Characterization

- DOE to study process sensitivity for off-nominal parameter settings with the intent to generate a gradient of increasingly defective material
- Design to be incrementally augmented to define the defect gradient



Inputs

Scan Speed
Hatch Spacing
Laser Power

Constraints

Layer Thickness
Machine Model
Machine S/N
Powder Lot

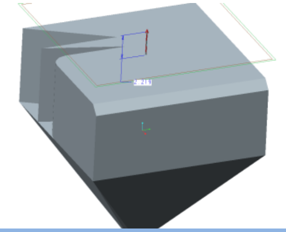
Outputs

Defect Characteristics

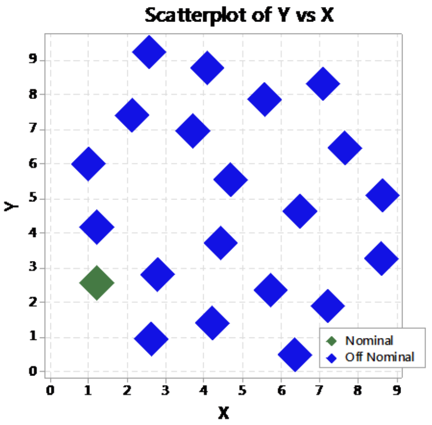
-Type
-Size/Morphology
-Frequency

Material Properties

-Tensile/Fatigue



Test Geometry and Build Plate Layouts



Statistically driven approach to show process sensitivity to defects

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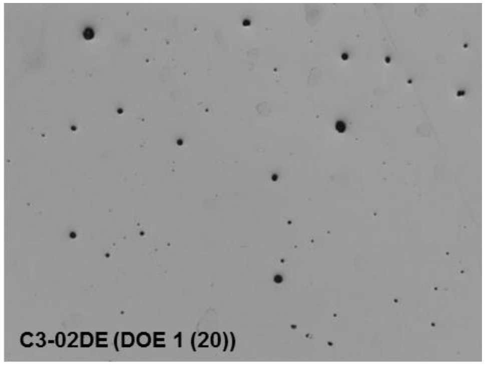
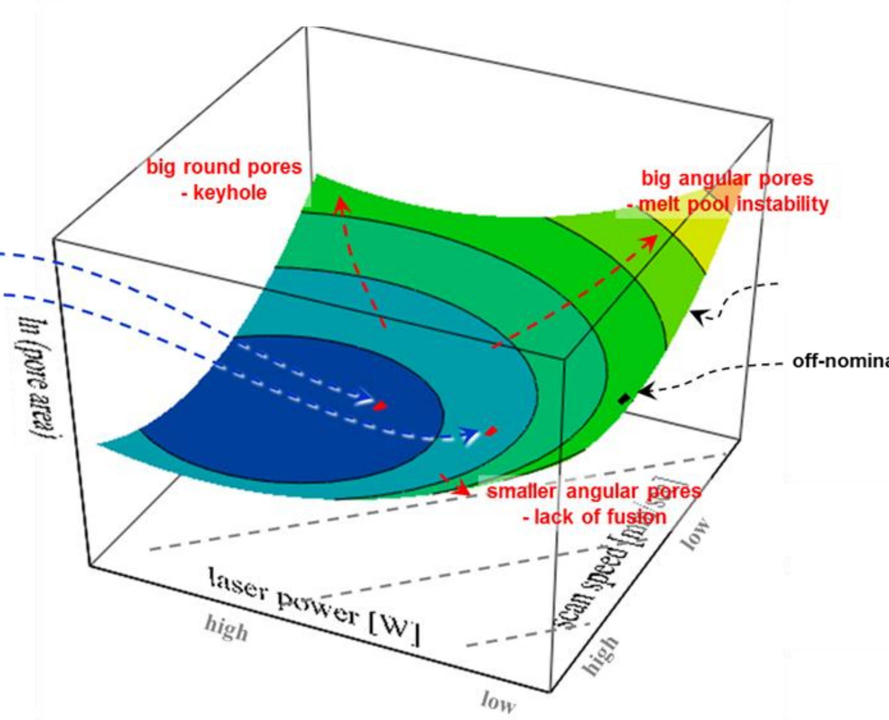
Mondaloy Processing Space Established

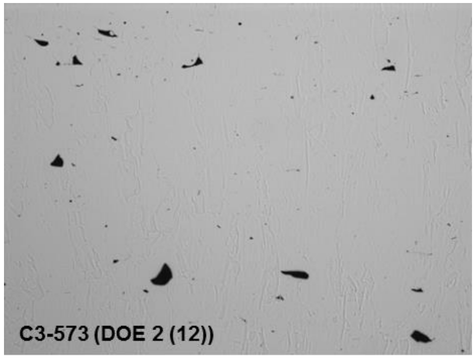


C3-02DE (DOE 1 (20))

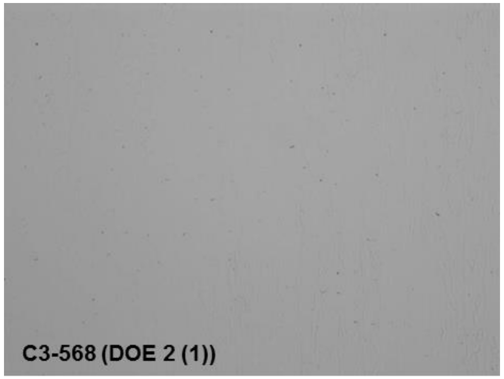
(vertical sections
through samples,
50X, as polished)

Pore Area and Flaw Type versus SLM Parameters

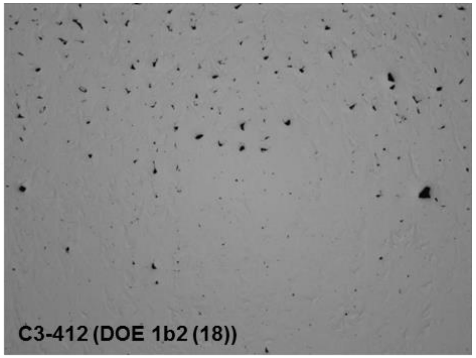




C3-573 (DOE 2 (12))



C3-568 (DOE 2 (1))



C3-412 (DOE 1b2 (18))

Flaw types clearly defined and correlated with pore area gradient.

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SLM Machine and Process Monitoring Equipment

Concept Laser M2

Sigma Labs PrintRite3D®

PR3D User Terminal and Data Acquisition System

Sensor Mount in SLM Chamber

Pyrometer

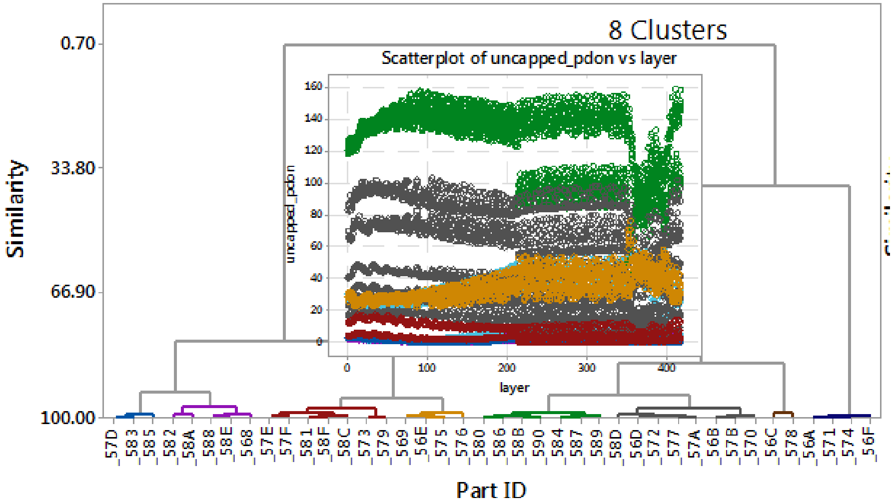
Photodiode

Sensor Mount Installed Within Build Chamber

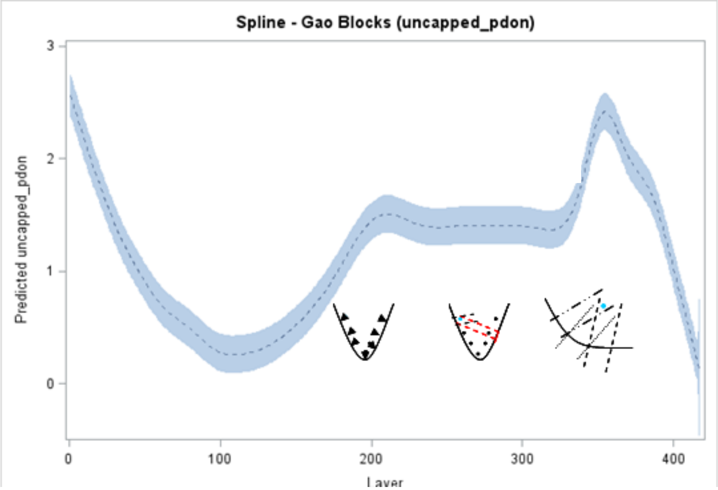
Concept Laser M2 Machine Modified to Enable Process Data Capture

In-Situ Data Reduction and Analysis Methods Required

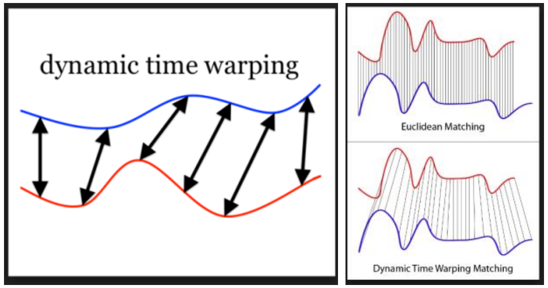
Unique Off-Nominal Signatures



Process Limit Approach Developed



Cluster Analysis Methodology



- Unique part signatures are generated for DOE processing condition and identified as discernably different than the nominal response

- Methodology to establish control limits around the nominal part signature

Unique Signatures Generated and Discernable For Each DOE Processing Condition

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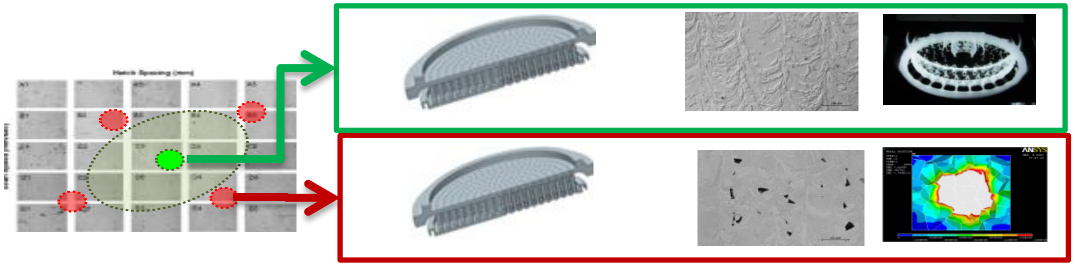
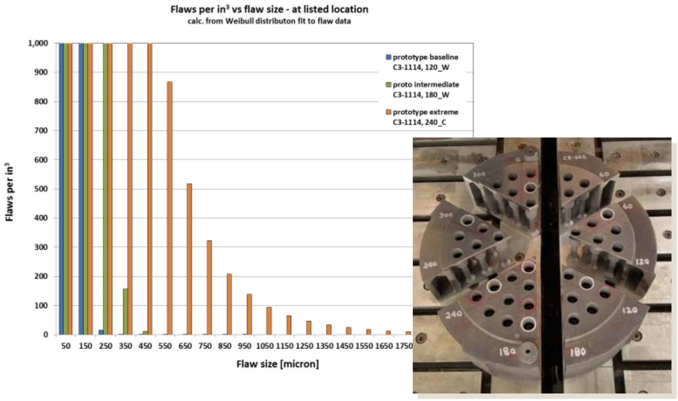
Part Design Validation of Process

- **Injector Predictive Modeling**
  - Monte Carlo simulation of structural performance utilizing generated defect distributions
  - Determine effects of off-nominal process conditions on nominal design condition
- **Cyclic Proof and Burst Test**
  - Test Injectors fabricated with nominal, off-nominal A and off-nominal B processing conditions

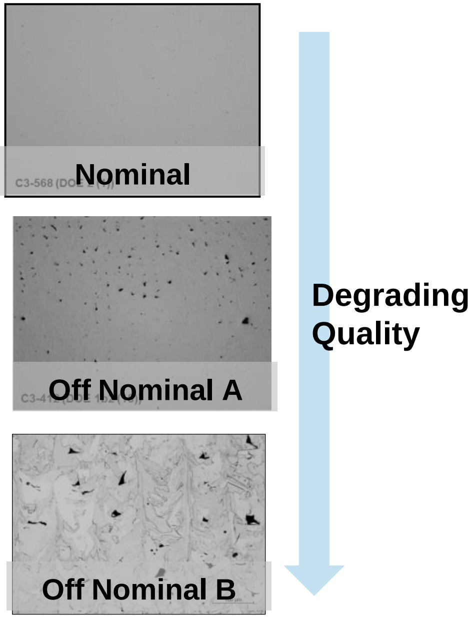


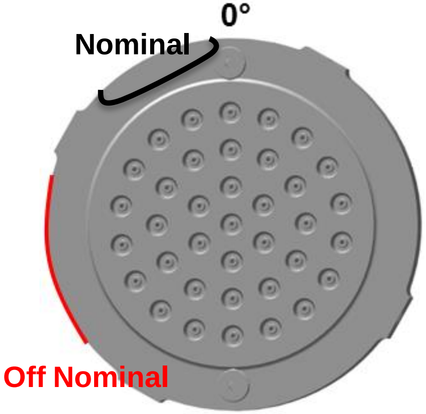


Demonstration AMQP Framework Scale-Up Capability

Burst Test Results

Unit	Identifier	Test Date	Operating Pressure	Proof Pressure	Vextec Calculated Burst	Actual Burst
Nominal	C3-11/28/16	6/30/17	6.5 KSI	7.8 KSI	>13 KSI	15.022KSI
Off-Nominal A	C3-11/14/16	7/18/17	6.5 KSI	7.8 KSI	11-13 KSI	12.218 KSI
Off-Nominal B2	C3-120816	Tentative Aug. 7-8	6.5 KSI	7.8 KSI	11-12 KSI	Aug. 14
Off-Nominal B3	C3-011217	7/24/17	6.5 KSI	7.8 KSI	11-12 KSI	10.555 KSI





Burst Locations and Magnitudes Agree With Pre-Test Predictions

Conclusions

- **Liquid rocket engines are good fit for additive manufacturing**
  - High complexity
  - Low rates

- **Robust design, development and qualification process identified and being applied**
  - Simultaneous developing requirements with customers
  - AM is a new product form to be conservatively implemented
- **Extensive system level testing and validation in process at AR**
- **Emerging process monitoring technology can compliment and possibly supplant traditional inspection methods**

Liquid rocket engine insertion of AM accelerating towards flight

APPENDIX DD—AN OVERVIEW OF THE ADDITIVE MANUFACTURING CONSORTIUM (AMC) PROJECTS AND COLLABORATIONS

An Overview of the AMC Projects and Collaborations

Francisco Medina, Ph.D.
Technology Leader, Additive Manufacturing
Director, Additive Manufacturing Consortium
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915.373.5047

The Third Joint FAA – Air Force Workshop
on Qualification / Certification of Additively Manufactured (AM) Parts
August 31st, 2017

About EWI

- **Non-profit applied manufacturing R&D company**
  - Develops, commercializes, and implements leading-edge manufacturing technologies for innovative businesses
- **Thought-leader in many cross-cutting technologies**
  - >160,000 sq-ft in 3 facilities with full-scale test labs (expanding)
  - >$40 million in state of the art capital equipment (expanding)
  - >170 engineers, technicians, industry experts (expanding)

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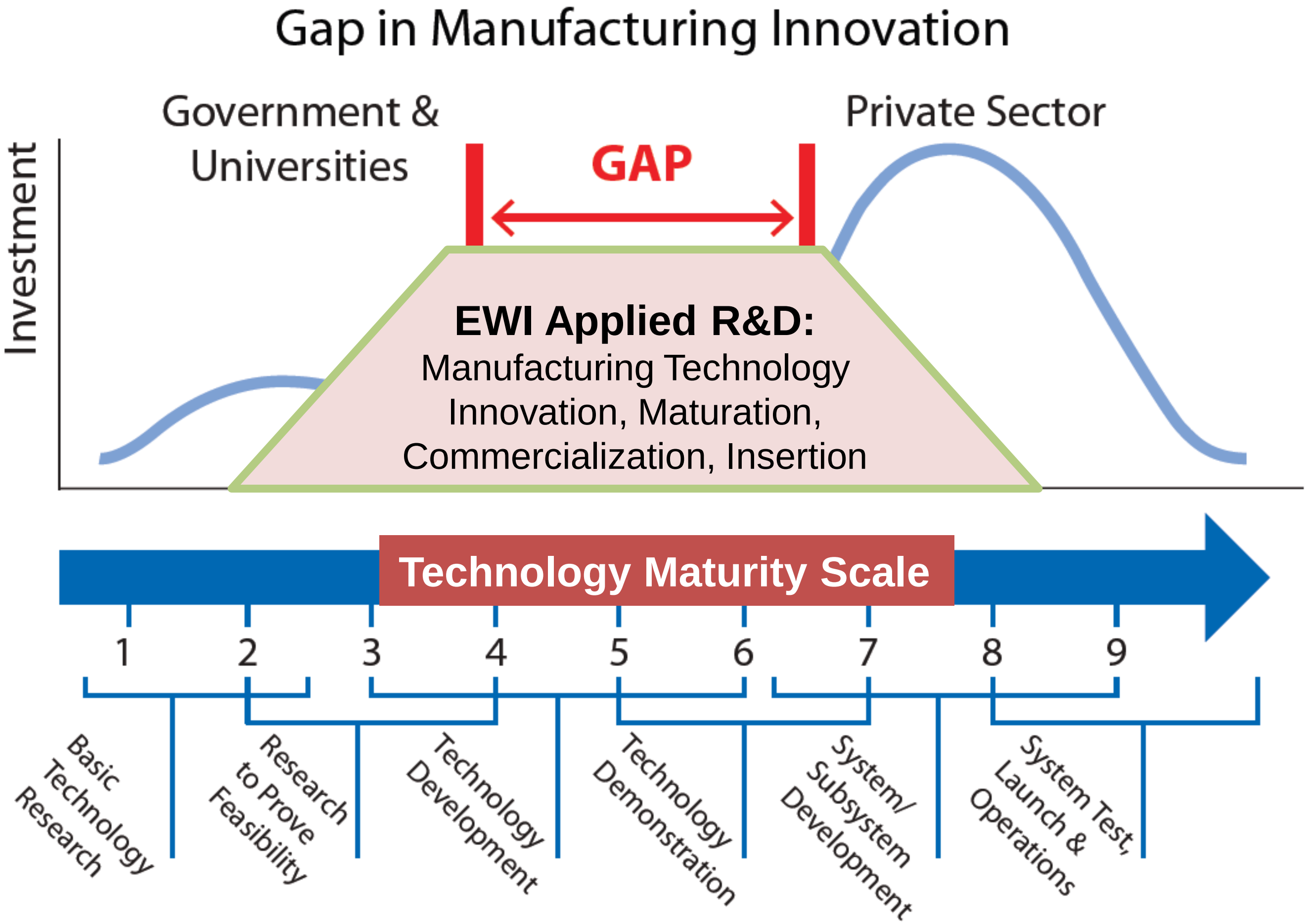
We Manufacture Innovation

EWI Applied R&D Bridges the Gap Between Research and Application



BUFFALO MANUFACTURING WORKS
OPERATED BY EWI

Source: NIST AMNPO presentation Oct. 2012

EWI®
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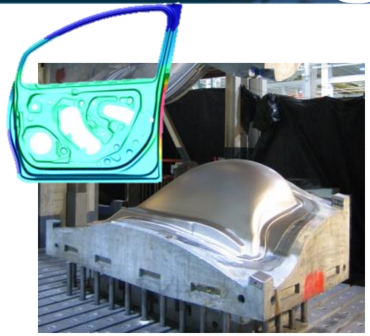
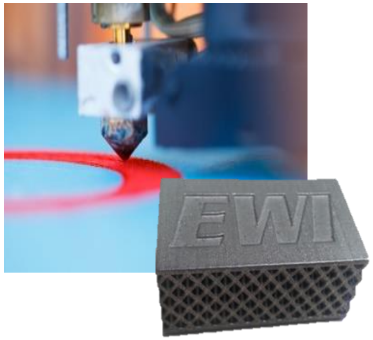
Growing Range of Cross-Cutting Manufacturing Technologies

Materials Joining



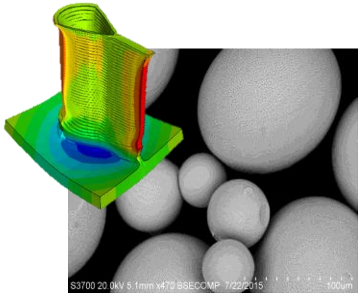
Forming

Machining & Finishing

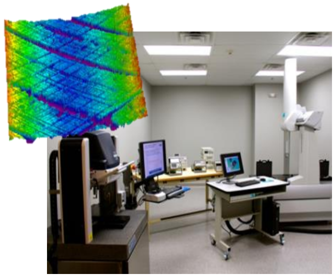


Additive Manufacturing

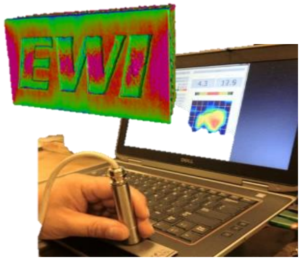
Agile Automation



Applied Materials Science



Testing & Characterization



Quality Measurement

BUFFALO
MANUFACTURING
WORKS
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EWI's Approach to Additive Manufacturing

- **Technical challenges rooted in EWI's expertise in materials joining.**

- **AM/3DP is another tool in the toolbox**

- **AM is more than the 'printing' process…many of the conventional manufacturing steps apply.**

EWI offers world-class capabilities in metal additive manufacturing to mature, innovate, and sustain the burgeoning metal AM industry.

BUFFALO MANUFACTURING WORKS
OPERATED BY EWI

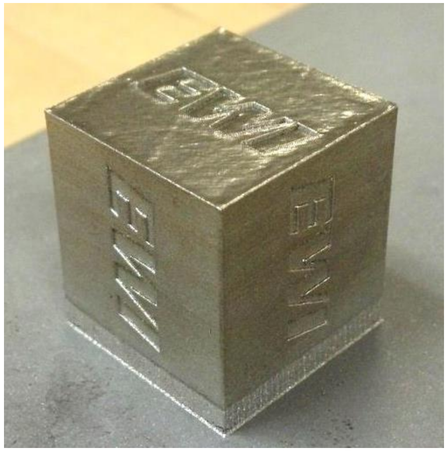
EWI®
We Manufacture Innovation

AM is Materials Joining

Manufacturing of complex 3D parts by *joining* successive beads and layers

675 feet of weld
(Audi R8)

1-inch L-PBF Cube



5 miles of weld

3,400 feet of weld

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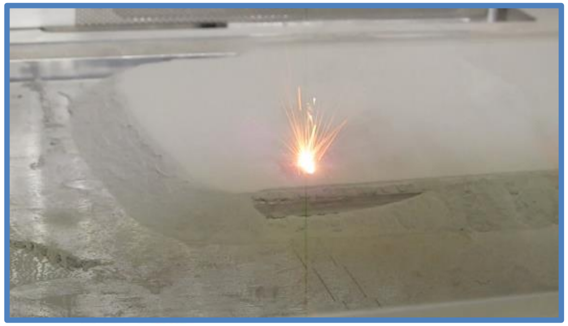
EWI AM Capabilities Overview

Laser PBF
EOS M280/ M290

Electron Beam PBF
Arcam A2X

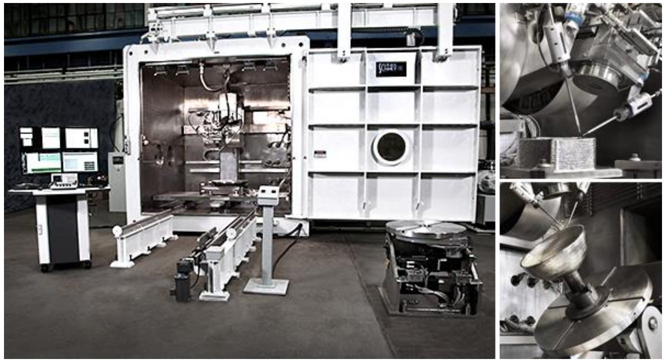
Laser DED
RPM 557

Laser PBF – Open Architecture
EWI-Designed and Built



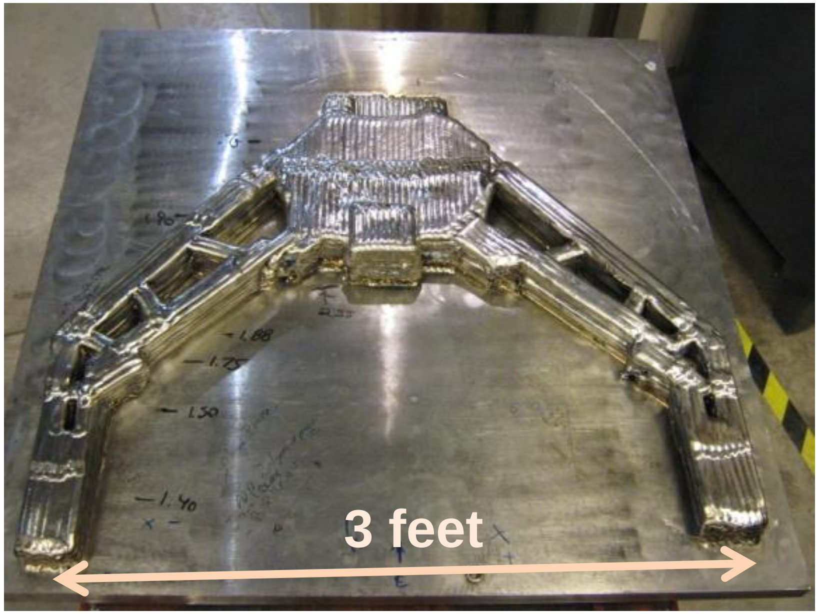
Sheet Lamination UAM
Fabrisonic

Electron Beam DED
Sciaky EBAM 110



Arc-Based Metal AM

- **Capabilities**
  - Robotic integration provides broad flexibility
  - Multiple arc processes provide productivity versus precision options



Ti-6-4 ELI component
Hot wire GTA deposition

Stainless steel
GMA deposition

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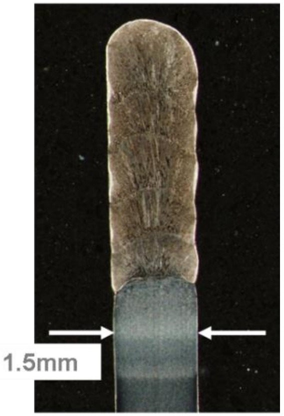
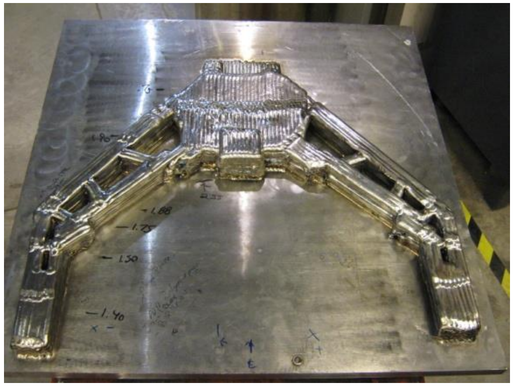
AM Capabilities: Robotic Arc Based DED

- **AM is not limited to laser or electron beam equipment for DED.**
- **Robotic arc based deposition methods: $500k- $1M investment**
  - Readily available equipment – transitioning to full robotic AM, CAD to part
  - Still requires much of the process control infrastructure needed for laser and EB AM processes.
- **Deposition rates from 1 in^3/hr to ~100 in^3/hr, up to 40 lbs/hr (18kg/hr)**
- **Serves aerospace and additional defense/commercial markets**



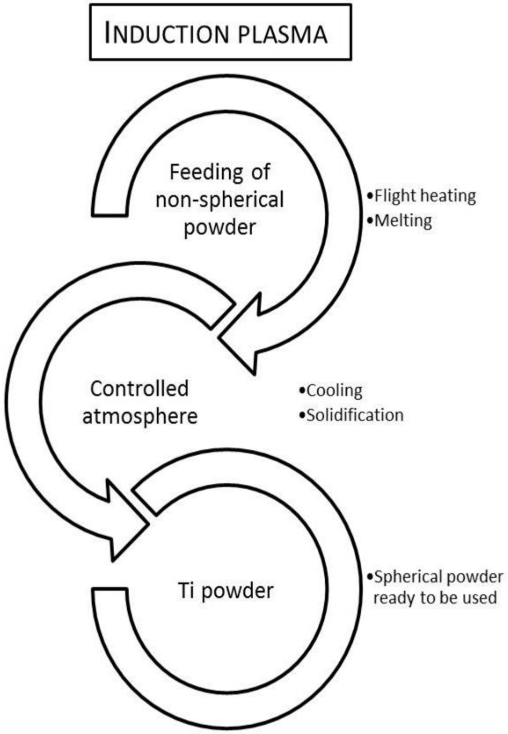


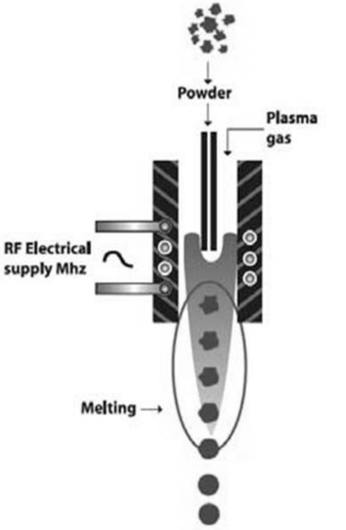
Defense ground vehicle 80 lb. build in Ti-6-4 using GTAW-HW

Nuclear component Using GMAW-P

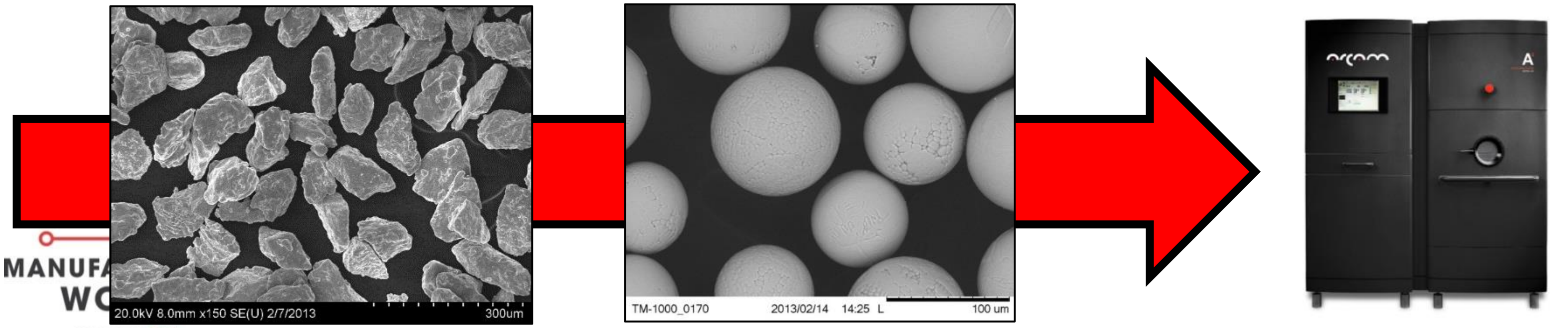
Wing stiffener/rib

Induction Plasma Spheroidization





http://www.tekna.com/technology/spherical-powder/



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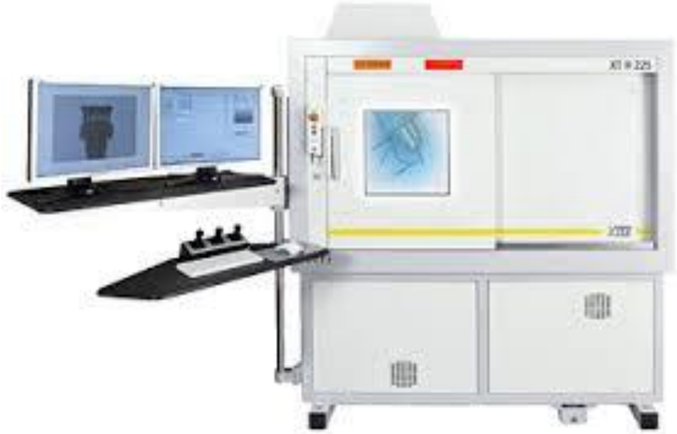
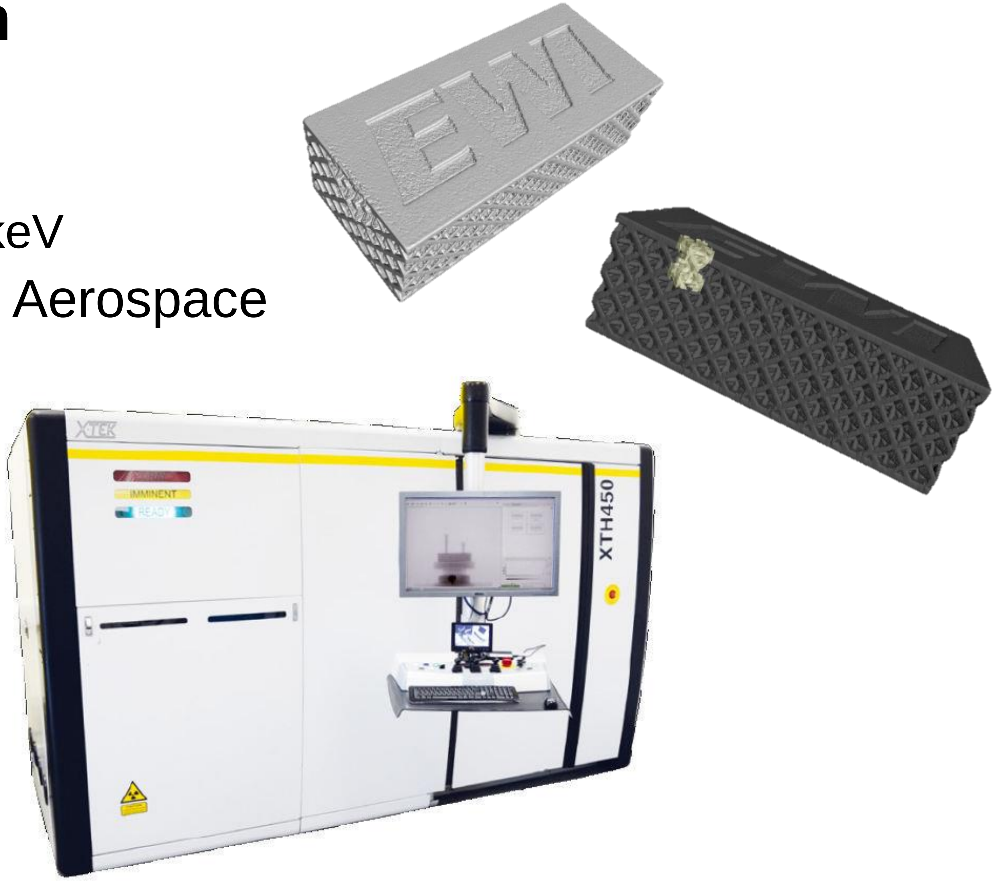
Computed Tomography

- **Partnership with Nikon**
  - Two Systems
  - Three X-ray tubes
    - 180 keV, 225 keV, 450 keV
  - Fully Capable: Medical to Aerospace





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EWI's Focus Areas are Aligned with the Needs of Industry

EWI Metal AM Focus Areas

In Process Quality Control

Post Process Inspection

Materials and Process Development

Support Design Allowable Database Generation

Advancements for Manufacturing Machines

Design for Additive / Technology Application

Industry Support:
Additive Manufacturing Consortium

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Industry Support: The Additive Manufacturing Consortium

Mission: Accelerate and advance the manufacturing readiness of Metal AM technologies

Goals:

- Participation from Academia, Government, and Industry
- Present timely case studies/research
- Execute group sponsored projects
- Collaborate on Government funding opportunities
- Forum for discussion/shaping roadmaps

Current Members

Full Members
- Aerospace – Engine (7)
- Aerospace – Airframe (3)
- Aerospace – Systems (4)
- Heavy Industry (3)
- Industrial Gas Turbine (1)

Non-Profit
- R&D (2)

Suppliers
- Powder (5)
- AM Equipment (2)
- AM Ancillary Equipment (1)
- AM Technical Service Providers (2)
- AM Software (1)

Research Partners
- Government (4)
- University (3)

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Industry Support: The Additive Manufacturing Consortium

- The AMC project portfolio continues to focus on addressing common, pre-competitive technical challenges in metal AM processes. Projects are focused on materials and processes. Members have access to $3.2 million in project funding.

- In 2016 and early 2017, the AMC experienced significant growth, doubling the number of full members in the U.S., Europe, South America, and Asia. As of September 2017, the AMC consisted of over 40 members, all users of AM technology.

- Past projects have included Inconel 625, Inconel 718, and Monel 400 theme development, heat treatment optimization, machine variability, and design allowable database generation.

CY16 AMC Project Themes

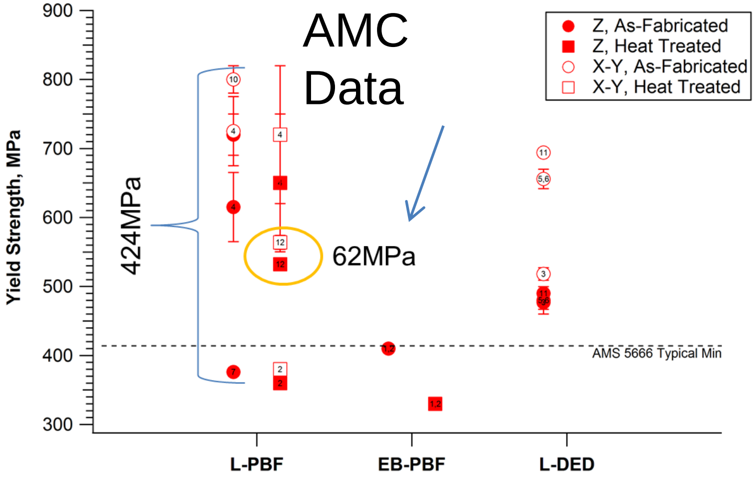
- **Continue to build upon current body of work**
  - Phase 3: 625
  - Phase 3: 718,
  - Phase 2: High Strength Aluminum Alloys
  - Phase 2: Monel 400

- **Over ~$550K of 2016 Project Contribution**
- **Incorporate NDI into project execution**
- **Cross-platform validation of PBF machines and powder suppliers**

AMC Nickel Alloy 625 Project

Objective:

- Develop manufacturing process controls
- Understand process variables as a foundation for database development.



Funding to Date:

- ~500K AMC / 160K Gov't

Deliverables to Date:

- Manufacturing Plan
- Room and Elevated Temperature Property Study across multiple L-PBF machines
- Heat treatment development

- Refine heat treatment to minimize anisotropy
- Develop high temperature mechanical property data.

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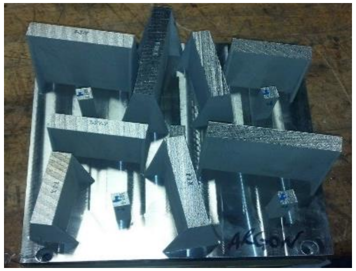
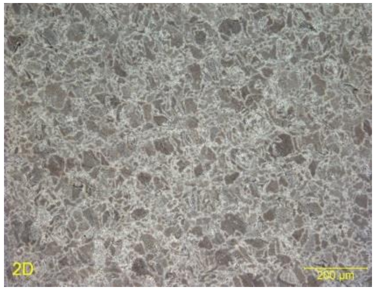
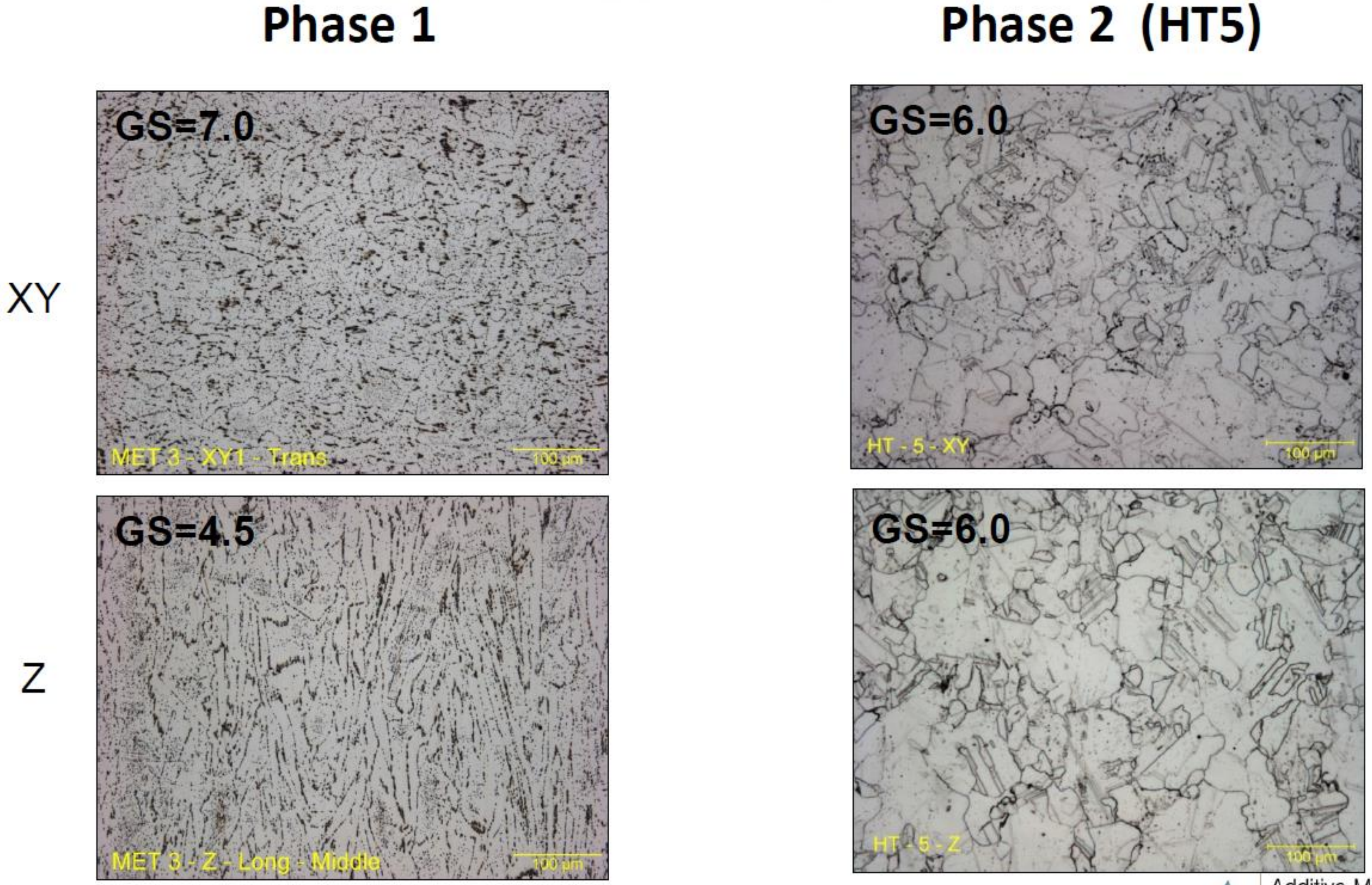
Phase 1 Nickel Alloy 625 AMC Project Roadmap

Material Issues	•Generate data on •powder recycling impact and best practice •chemistry heat to heat variation
Design Issues	•CY16, generate data on •Wall thickness •Surface finish/orientation
Phase 3: Machine Issues	•CY15, Generate data on: •LPBF (EOS, Concept, 3DS, Renishaw) •EB-BPF (Arcam)
Phase 2: Heat Treatment Optimization	•CY14, Generate data for •Improve HT schemes •Understand impact of HT
Phase 1: Manufacturing Plan, Foundational Data	•CY12-13 •Demonstrate plan •Establish SOA perf. data

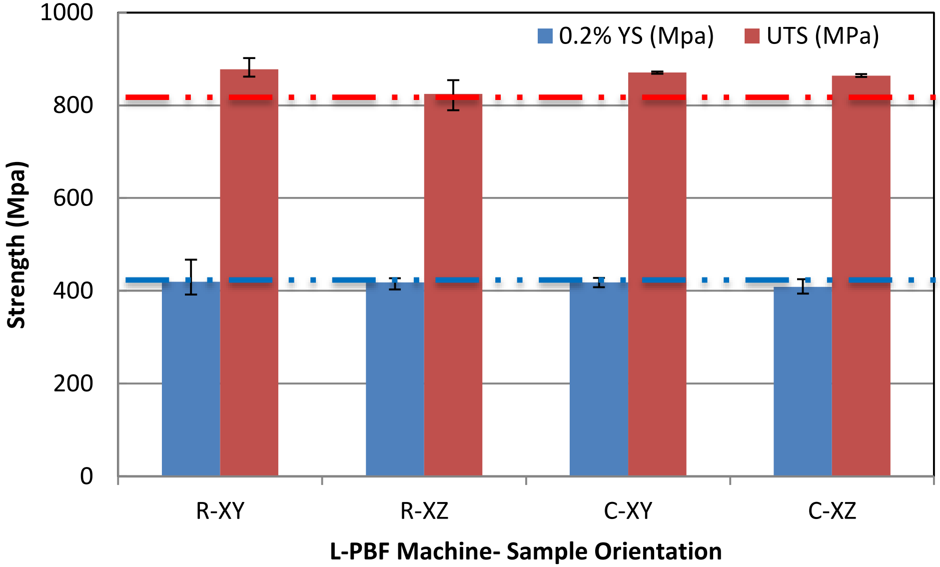




Phase 2 Refine Heat Treatment to Minimize Anisotropy



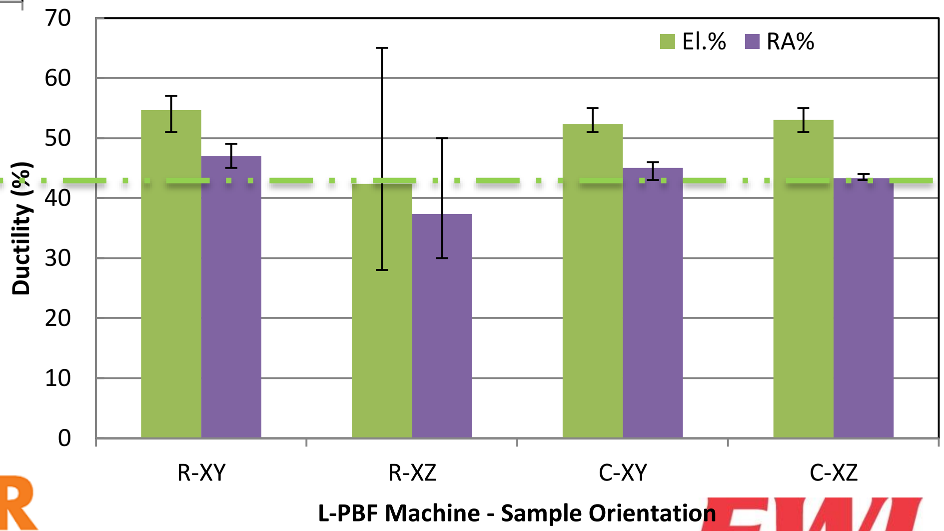
Phase 3 Tensile Test Results of Alloy 625 Across Multiple Machine Manufactures



UTS - EOS material

YS – EOS material

El% - EOS



eos

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CONCEPTLASER

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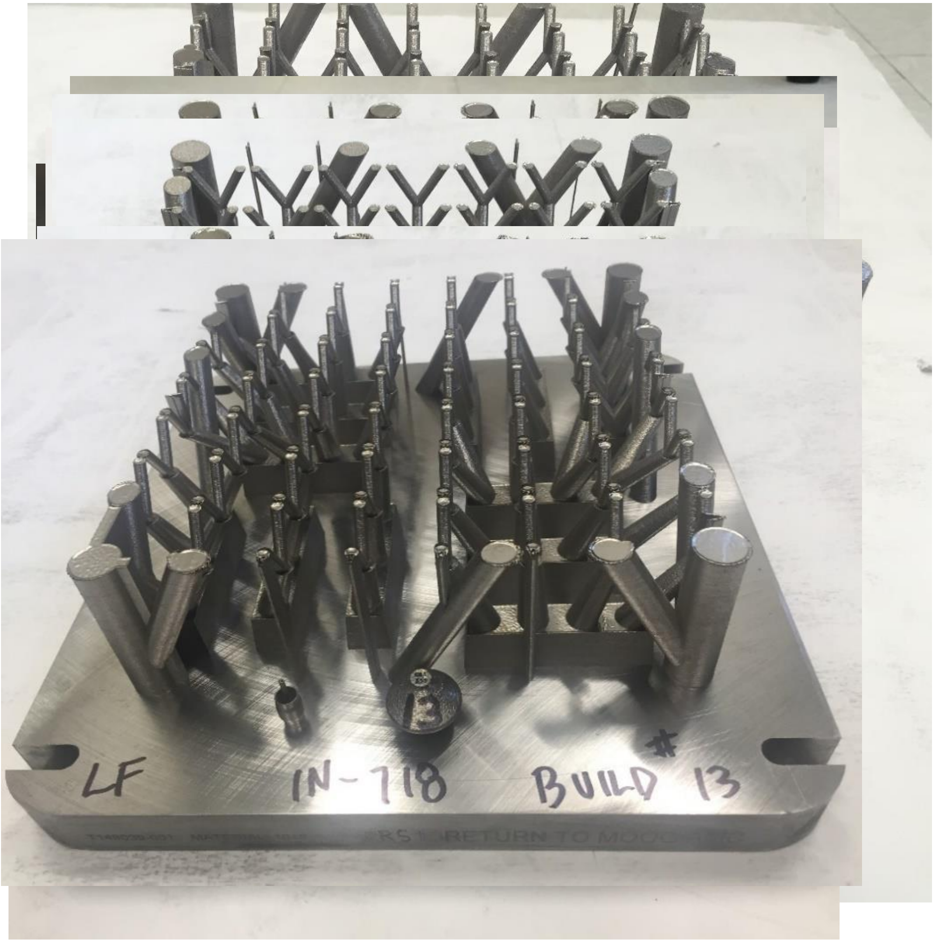
Phase 3 Alloy 718– Recycling Study

- **13 builds completed on the Renishaw AM250 at MOOG**



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2017 Project Selection Process

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2017 Potential projects – Member Interest (8 Projects)

1. **Literature Reviews**
   - Microstructure Control
   - In-Process Monitoring
2. **AM Weldability Study (Northrop)**
3. **Extended 718 Recyclability of other Systems**
4. **RPM 718 Optimization (Raytheon) 316**
5. **ARCAM Ti64 Defects vs. Properties (SSL)**
6. **TEKNA Powder Cleaning/ Reshaping/Economics (Moog)**
7. **Removing Impurities in AM Powders (UTC)**
8. **Development of custom AM alloys using commercial off the shelf tools or services (UTC)**
9. **AM Monitoring**
   - Sensor Enhancement: Fringe Projection
   - Data Fusion & Visualization
   - Defect Rectification
   - On-Axis High-Speed Imaging
   - Additional Focus on laser-powder interaction
10. **AM Inspection**
    - CT Inspection
    - Ultrasound
    - AM Test Geometries
    - Other inspection tech (electromag, thermography, etc)
11. **Monel 400 Phase 3**
    - Recyclability
    - Heat Treatment
12. **Aluminum**
    - Chemistry Change
    - Other Alloys
13. **Other Materials - 15-5 Ph, 17-4 Ph, etc**
14. **Phase 4 625 Rapid Test**
15. **Phase 4 718 Rapid Test**
16. **Properties based on geometry/orientation**
17. **Automated sieving/mixing (robotic/modular)**
18. **L-PBF/Welding of other crack-prone alloys (Haynes 230, 247)**

Round 2 Votes (4 pick's each)

Round 2																		Full Vote Totals	
Initial Voting																			
2 and 18	1	1	1						1	1		1		1		1		8	
6	1	1	1	1	1	1	1	1	1		1	1						11	1
9	1				1		1	1			1	1	1	1	1		1	10	3
10	1			1				1	1	1	1		1	1	1	1	1	11	2
12			1			1	1		1	1		1	1		1	1	1	10	4
14 and 15		1	1	1	1	1		1		1	1					1		9	
16		1		1	1	1	1						1	1	1		1	9	

- **(6) AM Powder Recycling and Reconditioning**
- **(9) In-Process Monitoring Of Defect Rectification in Laser Powder Bed Fusion (L-PBF)**
- **(10) Nondestructive Post-Process Evaluation of Additively Manufactured (AM) Parts**
- **(12) Aluminum: (assuming direct continuation from Phase 2)**

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Selective 2017 Project Update

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Nondestructive Post-process Evaluation of AM Parts

NDE Technology	Near-surf Imaging	Sub-surf Imaging	Ideas for Sizing*	Stretch Goals*
XrayCT	✖	✖	✖	Ideas for new reconstruction
Ultrasound (Phased Array)		✖	✖	Ideas for complex geometry resonance
Ultrasound (Surf Wave)	✖			Ideas for non-contact and high resolution
Eddy Current	✖		✖	Ideas for surface roughness effects
Pulsed Thermography	✖			
Single ICME Ultrasound Simulation		✖		Ideas for "virtual" (ICME) probability of detection (POD) methods

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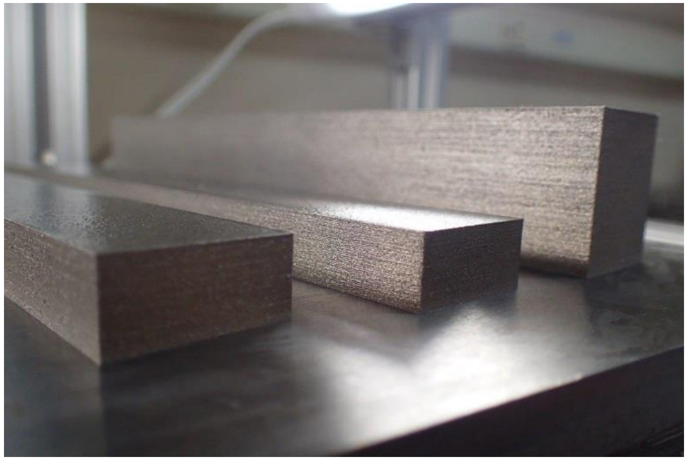
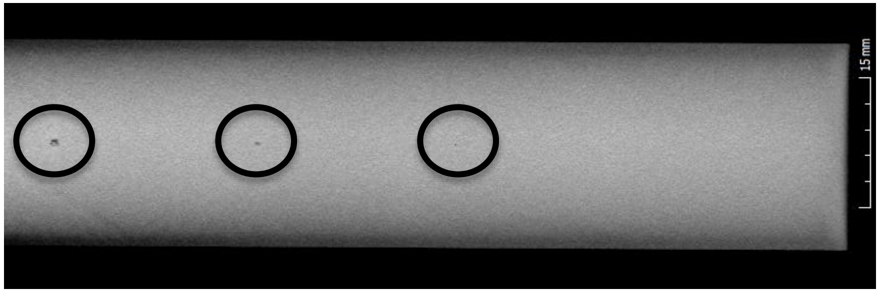
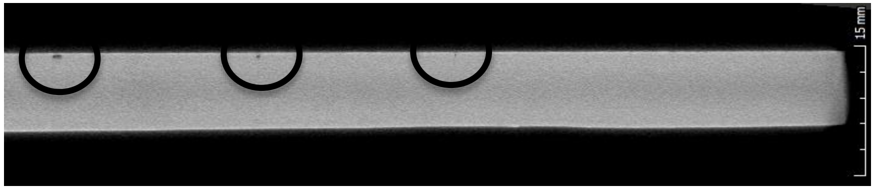
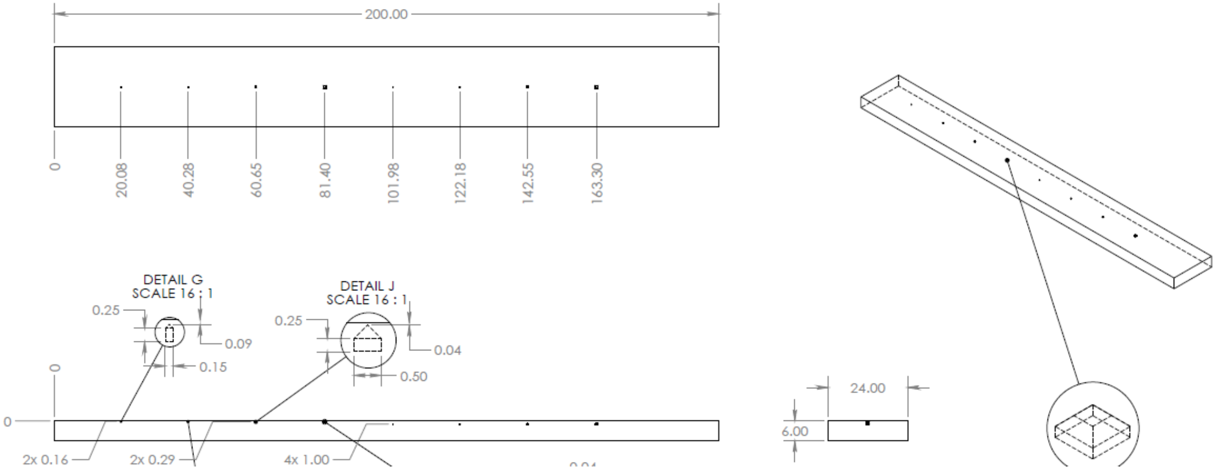
Nondestructive Post-process Evaluation of AM Parts









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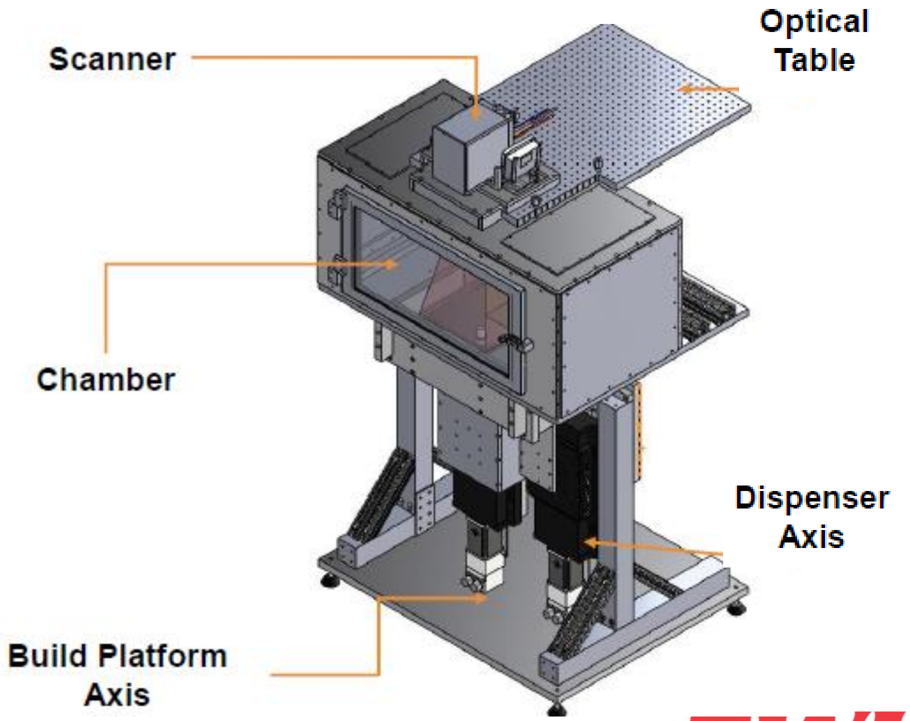
In-Process Monitoring Of Defect Rectification in Laser Powder Bed Fusion (L-PBF)
Previous Experience

◆ EWI studied the in-process monitoring of L-PBF through a project funded by NIST.

