DOT/FAA/TC-20/16

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

Joint FAA—EASA Workshop on Qualification & Certification of Metal Additively Manufactured Parts

21 – 23 August 2018

National Center for Aviation Training Wichita, KS

April 16, 2020

Final report



U.S. Department of Transportation
Federal Aviation Administration

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-20/16		

4. Title and Subtitle	5. Report Date
SUMMARY REPORT: JOINT FEDERAL AVIATION ADMINISTRATION–EUROPEAN AVIATION SAFETY AGENCY WORKSHOP ON QUALIFICATION & CERTIFICATION OF METAL ADDITIVELY MANUFACTURED PARTS	April 16, 2020
	6. Performing Organization Code
7. Author(s) Dr. R. E. Dutton	8. Performing Organization Report No.
9. Performing Organization Name and Address Universal Technology Corp. 1270 North Fairfield Road Dayton, OH 45432	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration 950 L'Enfant Plaza, S.W. Washington, DC 20024	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code AIR-600

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Mr. Jim Hayes.

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16. Abstract

The Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) jointly organized a workshop on Qualification and Certification (Q&C) of Metal Additively Manufactured (AM) Parts, which was held from August 21 to August 23, 2018, at the National Center for Aviation Training (NCAT) in Wichita, KS. From the FAA perspective, the workshop was conducted and sponsored within the framework of the FAA's Annual Chief Scientific and Technical Advisor (CSTA) Workshop (workshop organizer – Dr. Michael Gorelik). This was the fourth such workshop: previous workshops were held in 2015, 2016, and 2017, in Dayton, OH, and organized jointly with US Air Force. There were 134 registered attendees, representing the FAA, EASA, Air Force, NASA, aerospace industry OEMs and suppliers, academia, several international companies and organizations, and selected other invitees. The objectives of the workshop 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 and EASA, regarding Q&C of metal AM parts.

The workshop consisted of 17 presentations addressing background, current programs, and Q&C challenges for additively manufactured metal parts as well as three Breakout Sessions that discussed: 1) Design Data for Qualification and Certification; 2) Fatigue and Fracture Considerations; and 3) NDE Inspection and In-situ Process Monitoring. In addition, a Regulatory Authorities Panel Session was held to discuss forthcoming FAA and EASA plans for the Qualification and Certification of Metal AM parts.

17. Key Words	18. Distribution Statement
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; certification; qualification	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGEMENTS

The author would like to acknowledge the following people and organizations who contributed to making this workshop a success through their sponsorship and participation:

Sponsors, organizers, and hosts:
- Michael Gorelik, FAA
- Simon Waite and Matthew Mercy, EASA
- Paul Jonas and Tracee Friess, NIAR and Wichita State University

Keynote speakers:
- Harinder Grewal, Director of Advance Repairs, Delta TechOps.
- Markus Heinimann, VP of Engineered Product and Process Technology, Arconic

Breakout session facilitators:
- Doug Wells, NASA
- Michael Gorelik, FAA
- Simon Waite, EASA
- Matthew Mercy, EASA
- Eric Lindgren, AFRL

In addition, there were 17 technical presentations from various US and European government agencies, international companies, and numerous US companies, research laboratories, and specification and standards organizations whose contributions to the workshop are gratefully acknowledged.

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LIST OF ACRONYMS

AIA	Aerospace Industries Association
ACO	Aircraft Certification Office
AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
AMNT	Additive Manufacturing National Team
ASTM	American Society of Testing and Materials
ASI	Aviation Safety Inspector
AWS	American Welding Society
CFR	Code of Federal Regulations
CSTA	Chief Scientific and Technical Advisor
DARWIN	Design Assessment of Reliability with Inspection
DED	Directed Energy Deposition
DMLS	Direct Metal Laser Sintering
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
F&DT	Fatigue and Damage Tolerance
FSDO	Flight Standards District Offices
ICME	Integrated Computational Materials Engineering
LPBF	Laser Powder Bed Fusion
MAMLS	Maturation of Advanced Manufacturing for Low-Cost Sustainment
MIDO	Manufacturing Inspection District Office
MMPDS	Metallic Materials Properties Development and Standardization
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NDE	Nondestructive Evaluation
NIAR	National Institute for Aviation Research
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
PMA	Parts Manufacturer Approval
Q&C	Qualification & Certification
RISC	Rotor Integrity Sub-Committee
SAE	Society of Automotive Engineers

EXECUTIVE SUMMARY

Additive Manufacturing (AM) is a rapidly emerging technology with 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. To ensure that AM parts are safe and robust, the requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control require careful consideration in qualification and certification (Q&C) procedures.

The FAA and EASA jointly organized a workshop on Qualification and Certification of Additively Manufactured Parts, which was held from August 21 through August 23, 2018, at the National Center for Aviation Training (NCAT) in Wichita, KS. This was the fourth FAA-sponsored workshop; the first three were organized jointly with AFRL and held in Dayton OH in September 2015, August 2016, and August 2017. The workshop was conducted and sponsored within the framework of the Annual CSTA Workshop. There were 134 registered attendees from the FAA, EASA, Air Force, DLA, NASA, industry OEMs and suppliers, academia, and several international organizations.

The overall objective of the workshop was to build on the outcomes of the 2017 (and prior) FAA-USAF and EASA AM workshops, which provided in-depth discussion on the technical considerations for the qualification and certification of AM parts. The workshop consisted of 17 presentations addressing background, current programs and aerospace applications, and Q&C challenges regarding AM metal parts, as well as three parallel breakout sessions:

Session #1: **Design Data for Qualification and Certification**
Session #2: **Fatigue and Fracture Considerations**
Session #3: **NDI Inspections and In-situ Process Monitoring**

In addition, the workshop included a moderated Regulatory Authorities Panel session comprised of seven panelists from the FAA, EASA, and NASA.

SUMMARY REPORT: JOINT FAA – EASA WORKSHOP ON QUALIFICATION & CERTIFICATION OF METAL ADDITIVELY MANUFACTURED PARTS

1. INTRODUCTION AND BACKGROUND

Additive Manufacturing (AM) is a rapidly emerging technology with 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. The main process types for structural metals include directed energy deposition (DED) (such as electron beam melting and deposit of metal wire), and powder bed fusion 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. Since the capital investment required for individual AM equipment is relatively modest, 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.

Over the past few years there has been a rapid increase in parts criticality (both engines and airframes) and a broad interest in moving from point design to part family qualification and certification (Q&C). In addition, there has been a rapid expansion of the AM supply chain with new entrants to the field and existing suppliers moving up the supply chain. Further, AM machines continue to evolve, becoming bigger, faster, incorporating multi-laser systems and in-situ process monitoring. 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 and between AM machines of similar type may be significant. To ensure that AM parts are safe and robust, the requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control require careful consideration in Q&C procedures.

The FAA and EASA jointly organized a workshop on the Q&C of AM parts, which was held from August 21 through August 23, 2018, at the National Center for Aviation Training (NCAT) in Wichita, KS. This was the fourth FAA-sponsored workshop; the first three were organized jointly with AFRL and held in Dayton OH in September 2015, August 2016, and August 2017[1,2,3]. The workshop was conducted and sponsored within the framework

[1] 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

of the FAA Annual CSTA Workshop. This document is intended to provide a brief reference paper to summarize the background, objectives, and key outcomes of the workshop.

2. WORKSHOP OVERVIEW

2.1 OBJECTIVES

The objectives of the workshop were to continue education of the FAA workforce by providing information on AM processes to FAA employees, provide a comprehensive review of industry and OEM progress and challenges regarding AM applications, and promote collaboration across the government, industry, and academia.

2.2 WORKSHOP FORMAT

The workshop was a two-and-a-half-day event held at the National Center for Aviation Training (NCAT) facility of the National Institute for Aviation Research (NIAR) in Wichita, KS.

The agenda included 17 formal presentations, plus brief opening remarks. Day 2 of the workshop included three parallel breakout sessions: 1) Design Data for Q&C ; 2) Fatigue and Fracture Considerations; and 3) NDI Inspections and In-situ Process Monitoring. On Day 3 of the workshop, in addition to debriefs from the breakout sessions, a Regulatory Authorities Panel session consisting of seven invited panel members from the FAA, EASA, and NASA was held. Panelists were each given a few minutes to describe their role in their respective agency, after which a moderated question-and-answer session was conducted.

The final agenda is available in Appendix A.

2.3 WORKSHOP ATTENDEES

There were 134 registered attendees, representing the FAA, EASA, US Air Force, NASA, DLA, TCCA, CAAS, aerospace industry OEMs and suppliers, academia, several international organizations, and selected other invitees. FAA participation included 39 people from numerous sites, which was a 25% increase in FAA participation compared to prior workshops. Attendance was generally by invitation of the organizers, but most requests to attend were accommodated, within the limitations of the venue's capacity.

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[2] 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

[3] 2017 Workshop Summary Report: "Joint Federal Aviation Administration-Air Force Workshop on Qualification / Certification of Additively Manufactured Parts," DOT/FAA/TC-18/3, Final report, February 2018. http://www.tc.faa.gov/its/worldpac/techrpt/tc18-3.pdf

3. SUMMARY OF WORKSHOP SESSIONS AND PRESENTATIONS

The workshop consisted of two and a half days of presentations and breakout sessions, with question and discussion time for each presentation within the allocated time. A Regulatory Authorities Panel session also was held on the third day.

All presentations were cleared for public release and are appended to this report. The presentations are listed below, with a brief statement regarding topics addressed.

3.1 DAY-1 PRESENTATIONS

Brief welcoming remarks to initiate the workshop were made by Prof. John Tomblin, VP of Research and Technology, Wichita State University. This welcome was followed by a presentation describing the ASTM Additive Manufacturing Center of Excellence given by Mohsen Seifi, ASTM International (available in Appendix T). Michael Gorelik from the FAA then gave an overview presentation on the objectives of the workshop, followed by the brief opening remarks from the workshop EASA co-organizers, Simon Waite and Matthew Mercy. The presentation summarized the evolution of the workshops since 2015 and noted that the 2018 workshop was the first joint FAA-EASA workshop (available in Appendix D). There were 11 presentations on Day 1, including industry keynote presentations by Harinder Grewal, Director of Advance Repairs, Delta TechOps, and Dr. Markus Heinimann, VP of Engineered Product and Process Technology, Arconic. Brief descriptions of the 11 presentations follow.

1. **Industry Keynote Presentation #1** Harinder Grewal, Director of Advance Repairs, Delta TechOps. This presentation summarizes the potential impact of AM at Delta. Delta has over $1B in parts inventory, any portion of which might or might not end up being used. The ability to "print what you want, when you want" could reduce inventory and eliminate shipping costs and delivery delays. Thus, sending a print file to build a part at a facility halfway around the world is very attractive to Delta. Further, this capability could potentially free up large amounts of facility space currently dedicated to spare part inventory. However, Delta has to see a reasonable ROI before making investments and has held back investment in 2018, and is considering future investments very carefully. They will continue monitoring and attending events such as the FAA-EASA AM workshops, and will consider getting involved in efforts that can guarantee safe parts. Delta sees the largest challenge in the area of certification. (Presentation notes are available in Appendix E.)
2. **Industry Keynote Presentation #2** Dr. Markus Heinimann, VP of Engineered Product and Process Technology, Arconic, "From the Lab to the Skies: Printing the Future of Flight." Arconic's interest in AM is based upon their customer's desires for part consolidation, affordable production of complex parts, potential performance impacts, reduced buy-to-fly ratios, and reduced time to market. Challenges include feedstock materials, product design, metallurgy, machine parameters and post-processing and qualification. Aluminum has proven historically challenging to additively manufacture. This has led to the development

of new aluminum-based, high-performance alloys that can leverage the advantages of AM processes in terms of geometry. In addition, Arconic has developed hybrid processes that combine the benefits of conventional and AM processes. (This presentation is available in Appendix F.)

3. Mark Shaw, GE Additive, "GE Approach to Part Family." This presentation discusses the attributes of part families in the context of AM. In effect, the AM machine is viewed as an "additive foundry" where the decision to include a new part in a part family depends upon design considerations such as part criticality, high-stress/lowest-margin areas, location of defect areas and inspection capabilities. (This presentation is available in Appendix G.)
4. Adam Hicks, AFRL, "Qualification and Certification of AM Parts: AFRL perspective and progress." This presentation focuses on key aspects of research at AFRL relevant to qualification and certification. An overview of the AFRL program "Maturation of Advanced Manufacturing for Low-Cost Sustainment" (MAMLS) was also presented. (This presentation is available in Appendix H.)
5. Rick Russell, NASA, "Update on NASA's Additive Manufacturing Standards Development Effort and Top Durability and Damage Tolerance Concerns." This presentation describes the creation of NASA standards for AM. These standards create requirements with guidance, which can then be used to develop manufacturing plans and provide product specifications for both general and program specific applications. In addition, the presentation used experimental results from a thin-walled composite overwrapped pressure vessel life test assessment to demonstrate that neither (traditional) Linear Elastic Fracture Mechanics nor Elastic-Plastic Fracture Mechanics consider length scales that capture the observed microstructural variation seen in thin-walled AM components. (This presentation is available in Appendix I.)
6. Rachael Andrulonis (NIAR) and Jeff Conner (GE), "Summary and Conclusions from the June 2018 EASA Workshop on AM Machine Producers Knowledge Transfer[4]." This presentation provides a summary of workshop results with AM machine manufacturers that included Type Certificate Holders, potential users of AM and Standardization Bodies. The importance of communication between the various stakeholders and AM machine makers was called out as essential to the successful implementation of AM. Baseline data for machine reference is required, as well as an understanding of the key characteristics/parameters that need to be controlled/monitored. Finally, it was noted that regulatory guidance should be proportional to part criticality. (This presentation is available in Appendix J).
7. Simon Waite, EASA "EASA Regulatory Update on AM." Provides an overview of EASA's perspective on AM. (This presentation is available in Appendix K.)
8. Stephane Bianco, Airbus, "Airbus Experiences in Qualification of AM Products." The Airbus approach to Q&C of AM parts was presented, including feedback from the first serial AM powder bed part. The importance of process stability was emphasized. (This presentation is available in Appendix L.)
9. Alexander Ladewig, MTU Aero Engines, "Quality Assessment during LPBF-Process by Optical Tomography Inspection of Systematic and Local Deviations."

[4]2017 EASA AM Workshop proceedings: https://www.easa.europa.eu/newsroom-and-events/events/2017-easa-workshop-additive-manufacturing#group-easa-event-proceedings

Optical tomography uses a long time exposure of the build process to provide a measurement of radiation over time, which allows the monitoring of all platform positions during every step of the process. A systematic design of experiments (DoE) was performed varying basic process parameters across a series of cube builds. Defect density was plotted vs power, speed, hatch spacing, and layer thickness. Each graph showed a significant slope, indicating a high impact on defect occurrence. A similar plot of the average radiation from the optical tomography sensor against these same parameters also found a strong sensitivity/response demonstrating that sensors could be used to identify upper and lower tolerance bands for successful builds (it also was noted that every job had a unique signature). It also was stated that the optical tomography sensor was able to sense defects not easily detected by X-ray or CT and that no false negatives were observed. Based on these results, MTU installed optical tomography sensors on each of their machines. The system is commercially available for EOS M290 machines. (This presentation is available in Appendix M.)

10. Michael Gorelik and Mark Freisthler, FAA, "FAA Regulatory Update on AM." This presentation provides an update of the FAA AM activities. The AM National Team (AMNT) roadmap has completed its first round of senior management reviews. Several documents are in process, including a Draft Advisory Circular AC 33.15-4 "Guidance Material for Turbine Engine Parts and Repairs Produced by Powder Bed Fusion Additive Manufacturing." An overview was given next of the Metallic Materials Properties Development and Standardization (MMPDS) Emerging Technology Working Group, which is focused on the development of processes and procedures that can be used to derive and publish design information for process-intensive materials such as AM. The view of the group is that the MMPDS Handbook will eventually be split into two volumes—one for traditionally produced materials, and the other for process-intensive materials. (This presentation is available in Appendix N.)
11. Donald Palmer, Boeing, "Certification and Qualification of AM Parts." The presentation started with an overview of the various definitions of part criticality within the DoD. This overview was followed by a novel "Rubik's Cube" approach to visualizing the risk associated with replacing a conventionally manufactured part with one that has been fabricated via AM. An overview of the NDE of AM parts including a future vision where process monitoring is used as in-process NDE concluded the presentation. (This presentation is available in Appendix O.)

Day 1 concluded following this presentation.

3.2 DAY-2 PRESENTATIONS

Day 2 began with three parallel breakout sessions:

Breakout Session #1: "**Design Data for Qualification and Certification** – static properties characterization, part family considerations, feature-based qualification, component vs. coupon properties."

Breakout Session #2: "**Fatigue and Fracture Considerations** – effect of defects, characterization of defects, characterization of Fatigue & Damage Tolerance (F&DT) properties, zoning considerations for F&DT."

Breakout Session #3: "**NDI Inspections and In-situ Process Monitoring** – validated NDI methods for AM (current state), flaw detection capabilities, in-situ monitoring (current and future use)."

12. Mr. Brandon Wegge from Boeing was an invited *luncheon speaker* on Day 2 and made a presentation titled, "Update on Additive Manufacturing at Boeing." The Boeing approach to AM was described at the enterprise level. (This presentation is available in Appendix P.)

Following lunch there were three presentations, the brief summaries of which follow.

13. Martin White, GKN Aerospace, "The Certification Toolbox Approach and Future Opportunities for Qualification." This presentation describes GKN's approach to AM product introduction and certification as an evolutionary process starting with equivalence-based qualification (empirical qualification), through part family qualification, to process-based qualification. Of particular interest was the design of unique traveler specimens that mimic key features of an AM component in a build. (This presentation is available in Appendix Q.)
14. Stuart Jackson, Renishaw PLC, "Influence of Atmospheric Control on LPBF Part Quality & Powder Life." Metal powder reuse in AM has a large impact on the economics of the process. This paper presents the mechanical properties from build using a powder after 18 months of reuse. (This presentation is available in Appendix R.)
15. Adam Ryba, USAF/AFLCMC "USAF Additive Manufacturing." This presentation provides an overview of the Air Force Life Cycle Management Center's (AFLCMC) vision for implementing AM. Their approach stresses standardization of process, machine, material, and operators within the USAF Airworthiness Bulletin (AWB)-1015 "Airworthiness Process for Deploying New or Substitute Materials, Processes, and New Product Forms." (This presentation is available in Appendix S.)

Day 2 concluded after the presentations.

3.3 DAY-3 PRESENTATIONS

Day 3 included debriefs from the previous day's breakout sessions and a Regulatory Authorities Panel discussion. Brief descriptions of the breakout session debriefs follow.

Breakout Session #1: "**Design Data for Qualification and Certification** – static properties characterization, part family considerations, feature-based qualification, component vs. coupon properties."

The breakout session includes a series of short opening presentations by GE Additive, Boeing, and SAFRAN. These presentations were intended to initiate discussion and raise questions for consideration. The starting point for the group discussion was to develop a consensus understanding of "part family considerations." Through vigorous debate, it was discovered that the definition and implication of a "part family" approach has various meanings. For example, "part family" could include everything beyond "point design," or it could imply the use of common design values that are not part-specific, or it could mean qualification of parts by similarity to avoid repeated requalification of very similar parts.

It was agreed that the term "part family" needs standardization before Q&C policy can be negotiated. In addition, consensus was strong that better definition of the design data requirements for Q&C of individual parts is needed before "part family" considerations are appropriate. Furthermore, as a precursor to "part family" approaches, considerations of requalification methodologies following major/minor changes needs better definition.

It is important to note that the conclusion to defer considerations for the "part family" approach does not imply that industry should remain at a "point design" methodology for AM. There was consensus that if every AM part is treated as fully unique, the certification burden is simply unsustainable and establishing an accepted framework that enables the use of common design values is the key first step to lessening certification burden.

A five-step system was proposed as a potential foundation for establishing design values suitable for the Q&C of AM aerospace quality hardware. The intent of this framework was to bridge the gap between a "point design" approach to design values where material property data is developed specifically in the context of a given AM part, and the traditional approach to design data "allowables" as developed and tabulated in resources such as the MMPDS. The enabling concept in the proposed framework is reoccurring evaluations that demonstrate material equivalency for the purpose of qualifying AM processes and monitoring the health of the AM process continuously through statistical process control (SPC).

The introductory presentations and debrief charts from the session are available in Appendix U-X. Authored by Doug Wells, NASA, Appendix Y is a detailed discussion of the five-step system described above in the context of recent AM technical standards published by NASA Marshall Space Flight Center: MSFC-STD-3716 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals" and MSFC-SPEC-3717 "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes."

Breakout Session #2: "**Fatigue and Fracture Considerations** – effect of defects, characterization of defects, characterization of F&DT properties, zoning considerations for F&DT."

The Fatigue and Fracture Considerations breakout session opened with a series of useful short presentations by Arconic, Lockheed-Martin, SwRI, and P&W. Key takeaways from the presentations and associated discussions include the need to extend an understanding

of Fatigue & Damage Tolerance (F&DT) philosophies across the product types. It was noted that that the broader range and/or different damage modes available when using AM might drive some product designs to damage modes with which the product designer may not be familiar, or expecting, but which may be familiar to other product designers. Failure to develop a broader understanding could risk further confusion between philosophies, which can already be challenging at product responsibility interfaces, e.g., airframe and propulsion. There could be value in standardizing an F&DT menu, then selecting the correct F&DT philosophy, dependent upon material and process damage modes. This would help to standardize the language across all products.

The presentations raised again the potential value of using casting experience and developing evidence that the use of casting factors for AM might be conservative, for similar materials, etc. It would seem that the challenge would be the determination of an adequate database for when, or not, this would be the case. Such an approach could be more readily accepted for less critical parts with high margins. Regarding probabilistic modelling, the potential for zoning was discussed, and the possibility of extending existing modelling to airframe from engine applications. Although there is potential, it would take further model development, e.g., to address more challenging strain deformation cases in airframe applications. This may well be achievable but is likely to require development of significant additional data. While there is a need to optimize the use of existing development tools, accepting that there also would be a need for significant additional data provided a key message from the concluding presentation.

Five topics were identified for further discussion:

- **Defect Characterization—** This topic often is brought up when technical capability and refinement in AM processes exceed the real need for a given application. The question raised was: "How do we define and understand the range of defect types and sizes of practical interest, e.g., minimum size etc.?" This raised the discussion regarding the challenge between sharing defects knowledge, which may be very process-specific, with the industry, while not compromising intellectual-property issues. The value of processes to share data was discussed, such as the Rotor Integrity Subcommittee (RISC) and Rotor Manufacturing Subcommittee (RoMan) and their Lessons Learned database as possible models, which allow some level of anonymous data sharing. Discussions moved to the challenges associated with defining and managing "rogue flaws."

- **Characterization of Effect of Defects—**There was significant discussion associated with the importance of build surface, and an interesting point was raised regarding the potential importance of surface treatments and machining outcomes being influenced by defects that remain close to the surface, but which are not removed by machining. Such issues may impact design values. Discussion moved on to what statistical data should be used to support S-N curve development and from how far up the test pyramid should it be taken. It also was highlighted that even notch data would be challenging to define, more so than for composites. The virtue of deterministic versus probabilistic methods was further discussed. It was

suggested that deterministic DT methods are potentially cheaper, and potentially might focus upon defects of more practical interest than probabilistic methods. However, a risk exists that the assumed defect types and size may mask other damage modes that could be more critical.

- **The Role of Fatigue and Fracture in Process Qualification—**During this discussion, it was stated that fatigue and fracture data is typically more sensitive to process variation than static data properties. This links with some of the discussions associated with defect characterization effects, i.e., a cruder F&DT assumption could mask the type of smaller defects that may drive fatigue. The breakout group also was reminded that material anisotropy is not new, e.g., composites, single crystal turbine blades, etc.

- **Regulatory Expectations—**The challenge of defining useful regulatory guidance for materials and processes that are very application-specific was discussed again.

- **Research & Development—**The discussion identified a number of R&D subjects generally considered to be of value within the breakout group. However, again, the dependency of the "engineering properties" upon a very specific material, process, and application combination presents a challenge to the development of large, common R&D programs of broader industry value.

The introductory presentations and debrief charts from the session are available in Appendix Z-BB.

Breakout Session #3: "**NDI Inspections and In-situ Process Monitoring** – validated NDI methods for AM (current state), flaw detection capabilities, in situ monitoring (current and future use)."

The session opened with short presentations by AFRL and Universal Technology Corp. The follow-on discussion focused on three distinct topics: in situ NDE, post-build NDE, and analysis.

- **In situ NDE—** Discussed how AM enables structural configurations that are not possible with traditional manufacturing processes, e.g., lattice structures that are a significant inspection challenge. Several parameters can be measured during the processing, such as thermal imaging of melt pools and optical methods to address powder placement and sample consolidation. There also was a heavy emphasis on all the parameters that can be extracted from the AM machines themselves and how they could be used to help ensure a high-quality product.

Specific threads emerging from this discussion include:

- Which instrument controls can be used and with what fidelity to manage the quality of the part, not just the process?

- What steps are required to ensure that the AM system remains within acceptable bounds (e.g., SPC)? Focus on parameters that will decrease variability, but recognize that this does not eliminate the rogue defects.

- Are there methods to process data from AM machines in a timely manner to reach decisional information during the build process?

- Which parameters are most valuable to assess build quality – optimized build data collection and evaluation (i.e., just because you can measure something does not mean it is important).

- How can in-process measurements be used to capture defects as the build is occurring and allow for either corrective action, or at least a halt before additional investments are made in a defective part?

- **Post build NDE—**A less focused discussion that generally gravitated back to process controls and the use of AM machine parameters to ensure a quality product. Some discussion points in the post-build NDE of AM parts include:

  - Gaps for NDE exist in all stages: during build, as built, as machined, as delivered, but defining the gaps remains a challenge.

  - Current approaches are too slow, provide insufficient coverage, are not addressing defects of concern, and are too sensitive to typical part variability, such as surface roughness.

  - Computed Tomography (CT) is held as gold standard for NDE, yet there are challenges in the types of defects it will detect and size ranges as a function of material, geometry, size, and defect geometry, plus it is slow and expensive.

  - While there are numerous ongoing programs in this area, many of them appear to be trial-and-error studies without extensive problem decomposition before experiments are designed/executed.

  - Generic studies on the effects of defects have not been completed (or shared in the public domain), so it is not clear to users how to establish requirements for NDE of AM parts.

  - Methods used in welding and casting should be leveraged to address NDE needs of AM: a gap analysis is needed.