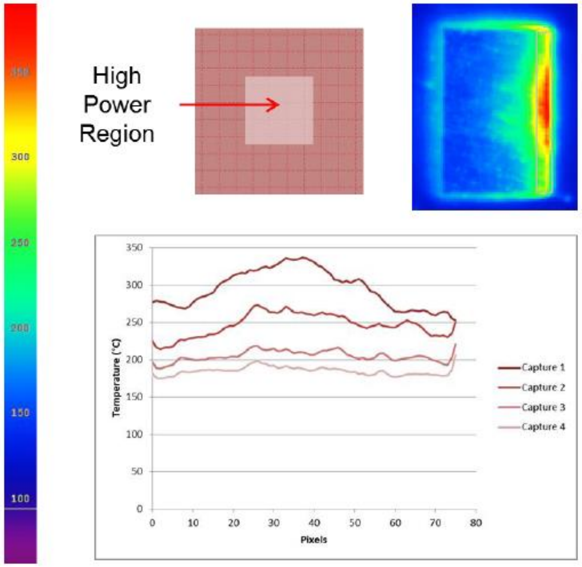
Local Sensors
- Thermal Melt Pool Imager
- Optical Melt Pool Imager
- Photodetector
- Spectrometer

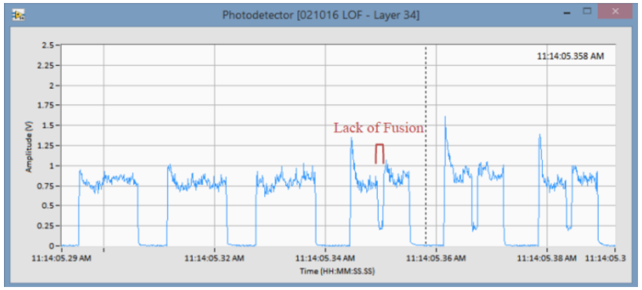
Global Sensors
- Thermal Build Area Imager
- Optical Build Area Imager
- Laser Profilometer
- Projection Moiré

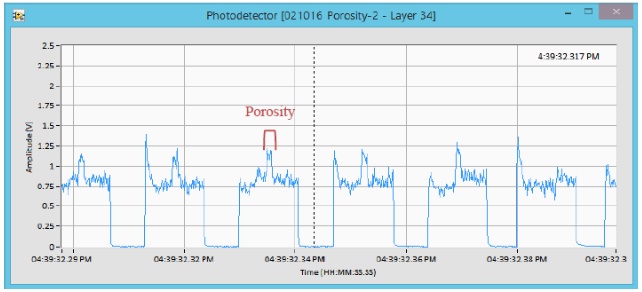


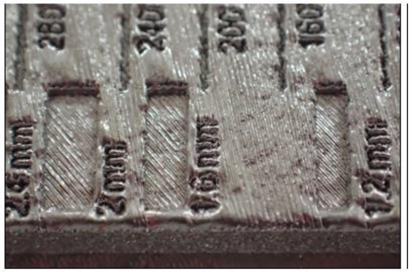
In-Process Monitoring Of Defect Rectification in Laser Powder Bed Fusion (L-PBF)
Previous Experience

- Develop a method for the in-process detection and rectification of open-to-surface defects in PBF processes

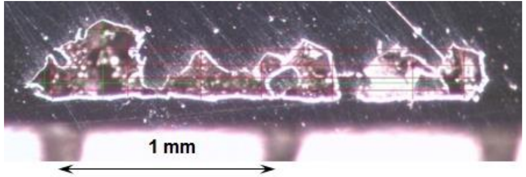




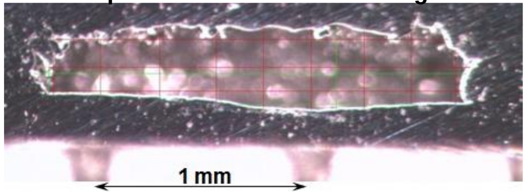


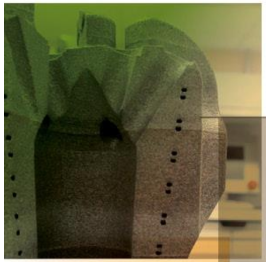


Not-Optimized Fabrication Setting



Optimized Fabrication Setting





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2018 Project Idea

Comparison of leading, commercially available AM simulation tools

- **Not a comparison of general-purpose simulation tools where an expert has to set up a simulation for AM**
- **NOT ANSY, ABAQUS, type of study**
- **Target Companies: 3DSIM, Autodesk Netfabb Simulate (Pan Computing), MSC Simufact-AM, Geonx, Additive Works**
- **Capabilities to include:**
  - Support Generation
    - Whether or not it uses simulation to generate them
  - Distortion Compensation
  - Distortion Predictions
  - Residual Stress Predictions
  - Simulation Modes
    - Inherent Strain
    - Scan Pattern-Dependent Strain
    - Thermal Strain
  - Reading in 3rd party supports
  - Predicting support failure
  - Predicting blade crash failure
  - Meltpool predictions
  - Thermal history predictions
  - Microstructure
  - Properties
  - Heat treatment
  - User experience
    - Subjective end-user measure for ease-of-use
  - Cloud
  - Computational speed vs accuracy
  - Subjective measure for the degree of validation

Project Scope:
    Phase 1 – capabilities analysis
    Phase 2 – accuracy/validation analysis through experiments

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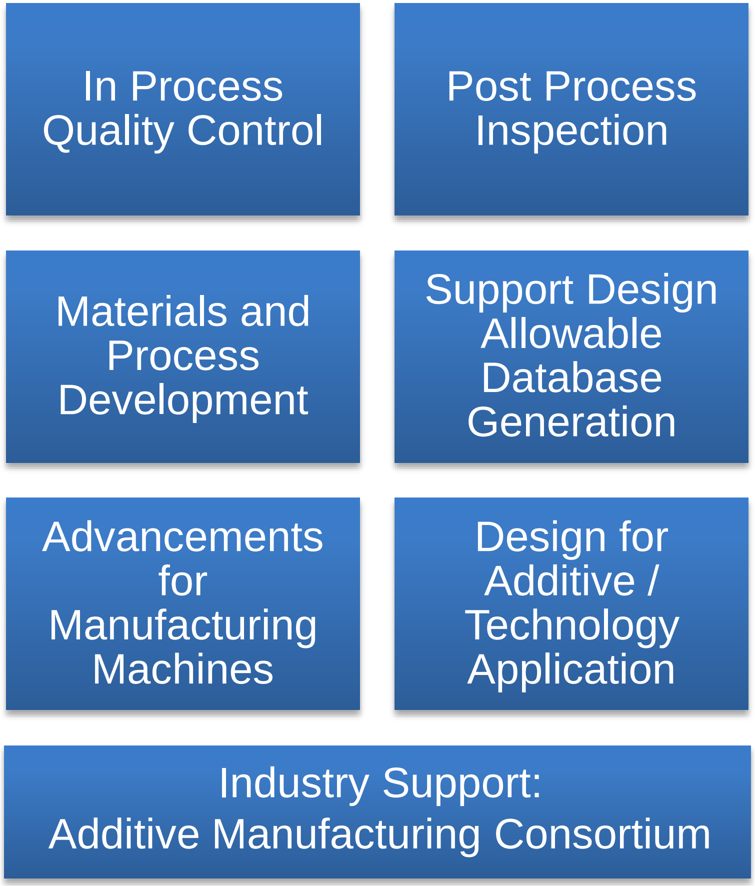
EWI is advancing metal AM to enable broader adoption by industry

- **Holistic view**
  - More than the 3D Printing Process
  - Requires Manufacturing support to be true additive manufacturing
- **Industry Support**
  - Understand application of conventional manufacturing.
  - Trusted Agent
  - Innovation



EWI AM Focus Areas

In Process Quality Control

Post Process Inspection

Materials and Process Development

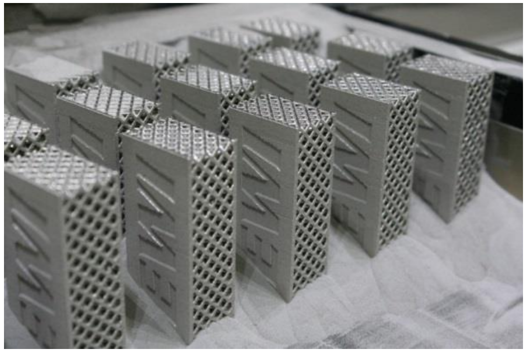
Support Design Allowable Database Generation

Advancements for Manufacturing Machines

Design for Additive / Technology Application

Industry Support:
Additive Manufacturing Consortium

Questions



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http://ewi.org/technologies/additive-manufacturing/

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EWI is the leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, EWI has offered applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors. By matching our expertise to the needs of forward-thinking manufacturers, our technology team serves as a valuable extension of our clients' innovation and R&D teams to provide premium, game-changing solutions that deliver a competitive advantage in the global marketplace.

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APPENDIX EE—OEM PERSPECTIVES ON AM QUALIFICATION AND CERTIFICATION

OEM Perspectives on AM Qualification and Certification

Dayton, Ohio
August 31, 2017

LOCKHEED MARTIN

Dr. Marilyn Gaska
Bill Fallon
LM Fellows

Agenda

- **Business Area AM Application Domains/Focus**
- **Qualification and Certification Context**
- **Rotary and Mission Systems Sikorsky Efforts**
- **Way Forward**

Business Area Domain/Focus

Aeronautics

- Tactical Fighters
- Tactical /Strategic Airlift
- Advanced Development
- Sustainment Operations

Missiles and Fire Control

- Air and Missile Defense
- Tactical Missiles
- Fire Control
- Combat Maneuver Systems
- Energy

Rotary and Mission Systems

- Maritime Solutions
- Radar and Surveillance Systems
- Aviation Systems and Rotorcraft Platforms
- Training and Logistics Solutions

Space Systems

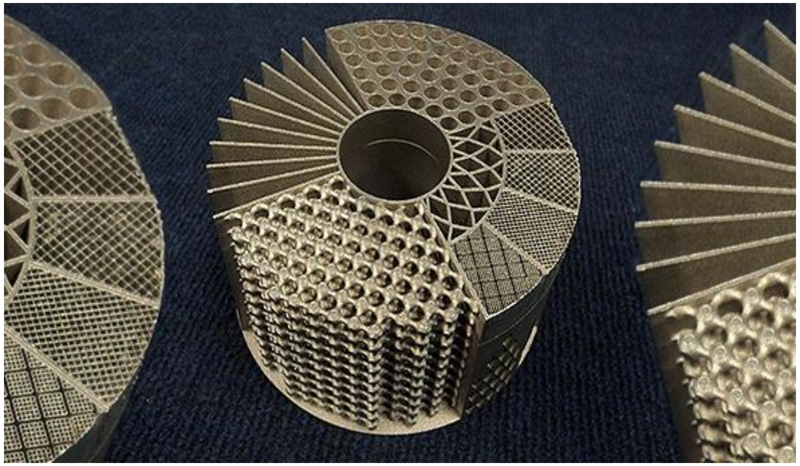
- Surveillance and Navigation
- Global Communications
- Human and Deep Space Exploration
- Strategic and Defensive Systems

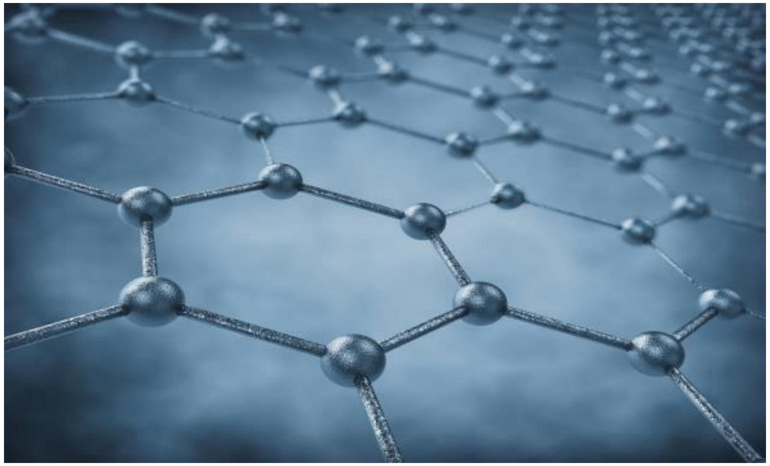
Corporate Engineering, Technology, and Operations (CETO)

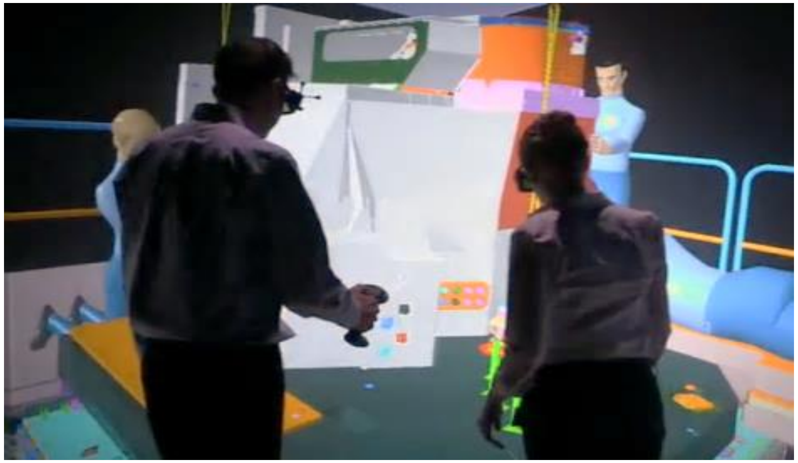
Manufacturing USA Institute leadership, Additive Manufacturing Community of Practice and LM Fellows for LM-Wide Subject Matter Experts (SMEs) and Action Teams, University engagement

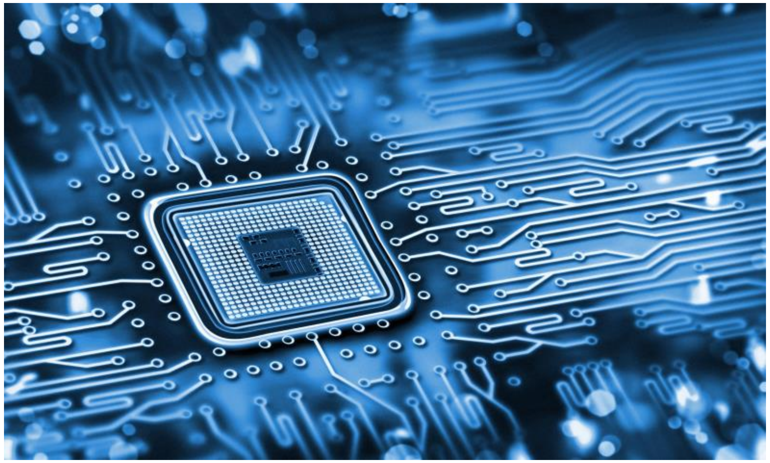
Supplier Network for Agile Manufacturing

Advanced Manufacturing Partnership Includes Qualification and Certification


Additive Manufacturing


Advanced Materials


Digital Manufacturing


Advanced Electronics

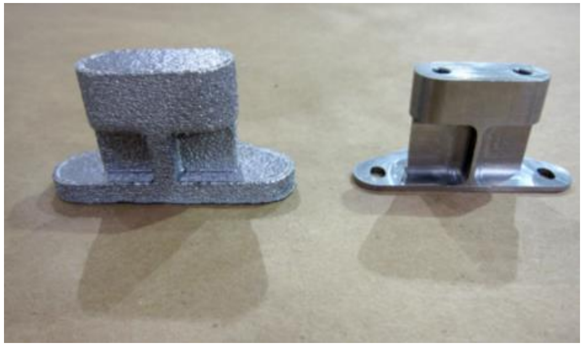
Partnering with Our Customers to Accelerate Manufacturing Innovation from the Laboratory to Production and Deliver Measurable Business Value

Space Systems Company

OUT OF THIS WORLD PARTS

Right now, 3D printed parts like these are flying to the asteroid Bennu.

The first 3D printed part flown in space traveled 1,700,000,000 miles to Jupiter on the Juno spacecraft. And right now, 3D printed parts are flying to the asteroid Bennu.



Juno, which arrived to Jupiter July 4, 2016, is the first Lockheed Martin spacecraft ever to fly 3-D printed parts—a set of eight titanium waveguide brackets.

THE SCIAKY PRINTER

Engineers can 3D print a dome for a spacecraft fuel tank in two weeks.

For many applications, 3D printing takes significantly less time than traditional manufacturing. Case in point, using a Sciaky printer, engineers can 3D print a dome for a spacecraft fuel tank in two weeks versus the 18 to 20 months it would take using traditional methods.

Aeronautics

AUTOMATED FIBER PLACEMENTS

This machine manufactures large-scale, complex-shaped structures, like airframes, with composite materials. Watch the video to the left to see it in action.

THE MAMMOTH

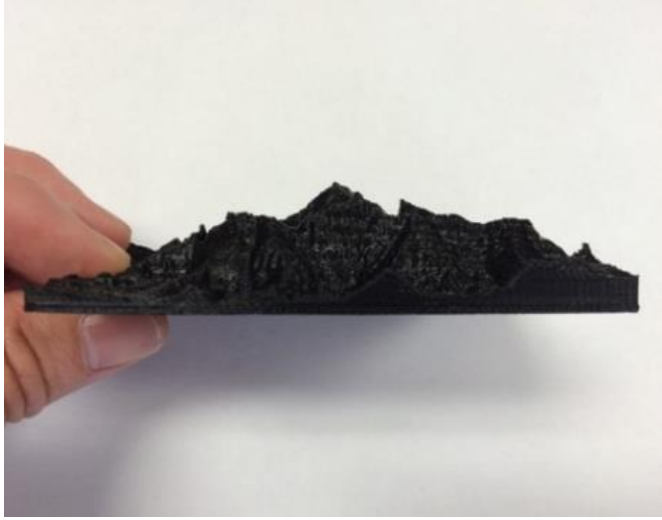
Big Area Additive Manufacturing (BAAM) is a 5 foot wide, 12 foot long and 6 foot tall 3D printing machine. It can print 80 pounds per hour, which can come in handy if you're looking to print life-size cars, large plane parts or hundreds of tools. You can find this machine at work at Lockheed Martin's Marietta, Georgia facility printing tools for the C-130 Hercules.

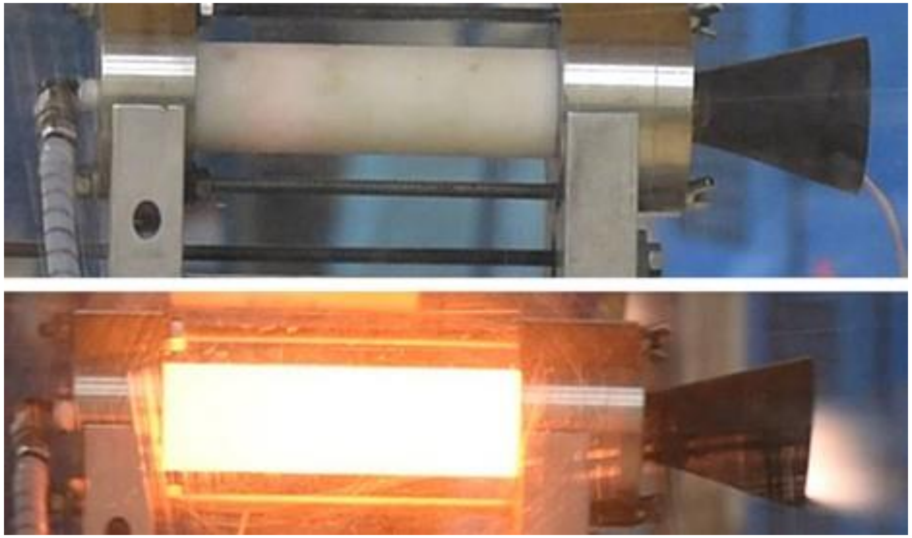
Missiles and Fire Control

TOPOGRAPHICAL MAPS

For those who still can't get the hang of digital maps, engineers have developed 3D printed maps.

By combining terrain data with real-time surveillance from drones, aircraft and satellites, you can develop a highly accurate, up-to-date 3D representation of any given area. The hardest decision you'll make is selecting the material—rubber to roll up for easy transportation, glow-in-the-dark fabric for nighttime use, or edible material in case you get lost in the middle of nowhere.

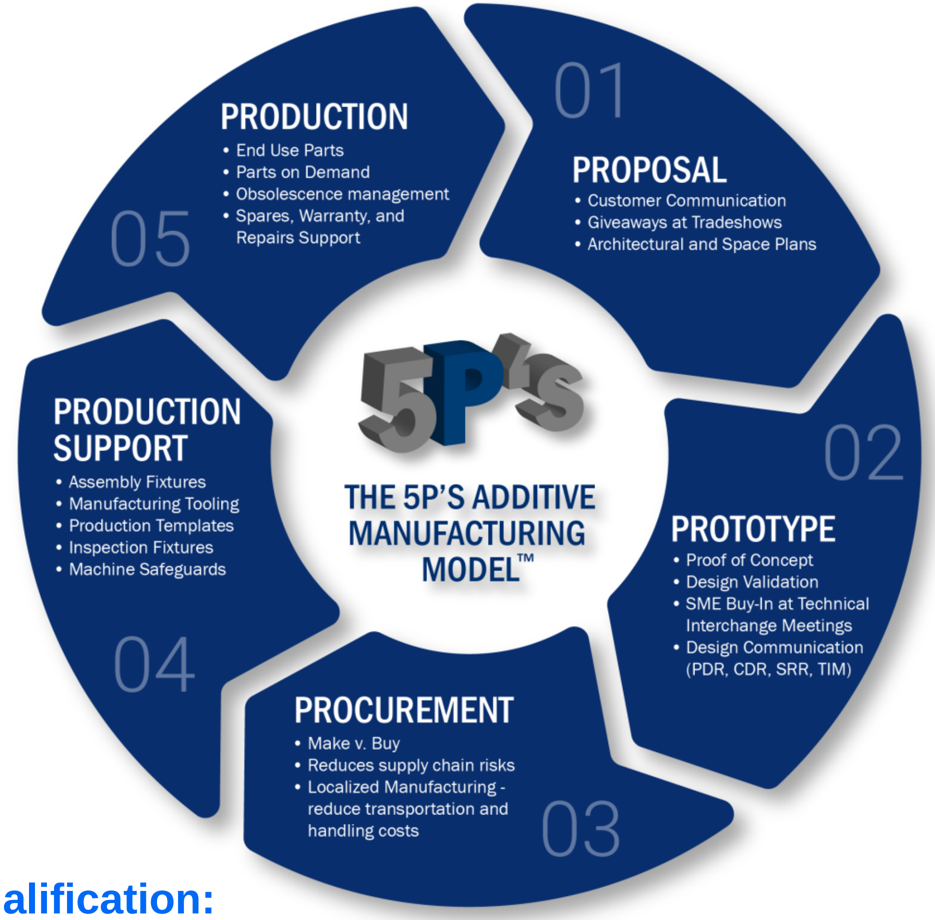




PROPELLANTS

Recently, a team of Lockheed Martin engineers successfully tested a six-inch rocket with 3D printed propellant grain

Rotary and Mission Systems (RMS)



5P's

THE 5P'S ADDITIVE MANUFACTURING MODEL™

01 **PROPOSAL**
- Customer Communication
- Giveaways at Tradeshows
- Architectural and Space Plans

02 **PROTOTYPE**
- Proof of Concept
- Design Validation
- SME Buy-In at Technical Interchange Meetings
- Design Communication (PDR, CDR, SRR, TIM)

03 **PROCUREMENT**
- Make v. Buy
- Reduces supply chain risks
- Localized Manufacturing - reduce transportation and handling costs

04 **PRODUCTION SUPPORT**
- Assembly Fixtures
- Manufacturing Tooling
- Production Templates
- Inspection Fixtures
- Machine Safeguards

05 **PRODUCTION**
- End Use Parts
- Parts on Demand
- Obsolescence management
- Spares, Warranty, and Repairs Support

The 5Ps AM Model is trademark of Lockheed Martin Corporation. For publishing permission, contact Robert Ghobrial, RMS Manufacturing Technology Lead, robert.g.ghobrial@lmco.com

Qualification:
Design
Part & Process
System
Platform/Agency

The RMS Additive Manufacturing Innovation Center is home to state-of-the-art polymer, metal and ceramic material development.

STRATASYS FUSED DEPOSITION MODELING (FDM) MACHINES

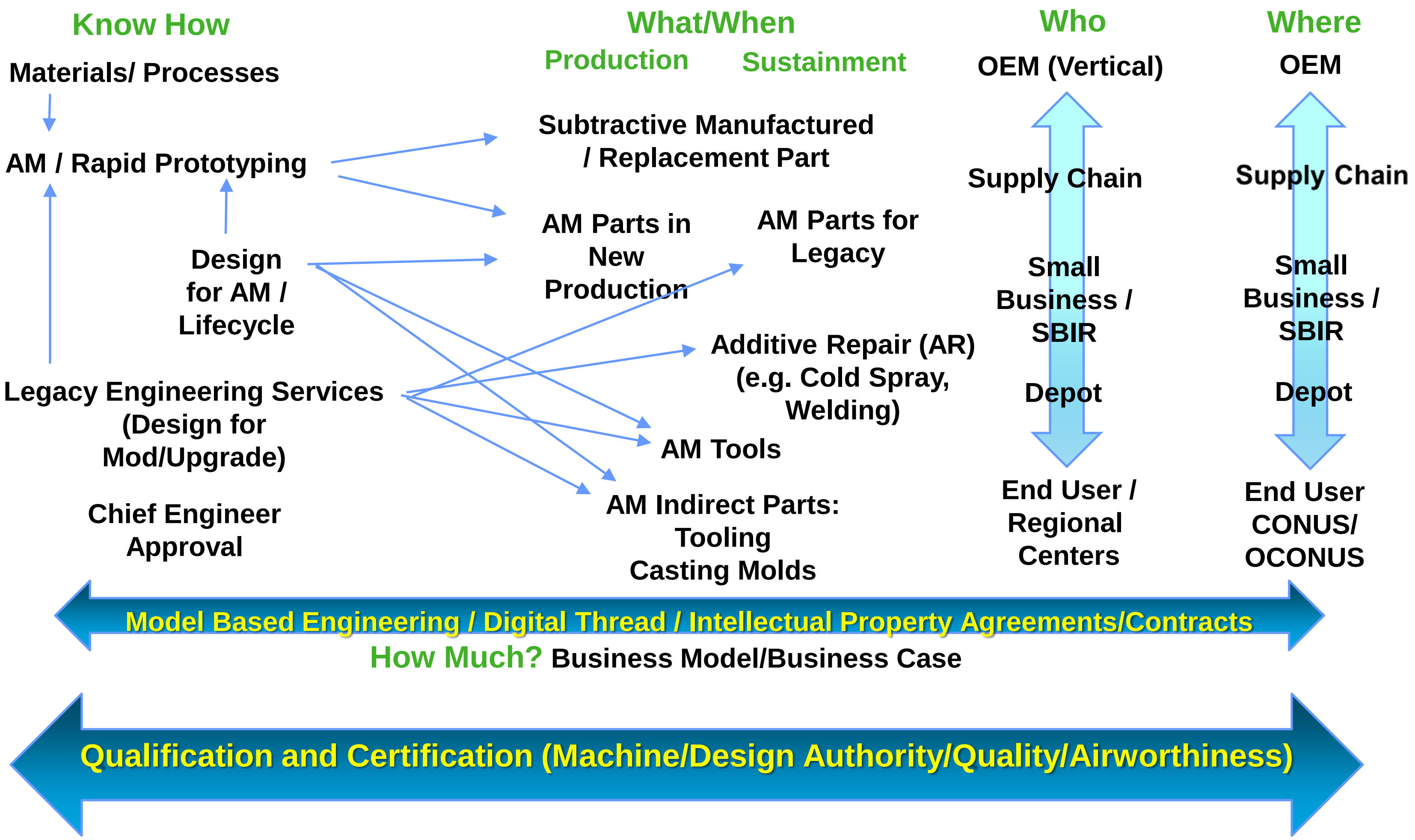
Utilizing the Stratasys FDM machines to create a wide variety of developmental, prototyping and small and large production parts.

Qualification & Certification Context: Underlies New Design and Sustainment

NCMS/CTMA Annual Partners Meeting, May, 2016

Additive Manufacturing (AM) for Sustainment Industry Use Cases and Value Chain

Why? Faster, Lower Cost, Improved Readiness, Lower Inventory/Warehousing



Know How

Materials/ Processes

AM / Rapid Prototyping

Design for AM / Lifecycle

Legacy Engineering Services (Design for Mod/Upgrade)

Chief Engineer Approval

What/When

Production **Sustainment**

Subtractive Manufactured / Replacement Part

AM Parts in New Production

AM Parts for Legacy

Additive Repair (AR) (e.g. Cold Spray, Welding)

AM Tools

AM Indirect Parts: Tooling Casting Molds

Who

OEM (Vertical)

Supply Chain

Small Business / SBIR

Depot

End User / Regional Centers

Where

OEM

Supply Chain

Small Business / SBIR

Depot

End User CONUS/ OCONUS

Model Based Engineering / Digital Thread / Intellectual Property Agreements/Contracts

How Much? Business Model/Business Case

Qualification and Certification (Machine/Design Authority/Quality/Airworthiness)

Sustainment Considerations

- Engage Service / OEM Engineering design authority early for education / approval process understanding
- Agree on required testing / quality, addressing as process/material change
- Manage part number impact and associated costs
- Help define classes of parts / part families to leverage success stories for reducing risk

Perspectives on Critical Technology Areas for Experimentation

Craig Brice, SSC, High Value Experimentation Needs for the Additive Manufacturing Community, Workshop on In Situ X-ray Characterization During Selective Laser Melting, Golden, CO, USA, October 4, 2016

There are (at least) 4 key technology areas within AM that require high value experimentation to help us understand process–performance relationships

1. **Solidification behavior**
2. **Residual stress**
3. **Defects & flaws**
4. **Microstructure**

Until we can begin to fully describe the process on its own using validated data, we will struggle with industrial implementation for critical applications

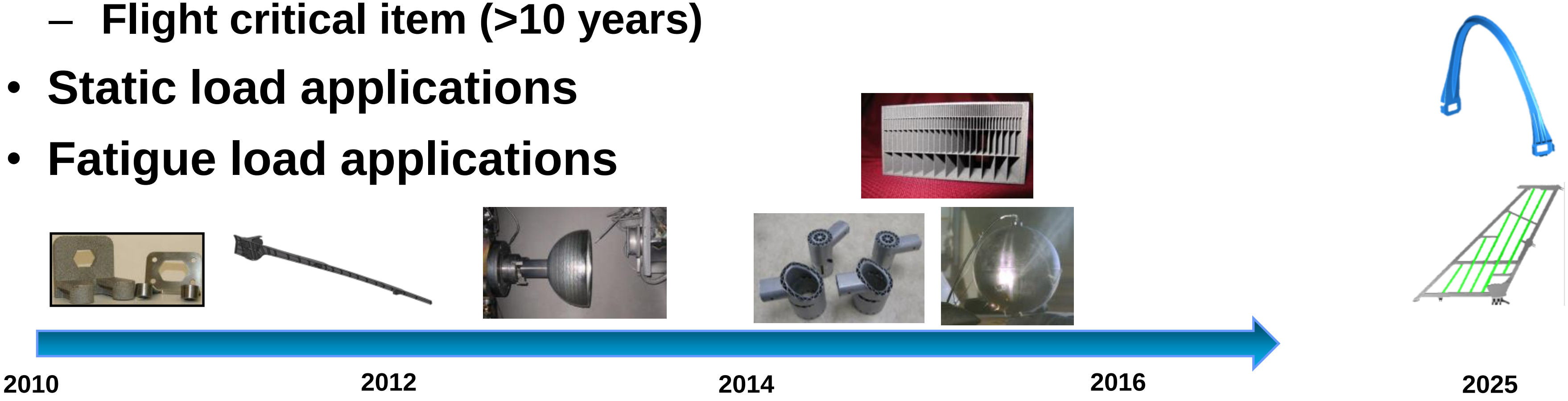
MFC Qualification and Certification Perspectives

- **Different requirements for missiles and unmanned systems**
- **Same FAA / NASA requirements apply for any process**
- **Qualify process / materials for additive manufacturing to meet requirements**
- **Shaping of AM Industry Specifications**
  - **Participating in SAE AMS AM committee and ASTM F42 AM Committee**
  - **Collaborating across Business Areas**
  - **Participating in America Makes projects determining allowables**

Qualification

IDTechEx, Additive Manufacturing Implementation Challenges For The Aerospace Industry, David Vos and Brian Rosenberger, Berlin, Germany, April 28, 2016

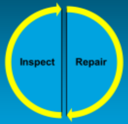
- **Manned or unmanned applications**
- **Acceptance by FAA/JAA**
- **End use**
    - **Prototype and tooling (today)**
    - **Non-load bearing structure (0-3 years)**
    - **Secondary structure (3-5 years)**
    - **Primary structure (5-10 years)**
    - **Flight critical item (>10 years)**
- **Static load applications**
- **Fatigue load applications**



RMS Sikorsky's AM Qualification Approach using Castings Analogy

Castings: Low Process Capability

Pour

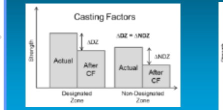


100% Repair

100% Testing (Prolongations)

FEEDBACK

Design (Considering Low Process Capability)

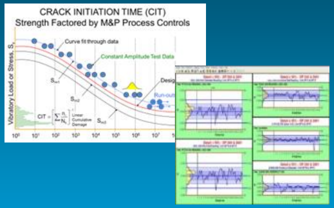


Knockdowns

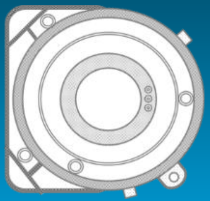
More Knockdowns

100% Inspection

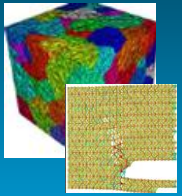
Proposed 3D Durability & Damage Tolerance Analysis (DaDTA) Approach



DaDTA Focused Quantification of AM Process Capability



Zoning of Part Design Considering Process Capability & Material Deposition Control



Modeling & Simulation of Performance

Verification & Validation of Simulation Tools

This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) under Purchase Order No. HR0011-17-P-0004." and, " Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the DARPA

Uniqueness of Sikorsky's DaDTA Approach

Aircraft Structural Components experience 3D states of stress

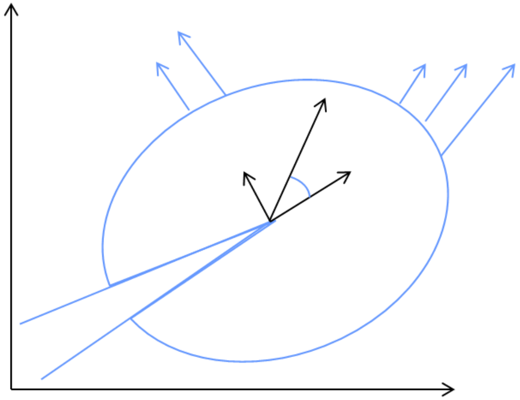
- **Since traditional S-N approach deals mostly with principle stresses, it cannot provide a comprehensive solution**

3D DTA is more appropriate for aircraft structural components

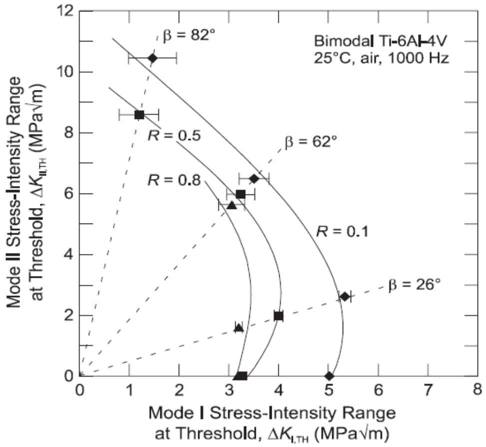
- **Crack growth data accommodates shear stresses and sharp gradients by allowing crack to propagate in any plane driven by 3D stresses**

Complementary to AM's material deposition ability

- **Scale of AM material deposition capability is an opportunity for critical controls to be applied at relatively small volumes of material. This enables 3D consideration for stress states for a weight optimized structural configuration**



J.P. Campbell, R.O. Ritchie / Engineering Fracture Mechanics 67 (2000) 209–227



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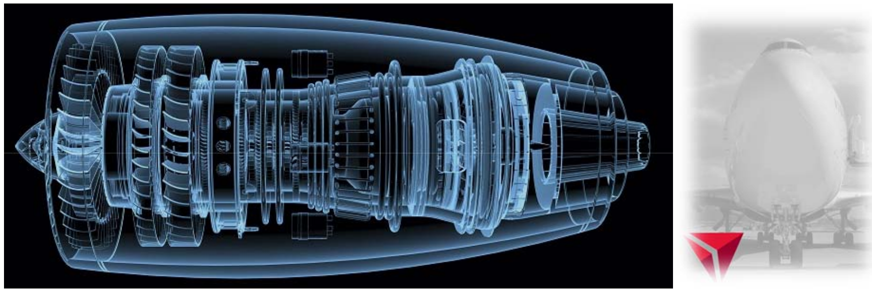
Way Forward

- Collaborate externally with regulators / standards groups
- Continue to work with program management, design authority, and quality assurance to understand risk management / approval process
- Continue to collaborate with Business Areas to leverage effort across domains
- Continue to assess cold spray / additive repair even if not in 7 AM categories in American Society for Testing and Materials “ASTM F42 – Additive Manufacturing”

APPENDIX FF—ADDITIVE MANUFACTURING IN THE AIRLINE & MRO WORLD – POTENTIAL, CHALLENGES AND PATH FORWARD – ONE AIRLINE’S EXPERIENCE

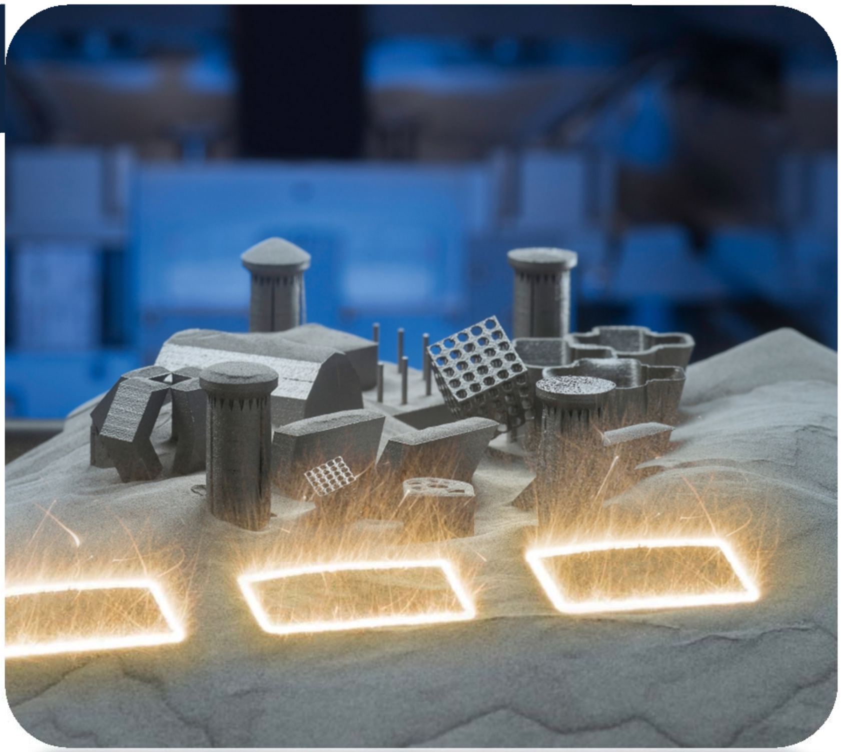
DELTA
TechOps



Additive Manufacturing in the Airline and MRO World

One Airline's Experience

R. Ramakrishnan
August 31st, 2017



Presented at The Third Joint FAA-Air Force Workshop on Qualification / Certification of Additively Manufactured (AM) Parts

AM at Delta Air Lines: Overview & Objectives

Part I. Overview of Delta TechOps capabilities and structure

Part II. Past use of AM and like technologies at Delta TechOps

Part III. Present Use & Plan for AM at Delta TechOps

Part IV. Existing regulations and guidance to use AM

Comments From Past FAA – Air Force Workshop

On PMA’s and Repairs

“Concern that barrier to entry for PMA type activity is low”

“High cost to understand the process beyond initial capital investment & Understand that AM may prove to be an expensive process when all things are considered (data required, NDE, post-processing, etc.)”

“Repairs, sustainment, reverse-engineered parts, replacement parts are possibly a bigger risk with AM. Ref: Parts 121 and 145”

“Need to prevent PMA of AM parts – (order 8110.42 rev needed?)”

Source: Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts; DOT/FAA/TC-15/16

Comments From Past FAA – Air Force Workshop

On Regulations & Guidance

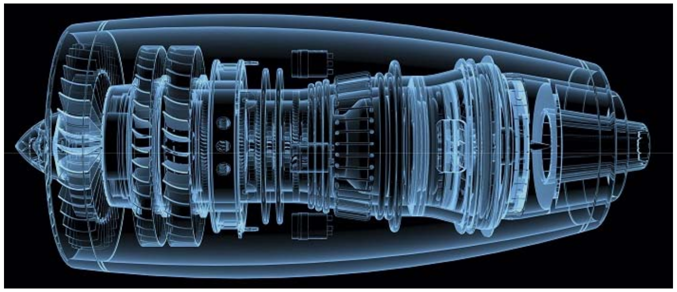
“Current regulations can likely handle AM. Similarity to policy memo adds for composite materials”

“Need policy or guidance first that can be matured into an AC later”

“Guidance to “applicants” would be beneficial to ensure complete compliance package is prepared”

Source: Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts; DOT/FAA/TC-15/16

DELTA
TechOps



Part I

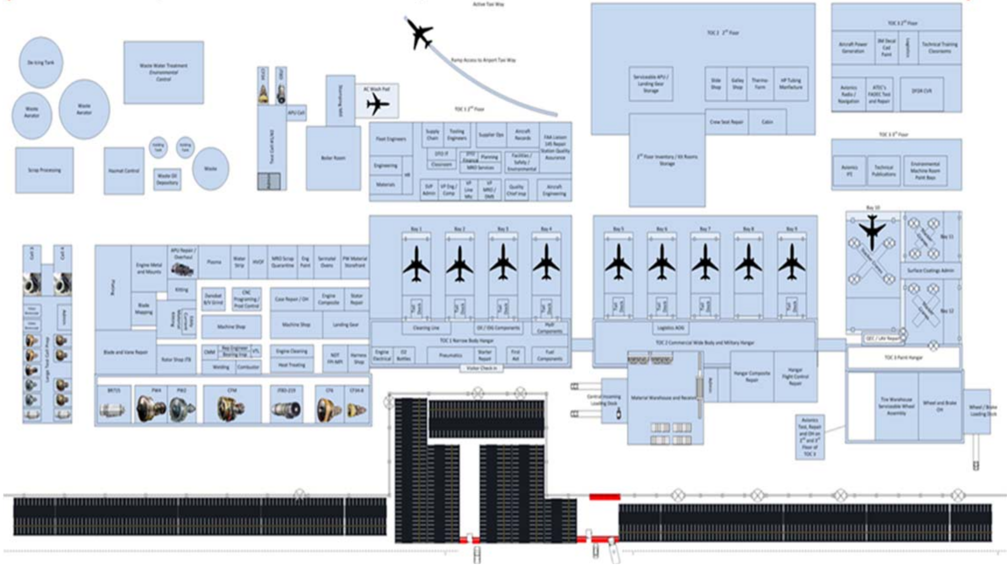
Delta Air Lines

Technical Operations

Overview

DELTA TechOps – Who We Are

- The third largest MRO in the world
- A fully-integrated global maintenance organization with an Atlanta-based main operation
- Supported by the largest and most experienced technical operations workforce in the world.
- Continually improving operational efficiency, utilizing 200+ engineers.
- 93 years of experience.



$4 BILLION

PRODUCTION CENTER IN ATLANTA, GA

2.7 MILLION

SQUARE FEET UNDER ROOF

10,000+

TECHNICIANS, ENGINEERS & SUPPORT STAFF

DELTA TechOps – Who We Are

DELTA AIR LINES FLEET

Delta operates: **18 aircraft types**

A fleet of **800+** mainline aircraft and **300+** regional jets

Average aircraft age: **17 years**

Delta TechOps maintains a large breadth and depth of technical knowledge and know-how.

DELTA TechOps – Who We Are

DELTA

A Full-Service MRO AND Airline

Engine and Component Overhaul

- 700+ engine & APU shop visits per year
- 200,000+ component repairs
- 150+ landing gear repairs and overhauls
- Thrust reverser and composite capabilities

Line Maintenance and Operational Support

- 58 maintenance stations (36 U.S. Domestic, 22 International)
- 200,000+ overnight checks per year

Aircraft Maintenance

- 200+ major visits (PSV)
- 260+ hangar overnight visits and letter checks
- 200+ modification and paint visits

Logistics and Inventory

- $1.1 billion in active inventory
- 12,000 part numbers supported
- 44 line stockrooms in 4 continents
- 150,000 transactions monthly from our warehouse

Engineering and Maintenance Control

- Active escalation of Delta's maintenance programs
- Leader in innovation – WiFi, PED, RFID
- 200+ engineers focused on cost and reliability
- Engineering solution database for 18 aircraft fleets

DELTA TechOps – Who We Are

AIRFRAME MAINTENANCE

Delta TechOps Capabilities

- Major Aircraft Visits (PSV)
- Aircraft Letter & Overnight Checks
- Airframe Modification Visits
- Aircraft Painting
- Disabled Aircraft Recovery Services
- Winglet Installation
- Corrosion prevention and control

200+ Major Visits (PSV) per year
260+ Hangar Overnight Visits & Letter Checks per year
200+ Modification & Paint Visits per year

Airframes Served

Boeing 717
Boeing 737
Boeing 747
Boeing 757
Boeing 767
Boeing 777
Airbus 320 Family
Airbus 330
MD-88
MD-90
MD-11

FAR/EASA 145 TechOps & Minneapolis Centers

- Capacity for 14 wide body and 20 narrow body aircraft together
- About 3 million sqf (285k sqm)
- Back shops, material management, administrative support

Military / Public Use Aircraft Serviced

Boeing 737NG [C40, P-8A]

Boeing 757 [C32]

Boeing 767 [KC46, KC767]

DELTA TechOps – Who We Are

ENGINE MAINTENANCE

Delta TechOps Capabilities

700+ engine & APU shop visits per year.
More than 30% of overhauls are for MRO customers.

10 Engine Lines Serviced

CF34-3
CF34-8
CF6-80A
CF6-80C2*
CFM56-5B
CFM56-7B
PW2000
PW4000-94
BR 715

*FADEC & PMC

APU

GTCP 131-9A
GTCP 131-9B
GTCP 331-200

ATL Shop

70+ Engine Bays

3 Engine Hospital Bays

4 Engine, 1 APU Test Cells

150 pieces of Machining

MSP Shop

12 Engine Bays

2 Engine Test Cells

DELTA TechOps – Who We Are

ENGINEERING SERVICES

Total Engineering Support
Fleet Engineering
Operations Support Engineering
Operational Reliability Teams

Organizational responsibilities and support include:

Provide Engineering Authorization for alterations, repairs and inspections

Provide engineering support to all engine, component and hangar shops

Provide 24-hour engineering support for all maintenance needs

Develop and approve major repairs and alterations through internal Designated Engineering Representatives (FAA-DER) or Organization Designation Authorization (FAA-ODA) resources

Provide Reliability Engineering, author Engineering Authorizations (EA) to accomplish Service Bulletins, FAA Airworthiness Directives and reliability improvements to aircraft and aircraft components

Provide Parts Manufacturer Approval PMA Engineering – FAA-PMA Approval and Service Evaluations

Authoring and administration of all technical manuals publications and procedures

Provide engineering support to other departments within Delta TechOps regarding modification projects

Design Aircraft Maintenance Programs, authoring tasks required to ensure the continuing airworthiness of aircraft, including any one or combination of overhaul, inspection, replacement, defect rectification, and the embodiment of an alteration or repair

Support Delta TechOps' emergency response and long-term mechanical performance monitoring program via representation of the department on the Technical Operations Executive Committee (TOEC)

DELTA TechOps – Who We Are

Shop Capabilities

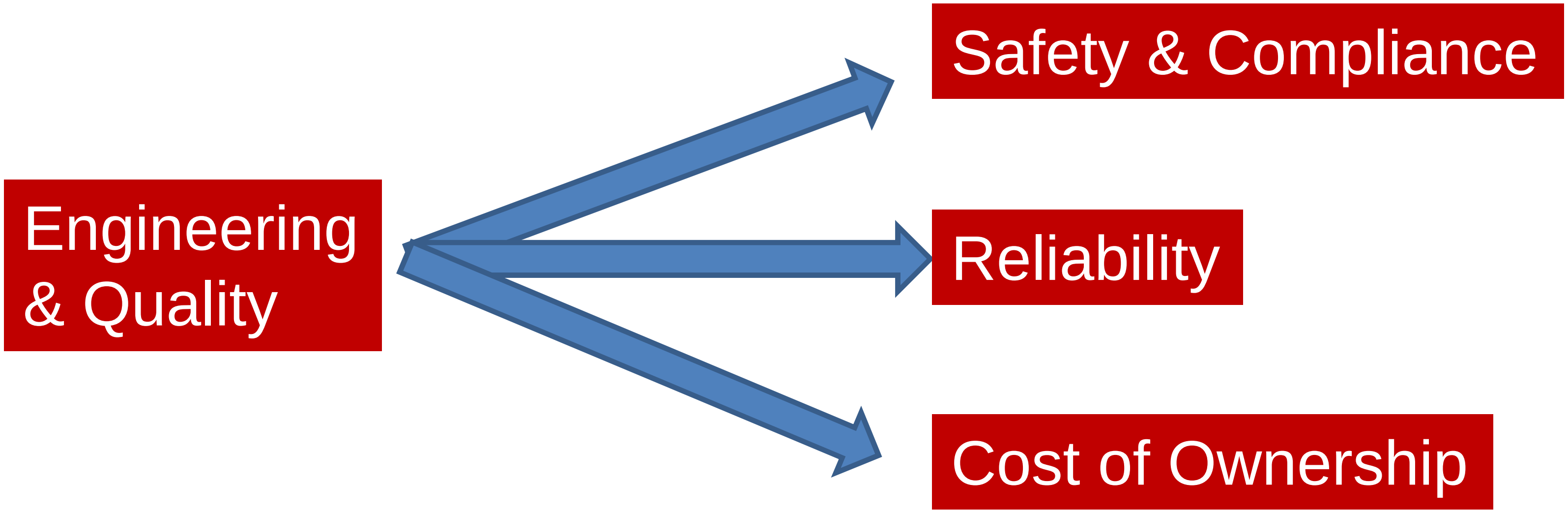
- Cleaning (FIC being built)
- Stripping including water jet
- Plating and CVD (being built)
- CNC Machine shops and EDM
- Danobat rotor and landing gear grinding
- Plasma spray and HVOF coating
- Heat treatment
- Welding including microplasma, EB, laser powder
- Brazing
- Shot peening
- Non Destructive Testing
- Test Cell Services
- Non Destructive Testing
- Honeycomb & Composite rebuild

With these capabilities Delta is able to repair and overhaul a large number of components and develop in-house repairs

DELTA TechOps – Who We Are

Provide the Airline with exceptional operational metrics

A record 200 maintenance-cancel free days so far in 2017 @ 3000+ flights/day



Engineering & Quality

Safety & Compliance

Reliability

Cost of Ownership

Numerous interwoven systems (CAMP, RCM, CAS, QSMG, SRM/SRA), groups, review boards and processes all ensure that only parts and repairs with a very good pedigree are introduced into our aircraft operations. Reliability Engg. rigorously monitors and corrects all Operational Difficulty Index drivers.

DELTA TechOps – Who We Are

DELTA

MRO – Why Work With Us?

EXPERIENCE & INDEPENDENCE

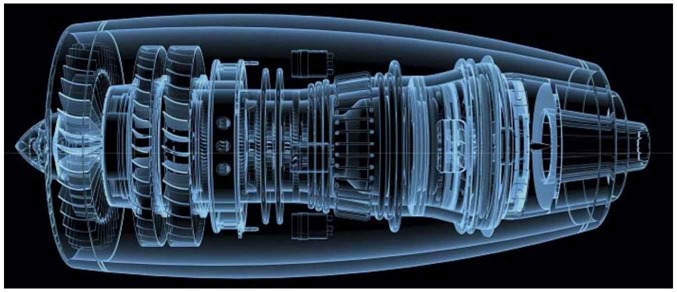
Our independence is a competitive edge. We're a leader in OEM-alternative solutions.