  - Gaps exist in how to convert in-process data to effective machine diagnostics and/or decisional information during the build.

  - While there was an extensive discussion on the value of coupons, there was a recognition that some form of ground truth is needed, such as destructive

characterization by serial sectioning. In addition, if coupons are to be used, the process must be appropriately specified so that artificially seeded defects have the same characteristics as real defects.

- Transfer functions could be developed between seeded defects and real defects, or between "measurables" in AM machines and the presence of defects.

- Process models to help understand what defects could emerge during the build would be very helpful, yet it is not clear if they exist or how mature they are to date.

- **Analysis—**Some form of structured analysis was referenced multiple times that include a complete decomposition of the process and the NDE-measured parameters that could be extracted from a build process. A possible approach was discussed that include:

  - Identification of NDE limitations considered during the part design phase.

  - Part criticality considerations (e.g., primary load carrying, or just a support structure) when defining NDE objectives.

  - What to look for and where, identifying the key parameters, in establishing a more focused approach to process monitoring.

  - What data to capture from AM machine, from in-situ measurements, and from post-build NDE to decision-making.

  - How this data would be combined to assess the condition of the built part, i.e., full diagnostic on whether or not it is acceptable (the analogy to 100% ultrasonic inspection of all aerospace polymer matrix composites was mentioned several times).

  - Consider developing some form of defects library for at least an initial sensitivity evaluation of any new NDE method/NDE data analytics to determine how good it is and what investments need to be made to mature it.

The introductory presentations and debrief charts from the session are included in Appendix CC-EE.

3.4 AUTHORITIES PANEL SESSION

Day 3 included a one-hour moderated panel session comprised of seven invited panelists from the FAA, NASA and EASA:

Bob Grant, Greg Edwards, Michael Gorelik (FAA)

Simon Waite, Matthew Mercy (EASA)
Rick Russell, Doug Wells (NASA)

Panelists were each given a few minutes for a description of their role in their respective agency after which a moderated question-and-answer session was conducted based on the following questions:

- What regulatory/certification challenges do you see with increasing use of AM parts in Aerospace?
- What is your perspective on the use of AM in repairs/sustainment/MROs?
- What are your expectations regarding the certification package for AM parts?
- How can Supply Chain (e.g., Tier X, Machine Makers) become more aware of the regulatory requirements for AM?

The essential message of the panelists was that continuous industry communication with the regulatory authorities is critical to the successful implementation of AM. Several documents are in process and will be forthcoming over the next year. In the interim, early engagement with the authorities will ensure that the level of regulatory oversight is commensurate with part criticality.

The workshop concluded following the Regulatory Authorities Panel Session with an optional tour of the NIAR lab facilities.

4. RESULTS AND CONCLUSIONS

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

4.1 SUMMARY OF THE 2017 WORKSHOP

A brief summary of key points from the 2017 workshop is presented here to serve as a baseline for the general observations and conclusions from the 2018 workshop:

- **High-rate production of AM parts is now a reality:** The GE 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 appear targeted for near-term implementation.** This appears to have significantly advanced compared to prior years, where many applications were being evaluated, but few appeared imminent.
    - Many gas turbine engine parts, including aggressive development of part family applications.
    - Many airframe parts, predominantly non-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, applications where the buy-to-fly ratio was significantly improved, and applications where reduced lead time was a significant driver for an AM approach.

- **Extensive efforts to develop AM standards, specifications, and guidelines continue:** ASTM, ASM, NIST continue to support extensive development efforts for AM standards, specifications, and recommended practices.
- **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 Q&C.** 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.
- **Q&C must address the manufacturing process, the specific part, and the potential system impact.** The Q&C process for AM parts clearly requires attention to the material and manufacturing process, and of course, to the specific requirements for any candidate part. It was emphasized that the "system requirements" must also be considered and addressed for every application.

4.2 GENERAL OBSERVATIONS AND CONCLUSIONS FROM THE 2018 WORKSHOP

The following general observations were derived from the 2018 workshop:

- More companies are entering into serial production of metal AM parts.
  - More AM applications are under development, but all appear to be point designs.
  - The variation of AM processes was a common theme throughout the 2018 workshop. Several presenters made anecdotal comments regarding the variability observed between identical AM machines making the same part.
  - Q&C of AM parts was again called out as the pacing issue by several speakers.
- Maturation of metals AM:
  - Alloys are being developed specifically for the purpose of AM. Fit-for-purpose alloys will mitigate some of the defects commonly observed in AM parts.
  - Hybrid processes are being developed where AM is used to make near-net, shape-forging preforms followed by final machining, reducing the buy-to-fly ratio of a conventional process.

- The development of standards continues with the potential introduction of a separate MMPDS Handbook for Process Intensive Materials (currently under discussion).

- Fatigue and Damage Tolerance methods:
  - Many potential AM applications, such as pressure vessels and heat exchangers, are thin-walled. Traditional Linear Elastic Fracture Mechanics and Elastic-Plastic Fracture Mechanics do not consider length scales that capture the observed microstructural variation seen in thin-walled structures.

  - Fatigue and fracture data are typically more sensitive to process variation than static data properties. Sub-surface defects very close to the surface may need special consideration.

  - The conventional S-N curve approach will have high scatter due to potential variability in material properties. Defect rates/population and alternative methods may need to be considered.

  - Conventional (regulatory) Damage Tolerance assessments may need to be modified for topologically optimized parts.

  - The Rotor Integrity Subcommittee (RISC) and Rotor Manufacturing Subcommittee (RoMan) are possible models for the sharing of F&DT data.

- Quality Control/In situ NDE:
  - Gaps for NDE exist in all stages: during build, as built, as machined, as delivered, but defining the gaps remains a challenge.

  - Current approaches are too slow, provide insufficient coverage, are not addressing defects of concern, and are too sensitive to typical part variability, such as surface roughness.

  - Process sensors are being used to perform quality control and in situ NDE. Probability of detection (POD) curves using optical tomography have been successfully developed.

5. RECOMMENDED NEXT STEPS

The following actions are recommended in the near term to ensure results of the workshop are effectively utilized:

1. **The FAA AM specialists should review results of the workshop for use in refinement of their roadmap and plans.**
   a. Refinement of the near-term action plans to address immediate needs in light of the results of this workshop.
   b. Refinement of the longer-term FAA plan consistent with an agency-level roadmap on certification of AM parts, and identification of any "gaps."

2. **Breakout Session follow up:** The breakout sessions developed excellent consensus problem statements relevant to the Q&C of metal AM parts. The FAA and EASA should establish joint working groups with industry to maintain the momentum of the breakout sessions.

6. FACILITATOR COMMENTS

This section offers a brief set of comments from the facilitator as an experienced observer of the development of new materials and processes. They represent the opinions of the author.

Workshop Comments: The workshop was very productive. There has been a change from presentations describing "what we're going to do" to presentations describing "what we've done." This shift to "use cases" marks the continued maturation of AM and the first steps of implementation. The breakout sessions were exceptionally valuable. Given that there was no pre-meeting homework for the attendees, it was somewhat surprising that participants were able to reach consensus on many challenging Q&C topics. Breakout sessions should be integrated into future workshops, but there should be pre-meeting homework assignments.

Qualification & Certification of Additively Manufactured Parts: The business case for AM is best for complex parts and small-lot production runs. In both instances, it is likely that certification authorities will be pushed to accept parts where post-build inspection of all features is not possible or where there is limited mechanical property data available from cut-ups of trial builds.

Information from in-situ process monitoring can be used to estimate the local "defect species" in key features enabling the component to be zoned for inspection or risk acceptance. Similarly, process information could be used to establish equivalency between baseline material property data obtained from coupons and data obtained from cut-ups facilitating the qualification of small-lot production runs.

To date, there are very few correlations between sensor data and microstructure (defect species) due to the time and expense required to fully characterize the material. The MTU Aero Engines presentation (Appendix M) showed how data from an in-situ optical tomography sensor could be used to develop a POD curve. It was clear from the presentation that the development of the correlation between optical tomography data and defect size required a great deal of effort and ingenuity (e.g., the PlastiX method).

In the near-term, correlations such as this can be used to establish process stability. In the longer term, they will support the development of material specifications, standards, and eventually, design allowables that enable the rapid comparison of component build data to baseline property data, especially in thin-walled structures such as pressure vessels, recuperators, hot zone components, and heat exchangers, where defect structures can dominate.

7. SUMMARY

The FAA and EASA jointly organized a workshop on Qualification and Certification of Additively Manufactured Parts, which was held from August 21 through August 23, 2018, at the National Center for Aviation Training in Wichita, KS. The workshop was conducted and sponsored within the framework of the Annual CSTA Workshop. There were 134 registered attendees from the FAA, EASA, Air Force, DLA, NASA, industry OEMs and suppliers, academia, and several international companies and organizations.

The overall objective of the workshop was to build on the outcome of the 2017 (and prior) FAA-USAF and EASA AM workshops, which provided in-depth discussion on the technical considerations for the Q&C of AM parts. The workshop consisted of 17 presentations addressing background, current programs and aerospace applications, and Q&C challenges regarding AM metal parts. The workshop also included three parallel breakout sessions: Session #1: “Design Data for Qualification and Certification”; Session #2: “Fatigue and Fracture Considerations”; and Session #3: “NDI Inspections and In-situ Process Monitoring.”

In addition, the workshop included a moderated Regulatory Authorities Panel session comprised of seven panelists from the FAA, NASA, and EASA.

All of the stated workshop objectives were accomplished.

APPENDIX A:
WORKSHOP AGENDA

Dress Code: ***Business Casual***

Joint FAA – EASA Workshop on Qualification / Certification of *Metal* Additively Manufactured Parts

August 21-23, 2018

Venue: National Center for Aviation Training (http://ncatkansas.org/)
Hosted by NIAR

Wichita, KS

- **Workshop Co-organizers**: Dr. Michael Gorelik (*FAA*); Dr. Simon Waite and Dr. Matthew Mercy (*EASA*)
- **Workshop Facilitator**: Dr. Rollie Dutton (*Universal Technologies Corp.)*

Day 1 – August 21

7:45 – 8:10	Arrival and Registration
8:15 – 8:40	Welcome Remarks – *Prof. John Tomblin, VP of Research and Technology, WSU*
8:40 – 9:10	Workshop Overview and Objectives (FAA / EASA)
9:10 – 9:40	*Industry Keynote* 1 – *Mr. Harinder Grewal*, Director of Advance Repairs, Delta TechOps
9:40 – 10:10	*Industry Keynote* 2 - "From the Lab to the Skies: Printing the Future of Flight", *Dr. Markus Heinimann*, VP of Engineered Product and Process Technology, Arconic
10:10 – 10:30	*Coffee Break / Networking*
10:30 – 11:00	"GE approach to part family", *Mark Shaw*, GE Additive
11:00 – 11:30	"Qualification and Certification of AM Parts: AFRL perspective and progress", *Adam Hicks*, AFRL / USAF
11:30 – 12:00	"Update on NASA's Additive Manufacturing Standards Development Effort and Top Durability and Damage Tolerance Concerns", *Rick Russell*, NASA
12:00 – 13:00	***Lunch & Networking*** *(* buffet-style, catered on site -- optional, but reservation and payment on-site required *for those who choose to participate)*
13:00 – 13:30	"Summary and Conclusions from the June 2018 EASA Workshop on AM Machine Producers Knowledge Transfer", *Rachael Andrulonis* (NIAR) and *Jeff Conner* (GE)
13:30 – 14:00	"EASA Regulatory Update on AM", *Simon Waite*, EASA
14:00 – 14:30	"Airbus experiences in qualification of AM products", *Stephane Bianco*, Airbus
14:30 – 15:00	*Coffee Break / Networking*
15:00 – 15:30	"Quality Assessment during LPBF-Process by Optical Tomography Inspection of systematic and local deviations", *Alexander Ladewig*, MTU Aero Engines
15:30 – 16:00	"FAA Regulatory Update on AM", *Michael Gorelik and Mark Freisthler*, FAA
16:00 – 16:30	"Certification and Qualification of AM Parts", *Donald Palmer*, Boeing Research and Technology
16:30 – 16:45	Summary of Day 1
18:00 – 20:00	No-host social *(and optional dinner)* - River City Brewing Co., 150 N. Mosley St.

APPENDIX A:
WORKSHOP AGENDA (CONTINUED)





Day 2 – August 22

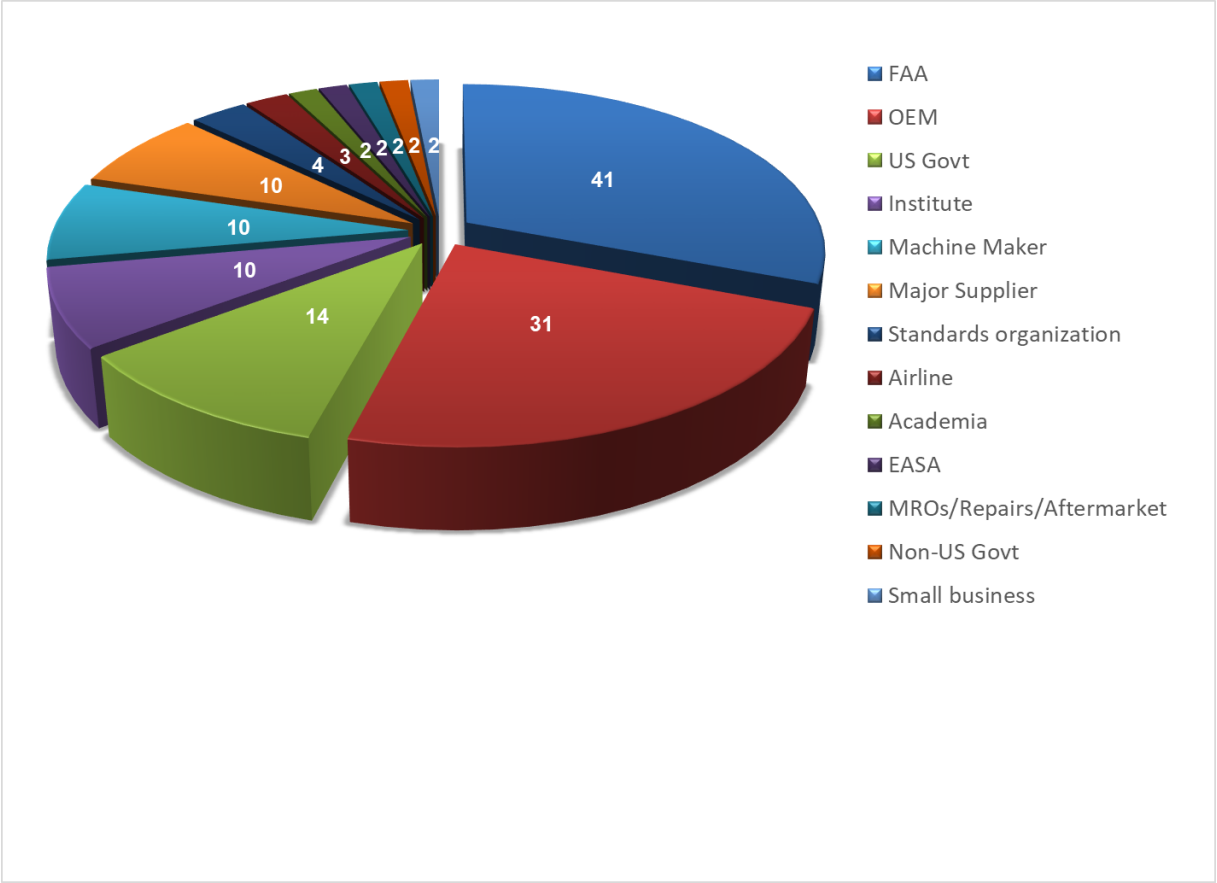
8:00 – 8:15 Arrival and registration
8:15 – 8:45 Introduction of breakout sessions (*objectives, format, list of participants, etc.*)
8:45 – 9:00 Transition to breakout session rooms (main auditorium + 2 additional rooms)
9:00 – 12:00 Breakout Session #1 (Main Auditorium) – *Co-chairs: R. Dutton (UTC) and D. Wells (NASA)*
"**Design Data for Q&C** – static properties characterization, part family considerations, feature-based qualification, component vs. coupon properties".
9:00 – 12:00 Breakout Session #2 (Breakout Room 1) – *Co-chairs: M. Gorelik (FAA) and S. Waite (EASA)*
"**Fatigue and Fracture Considerations** – effect of defects, characterization of defects, characterization of F&DT properties, zoning considerations for F&DT".
9:00 – 12:00 Breakout Session #3 (Breakout Room 2) – *Co-chairs: E. Lindgren (USAF) and M. Mercy (EASA)*
"**NDI Inspections and In-situ Process Monitoring** – validated NDI methods for AM (current state), flaw detection capabilities, in-situ monitoring (current and future use)".
12:00 – 13:00 ***Lunch & Networking*** *(* buffet-style, catered on site -- optional, but reservation and payment on-site required *for those who choose to participate)*
12:30 – 13:00 Luncheon Speaker*: Mr. Brandon Wegge,* Chief Engineer – Boeing Additive Manufacturing, "Update on Additive Manufacturing at Boeing"
13:00 – 15:00 Breakout Session #1 – *Continued* (Main Auditorium)
13:00 – 15:00 Breakout Session #2 – *Continued* (Breakout Room 1)
13:00 – 15:00 Breakout Session #3 – *Continued* (Breakout Room 2)
15:00 – 15:30 Coffee Break / Networking
15:30 – 16:00 "The Certification Toolbox Approach and Future Opportunities for Qualification", *Martin White*, GKN Aerospace
16:00 – 16:30 "Influence of Atmospheric Control on LPBF Part Quality & Powder Life", *Stuart Jackson*, Renishaw Plc
16:30 – 17:00 "USAF Additive Manufacturing", *Adam Ryba*, USAF / LCMC
17:00 – 17:15 Summary of Day 2

Day 3 – August 23

8:00 – 8:15 Arrival and Coffee
8:15 – 8:45 Breakout Session **#1** Debrief – session lead(s)
8:45 – 9:15 Breakout Session **#2** Debrief – session lead(s)
9:15 – 9:45 Breakout Session **#3** Debrief – session lead(s)
9:45 – 10:15 Coffee Break / Networking
10:15 – 11:30 Authorities Panel Session. *Moderator: R. Dutton*
11:30 – 12:00 Summary of Workshop Observation and Next Steps (FAA, EASA)
12:00 – 13:00 ***Lunch & Networking*** *(* buffet-style, catered on site -- optional, but reservation and payment on-site required *for those who choose to participate)*
13:00 – 15:00 Tour of NIAR AM Labs (*registration required, details to be announced*)
Optional tour – please indicate interested at the NIAR registration site
15:00 *Adjourn*

Rev_Final

APPENDIX B:
WORKSHOP DEMOGRAPHICS



APPENDIX C:
TABLE OF PRESENTATIONS

1. Michael Gorelik, FAA, Workshop Overview and Objectives, Appendix D

2. Harinder Grewal, Delta TechOps, Industry Keynote 1, Appendix E

3. Markus Heinimann, Arconic Industry Keynote 2 - "From the Lab to the Skies: Printing the Future of Flight," Appendix F

4. Mark Shaw, GE Additive "GE Approach to Part Family," Appendix G

5. Adam Hicks, AFRL, "Qualification and Certification of AM Parts: AFRL Perspective and Progress," Appendix H

6. Rick Russell, NASA, "Update on NASA's Additive Manufacturing Standards Development Effort and Top Durability and Damage Tolerance Concerns," Appendix I

7. Rachael Andrulonis (NIAR) and Jeff Conner (GE), "Summary and Conclusions from the June 2018 EASA Workshop on AM Machine Producers Knowledge Transfer," Appendix J

8. Simon Waite, EASA "EASA Regulatory Update on AM," Appendix K

9. Stephane Bianco, Airbus, "Airbus Experiences in Qualification of AM Products," Appendix L

10. Alexander Ladewig, MTU Aero Engines "Quality Assessment during LPBF-Process by Optical Tomography Inspection of Systematic and Local Deviations," Appendix M

11. Michael Gorelik and Mark Freisthler, FAA, "FAA Regulatory Update on AM," Appendix N

12. Don Palmer, Boeing, "Certification and Qualification of AM Parts," Appendix O

13. Brandon Wegge, Boeing, "Update on Additive Manufacturing at Boeing," Appendix P

14. Martin White, GKN Aerospace, "The Certification Toolbox Approach and Future Opportunities for Qualification," Appendix Q

15. Stuart Jackson, Renishaw PLC, "Influence of Atmospheric Control on LPBF Part Quality & Powder Life," Appendix R

16. Adam Ryba, USAF / AFLCMC "USAF Additive Manufacturing," Appendix S

17. Mohsen Seifi, ASTM International, “ASTM AM CoE,” Appendix T

PRESENTATIONS FROM THE BREAKOUT SESSIONS:

Session #1: **Design Data for Qualification and Certification**

1. Mark Shaw, GE Additive, Appendix U
2. David Polland, Boeing, Appendix V
3. Bénédicte Valette, SAFRAN, Appendix W
4. Breakout Session #1 Debrief, Appendix X
5. Doug Wells, NASA, Appendix Y

Session #2: **Fatigue and Fracture Considerations**

1. Markus Heinimann, Arconic, Appendix Z
2. Craig McClung, SwRI, Appendix AA
3. Breakout Session #2, Debrief, Appendix BB

Session #3: “**NDI Inspections and In-situ Process Monitoring**

1. Eric Lindgren, AFRL, Appendix CC
2. Michael Lander, Universal Technology Corp., Appendix DD
3. Breakout Session #3 Debrief, Appendix EE

APPENDIX D
MICHAEL GORELIK, FAA
WORKSHOP OVERVIEW AND OBJECTIVES

Welcome to the 1st Joint FAA – EASA AM Workshop

Opening Remarks

August 21, 2018

Wichita, KS

Presented by:

Michael Gorelik (FAA)

with additional remarks from

Simon Waite and Matthew Mercy (EASA)

Hosted by NIAR

NIAR Wichita State University National Institute for Aviation Research

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*)

Joint FAA - USAF AM Workshops

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

2018 Workshop

- **First *joint* FAA – EASA workshop**
- **First workshop with parallel breakout sessions**
- **Continued focus on Q&C**
- **Tracking of the key industry trends (in the Q&C context) → *see next chart***

Key Trends *(a partial list)*

- **Rapid increase in parts criticality (both engines and airframes)**
- **Moving from *Point Design* to *Part Family* Q&C**
- **Rapid expansion of Supply Chain**
  - *New entrants; existing suppliers moving up the chain*
- **Evolution of AM machines (bigger, faster, …)**
  - Multi-laser systems, in-situ process monitoring, …
- **Evolution of Public Standards (SDOs) landscape**
  - ***AMSC AM Standards Roadmap Ver. 2.0***
- **Expanding applications domain**
  - *New Products, Repairs / MRO, Aftermarket*
- **More R&D programs with focus on Q&C**

Agenda at a Glance

- **Two Keynotes:**
  - **Director of Advance Repairs, *Delta TechOps***
  - **VP of Engineered Product and Process Technology, *Arconic***
- **15 presentations from industry and government**
- **3 Breakout Sessions**
- **Regulatory Panel**
- ***Professional Networking***

- ***Design Data for Q&C***
- ***F&DT Considerations***
- ***NDI and Process Monitoring***



Dress Code: *Business Casual*

Joint FAA – EASA Workshop on Qualification / Certification of *Metal* Additively Manufactured Parts

August 21-23, 2018

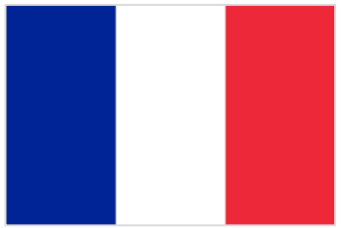
Venue: National Center for Aviation Training (http://ncatkansas.org/)
Hosted by NIAR

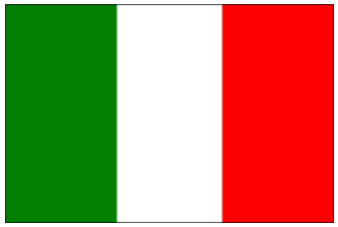
Wichita, KS

- **Workshop Co-organizers**: Dr. Michael Gorelik (*FAA*); Dr. Simon Waite and Dr. Matthew Mercy (*EASA*)
- **Workshop Facilitator**: Dr. Rollie Dutton (*Universal Technologies Corp.*)

Global Participation in 2018



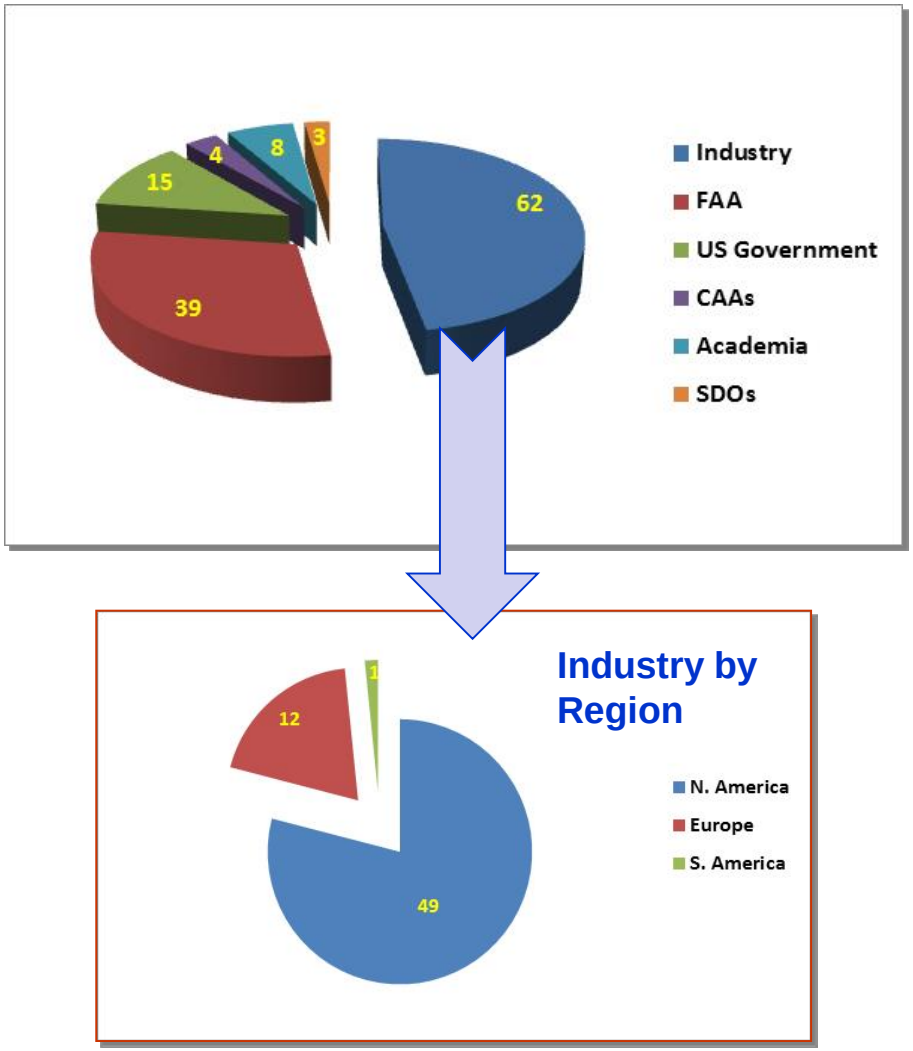








- *Canada*
- *France*
- *Germany*
- *Italy*
- *Norway*
- *Singapore*
- *Spain*
- *UK*
- *US*

Demographics by Organization Type



Thank you for your continuing support

Enjoy the Workshop !

... and Wichita



APPENDIX E
MR. HARINDER GREWAL, DELTA TechOps
INDUSTRY KEYNOTE 1

Industry Keynote 1

Mr. Harinder Grewal
Director of Advance Repairs
Delta TechOps

The airlines have done well in the last 7-8 years. The business model is working and appears to be sustainable. However, they are experiencing major issues with cost increases, which are rising at a faster pace and may upset the business model.

As far as Delta is concerned, most of the key performance metrics, Completion Factor, On-time departures, On-time arrivals, baggage handling, etc. are trending right. Just one exception - the costs are trending in the wrong direction.

The airline industry needs to improve both, fuel and non-fuel unit costs. Recent spikes in fuel prices are not helping. Delta will spend $2B more on fuel in 2018 over 2017. While Additive Manufacturing (AM) may improve fuel efficiency by reducing the weight of components this is not expected until 2022 or later.

Non-fuel unit costs are rising as well – 2.9% increase YoY. Maintenance costs are a large part of this cost group. Both labor and material costs are adding pressure. As such, Delta is investing in several areas to reduce engine maintenance costs. Investments are being made in hot section and compressor airfoils, expansion of x-ray/CT scan capabilities, establishing a standalone cell for LLPs, and last but not the least, Additive Manufacturing Technology.

When we talk about the Additive Manufacturing technology, it is music to the airlines maintenance executives.

- Opportunity to Cut weight and cost

    - Great potential for direct impact on fuel costs
    - Perhaps applicable on newer aircraft
    - Some retrofitting may happen over time
- Print what you need, when you need and where you need …….
    - It doesn't get better than that, does it?
    - Delta has numerous line maint shops around the US and the world
    - It would be perfect to have that capability
- Batch size as small as possible……. Yes even 1
- No lead time
- Produce complex structures directly from 3D CAD models
- Anything – replacement part, tool, mold
- Eliminate the need for inventory.
    - I am already excited about the opportunity to repurpose 100,000 sq ft of space it will open up
- Rapid prototyping

This gets attention and the airlines are very excited about the AM technology. Delta stepped up and the board approved funding for the AM capability in 2015

What have we done to date?

- My colleague, Ramesh Ramakrishnan provided an update last year. It's available in last year's folder.
- At a high level, TechOps AM Center was established last year – Phase 1 capability
- It includes Polymeric and metallic capabilities
- We have set up a good team of engineers
- In addition to the projects undertaken internally, the team has several projects in works with external agencies – govt. labs, universities and other providers
- We have additional funding to invest in this technology

The results so far have been very encouraging ……..

- Quick prototyping has been a big hit and very helpful to several depts.

- Tool manufacturing has helped speed up repair projects
- Couple of repair projects, which would not have been possible without reverse engineering and AM capability were completed successfully

While this looks very encouraging, I am concerned if the AM technology is going to live up to the expectations. Would we ever get to a point when we will be able to print what we need, when we need and where we need? Potential is there, but so are the hurdles facing the industry, primarily,

- Limited availability of approved powders
- Real time process control
- Certification and approval

So, the dilemma the business leaders are facing is whether to invest more in this technology now or wait and see. There has to be a reasonable ROI before making investments. Delta has held back investment in 2018, and is considering future investments very carefully.

Having said that, I have full confidence in the ability of this forum/team to address the issues ASAP, so that this once in a lifetime disruptive technology reaches to its full potential.

Thank you!!

APPENDIX F
DR. MARKUS HEINIMANN, ARCONIC
INDUSTRY KEYNOTE 2
“FROM THE LAB TO THE SKIES: PRINTING THE FUTURE OF FLIGHT”

From the Lab to the Skies

Printing the Future of Flight

Markus Heinimann, Vice President – Engineered Product and Process Technology

ARCONIC

Innovation, engineered.



Arconic Engineered Products and Solutions

Manufacturer of multi-material, engineered products and solutions

$5.9B
2017 revenue

91* Locations

12 Countries

- Manufacturer of high-performance engineered products and solutions for the **aerospace, industrial gas turbine, commercial transportation and oil and gas markets**
- Strategic global footprint with **key innovation centers adjacent to customer clusters** in North America and Europe and a **low-cost manufacturing footprint**
- **Able to supply >90% of structural and rotating aero engine components**







- **Arconic Engineered Structures:** World-class producer of titanium aero ingots and mill products, as well as forged, extruded and 3D printed structures for aerospace and defense
- **Arconic Engines:** World-class producer of aero engine and industrial gas turbine components, including airfoils, rings, disks and forgings
- **Arconic Fastening Systems:** Global leader in fastening systems with high-tech, multi-material solutions found on aircraft, aero engines, and numerous other end markets

ARCONIC

* Includes13 locations that serve as sales and administrative offices, distribution centers or warehouses.

3D printing is on the rise

Analysts forecast the global aero 3D printing market to grow at a CAGR of 55.85% from 2016-2020 (TechNavio)

Why our customers want it:

- Affords opportunities for part consolidation (Cost Reduction, Improved Performance)
- Enables production of complex parts not possible w/traditional manufacturing (Equal Cost , Lower Weight)
- Offers component performance and efficiency benefits not possible before (Lower Life Cycle Cost)
- Reduces the buy-to-fly ratio – or the amount of material and tooling needed to make a part (Lower Cost)
- Speeds time to market



But AM is also complex

You can't just download a design, add powder and press print





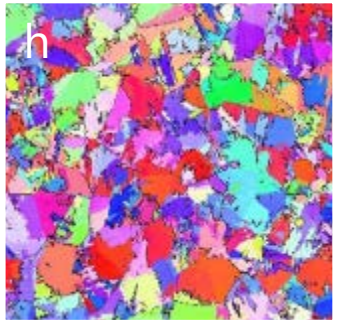
Taking 3D printing from the lab to large-scale manufacturing requires **expertise** in:

- Feedstock materials
- Product design
- Metallurgy
- Machine parameters
- Post processing and qualification

Arconic is leveraging comprehensive AM capabilities

From advanced alloy development to finished part production

New Material Discovery



- >20 patents on Al, Ti and Ni alloys
- ~$40M invested in powder pilot-scale development

Direct Manufacturing



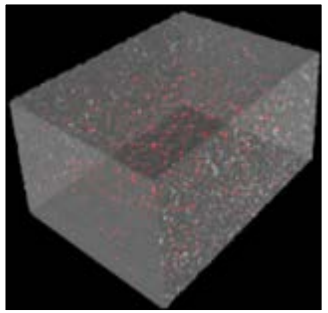
- Capabilities across all technologies
- Awarded contracts for Ti and Ni Aerospace parts

Indirect and Hybrid Manufacturing



- Indirect mfg. reduces development time and cost by >50%
- Hybrid mfg. combines additive with advanced conventional mfg.
  - E.g., Ampliforge™ & Hybrid Aero Engine Rings and Castings

Post Print Processing and Qualification



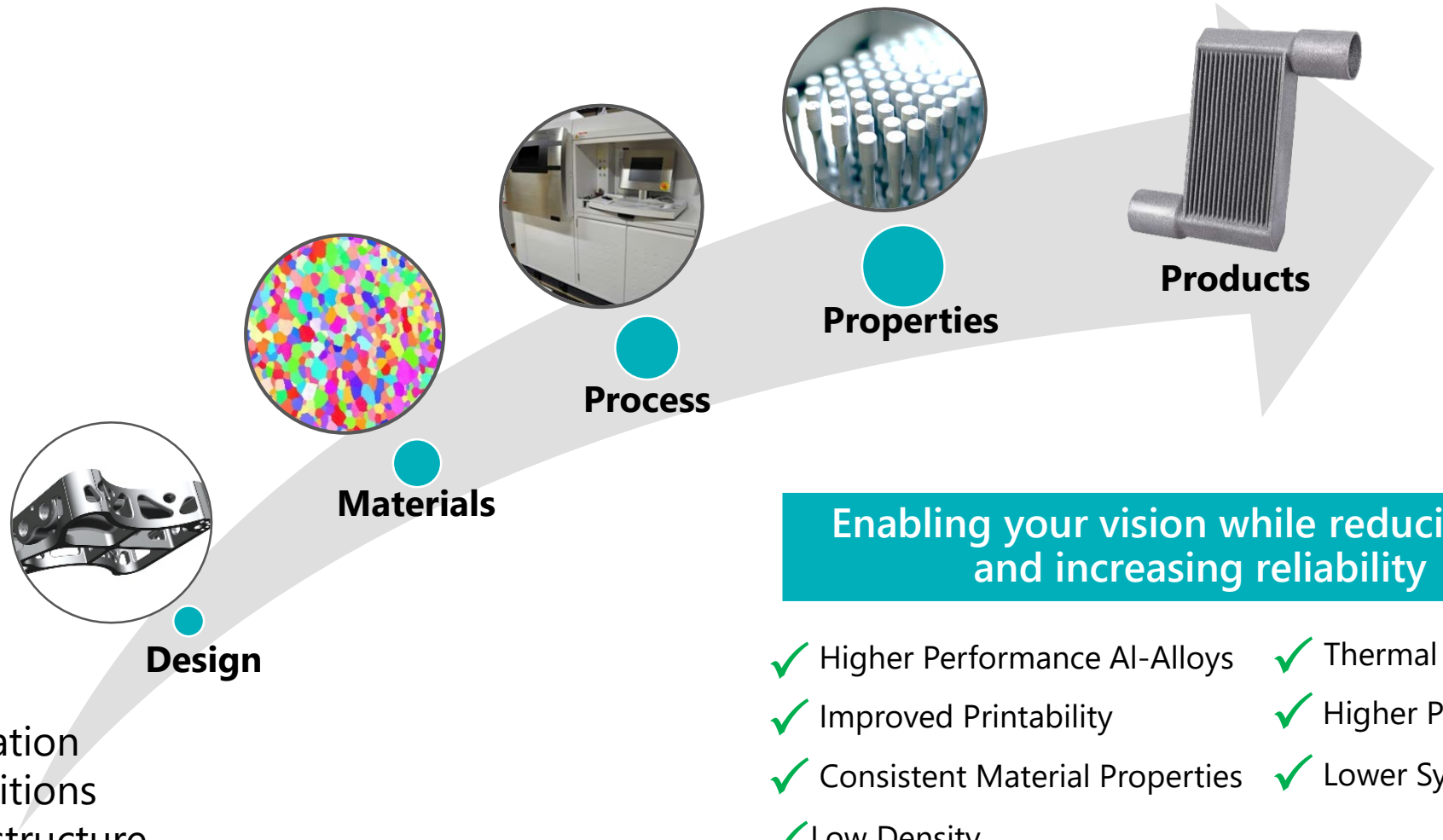
Unique capabilities in:

- Thermo-mechanical processing
- Inspection and certification
- Hot isostatic pressing and metallic surfaces

ARCONIC

Arconic's pathway for customer success

Building a bridge to future AM applications as a legacy materials leader



Levers with AM

- Rapid Solidification
- Novel Compositions
- Tailored Microstructure

Enabling your vision while reducing risk and increasing reliability

- ✓ Higher Performance Al-Alloys
- ✓ Improved Printability
- ✓ Consistent Material Properties
- ✓ Low Density
- ✓ Thermal Stability
- ✓ Higher Productivity
- ✓ Lower Systems Cost

New Material Discovery

ARCONIC



Metal powder is the “smart ink” in our 3D printing processes

Arconic is developing proprietary metal powders optimized for 3D printed aerospace parts



Metal Powder



Quality Laboratory

- New material discovery R&D
- Powder production & processing R&D
- Feedstock for prototypes and low rate initial production
- Draws on our deep expertise in metal alloy development



Nickel Atomizer



Aluminum Atomizer



Plasma Arc Melter



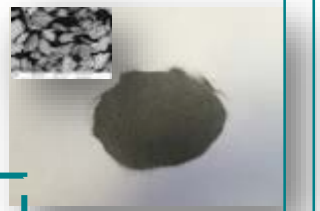
Titanium Atomizer

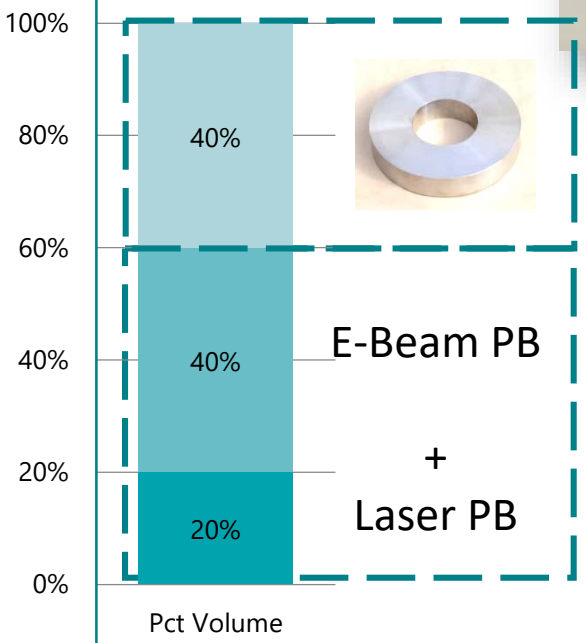
ARCONIC

Low cost Ti powder – driving 20% of the cost

Near Term | Mid Term | Long Term

Existing Suppliers

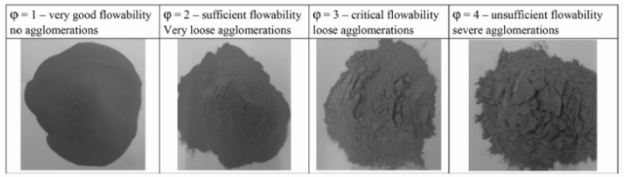






Ti

ATC Investment

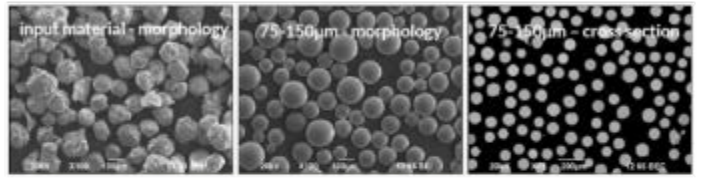




Ti, Ni & Al

Disruptive Technology

METALYSIS



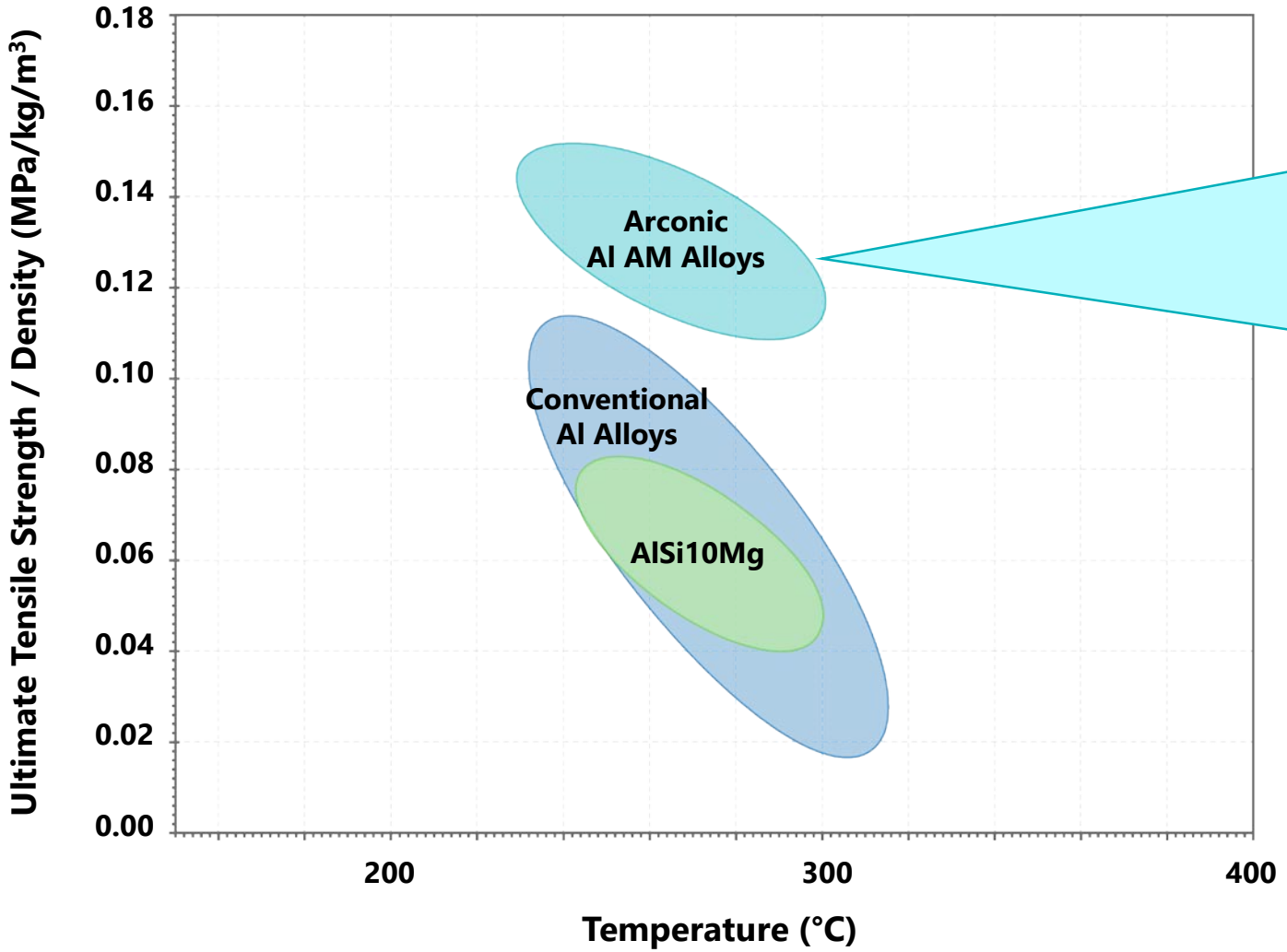


THE UNIVERSITY OF UTAH

ARCONIC

Our differentiated AM materials drive property improvements

Developing, and launching new alloys optimized for Additive Manufacturing



Arconic's new aluminum alloys were **designed specifically for AM**

Enhanced properties deliver better performance

Stronger more printable alloys

Arconic has developed thermally stable aluminum offerings

Compositions designed to leverage the rapid solidification rates of laser powder bed AM

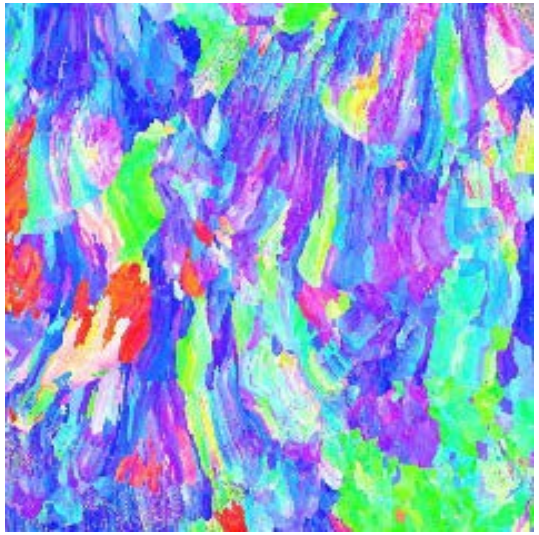
Demonstrated high performance alloys

- **2X the strength** of conventional elevated temperature aluminum alloys at 230˚C (~ 350 MPa TYS)
- **10X elevated temperature fatigue life** compared to Al-10Si-Mg at 230˚C
- >**4X the creep rupture life** of conventional elevated temperature aluminum alloys at 180˚C
- **85% higher** room temperature strength than Al-10Si-Mg

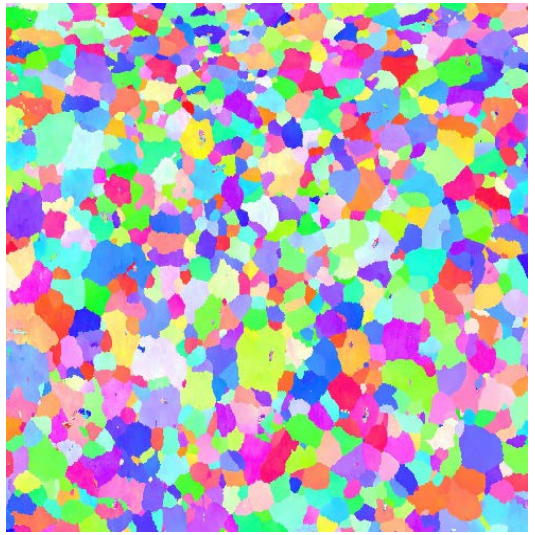
Arconic alloys balance printability, performance and cost

- **30% faster build rates** than Al-10Si-Mg

Arconic Al-ET255 - Highest Performance



Arconic Al-ET389 - Highest Printability

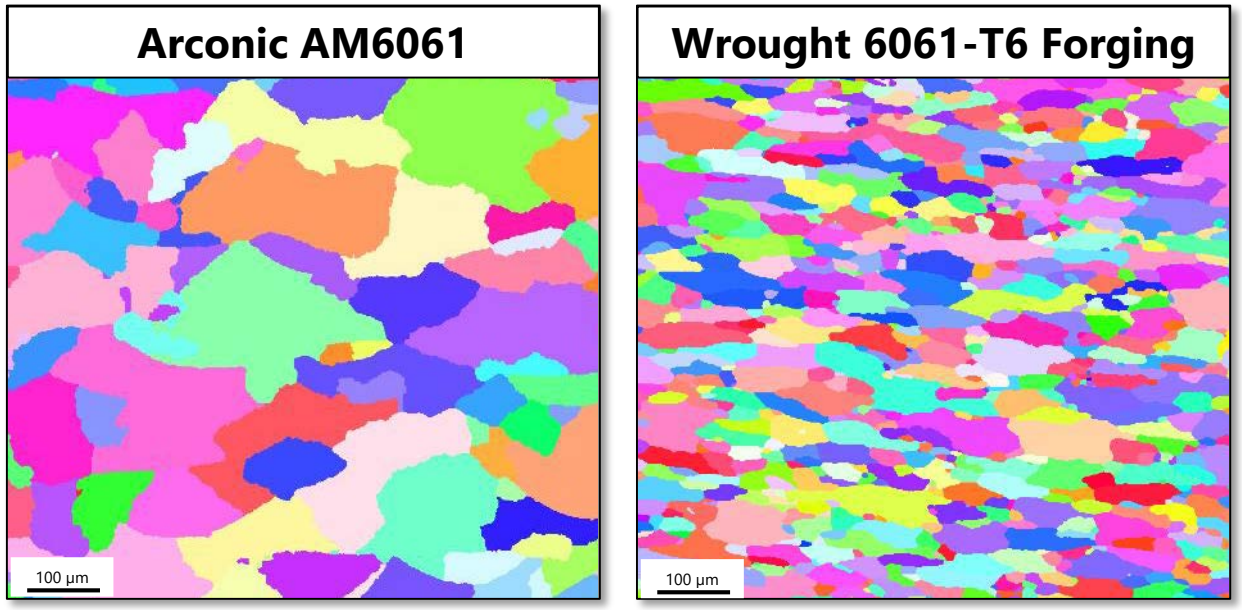


ARCONIC

Arconic alloys bring better properties, better printability, better products

Demonstrated success in historically difficult wrought alloys

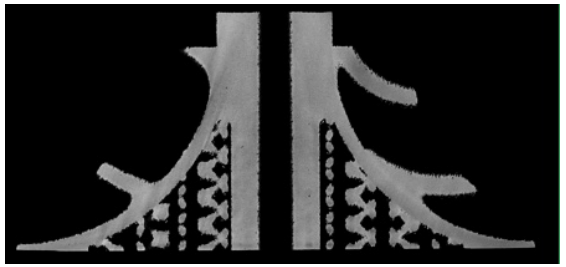
- Complex turbocharger wheel **printed crack-free** in Arconic AM6061
- Wrought **6061-T6 properties achieved with** Arconic AM6061
- Printability and performance enabled through **material & process optimization** for AM

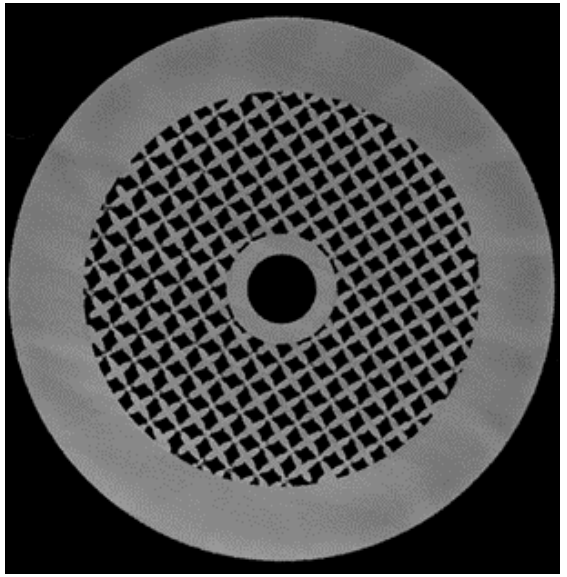


Complex turbocharger wheel



Crack-free in CT scans





Direct Manufacturing

ARCONIC



Optimization of Materials and Processes

Challenges in serial production

CHALLENGE

There is a limited understanding on part quality and performance of AM parts produced in a serial production setting.