- 93 years of knowledge developing **cost-saving** processes and procedures.
- We leverage our experience to **offer *2,000+ OEM-alternate repairs/parts - PMA's included***
- Investing in the future. We will continue to invest in services for ourselves *and* our customers
- Purchasing power and benefit from ***$1 billion+ supply chain initiatives*.**

Potential for AM introduction

WE UNDERSTAND THE IMPORTANCE OF **UPTIME.**
AND THE COST OF **DOWNTIME.**
IF AM CAN HELP US WITH UPTIME & COSTS WE WILL USE IT

DELTA TechOps



Part II

Additive Manufacturing

at

Delta TechOps

AM at Delta Tech Ops – Repair Programs

Blown powder laser cladding repair of HPC blades
2013

2014
Repair of HPT Shrouds to Restore Rub Face

Cold Spray Repair of Al and Mg alloy die castings
2015

Focus was on developing repairs to reduce scrap replacement costs

AM at Delta Tech Ops – Repair Programs

Cold Spray Repairs

Low pressure system; used for low strength applications and dimensional restoration

Material Properties

Composition:	**Al 99.5% Min.**
Particle Size:	**-45 to +5 µm**
Characteristics:	**Irregular shaped particles for maximum velocity.**

Typical Coating Properties

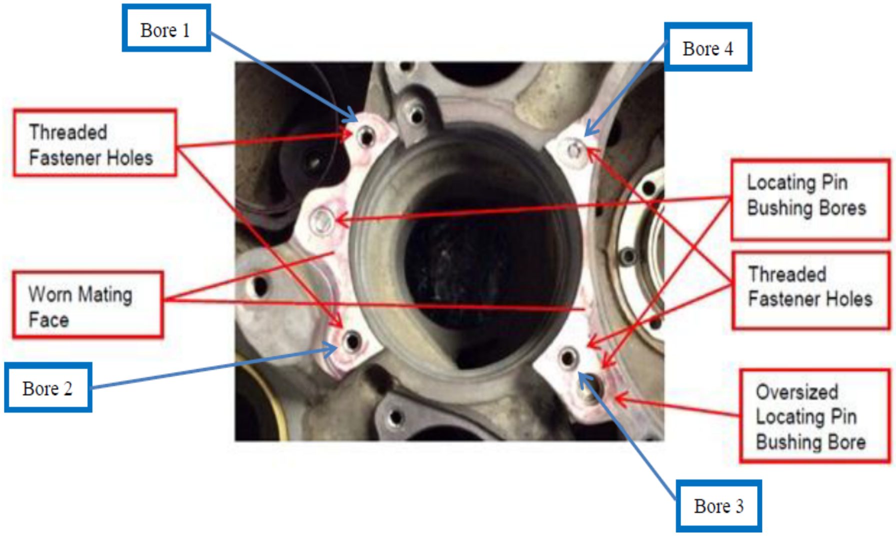
	Series P
Bond Strength:	**> 3200 psi**
Deposition Efficiency:	**Up to 38%**
Deposition Rate:	**Up to 6 g/min**
Hardness (Brinell):	**34 – 37**
Density:	**> 99%**

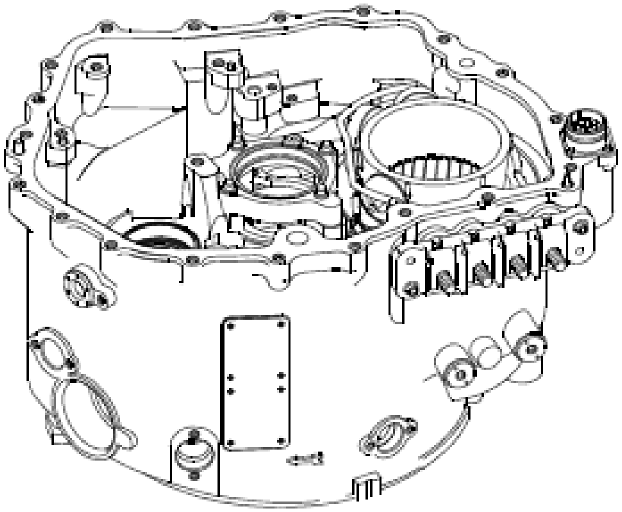
AM at Delta Tech Ops – Repair Programs

Cold Spray Repairs

At DAL, most commonly used on IDG housings

- Single piece machined magnesium alloy casting
- Several areas can be cold sprayed on this part

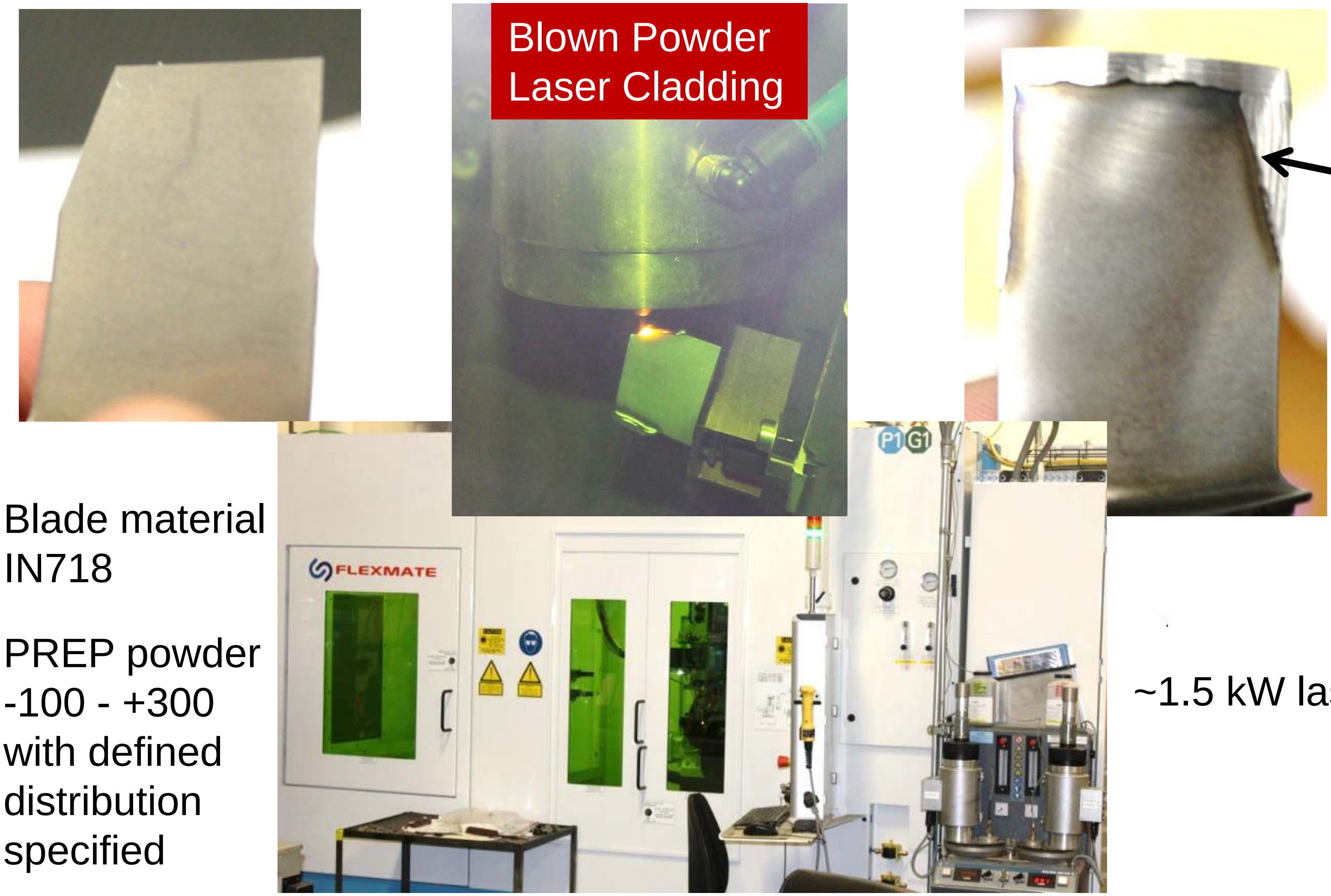




Successful repairs developed and in use with OEM help

AM at Delta Tech Ops – Repair Programs

Compressor Blades Edge Restoration



Blown Powder Laser Cladding

Deposited metal

Blade material IN718

PREP powder -100 - +300 with defined distribution specified

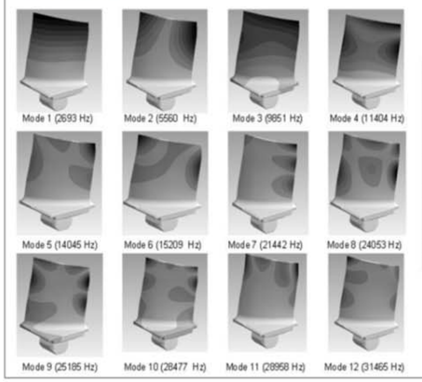
~1.5 kW laser

AM at Delta Tech Ops – Repair Programs

Compressor Blades Edge Restoration – Substantiation for Certification

CFD and FEA Stress Analysis

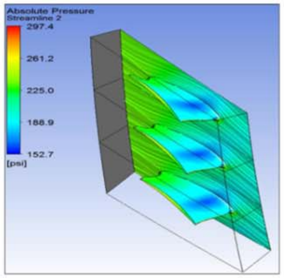
- Determined Aero and Mechanical loads
- Determined Mode Shapes and Frequency Response



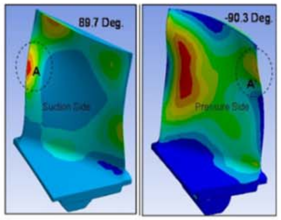
Stage 8 Mode	Prestressed Fixture Frequency (Hz)
1	2693.3
2	5559.6
3	9850.8
4	11404
5	14045
6	15209
7	21442
8	24053
9	25185
10	28477
11	28958
12	31465
13	35725

Predicted Fixture Testing Modes

FEA Prediction of Mode Shapes



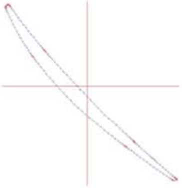
CFD Prediction of Flow and Loads

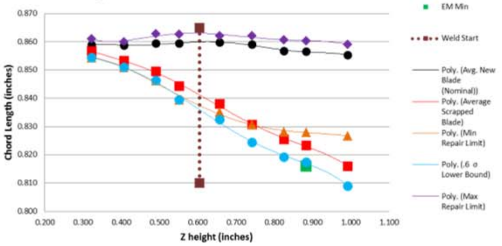


FEA from 3D Model for Stress Analysis

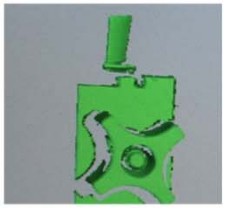
Reverse Engineering

- Laser Scan for Full 3D Model
- Core-DS Optical CMM for Accurate Airfoil Profiles and Dimensional Data Gathering





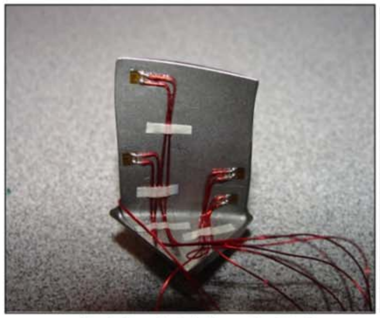
9th Stage Chord Length Trend Analysis and Repair Limits



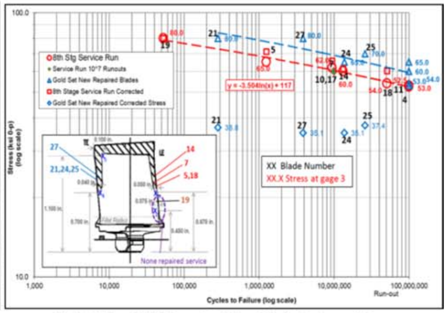
Laser Scan Data Acquisition

Fatigue Testing and Verification

- Determine Mechanical Properties of New Blades
- Test Repaired Parts
- Used Data to Verify FEA Stress Model



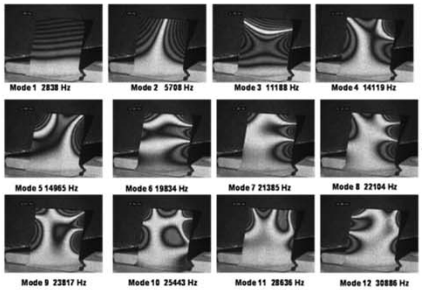
Strain Gage Installation on Test Blade



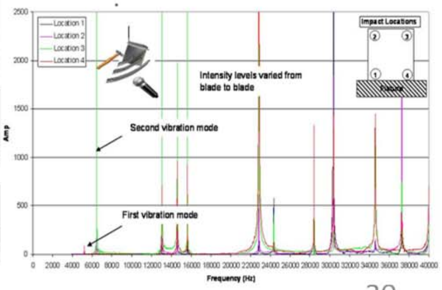
Triple Edge Weld Repaired New Blade Fatigue Data

Harmonic and Modal Testing

- Measured Frequency Change Between Pre and Post Repair Blades
- Used data to Validate FEA Vibration Models



Laser Holography Test Data



Free Vibration Test Data

AM at Delta Tech Ops – Repair Programs

Compressor Blades Edge Restoration

The repair is still in approval process for production by engineering

One of the Reasons:

Inconsistent deposited material quality; excellent fusion with parent material, excellent microstructure and minimal HAZ
but unpredictable porosity shows up in batches of blades

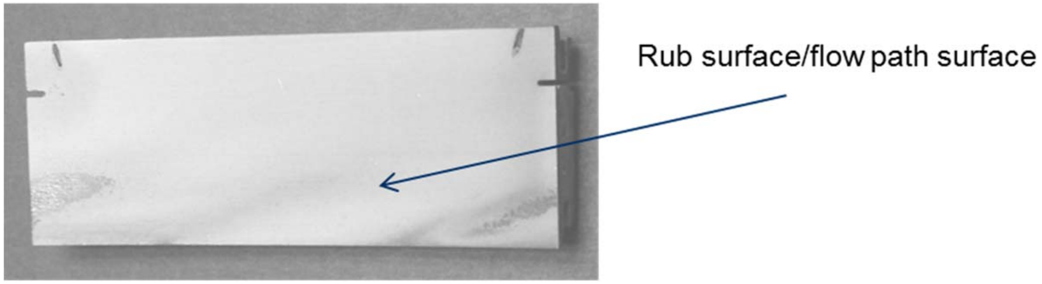
Likely Causes that we are working through to control:

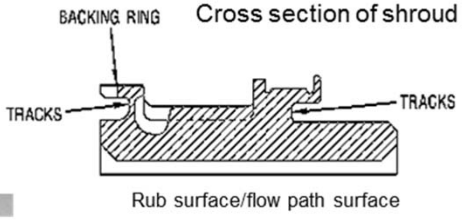
- Powder quality
- Environment in the chamber and at machine location
- Old nozzle design (to be replaced by new Fraunhofer ILT designed nozzle)

AM at Delta Tech Ops – Repair Programs

Pilot Repair Program – HPT Shrouds

Since 2014 Delta
has been working with
a start up AM company
to use their technology,
Scanning Laser Epitaxy,
to rebuild worn rub faces
of HPT Shrouds made of
Single crystal Ni-superalloy



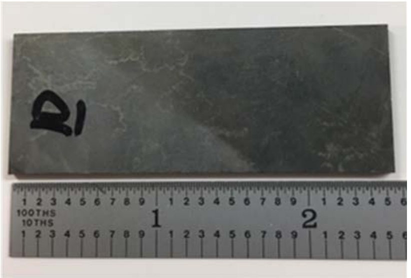


For the HP turbine shrouds, which typically sees oxidative distress on the rub surface (flow path surface) the repair would consist of additively depositing material similar to the parent metal using SLE^{TM} machines. Following this the shrouds will have to be machined to finish geometry and coated as required thereafter.

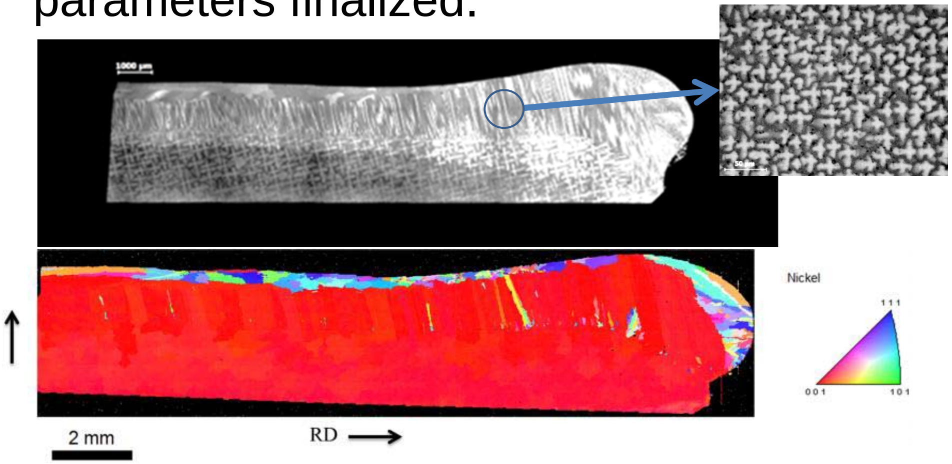
AM at Delta Tech Ops – Repair Programs

Pilot Repair Program – HPT Shrouds

Phase I: Bare Single Crystal Ni-Superalloy narrow coupons with single crystal deposit



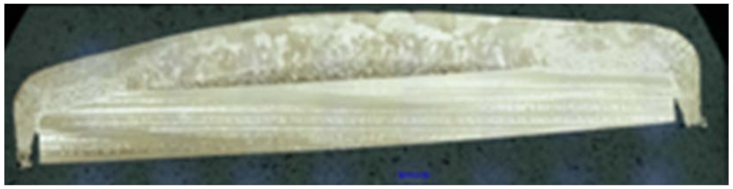
Cross section of typical coupon shown below shows that crack free, delamination free, fully dense, fully fused, single crystal deposit was obtained and process parameters finalized.



Phase II and III transferred the process parameters to wider and longer coupons, example shown below, that were surrogates for the stage I and II shrouds.

AM at Delta Tech Ops – Repair Programs

Pilot Repair Program – HPT Shrouds



Cross section of shroud with deposit showed crack free, delamination free, fully dense, single crystal deposit was obtained but shroud warpage and fusion issues were observed

Equipment & Process stability is still being worked out

AM at Delta Tech Ops – Repair Programs

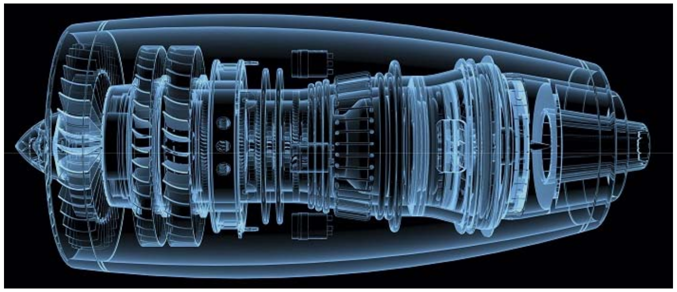
Conclusions from DTO's experience with the example AM repair cases

- The risk of using AM in repairs or in new parts is not that it will introduce poor quality parts into aircraft but the business risk of failing to reach ROI goals and timelines

- To accomplish goals and timelines very high organizational investment in people, technical and technological support is needed

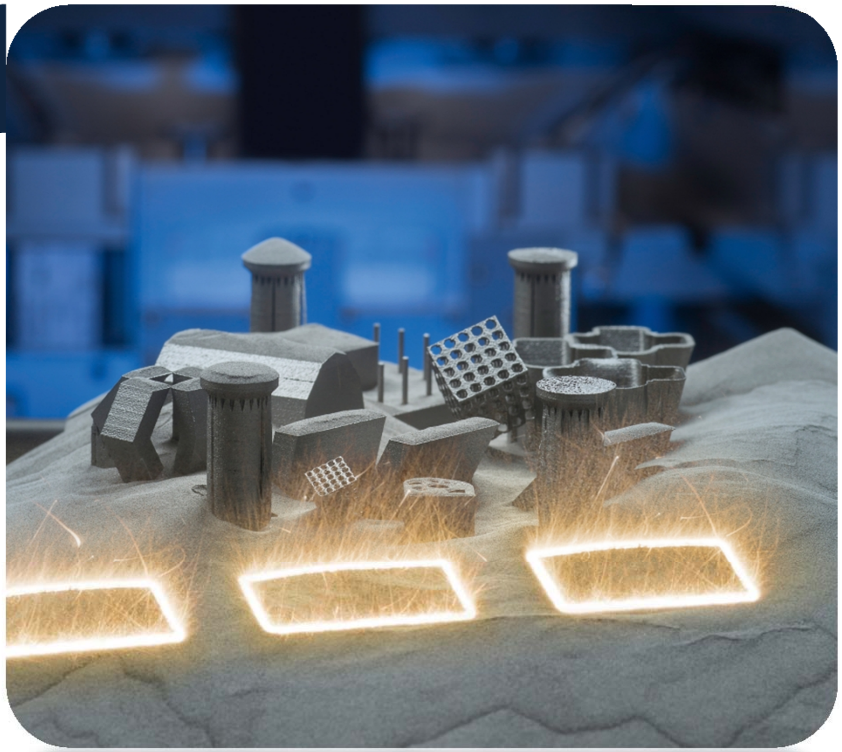
- The above automatically raise the bar for entry into AM for all but the most committed organizations which also have deep pockets and plenty of patience

DELTA TechOps



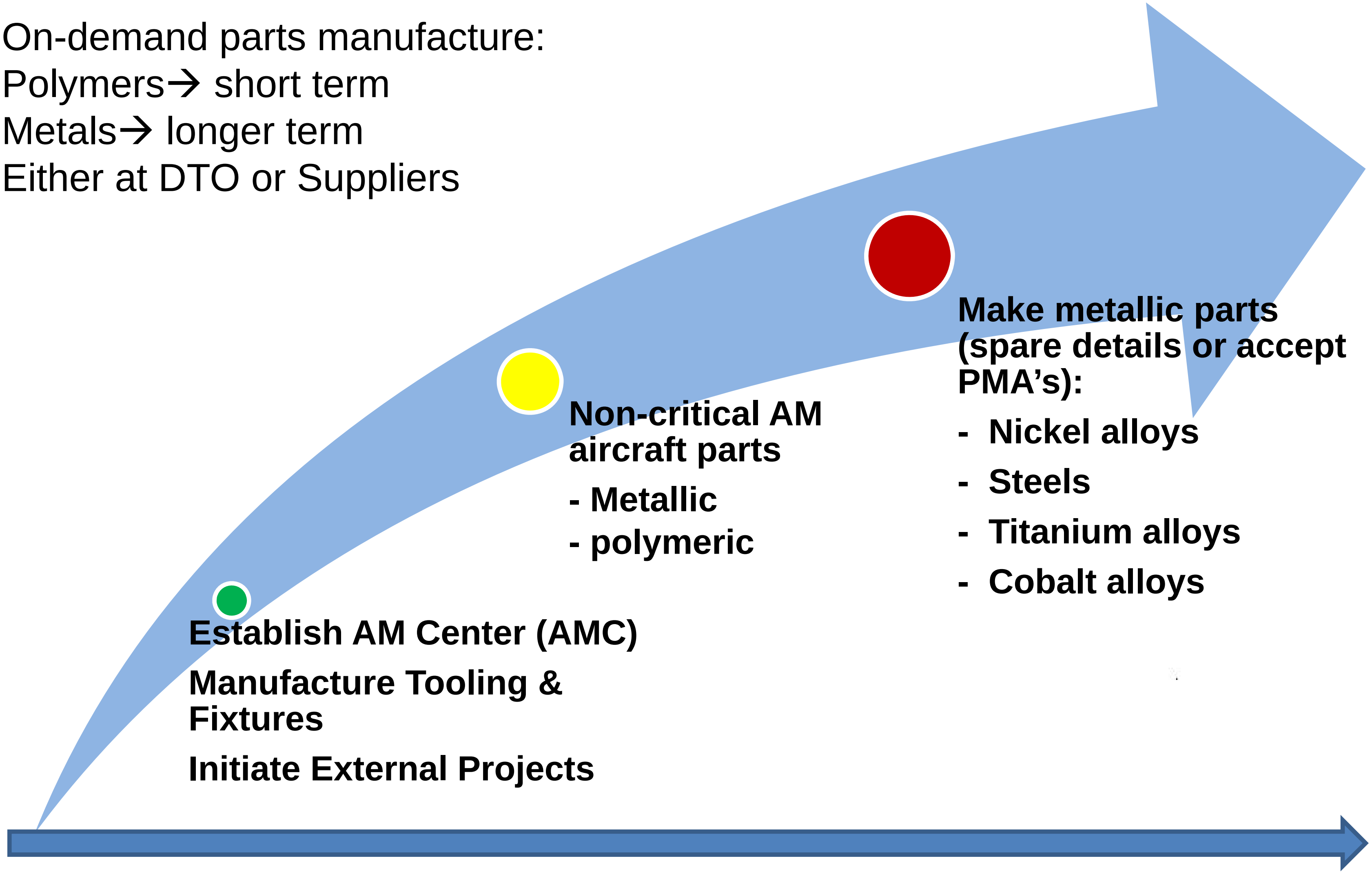
Part III

Future Plan for AM at Delta TechOps



AM at Delta Tech Ops - Plan

On-demand parts manufacture:
Polymers→ short term
Metals→ longer term
Either at DTO or Suppliers



Establish AM Center (AMC)

Manufacture Tooling & Fixtures

Initiate External Projects

Non-critical AM aircraft parts

- Metallic
- polymeric

Make metallic parts (spare details or accept PMA's):

- **Nickel alloys**
- **Steels**
- **Titanium alloys**
- **Cobalt alloys**

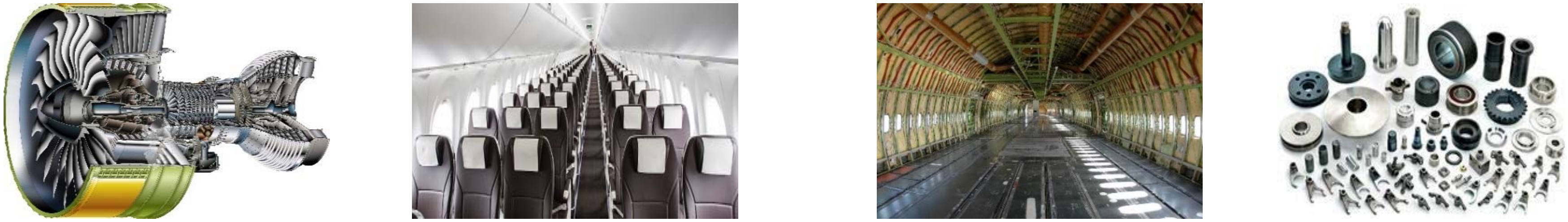
2016/2017 **2018/2019** **2020/2021**

AM Center Users/Beneficiaries

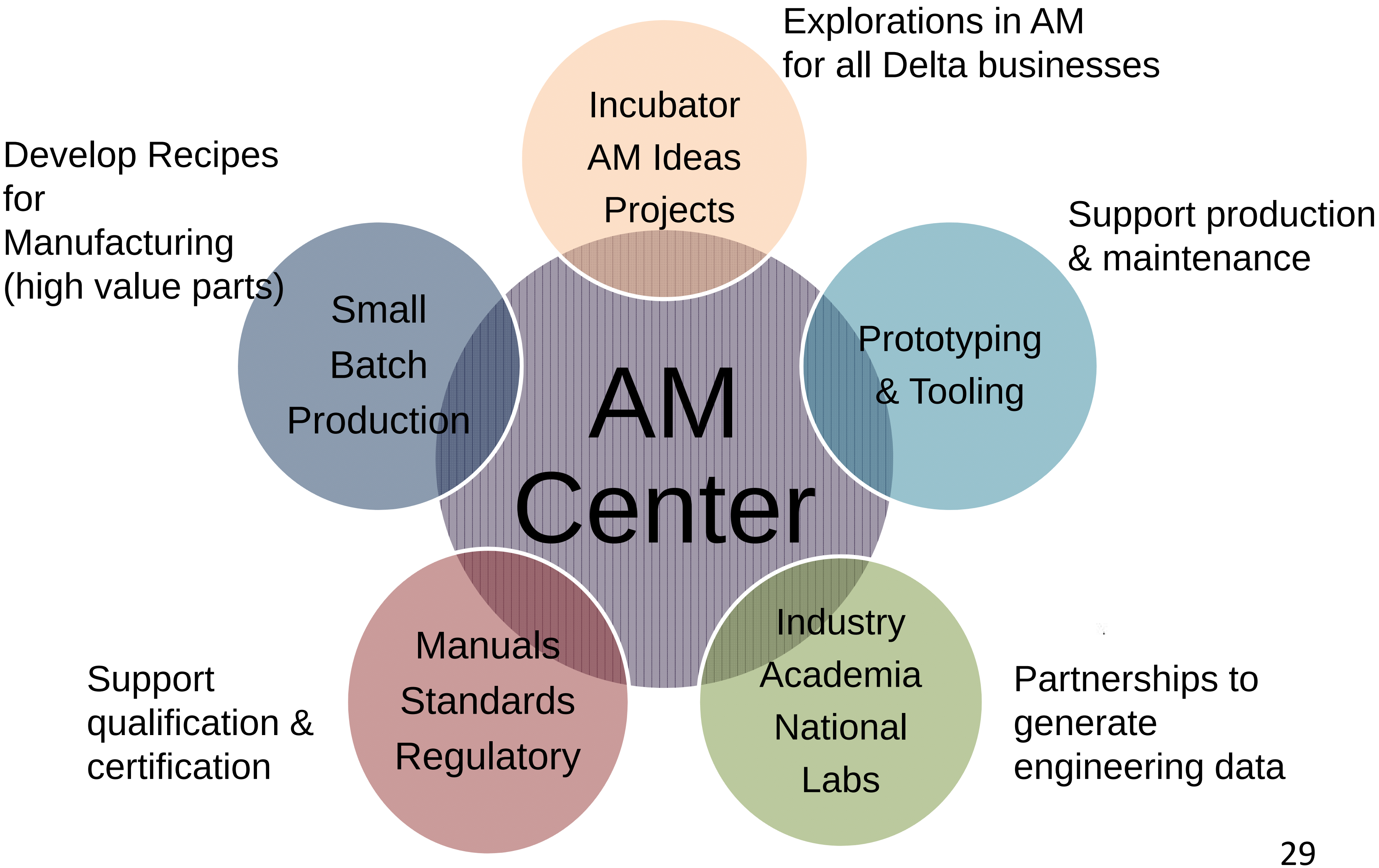
AM Center will benefit all DTO business units

Delta Tech Ops Maintenance Units

- Engines
- Cabins/DFS
- Airframes/Bases
- Components



AMC Roadmap - AM Center Goals



Explorations in AM
for all Delta businesses

Incubator
AM Ideas
Projects

Develop Recipes
for
Manufacturing
(high value parts)

Small
Batch
Production

AM
Center

Support production
& maintenance

Prototyping
& Tooling

Support
qualification &
certification

Manuals
Standards
Regulatory

Industry
Academia
National
Labs

Partnerships to
generate
engineering data

AMC Processes and Capabilities

AM Pre-processing

Reverse Engineering & Design

- Scanners & CMM √
- Microscopes & SEM √
- Modelling and design software √
- Analysis software √

AM Processing

Laser Powder Bed & Directed Energy Methods

- AM Equipment
- Feedstock analysis
- AM build software
- Servers and storage
- Powder recycling & sieving

AM Post processing

HT Treat, Finishing and QA

- Hot isostatic pressing
- Inspection (CT)
- SQC (MTS)
- Part machining √
- Blasting & peening √

√ indicates existing capability at DTO outside of AM Center

AMC - Polymeric AM Equipment

Laser Powder Bed Fusion technology based machine

On order

Stereo lithography – vat photo-polymerization technology based machine

√

Fused Deposition Modeling based technology based machines

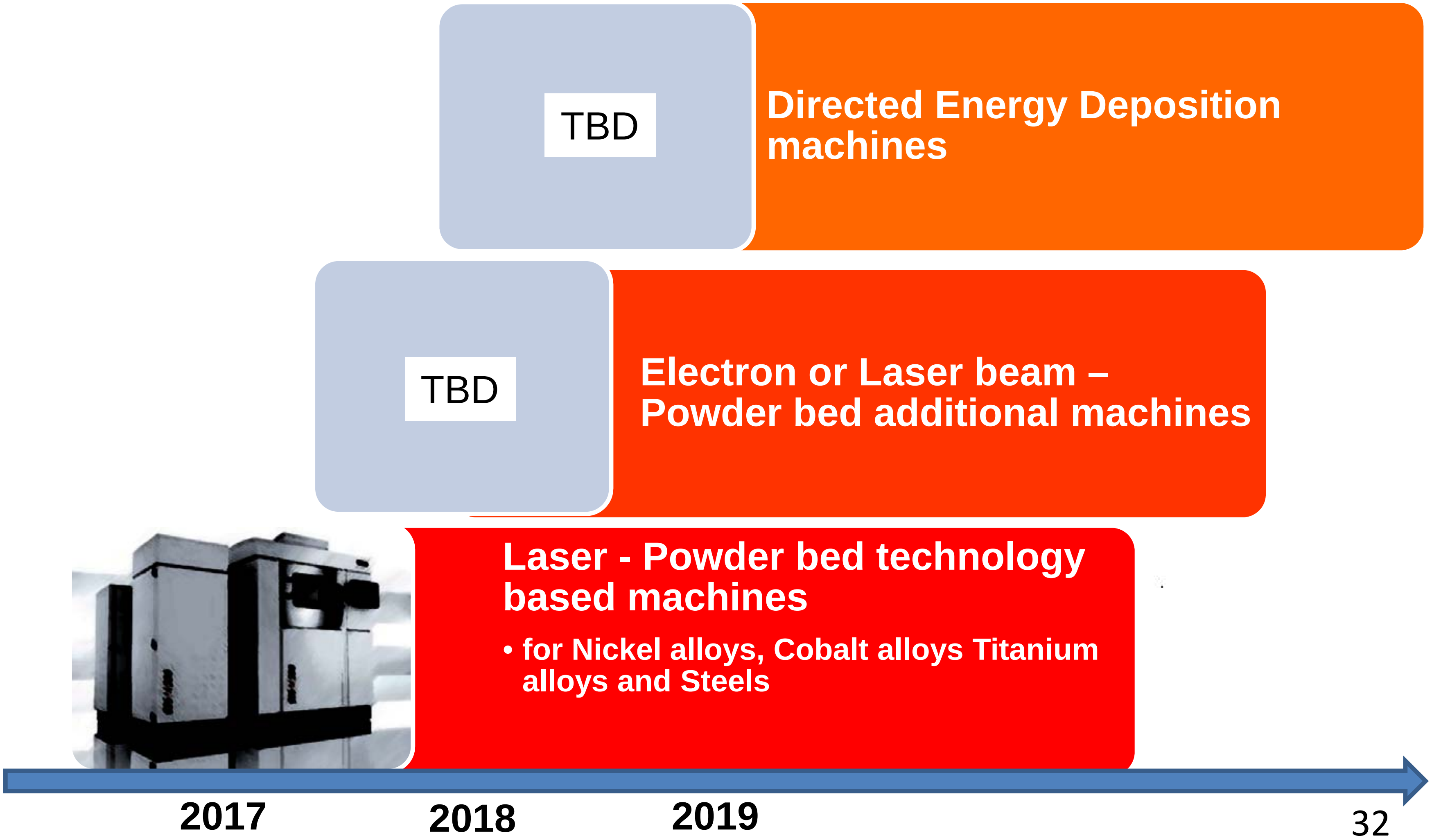
√

4Q 2016

4Q 2017

DELTA

Metallic AM Equipment



TBD

Directed Energy Deposition machines

TBD

Electron or Laser beam – Powder bed additional machines

Laser - Powder bed technology based machines

- **for Nickel alloys, Cobalt alloys Titanium alloys and Steels**

2017

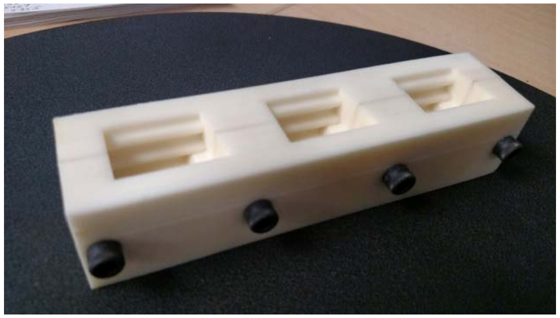
2018

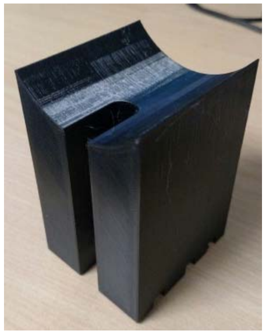
2019

Example of Typical Polymeric AM Parts

Time horizon: Now

Assorted Shop Tooling and Masking for Continuous Improvement and Productivity Gains





Example of Typical Metallic Parts for AM Production

Time horizon: 2 years (by 2019)

Bell cranks for HPC variable-vanes

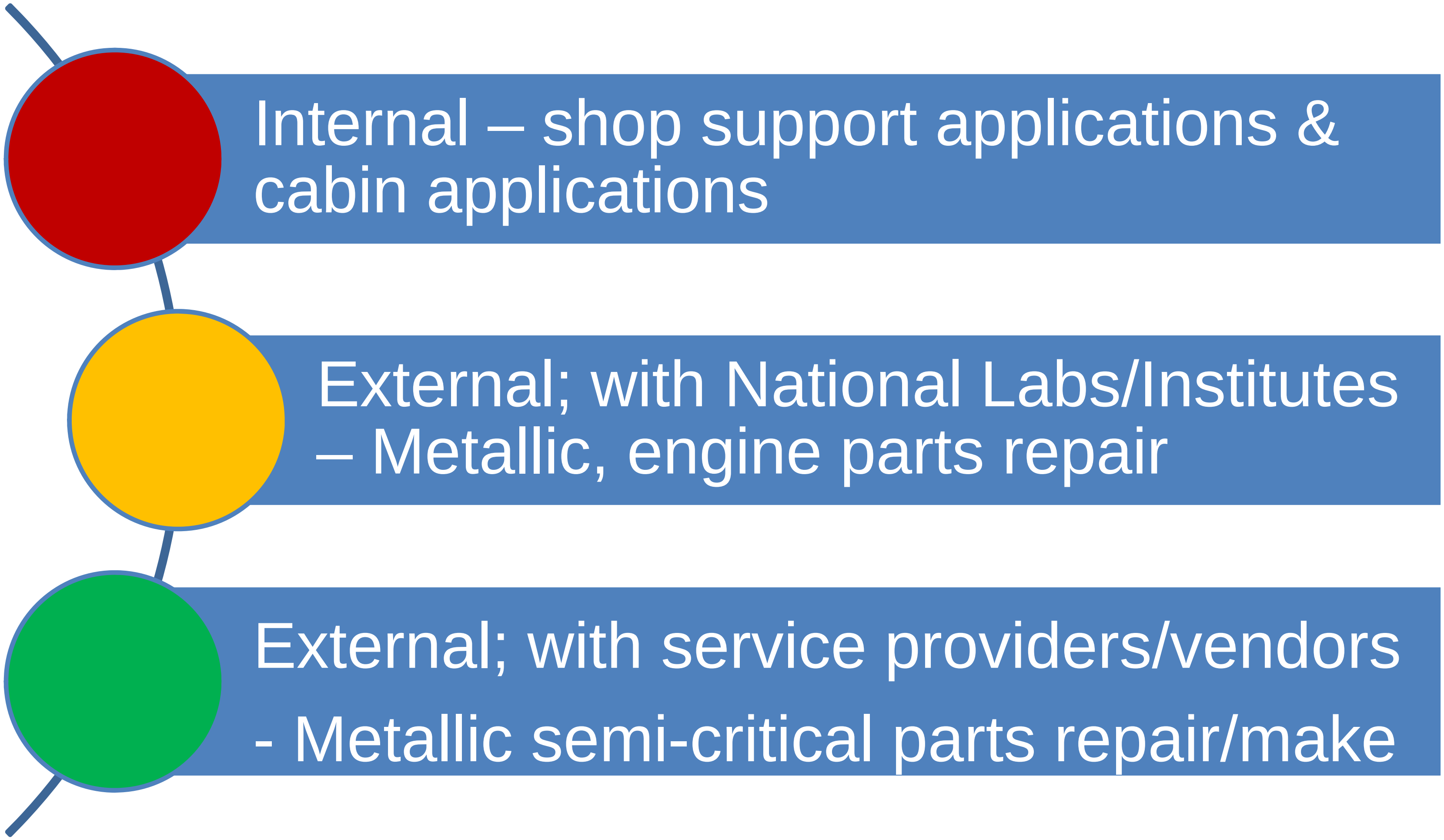
Fuel nozzles and swirlers

Assorted non-repairable hardware

HPC variable-vane shrouds

Assorted gearbox parts

AM Intellectual Property Development



- Internal – shop support applications & cabin applications
- External; with National Labs/Institutes – Metallic, engine parts repair
- External; with service providers/vendors

  - Metallic semi-critical parts repair/make

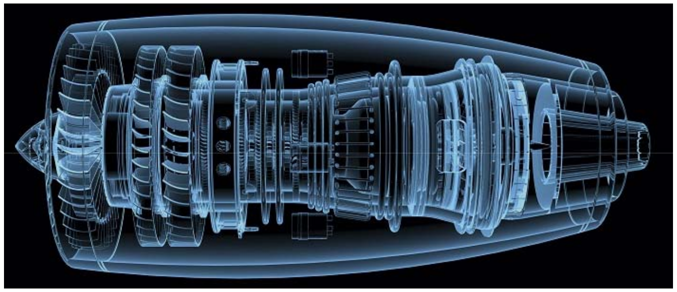
External partners will help shorten cycle time of AM projects to production

Integration of AM in DTO Operations

The Challenge:
Many new processes and controls have to be implemented for AM to be in compliance with FAA requirements

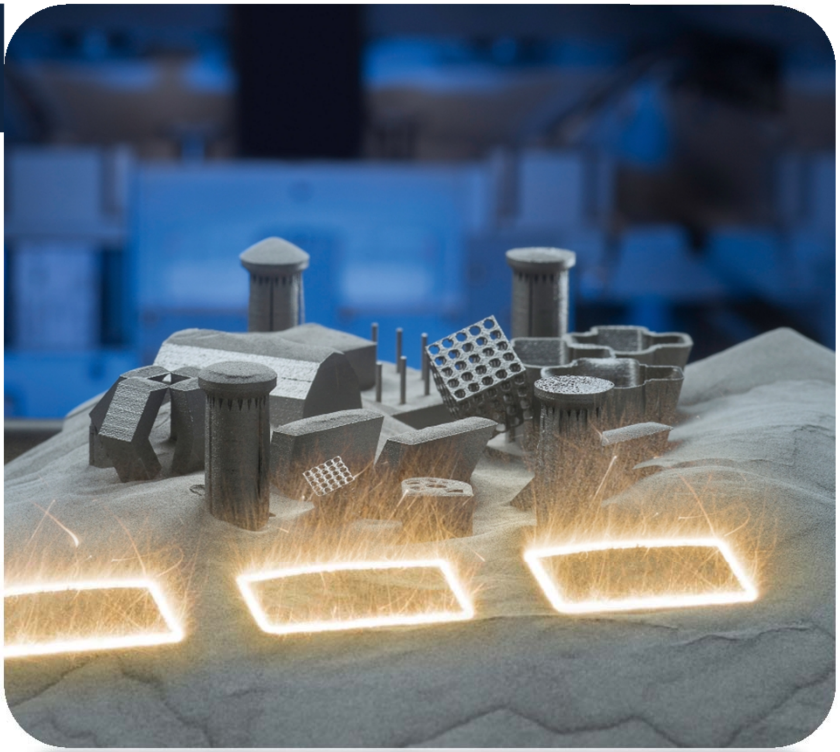
Manuals/SOP's
Standards
Supply Chain
Training
Certification
Approvals

DELTA
TechOps



Part IV

Regulatory Authorization to use AM in making parts at Delta TechOps



AMC - Regulatory Authorization

This section describes the regulatory authorization under which Delta would repair or manufacture parts and an overview of the requirements to be followed to show engineering and manufacturing compliance to the respective CFR's

- ❖Existing, applicable Delta manuals
- ❖Qualification Methodologies to Repair & Manufacture Parts (OOPP & PMA)
- ❖Requirements for engineering and manufacturing
  - ✓FAA Orders, Notices, Policies, Memos, Job Aids, Advisory Circulars

AM Parts – Regulatory Authorization for DAL Use

Owner/Operator Produced Parts (OOPP)

The procedures for OOPP are based on the requirements of 14 CFR § 21.9(a)(5) and (6), and Part 43.13, as well as, the guidance material contained in Advisory Circular (AC) 20-62E and (AC) 43-18.

Part Categorizations that will be considered in pursuing parts for AM:

Category 1. Failure of the fabricated part could prevent continued safe flight and landing; resulting consequences could reduce safety margins, degrade performance, or cause loss of capability to conduct certain flight operations.
Additive Manufacturing will not be used for this category for the foreseeable future at Delta.

Category 2. Failure of the fabricated part would not prevent continued safe flight and landing; however, resulting consequences would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions or subsequent failures.

Category 3. Failure would have no effect on the continued safe flight and landing of the aircraft.
Category 2 & 3 parts would be considered for AM applications.

AMC Parts– Regulatory Authorization for MRO Use

Parts Manufacturer Approval (PMA)

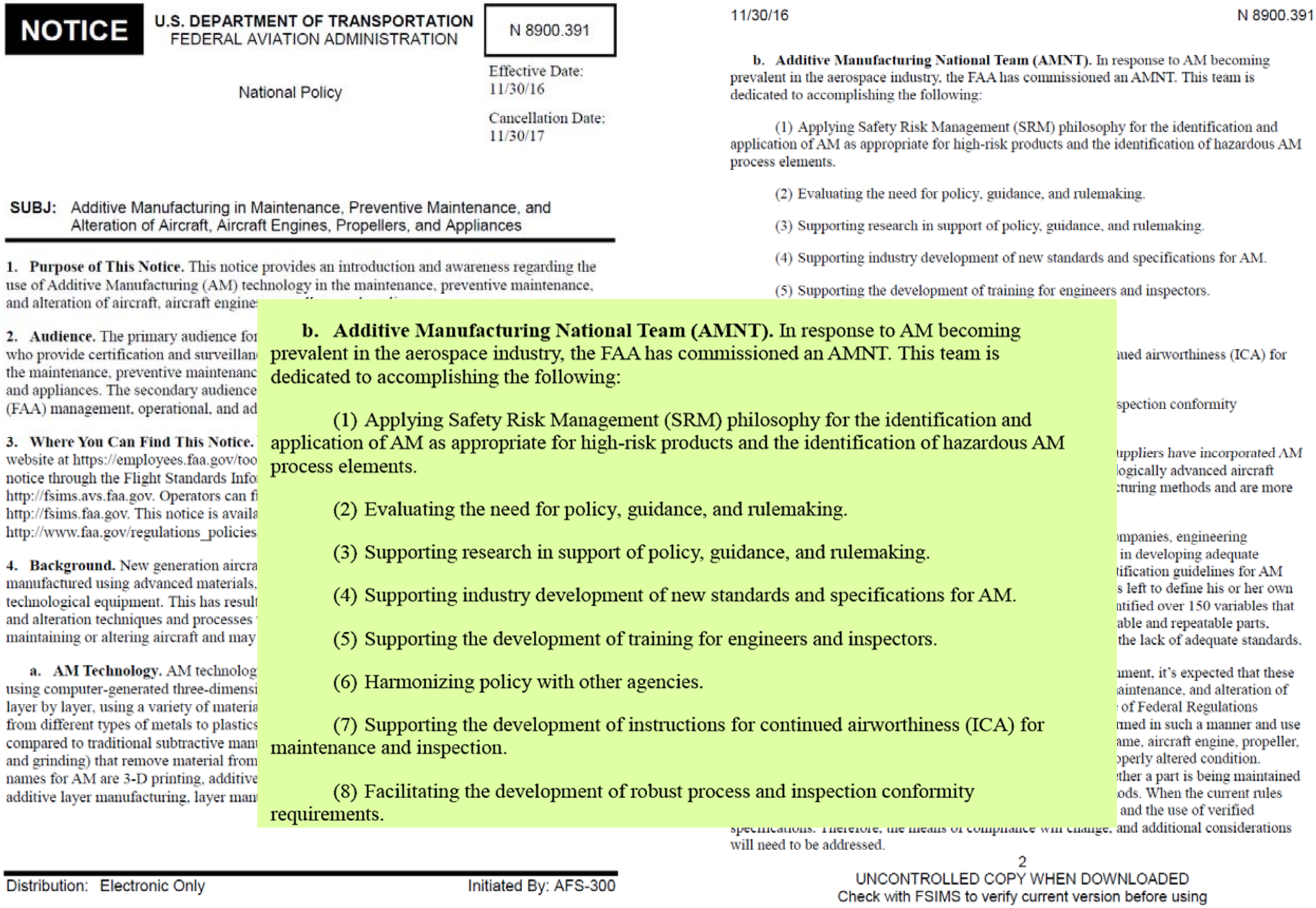
The Parts Manufacturer Approval (PMA) process based on 14 CFR, Chapter 1, Part 21, Subpart K, and 21.305 would also be considered applicable for manufacture of AM parts at Delta.

Quality System to make OOPP and PMA

The PMA quality system which provides the general framework by which AM manufactured OOP or PMA parts can be accepted for use by DAL or MRO is based on the requirements of 14 CFR 21.138 relating to the maintenance of a quality system which ensures that all completed parts conform to FAA approved design data and are in a condition for safe operation on FAA Type Certificated Products per 14 CFR 21.137.

However extensive revisions/additions will be required to account for the quality control of AM parameters and processes.

AMC Parts – FAA Support & Oversight of AM OOP & PMA Quality System



NOTICE

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

National Policy

N 8900.391

Effective Date:
11/30/16

Cancellation Date:
11/30/17

SUBJ: Additive Manufacturing in Maintenance, Preventive Maintenance, and Alteration of Aircraft, Aircraft Engines, Propellers, and Appliances

1. Purpose of This Notice. This notice provides an introduction and awareness regarding the
use of Additive Manufacturing (AM) technology in the maintenance, preventive maintenance,
and alteration of aircraft, aircraft engine

2. Audience. The primary audience for
who provide certification and surveillan
the maintenance, preventive maintenanc
and appliances. The secondary audience
(FAA) management, operational, and ad

3. Where You Can Find This Notice.
website at https://employees.faa.gov/too
notice through the Flight Standards Info
http://fsims.avs.faa.gov. Operators can fi
http://fsims.faa.gov. This notice is availa
http://www.faa.gov/regulations_policies

4. Background. New generation aircra
manufactured using advanced materials,
technological equipment. This has result
and alteration techniques and processes
maintaining or altering aircraft and may

a. AM Technology. AM technolog
using computer-generated three-dimensi
layer by layer, using a variety of materia
from different types of metals to plastics
compared to traditional subtractive man
and grinding) that remove material from
names for AM are 3-D printing, additive
additive layer manufacturing, layer man

Distribution: Electronic Only

Initiated By: AFS-300

11/30/16

N 8900.391

b. Additive Manufacturing National Team (AMNT). In response to AM becoming prevalent in the aerospace industry, the FAA has commissioned an AMNT. This team is dedicated to accomplishing the following:

(1) Applying Safety Risk Management (SRM) philosophy for the identification and application of AM as appropriate for high-risk products and the identification of hazardous AM process elements.

(2) Evaluating the need for policy, guidance, and rulemaking.

(3) Supporting research in support of policy, guidance, and rulemaking.

(4) Supporting industry development of new standards and specifications for AM.

(5) Supporting the development of training for engineers and inspectors.

ued airworthiness (ICA) for

spection conformity

uppliers have incorporated AM
logically advanced aircraft
cturing methods and are more

mpanies, engineering
in developing adequate
tification guidelines for AM
s left to define his or her own
ntified over 150 variables that
able and repeatable parts.
the lack of adequate standards.

ment, it's expected that these
aintenance, and alteration of
of Federal Regulations
rmed in such a manner and use
ame, aircraft engine, propeller,
perly altered condition.
ther a part is being maintained
ods. When the current rules
and the use of verified
specifications. Therefore, the means of compliance will change, and additional considerations
will need to be addressed.

2
UNCONTROLLED COPY WHEN DOWNLOADED
Check with FSIMS to verify current version before using

b. Additive Manufacturing National Team (AMNT). In response to AM becoming prevalent in the aerospace industry, the FAA has commissioned an AMNT. This team is dedicated to accomplishing the following:

(1) Applying Safety Risk Management (SRM) philosophy for the identification and application of AM as appropriate for high-risk products and the identification of hazardous AM process elements.

(2) Evaluating the need for policy, guidance, and rulemaking.

(3) Supporting research in support of policy, guidance, and rulemaking.

(4) Supporting industry development of new standards and specifications for AM.

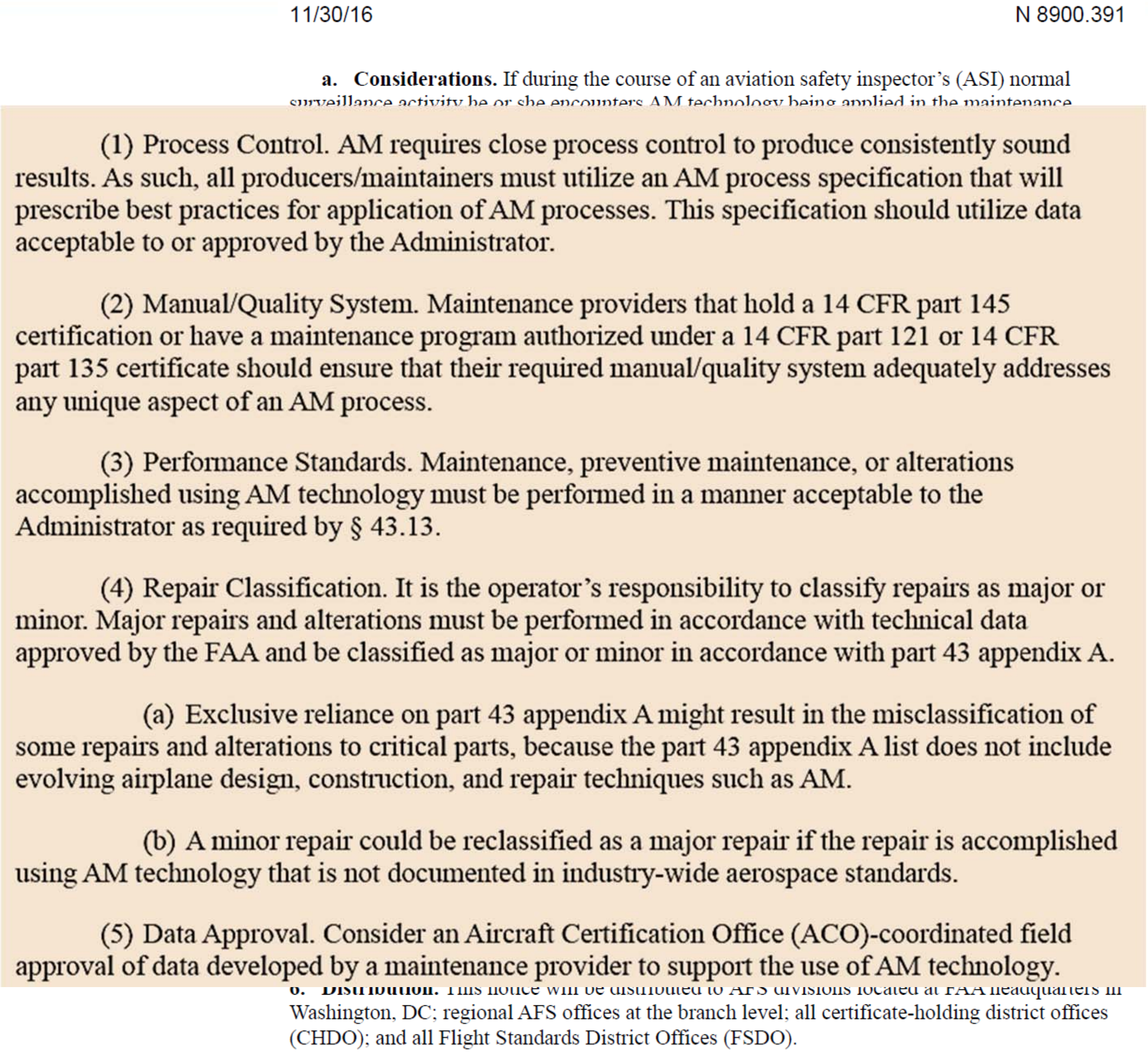
(5) Supporting the development of training for engineers and inspectors.

(6) Harmonizing policy with other agencies.

(7) Supporting the development of instructions for continued airworthiness (ICA) for maintenance and inspection.

(8) Facilitating the development of robust process and inspection conformity requirements.

AMC Parts – FAA Support & Oversight of AM OOP & PMA Quality System



11/30/16 N 8900.391

a. Considerations. If during the course of an aviation safety inspector's (ASI) normal surveillance activity he or she encounters AM technology being applied in the maintenance

(1) Process Control. AM requires close process control to produce consistently sound results. As such, all producers/maintainers must utilize an AM process specification that will prescribe best practices for application of AM processes. This specification should utilize data acceptable to or approved by the Administrator.