Data analytics and models are needed to understand:

- Machine performance over time
- Machine to machine variability
- Stability and process control of properties

DEVELOP DATABASE

Databases needed to understand:

- Correlation between powder chemistry and fabricated part chemistry
- Machine performance and process robustness

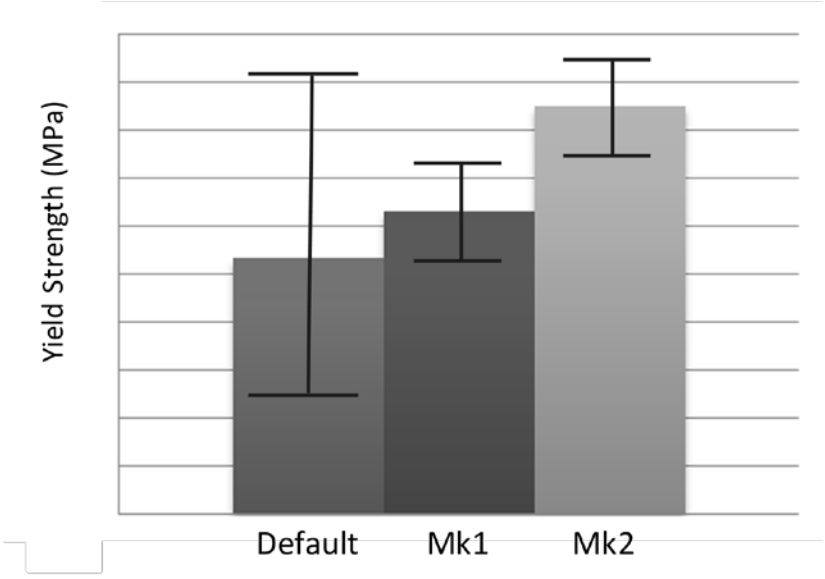
DEVELOP MODEL

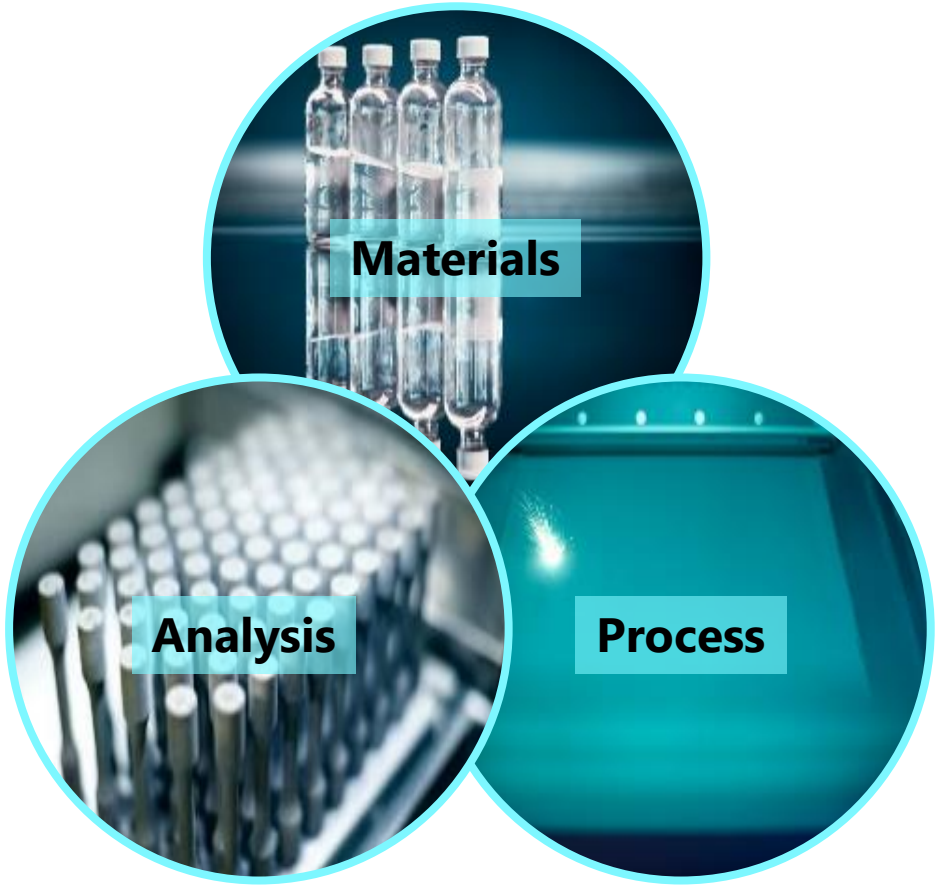
Develop models to determine the powder chemistry refinement for mechanical property optimization

Our materials and process expertise enables differentiated products

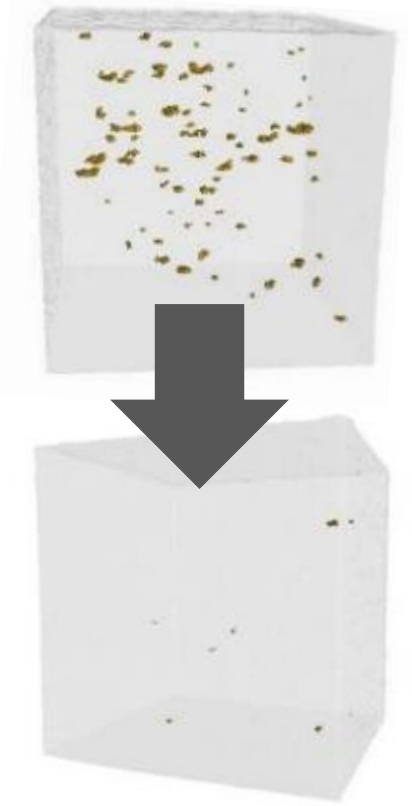
Taking a holistic and multidisciplinary approach

Improvement in Material Response vs. Machine OEM Default Settings





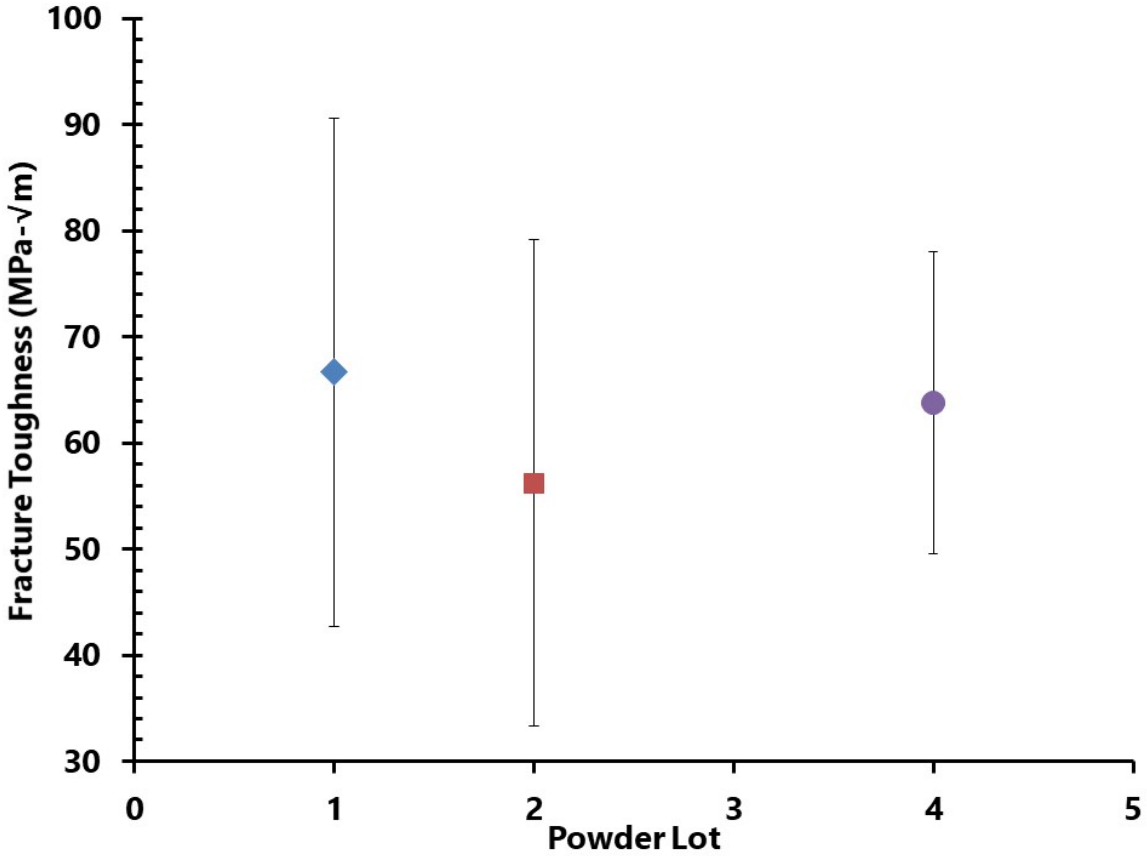
CT Scan of Cubes

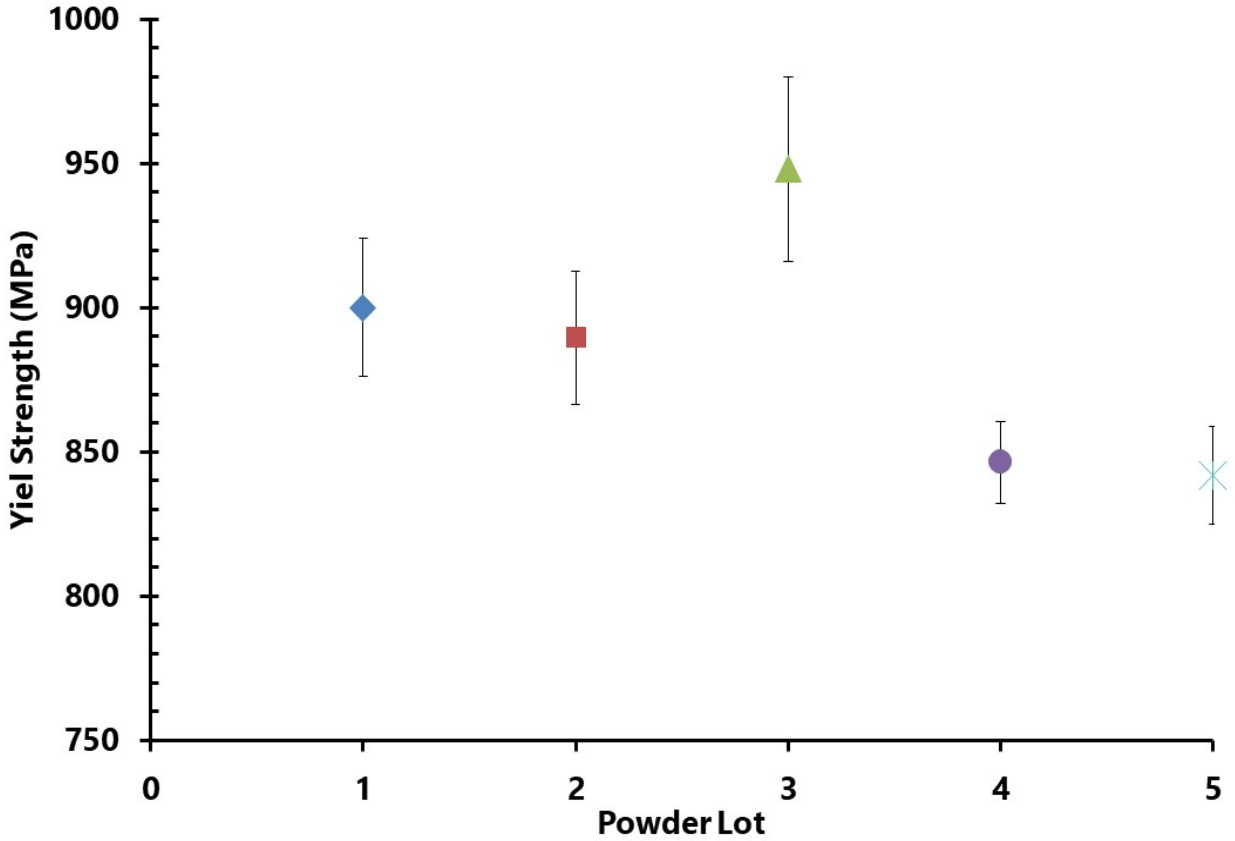


98% Improvement

AM-LPB Ti64 Property Optimization

Balancing Fracture and Tensile Properties



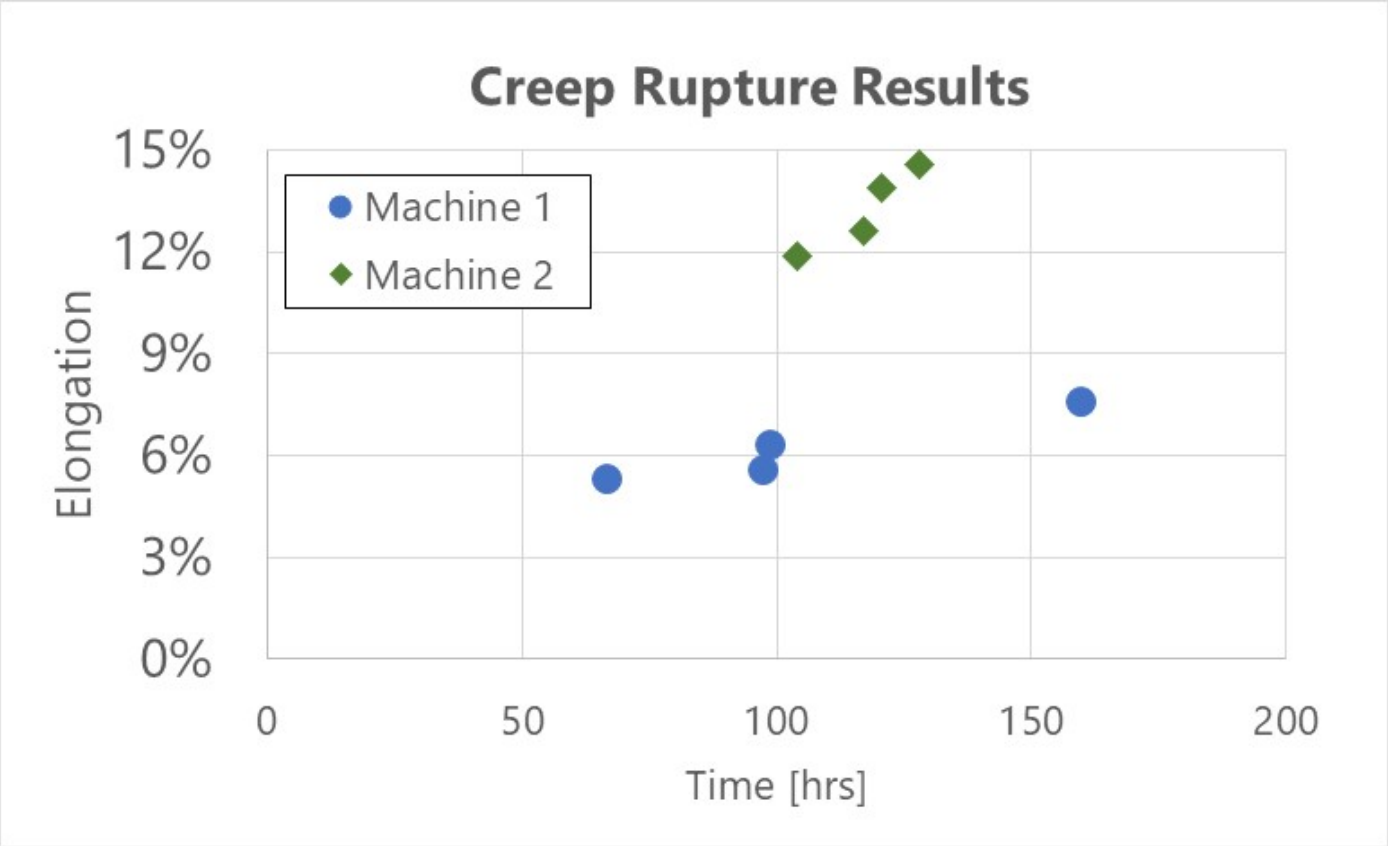


- Observed significant toughness and strength powder lot-to-lot variation
- All powder lots met specifications

Equipment Variation – IN718 Creep Results

Creep differences machine-to-machine

- Creep specimens meet requirements
- Differences in elongation were noted
- Microstructures appear similar
- Thermal cycles that could impact properties were verified to be conforming
- Printing energy inputs comparable



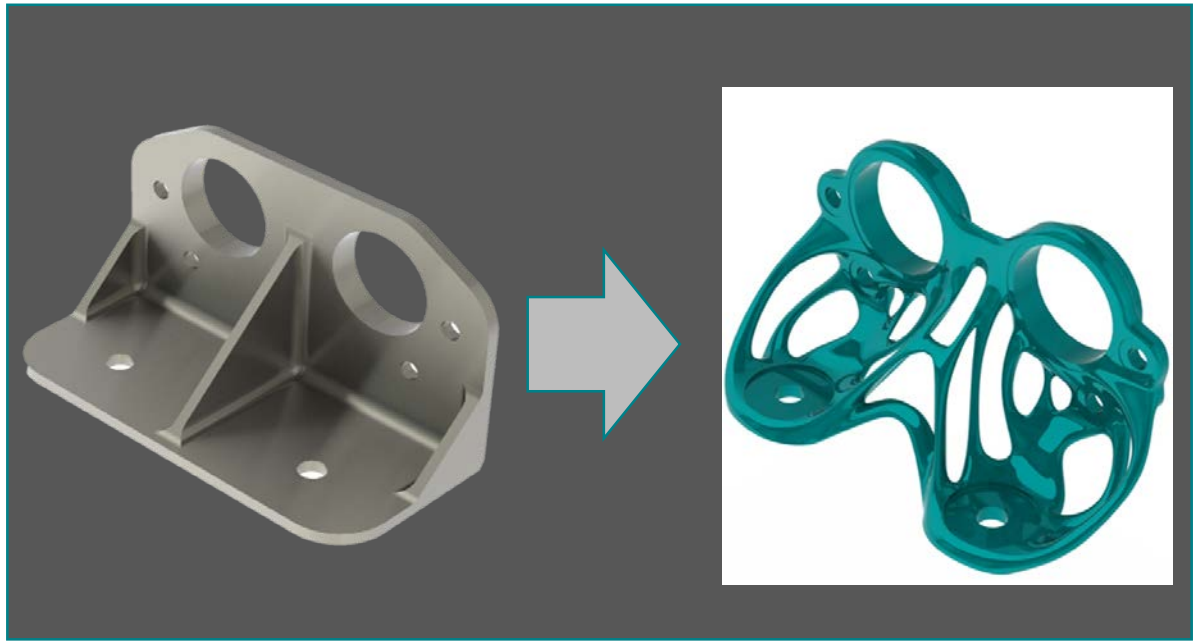
Unlocking the true value of powder bed AM

Part count reduction and design optimization

Orion Vent Housing (IN718)
6 Part Assembly > Single AM Part



Airframe Bracket (Ti6Al-4V)
Machined Plate Design > Optimized AM Design > 50% lighter; up to 50% cost savings



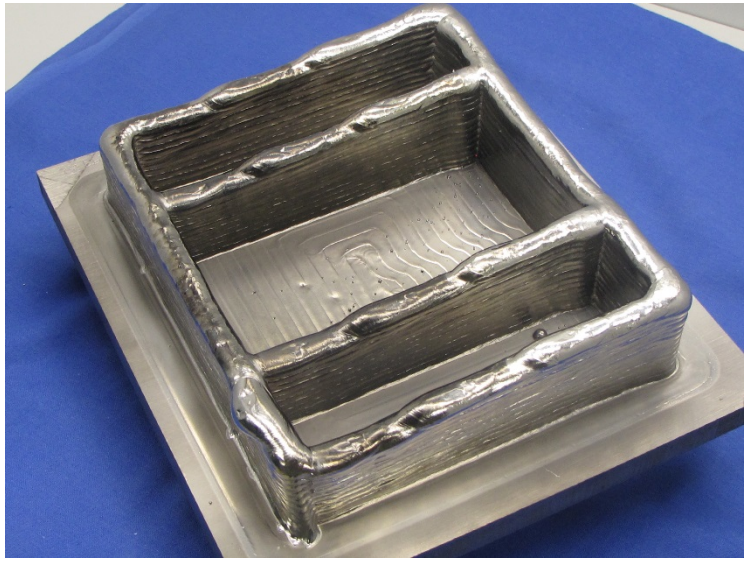
High Deposition Rate (HDR) Additive Layer Manufacturing

High deposition rate additive typically refers to directed energy deposition methods (DED), especially wirefeed.

Opportunity: Deposit material quickly to produce a near-net preform that reduces the buy-to-fly for the customer. The objective is to reduce the cost of Ti-6Al-4V components.

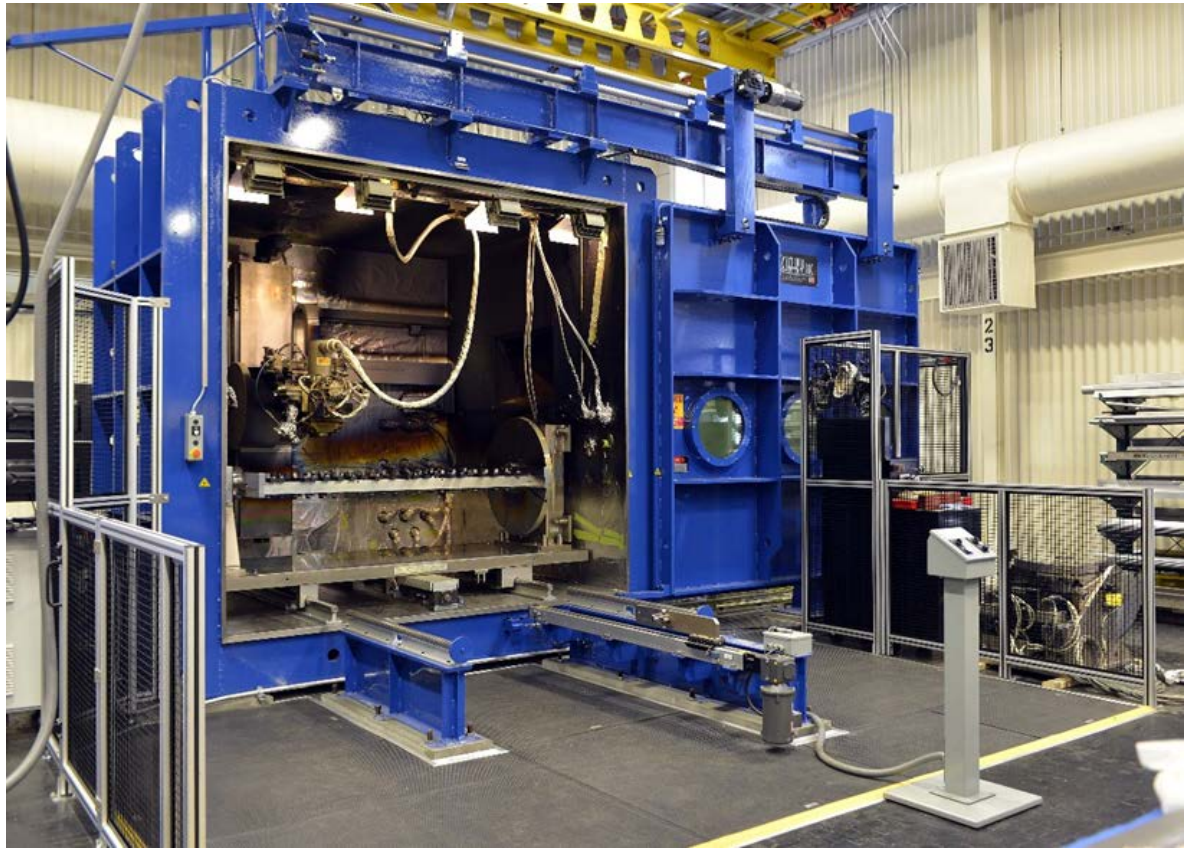
Considerations:

- Post machining operations still required; There may be significant overbuild.
- Additional wire cost and AM processing cost need to be balanced against the ability to reduce material input of plate or forged products.
- Properties don't (yet) achieve the performance of the conventional wrought plate and forged products.



Ti-6Al-4V Fitting:
- AM Preform: 5.5 kg (12.1 lbs)
- Conventional Plate: 14.8 kg (32.6 lbs)

Arconic DED ALM Development



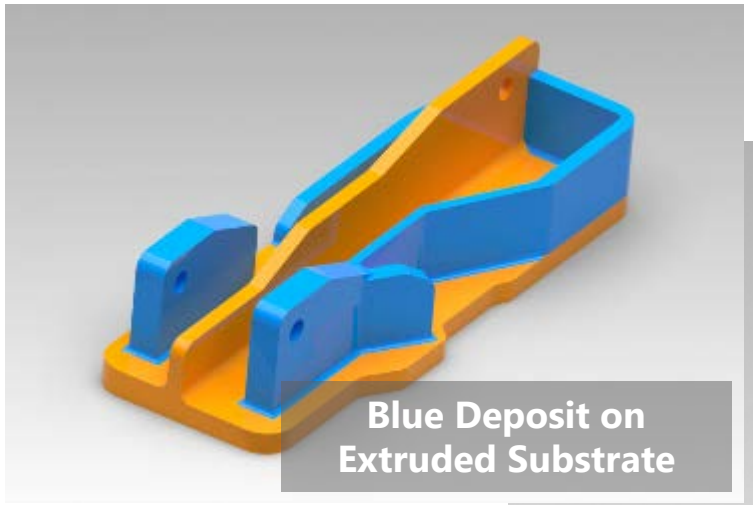
Arconic has developed Ti-6-4 DED ALM capability using the Sciaky EBAM™(electron beam additive manufacturing) system.

Using a custom parameter set, Arconic is able to achieve a metallurgically sound build that minimizes costs to meet dimensional and metallurgical requirements.

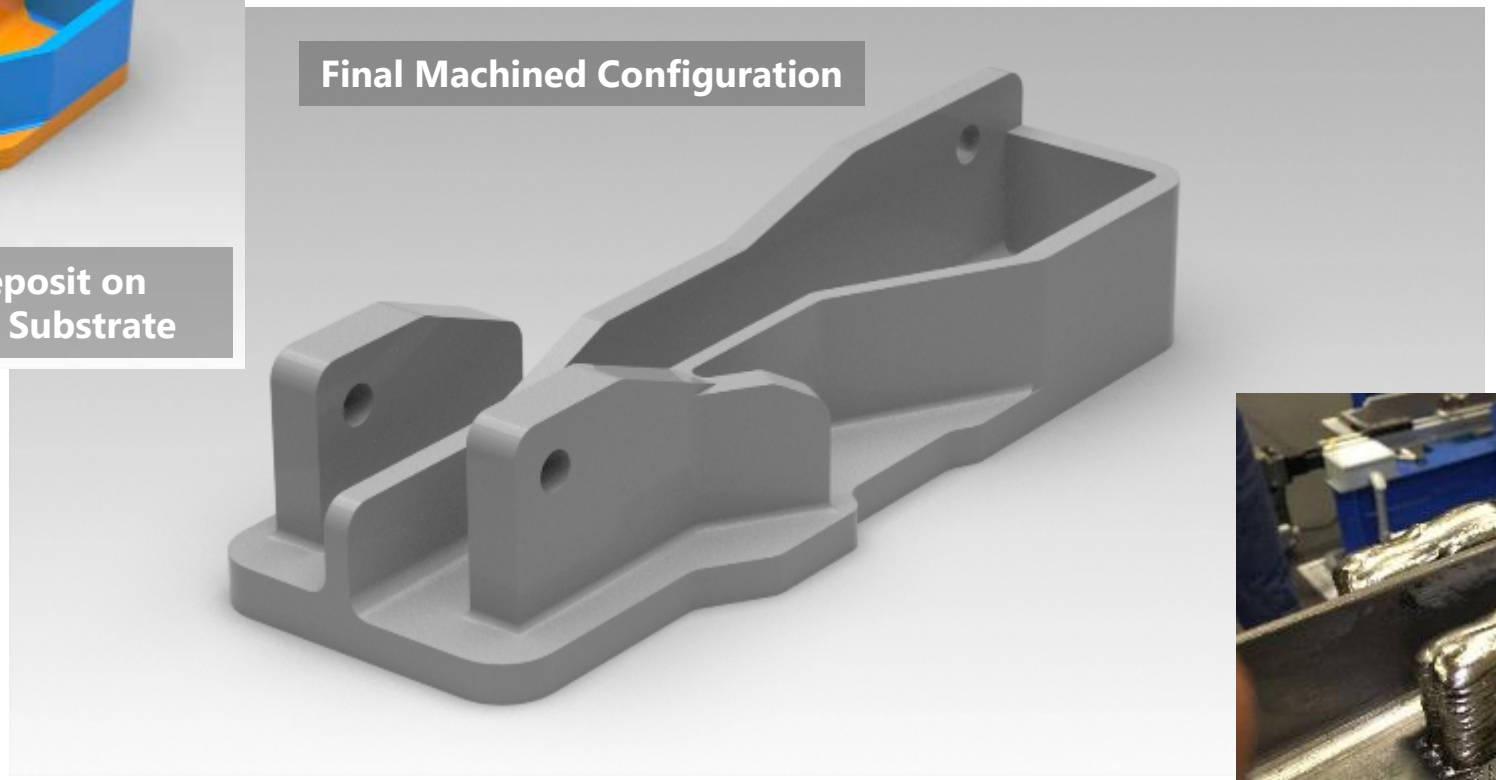
* EBAM™ is a registered trademark of Sciaky, Inc.

We’re leveraging high deposition rate processes for larger scale parts

Arconic has demonstrated complex deposits on extruded preforms, reducing wire content and disposition time.



Blue Deposit on Extruded Substrate



Final Machined Configuration



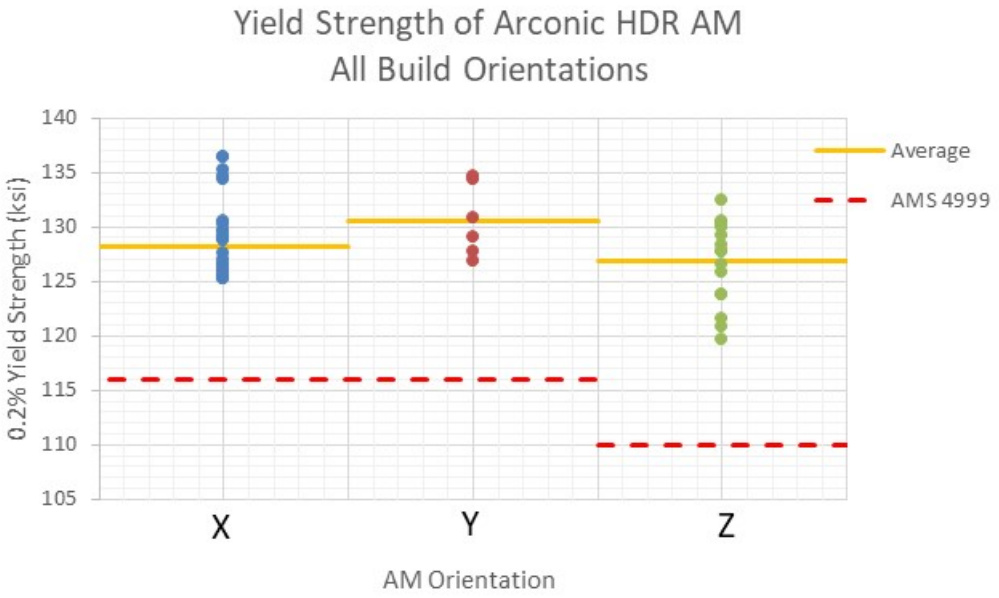
Sciaky EBAM™ Raw Deposit

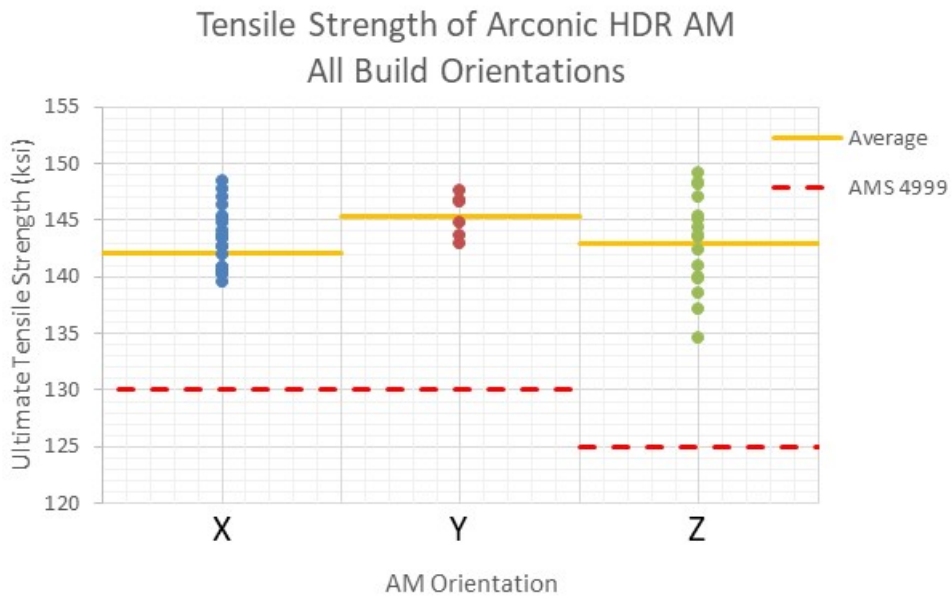
ARCONIC

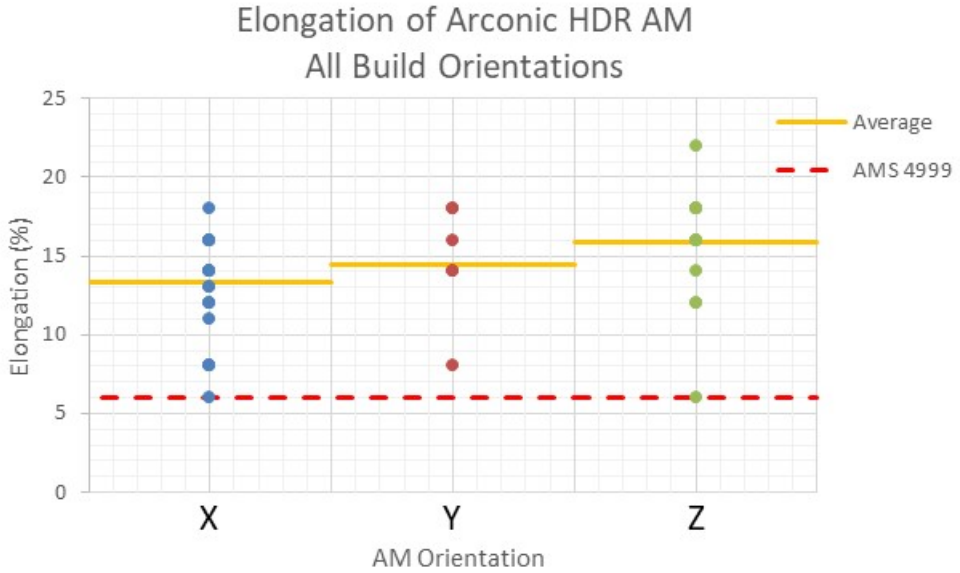
* EBAM™ is a registered trademark of Sciaky, Inc.

DED ALM Mechanical Properties Over Varying Thicknesses (0.5-2.5 in.)

Through development of a custom parameter set, Arconic is able to exceed strength minimums of industry specifications



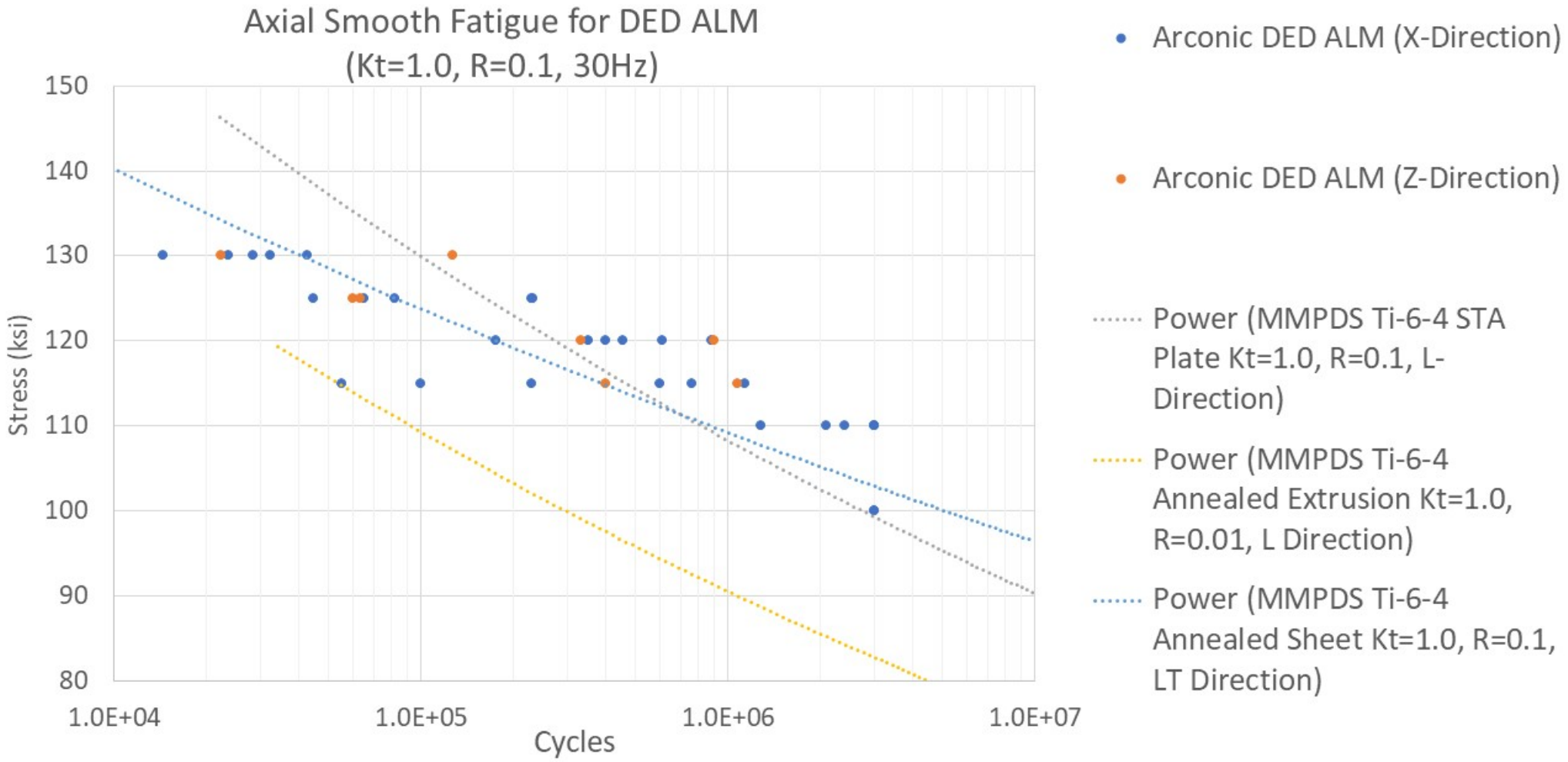




ARCONIC

Arconic DED ALM Fatigue Performance

Arconic DED parts over range of thicknesses (0.5-2.5 in.) meet fatigue results of conventional products



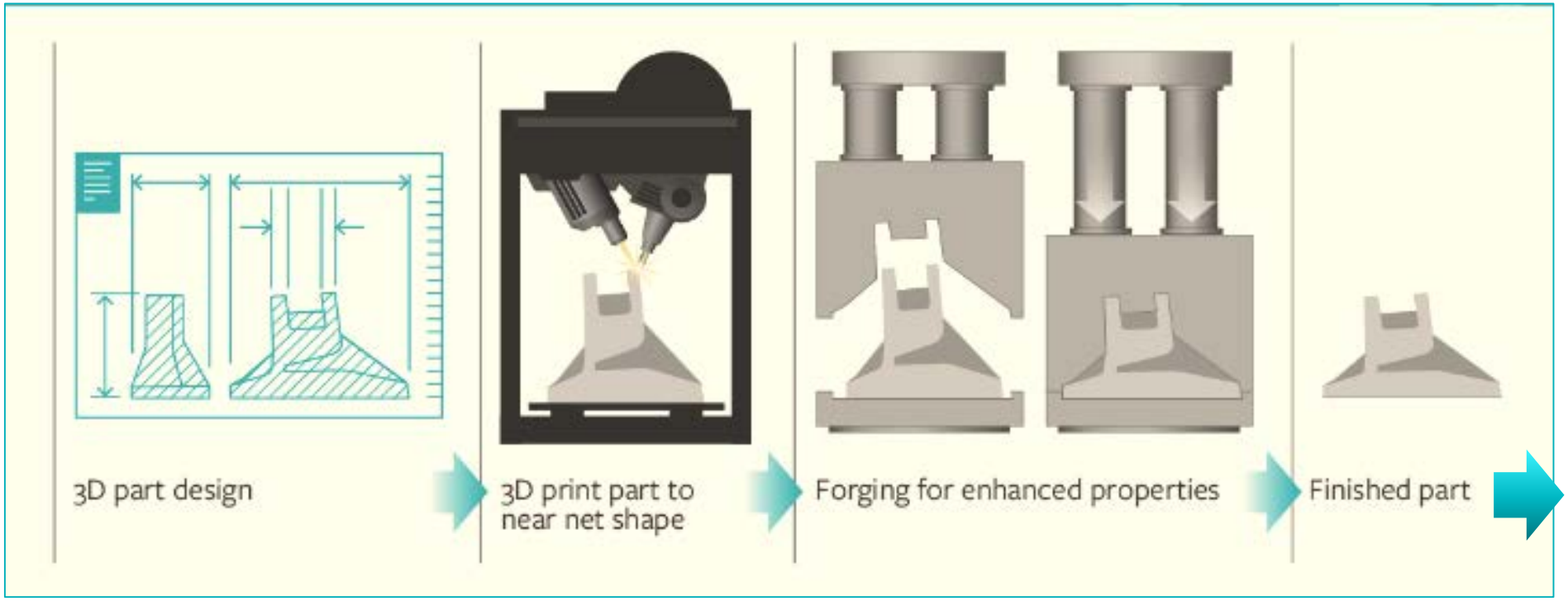
Indirect and Hybrid Manufacturing

ARCONIC



Arconic Ampliforge™ combines benefits of conventional & AM processes

Proprietary hybrid process combines additive and advanced forging technologies





Ampliforge™
Ti Pylon Component

Ampliforge™ Advantages

- ✓ Nearer-net forgings
- ✓ Reduced material input
- ✓ Fewer forging operations
- ✓ Reduced tooling NCRs
- ✓ Extended tooling life
- ✓ Notice-of-Allowance for first U.S. patent for Ti parts

Ampliforge™ process – plant demonstration

Full-scale commercial aircraft part produced using the Ampliforge™ process, currently in test.

Ti-6Al-4V Ampliforge™ Preform

- Optimized design for single forging operation
- Produced using EBAM
- 1500mm x 400mm x 100mm (60”x16”x4”)



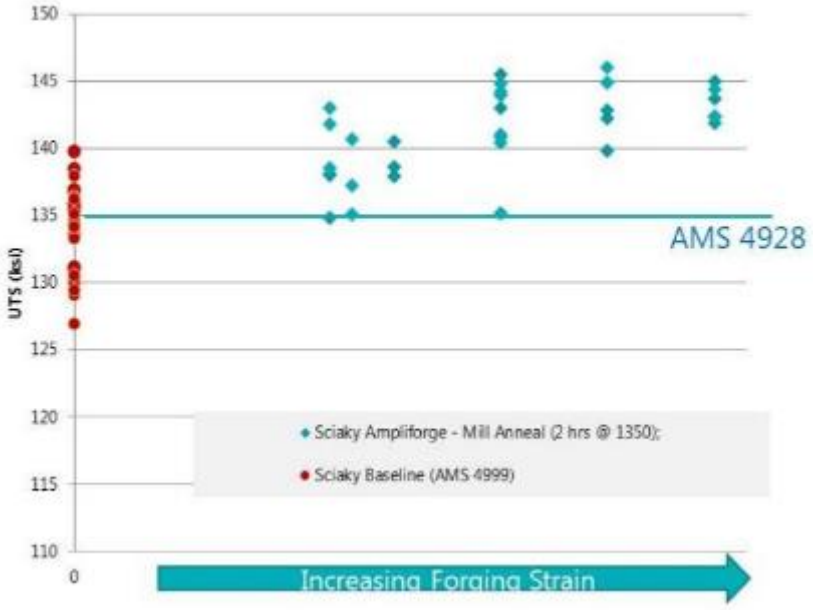
Final Forging

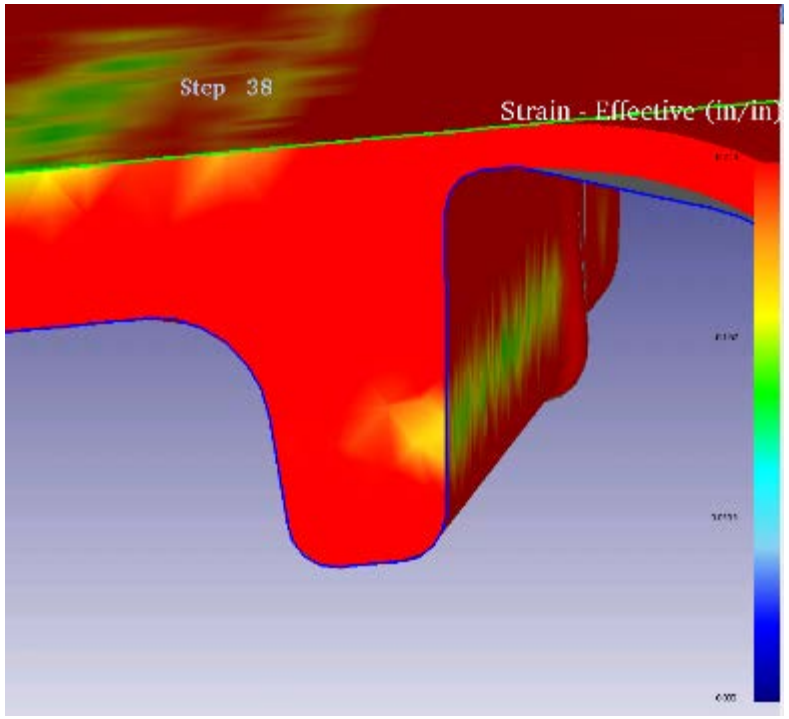
- Forged on 45MN press in Cleveland, Ohio.
- Eliminated three forging operations and flash



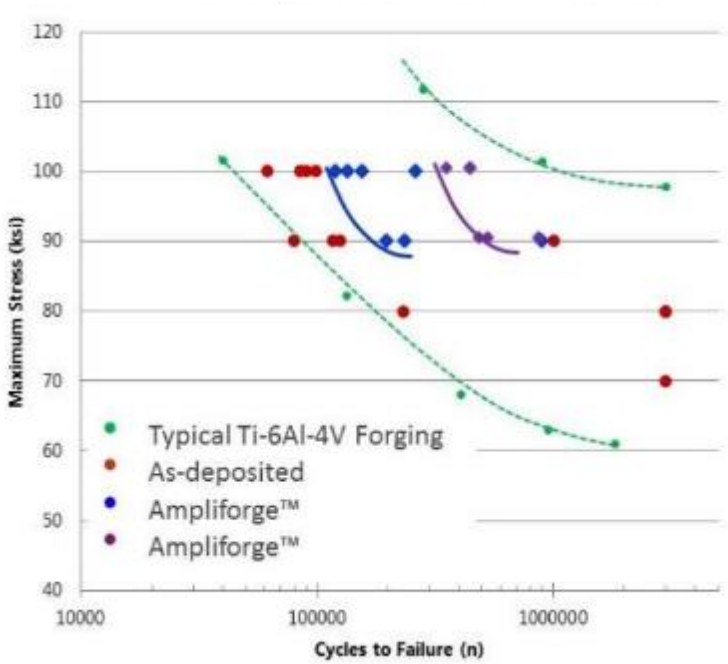
Ampliforge™ process meets static/fatigue requirements of forgings

Tensile Strength





S-N Curve



Post Print Processing and Qualification

ARCONIC



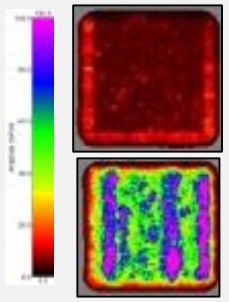
Key challenge of getting 3D printed parts flying is qualifying them to do so

Arconic has the manufacturing expertise to certify the material, process and part

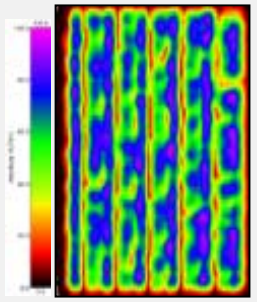
Qualification Requirements:

- Process verification techniques
- Inspection processes
- Customer collaborations
- Engagement with certification

Ultrasound

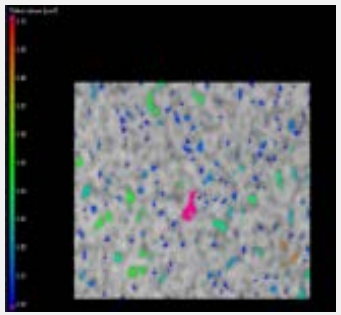


Discontinuity Detection

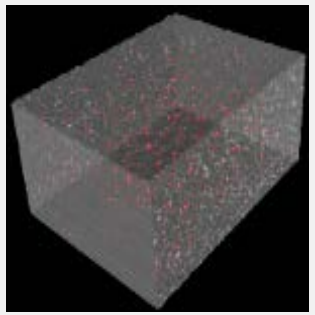


Build Feature Identification

Radiography



Void Analysis



3D Computed Tomography

Post Print Processing Routing:

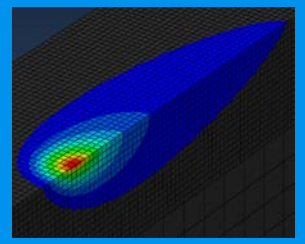
Support removal → Stress Relief → HIP/Heat Treatment → Machining → Dimensional Inspection → CT Scan/X-Ray → X-Ray → FPI

Digital Tools Enabling AM Design, Materials & Process Optimization

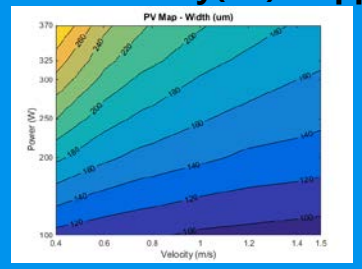
Enhancing AM based on decades of connection materials & processing to deliver fit & function

Materials Development

Thermal Process Model (FEA)



Power & Velocity(PV) Mapping



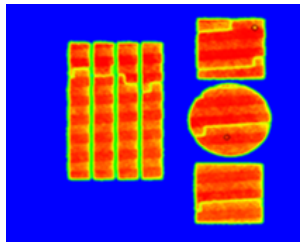
Porosity & Microstructure Models

Property Models

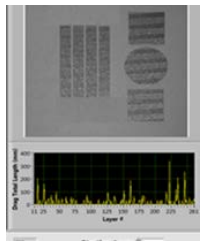
Process Development

Detect flaws during printing

In-Situ Monitoring

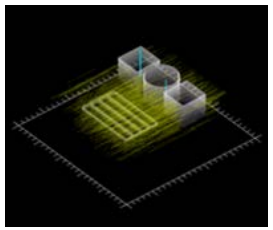


Thermal



Visual

3D Volume Quality Model (VQM)



3D Volume Quality Model

3D Build History

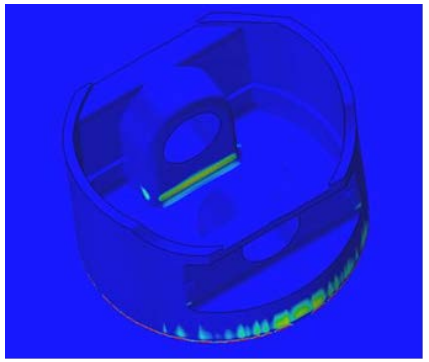
Quality Log

Parameter Adjustment

Product Design

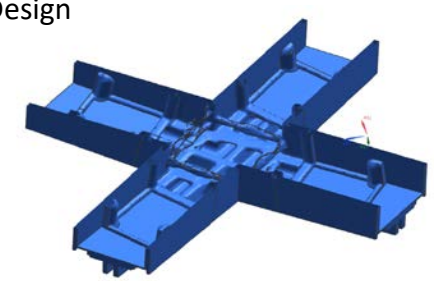
In-house & commercial systems

- Cost models – all processes
- Build orientation optimization
- Residual stress and distortion