(2) Manual/Quality System. Maintenance providers that hold a 14 CFR part 145 certification or have a maintenance program authorized under a 14 CFR part 121 or 14 CFR part 135 certificate should ensure that their required manual/quality system adequately addresses any unique aspect of an AM process.

(3) Performance Standards. Maintenance, preventive maintenance, or alterations accomplished using AM technology must be performed in a manner acceptable to the Administrator as required by § 43.13.

(4) Repair Classification. It is the operator's responsibility to classify repairs as major or minor. Major repairs and alterations must be performed in accordance with technical data approved by the FAA and be classified as major or minor in accordance with part 43 appendix A.

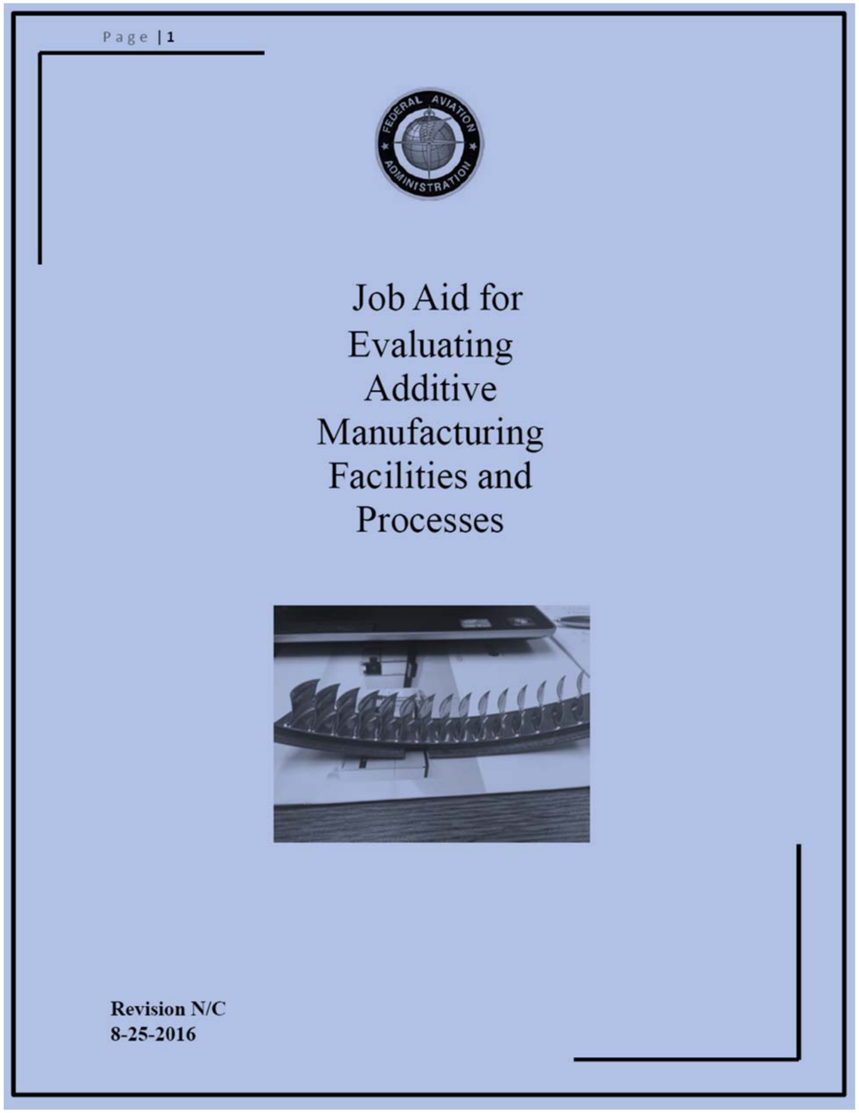
(a) Exclusive reliance on part 43 appendix A might result in the misclassification of some repairs and alterations to critical parts, because the part 43 appendix A list does not include evolving airplane design, construction, and repair techniques such as AM.

(b) A minor repair could be reclassified as a major repair if the repair is accomplished using AM technology that is not documented in industry-wide aerospace standards.

(5) Data Approval. Consider an Aircraft Certification Office (ACO)-coordinated field approval of data developed by a maintenance provider to support the use of AM technology.

6. Distribution. This notice will be distributed to AFS divisions located at FAA headquarters in Washington, DC; regional AFS offices at the branch level; all certificate-holding district offices (CHDO); and all Flight Standards District Offices (FSDO).

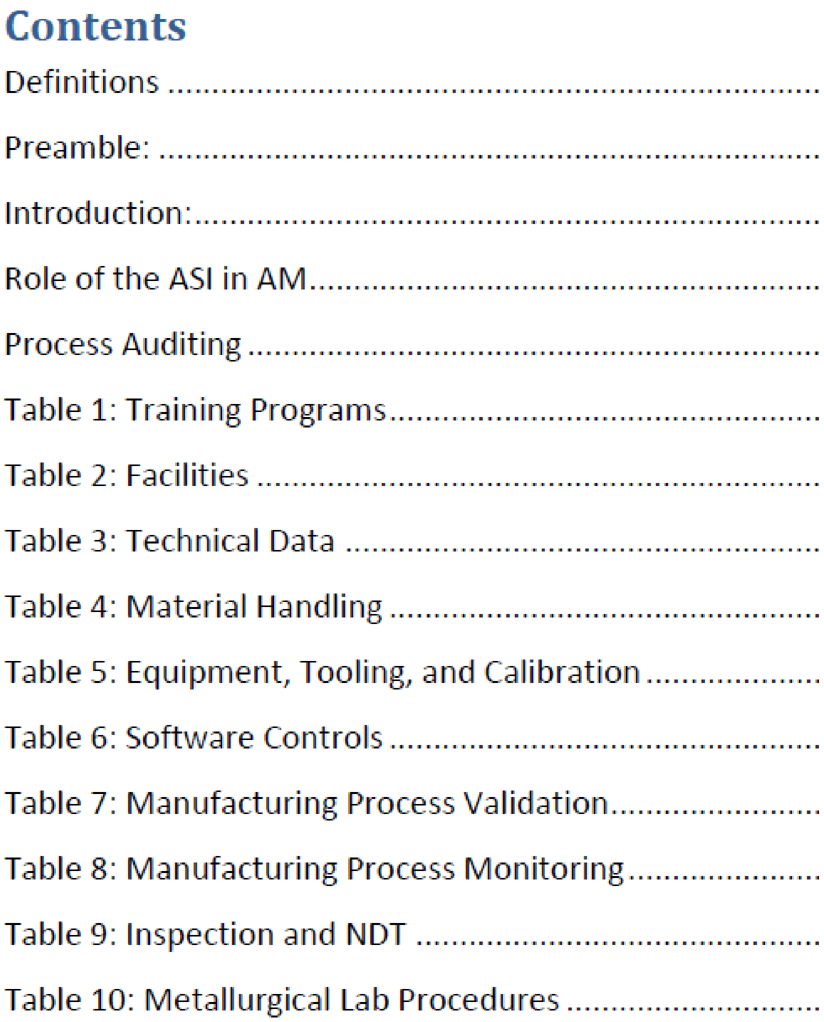
AMC Parts – FAA Guidance for Development of AM OOP & PMA Quality System



Page | 1

Job Aid for
Evaluating
Additive
Manufacturing
Facilities and
Processes

Revision N/C
8-25-2016



Contents

Definitions ....

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Process Auditing ....

Table 1: Training Programs...

Table 2: Facilities ....

Table 3: Technical Data ....

Table 4: Material Handling ....

Table 5: Equipment, Tooling, and Calibration ....

Table 6: Software Controls ....

Table 7: Manufacturing Process Validation........................

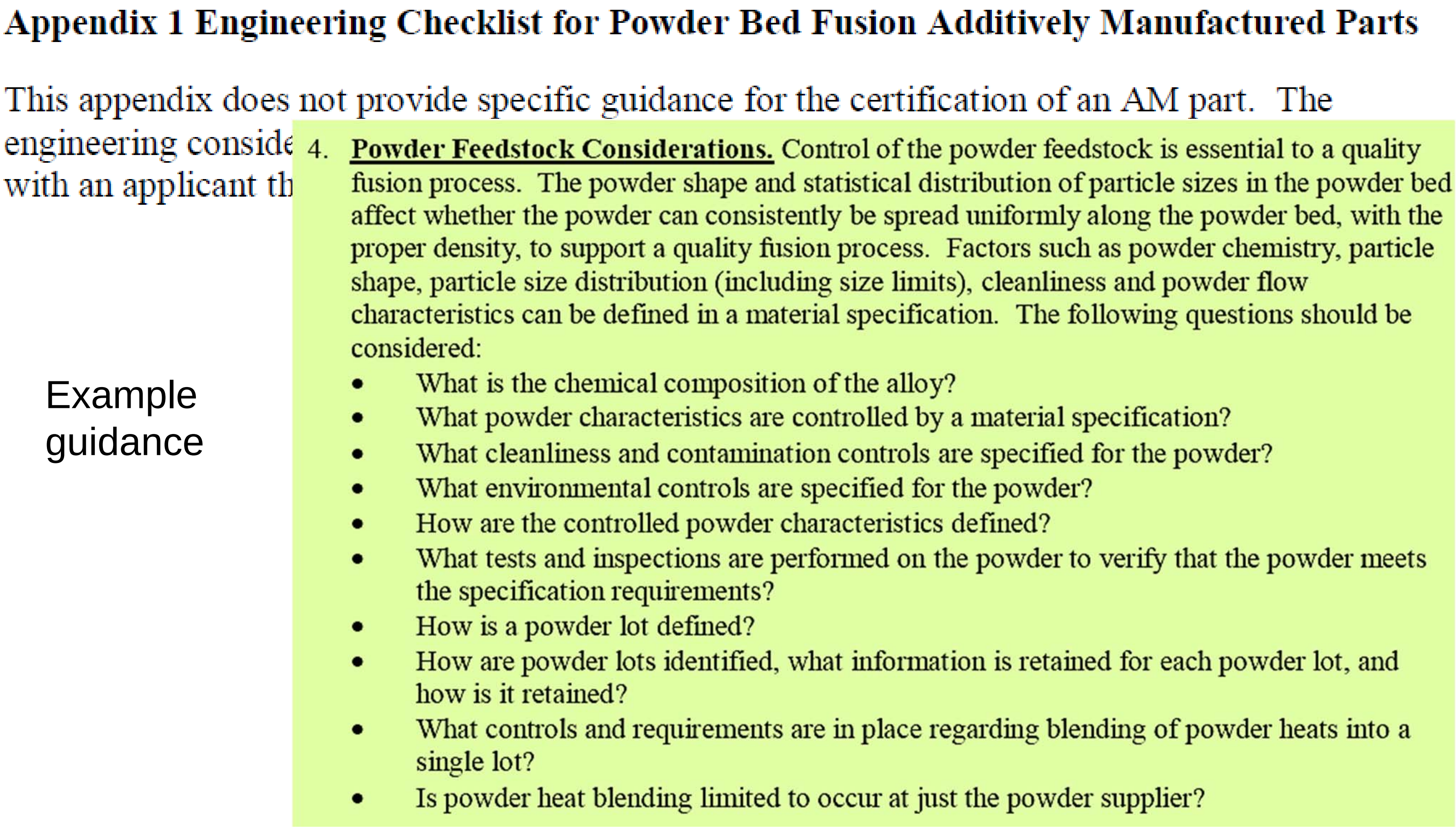
Table 8: Manufacturing Process Monitoring......................

Table 9: Inspection and NDT ....

Table 10: Metallurgical Lab Procedures ....

AMC Parts – FAA Guidance for Development of AM OOP & PMA Engineering Data

DELTA



Appendix 1 Engineering Checklist for Powder Bed Fusion Additively Manufactured Parts

This appendix does not provide specific guidance for the certification of an AM part. The engineering conside

with an applicant th

4. **Powder Feedstock Considerations.** Control of the powder feedstock is essential to a quality fusion process. The powder shape and statistical distribution of particle sizes in the powder bed affect whether the powder can consistently be spread uniformly along the powder bed, with the proper density, to support a quality fusion process. Factors such as powder chemistry, particle shape, particle size distribution (including size limits), cleanliness and powder flow characteristics can be defined in a material specification. The following questions should be considered:

- What is the chemical composition of the alloy?
- What powder characteristics are controlled by a material specification?
- What cleanliness and contamination controls are specified for the powder?
- What environmental controls are specified for the powder?
- How are the controlled powder characteristics defined?
- What tests and inspections are performed on the powder to verify that the powder meets the specification requirements?
- How is a powder lot defined?
- How are powder lots identified, what information is retained for each powder lot, and how is it retained?
- What controls and requirements are in place regarding blending of powder heats into a single lot?
- Is powder heat blending limited to occur at just the powder supplier?

Example guidance

(AIR100-16-130-GM18)

FAA could consider converting this into an Advisory Circular

Thank You

Questions?

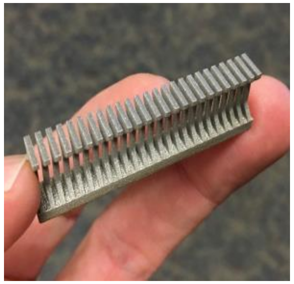
APPENDIX GG—THE IMPACT OF CRITICAL DEFECTS ON MATERIAL PERFORMANCE AND QUALIFICATION FOR METAL LASER POWDER BED FUSION

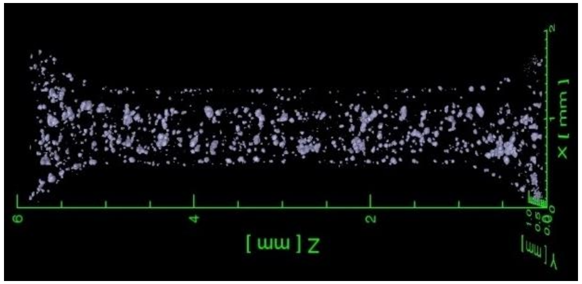
MATERIALS SCIENCE & ENGINEERING

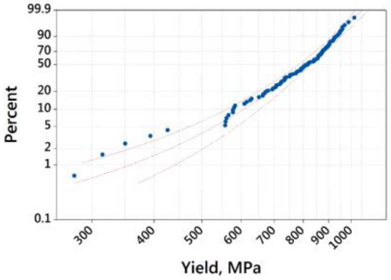
The Impact of Critical Defects on Material Performance and Qualification for Metal Laser Powder Bed Fusion

Bradley Jared

Materials Engineering & Manufacturing S&T







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U.S. DEPARTMENT OF ENERGY

NNSA
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Acknowledgements

- AM
  - Brad Boyce, Jon Madison, Jake Ostien, Jeff Rodelas, Brad Salzbrenner, Laura Swiler, Olivia Underwood, David Saiz , Kevin Webb (Georgia Tech)
  - Lisa Deibler, Allen Roach, Phil New, Joe Michaels, Kate Helean, Deidre Hirschfeld
- NDE
  - David Moore, Burke Kernan, Kyle Thompson, Ciji Nelson, Sarah Stair
  - Joe Bishop, Larry Jacobs (Georgia Tech)
  - Eric Biedermann (Vibrant)

Outline

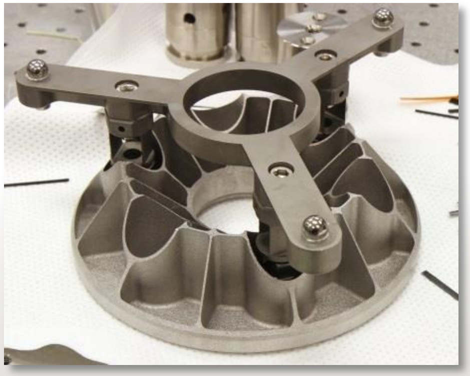
- Motivation
  - AM at Sandia
  - qualification
- Critical defects
- 17-4PH inter-build study
  - performance
  - characterization
  - correlations
- 316L intra-build study
- Additional NDE research
- Summary

Sandia National Laboratories

- A National Security Science & Engineering Laboratory
  - “Exceptional service in the national interest”
- Nuclear Weapons
- Defense Systems & Assessments
- Energy & Climate
- International, Homeland, & Nuclear Security

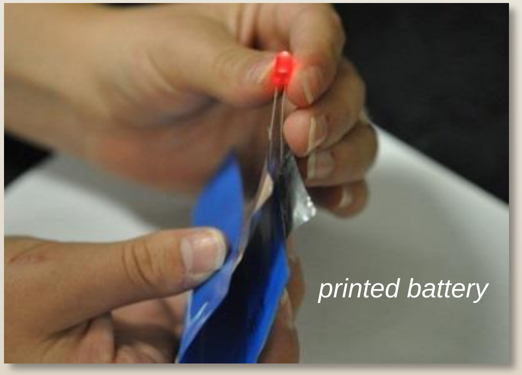
SNL’s Additive Interests

- Reduce risk, accelerate development
    - simplify assembly & processing
    - prototypes, test hardware, tooling & fixturing
- Add value
    - design & optimize for performance, not mfg
        - complex freeforms, internal structures, integration
    - engineered materials
        - gradient compositions
        - microstructure optimization & control
        - multi-material integration
            - “print everything inside the box, not just the box”



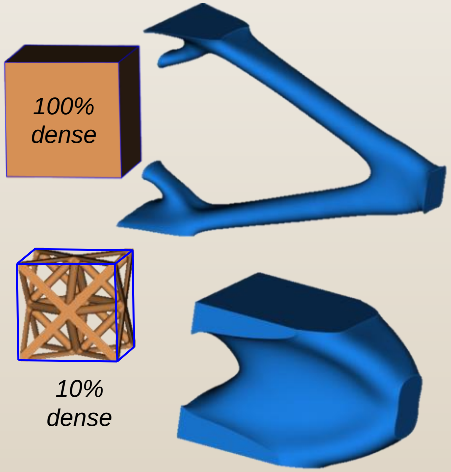
prototype AM mirror & structure

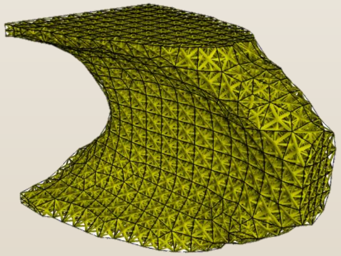
full scale additive weapon mock-up



printed battery

ceramic-thermoplastic 3D (CT3D) printing of alumina

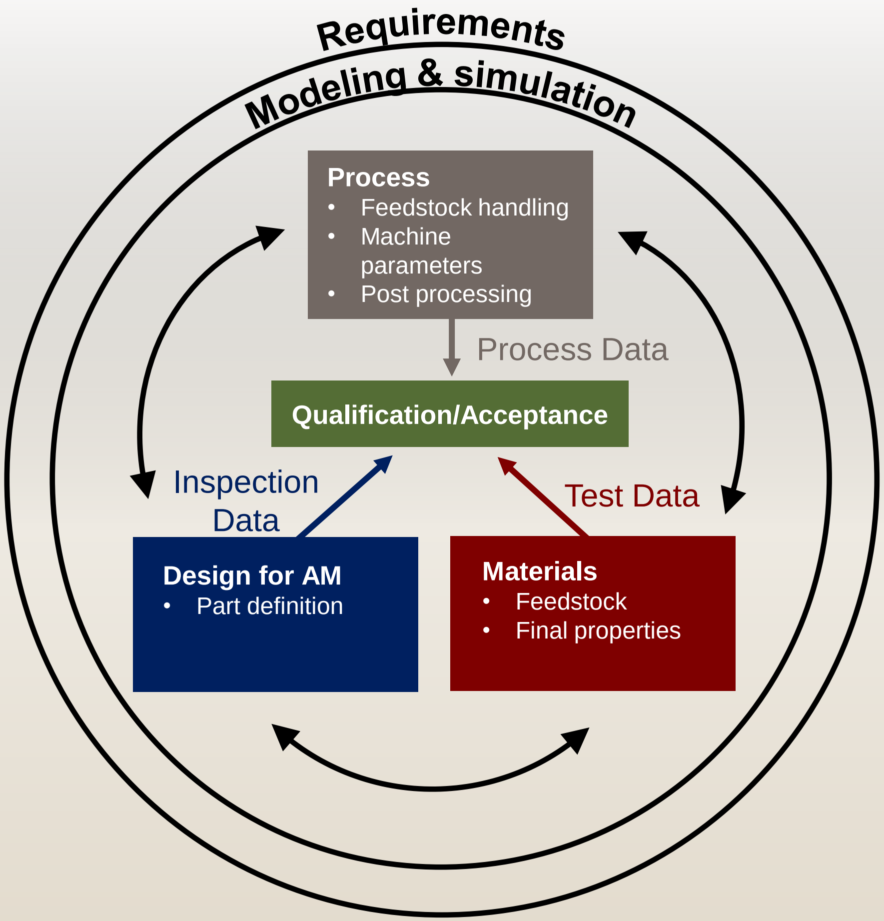




lattice implementation w/TO solutions from PLATO

AM Qualification Elements

- Development
  - same phase gate process
  - develop & evaluate “new” materials
    - establish property distributions w/probabilities & worst case
  - requirements, requirements, requirements
- Production
  - product acceptance is major challenge
    - destructive sampling
    - test artifacts (tensile, Charpy, density, composition, powder, …)
    - inspection (CT, dimensional, powder, NDE)
  - design labs & plants working together on requirements, specifications & methods



Sandia qualification / product acceptance paradigm for AM

AM Qualification Elements

DESIGN

Component requirements
mechanical envelope, environments (mechanical, thermal, electrical, environmental)

- Design for AM
- Part Definition

MATERIAL

Derived from Design requirements
mechanical, thermal, electrical, corrosion, compatibility, surface finish

- Feedstock
- Part Properties

PROCESS

Derived from Design & Material requirements

- Printing
- Post Processing

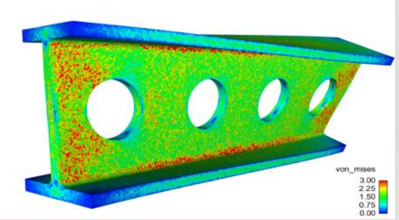
ACCEPTANCE

Quality policy to ensure that all requirements are met

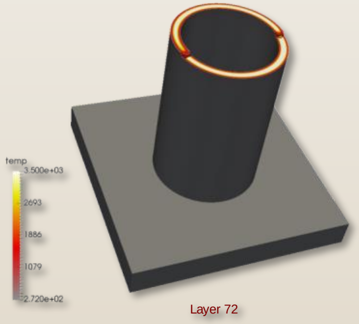
- Defects
- Process Control
- Part/Material Verification

Qualification Tomorrow

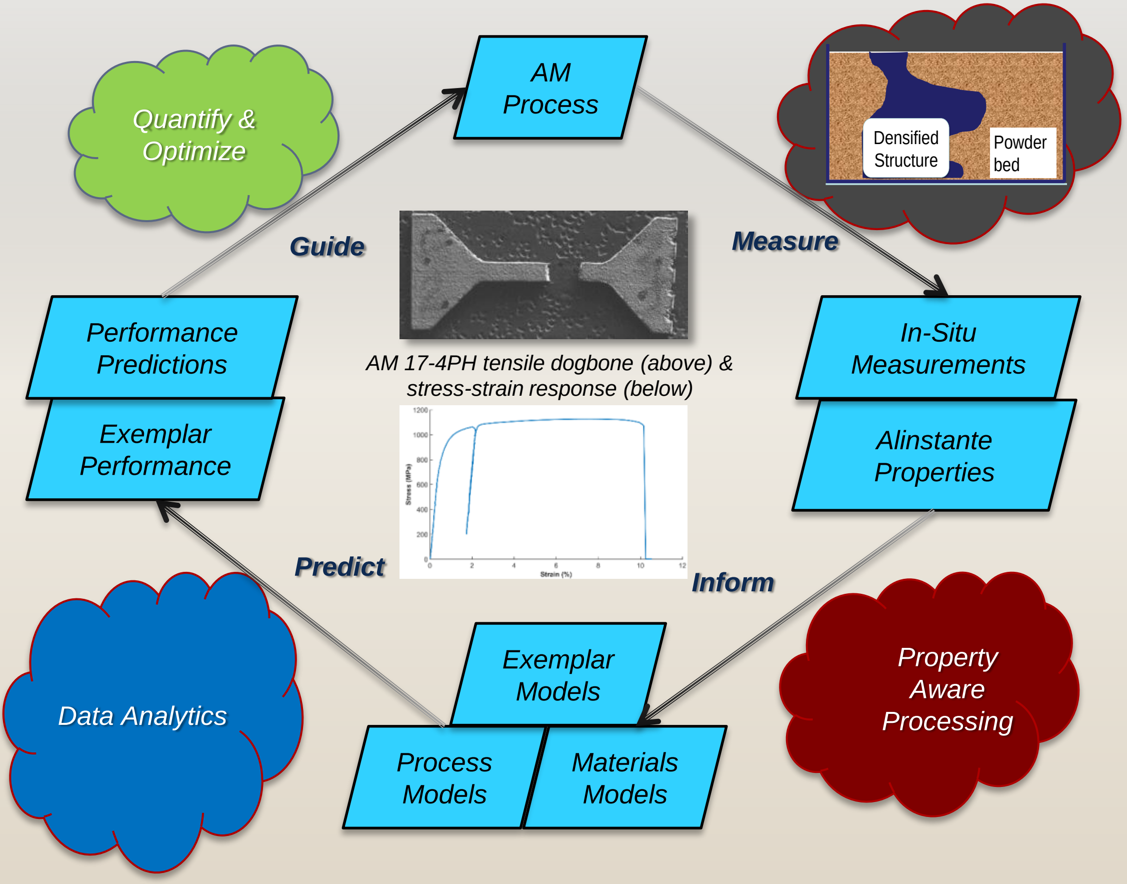
- "Changing the Engineering Design & Qualification Paradigm"
  - leverage AM, in-process metrology & HPC to revolutionize product realization



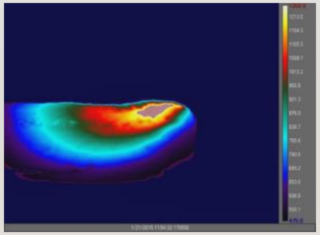
material / part performance simulation



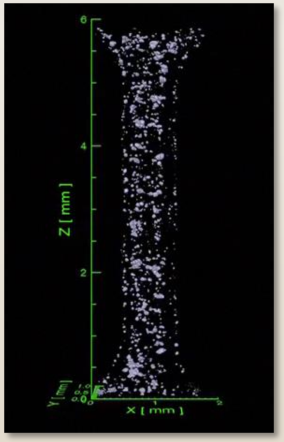
process simulation



AM 17-4PH tensile dogbone (above) & stress-strain response (below)



thermal history during bi-directional metal deposition

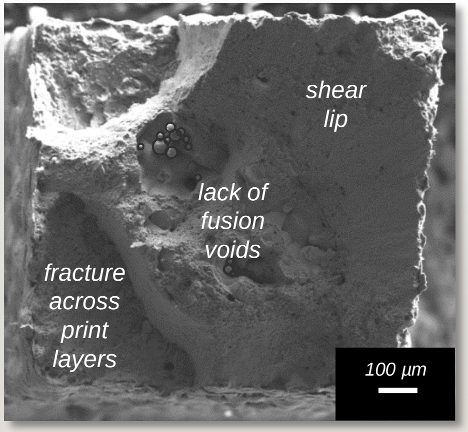


17-4PH dogbone porosity

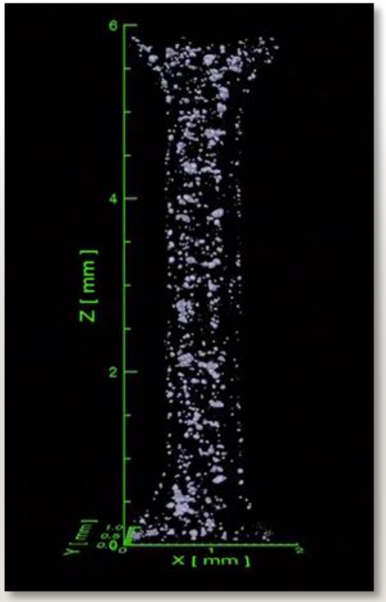
Allen Roach, et al

Material Assurance

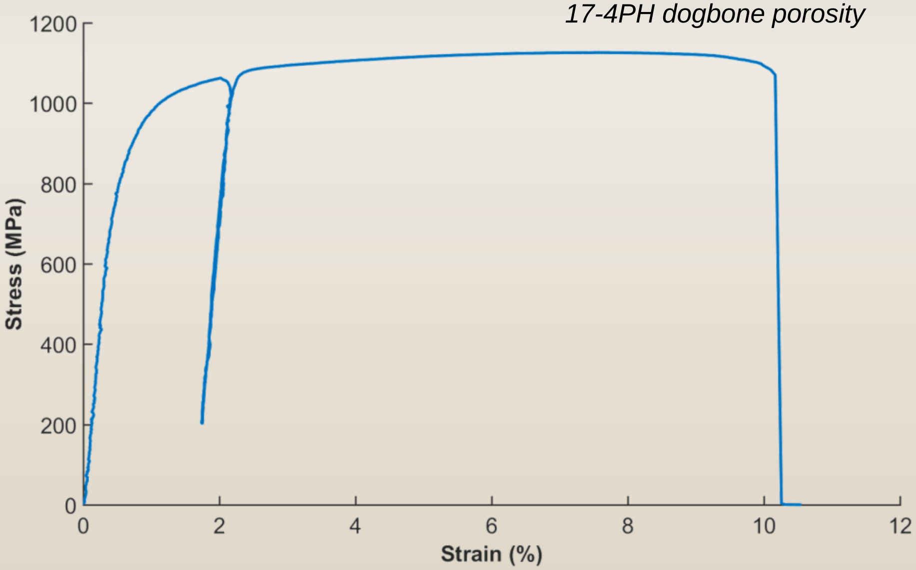
- Material formation concurrent w/geometry
  - want to predict part/material performance
  - **how to ID a bad part?**
    - complexity isn't "free"
    - requires significant design margins **and/or** rigorous post-process inspection / validation
- Quantify *critical* material defects & *useful* "signatures"
  - D-tests, NDE, process monitoring, mod-sim, ?
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict margins & reliability
  - characterize stochastic response to design for uncertainties
  - provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface

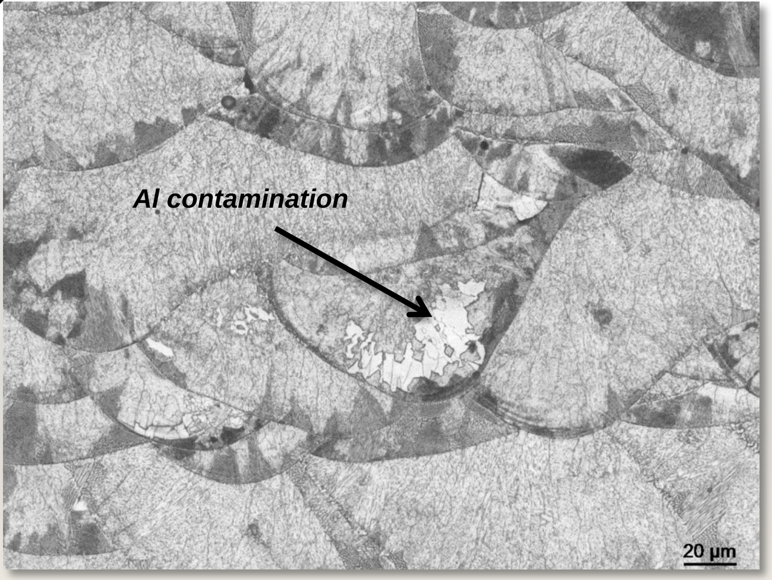


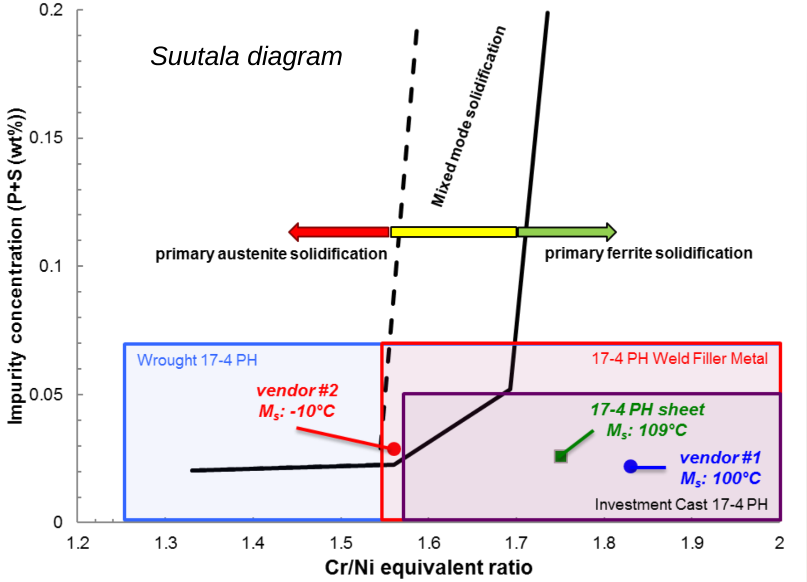
17-4PH dogbone porosity

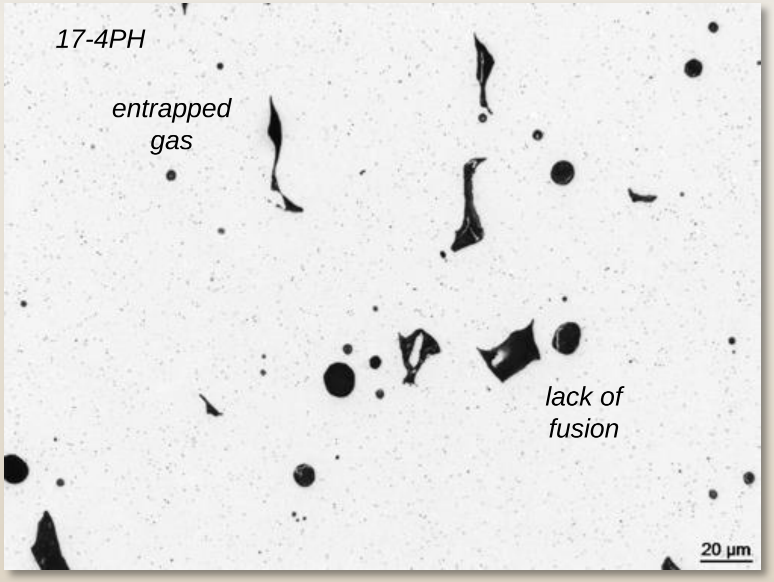


17-4PH dogbone stress-strain response

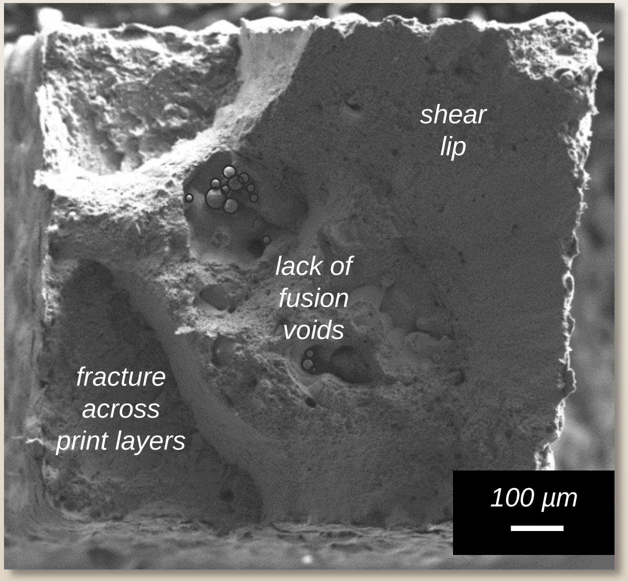
Representative Material Defects





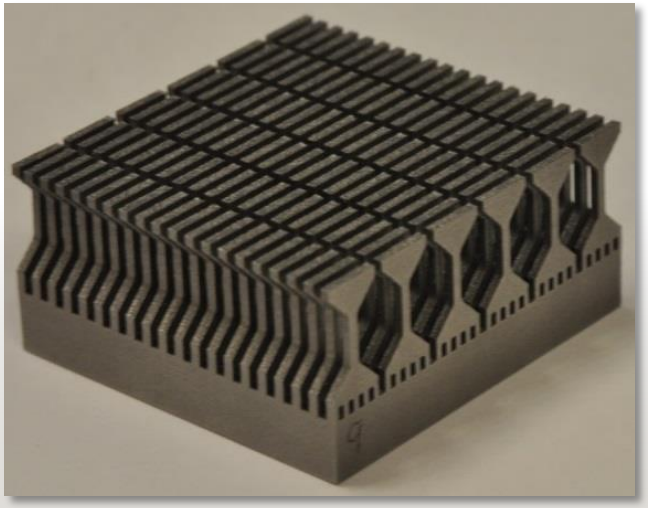


defect dominated failure, 2% elongation, 17-4PH

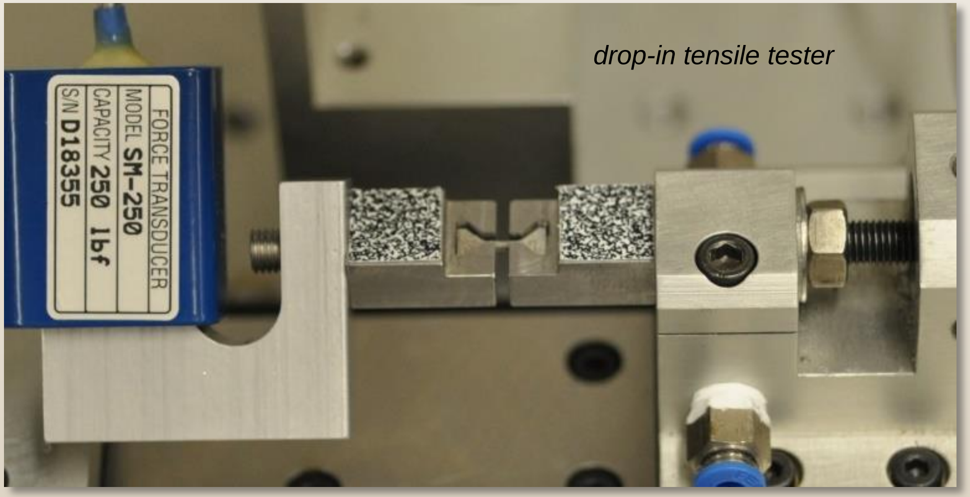


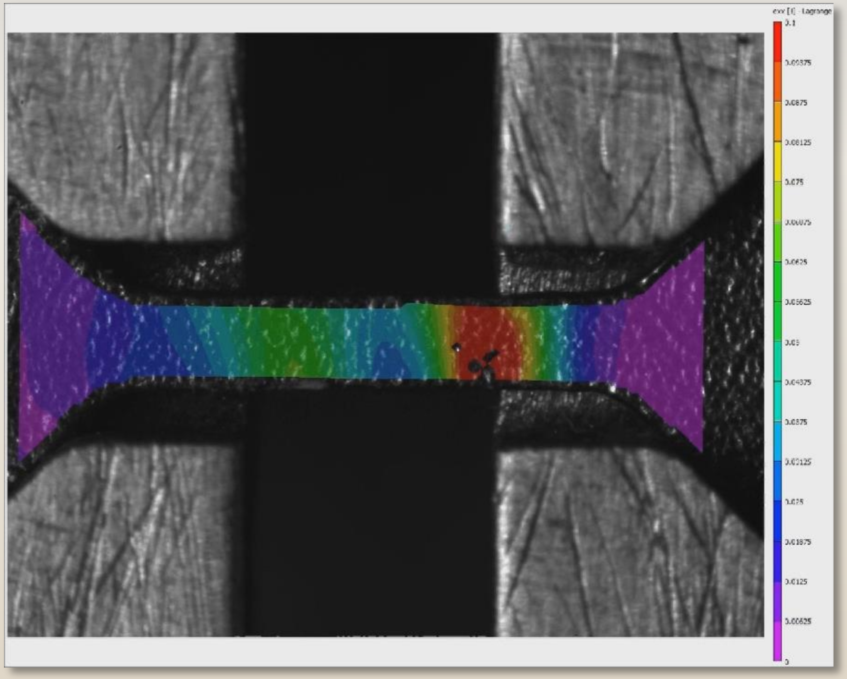
17-4PH Study

- Exploring as alternate to 304L
  - higher strength w/multiple strengthening mechanisms
- Monolithic build w/110 dogbones
  - custom design per ASTM
  - external vendor w/constant process
  - SHT + H900 HT @ Sandia
- High-throughput testing
  - digital image correlation (DIC)
  - necessary to rapidly capture material distributions
  - applicable for the lab & production



high throughput test sample w/120 dogbones, 1x1mm gage x-section



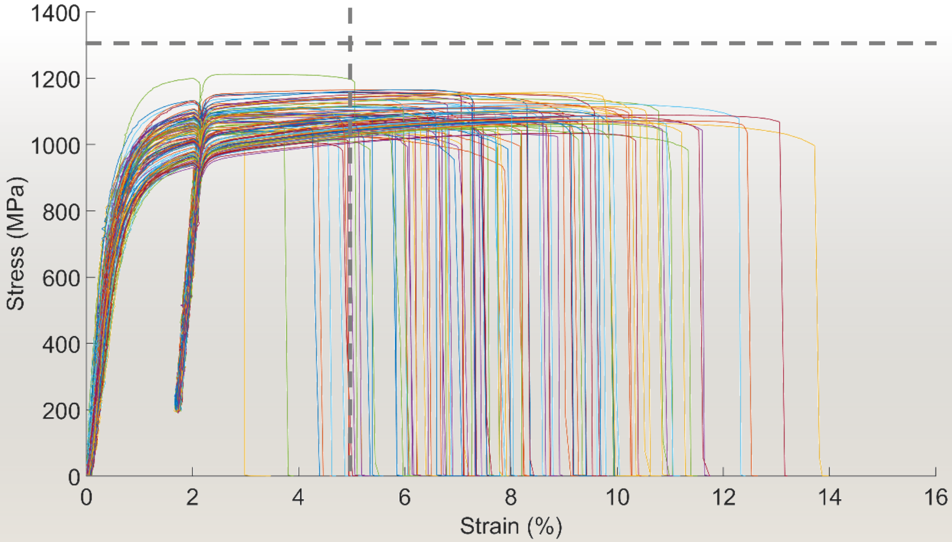


tensile test w/DIC strain field overlay

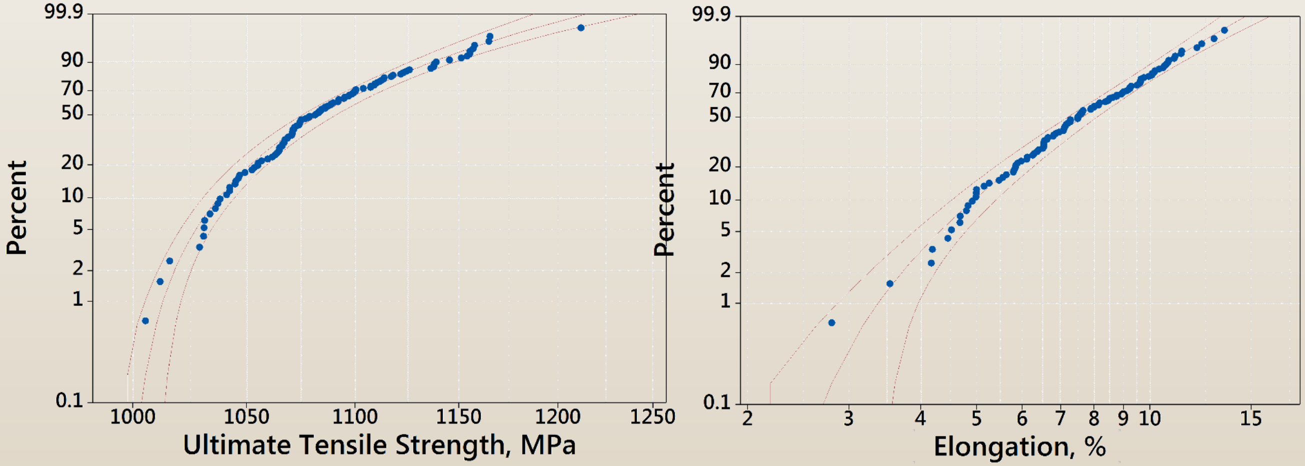
Salzbrenner, B., **Journal of Materials Processing Technology**, 2017; Boyce, B., **Advanced Engineering Materials**, 2017

Stochastic Response

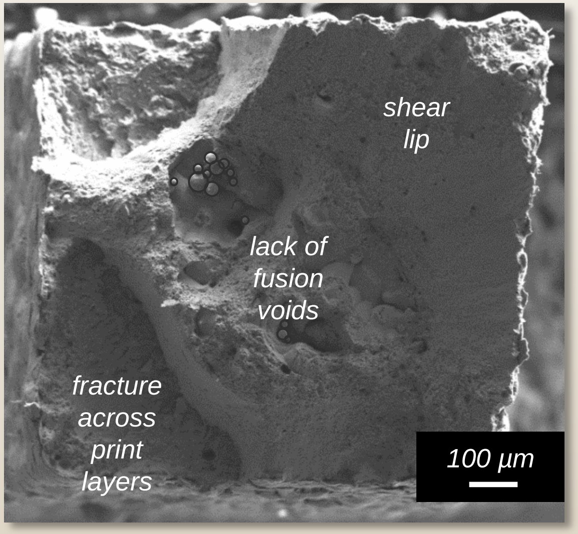
- Defect dominated failure
  - 3-parameter Weibull fits inform design threshold
  - ductile dimples & shear rupture planes
  - voids & lack-of-fusion boundaries are likely crack nucleation sites
- Extensive performance variations
  - can inter-build performance be predicted?



110 stress-strain curves for 17-4 PH after SHT+H900



material performance fit to 3-parameter Weibull distributions



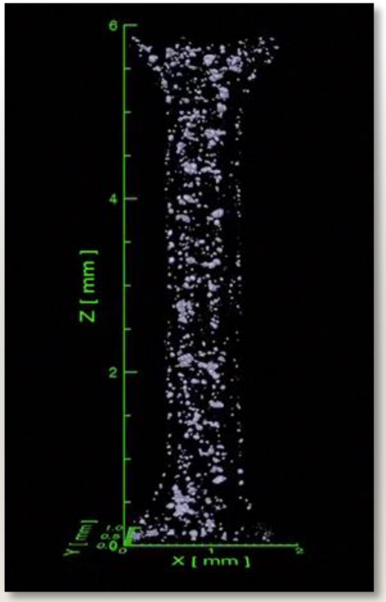
failure at 2% elongation, SHT+H900

AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

Material Characterization

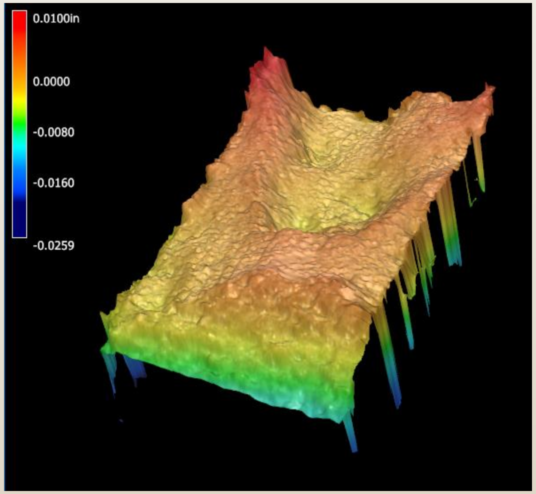
- NDE before testing
  - detect defects, performance correlations
  - density (Archimedes)
  - resonant ultrasound spectroscopy (RUS)
  - optical surface measurements
  - computed tomography (CT)
- Post mortem after testing
  - inform performance & failure mechanisms
  - fractography
  - metallography
  - composition
  - XRD

- **Do reasonable defect signatures exist which tie to performance tests?**



17-4PH dogbone porosity

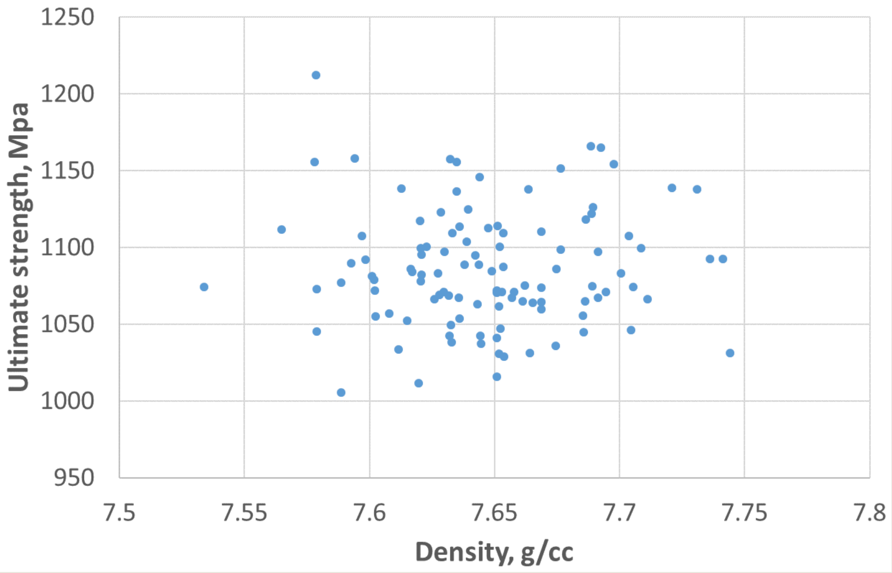
dogbone in 2-point RUS test fixture

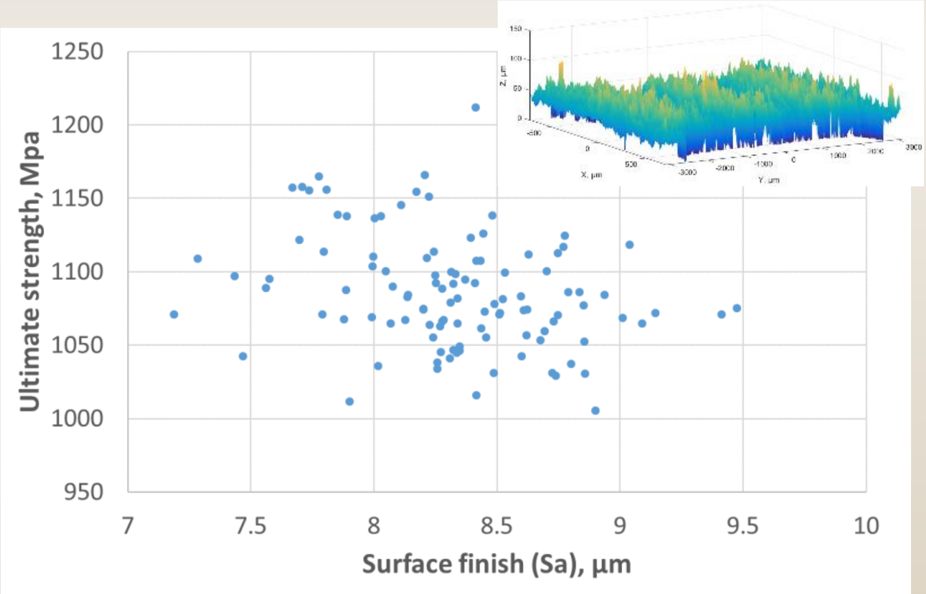


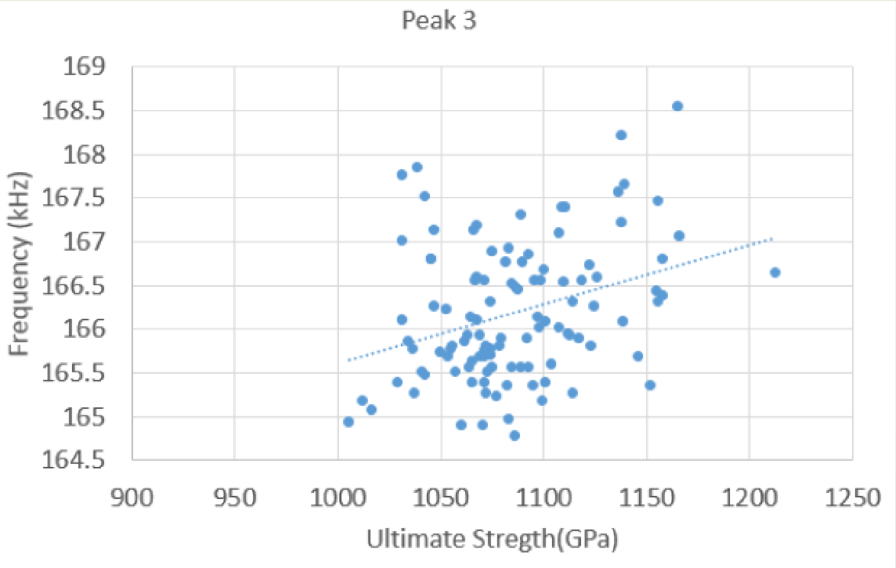
fracture surface

Implicit Part Correlations

- Archimedes density
- Resonant Ultrasound Spectroscopy
    - swept sine wave input from 2-point transducer (74.2 kHz - 1.6 MHz)
    - 19 resonance peaks
- Surface finish
- No significant trends observed

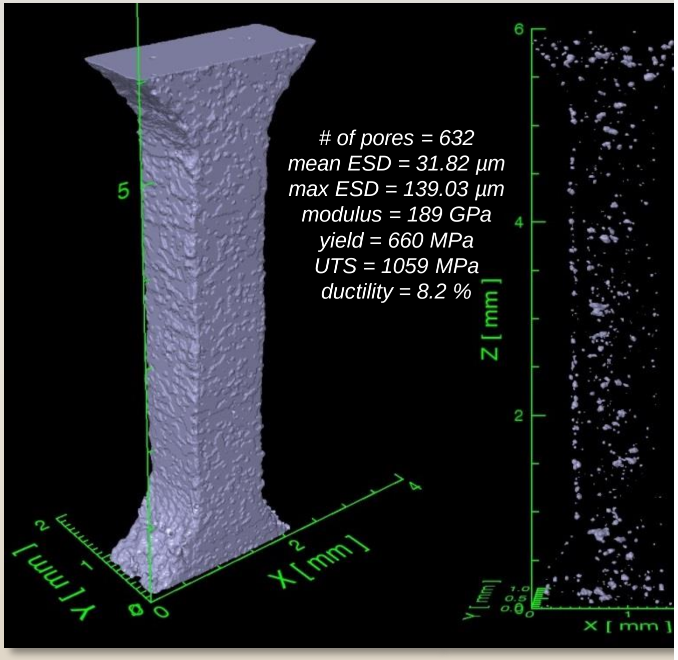






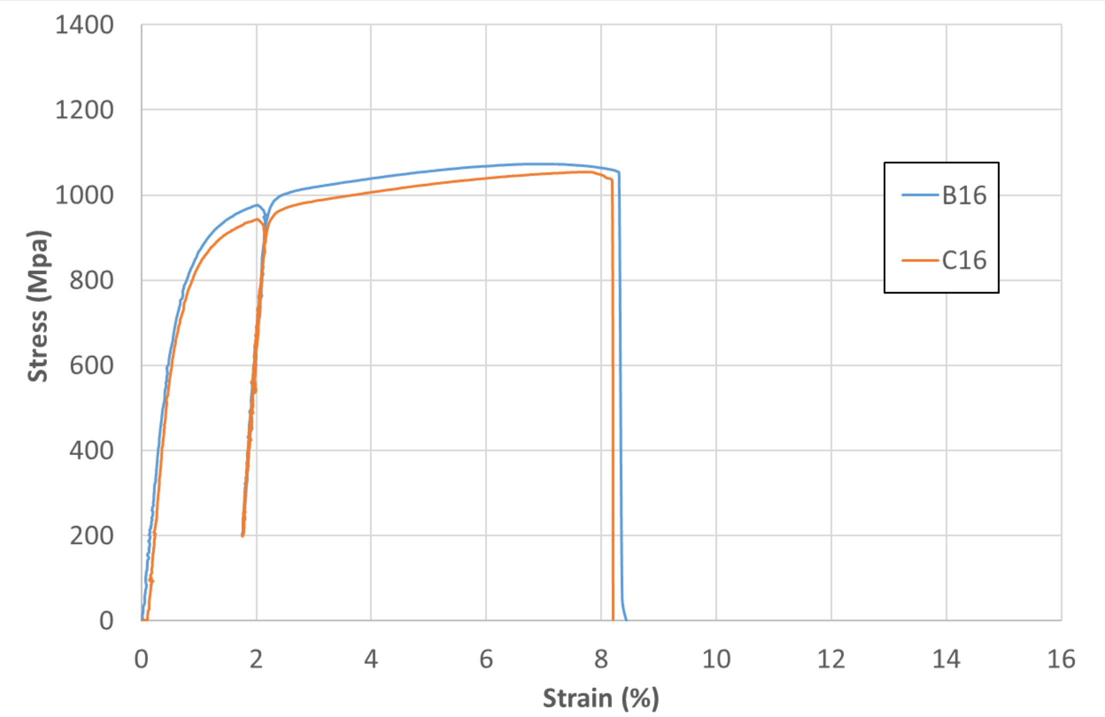
Explicit Porosity Measurements

- Computed tomography (CT)
  - NDE “gold standard” for porosity measurement
  - gage sections imaged w/resolution of 7 or 10 µm voxel edge length
- What can we see? Does it inform material behavior predictions?
  - justifiable for qualification and/or production?