Applying state-of-the-art modeling

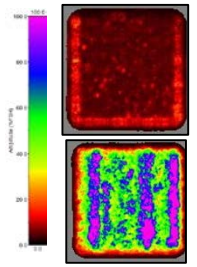
- Topology Optimization for Product Design



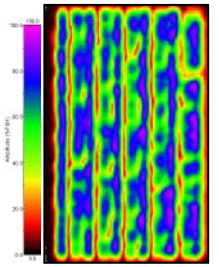
Qualification

Developing unique techniques for each AM process & connecting to Volume Quality Model

Ultrasound

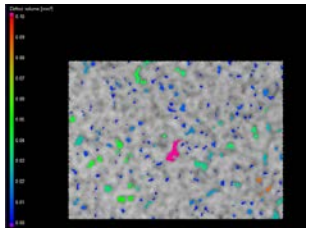


Discontinuity Detection

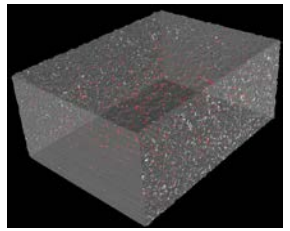


Build Feature Identification

Radiography



Void Analysis



3D Computed Tomography

ARCONIC

Arconic is taking 3D printing from the lab, to the sky, to space

Arconic Signs Development Agreements with Airbus, Lockheed

- Cooperative research agreement with Airbus to develop customized processes, parameters to make large-scale, structural, 3D printed metal parts using HDR technologies
- Joint development agreement with Lockheed to develop 3D printing processes for current and next-gen aero and defense platforms



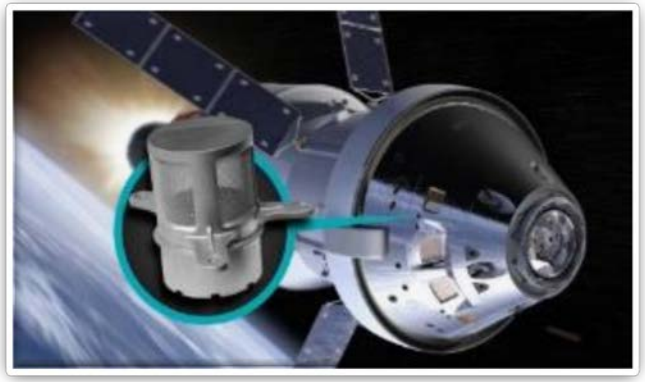
Arconic, Airbus Take 3D Printing to Skies with AM 1st

- Arconic announced a 3D printing 1st with Airbus in Sept. 2017 – installation of titanium bracket on a series production Airbus commercial aircraft
- Builds on three agreements with Airbus to produce titanium and nickel 3D printed parts for commercial aircraft



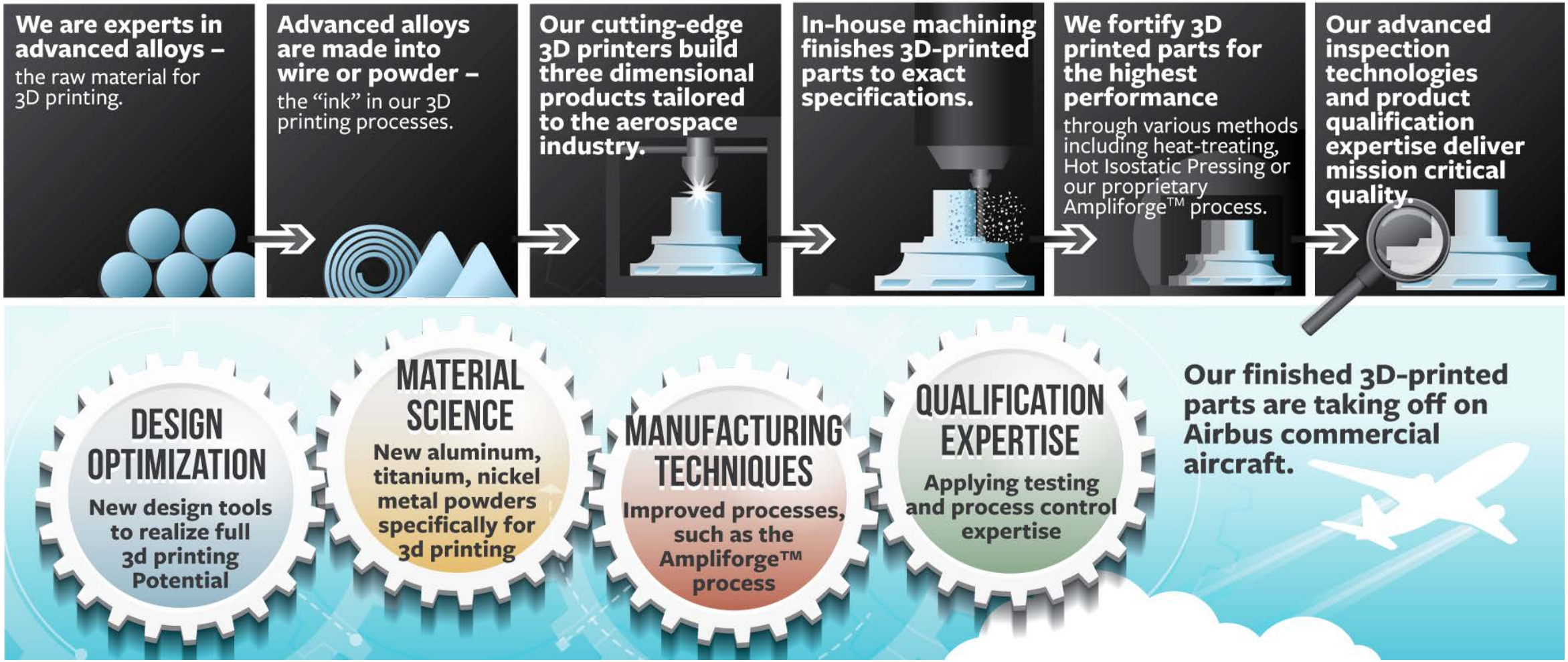
Arconic Takes 3D Printing Out of This World with Orion Spacecraft

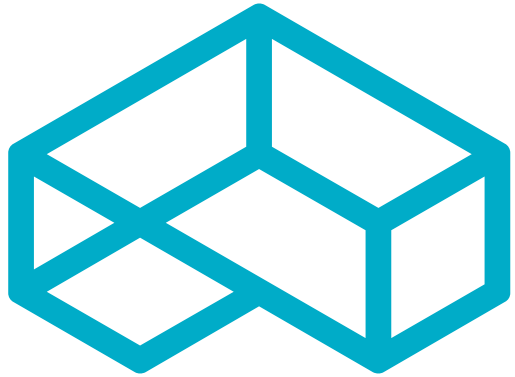
- 3D printed nickel superalloy vent housings for Lockheed Martin for service on the NASA Orion spacecraft
- Arconic's first additively manufactured, flying space parts
- Reduces manufacturing time from weeks to ~40 hours, and consolidates part count



Additive Manufacturing: our comprehensive approach

Reduces material input, consolidates part count, affords design freedom, speeds time to market





ARCONIC

Innovation, engineered.

APPENDIX G
MARK SHAW, GE ADDITIVE
"GE APPROACH TO PART FAMILY"

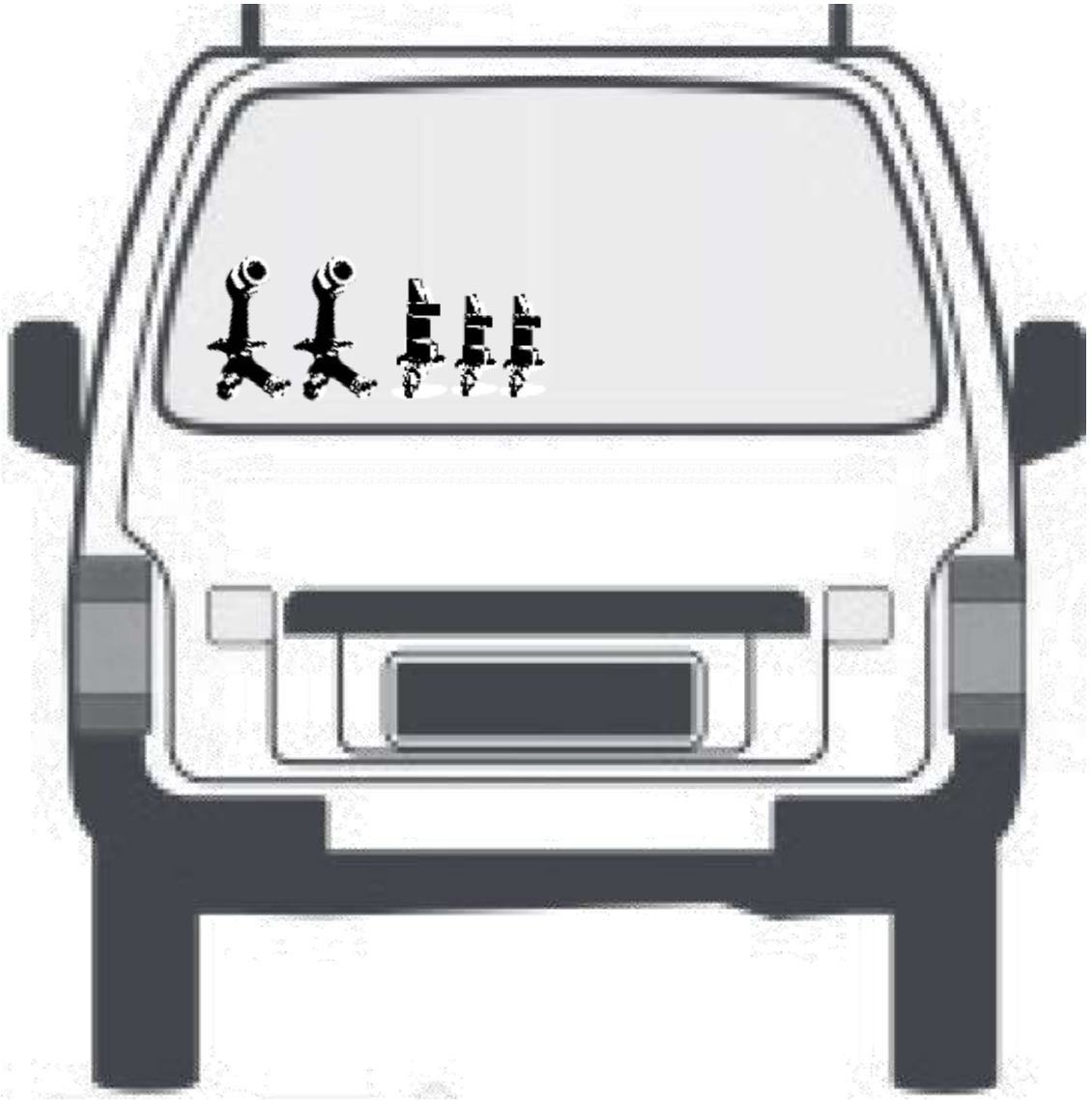
GE Part Family Approach

2018 FAA-EASA Metal Additive Manufacturing Workshop

2018

Mark Shaw

GE’s First Part Family…





LEAP Fuel Nozzle



GE90 T25 Sensor

What is in a Part Family?

Repair – AC No: 33-9 (e.g. HPT, LPC, HPT, Combustor, Externals…)

Quality – GE S1002, *"A group of parts with similar processes, materials, complex form, and tolerances, which have been produced by similar manufacturing methods"*

Material – GE Design Practice (Part type, Part criticality, Material property)

Design – GE Design Practice (Part criticality)

Supply Chain (Sustainment) – Part Qualification (Machine, Material, Process)

Certification – Part Certification (Type, Material, Criticality)

Industry – Standard (Part type, Part criticality, Material, Material Basis, Process, Part Feature, Tolerances, Anomalies Allowables…)

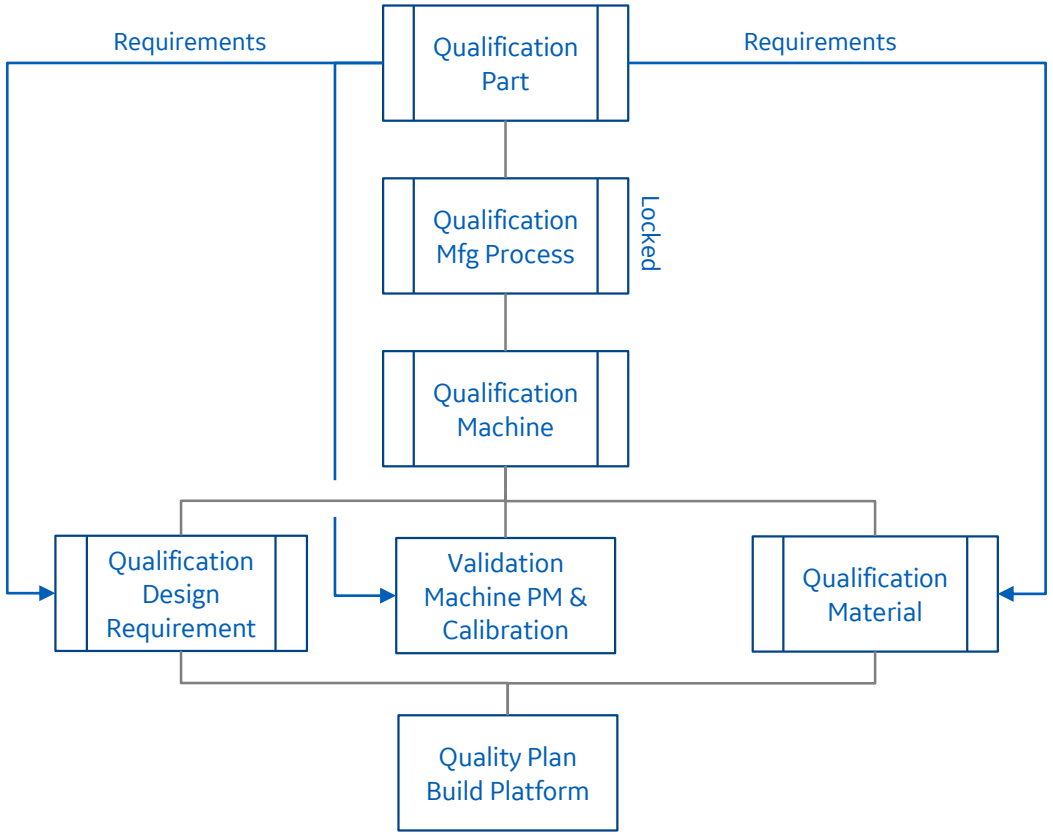
GE Additive Supply Chain Example:

A group of components which by the nature of their attributes can be manufactured within a common manufacturing cell.

Common attributes are:

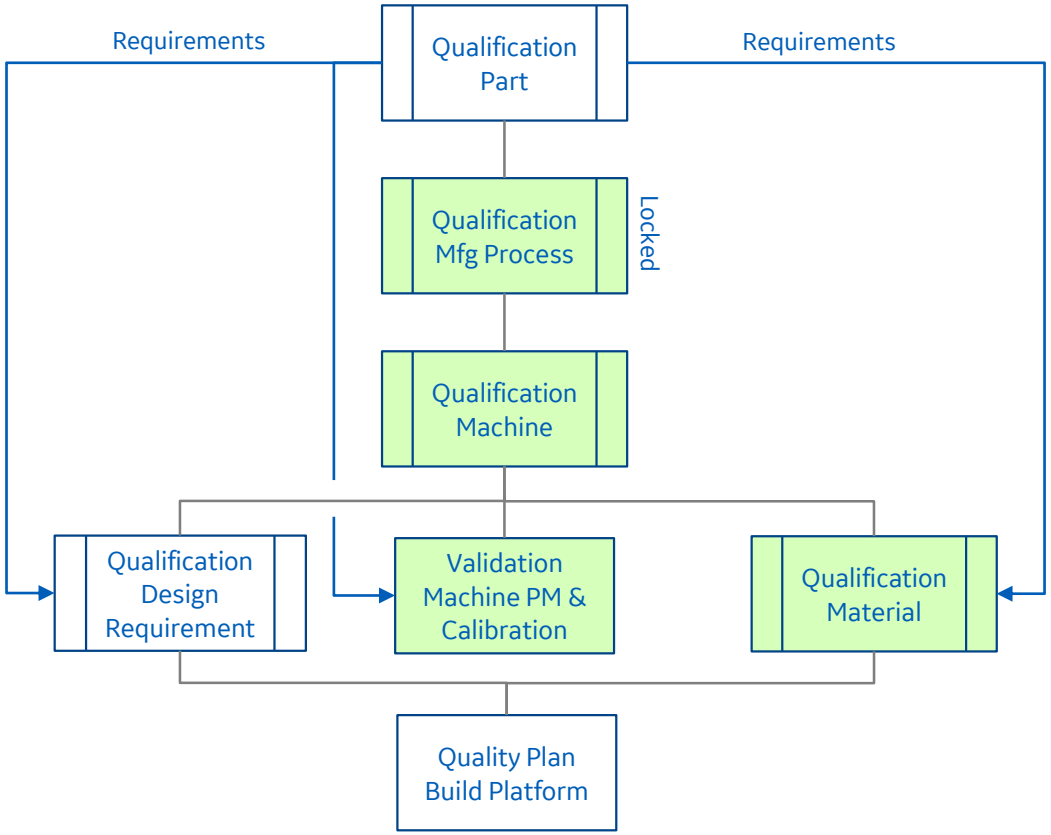
- Manufacturing process such as casting, forging, or additive
- Machine type such as Concept Laser M2 or Arcam Spectra H
- Material such as Inconel 718, stainless steel 321, or titanium 6Al4V
  - Material class, such as GE Class 1, or MMPDS A-Basis

Part Qualification Process



Part Qualification Process

*…What attributes must be **common** for part families?*





Machine Qualification

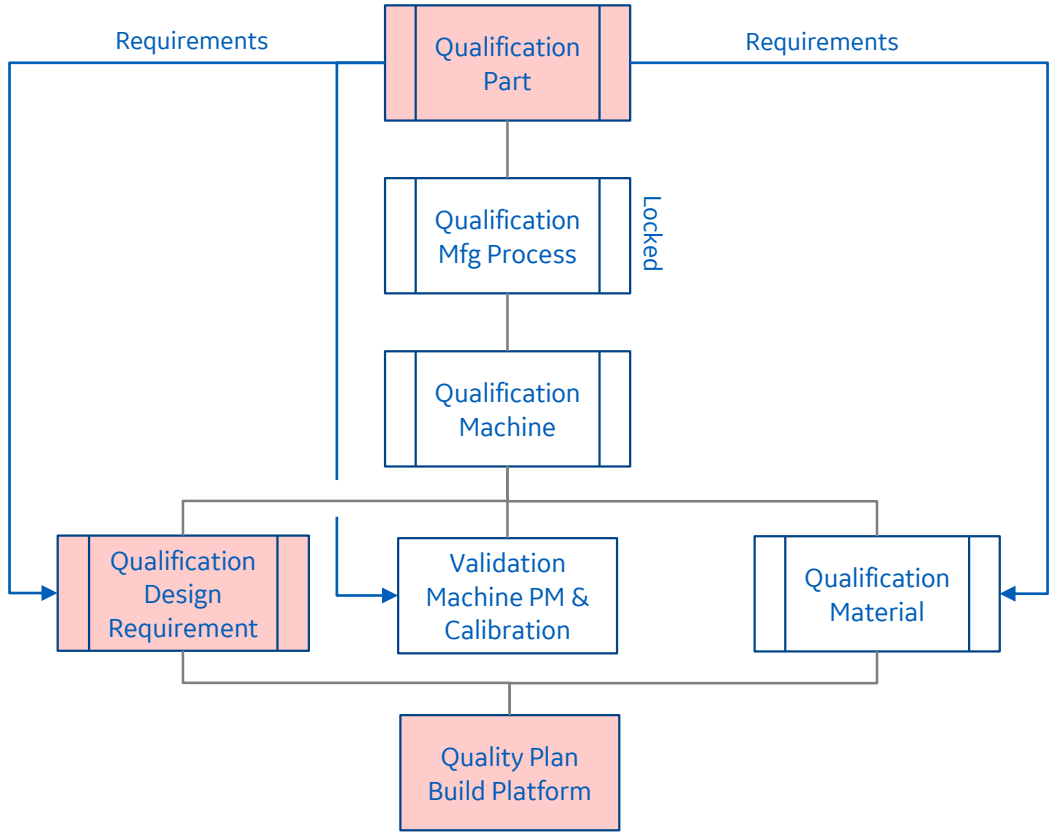
- Validation Build
- Material Qualification

Process Qualification

- Locked Process

Part Qualification Process

*…What attributes can be **unique** within part families?*





Part Qualification

- Unique analysis and test

Design Requirement Qualification

- Unique part requirements

Quality Plan, Build Platform

- Unique part requirements

Establishing the Build Platform Quality Control Plan

Considerations:
- Part criticality
- High stress / lowest margin areas
- Higher probability defect areas
- Inspection gage accuracy
- Inspection efficiency
- Company quality system policy

Participants:
- Design
- Manufacturing (development & production)
- Quality
- Inspection technology expert
- Certifying Agent (process expert)



CT scan



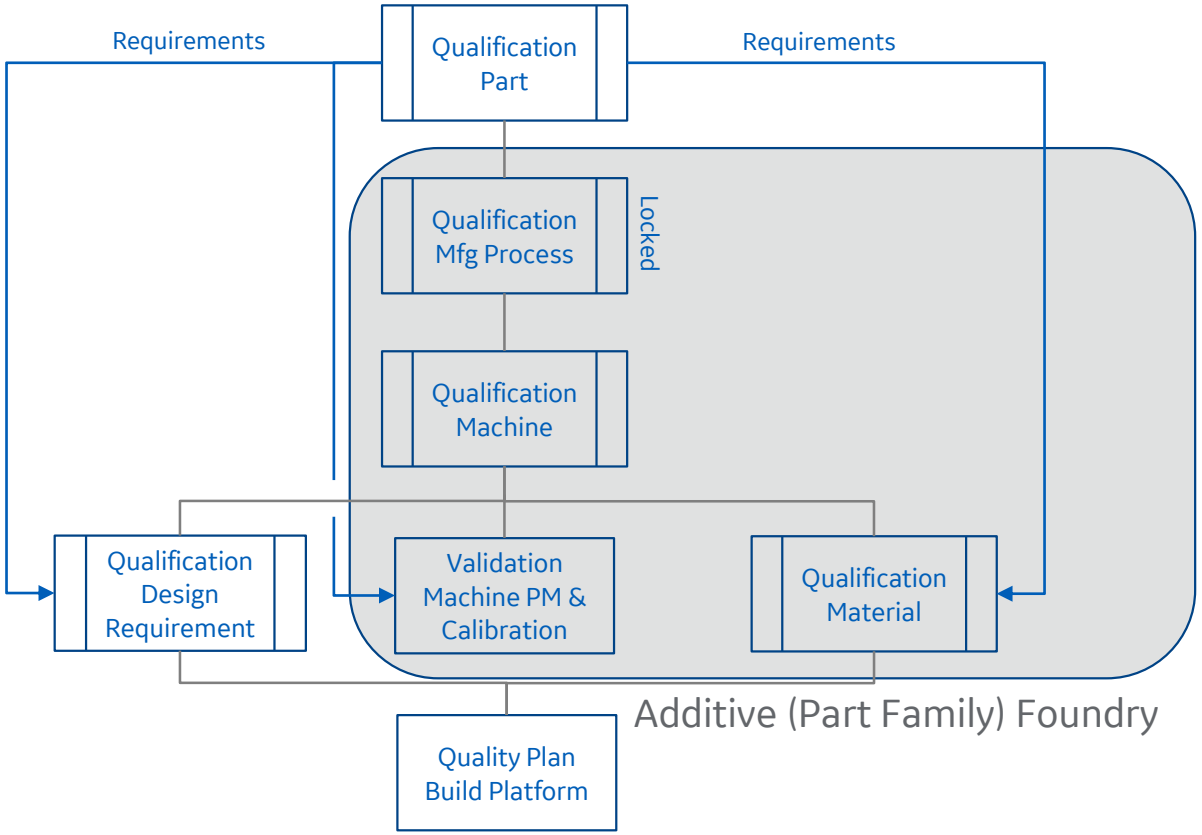
FPI



- Material Properties
- Tensile Bars
- Full Z-Height Bars
- Bar location
- Bar direction
- Bar geometry
- Thin wall
- Part cut-up plan
- X-Ray
- CT scan
- FPI
- Other NDI
- Geometric accountability
- Long term storage

Identifying Part Families

for the "additive foundry"



GE90



CoCr, 250mm, CL2 material

LEAP



CoCr, 250mm, CL2 material

GE9X









CoCr, 250mm, CL2 material

Catalyst





CoCr, 250mm, CL2 material

Catalyst

Not in part family



F357, 250mm, CL2 material

Part Family Considerations…

No Common Definition of Criticality Levels… *FAA, EASA, USAF, NAVAIR, TCHs*

- *Certification considerations… criticality, part type, material*
- *Process Agnostics… not unique to AM*

Many “Part Family” Definitions… *this is OK, but can be confusing*

Certification: Basis of evaluation has not changed
Supply Chain: based on process, is useful for economic manufacturing



APPENDIX H
ADAM HICKS, USAF AFRL
"QUALIFICATION AND CERTIFICATION OF AM PARTS: AFRL PERSPECTIVE AND PROGRESS"

Qualification and Certification of AM Parts: AFRL perspective and progress

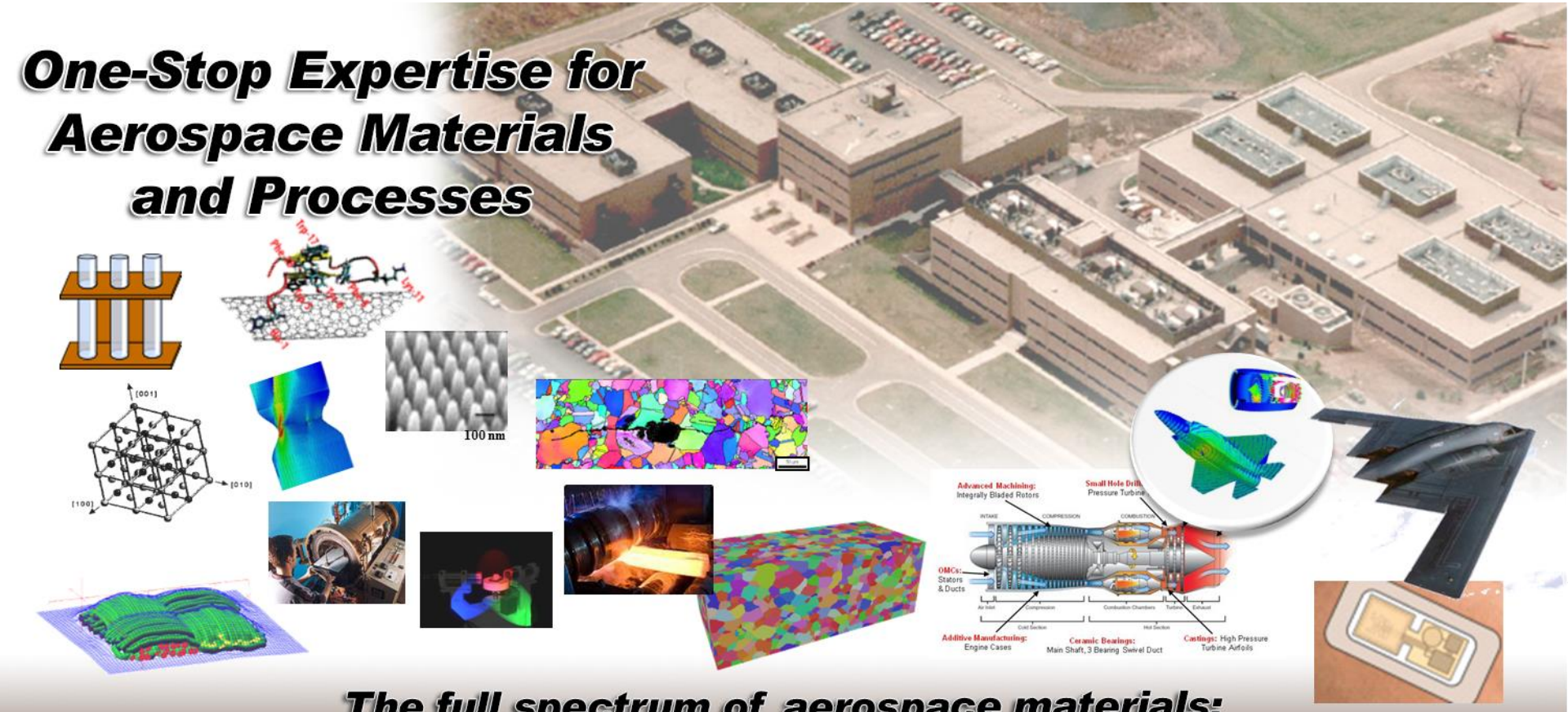
August 2018

Mr. Adam Hicks
Materials and Manufacturing
Air Force research Laboratory

Integrity ★ Service ★ Excellence

Distribution A. Cleared for Public Release (88ABW-2018-4042)

AFRL Materials and Manufacturing Directorate



The full spectrum of aerospace materials:

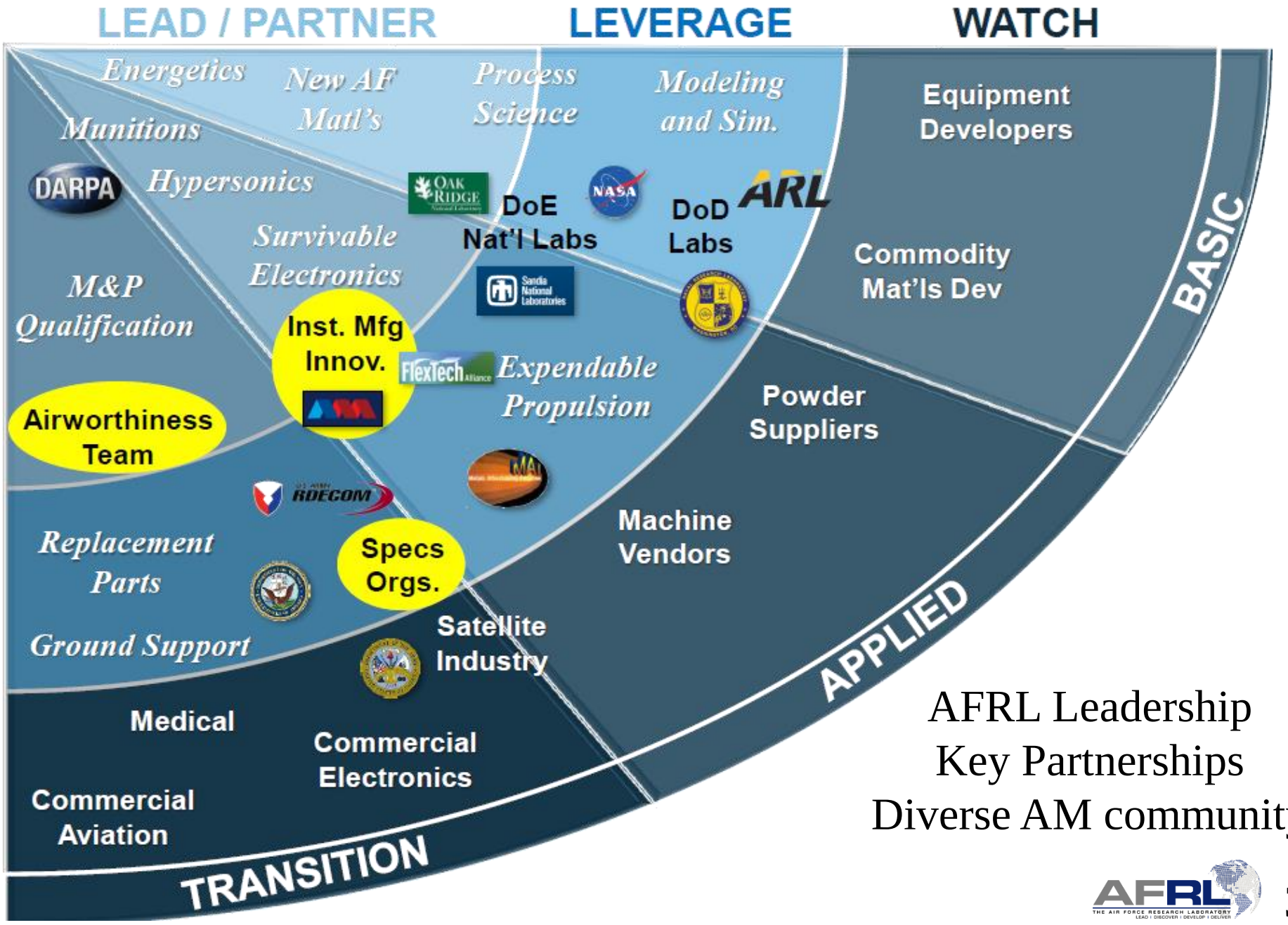
Metals | Ceramics | Polymers | Semiconductors | Composites

Discover • Develop • Process • Characterize • Manufacture • Sustain

Legacy ... Current ... Future

Integrated Experimental & Computational Approaches | Structural & Functional Materials

AFRL Tech Approach for AM



AFRL Leadership
Key Partnerships
Diverse AM community

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

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

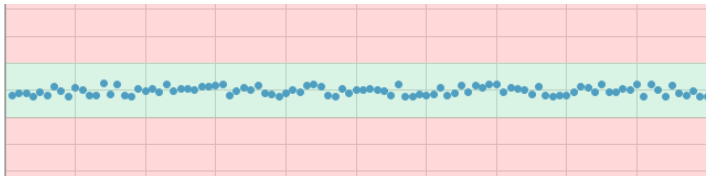
- **Airworthiness**
  - Stability
  - Reproducibility
  - Sustainability

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

  - Characterized Mechanical & Physical Properties
  - Predictability of Performance

Durability & Damage Tolerance

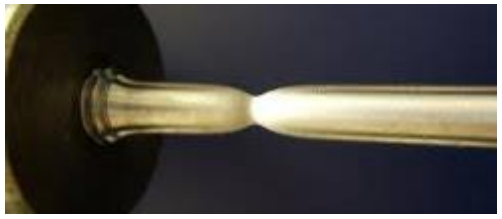
1. **Stability -** consistent and repeatable quality and predictable costs can be achieved to meet system performance and production requirements.

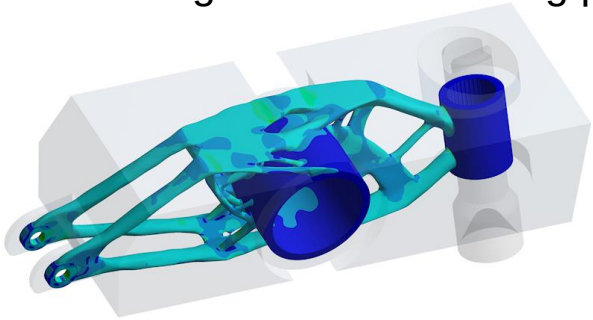




2. Producibility - scale-up to production sizes and rates can be achieved without adversely affecting performance, costs, and quality.

3. Characterization – Well understood mechanical and physical properties for the appropriate environments in the as-fabricated condition using the manufacturing processes and joining methods.





4. Predictability - validated analysis/empirical methods are established to enable <u>accurate prediction of structural performance</u>



5. Supportability - cost-effective inspection and repair methods are available/ can be developed in a timely manner

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

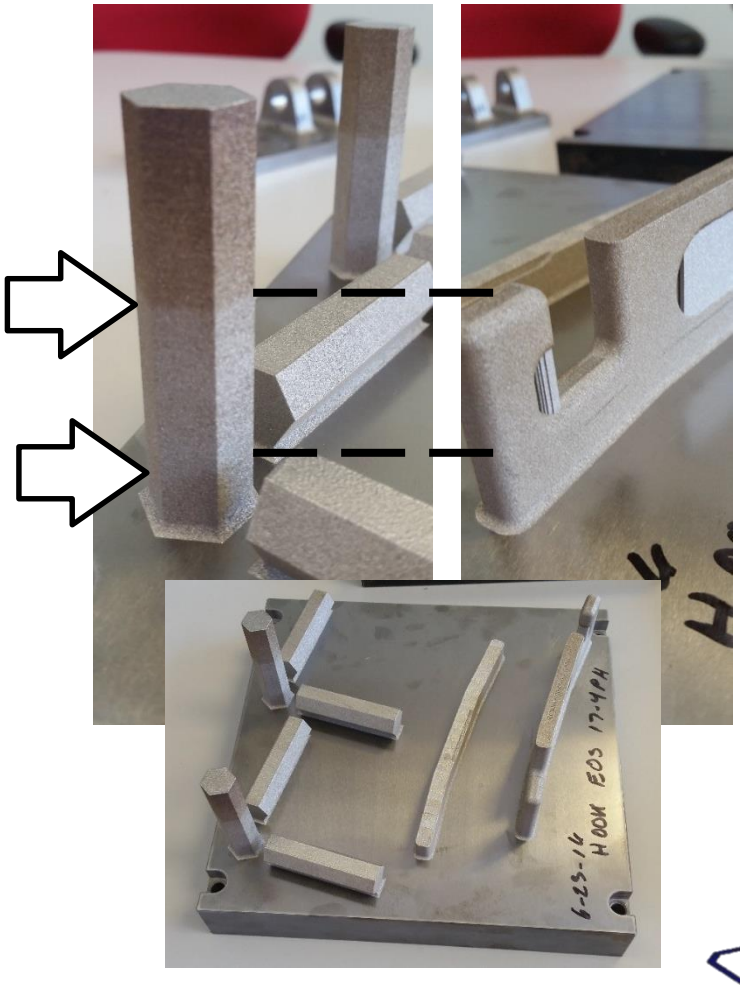
- **Developing Validated Knowledge – PART FAMILY DESIGN?**
  - Conventional process specification protocols being developed to manage "**outside the bed**" design influences: machine, operator, machine settings, calibration, feedstock, etc.
  - power & velocity **necessary but not sufficient** for control
  - R&D to investigate the "**inside the bed**" influences. Can geometric influences to process be *generically characterized* for process design:

    melt area, interpass temperature, part thicknesses, … others

Departing from a Point Design Approach

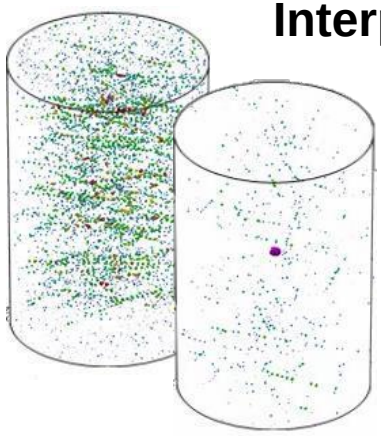
Controlling “Inside the Powder Bed” Influences

Melt Area



Courtesy UDRI, AFLCMC/EZP

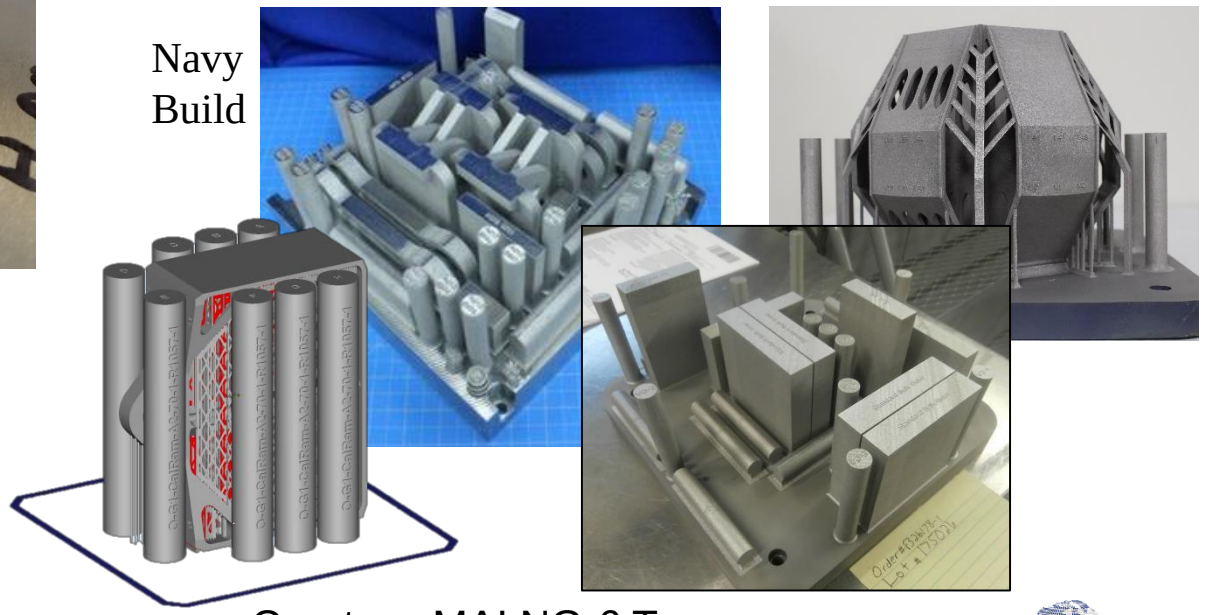
Interpass Temperature





Component Performance Equivalency ???

Navy Build



Courtesy MAI NG-6 Team

Qualification Readiness by Material

Powder Bed Fusion

- CoCr, IN 625, IN 718
  - Lower sensitivity 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
- Experience with other alloys with some experience at AFRL:
  - $AlSi_{10}MG$, CuCr, Haynes 230, A357 Al

Research to Support Qualification & Certification

Data being generated

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

Other Avenues Explored

- 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



Program Overview

Problem Statement

- The AF faces significant challenges sustaining legacy aircraft operating in extended periods of service.

- Sustainment challenges include:
  - low-volume parts.
  - Out-of-Production Spares (OOPS).
  - Tooling, fixtures, jigs availability
  - Lack of advanced workforce training.



B52 Stratofortress: 64 years in air (Aug 2018)

- To effectively maintain and sustain aircraft, the AF must:
  - Implement additive and other advanced manufacturing technologies.
  - Leverage existing expertise in advanced manufacturing technologies
  - Utilize advanced capabilities existing in the supply chain.

What is MAMLS?

- Congressionally directed program
  - executed by America Makes
  - AF as the executive agent.



Goal: Enhance and improve Air Force sustainment operations through the development, demonstration, and transition of additive manufacturing and related advanced manufacturing technologies.

- Strong interface with AF sustainment operations
  - Improve the efficiency of organic sustainment operations for rapid part replacement of legacy aircraft
  - Accelerate the adoption of additive manufacturing.

- Success is enabled through:
  - Collaborative infrastructure of America Makes
  - Leveraging cross-cutting enabling technologies
  - Technology deployment aligned with AF and industry requirements.
  - Development of commercial supply chains for rapid part replacement.

MAMLS Objectives and Benefits

Objectives

- Develop and demonstrate advanced manufacturing technologies related to additive manufacturing that improve rapid part replacement or maintenance processes for legacy aircraft.
- Enable on-demand replacement of critically damaged or obsolete components.
- Develop and demonstrate rapid fabrication of shop tools such as assembly aids, jigs, and fixtures for sustainment operations.
- Identify technology gaps and workforce issues that need to be solved prior to effective AF implementation.
- Conduct air worthiness pathfinding research to develop data and strategies for qualification of additive manufactured parts for demanding part families.

Benefits

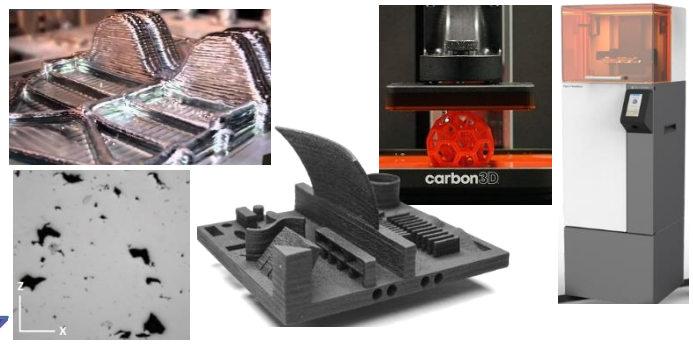
- Reduction of lead time and cost to fabricate replacement components for legacy aircraft as well as to support rapid tooling, masks, fixtures, etc.
- Technology demonstrations and learning for future implementations of both flying components and applications on the shop floor.

Program Phases

LESS CHALLENGING RESEARCH APPLICATIONS







	CY 2016	CY 2017	CY 2018	CY 2019	CY 2020
Phase 1: "Low Hanging Fruit" - Tooling; reverse engineering; organic sustainment applications; business case development; and OEM supply chain activities. (broad-based sustainment support activities)	★ 8 Feb 2016 Phase 1 Award date $8.99M (FY15 CII funding)				
Phase 2: "Qualification Pathfinding for Direct Part Replacement" - Direct part replacement research; tech gap ID; qualification issues; material issues; business cases; etc. (focused OEM component demos for feasibility studies)		★ 9 May 2017 Phase 2 Award date $9.056M (FY16 CII funding)			
Phase 3: Rapid Transition & New Start Research Topics - Feature-based Qualification Using DED Understanding AM Mfg Realities Emerging Technologies for Low-criticality Part Families			★ 23 Apr 2018 Phase 3 Award date $9.0M (FY17 CII funding)		
TOTAL FEDERAL FUNDING ($)					$27M

MORE CHALLENGING RESEARCH APPLICATIONS

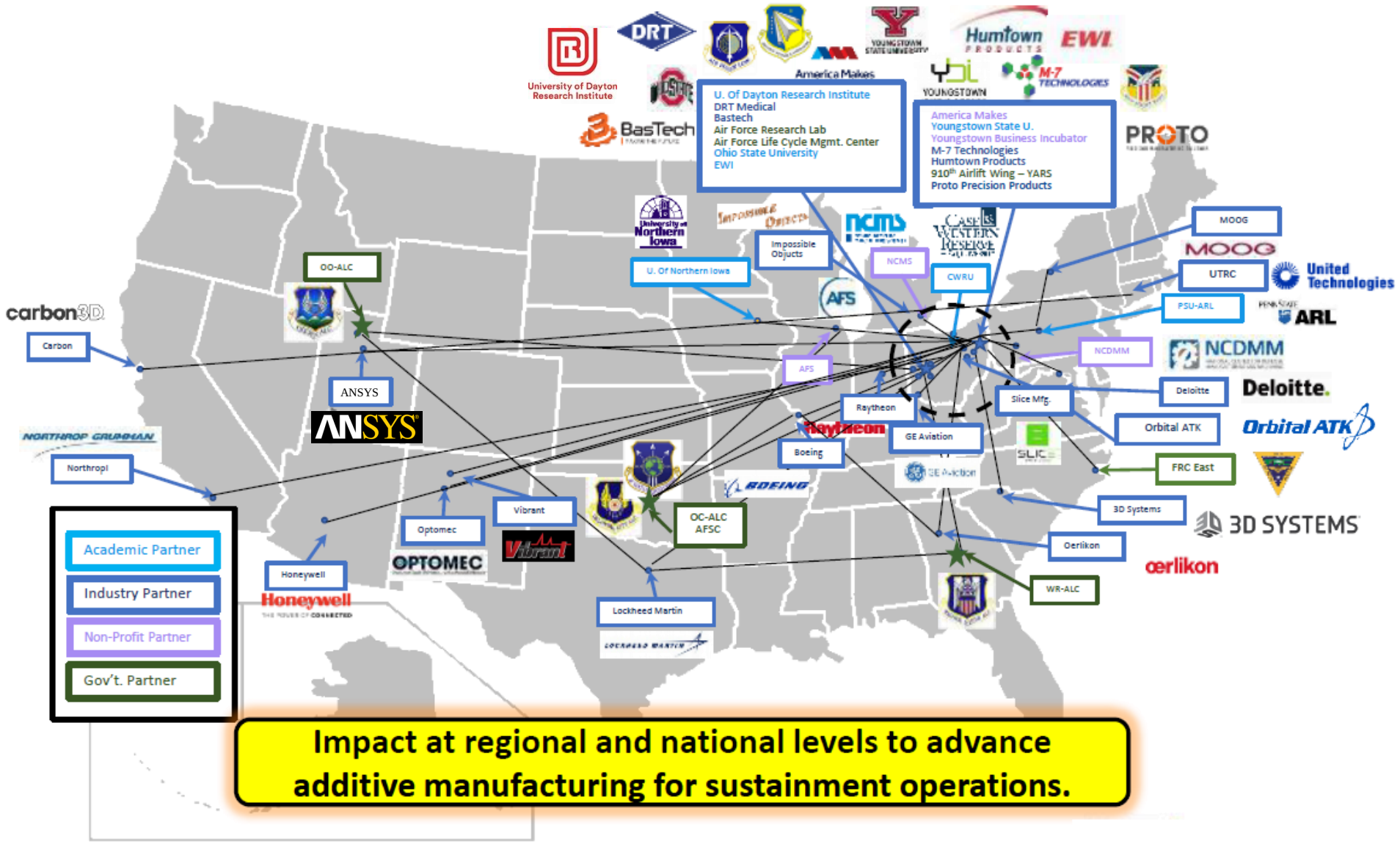
MAMLS Diversity: Team Members

Industry/Academia Members

Government Members



MAMLS Diversity: Ecosystem



Impact at regional and national levels to advance additive manufacturing for sustainment operations.

MAMLS Technologies



Reverse Engineering & Modeling



Assembly & Manufacturing Aids



Metal Form Tooling



Composite Autoclave Tooling



Metal Part Repair



Metal Cast Tooling



Direct Digital Part Demonstrations





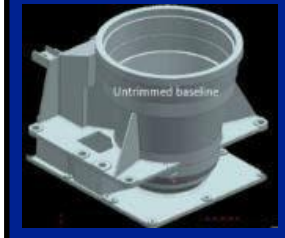












Handy Scan



Fused Deposition Modeling (FDM)



Big Area Additive Manufacturing



FDM



Directed Energy Deposition (DED)



3D Sand Printing (3DSP)/Quickcast



Laser Powder Bed Fusion

MAMLS Phase 1: Low Hanging Fruit

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



Printed Sand Casting Mold



Final Al Casting

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



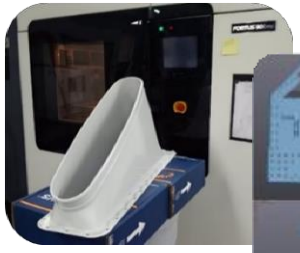
Assembly Fixture Pre- and Post-repair



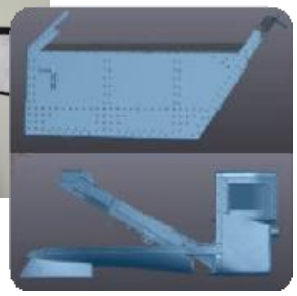


Paint Masks for Engine Housings

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



Environmental Ducting





Digital Scanning Tools

MAMLS Phase 2: Direct Part Manufacturing Demos

Phase 2 projects focus on **finding qualification barriers** for direct part fabrication. Research topics include repeatability across machines, supply chain requirements, and tech data package requirements such as fabrication, qualification, and process certification.

1. Bell crank family of parts (YSU, PSU, YBI, M-7, Boeing, Oerlikon)

- Flight and fracture critical part with varying thicknesses & complex geometries
- Feature-based bell crank from aircraft design to be used for demonstration
- Aluminum powder bed fusion technology



Example Bell Crank

2. Fuel oil cooler family of parts (UDRI, YSU, YBI, DRT, ANSYS, GE Aviation)

- Lightly loaded, complex geometry, & constant functionality demands
- Generic oil cooler core design and fabrication will be demonstrated
- Aluminum powder bed fusion technology



Example Oil Cooler.