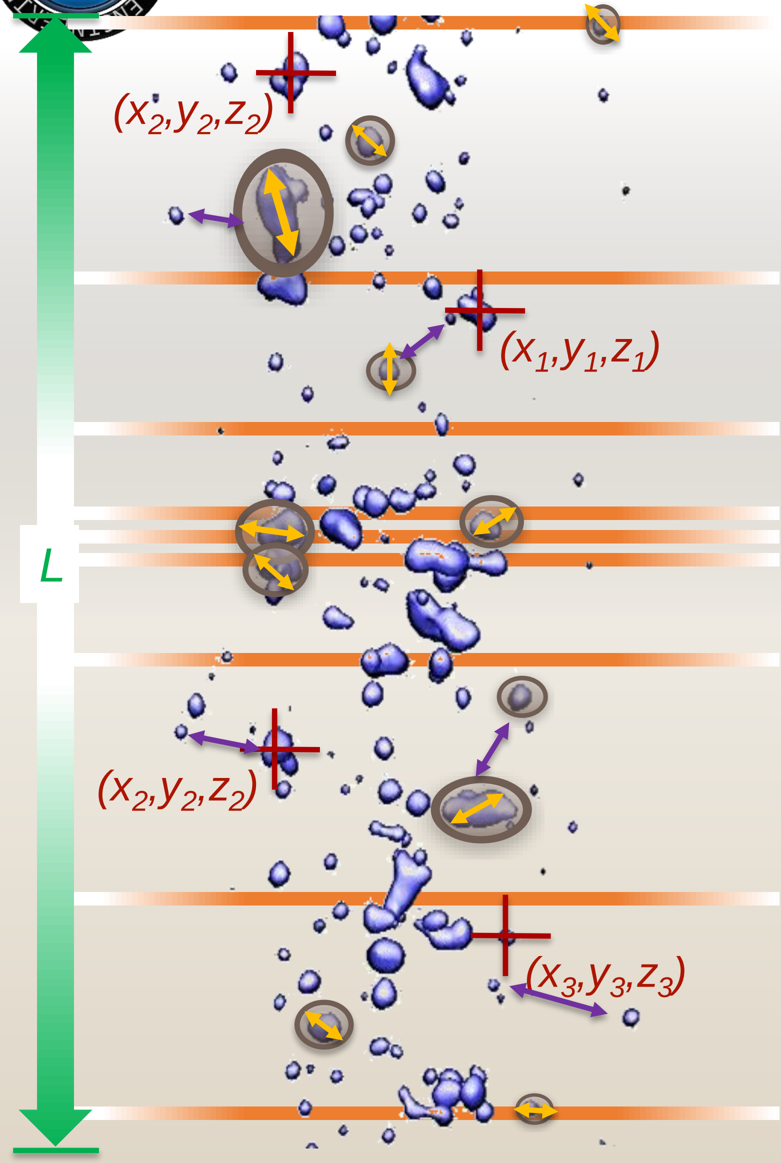
# of pores = 632
mean ESD = 31.82 µm
max ESD = 139.03 µm
modulus = 189 GPa
yield = 660 MPa
UTS = 1059 MPa
ductility = 8.2 %

dogbone B,16 CT surface image (left), porosity map (



ESD = equivalent spherical diameter

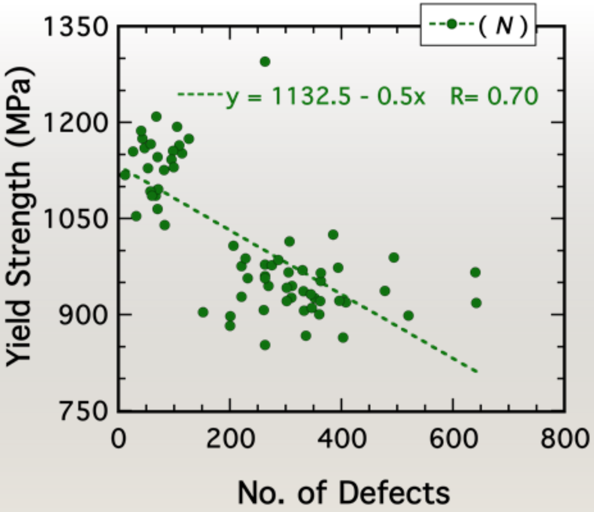
Defect Characterization

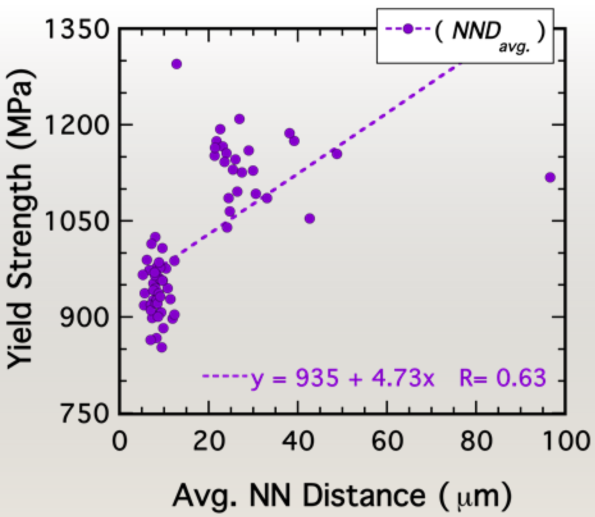


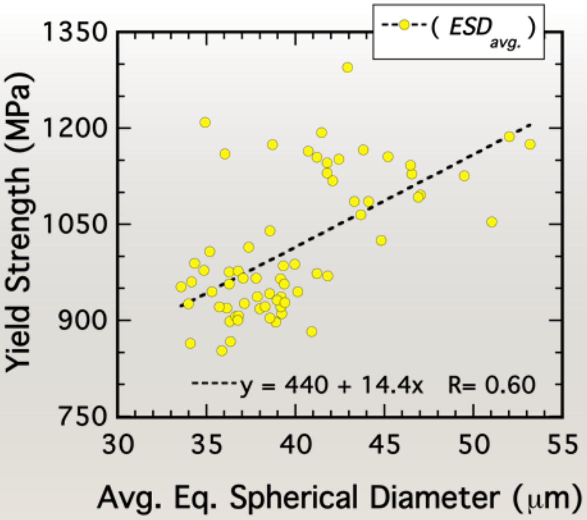
- Total Volume of Defects (V_{tot})
- Pore Volume Fraction (V_{fract})
- Spatial Location of Pores (x, y, z)
- Total Number of Defects (N)
- Total Defects/Length (N/L)
- Average Defect Volume ($V_{avg.}$)*
- Average Equivalent Spherical Diameter ($ESD_{avg.}$)*
- Average Cross-Sectional Area ($CSA_{avg.}$)*
- Average Nearest Neighbor Distance ($NND_{avg.}$)*

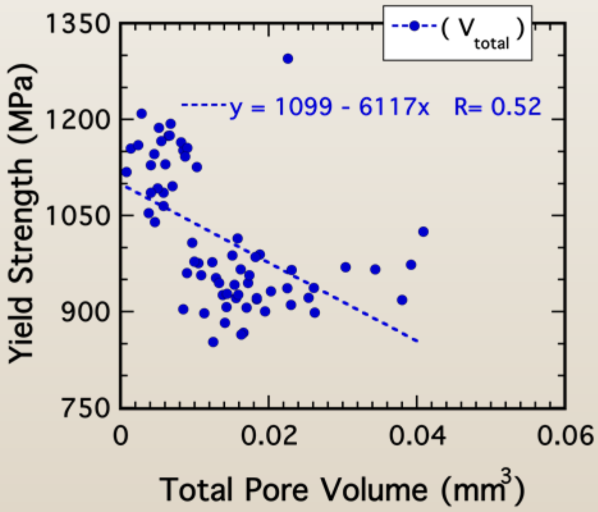
How do we *best* represent the defect populations present?

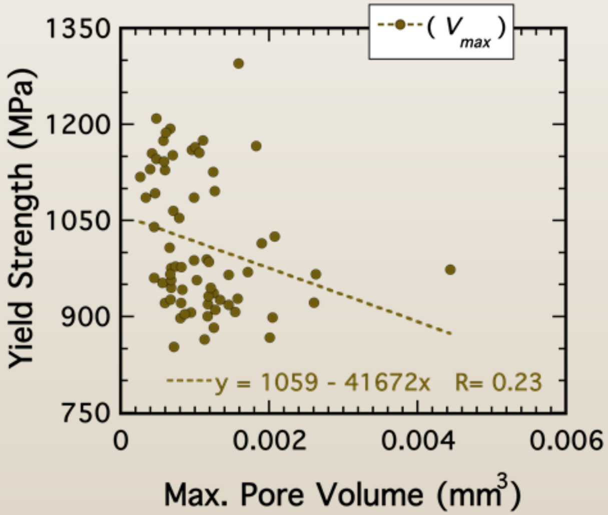
Statistical Correlations Are Elusive







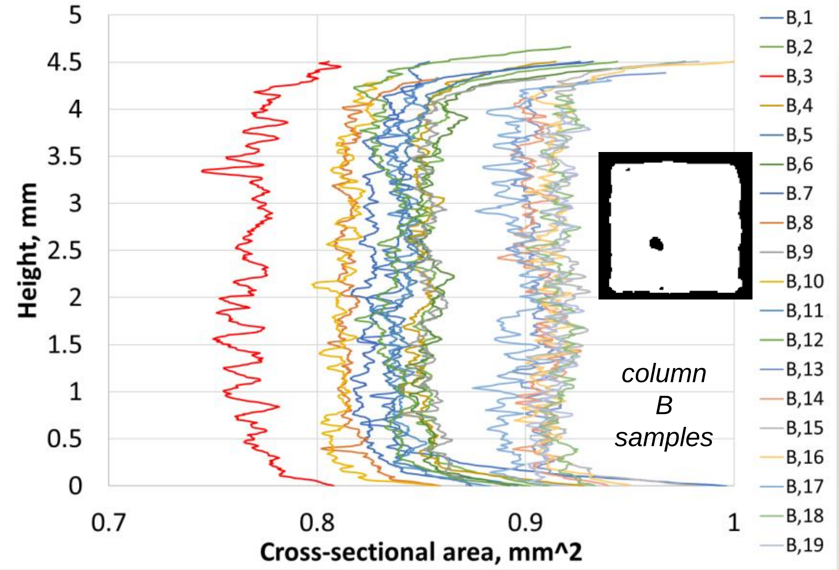


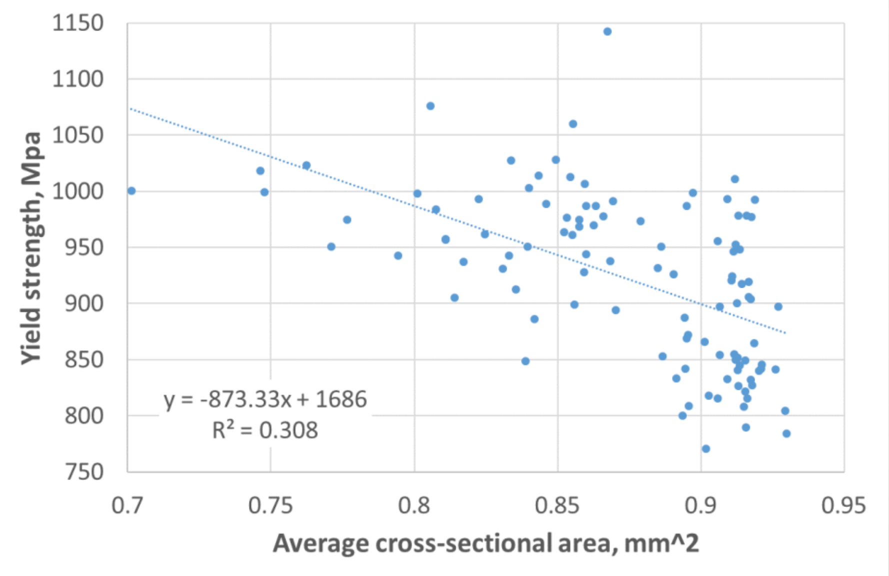


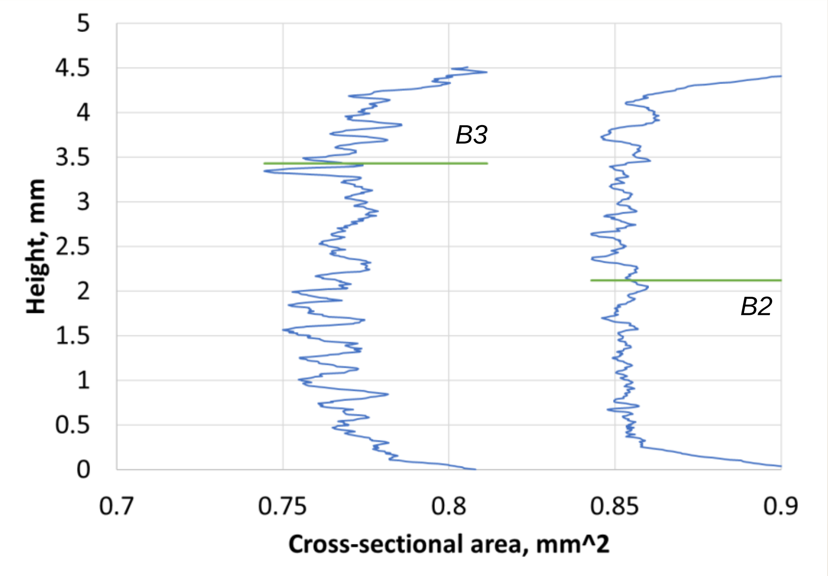
Measure	R^{2}
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm^{2})	0.38
Total Pore Volume (mm^{3})	0.27
Avg. Defect Vol. (mm^{3})	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

Post Mortem Analyses

- Can forensic trends be identified?
- CT data analysis
    - calculate cross-section per layer
    - gage sections are rough & porous
    - fractures sometimes correspond to minimum areas
    - general trends remain weak



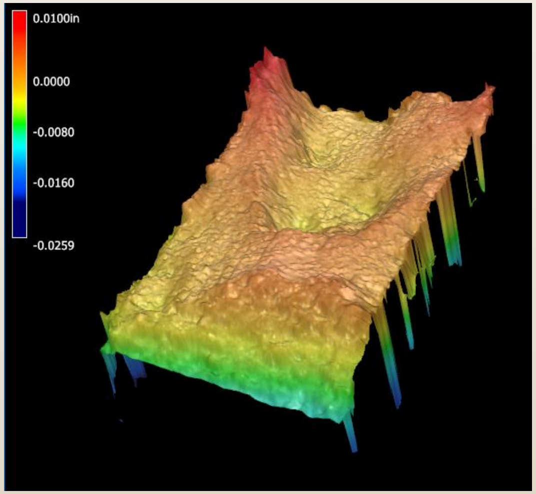


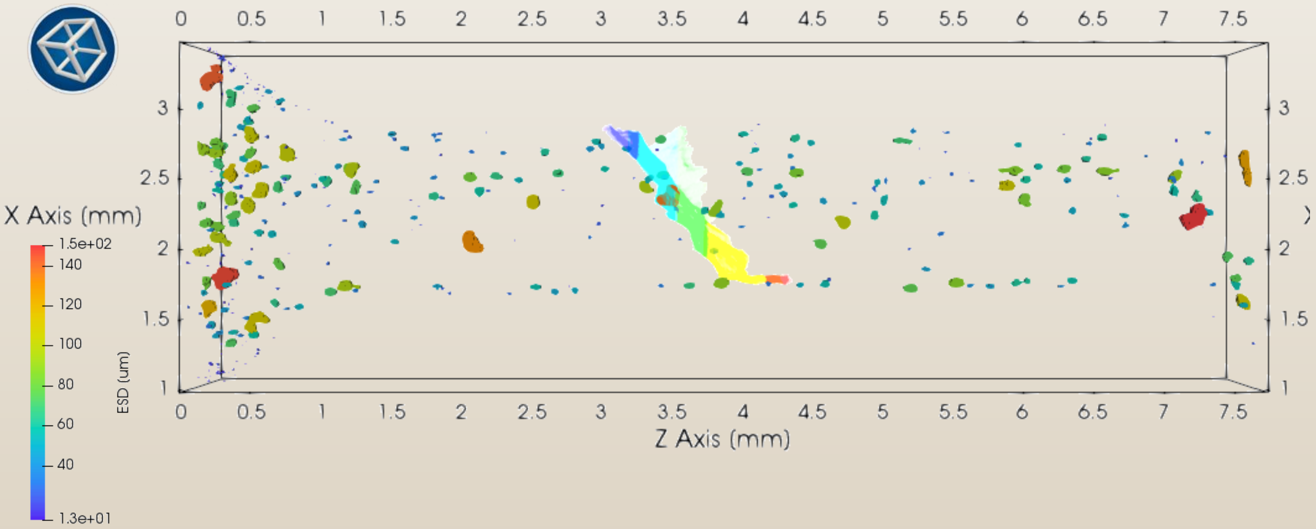


Fractography

- Defect dominated failure observed
- Increasing data fidelity & integration
  - overlay fracture surface w/porosity map using DREAM.3D
  - roughness inhibits registration accuracy
  - fracture surface may correlate to large pore

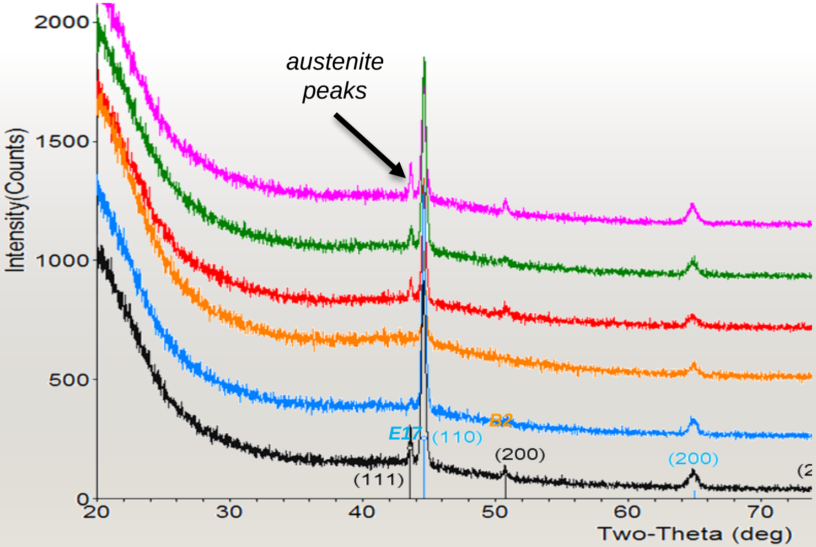
B2, fracture surface optical image by structured light scanning



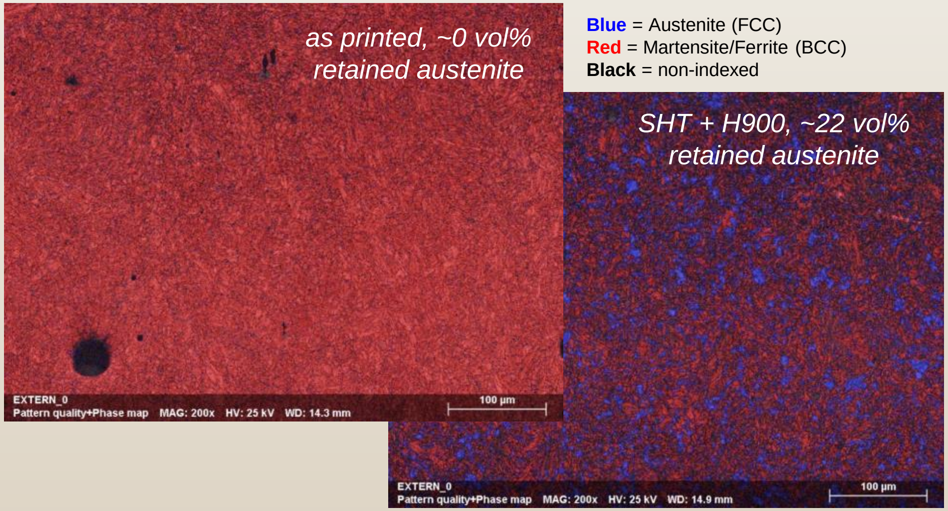


Microstructure Examination

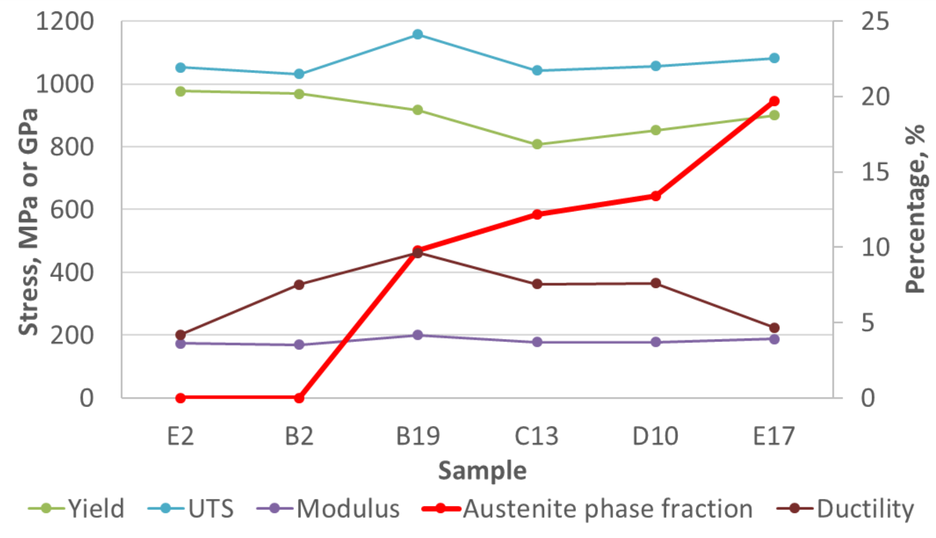
- Compositional analysis identified no anomalies
- XRD revealed unexpected austenite variation in X-Y
  - what about Z?
  - further complication to dogbone performance
  - source = powder, atmosphere?



XRD analysis of dogbones across the build sample



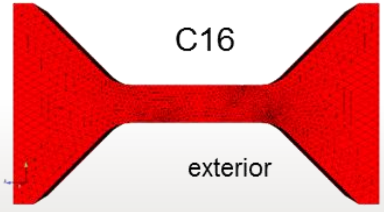
Blue = Austenite (FCC)
Red = Martensite/Ferrite (BCC)
Black = non-indexed

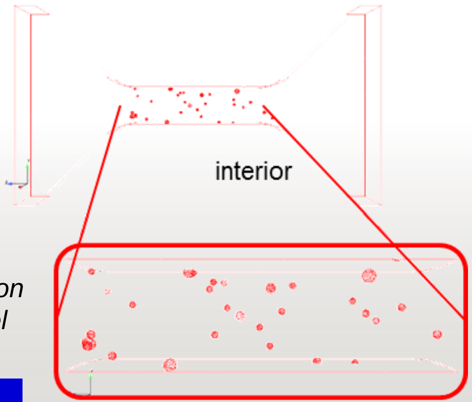


material performance variation w/austenite phase fraction

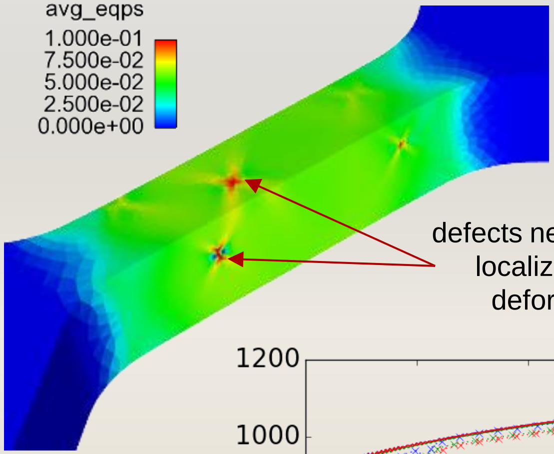
Material Models

- Want to inform & predict material variability
- Approach
  - explicitly subtract spherical CT porosity volumes from dogbones
  - solve tensile loading
    - ignore residual stress, surface finish & defects w/volume below ~90µm³
    - continuum properties calibrated to low porosity sample D16
- Expectations
  - large defects will intensify & localize deformation
  - microscale void mechanisms will drive failure

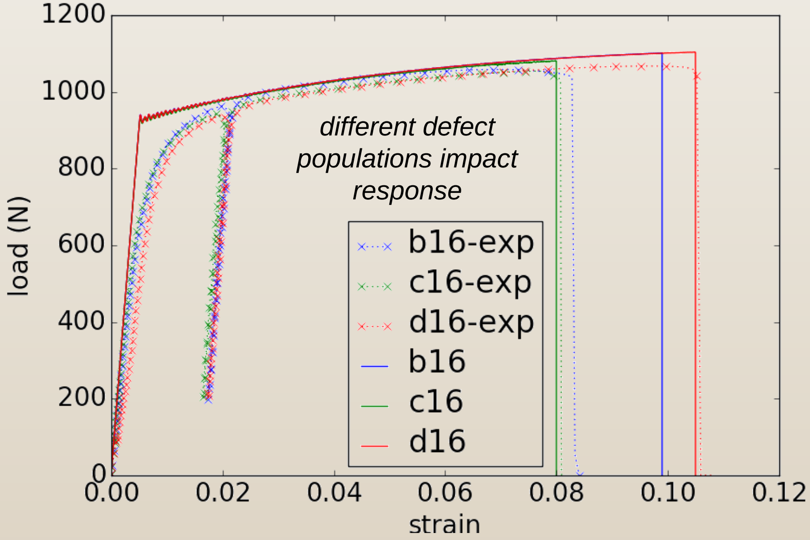




explicit defect representation applied to dogbone model



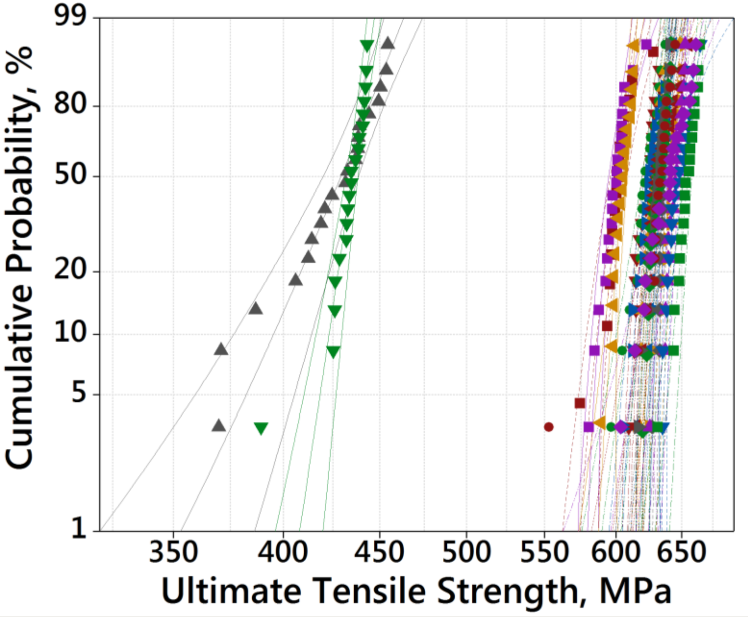
defects near surfaces localize plastic deformation



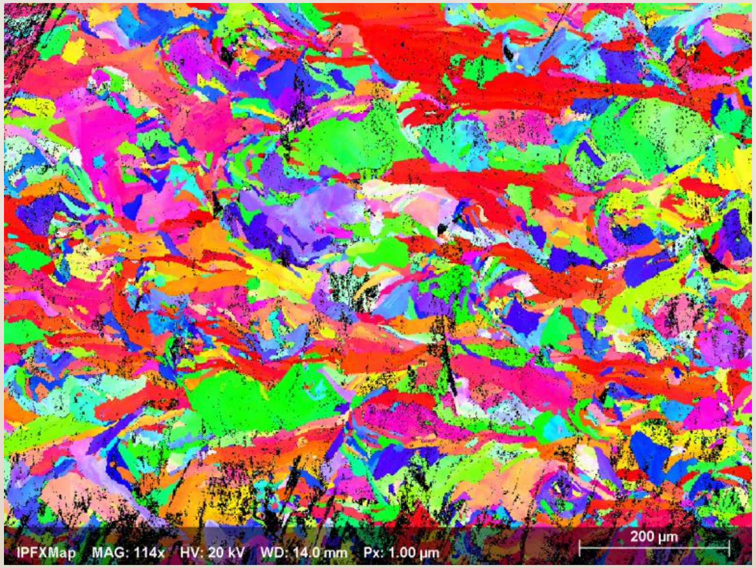
different defect populations impact response

316L SS Study

- Exploring intra-build variations, process sensitivities / margins / optimization
  - leveraging analysis tools developed
- 316L SS printed on Sandia ProX 200
  - 25 dogbones / process setting
  - parameters
    - power, velocity, cross-feed, scan strategy, # parts/plate
    - represents ~2500 dogbones
    - Gen2 HTT development
  - measurements
    - top surface distortion (after EDM)
    - surface finish (top, side, angles)
    - Archimedes density
    - CT
    - resonance testing
    - tensile testing
    - metallography, fractography

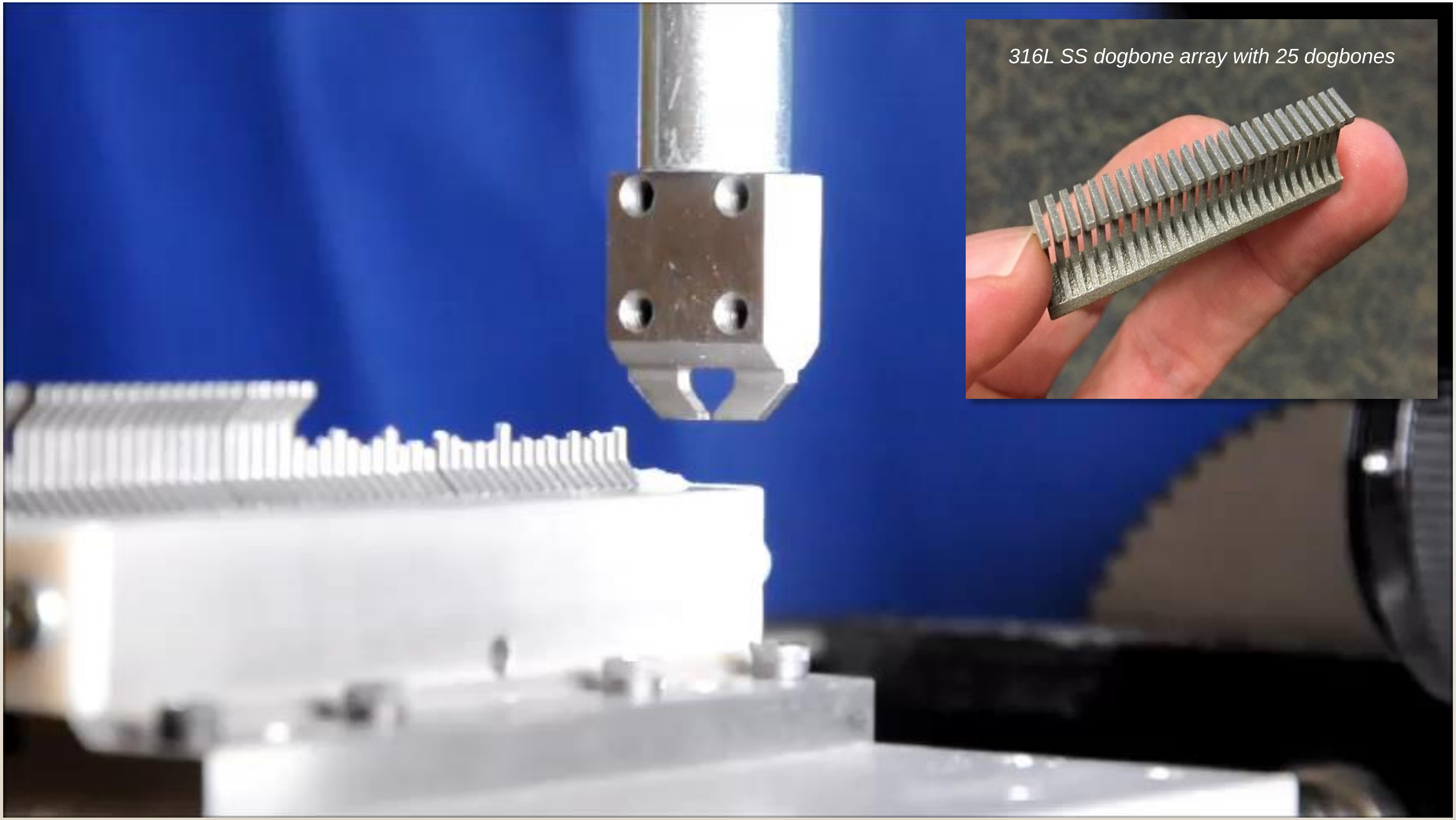


UTS variation w/power, velocity & scan pattern



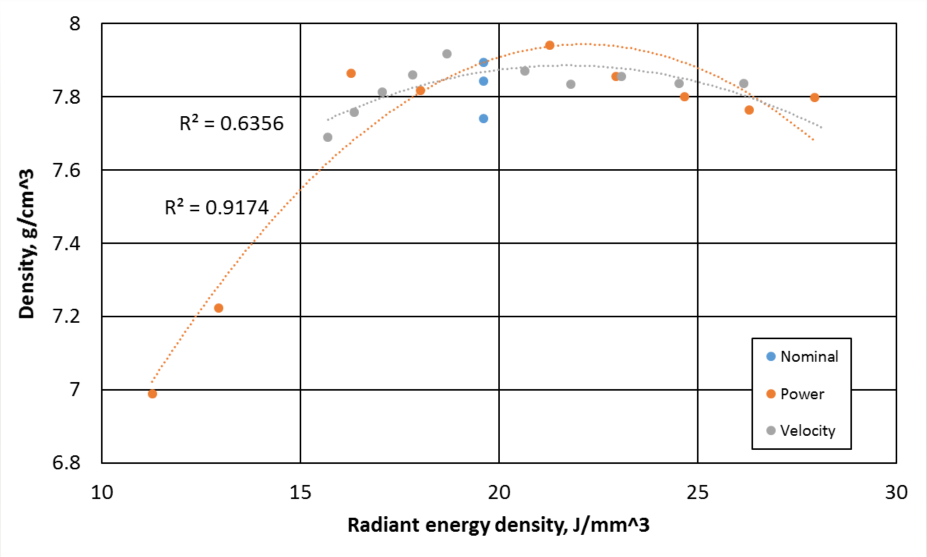
representative texture map via EBSD, phase content has been relatively consistent across process settings

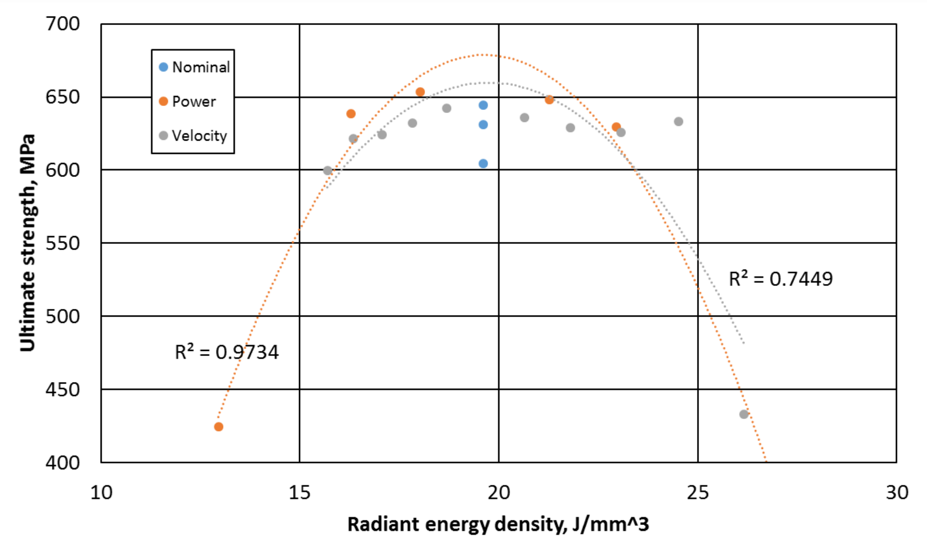
High Throughput Testing: Gen 2

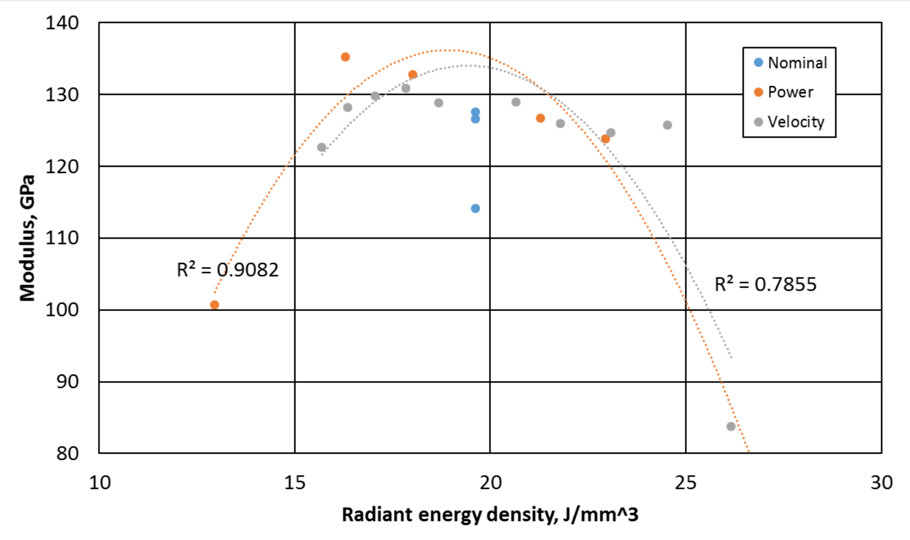


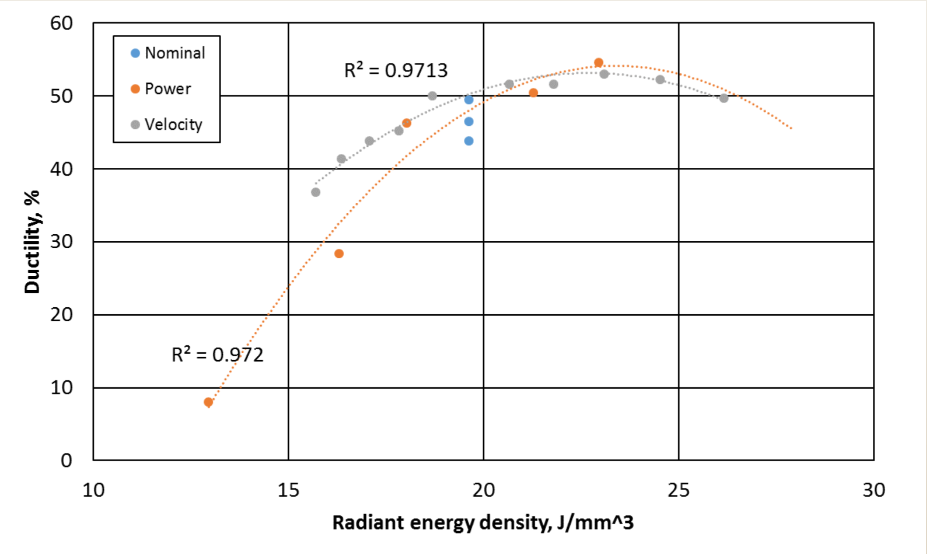
316L SS dogbone array with 25 dogbones

Intra-Build Process Trends



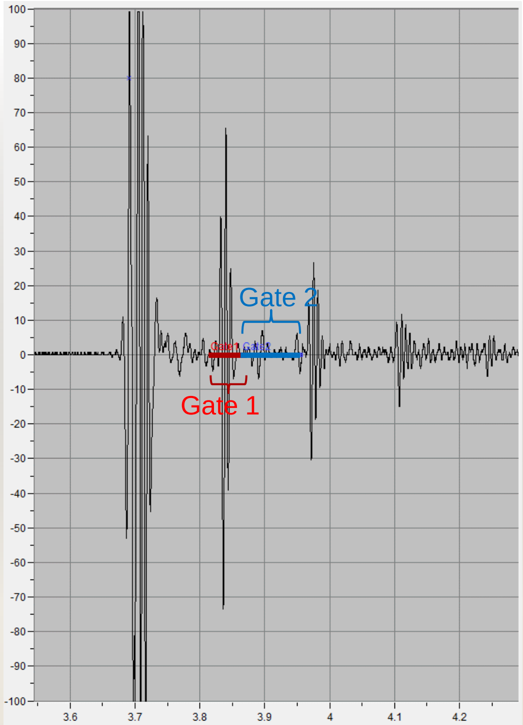


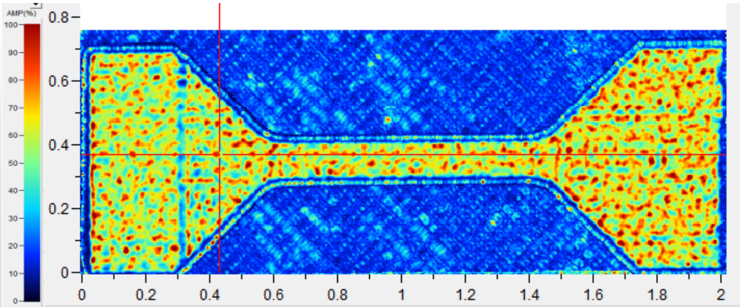




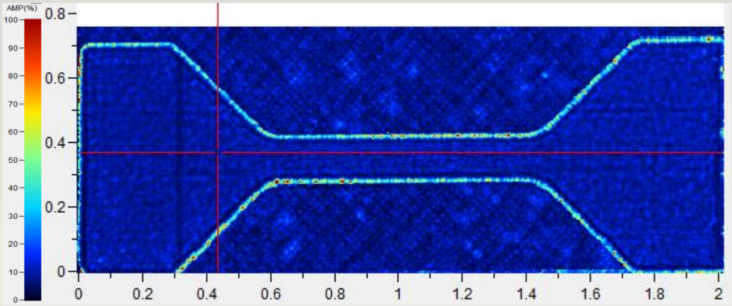
Pulse-Echo Ultrasound Inspection

- Single probe emits incident wave & receives reflected signal
  - gate 1 – backwall surface
  - gate 2 – part thickness
- Material density
  - 17-4PH, Al10SiMg, Ti6Al4V

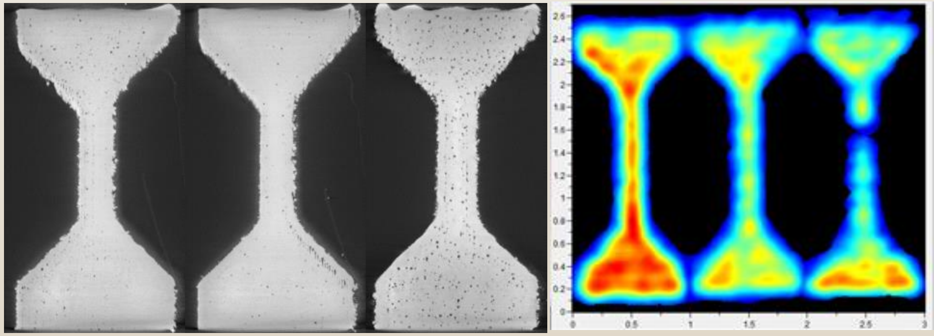




Gate 1 signal

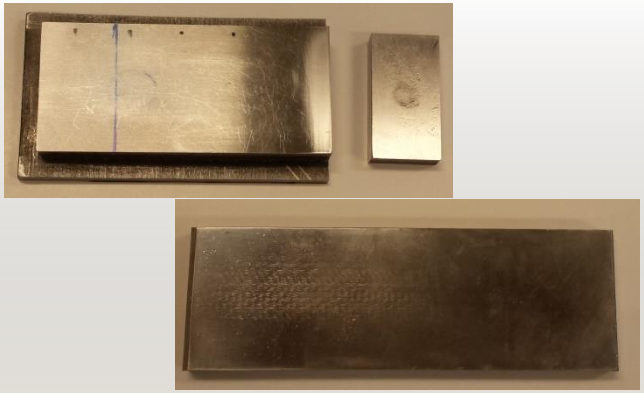


Gate 2 signal

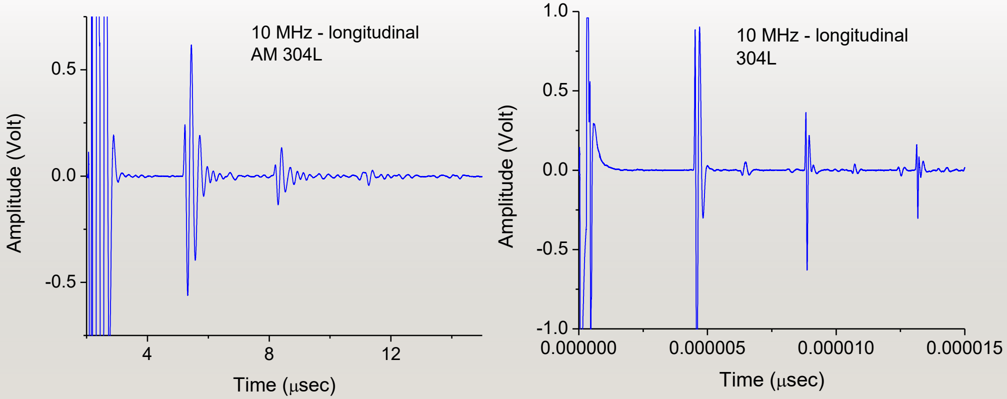


CT images of 98% (left), 96% (center) & 93% (right) dense Al10SiMg dogbones (left) & attenuation of 10MHz ultrasonic backwall reflections (right)

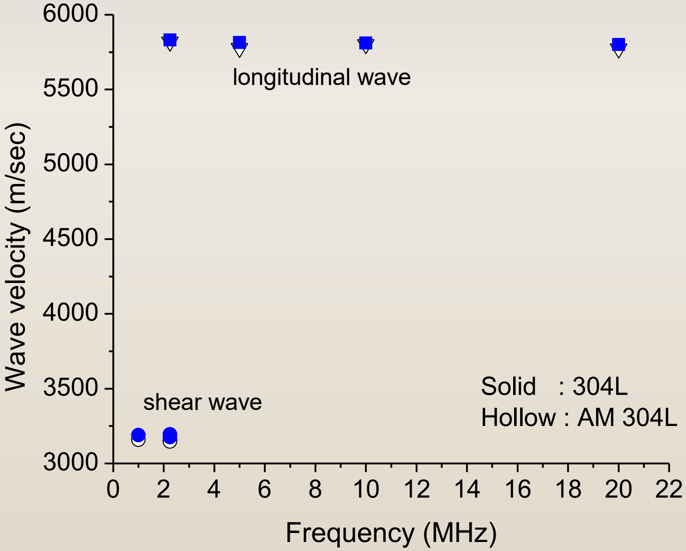
Exploring Wave Propagation to Measure Residual Stress



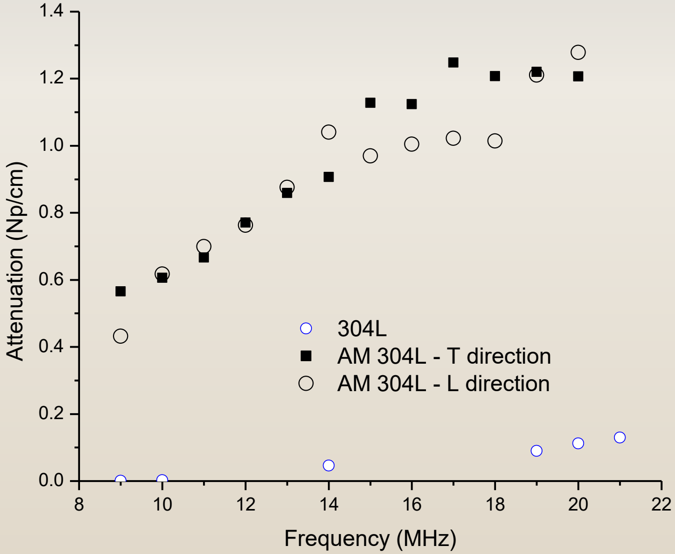
LENS 304L (top) & wrought 304L (bottom) samples



10MHz longitudinal wave time domain signals for AM 304L (left) & wrought 304L (right)



wave velocities of longitudinal & shear waves in AM-304L & 304L specimens

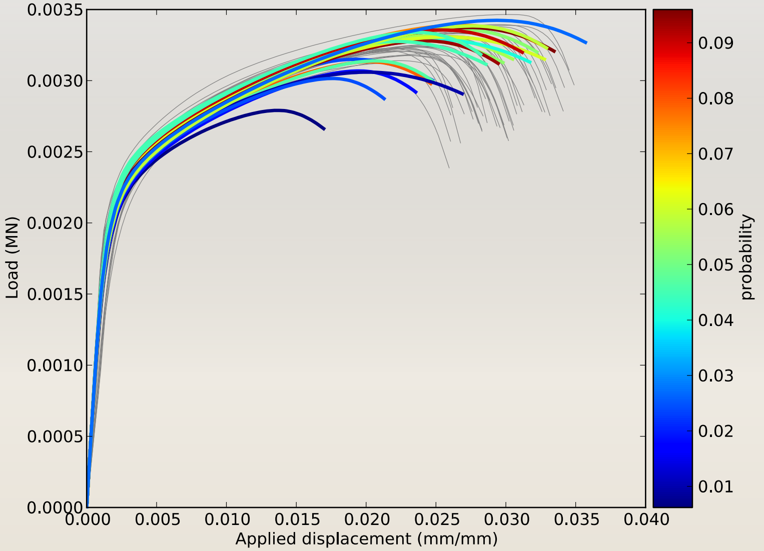


attenuation coefficients of longitudinal wave in AM-304L & 304L specimens, AM-304L acoustic nonlinearity parameter = 3X wrought 304L

Larry Jacobs, Jin Yeon Kim (Georgia Tech), Joe Bishop (Sandia PI)

Summary

- Material assurance is a challenge
  - material behavior is complex
    - predictive inter-build correlations for 17-4PH have not been straight-forward
    - contributing factors include process, feedstock, measurement, surface finish, microstructure
  - orthogonal testing pursuing multiple signatures is invaluable (& necessary) for qualification / product acceptance
- Tools developed to interrogate & analyze defects
  - performance distributions can be captured efficiently & used to understand material & process
    - tracking intra-build population shifts may be possible
  - intra-build / process change correlations identified for 316L SS



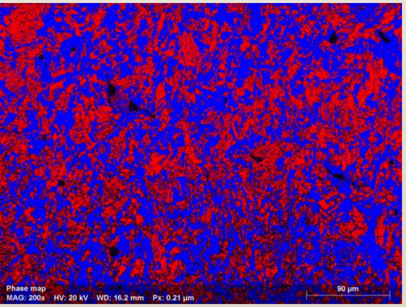
predicted (color) vs. measured (grey) response for welds (PPM)

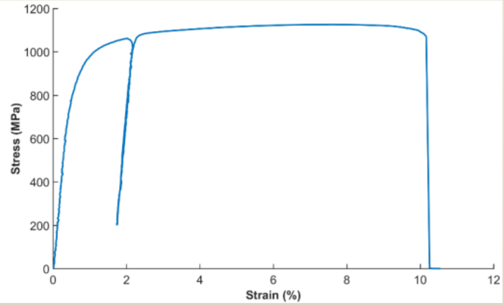
QUESTIONS?

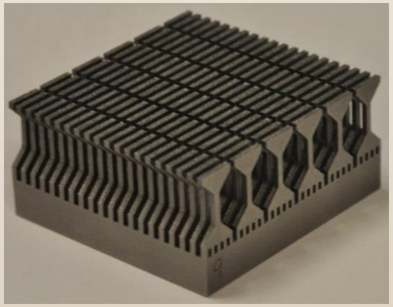
Bradley Jared, PhD

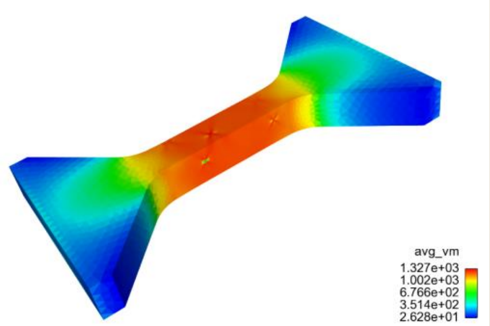
bhjared@sandia.gov

505-284-5890







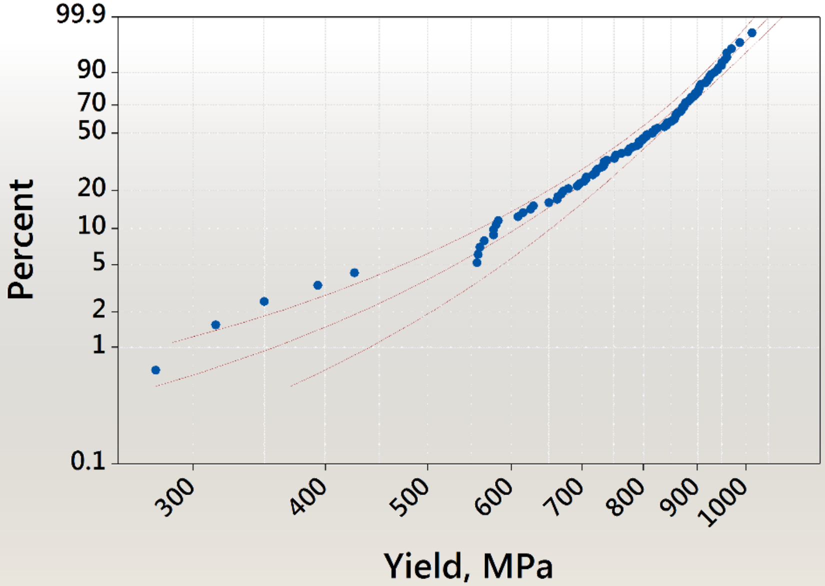


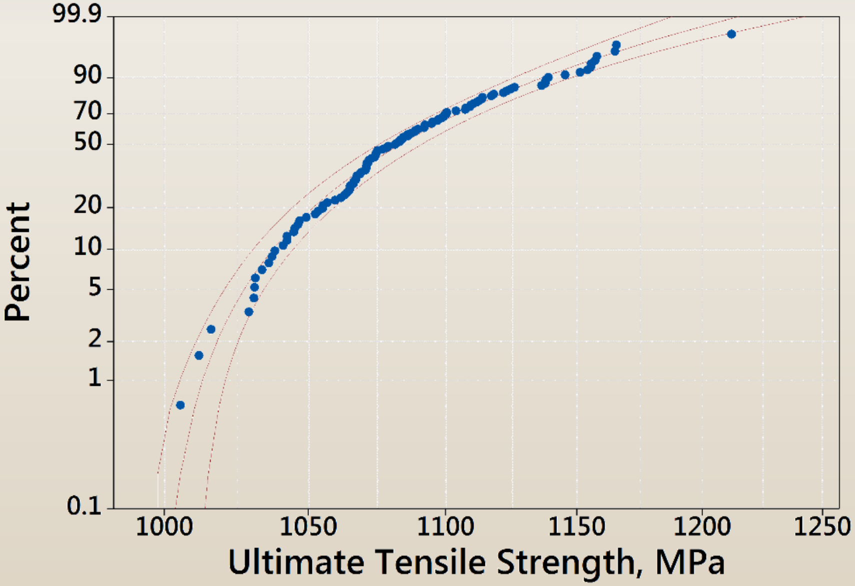
Material Performance Fit to 3-Parameter Weibull Distributions

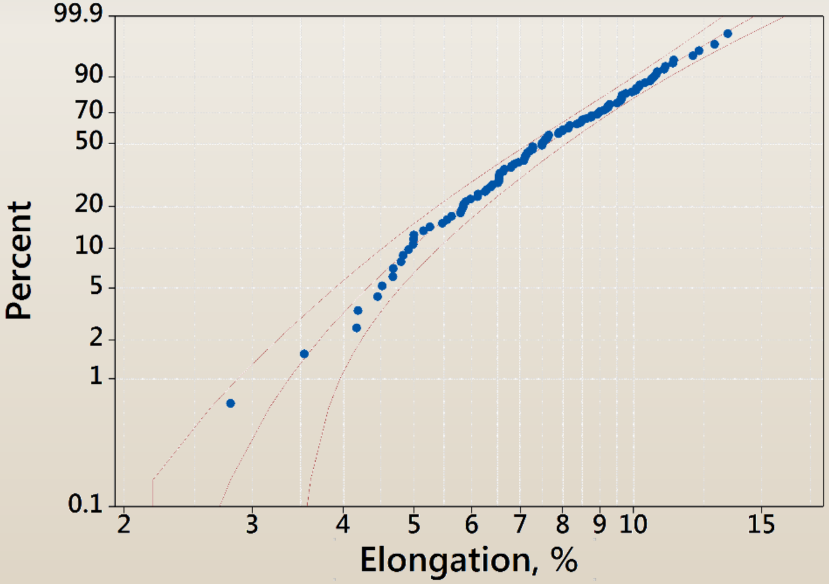
- Based on weakest link theory

$$P = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$

- where
  - P = probability of failure at stress, σ
  - m = Weibull modulus, i.e. scatter
  - σ_θ = characteristic strength
  - σ_o = threshold, strength where P = 0

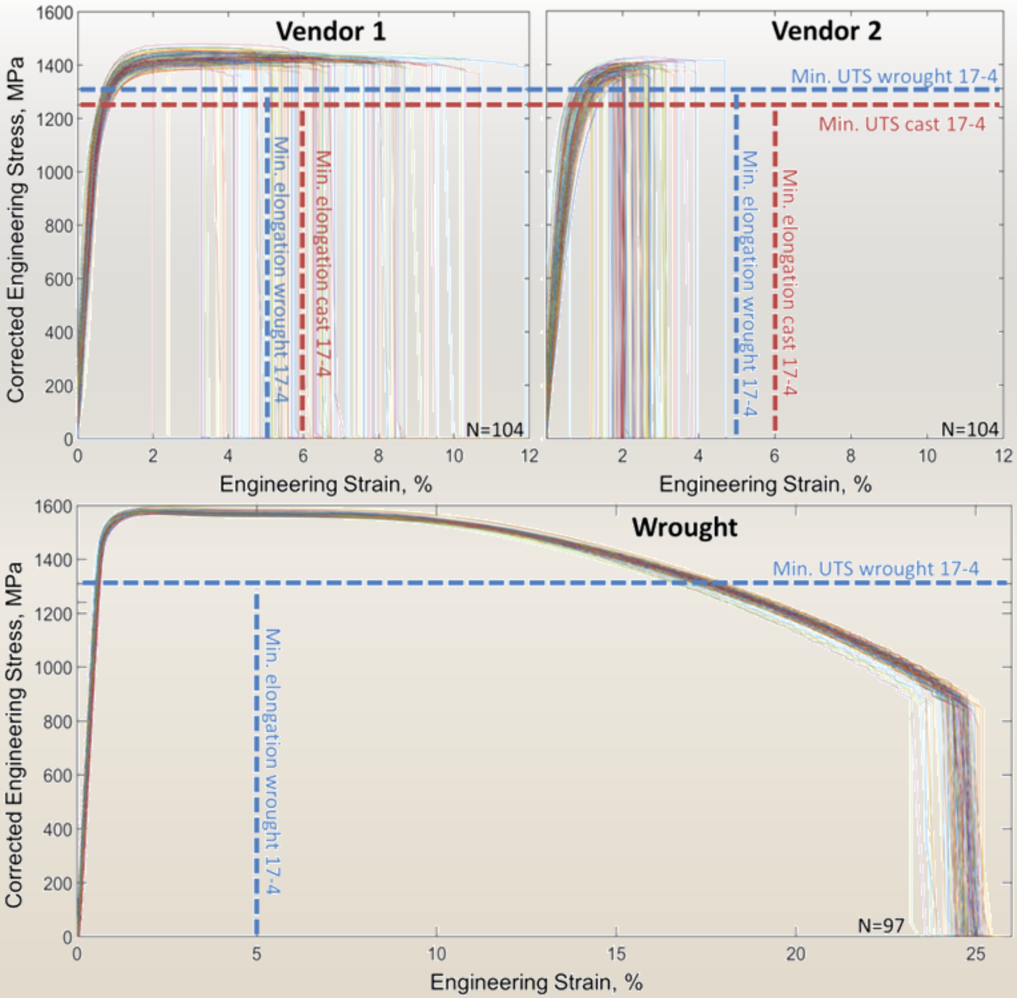




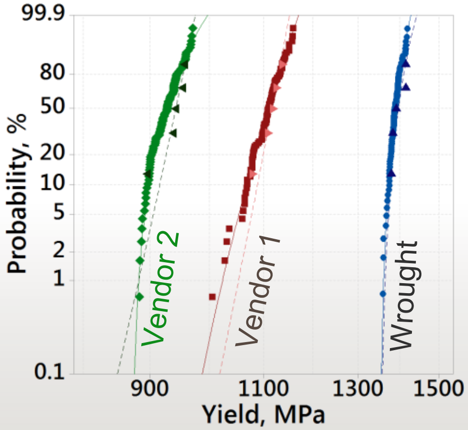


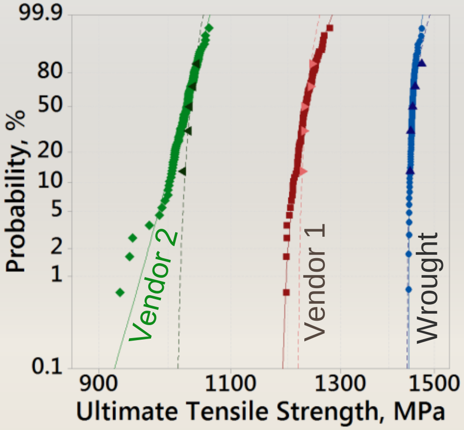
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

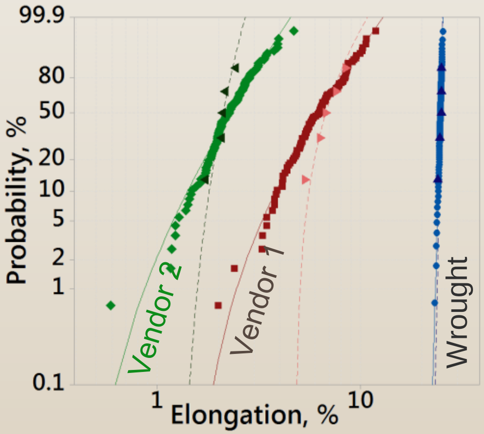
AM vs. Wrought 17-4PH



H900 data for vendor 1 (top left), vendor 2 (top right) & wrought (bottom) w/corrected stress area



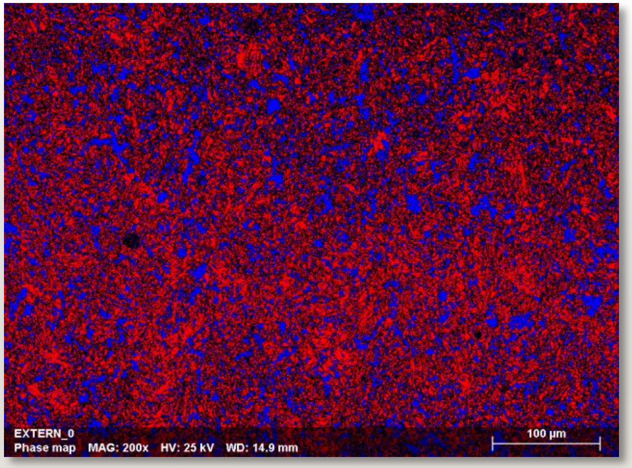




AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

Metallurgical Interrogations

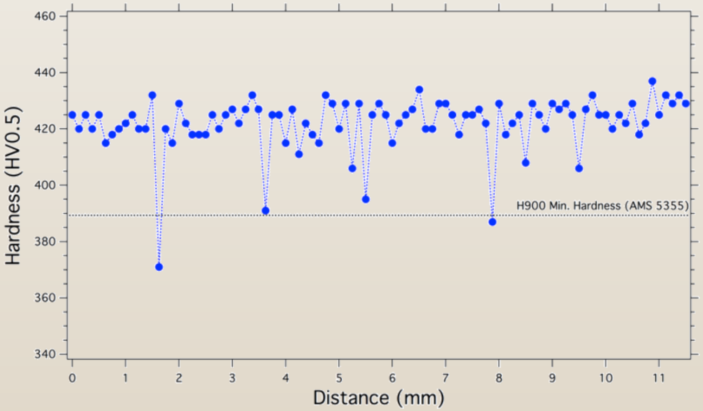
- Microstructure
  - optical, SEM, EBSD, WDS micro-probe
- Composition
  - LECO combustion, ICP mass-spec, XRD
  - powder analysis
- Microhardness



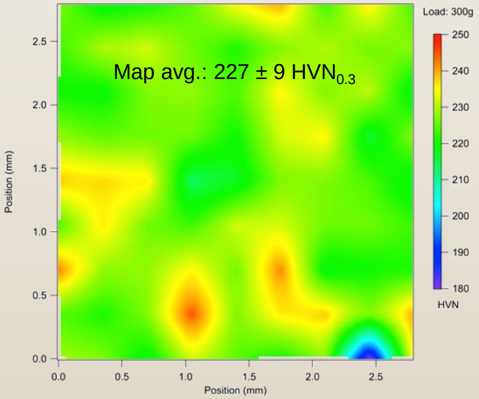
EBSD phase map, SHT+H900, 22% retained austenite

Element	Vendor 1, run 2 (wt%)
Cr	16.64
Mo	0.045
Si	0.38
Nb	0.3
V	0
W	0
Ti	0
Ta	0
Al	0
Ni	4.24
Mn	0.24
C	0.012
N	0.056
Co	0
Cu	4.05
P	0.019
S	0.003
O	0.100
Nb	0.30

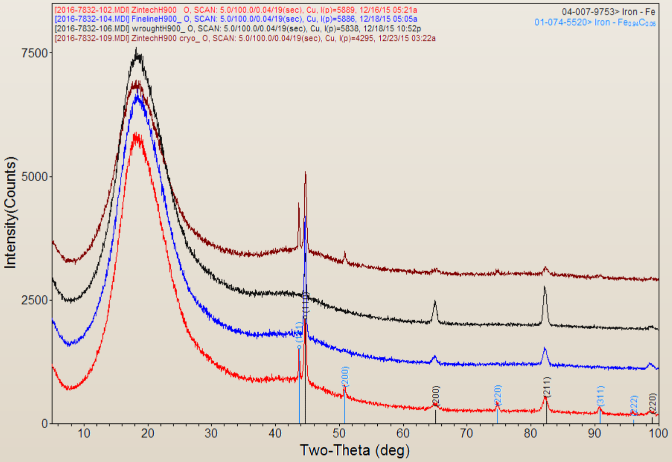
bulk chemical analysis



SHT+H900 microhardness along dogbone length

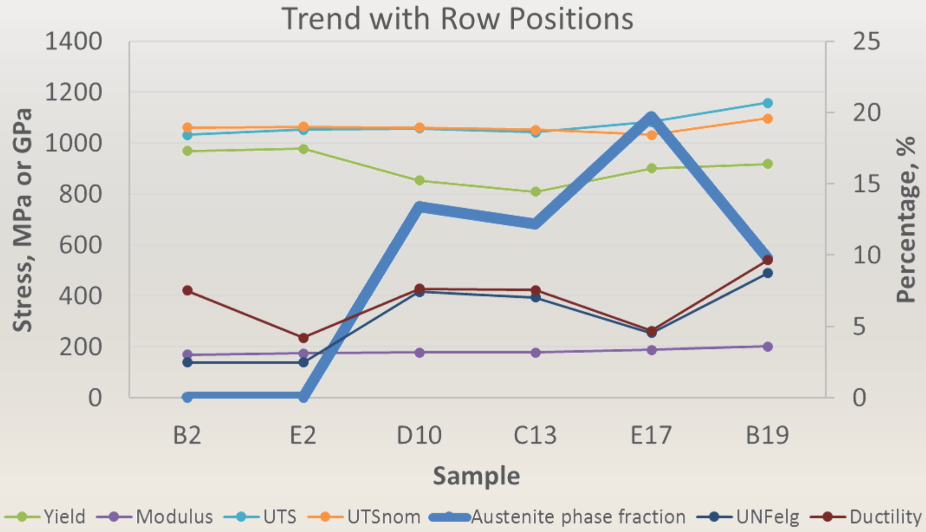


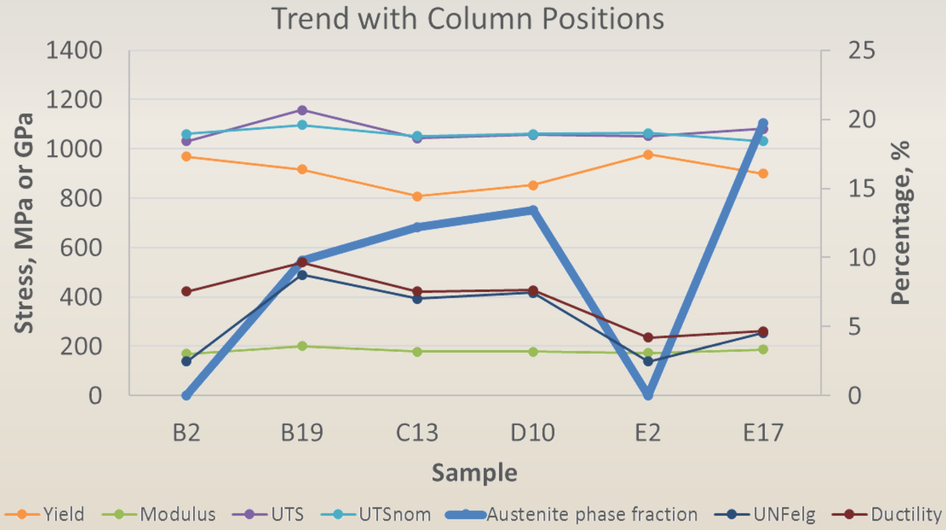
as-printed microhardness on gauge cross section



bulk XRD analysis

Austenite Spatial Variation

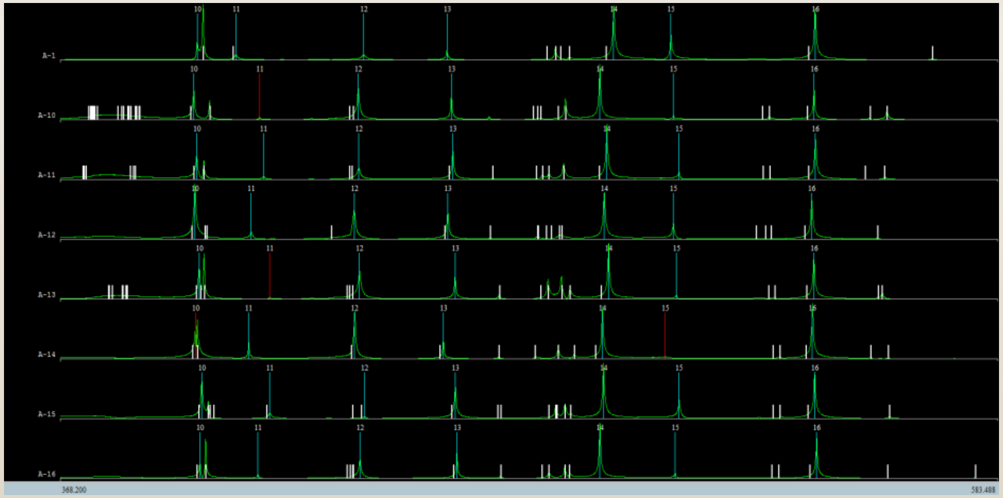




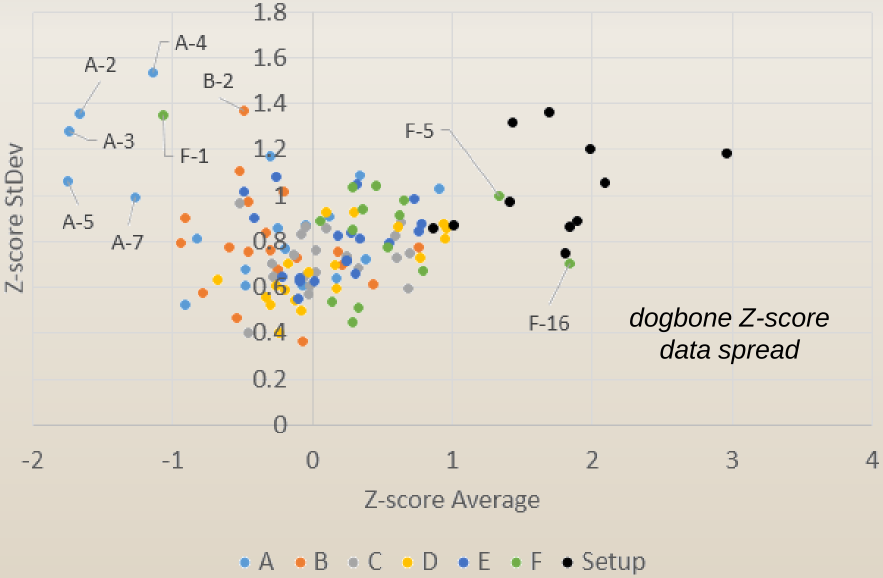
Resonant Ultrasound Spectroscopy

- Swept sine wave input from 2-point transducer
  - spectrum = 74.2 kHz to 1.6 MHz
  - intent is to identify outliers, variations, process limits, defects
- Identified 19 resonance peaks
  - Z-score compares peak frequency w/average & std. dev.
  - no strong trends across 17-4PH dogbone population


dogbone in the 2-point test fixture



resonance response spectra



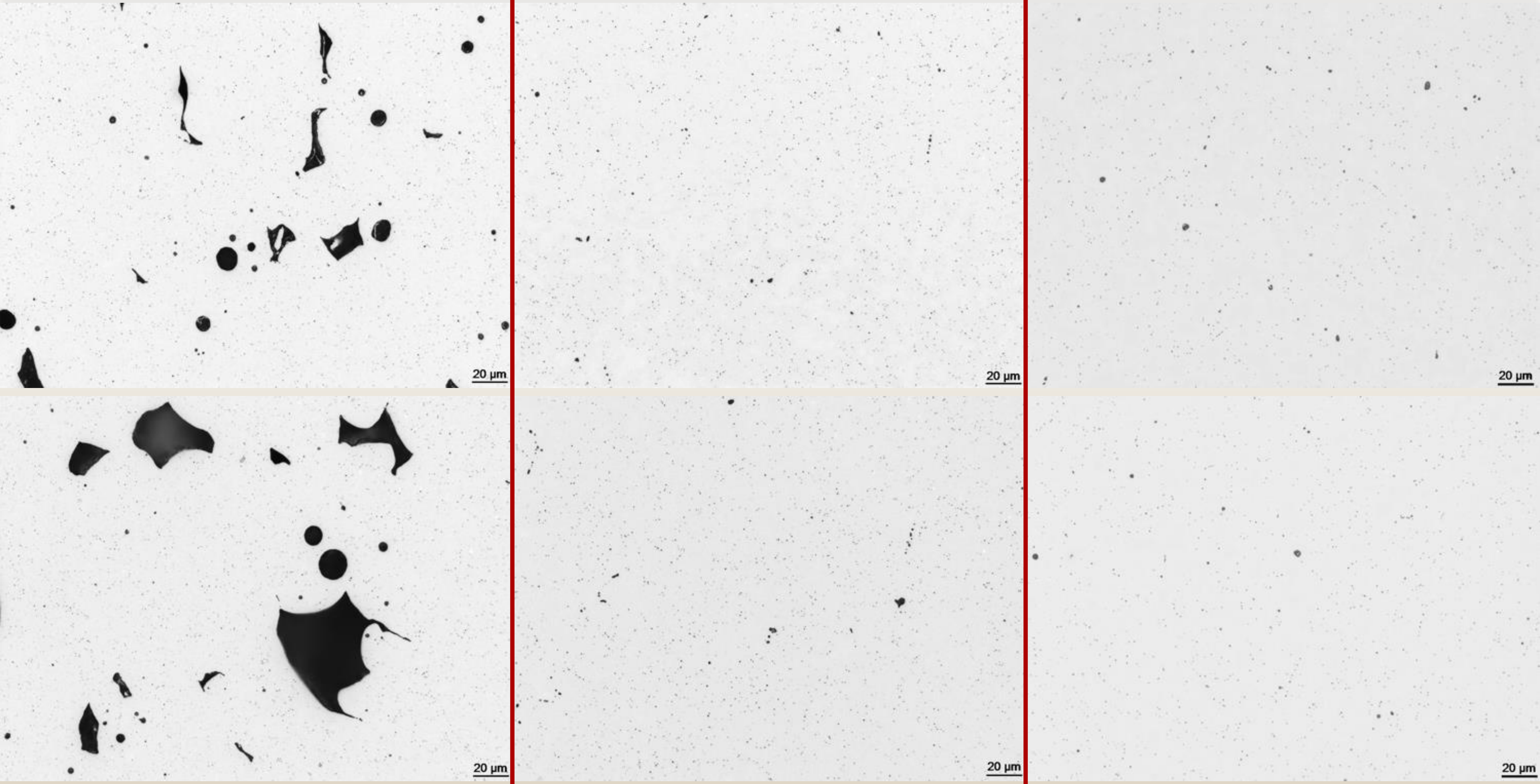
dogbone Z-score data spread

As-Polished Microstructures

As-printed (no HIP)

HIP (15 ksi, 1093°C, 6 hrs)

HIP (15 ksi, 1093°C, 6 hrs) + ambient pressure 1200°C, 2 hrs



APPENDIX HH—OPPORTUNITIES FOR AM IN THE AFTERMARKET SUPPLY CHAIN—AN INDEPENDENT PERSPECTIVE

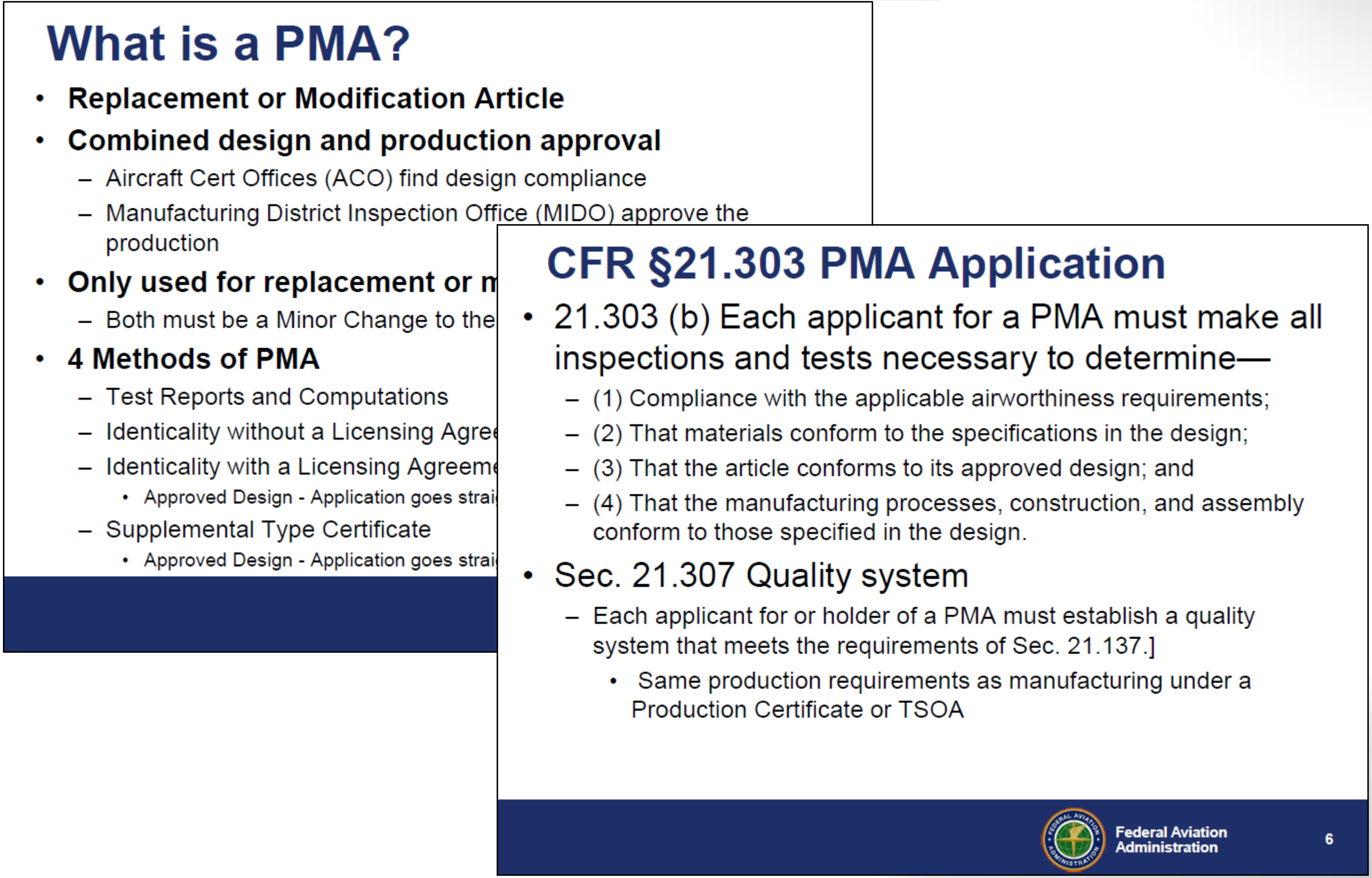
This presentation was considered proprietary and is not appended to the report.

APPENDIX II—THE USE OF ADDITIVE MANUFACTURING FROM A PMA’S PERSPECTIVE

HEICO

The Use of Additive Manufacturing from a PMA’s Perspective

What is PMA? (and How does AM Fit?)



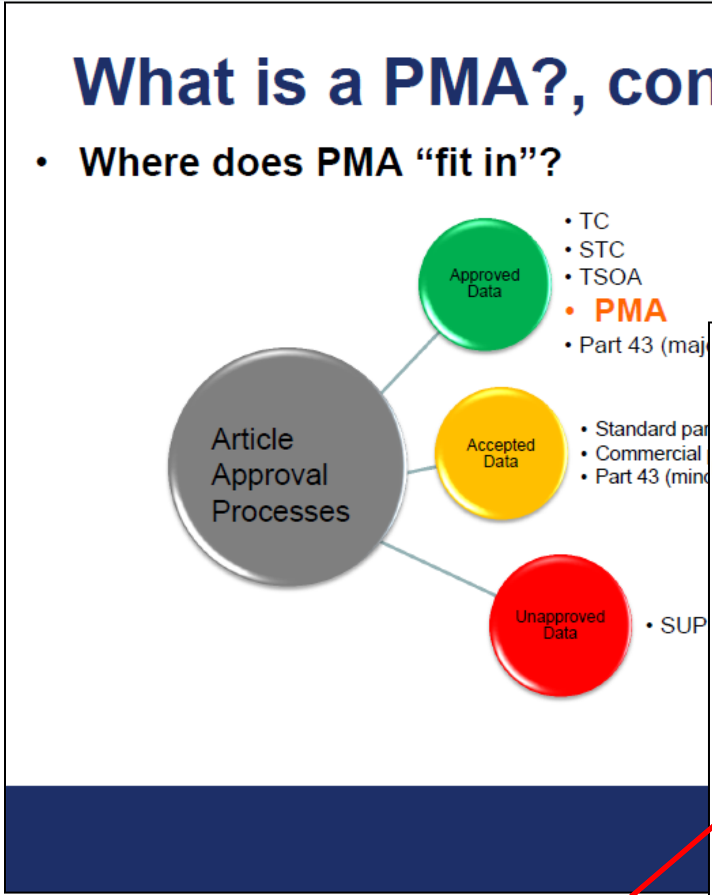
What is a PMA?

- **Replacement or Modification Article**
- **Combined design and production approval**
  - Aircraft Cert Offices (ACO) find design compliance
  - Manufacturing District Inspection Office (MIDO) approve the production
- **Only used for replacement or m**
  - Both must be a Minor Change to the
- **4 Methods of PMA**
  - Test Reports and Computations
  - Identicality without a Licensing Agre
  - Identicality with a Licensing Agreem
    - Approved Design - Application goes strai
  - Supplemental Type Certificate
    - Approved Design - Application goes strai

CFR §21.303 PMA Application

- 21.303 (b) Each applicant for a PMA must make all inspections and tests necessary to determine—
  - (1) Compliance with the applicable airworthiness requirements;
  - (2) That materials conform to the specifications in the design;
  - (3) That the article conforms to its approved design; and
  - (4) That the manufacturing processes, construction, and assembly conform to those specified in the design.
- Sec. 21.307 Quality system
  - Each applicant for or holder of a PMA must establish a quality system that meets the requirements of Sec. 21.137.]
    - Same production requirements as manufacturing under a Production Certificate or TSOA

What is PMA? (and How does AM Fit?)



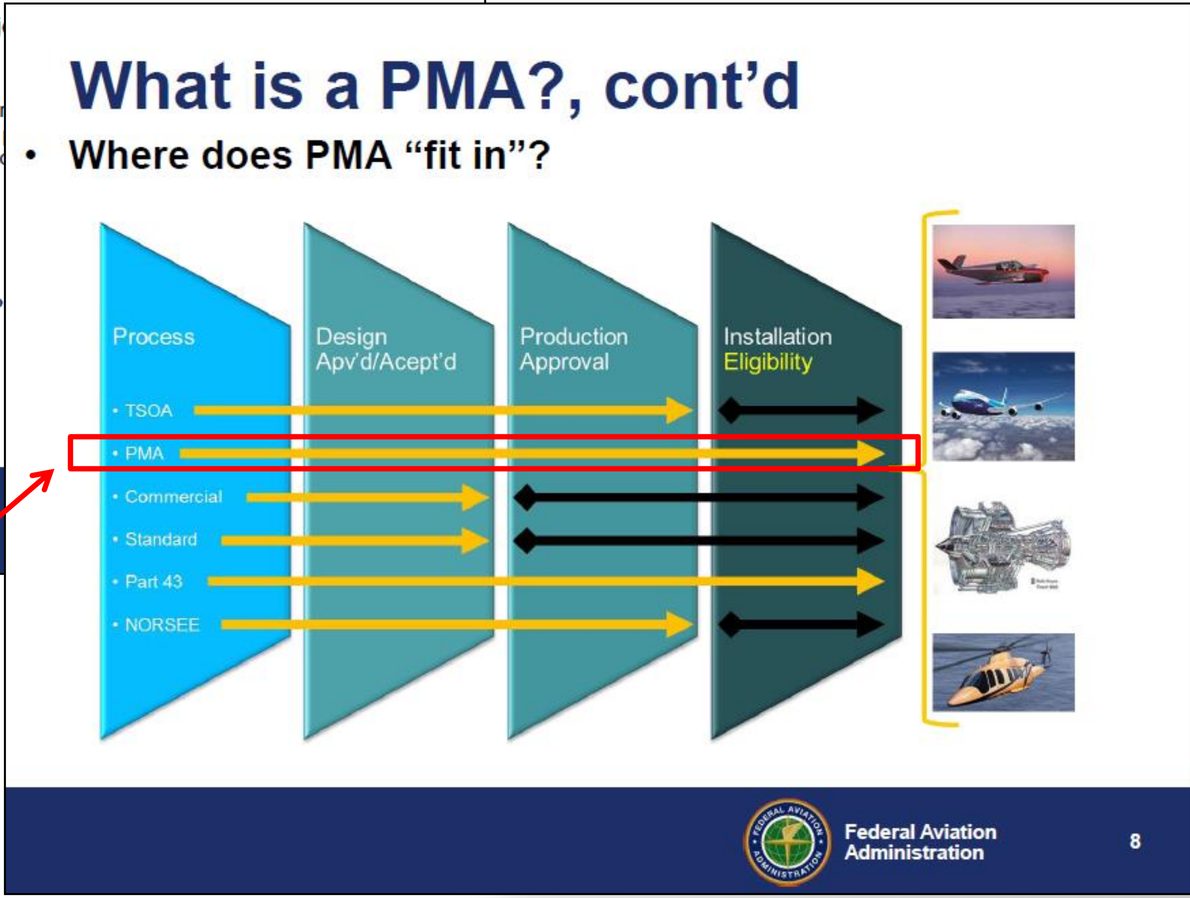
What is a PMA?, cont'd

- Where does PMA "fit in"?

- TC
- STC
- TSOA
- **PMA**
- Part 43 (maj

- Standard par
- Commercial
- Part 43 (minc

- SUP



What is a PMA?, cont'd

- Where does PMA "fit in"?

Federal Aviation Administration

PMA is Design, Production and Installation Approval

Replacement Part Options

- Owner/Operators have a variety of sources to obtain parts; TC/PC Holder, PMA Holder, TSOA, repair or alter existing parts, fabricate parts during maintenance, owner produce parts, etc.
- Each of these sources can use a wide range of proven manufacturing methods (traditional, additive, conventional, non conventional) to produce these parts.
- In order to approve these parts for installation on a type certificated aircraft, All must comply with applicable airworthiness standards, conform to the approved data and be safe for operation

Replacement Part Options (including AM)

Typical OEM Parts

Typical PMA Parts

O/O Parts

Part Type	TC/PC holder	TSOA holder	STC/PC-PMA holder	PMA holder	Owner/ Operator
Design (Approval)	TC holder	TSOA holder	STC holder	PMA holder	Owner/ Operator
Quality System (Approval)	PC holder	TSOA holder	PC or PMA holder	PMA holder	Owner/ Operator
Application	Part for a Product	Part for an Article	Part on a Product	Part on a Product	Only Owner/ Operator fleet

All replacement parts follow a robust Design and Production Approval Process.

Additive Manufacturing can be used in any option.

14 CFR Design Requirements

PMA Applicant

§21.303 Application.

(a) (3) The design of the article, which consists of—

- (i) Drawings and specifications necessary to show the configuration of the article; and
- (ii) Information on dimensions, materials, and processes necessary to define the structural strength of the article.

Same requirements

Type Certificate Applicant

§21.31 Type design.

The type design consists of—

(a) The drawings and specifications, and a listing of those drawings and specifications, necessary to define the configuration and the design features of the product shown to comply with the requirements of that part of this subchapter applicable to the product;

(b) Information on dimensions, materials, and processes necessary to define the structural strength of the product;

Drawings and Specifications necessary

to define the **structural strength**

Also Apply in Additive Manufacturing

14 CFR Compliance Requirements

PMA Applicant

§21.303 Application.

(a) The applicant for a PMA must apply in a form and manner prescribed by the FAA, and include the following:

(4) Test reports and computations necessary to show that the design of the article meets the airworthiness requirements of this subchapter. …

(5) An applicant for a PMA based on test reports and computations must provide a statement certifying that the applicant has complied with the airworthiness requirements of this subchapter.

Same requirements

Type Certificate Applicant

§21.20 Compliance with applicable requirements.

The applicant for a type certificate, including an amended or supplemental type certificate, must—

(a) Show compliance with all applicable requirements and must provide the FAA the means by which such compliance has been shown; and

(b) Provide a statement certifying that the applicant has complied with the applicable requirements.

Show Compliance with airworthiness requirements.

Provide Certifying Statement

Also Apply in Additive Manufacturing

14 CFR Quality System Requirements

PMA Applicant

§21.303 Quality System.

Each applicant for or holder of a PMA must establish a quality system that meets the requirements of §21.137.

Same requirements

Quality Systems:

Mfg Process Control and Inspections and Testing to ensure article conforms to its design.

Production Certificate Applicant

§21.137 Quality system.

Each applicant for or holder of a production certificate must establish and describe in writing a quality system that ensures that each product and article conforms to its approved design and is in a condition for safe operation. This quality system must include:

(a) *Design data control.* Procedures for controlling design data and subsequent changes to ensure that only current, correct, and approved data is used.

(d) *Manufacturing process control.* Procedures for controlling manufacturing processes to ensure that each product and article conforms to its approved design.

(e) *Inspecting and testing.* Procedures for inspections and tests used to ensure that each product and article conforms to its approved design. These procedures must include the following, as applicable:

Also Apply in Additive Manufacturing

Requirements for Additive Manufacturing

The **same requirements** for design, manufacturing, quality control, certification and Continued Operational Safety apply to **ALL design** approval holders (TC/PC, PMA, STC, TSOA) across **ALL methods** of manufacture

PMA (TC/PC, TSOA, etc) perspective on AM

The **same requirements** for **ALL design** approval holders across **ALL methods** of manufacture

Drawings and Specifications necessary to define the **structural strength**

Show Compliance with airworthiness requirements.

Provide Certifying Statement

Mfg Process Control and Inspections and Testing to ensure article conforms to its design.

Also Apply in Additive Manufacturing

AM Benefits

Rapid production of a part, prototype, or tooling

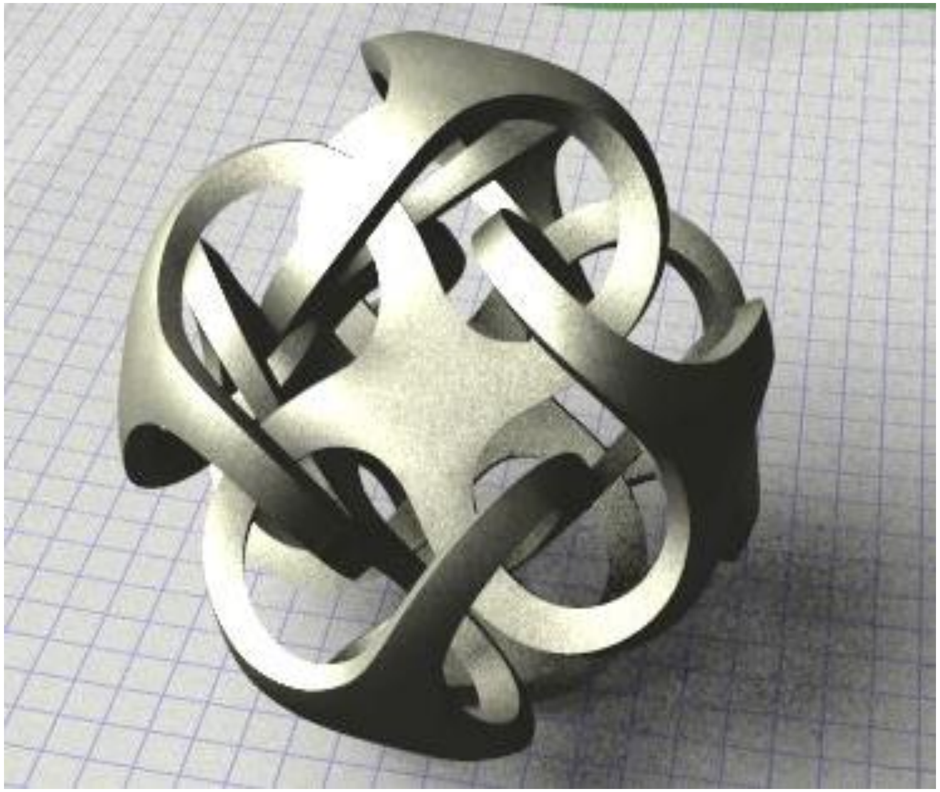
- An actual part/prototype/tool may be produced in a few days or less
- Minimal machining possible as parts can be near net shape
- Ideal for when low volumes are necessary

Complex parts can be produced that cannot be produced conventionally

- Welded and Brazed configurations can be replaced by a 1 piece part
- Lightener holes can be introduced that are not even open to the surface
- No Geometric Complexity Penalty

Much less waste generated from AM near net Shape as compared to conventional “Subtractive” manufacturing

AM Benefits



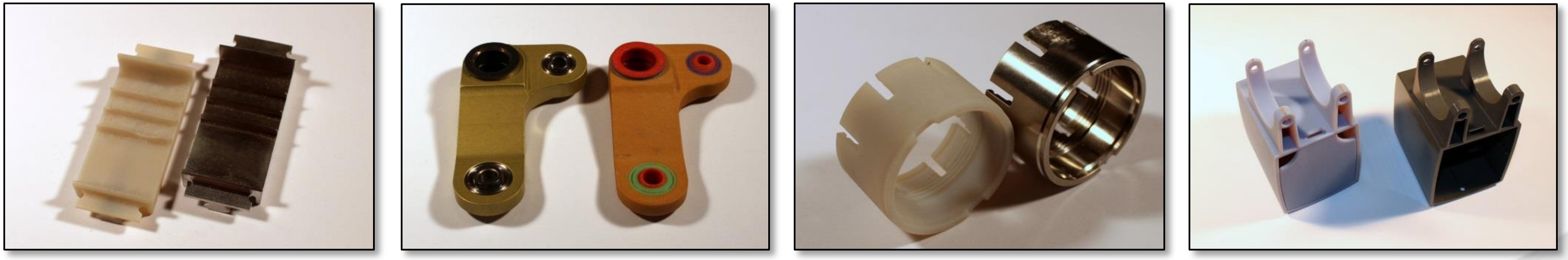
Parts that are impossible to produced by conventional manufacturing can be produced by additive manufacturing

AM Application Sequence

Non-Certified Parts - (in current use at HEICO)

- Prototype validation
- Inspection Tools

- Tooling Production
- Assembly Tools
- Casting Cores



Certified / Airworthy Parts - (future development)

- Non-Structural (non-Metallic)
- Structural non-Metallic

- Non-Structural Metallic
- Structural metallic

Future Use (and non-Uses)

Future Uses (Good AM Applications)

- Complex Geometry
- Low Volume / Time Sensitive Production
- Tooling Intensive Parts

Non-Future Uses (Not good AM Applications)

- Simple Geometry
- Simple MFG methods
- Large Volume Productions

- Questions

APPENDIX JJ—FAA AM ROADMAP OVERVIEW

Federal Aviation
Administration

Metal Additive Manufacturing FAA Roadmap Update

Presented at:

3rd Joint FAA – AFRL AM Workshop

August 31, 2017

Dayton, OH

Prepared by:

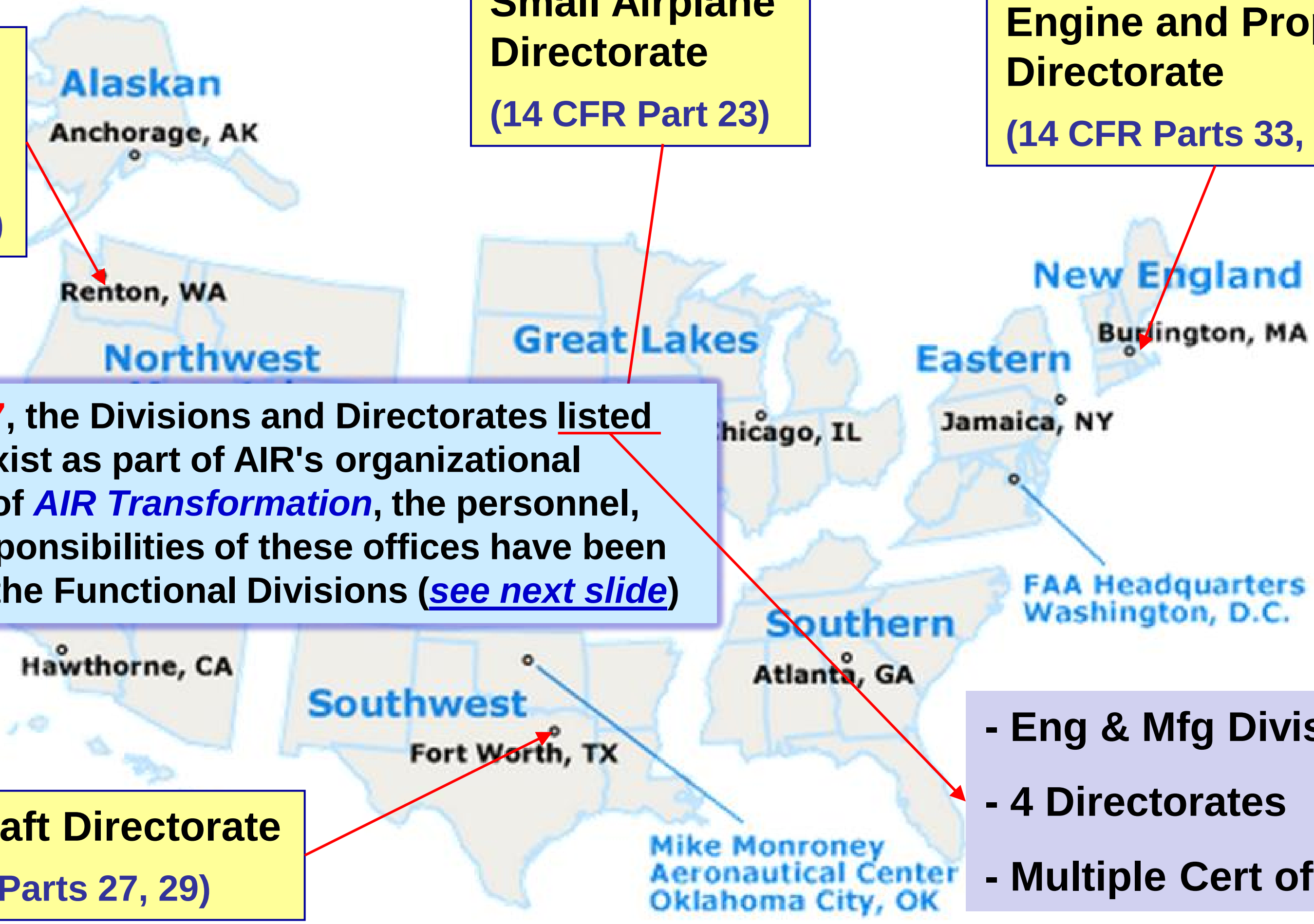
Dr. Michael Gorelik

FAA Chief Scientist and Technical Advisor

for Fatigue and Damage Tolerance

Pre-realignment AIR Structure

(AIR = FAA Aircraft Certification Service)



Transport Airplane Directorate

(14 CFR Part 25)

Small Airplane Directorate

(14 CFR Part 23)

Engine and Propeller Directorate

(14 CFR Parts 33, 35)

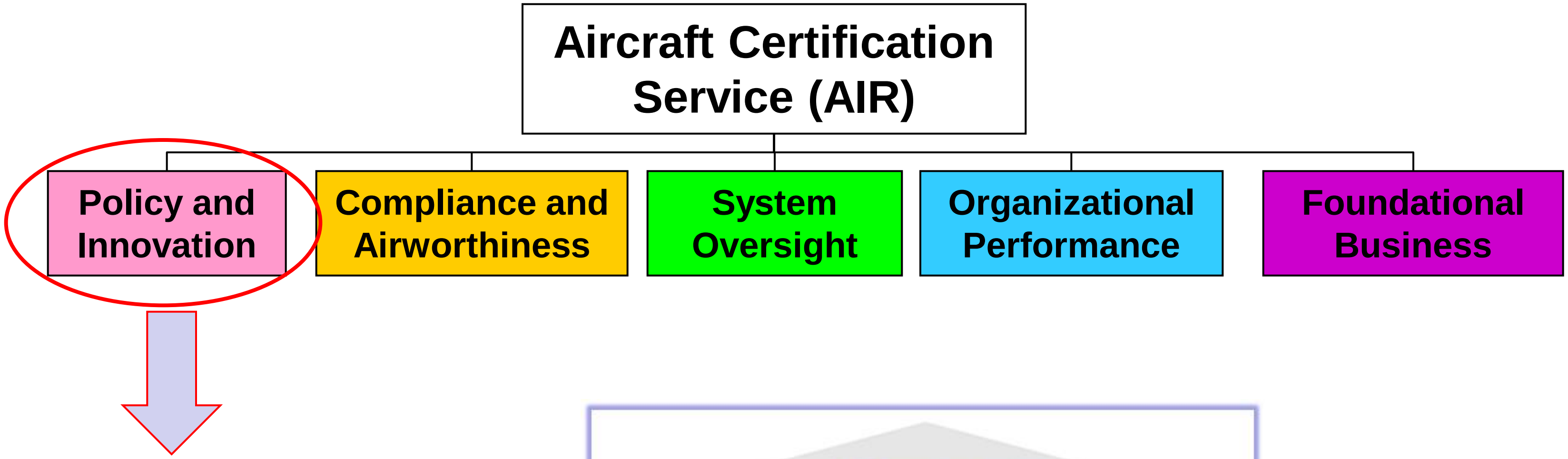
Rotorcraft Directorate

(14 CFR Parts 27, 29)

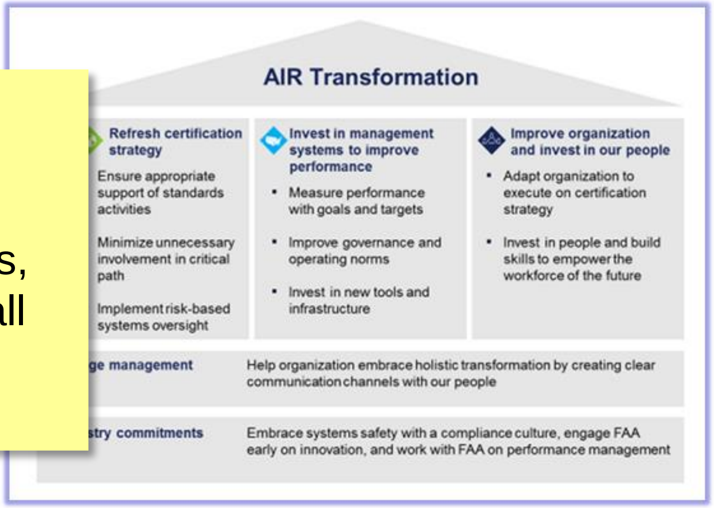
As of July 23, 2017, the Divisions and Directorates listed below no longer exist as part of AIR's organizational structure; as part of *AIR Transformation*, the personnel, functions, and responsibilities of these offices have been incorporated into the Functional Divisions (*see next slide*)

- Eng & Mfg Division (HQ)
- 4 Directorates
- Multiple Cert offices

AIR Transformation *(effective 7-23-17)*



The **Policy & Innovation Division** *supports aerospace innovation* by creating novel means of compliance, develops and maintains AIR regulations, manages the CSTA program and overall fleet safety, as well as educational outreach.



AIR Transformation

Refresh certification strategy

Ensure appropriate support of standards activities

Minimize unnecessary involvement in critical path

Implement risk-based systems oversight

Invest in management systems to improve performance

- Measure performance with goals and targets
- Improve governance and operating norms
- Invest in new tools and infrastructure

Improve organization and invest in our people

- Adapt organization to execute on certification strategy
- Invest in people and build skills to empower the workforce of the future

ge management Help organization embrace holistic transformation by creating clear communication channels with our people

stry commitments Embrace systems safety with a compliance culture, engage FAA early on innovation, and work with FAA on performance management

Public-facing AIR Transformation Web Site:

https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/air/transformation/

Concept of Innovation Centers

- *Key element of the new AIR* ***Policy & Innovation*** *function*
- *Provides robust mechanism* ***to address new technologies*** and MOC (means of compliance)
  - Late awareness can result in project delays
- Be more proactive prior to the initial project application
  - Identify new technology or MOCs beyond the scope of existing regulations and policy
- Supports FAA efforts to streamline certification process
- Success is dependent on OEMs buying into the concept
  - Early engagement
  - Company proprietary / intellectual property concerns

Emerging technologies similar to AM will be addressed by Innovation Centers once they are implemented

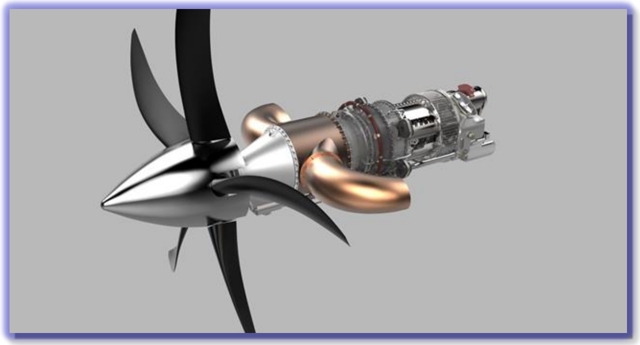
Excerpts from AMNT Charter

- **AIR-100 management *requested the development of a roadmap for determining the needs for policy and guidance along with any training for certifying projects utilizing AM parts*.**
- **The *roadmap will be developed and implemented by the Additive Manufacturing National Team* (AMNT) which will require resources, input, and support from AIR directorates, Flight Standards and offices.**
- **The roadmap *will identify FAA concerns and recommendations to insure application of robust and consistent safety standards* for design, manufacture and field management of AM products.**
- **The development of this roadmap *will require coordination with other government agencies, academia and industry organizations*.**

Examples of Expanding Use of AM

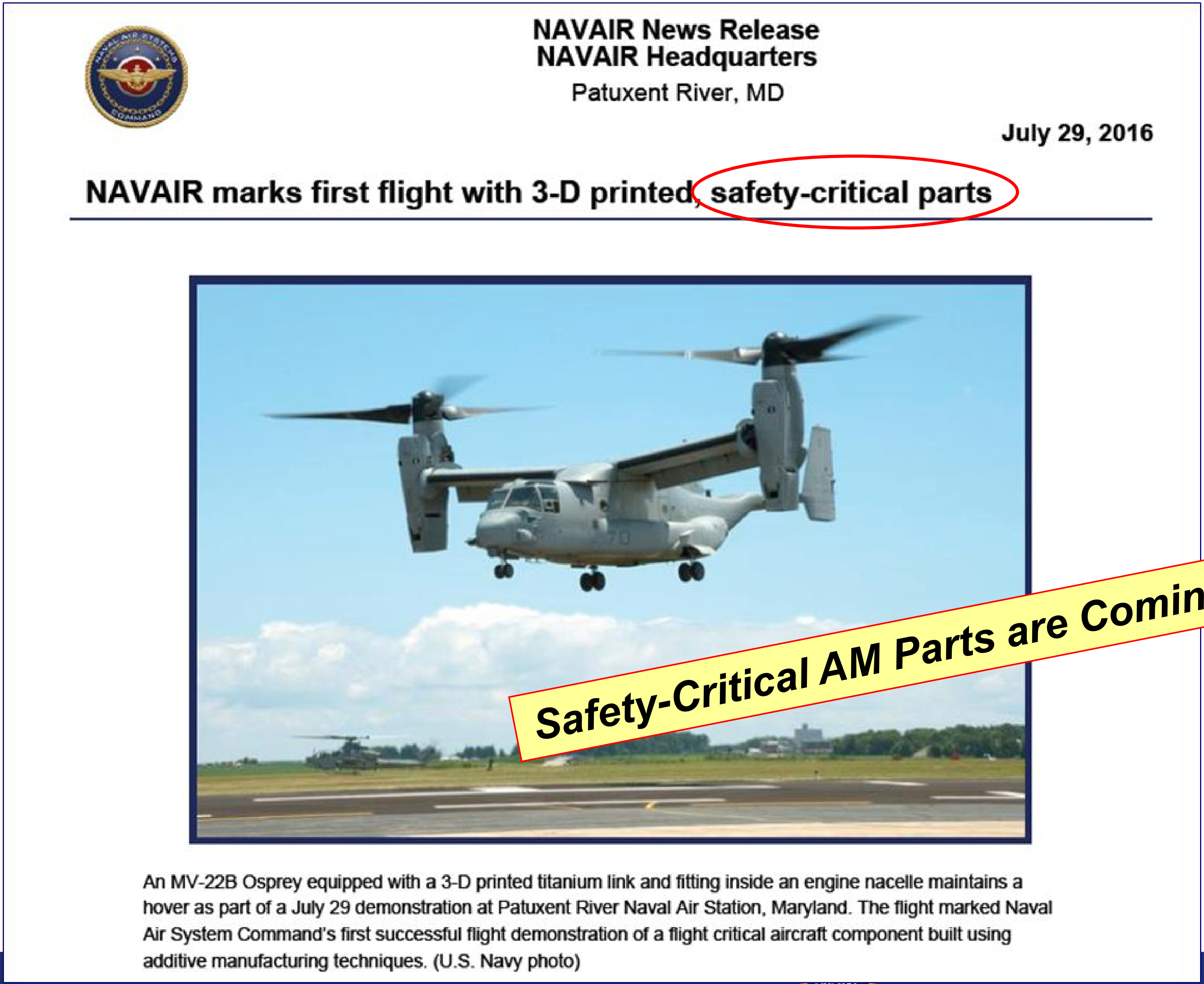
- **"GE *Advanced Turboprop* is the first Aviation product to fully utilize additive tools…"**
  - **It has 30% fewer parts (from 800+ to *15 parts*), and will be completed with a 50% reduction in cycle time**

From GE 2016 Annual Report



"By 2018 Airbus expects to print about *30 tons of metal AM parts every month*, according to a company statement…"

http://www.3dcadworld.com/manufacturers-turn-additive-made-metal-parts/



NAVAIR News Release
NAVAIR Headquarters
Patuxent River, MD

July 29, 2016

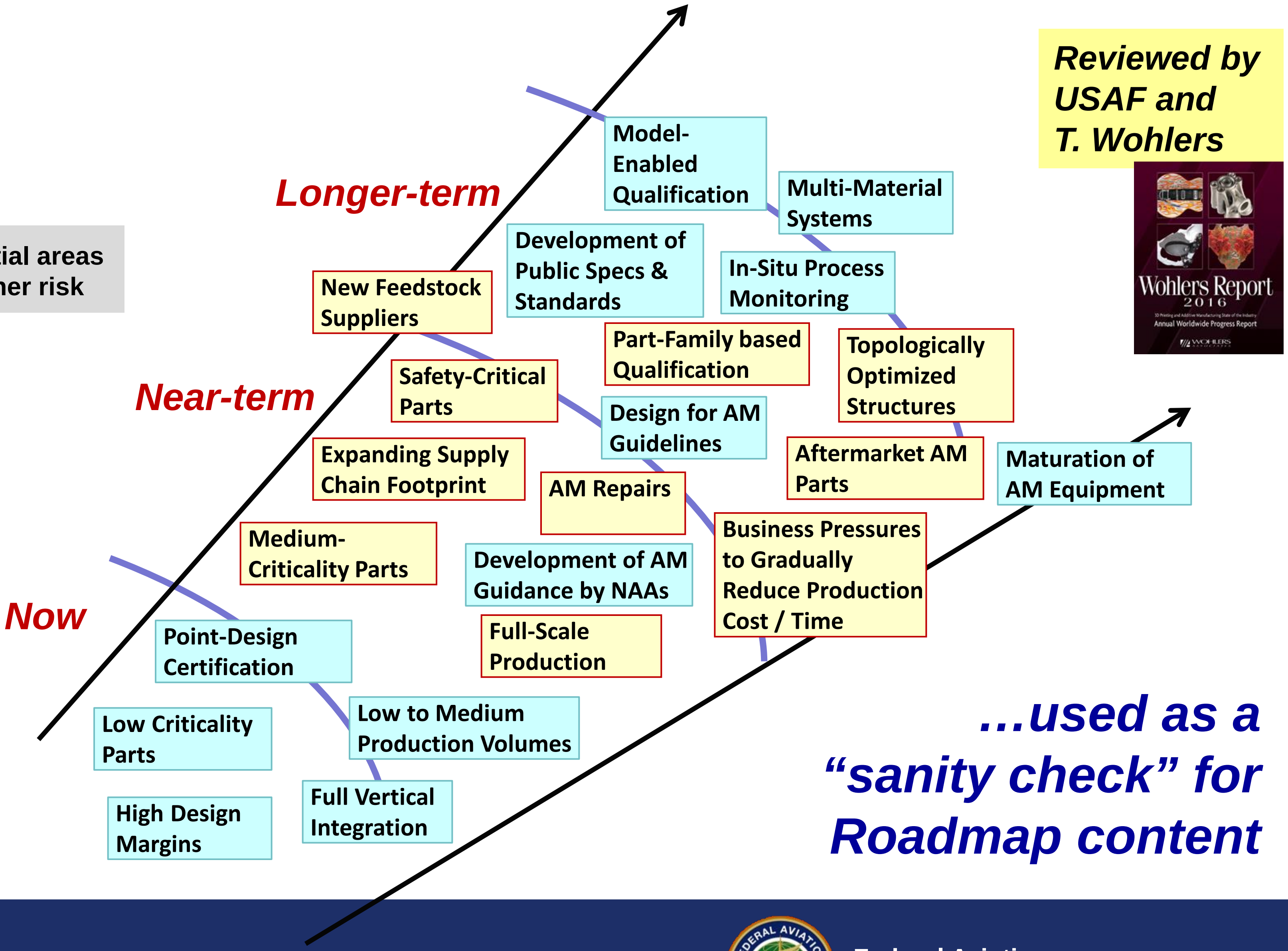
NAVAIR marks first flight with 3-D printed, safety-critical parts

An MV-22B Osprey equipped with a 3-D printed titanium link and fitting inside an engine nacelle maintains a hover as part of a July 29 demonstration at Patuxent River Naval Air Station, Maryland. The flight marked Naval Air System Command's first successful flight demonstration of a flight critical aircraft component built using additive manufacturing techniques. (U.S. Navy photo)

Safety-Critical AM Parts are Coming…

Expected Evolution of AM Landscape…

🟨 Potential areas of higher risk



Longer-term

Near-term

Now

Model-Enabled Qualification

Multi-Material Systems

Development of Public Specs & Standards

In-Situ Process Monitoring

New Feedstock Suppliers

Part-Family based Qualification

Topologically Optimized Structures

Safety-Critical Parts

Design for AM Guidelines

Expanding Supply Chain Footprint

Aftermarket AM Parts

Maturation of AM Equipment

AM Repairs

Medium-Criticality Parts

Business Pressures to Gradually Reduce Production Cost / Time

Development of AM Guidance by NAAs

Full-Scale Production

Point-Design Certification

Low to Medium Production Volumes

Low Criticality Parts

Full Vertical Integration

High Design Margins

Reviewed by USAF and T. Wohlers

…used as a "sanity check" for Roadmap content

AM Roadmap – Main Focus Areas (“swimlanes”)

(1) *Engineering Certification*

(2) *Production / QA*

(3) *Maintenance / MROs*

(4) *COS*

Enablers

(5) *Workforce Education (FAA + Designees + Industry)*

(6) *R&D*

Key Elements of the AM Roadmap Content

(4 regulatory swimlanes)

- **Key Risk Factors**
- **Regulatory gap analysis**
- **Proposed new or revised documents (policies, ACs, …)**
  - ***No rule changes expected***
- **Key Tasks and Project Plan (high level)**
- **"Inter-dependencies" between the 4 swimlanes**
- **Input into R&D and Training swimlanes**

Note:

- ***It is recognized that we may not currently have enough internal knowledge and experience to address some of the items above →***

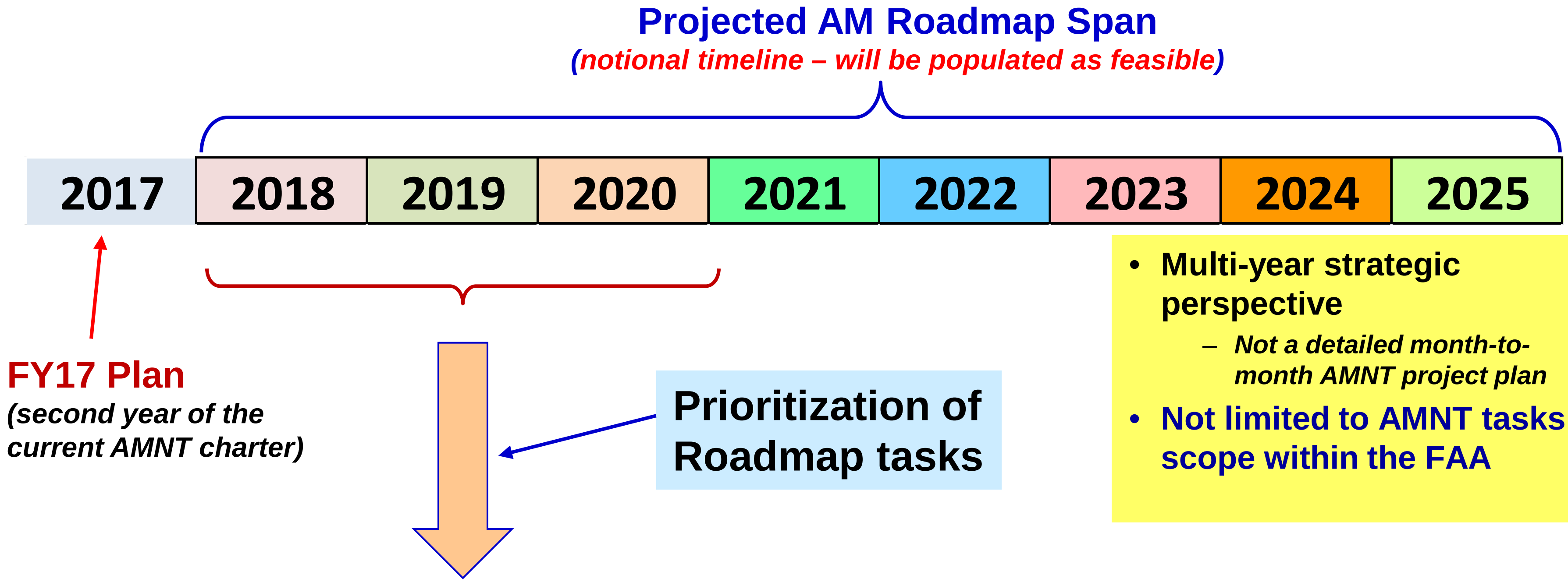
see next page

Options to Address Current Knowledge Gaps

- **Industry engagement (AIA, GAMA, MARPA, other..?)**
- **Engagement with SDOs (SAE, ASTM, AWS, …)**
- **Government engagement (USAF, NAVAIR, NASA, NIST, America Makes…)**
- **R&D (internal / external)**
- **CSTA and other targeted workshops (e.g. DER conferences, ARSA, …)**
- **FAA AM certification projects benchmarking**
- **Manufacturing surveillance**
- **AMNT site visits to production facilities (outreach)**
- **Coordination with NAAs**

Most of these mechanisms are already engaged

AM Roadmap Timeline



Projected AM Roadmap Span

(notional timeline – will be populated as feasible)

2017	2018	2019	2020	2021	2022	2023	2024	2025

FY17 Plan

(second year of the current AMNT charter)

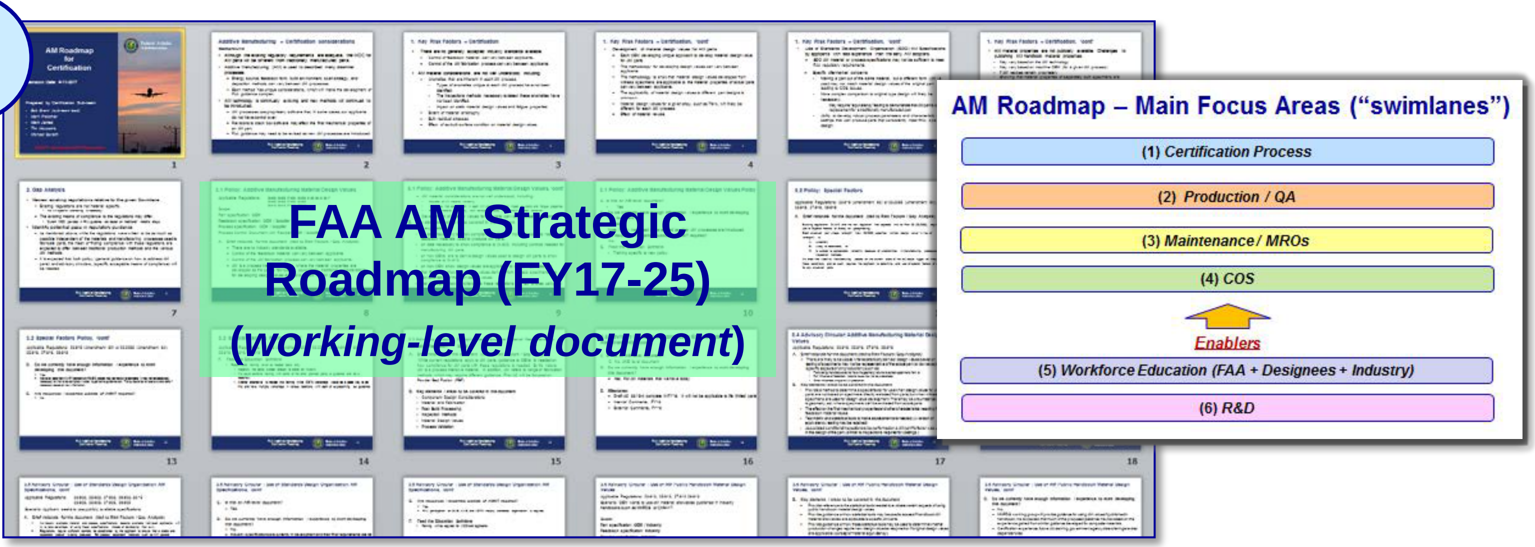
Prioritization of Roadmap tasks

- **Multi-year strategic perspective**
  - *Not a detailed month-to-month AMNT project plan*
- **Not limited to AMNT tasks / scope within the FAA**

FY18-20 **"tactical" project plan**

3-Tier Documentation Approach

1



FAA AM Strategic Roadmap (FY17-25)

(working-level document)

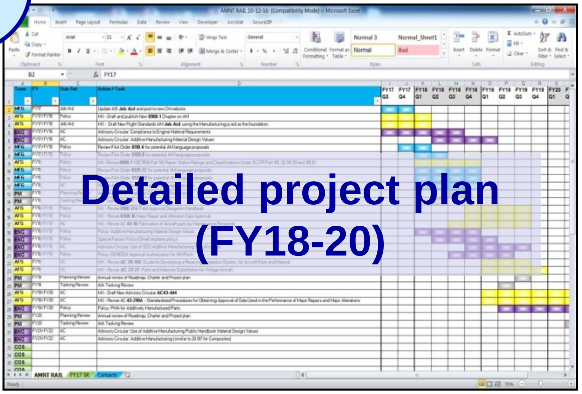
AM Roadmap – Main Focus Areas ("swimlanes")

- *(1) Certification Process*
- *(2) Production / QA*
- *(3) Maintenance / MROs*
- *(4) COS*

Enablers

- *(5) Workforce Education (FAA + Designees + Industry)*
- *(6) R&D*

2



Detailed project plan (FY18-20)

coordinated

3

Deliverable to AIR-1

FAA
Aviation Safety (AVS)

Additive Manufacturing
AVS Strategic ~~Composite~~ Plan

Executive Summary

The purpose of the AVS Strategic Composite Plan is to ensure safe and efficient use of composite materials in aircraft products. [illegible] international safety and certification initiatives for composite airplane structures. This plan focuses on three main areas: Continued Operational Safety (COS); Certification Efficiency (CE); and Workforce Education (WE). The plan is updated annually to reas[illegible] approach involving [illegible] authorities, research organizations, and other government agencies. The plan is [illegible] practices, certification and field experiences, research, and projected technological

AVS Business Plan Items (FY17-25)

Due by the end of FY17

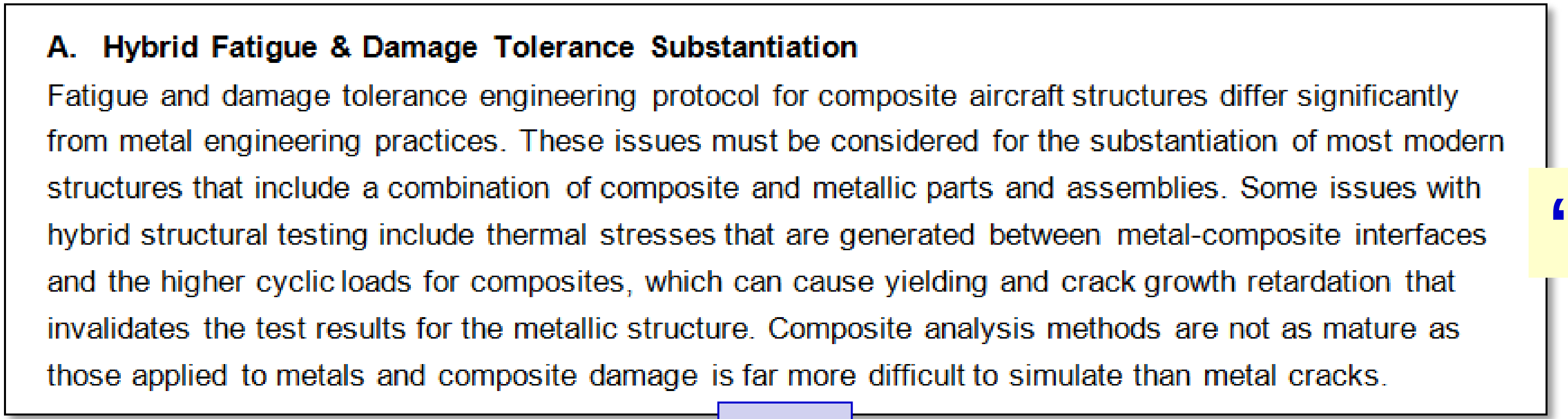
Benchmarking of Composites ACs

- **Three ACs from the "Early Days" of Composites**
  - Composite aircraft structure → **AC 20-107A** (1984)
  - Composite manufacturing quality control → **AC 21-26** (1989)
  - Repair Stations for Composite and Bonded Aircraft Structure → **AC 145-6** (1996)

These and Similar Documents are Being Considered by the AM Roadmap Team

Benchmarking of AVS Composite Plan

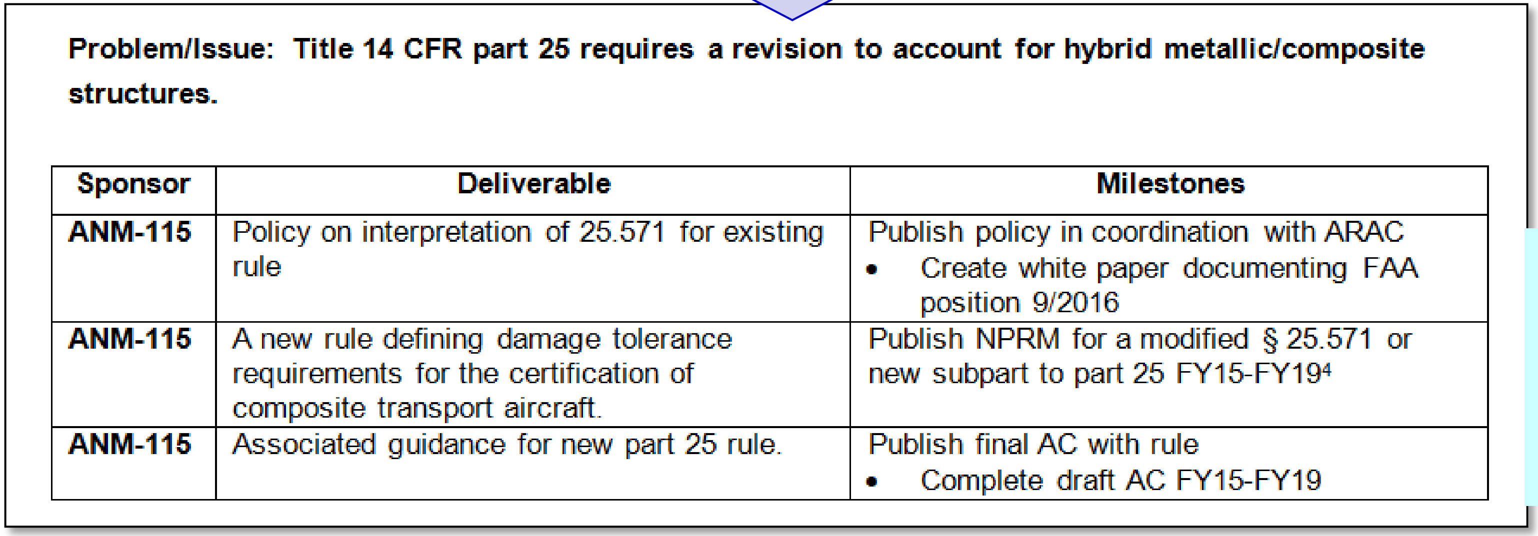
(will be used as a template for the final MS Word version of the Roadmap document)



A. Hybrid Fatigue & Damage Tolerance Substantiation

Fatigue and damage tolerance engineering protocol for composite aircraft structures differ significantly from metal engineering practices. These issues must be considered for the substantiation of most modern structures that include a combination of composite and metallic parts and assemblies. Some issues with hybrid structural testing include thermal stresses that are generated between metal-composite interfaces and the higher cyclic loads for composites, which can cause yielding and crack growth retardation that invalidates the test results for the metallic structure. Composite analysis methods are not as mature as those applied to metals and composite damage is far more difficult to simulate than metal cracks.

"What"



Problem/Issue: Title 14 CFR part 25 requires a revision to account for hybrid metallic/composite structures.

Sponsor	Deliverable	Milestones
ANM-115	Policy on interpretation of 25.571 for existing rule	Publish policy in coordination with ARAC • Create white paper documenting FAA position 9/2016
ANM-115	A new rule defining damage tolerance requirements for the certification of composite transport aircraft.	Publish NPRM for a modified § 25.571 or new subpart to part 25 FY15-FY19[4]
ANM-115	Associated guidance for new part 25 rule.	Publish final AC with rule • Complete draft AC FY15-FY19

"How"
and
"When

External Benchmarking

National Aeronautics and
Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

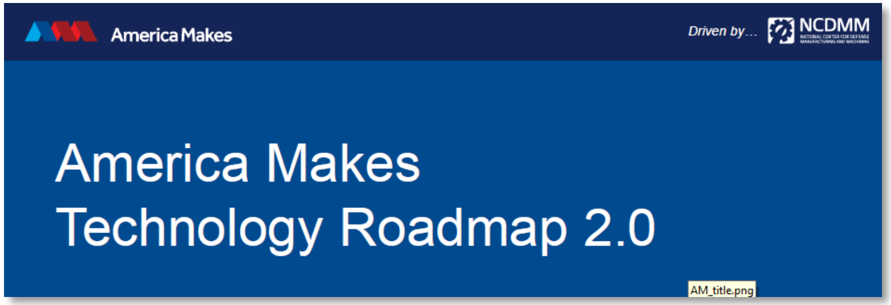
EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard
for Additively Manufactured
Spaceflight Hardware

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

Measurement
Science
Roadmap for
Metal-Based
Additive
Manufacturing

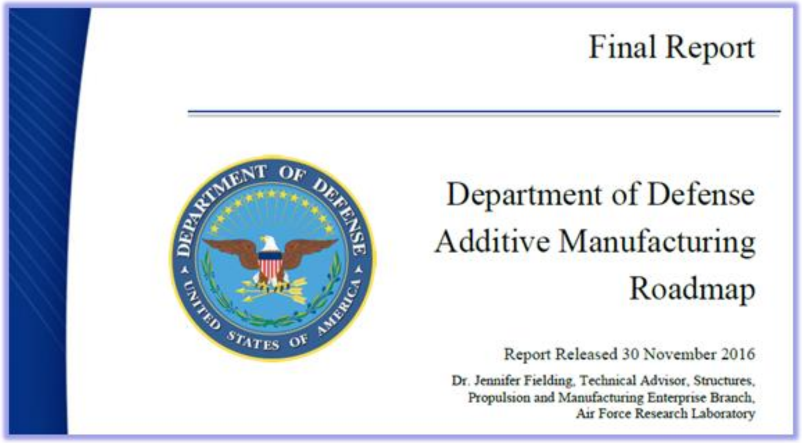


America Makes

Driven by… NCDMM

America Makes
Technology Roadmap 2.0

AM_title.png



Final Report

Department of Defense
Additive Manufacturing
Roadmap

Report Released 30 November 2016

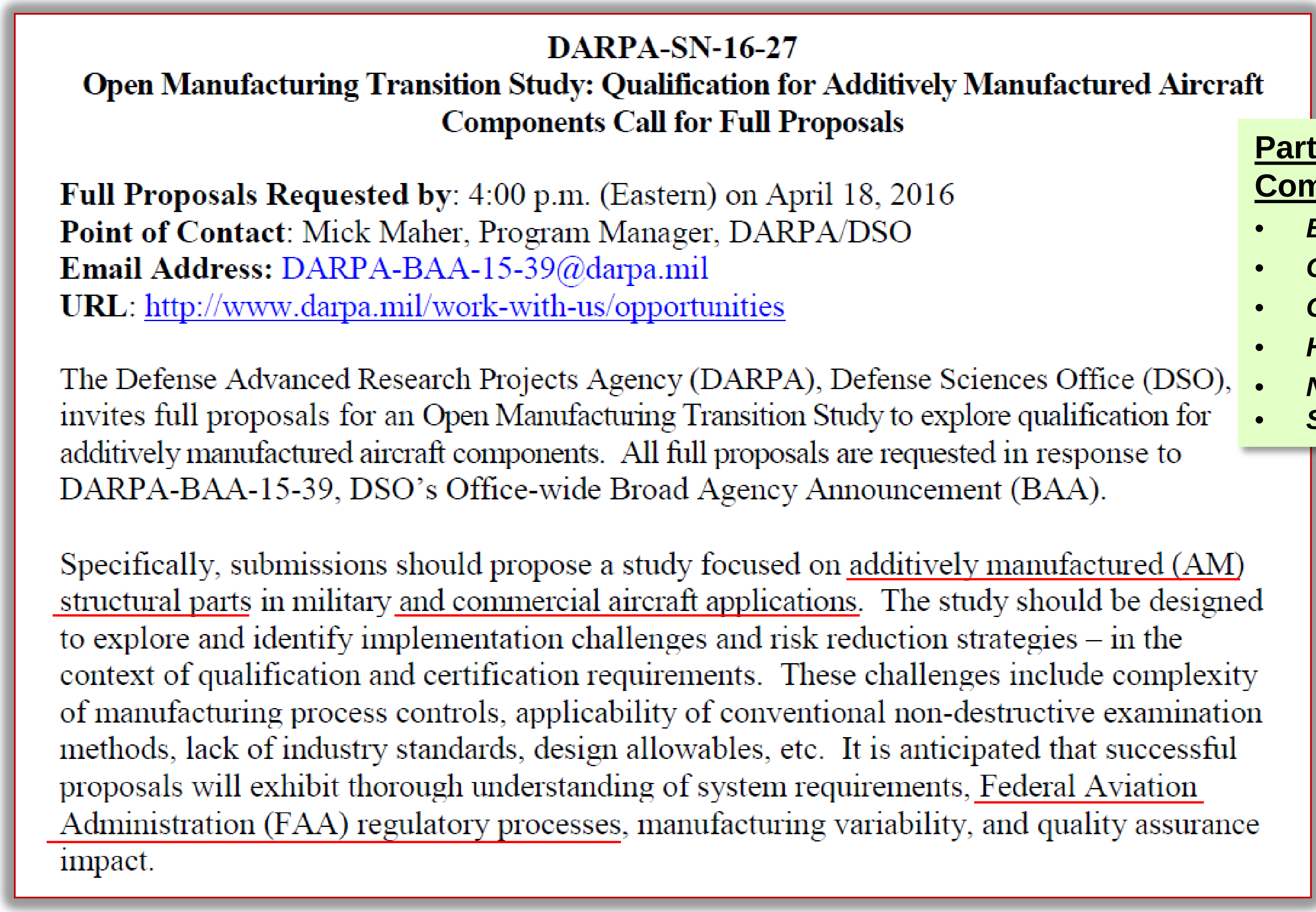
Dr. Jennifer Fielding, Technical Advisor, Structures,
Propulsion and Manufacturing Enterprise Branch,
Air Force Research Laboratory

Prioritization Considerations

- **Safety impact**
  - Expected increase in criticality of applications
    - "minor effect" → "major effect" → "safety-critical" / timeline?
  - Various industry segments (e.g. OEMs, Tier 1, PMAs, MROs…)
- **Certification process**
  - Breadth of application (e.g. multiple categories of parts / multiple product types)
  - Industry deployment timeline (e.g. current TRL / MRL levels)
  - Regulatory gaps (applicability of current policies / advisory materials)
  - Current experience level (development / full-scale production / field)
- **Other considerations**
  - Availability of industry specs and standards (materials, processes)
  - Availability of industry design / properties data

Example of Inter-agency Collaboration

(Leveraging R&D Resources of Other Agencies)



DARPA-SN-16-27

Open Manufacturing Transition Study: Qualification for Additively Manufactured Aircraft Components Call for Full Proposals

Full Proposals Requested by: 4:00 p.m. (Eastern) on April 18, 2016
Point of Contact: Mick Maher, Program Manager, DARPA/DSO
Email Address: DARPA-BAA-15-39@darpa.mil
URL: http://www.darpa.mil/work-with-us/opportunities

The Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office (DSO), invites full proposals for an Open Manufacturing Transition Study to explore qualification for additively manufactured aircraft components. All full proposals are requested in response to DARPA-BAA-15-39, DSO's Office-wide Broad Agency Announcement (BAA).

Specifically, submissions should propose a study focused on additively manufactured (AM) structural parts in military and commercial aircraft applications. The study should be designed to explore and identify implementation challenges and risk reduction strategies – in the context of qualification and certification requirements. These challenges include complexity of manufacturing process controls, applicability of conventional non-destructive examination methods, lack of industry standards, design allowables, etc. It is anticipated that successful proposals will exhibit thorough understanding of system requirements, Federal Aviation Administration (FAA) regulatory processes, manufacturing variability, and quality assurance impact.

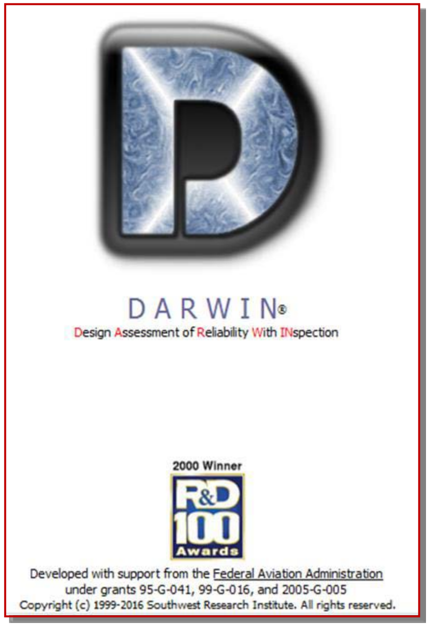
Participating Companies:

- ***Boeing***
- ***General Electric***
- ***GKN Aerospace***
- ***Honeywell***
- ***Northrop Grumman***
- ***Sikorsky***

~ $400K value

Leveraging *Prior* FAA Investments

- **Analysis framework (and software code) that can assess a component with a known population of anomalies and location-specific properties.**
- **Represents *~20 years of R&D and over $30M of investment* by the FAA and other agencies**
- **Has the following attributes:**
  - **Validated by industry**
  - **Accepted by multiple companies and regulators**
  - **Commercial grade software**
  - **Can account for *location-specific* properties:**
    - **Various populations of material anomalies**
    - **Inspectability / POD**
    - **Material properties**
    - **Residual stresses**
    - **Etc.**



DARWIN®

Design Assessment of Reliability With INspection

2000 Winner

R&D 100 Awards

Developed with support from the Federal Aviation Administration
under grants 95-G-041, 99-G-016, and 2005-G-005

Features Can Be Customized For AM With Relatively Moderate Incremental Investment (specific plan is being discussed)

Summary

- AIR Transformation → new P&I Division
  - *Big focus on developing certification approaches for new technologies (Innovation) and collaboration with industry*
- First FAA AM Roadmap will be finalized later this year
  - Provides a sequence of regulatory documents (policy, guidance, …) to be developed over the next few years
  - *No rule changes are envisioned at this time*
  - Roadmap is a living document - will be revisited / updated *annually*
- Very large scope - *collaboration* with other agencies and industry / societies / academia is important:
  - Qual and Cert experience
  - R&D
  - Training and Education

APPENDIX KK—TRAINING AND EDUCATION PANEL SESSION: AMERICA MAKES

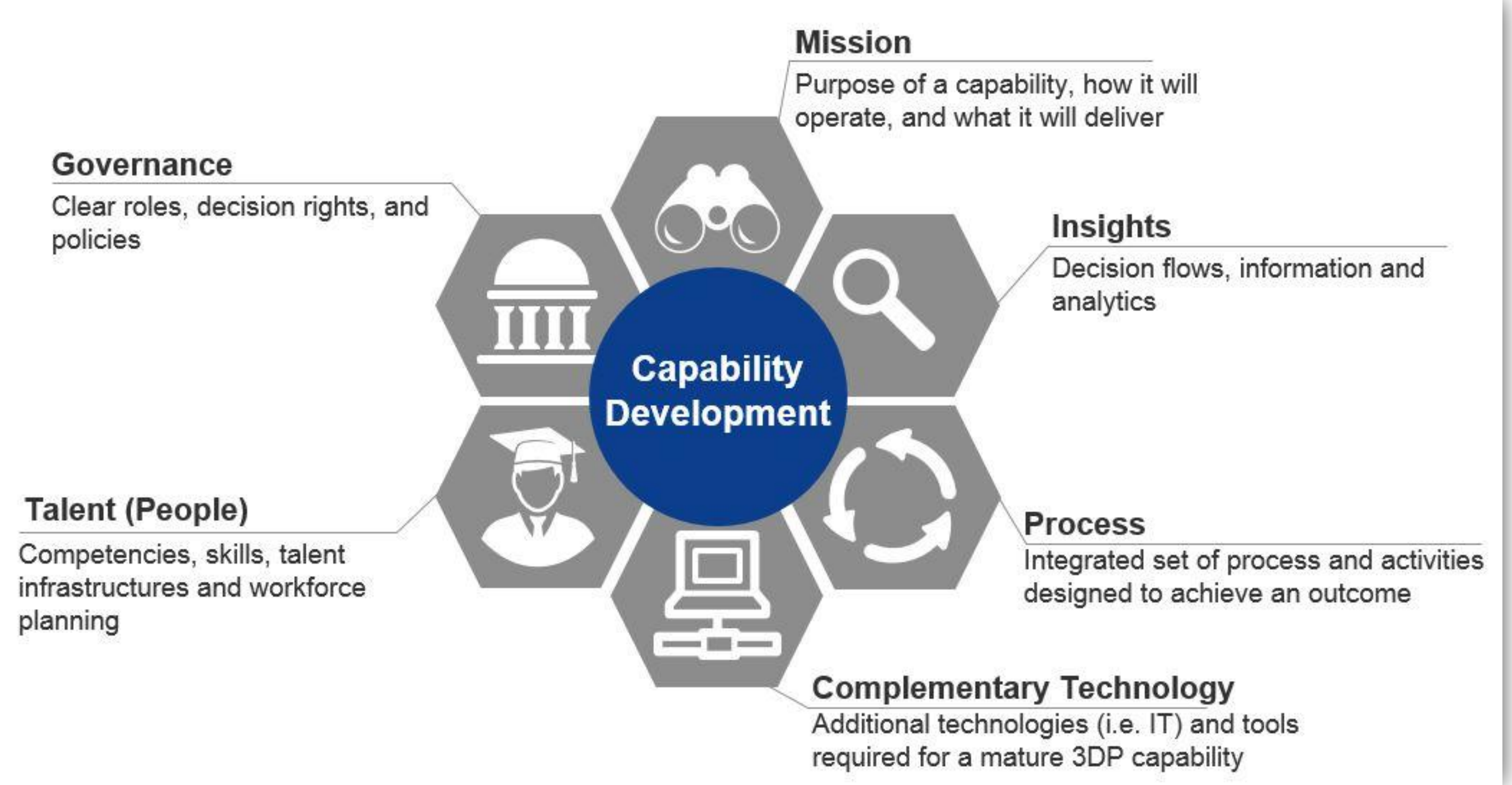
America Makes

The National Additive Manufacturing Innovation Institute

Smart Collaboration – Leveraging a rich knowledge base to gain competitive advantage in the additive manufacturing industry: Workforce Discussion

Rob Gorham
America Makes
Executive Director

Focus: Robust, Sustainable Value Chain



Capability Development

Mission
Purpose of a capability, how it will operate, and what it will deliver

Governance
Clear roles, decision rights, and policies

Insights
Decision flows, information and analytics

Talent (People)
Competencies, skills, talent infrastructures and workforce planning

Process
Integrated set of process and activities designed to achieve an outcome

Complementary Technology
Additional technologies (i.e. IT) and tools required for a mature 3DP capability

Widespread adoption of AM depends on organizations developing AM ***capabilities***, not just purchasing machines (see link)

Additional Context – DoD Technology Roadmap

Cross-Cutting Technology Enablers for AM

Cultural Change (Mission) - Enabling cultural change will facilitate increased buy-in for and understanding of AM / 3DP

Workforce Development (Talent) - Appropriately educating staff enables increased AM / 3DP understanding and production effectiveness

Data Management and Use of Digital Thread (Insights) - Successful data management facilitates appropriate information exchange to inform key decisions and securing sensitive data

DoD Integrated Additive Manufacturing Roadmap Download

Workforce and Education

What We Have Learned

EDUCATION RECOMMENDATIONS

- Promote K-12 Education STEAM programs across formal and informal environments
- Ensure AM Curriculum provides students with understanding of processes, material properties and Design for AM
- Recommendation to develop a national network for AM Education
- Provide support for collaborative and community-oriented maker spaces
- Develop Opportunities for Trans-Disciplinary Learning

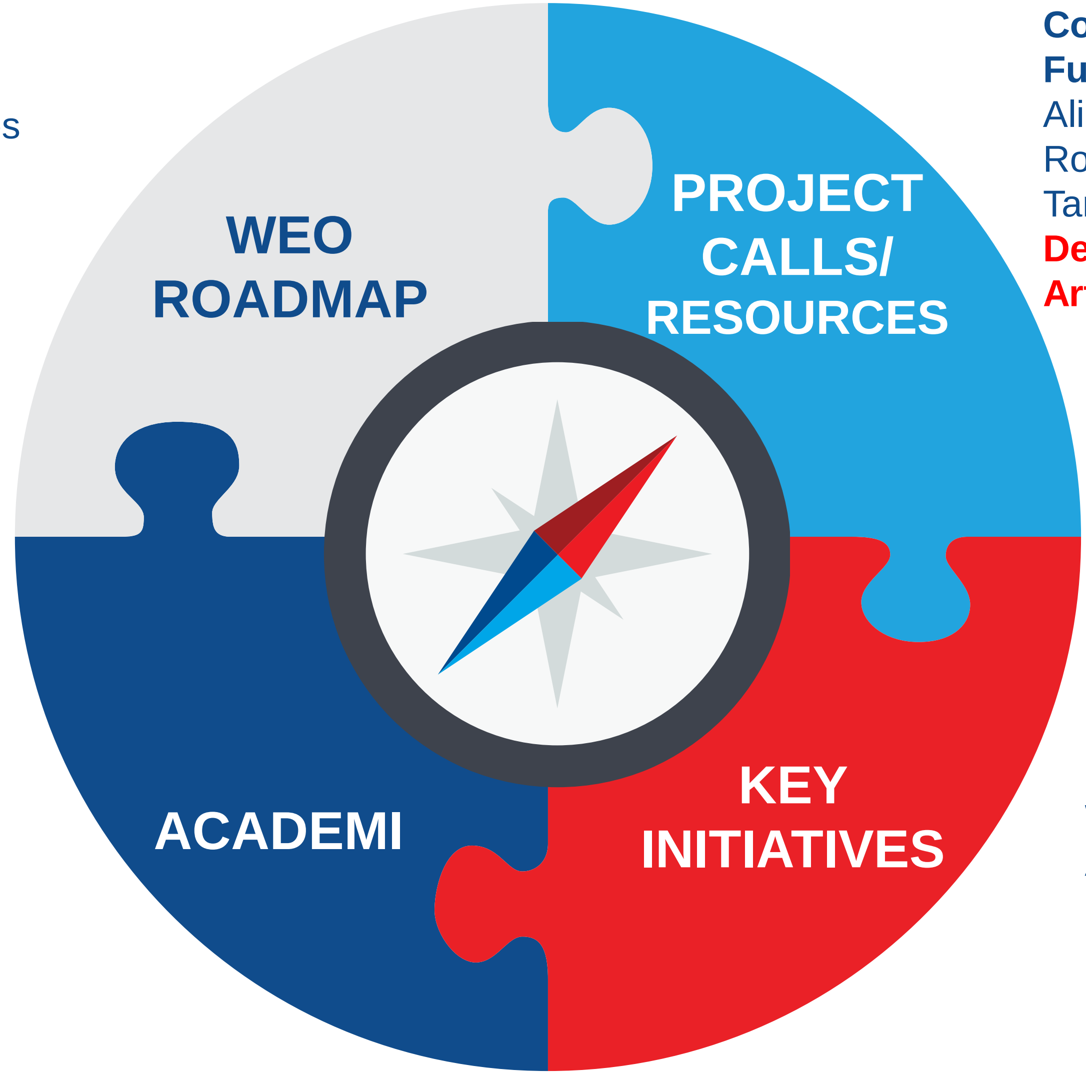
WORKFORCE CHALLENGES

- Insufficient skills for using current design/analytical tools
- Lack of training for equipment use/maintenance
- Lack of "design for additive manufacturing" awareness
- Lack of general understanding of use-cases for additive manufacturing
- Lack of understanding of commercial and economic considerations
- Lack of credible industry-wide source for hands-on training, resulting in reliance on webinars

Workforce and Education

Investment Strategy
Roadmap Provides the **Big Picture,** Prioritizes Major Initiatives and Investments as a Living Document

Core Projects Funded
Aligned to WEO Roadmap, Provides Tangible **Deliverable Artifacts**



High Impact, Hands-on Training
Advanced Curriculum in Additive Design, Engineering and Manufacturing Innovation

Key Initiatives
With **Partners**
Align to Roadmap
Focus on AM Impact and Scale

Workforce and Education Roadmap Framework

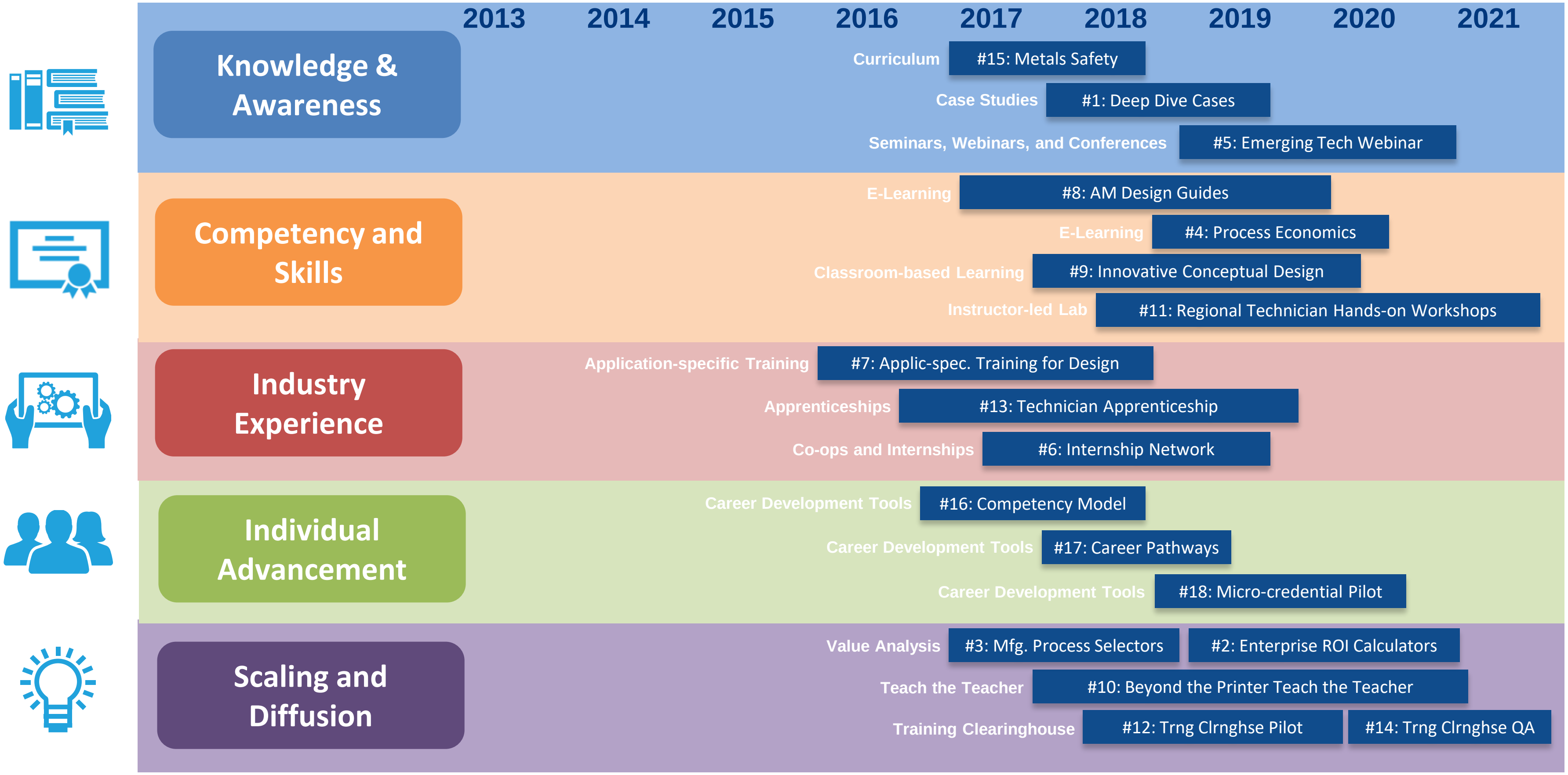
Knowledge & Awareness	Curriculum	Extracurricular STEAM programs	Learning Media	Seminars, Webinars, and Conferences	Case Studies	
Competency and Skills	Classroom-based Learning	E-Learning Courses	Maker Spaces and Fab Labs	Capstone Projects	Instructor-led Labs	
Industry Experience	Co-ops & Internships	Apprenticeship	Application-specific training	Industrial Experience Accelerators		
Individual Advancement	Career Dev. Tools	Mentoring	Employer Needs	Scholarships & Fellowships		
Scaling and Diffusion	Tech Transfer to SMBs	Training Clearinghouse	Value Analysis	Teach the Teacher	Grand Challenges	Talent Supply Chain Optimization

High Priority, Unmet Needs

Emerged by clustering identified talent gaps

	Unmet Needs (# gaps)	Definition
AM Economics	**Enterprise ROI Transparency (12)**	Ensure business managers and leaders have knowledge in the potential benefits and costs of AM (initial capital investments, production costs, inventory carrying impacts, speed to market, potential value capture through part consolidation or optimization)
	Basic AM Process Comparison (11)	Ensure designers and managers have knowledge and skills to understand the trade-offs of the seven AM processes (process and business economics)
	Emerging Technology Awareness (5)	Ensure AM industry users have knowledge of the latest advances in AM technology (design methods, materials, and processes)
AM Design	**Fundamental DfAM Process (17)**	Ensure designers have the knowledge, skills, and experience to realize the advantages of additive across the available materials and technology palette and those yet to be developed (concept, system-level, detailed, and iterative design practices)
	Broadening Designer Competence (6)	Ensure designers have knowledge, skills, and experience in the AM design process beyond designing the shape (impact of build processes, post-processing, IP management, and validation & testing)
Safety & QA	**Part Quality Assurance (8)**	Ensure personnel responsible for quality have knowledge of AM design and production processes and their impacts on quality and verification (non-destructive testing, support structures, platform/material-specific issues)
	Metal Processes and Safety (10)	Ensure designers and technicians have knowledge in the proper handling, storage, and use of metallic feedstock (properties, related processes, and safety implications)
Advancement	**Expanding Technician Capabilities (14)**	Ensure technicians have skills and experience with machine-specific design processes (file manipulation, process file management, digital thread, PLM) and how they impact the operation of the equipment (machine calibration and preventative maintenance)
	Role Progression Clarity (3)	Ensure potential and incumbent workers understand the various employment opportunities in AM and pathways to them (competencies required, associated compensation, career ladders/lattices)

Key Roadmap Project Recommendations



Project Call and Education Resource Repository

5 years and 66 projects later…

Courses

Modules

Resources

Trainings

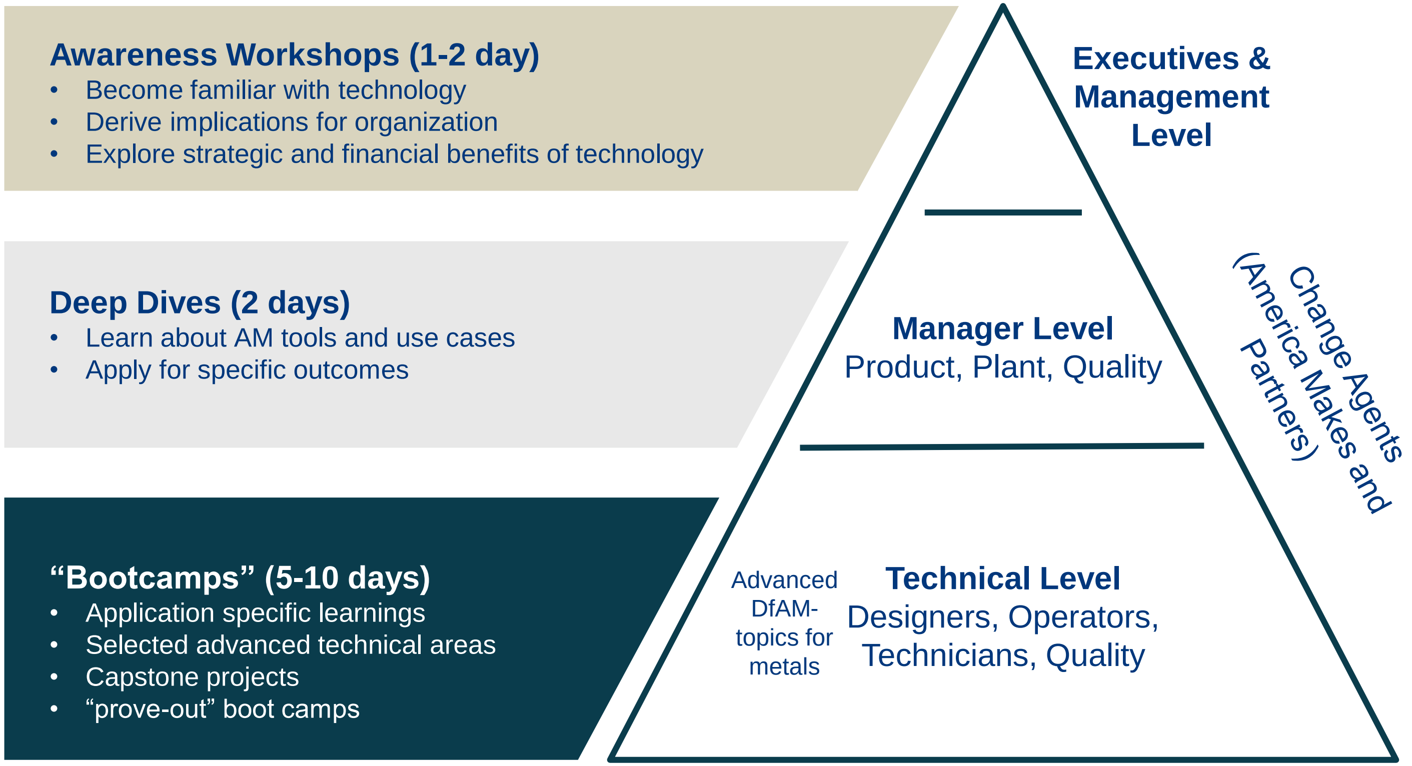
Workshops

Undergraduate and Graduate Degree Programs

America Makes
DIGITALSTOREFRONT
IDENTIFY ACCESS CONSUME

VISION: Leverage subject matter expertise and mature research technology from America Makes membership and partners to create a portfolio of AM learnings that act as change agents for broader industry adoption of AM technologies

The AM Learning Model Factory of the Future



Awareness Workshops (1-2 day)
- Become familiar with technology
- Derive implications for organization
- Explore strategic and financial benefits of technology

Deep Dives (2 days)
- Learn about AM tools and use cases
- Apply for specific outcomes

“Bootcamps” (5-10 days)
- Application specific learnings
- Selected advanced technical areas
- Capstone projects
- “prove-out” boot camps

Example: Core DoD Training Offerings

INTRO TO AM

(AMRDEC and AFRL)

POINT OF NEED AM TRAINING

(DoD)

ACADEMI BOOTCAMP TRAINING

(AFRL)

BROAD AM FAMILIARIZATION Building Blocks
(i.e., CAD, design, applications)

FUNDAMENTALS
(i.e., understanding of mfg. process, basic machine operation, basic design for AM)

APPLIED
(i.e., biomimetic design, simulation, material science, metrology, machine operation, finishing, topology optimization)

Core Offering: Introduction to AM

Target Audience: Personnel, including management personnel and program managers with various levels of experience utilizing additive manufacturing who are or will be applying AM

Course Objectives: This two day, lecture based training will provide big picture concepts critical to additive manufacturing community. After completing this two day course, students will have the foundational knowledge to begin implementing additive manufacturing and will be prepared for targeted, in depth follow on training

Day 1:

- Introductions
- History and Purpose
- Additive Manufacturing Technologies Overview and Videos (Process Details, Advantages, and Limitations)
  - Overview and F-42 Taxonomy
  - Sterolithography
  - Fused Deposition Modeling
  - Selective Laser Sintering
  - Electron Beam Melting
  - Material Jetting
  - Directed Energy
  - Binder Jetting
  - Sheet Lamination
- Summary and Discussion
- Hands-on Demonstration TBD*
- Discussion and Wrap-up

Day 2:

- Design Overview: Part Design Approach – Managing and Controlling Undesirable and Unintended Variability
- Material and Process Selection
- Part Orientation, Placement
- Defect Prevention
- Empirical Design
- Microstructure Modeling
- Combination and Articulated Parts
- Topological Optimization
- Special Geometry Considerations (biomimetic and organic, lattice structures, cellular structures, auxetic structures)
- Tooling via Additive Manufacturing
- Application Overview and Use Case *
- Emerging Research (Hybrid, graded, composite, multi-process, in-situ monitoring)
- Introduction to the America Makes Technology Roadmap and key project overviews

Core Offering: Point-of-Need Level 1 and 2

TRAINING FOCUS: The training is structured to broaden awareness of the ability of additive manufacturing to design and produce valuable hardware currently not able to be manufactured through conventional means. The delivery of the training will expand the way operators and support personnel think and deliver custom mission support hardware to the warfighter

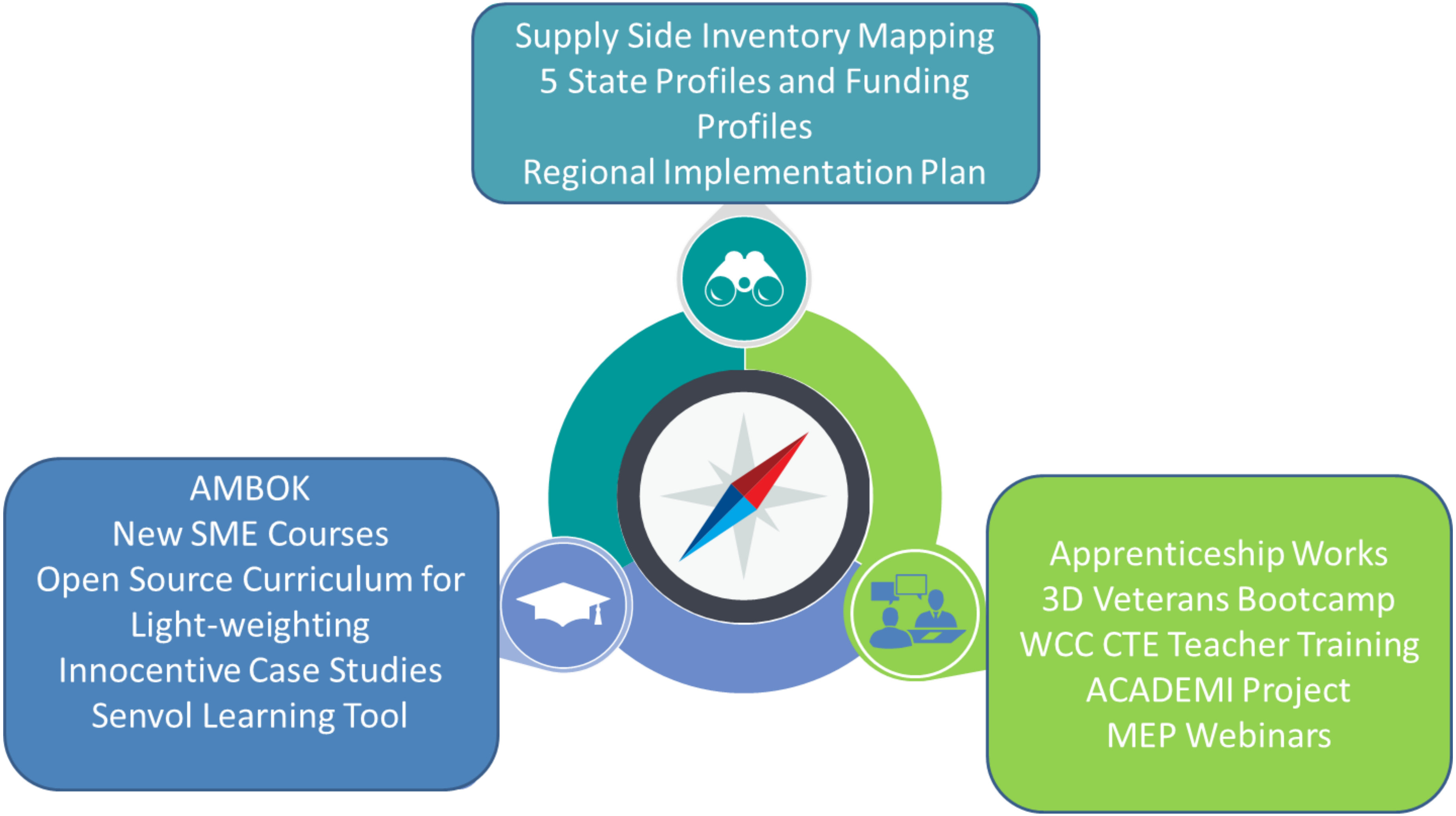
Level 1:

- Additive manufacturing technology overview
- Basic SolidWorks training
- Additive manufacturing fundamentals and limitations
- Additive manufacturing process chain
    - Design for additive manufacturing
    - Process parameters
    - Post-processing and inspection
- Additive manufacturing application breadth and depth for polymer desktop printing
- Maintenance and troubleshooting
- Research frontiers
    - Advances in metal additive manufacturing
    - 3D printing multi-functionality
    - Week 1 capstone project

Level 2

- SolidWorks level 1 skills refresher
- Reverse engineering introduction
- Introduction to 3D scanning: benefits and limitations
- Tour and hands on with industrial printers at Partners
- Hands on with the NextEngine scanner and editing software
- Rapid prototyping; scan, print and assemble
- Polymer material properties
- Mechanical properties vs. build orientation studies
- Material properties, handling and hazards of various AM tech
- Advanced SolidWorks training
- Intuitive engineering and design
- Finite element analysis (FEA): Intro to advanced stress modeling
- Metrology: Scanning, coordinate measuring machine etc.
- Week 2 capstone – Design optimization for additive manufacturing

Key Initiatives Highlights



Supply Side Inventory Mapping
5 State Profiles and Funding Profiles
Regional Implementation Plan

AMBOK
New SME Courses
Open Source Curriculum for Light-weighting
Innocentive Case Studies
Senvol Learning Tool

Apprenticeship Works
3D Veterans Bootcamp
WCC CTE Teacher Training
ACADEMI Project
MEP Webinars

Core Initiative: ACADEMI

Advanced **C**urriculum in **A**dditive **D**esign, **E**ngineering, and **M**anufacturing **I**nnovation

- Outcome of 15 month study to find **best member value of the America Makes Innovation Factory**
- Shaped from the inputs from over **100+ America Makes members** and non-members
- **Addresses market gaps and issues** with current training environments and/or barriers for greater AM innovation
- Focused on a portfolio of **immersive, hands-on, cross-disciplinary** training programs into DfAM classes
- Developed and delivered by industry experts
- Aligns with America Makes Mission Objectives

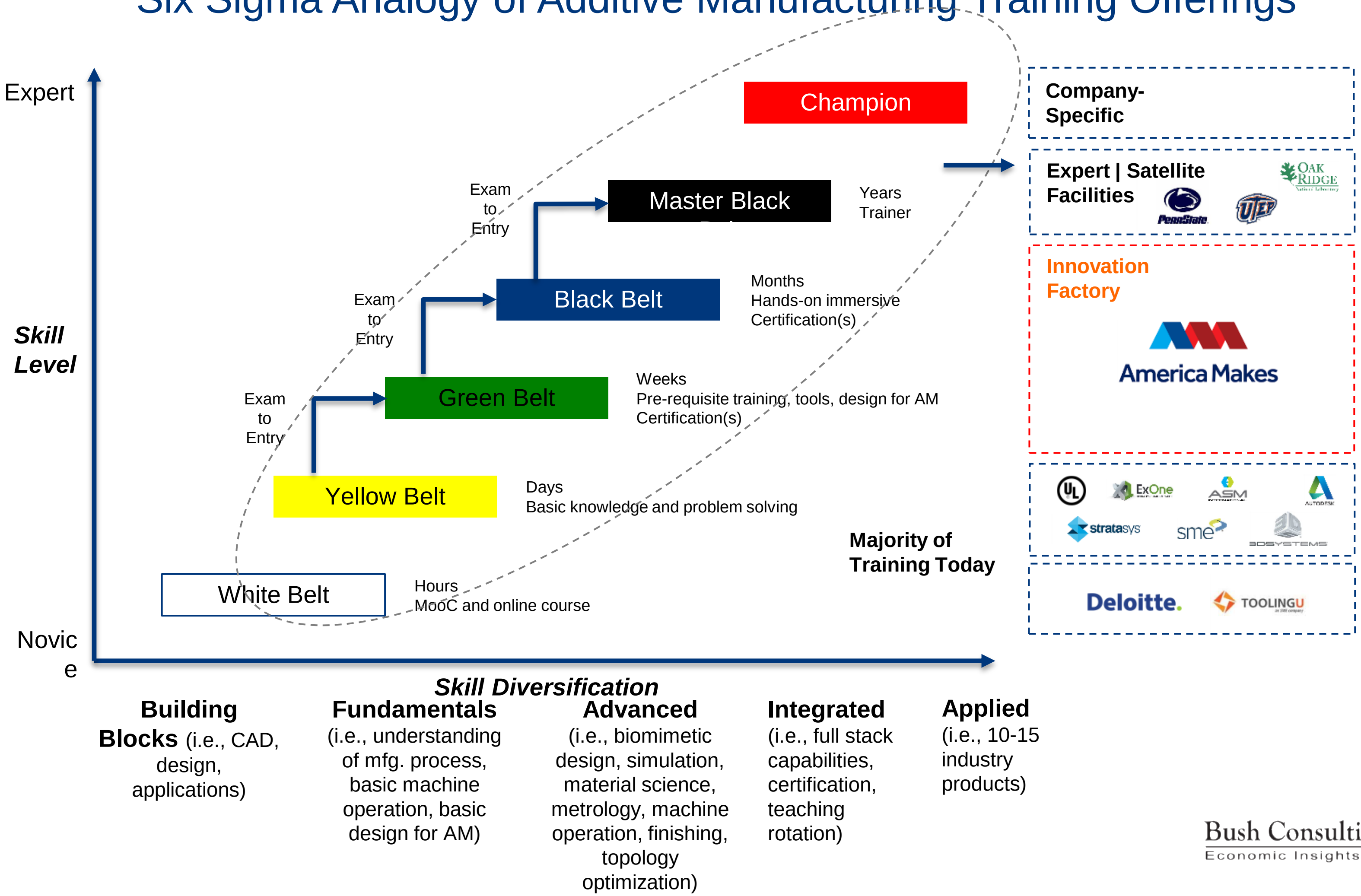
- Integrated into the WEO Roadmap
- **Unique and differentiated value proposition**: immersive, application orientation, rigorous curriculum
- **Strategic and competitive advantage** without competing with membership
- A foundational platform on which other classes can be built with a path towards **professional certification**

ACADEMI America Makes

Advanced Curriculum in Additive Design, Engineering, and Manufacturing Innovation

The ACADEMI training program is unique relative to other industry training models

Six Sigma Analogy of Additive Manufacturing Training Offerings



Expert

Skill Level

Novice

Champion

Exam to Entry

Master Black

Years
Trainer

Exam to Entry

Black Belt

Months
Hands-on immersive
Certification(s)

Exam to Entry

Green Belt

Weeks
Pre-requisite training, tools, design for AM
Certification(s)

Yellow Belt

Days
Basic knowledge and problem solving

White Belt

Hours
MooC and online course

Majority of Training Today

Skill Diversification

Building Blocks (i.e., CAD, design, applications)

Fundamentals (i.e., understanding of mfg. process, basic machine operation, basic design for AM)

Advanced (i.e., biomimetic design, simulation, material science, metrology, machine operation, finishing, topology optimization)

Integrated (i.e., full stack capabilities, certification, teaching rotation)

Applied (i.e., 10-15 industry products)

Company-Specific

Expert | Satellite Facilities

Innovation Factory

Bush Consulting Group
Economic Insights for Strategy

When America Makes America Works

America Makes

AmericaMakes.us

@AmericaMakes

/AmericaMakes

APPENDIX LL—TRAINING AND EDUCATION PANEL SESSION: BOEING

Engineering, Test & Technology
Boeing Research & Technology

Additive Manufacturing Training at Boeing

August 2017

Paul Dufour, St. Louis, MO

BR&T Structures Technology

AM Training Challenges

- Chicken and Egg Situation:
    - Is the technology mature enough to train people? Are we ready for this? *But*,
    - How can we mature the technology without starting to train people and having them learn by doing?
- Additive Manufacturing is not one technology. The breadth of the field and the many different processes and the pros/cons of each one can be very daunting to beginners.
- Boeing engineers span across the country & globe. Need to have an ecosystem and training compatible with a virtual team environment.
- Learning takes time, and works best in smaller digestible chunks rather than a fire hose. On-demand or in-person?
- Advanced tools are an important part of the answer, but just one piece.
- Training needs to allow for the “design freedom” of additive to be exploited, but also provide robust processes to ensure standardization, producibility, etc.

AM Training Approach

- Boeing specific with our own parts, goals, methods, and tools for additive manufacturing. Not generic.
- AM training needs an integrated approach between, materials, design, analysis, and manufacturing. Cross training is essential. Elements can include:
  - *Why Additive Manufacturing:* Benefits, get people excited about possibilities but be honest about the challenges, and what our goals are.
  - *AM Processes and Materials:* Concise overview of technologies and how they work, pros/cons, what each technology is good at, lots of example parts, and process reference documents.
  - *AM Design Process:* Thinking about design for AM in a holistic way, design considerations (cost, feasibility, manufacturing, strength, etc), software tools, concept design for AM, support structures, part orientation, post processing, NDE, and certification strategies.
- Recipe for success,
  1. Education on AM processes & design.
  2. The right software tools and knowing how to use them.
  3. Practice. More practice. Hands-on is important.

APPENDIX MM—TRAINING AND EDUCATION PANEL SESSION: GE AVIATION

AM Training & Education Panel Discussion

3rd Joint FAA & USAF Additive Workshop

Luana Iorio
General Manager,
Engineering Material Systems
GE Aviation

August 2017

Accelerating Additive Adoption … Expertise Development

Pipeline

Material Development

Technology Development

Product Design

Product Development

Production Maturation

High Rate Manufacturing

Sustainment

In House Training

Pipeline:

Providing printers to schools, colleges & universities

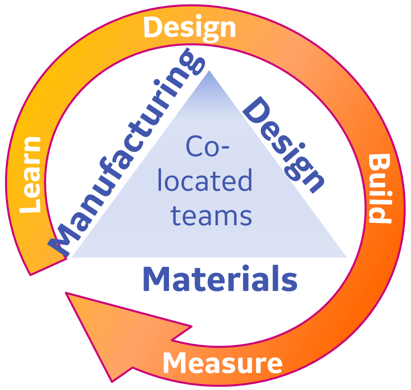
CONCEPT ACADEMY

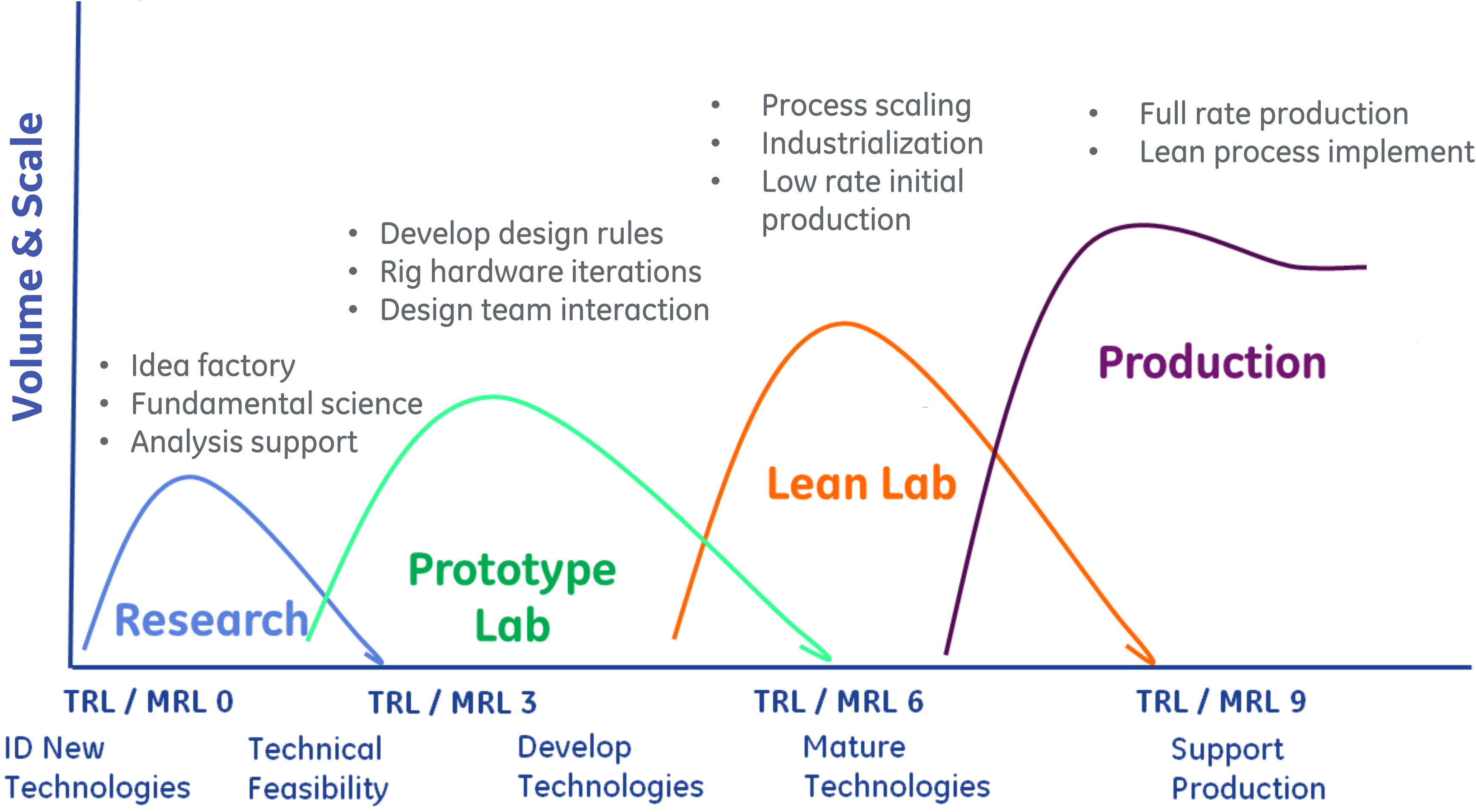
Design:

- **Embedded Design-for-Additive experts**
- **Incorporated Additive training modules into Engineering training programs**
- **Built Knowledge sharing communities, on-demand training modules**
- **Launched AddWorks™**

Infrastructure to Support Industrialization

A 4-step model to accelerate new material & manufacturing technology introductions





- Idea factory
- Fundamental science
- Analysis support

- Develop design rules
- Rig hardware iterations
- Design team interaction

- Process scaling
- Industrialization
- Low rate initial production

- Full rate production
- Lean process implementation

TRL / MRL 0 — ID New Technologies — Technical Feasibility

TRL / MRL 3 — Develop Technologies

TRL / MRL 6 — Mature Technologies

TRL / MRL 9 — Support Production

Evolving Training Programs

Examples of additive-specific skillset requirements:

Design

- Systems vs component approach
- Multi-variable optimization
- CAD complexity

Materials

- New process-microstructure-property relationships
- AM & Post process optimization
- Location-specific properties
- Expanded alloying windows
- Powder characterization

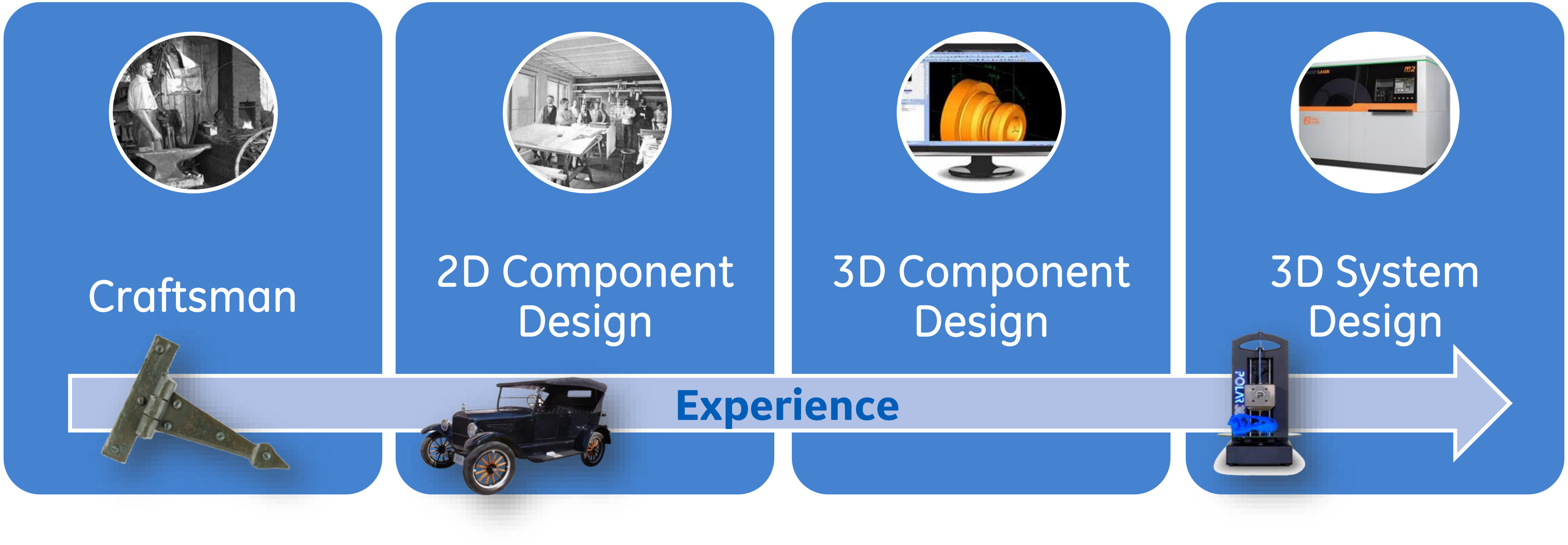
Manufacturing

- Build file preparation
- Machine operation
- Laser/Electron Beam calibration & maintenance
- Powder handling
- Digital data management

How Additive Manufacturing Impacts On-the-Job Training by Role:

Design Engineers	25%
Material Engineers	25%
Manufacturing Engineers	35%
Quality Engineers	10%
AM Machine Engineers	90%
Machine Technicians	90%
Machine Operators	50%

Changing the Design Paradigm



Craftsman

2D Component Design

3D Component Design

3D System Design

Experience

Growing need for more multi-disciplinary, multi-skilled engineers to realize potential of new technology

APPENDIX NN—TRAINING AND EDUCATION PANEL SESSION: PENN STATE UNIVERSITY

Center for Innovative Materials Processing through Direct Digital Deposition

Dr. Richard Martukanitz

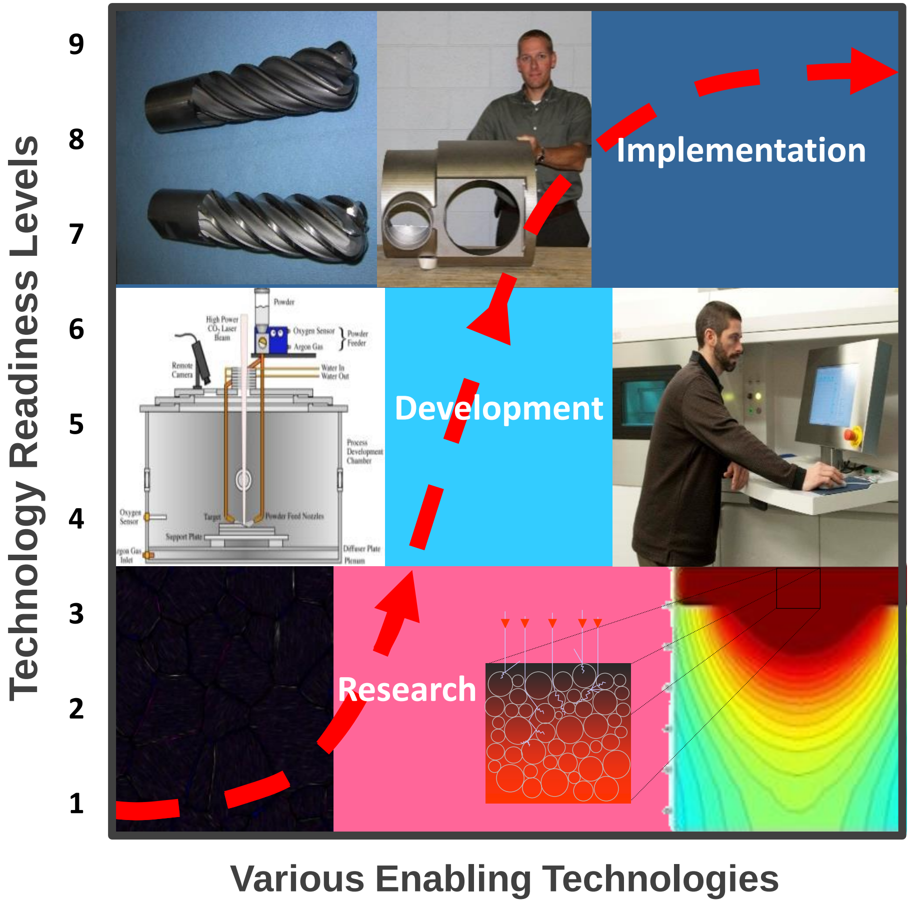
Director-CIMP-3D, Applied Research Laboratory

Presented During the Training and Education Panel of the
2017 FAA - USAF Workshop on Qualification and Certification of AM Parts

August 29, 2017

This Presentation is Approved for Public Distribution

CIMP-3D



- A national resource for additive manufacturing technologies:
  - university-wide initiative
  - operated by Penn State’s Applied Research Laboratory, a DoD University Affiliated Research Center (UARC)
- An Additive Manufacturing Demonstration Center (AMDF) under the DARPA Open Manufacturing Program
- With a mission to:
  - advanced additive manufacturing technologies,
  - promote adoption through process and product demonstrations, and
  - promote and sustain additive manufacturing.

PennState
CIMP-3D

Our Faculty

Rich Martukanitz, Ph. D.
Director of CIMP-3D
Head of Laser Processing Division
Applied Research Laboratory

Gary Messing, Ph. D.
Co-Director of CIMP-3D
Department Head of the Materials Science and Engineering
Distinguished Professor of Ceramic Science and Engineering

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McFarlane Assistant Professor of Materials Science and Engineering

Sven G. Bilén, Ph. D.
Head, School of Engineering Design, Technology, and Professional Programs
Chief Technologist, Center for Space Research Programs

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Associate Professor of Engineering

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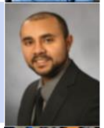
Professor of Electrical Engineering
Chair, Intercollege Graduate Degree Program in Materials Science and Engineering



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Department of Engineering Science and Mechanics

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Associate Professor of Materials Science and Engineering
Head, Process Technologies Department of the Applied Research Laboratory
Applied Research Laboratory

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Professor of Electrical Engineering
Applied Research Laboratory

Vittal Prabhu, Ph. D.
Professor of Materials Science and Engineering

Edward W. Reutzel, Ph. D.
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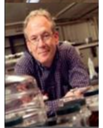
Head, Process Technologies Department of the Applied Research Laboratory
Applied Research Laboratory



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Professor of Materials Science and Engineering

Al E. Segall, Ph. D.
Professor of Engineering Science and Mechanics and Graduate Officer

Jeff Shiano, Ph. D.
Professor of Engineering and Science & Mechanics
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P.B. Breneman Chair and Professor of Engineering Science and Mechanics
Head, Department of Engineering Science and Mechanics

Robert C. Voigt, Ph. D.
Professor of Industrial & Manufacturing Engineering

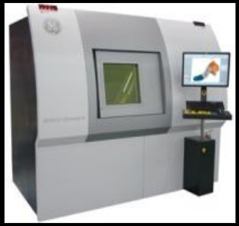
Qing Wang, Ph. D.
Professor of Mechanical Engineering

PennState
CIMP-3D

Our Capabilities

DMG Mori Lasertec 65

GE Vtomex-M CT



Stratasys Fortus 400 mc

ExOne MLab

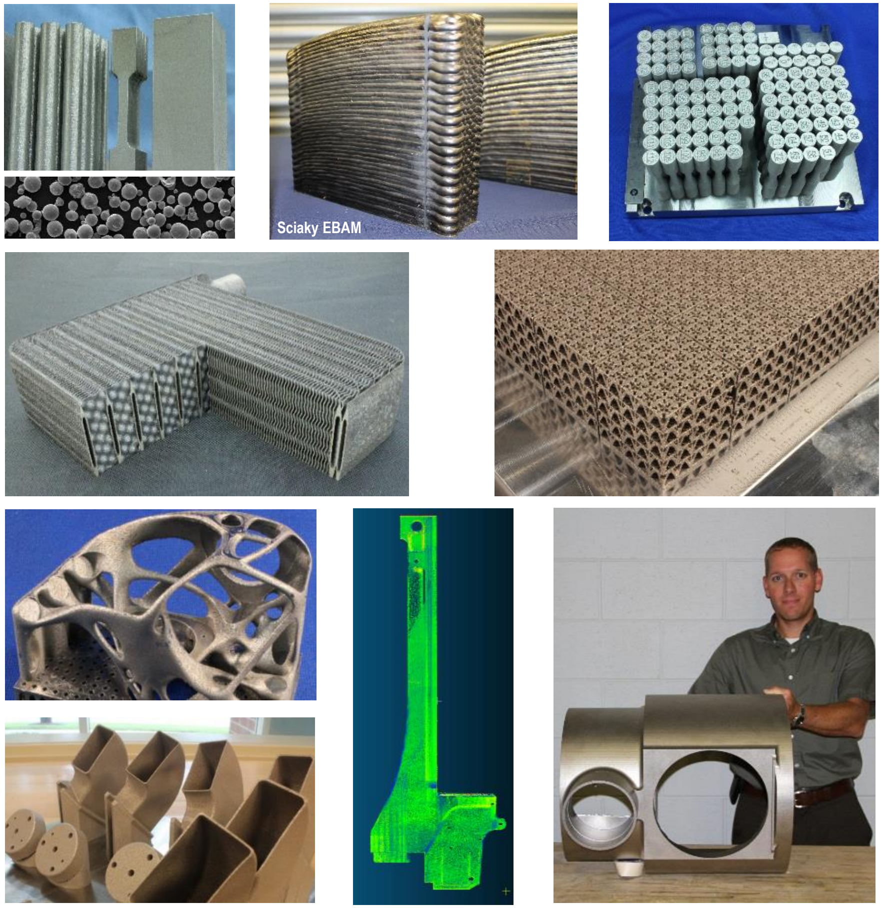
Optomec LENS

3D Systems ProX 200

HPLD

EOS M280

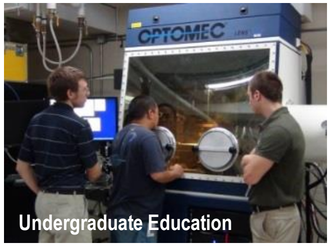
3D Systems ProX320



Our Presence


Technology Exchange on Coordination of U.S. Standards


Industry Training



Undergraduate Education


Graduate Education

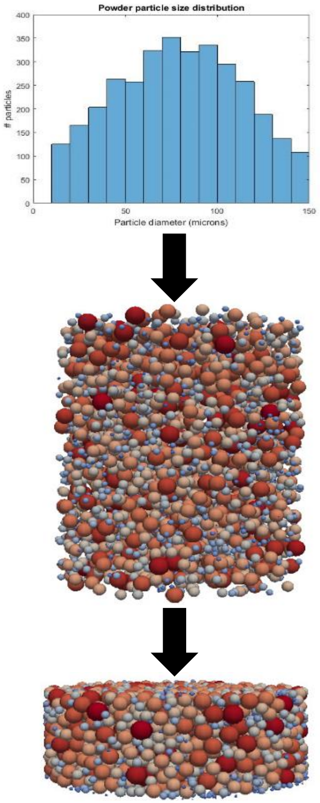
- Undergraduate and graduate education:
  - Undergraduate Summer Internship in AM
  - Masters Program in Additive Manufacturing and Design in 2017
- Founding member of America Makes
- Industry Practicums and Technology Exchanges
- Close collaboration with numerous government organizations
- Healthy commercial R&D portfolio
- Engaged in several governing agencies on standards:
  - ASTM F42 Subcommittee
  - AWS C7 and D20 Committees
  - Metallic Materials Properties Development and Standardization (MMPDS)
  - ASME Design, Materials, and Manufacturing Segment

PennState
CIMP-3D

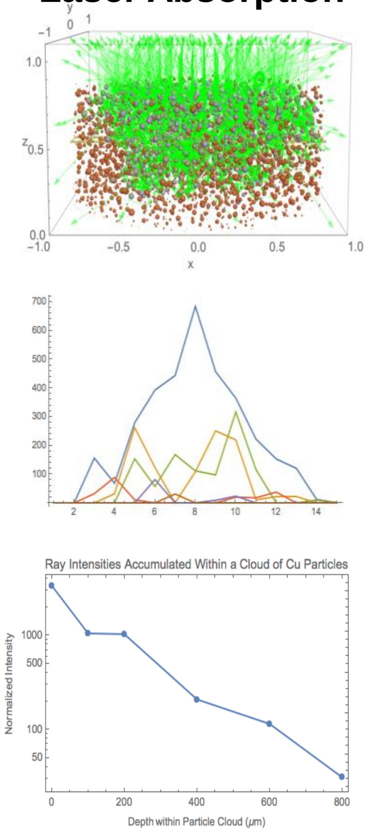
Our Interests

Improving Process Understanding Through Integrated Simulations Tools

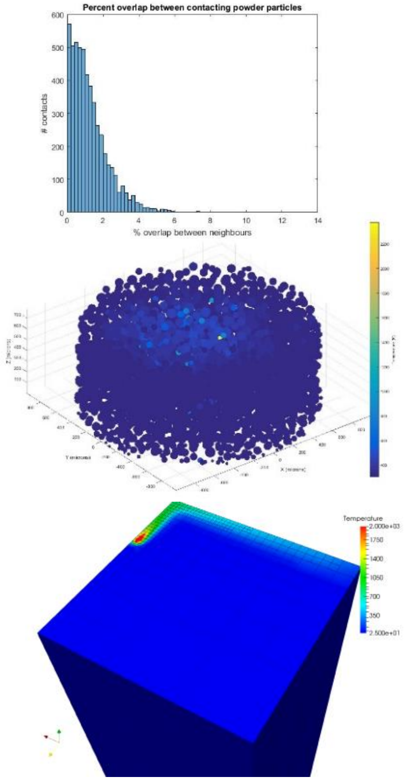
Power Packing



Laser Absorption



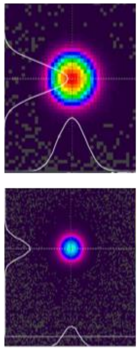
Energy Transport



Our Interests

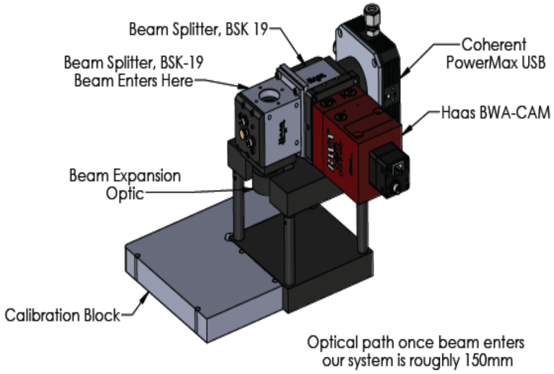
Development and Application of Process Diagnostics for Increasing Process Reliability

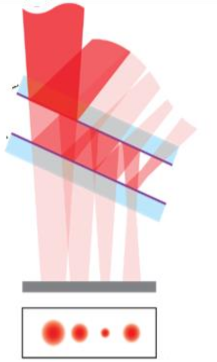
Ophir Spiricon Device



- Ophir device:
  - SP620U USB2 Camera and LBS-300 Baem Sampler/Attenuator
  - thermal detector for power
  - BeamGage Professional Software

Coherent – Haas Optical Device

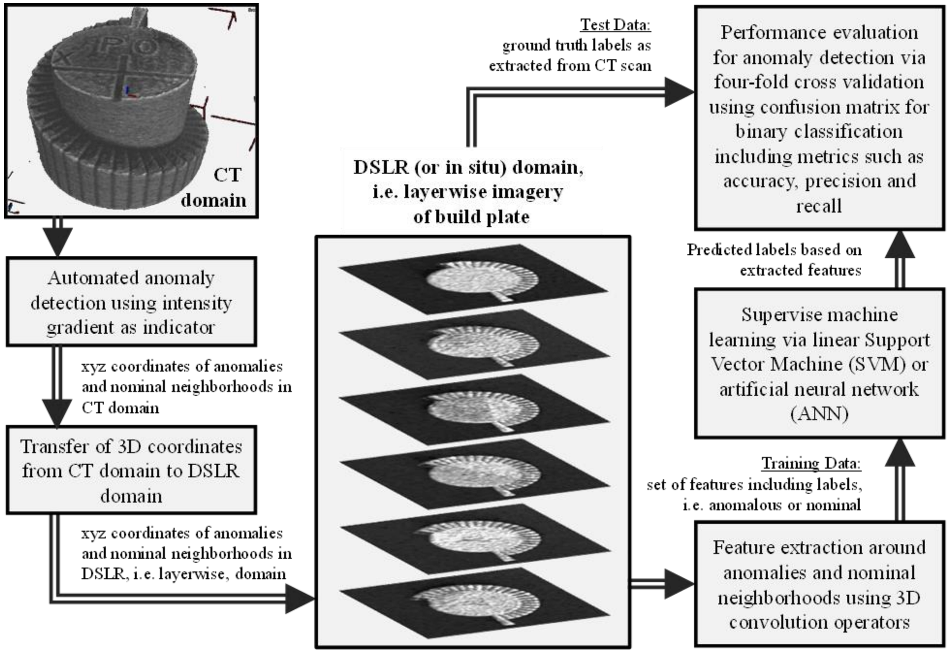




- Coherent – Haas device:
  - optical attenuation of beam
  - utilizes Fabry-Perot interferometer technique to measure all distributions through propagation
  - thermal-pile detector for beam energy and power

Our Interests

Advanced Sensing Technology for Ensuring Product Performance



CT domain

Automated anomaly detection using intensity gradient as indicator

xyz coordinates of anomalies and nominal neighborhoods in CT domain

Transfer of 3D coordinates from CT domain to DSLR domain

xyz coordinates of anomalies and nominal neighborhoods in DSLR, i.e. layerwise, domain

DSLR (or in situ) domain, i.e. layerwise imagery of build plate

Test Data: ground truth labels as extracted from CT scan

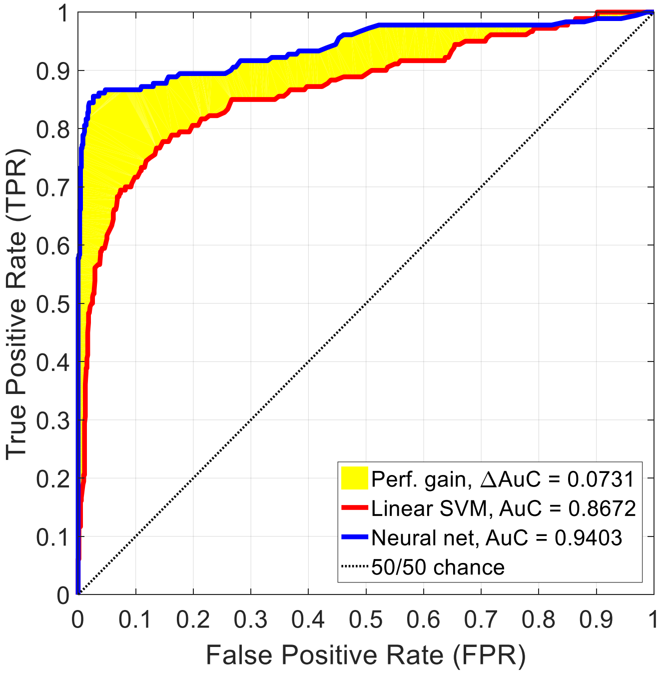
Performance evaluation for anomaly detection via four-fold cross validation using confusion matrix for binary classification including metrics such as accuracy, precision and recall

Predicted labels based on extracted features

Supervise machine learning via linear Support Vector Machine (SVM) or artificial neural network (ANN)

Training Data: set of features including labels, i.e. anomalous or nominal

Feature extraction around anomalies and nominal neighborhoods using 3D convolution operators



PennState
CIMP-3D

Our Story

www.comp3d.org

APPENDIX OO—TRAINING AND EDUCATION PANEL SESSION: SOCIETY OF MANUFACTURING ENGINEERS

SMART MANUFACUTRING:
ADDITIVE WORKFORCE DEVELOPMENT

Kris Ward
Marketing & Business Development Director
Tooling U-SME

KEY TAKEAWAYS

1. SME is a core resource for Additive Manufacturing technology advancement & workforce development
2. Tooling U-SME, the workforce development arm of SME, is committed to developing the manufacturing workforce through competency-based learning solutions
3. Tooling U-SME can design, develop and deliver programs to meet additive learning & development needs of manufacturers

ABOUT SME

SME is a nonprofit organization that supports manufacturing based on our core belief: Manufacturing is key to economic growth and prosperity. Our mission is to promote manufacturing technology and develop a skilled workforce.

Education Foundation

The SME Education Foundation has invested more than $8 million in youth programs, helping over 60,000 students explore career opportunities in science, technology, engineering and mathematics (STEM). The Foundation also provides scholarships, grants and awards totaling more than $25 million.

Membership

SME members are manufacturing professionals, researchers, educators and students who are looking to connect with peers, gain knowledge related to manufacturing technology and trends, solve problems and participate in leadership opportunities.

Learning & Development

Companies use Tooling U-SME's versatile solutions to educate their workforce, increase productivity and improve product quality. Educational institutions turn to Tooling U-SME to augment their learning plans and provide instructors with more time for hands-on instruction. Individuals use our solutions to gain new skills and advance their careers.

Events

You don't have to have a big business to find big solutions and new prospects at SME events. Attendees from all walks of manufacturing find revolutionary technologies, business-changing innovations and their next competitive advantage -- all on display in a hands-on, flexible learning environment.

Media

SME's Advanced Manufacturing Media (AMM) group is a leading source for news and in-depth technical information about advanced manufacturing in North America. More than 100,000 manufacturing professionals subscribe to our *Manufacturing Engineering* magazine, iTunes app, annual yearbooks, e-newsletters, technical papers and other products.

HIGHLIGHTS:

SME’s ADDITIVE MANUFACTURING HERITAGE: 1990-TODAY

Technology Advancement

- Rapid + TCT
- **ITEAM Consortium**
- Advanced Manufacturing Media
- **AMSC**
- **Additive Standards Database (beta)**
- SMART Manufacturing Event Series

Community Connections

- Additive Manufacturing Community
- North American Manufacturing Research Institute (NAMRI) and NAMRC
- **Partnerships:** America Makes, TCT, MSOE, NCATC, TEAMM, Rippl3d.com, etc.

Workforce Development

- SkillsUSA Additive Manufacturing Competition, Student Summits & Competitions
- SME Education Foundation: PRIME, Scholarships, NASA HUNCH partnership
- **Tooling U-SME**: Competency-based workforce solutions

www.sme.org/3D

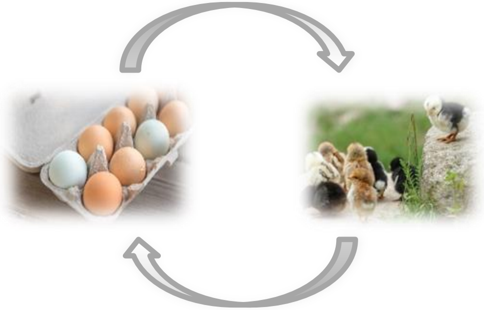
TOOLINGU | sme

Progress happens when you leverage investment in technology and people within the manufacturing community. By building the capabilities of both today and tomorrow's workforce, we are a catalyst within manufacturing to drive meaningful economic growth.

LACK OF SKILLED WORKERS IMPACTS BUSINESS

BUSINESS INNOVATION
is a strategic imperative

A HIGHLY SKILLED AND EDUCATED WORKFORCE
is the most critical element for innovation success



MOST functions in manufacturing require up-skilling for additive.

WHAT MAKES TOOLING U-SME DIFFERENT?

Accelerate Methodology

Tooling U-SME's Accelerate Methodology provides tailored training solutions that drive a measurable difference in your organization.

Over 80 Years' Experience

We understand the challenges manufacturers face in staying competitive.

Unrivaled Content

All of Tooling U-SME's content has been designed and developed around a simple, repeatable approach.

Partnered Approach

We're with you every step of the way, from our initial consultation through the life of your program.

Community Involvement

We believe educators and employers need to collaborate on building the next-generation manufacturing workforce.

WORLD CLASS LEARNING AND DEVELOPMENT ATTRIBUTES

High Performance Onboarding

Flexible Workforce

Superior Content and Delivery System

Job-Based Competencies

Positive Learning Culture

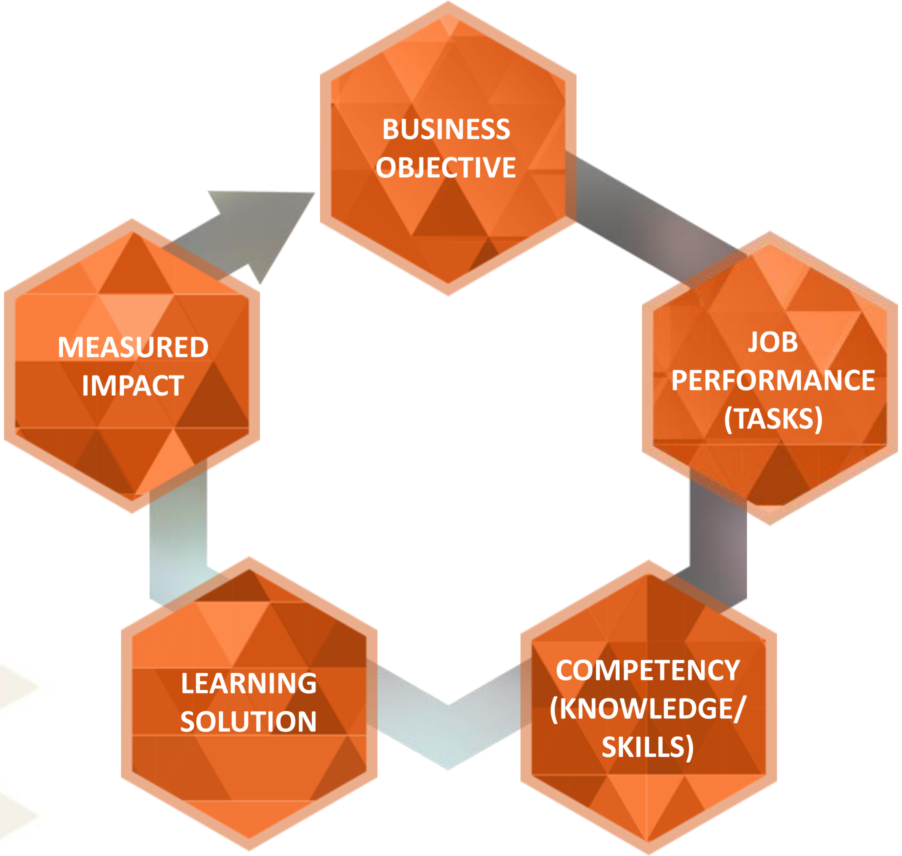
Community Focus

Career Pathways

Strategic Partnerships (L&D, HR, Production)

Measuring Learning and Development, Impact on Business

COMPETENCY-BASED DEVELOPMENT PROGRAMS



BUSINESS OBJECTIVE

JOB PERFORMANCE (TASKS)

COMPETENCY (KNOWLEDGE/ SKILLS)

LEARNING SOLUTION

MEASURED IMPACT

COMPETENCY-BASED BLENDED LEARNING SOLUTIONS DRIVE RESULTS

- ONLINE
- INSTRUCTOR LED
- BOOKS & VIDEO
- CERTIFICATION
- CUSTOM
- ASSESSMENTS

CHALLENGE: BUILDING A NEW GENERATION
GEN Y = 50% OF THE WORKFORCE

LOOMING RETIREMENT

UNSKILLED MILLENNIALS

GEN YERs MAKE A DECISION ABOUT WHETHER TO STAY WITH A COMPANY LONG-TERM BY THE END OF THE FIRST DAY.

WHAT DOES THAT REQUIRE?

- Pipeline development
- Corporate mission
- Onboarding
- Career Pathways

- Capture tribal knowledge from experienced personnel
- Provide structured, consistent and scalable training
- Build career pathways and development models for new and incumbent workers
- Provide a learning culture and infrastructure to support training and development needs

TOOLINGU | sme

ENHANCING THE SUPPLY CHAIN

ALIGNMENT WITH SCHOOLS

High Schools

Technical College

Company

STACKABLE MODEL for ADDITIVE in PRODUCTION

ADDITIVE MANUFACTURING FUNDAMENTALS CERTIFICATION
Assessment aligned to the AMLI Body of Knowledge. End of program for high school/post-secondary CTE

ADDITIVE MANUFACTURING TECHNICIAN CERTIFICATION
Assessment + competency-based skills guidance; leads entry-level/pre-apprenticeship

ADDITIVE MANUFACTURING TECHNICIAN APPRENTICESHIP
Under review for DOL approval. Collaborative effort with RCBI and America Makes. Competency-based.

ADDITIVE MANUFACTURING – BUILDING ENTERPRISE CAPABILITY
Competency-based programs to increase additive capability across the enterprise: safety, design, inspection, metrology, secondary processing, engineering, transitioning from traditional manufacturing, etc.

Certifications co-sponsored by: America Makes

eLearning and Instructor-led training support additive education

- Intro
- Processes
- Safety
- Methods & Materials
- DFAM
- Materials Science
- Integrating with Traditional Manufacturing
- Post-processing/secondary processing
- Additive as a Secondary Process
- Inspection/metrology for AM
- Transitioning to Additive

TOOLINGU | sme

ADDITIVE LEARNING & DEVELOPMENT – EXTENDED ENTERPRISE

We train individuals at every level within an organization—from engineers to production workers.

HR / LEARNING & DEVELOPMENT

Human Resource Managers
Training Managers
Learning & Development Professionals
Organizational Development

TECHNICAL MANAGERS

Production Supervisor
Engineering
Plant Manager / Supervisor
Shop Floor Manager / Supervisor

EXECUTIVES

C-Suite
Vice President / Manufacturing

PRODUCTION WORKFORCE

Maintenance
Machinist
Welders
Assembly

SALARIED WORKFORCE

Engineers
Supervisors
Sales
Procurement

EDUCATION

High School
Community College
University

KEY TAKEAWAYS

1. SME is a core Resource for Additive Manufacturing technology advancement & workforce development
2. Tooling U-SME, the workforce development arm of SME, is committed to developing the additive workforce
3. We can help design, develop and deliver programs to meet additive training needs for manufacturers

Kris Ward
Marketing & Business Development Director
toolingu.com
www.sme.org
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APPENDIX PP—TRAINING AND EDUCATION PANEL SESSION: UNDERWRITERS LABORATORIES

FAA AM Workshop

UL’s perspective on training

August 2017

Paul Bates

TO PROMOTE SAFE WORK AND LIVING ENVIRONMENTS FOR ALL PEOPLE

World’s leading electrical safety testing and certification company

- Over 12,000 employees

Leading safety brand

- 22 billion UL Marks on products
- 100,000 products tested annually

Worldwide presence

- Over 70,000 customers in 104 countries
- 131 labs and certification facilities in 39 countries

ADDITIVE MANUFACTURING AT UL

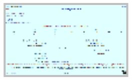
Design & Product Development

Design Validation

Material

Material Compliance

Blue Card Program



Chemical Safety

Printing Process

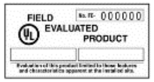
Equipment Compliance & Emissions

Material & Process Verification

Facility

AM Facility Safety

Field Evaluations



Applications

- Consumer Goods
- Medical
- Automotive
- Aerospace
- Energy Power & Technologies
- Appliances
- ….

Simulation 3DSIM

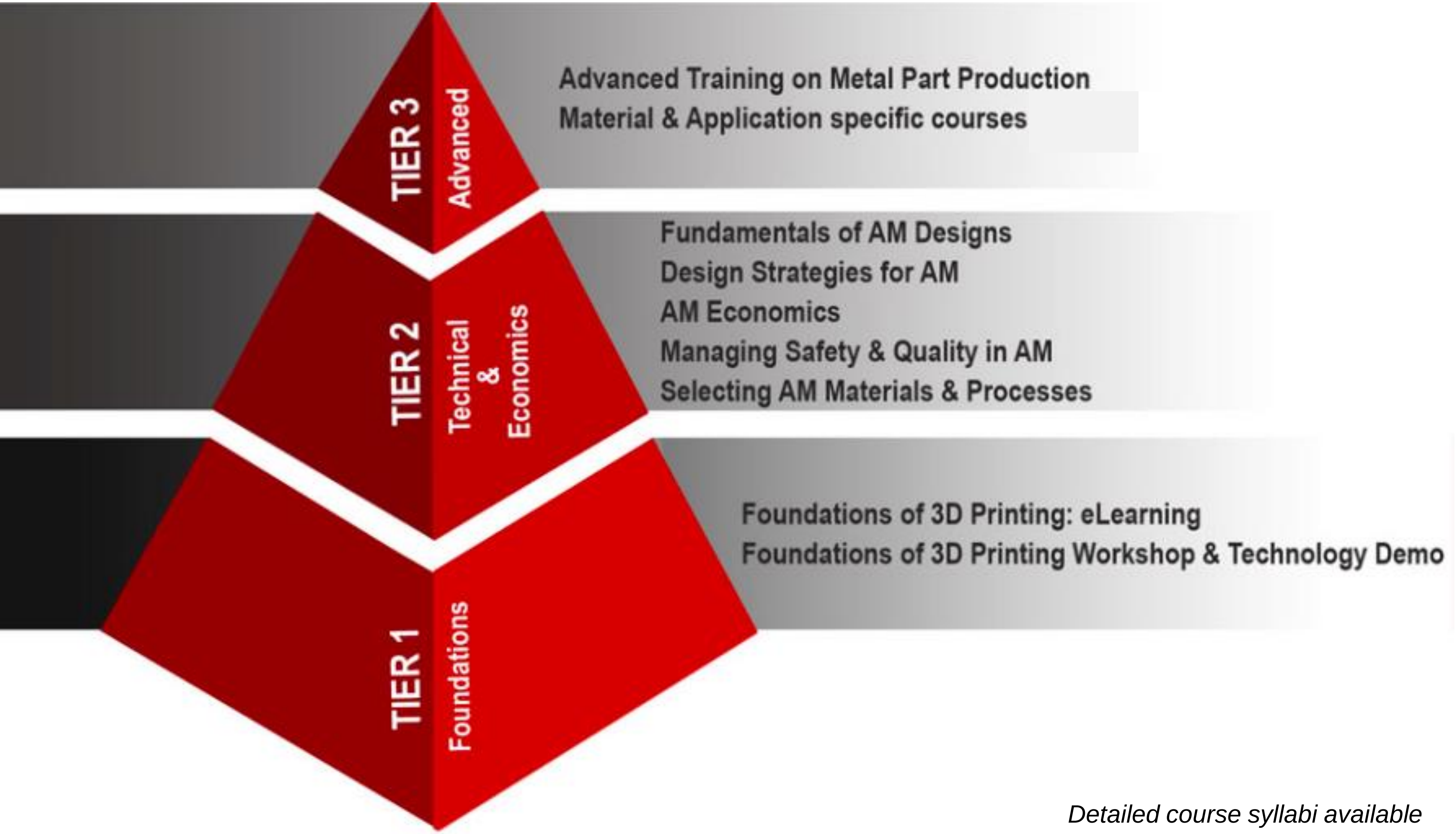
Workforce Development & Training

Partnering to Advance Innovation, Safety and Quality

Challenges to the AM industry

Where will they come from?

UL’s Additive Manufacturing Training Program



TIER 3 Advanced

Advanced Training on Metal Part Production

Material & Application specific courses

TIER 2 Technical & Economics

Fundamentals of AM Designs

Design Strategies for AM

AM Economics

Managing Safety & Quality in AM

Selecting AM Materials & Processes

TIER 1 Foundations

Foundations of 3D Printing: eLearning

Foundations of 3D Printing Workshop & Technology Demo

Detailed course syllabi available

What makes UL’s program unique?

Safety – training on materials

Safety – training on facility operations

SAFETY APPLIES TO EVERYONE

- Process Technicians
- Manufacturing Engineers
- OEM’s
- Material suppliers
- Field Service Technicians
- Janitorial Service providers

Collaboration Partners

e-Manufacturing Solutions

UL to provide additive manufacturing training to EOS users

Collaboration between UL and EOS will provide additive manufacturing (AM) training, together with facility safety services to EOS clients.

March 28, 2017
Edited by Elizabeth Engler Modic

SUBSCRIBE

3D/Additive/Alternative
Manufacturing

Officials from UL and EOS announce a joint collaboration in which UL will provide additive manufacturing (AM) training and facility safety services to EOS clients – with the goal of advancing quality and safety within the AM industry and enhance the EOS customer experience.

UL partners with NAMIC on AM Training

UL, in partnership with the National Additive Manufacturing Innovation Centre (NAMIC), introduces AM training specifically designed for Singapore-based companies.

Known as the UL AM Training & Certification Guidance Program (TCP), the class provides guidance on whether your 3D printed part can be manufactured and how to explore certification for market adoption. As part of the collaboration with NAMIC, TCP participants can be reimbursed for related AM testing and services up to the value of the course fees.

UL Signs MOU with Taiwan to Collaborate on Globally Recognized Digitized Manufacturing Processes

UL announces the signing of a memorandum of understanding (MOU) to collaborate with the Ministry of Economic Affairs (MOEA) of Taiwan. UL will join Taiwan Industrial Development Board (IDB) organizations including the Industrial Technology Research Institute (ITRI) and the Plastic

7 November 2016 10:16

UNDERWRITERS LABORATORIES AND BRIGHTLANDS MATERIALS CENTRE ANNOUNCE AM TRAINING PARTNERSHIP

The collaboration will provide a three-tier training and education process in additive manufacturing.

by Sam Davies

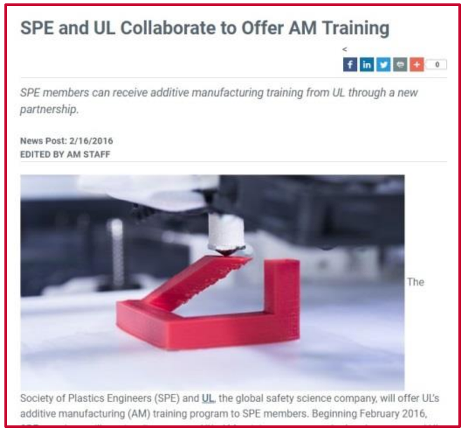
0 RSS Print

Brightlands Materials Center

Brightlands Materials Centre

Brightlands Materials Centre logo

A new research and development centre has collaborated with global safety science organisation, Underwriters Laboratories to provide additive manufacturing training to emerging markets.



SPE and UL Collaborate to Offer AM Training

0

SPE members can receive additive manufacturing training from UL through a new partnership.

News Post: 2/16/2016
EDITED BY AM STAFF

The Society of Plastics Engineers (SPE) and UL, the global safety science company, will offer UL's additive manufacturing (AM) training program to SPE members. Beginning February 2016,

6 February 2017 15:53

UL AND RICOH TEAM UP ON ADDITIVE MANUFACTURING TRAINING PROGRAMME

1 RSS Print

UL and Ricoh USA, Inc. have announced a partnership to promote the proper usage and advancement of additive manufacturing (AM) technologies.

Using UL's three-tier AM training curriculum, the programme will initially be held at Ricoh's US-based training locations, starting at its Lawrenceville, Georgia location in

UL Partners with ARTC to Launch Design for Additive Manufacturing Training Course in Singapore

UL, in partnership with the Advanced Remanufacturing and Technology Centre (ARTC), will host an exclusive training program on "Design for Additive Manufacturing (AM)." The five-day hands-on training course will take place at ARTC from August 17-21, 2015. ARTC is Asia's first centre for test-bedding and developing manufacturing technologies.

Contact Info:

Paul Bates

Manager | UL AMCC

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W: www.ul.com/AM