3. Structural sandwich panels using hybrid AM approach (Boeing)

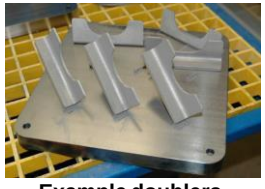
- Alternate approach to traditional metal core/composite skin manufacturing
- Pylon fairing design to be used for demonstration
- FDM technology using ULTEM for the honeycomb core



Example Pylon Fairing

4. Structural repair brackets/bathtup fittings/doublers (Lockheed)

- Alternate approach to Aluminum machined brackets with long lead time
- Titanium powder bed fusion approach being investigated
- 100% cost share effort added to original Phase 2 program



Example doublers

MAMLS Phase 3 Awards

3 Topic Areas

Feature-based Qualification Using Directed Energy Deposition	Understanding Manufacturing Realities	Emerging Process Technologies for Low Criticality Part Families
Large Scale DED	Laser Powder Bed AM	Non-Metallic Applications

7 Project Awards

Title	Lead Organization	Duration
Feature-based Qualification Method for Directed Energy Deposition (DED)	General Electric Global Research Center (GRC)	24 Months
Accelerating Direct Part Production: Effects of Defects in Laser Powder Bed Fusion AlSi10Mg	Youngstown State University (YSU)	24 Months
Understanding Stochastic Powder Bed Fusion AM Flaw Formation and Impact on Fatigue	Penn State University (PSU)	24 Months
Evaluation of Defects in Metal LPBF AM using Multiple Lasers	Ohio State University (OSU)	12 Months
Demonstration of 3D Composite Based AM (CBAM) Build Process for Low Criticality Part Families	Utah Advanced Materials and Manufacturing Initiative (UAMMI)	24 Months
AM of Low Criticality Part Families via Continuous Liquid Interface Production (CLIP)	United Technology Research Center (UTRC)	18 Months
Rapid Part Replacement via Digital Light Processing	University of Dayton Research Institute (UDRI)	24 Months

Feature-based Qualification Method for Directed Energy Deposition (DED)

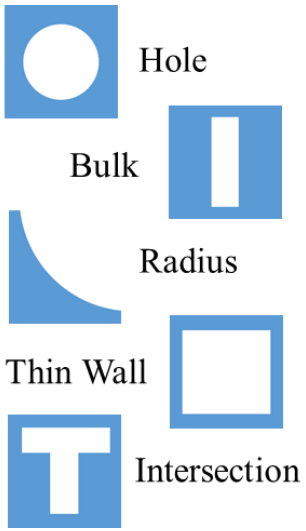
Problem: Current "point solution" qualification approaches are geometry dependent, time consuming and expensive, eliminating much of the benefit AM provides.

Objective: Apply FBQ approaches to DED production of large scale, aerospace components to:

- demonstrate the utility of the FBQ approach
- identify associated implementation challenges and risk reduction of alternative qualification strategies



FBQ is seen as a potentially viable strategy for avoiding non-statistical based and inefficient point design approaches.



GE Global Research

GE Aviation

Raytheon

YOUNGSTOWN STATE UNIVERSITY

EWI

AFRL THE AIR FORCE RESEARCH LABORATORY

Accelerating Direct Part Production: Effects of Defects in LPBF $AlSi_{10}Mg$

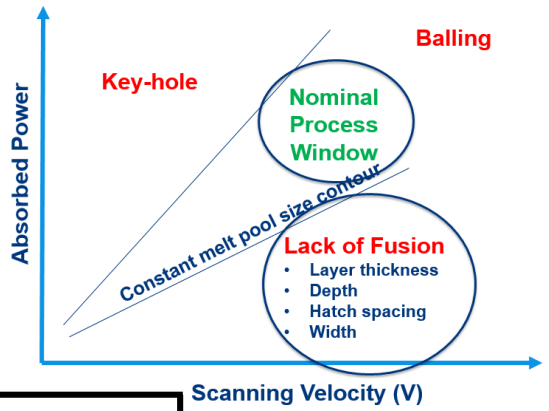
Problem: Many factors lead to scrapped material from the AM process.

- Powder contamination - Lack of fusion (LoF) voids - Distributed porosity

Objective: Quantify the effect of defects on the performance of LPBF $AlSi_{10}Mg$.

- Evaluate LoF and distributed porosity generated through specifically engineered “Off-nominal” parameters through post-build inspection and in-situ monitoring.
- Evaluate the effect of Inconel 718 powder contamination in printed $AlSi_{10}Mg$ material.

Engineered parameters and controlled contamination will ensure defects in a relevant sample quantity.



YOUNGSTOWN STATE UNIVERSITY
BOEING
CASE WESTERN RESERVE UNIVERSITY think beyond the possible
oerlikon
3D SYSTEMS
PennState Applied Research Laboratory
LOCKHEED MARTIN
Vibrant
University of Dayton Research Institute

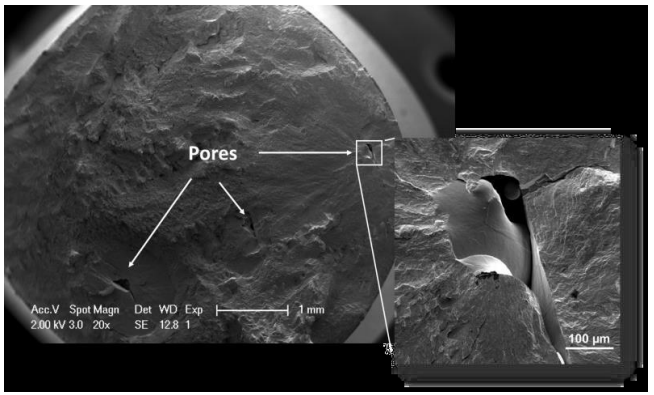
Understanding Stochastic LPBF Flaw Formation and Impact on Fatigue

Problem: Current LPBF processes contain stochastic (as opposed to preventable) flaws. These flaws have an effect on mechanical properties that is not yet well understood.

Objective: Quantify the effect of defects on the performance of LPBF Ti6Al4V.

- Quantify the impact of stochastic flaw generation on fatigue properties
- Gain an understanding of the root causes of stochastic flaw formation through post build inspection and in-situ monitoring

Processing coupons at optimal parameters will ensure relevant flaw formation. Careful post-build inspection will allow mechanical data correlation to flaw generation.



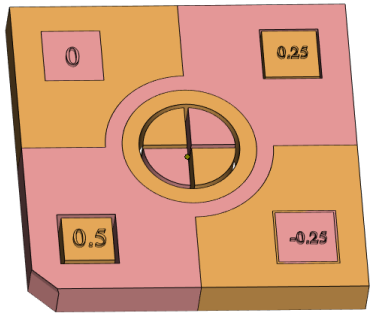
PennState Applied Research Laboratory
United Technologies
YOUNGSTOWN STATE UNIVERSITY
3D SYSTEMS
MOOG
oerlikon
AFRL THE AIR FORCE RESEARCH LABORATORY

Evaluation of Defects in Metal LPBF AM using Multiple Lasers

Problem: While Multi-Laser powder bed fusion (M-LPBF) processes offer increased productivity, there is neither current defect library specific to M-LPBF nor does an accepted test standard exist.

Objective: Gather data by producing Inconel 718 samples created with multiple laser sources.

- Characterize M-LPBF specific defects (Overlap LoF, spatter interaction, etc…)
- Generate a standard test geometry to screen for the identified defects





The data provided will allow the AM community to begin to understand the specific challenges with M-LPBF and allow future research to begin to solve these issues.

THE OHIO STATE UNIVERSITY

GE Additive

PROTO PRECISION MANUFACTURING SOLUTIONS

Summary

- **AFRL is the AF SME for development, maturation and qualification of materials & processes**
- **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**


AFRL
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

Demonstration of 3D Composite Based AM (CBAM) Low Criticality Part Families

Problem: There remain significant opportunities to address current sustainment needs for non-structural and non-critical composite part replacements. However, composite printing processes have not yet been fully evaluated to solve these AF issues.

Objective: Evaluate CBAM's ability to supply low criticality components.

- Assess the material/mechanical properties of CBAM coupons (static, density, geometry, etc.)
- Evaluate CBAs ability to produce non-critical parts
- Perform a Cost Benefit trade study



This evaluation data can be used to determine the technology trade-space and possibly identify immediate transition opportunities.

uammi
UTAH ADVANCED MATERIALS + MANUFACTURING INITIATIVE

IMPOSSIBLE OBJECTS

Utah Composites Laboratory

AFRL THE AIR FORCE RESEARCH LABORATORY

AM of Low Criticality Part Families via CLIP

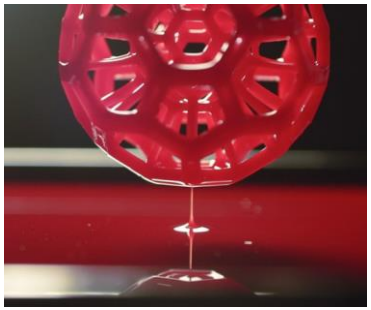
Problem: Hard to source non-structural polymer components are prevalent in the sustainment community. A ready supply of support hardware (masks) and non-structural, non-critical components could have a large impact on the sustainment community.

Objective: Evaluate the Carbon3d CLIP process for non-critical parts.

- Evaluate materials for field appropriate properties
- Assess reproducibility of the process
- Demonstrate capability to produce identified hardware



This Digital Light Processing (DLP) technology has the promise of rapidly producing support hardware which could have immediate impacts.





United Technologies Research Center

UTC Aerospace Systems

carbon3D

Problem: Hard to source non-structural polymer components are prevalent in the sustainment community. Broken and missing support hardware, such as electrical connecters and instrumentation knobs, can delay other high-value maintenance processes.

Objective: Evaluate the 3D Systems Figure 4 process for non-structural support hardware.

- Evaluate materials for field appropriate properties
- Assess reproducibility of the process
- Perform a Cost Benefit trade study





This evaluation data can be used to determine the technology trade-space and possibly identify immediate transition opportunities.



University of Dayton Research Institute

3D SYSTEMS

NORTHROP GRUMMAN

Orbital ATK

LOCKHEED MARTIN

AFRL THE AIR FORCE RESEARCH LABORATORY

APPENDIX I
RICK RUSSELL, NASA
"UPDATE ON NASA'S ADDITIVE MANUFACTURING STANDARDS DEVELOPMENT EFFORT AND TOP DURABILITY AND DAMAGE TOLERANCE CONCERNS"

Update on NASA's Additive Manufacturing Standards Development Effort and Top Durability and Damage Tolerance Concerns

Rick Russell, Materials Technical Fellow

NASA Engineering and Safety Center

Creation of a NASA Standard

- The NESC has formed a team to explore the creation of an Agency Specifications for Additive Manufactured (AM) components.
  - This team includes representatives from nine NASA centers along with representatives from the FAA, Air Force, Navy and Army.
- The intent is that this standard will be Agency policy for AM
- The standards will create requirements with guidance which can then be used to develop manufacturing plans and provide product specifications for both general and specific applications
- The standards will not specifically state how to manufacture or certify a component but the requirements will identify factors that need to be addressed for all phases of design, manufacture, and qualification.

Applicability

- The team agreed that the standard(s) should be applicable to mature technologies.
  - Specific technologies and will be listed but explicitly NOT limited
  - Details will be included in the Scope
  - Specific materials type to be included are:
    - Metals
      - Powder
      - Wire
    - Polymers
      - Stereo Lithography
      - Wire/FDM
      - Powder/Beads
      - Polymer systems w/ Graphite reinforcement
    - Ceramics (recently added)
    - Composites (recently added)
  - Materials determined to be out of scope are:
    - Regolith
    - Printed Circuits

Interaction of Part and Mission Class

- Part Class and Mission Class together influence the requirement set to maintain appropriate levels of mission assurance commensurate with the scenario.
- Possible Approaches:
  1. Part Class determined independent of Mission Class
     - Part class determines requirement set
     - Mission class does not affect requirement set
     - Mission class may influence risk acceptance or requirements waiver

     Team consensus and recommended approach
  2. Mission Class influences Part Class through Consequence of Failure or other criteria
     - Part Class determines requirement set
     - Mission Class influences requirement set broadly (e.g., no Class A parts in Class B-D missions)
  3. Part Class and Mission Class Independent -> Combined Class sets requirement level
     - Uses matrix of Part Class and Mission Class similar to common risk matrix.

Based on this decision the team decided that the three separate standard should be created:

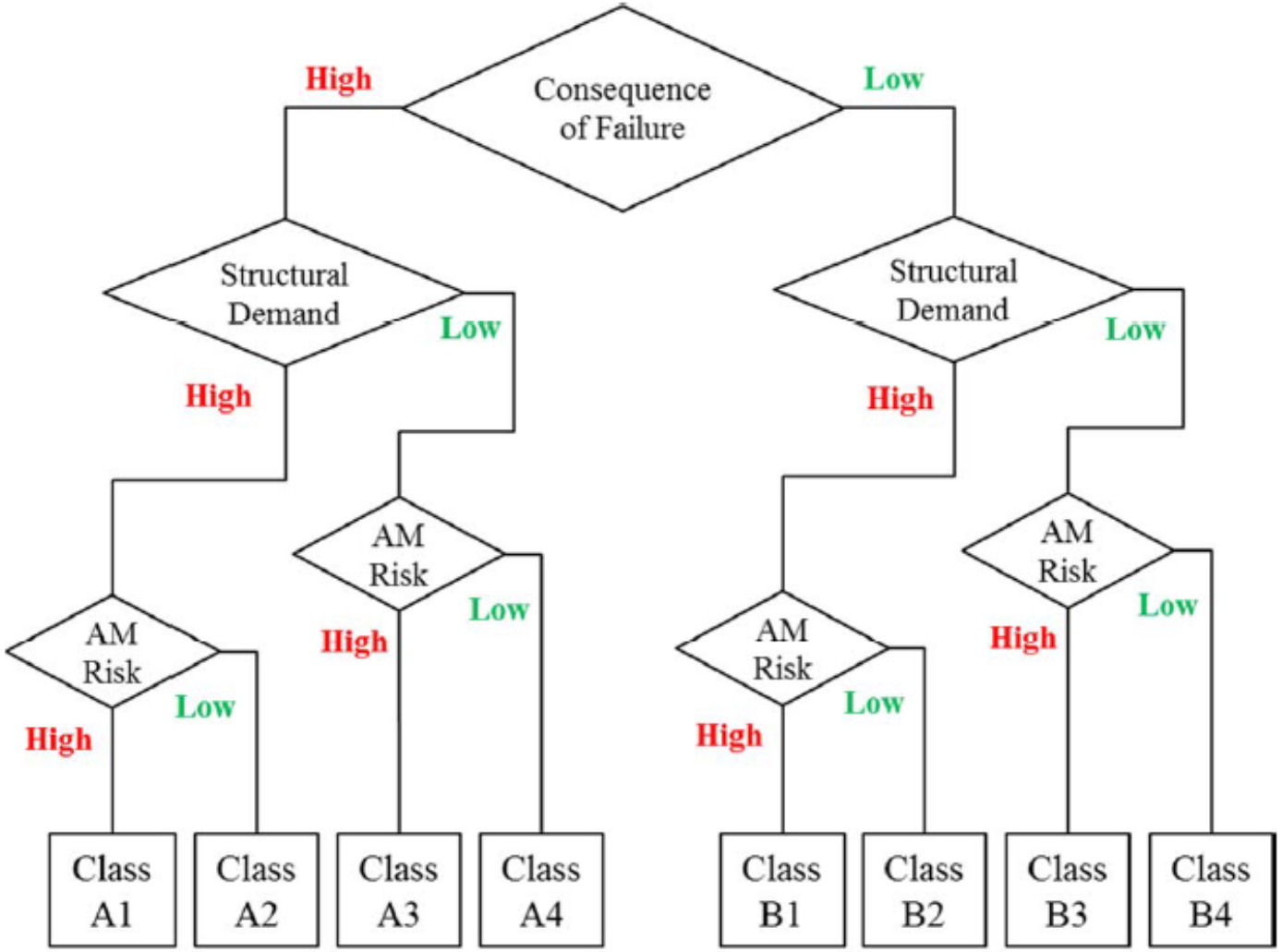
- Manned Space Flight
- Non-Manned Space Flight
- Aeronautics

Proposed Document Structure

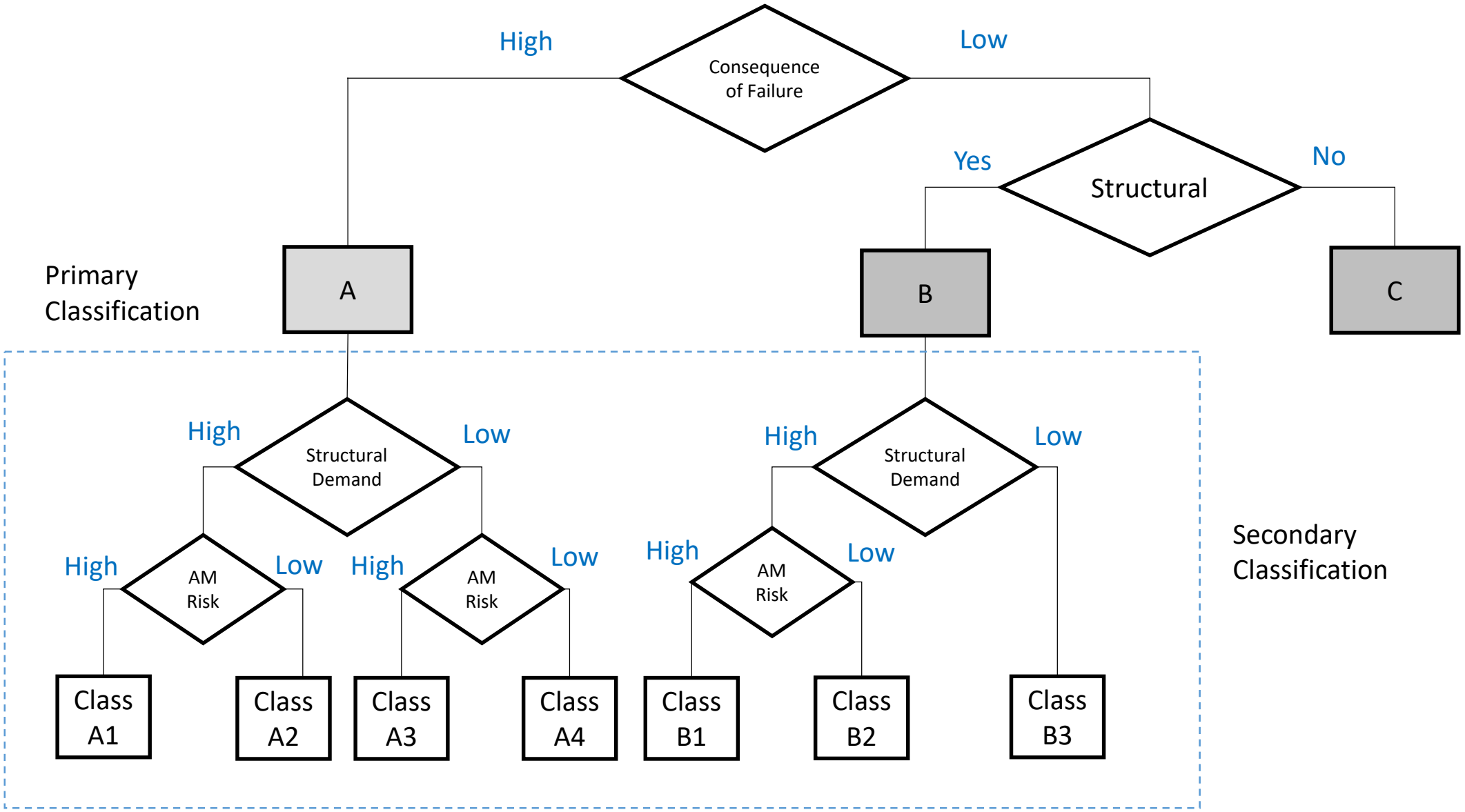
- Documents will be based on the principles of MSFC-STD-3716
  - The requirements summary as listed in Appendix F, Table VIII will be utilized and modified as appropriate.
  - Portions of MSFC-SPEC-3717 will be pulled into the NASA standards and generalized
    - Metallurgical Process definitions
    - Qualification of metallurgical processes
  - A separate specification will be written to cover Equipment and Facility Process Control
- A separate specification will be written with guidelines on how to write specifications
  - Material
  - Processes
  - Procurement
    - Purchase of parts from mature supplier

Part Classification

- The MSFC-STD-3716 classification system was used as the starting point
  - This system is risk based and stems from the three primary questions typically asked when evaluating part risk:
    - Consequence of failure (What happens if the part fails?)
    - Structural demand (How severe is the stress environment?)
    - AM Risk (How challenging is part design and can the part be reliably inspected?)



Revised Classification system



Consequence of Failure

- A part will be designated as Class A (High Consequence of Failure) if one or more of these criteria are applicable:
  - Fracture Critical per NASA-STD-5019A
  - If failure would lead to a catastrophic hazard (loss of life, disabling injury or loss of a major national asset)
  - If failure would lead to the loss of one or more primary/minimum mission objectives

Non-Structural

- A part will be designated as Class C (Non-Structural) if one or more of these criteria are applicable (things we wrote on the board):
  - Not part of primary or secondary load path
  - No Structural analysis is required
  - Not proto-flight (JPL and GSFC may define differently)
  - Not fasteners

- Parts that are NOT class A or C will be designated as class B.

Structural Demand

Material Property	Criteria for High Structural Margin
Loads Environment	Well-defined or bounded loads environment
Environmental Degradation	Temperature only
Ultimate Strength	30% margin over factor of safety
Yield Strength	20% margin over factor of safety
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	4x additional life factor or 20% below required fatigue limit cyclic stress range
High Cycle Fatigue, As-built Surfaces	10x additional life factor or 40% below required fatigue limit cyclic stress range
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	10x additional life factor
Creep Strain	No predicted creep strain

AM Risk Criteria

Additive Manufacturing Risk	Yes	No	Score
All critical surface and volumes **can be reliably inspected**, or the design permits **adequate proof testing** based on stress state?	0	5	
As-built surface **can** be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports **are fully accessible** and improved?	0	3	
Structural walls or protrusions are ≥ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

AM risk = HIGH, if cumulative AM Risk score >=5

Requirements Matrix

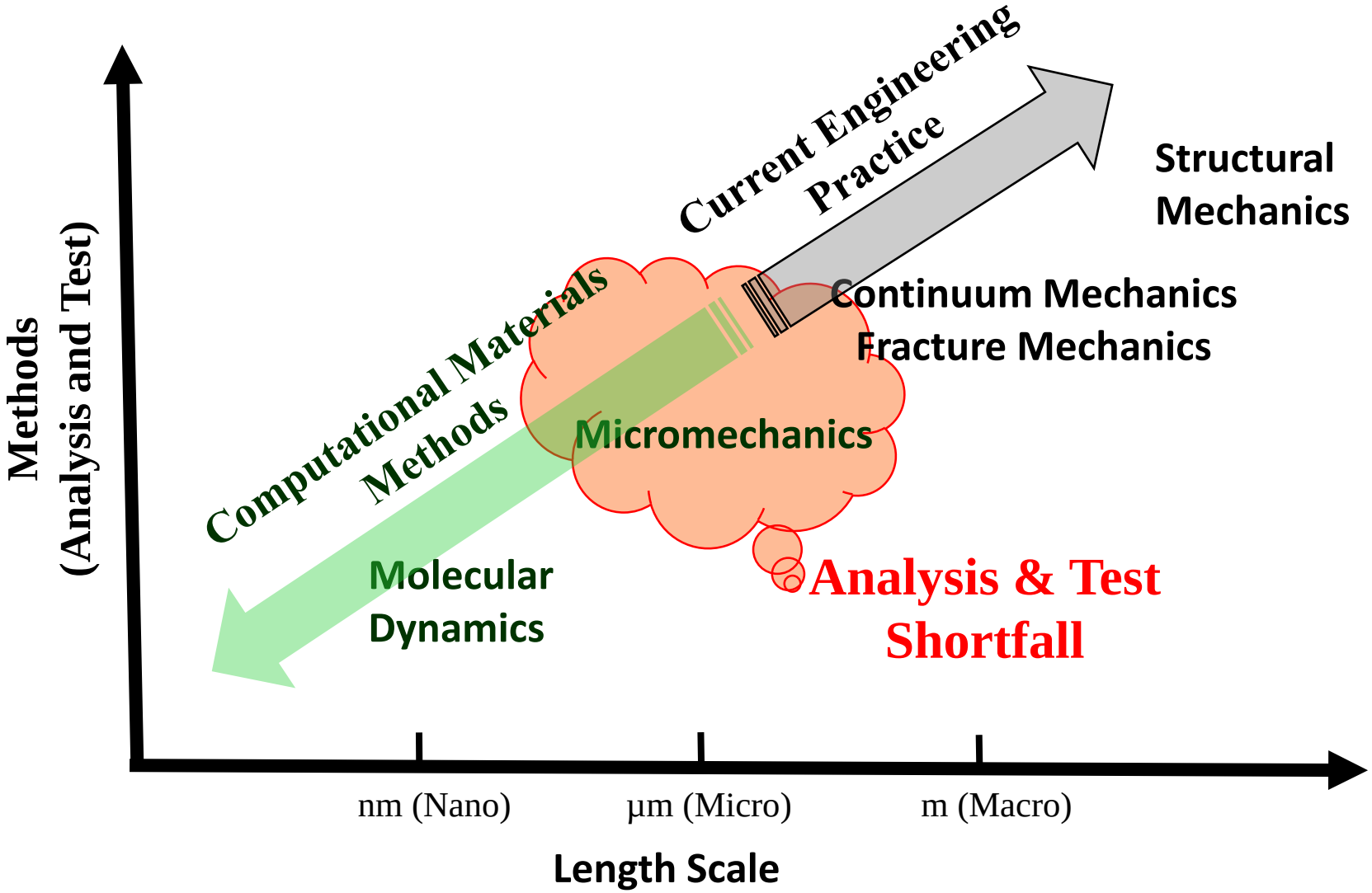
Requirement	Requirement Description	MSFC-STD-3716	NASA-STD (proposed language)	A	B	C	Notes
AMR-3	Additive Manufacturing Control Plan	[AMR-3] The CEO responsible for the design and manufacture of L-PBF hardware shall provide an AMCP that accomplishes each of the following: a. Documents the implementation of each of the requirements of this MSFC Technical Standard. b. Documents and provides rationale for any tailoring of the requirements of this MSFC Technical Standard. c. Documents the methods used to control compliance with these requirements by subcontractors and vendors. d. Provides for complete governance for the implementation of L-PBF such that, once approved by the procuring authority, the AMCP becomes the document used for verification of L-PBF requirements.	[AMR-3] The CEO responsible for the design and manufacture of AM hardware shall provide an AMCP that accomplishes each of the following: a. Documents the implementation of each of the requirements of this NASA Technical Standard. b. Documents and provides rationale for any tailoring of the requirements of this NASA Technical Standard. c. Documents the methods used to control compliance with these requirements by subcontractors and vendors. d. Provides for complete governance for the implementation of AM such that, once approved by the procuring authority, the AMCP becomes the document used for verification of AM requirements.	AW	T	O	See Appendix for Tailoring Guidelines

Durability and Damage Tolerance Shortfall

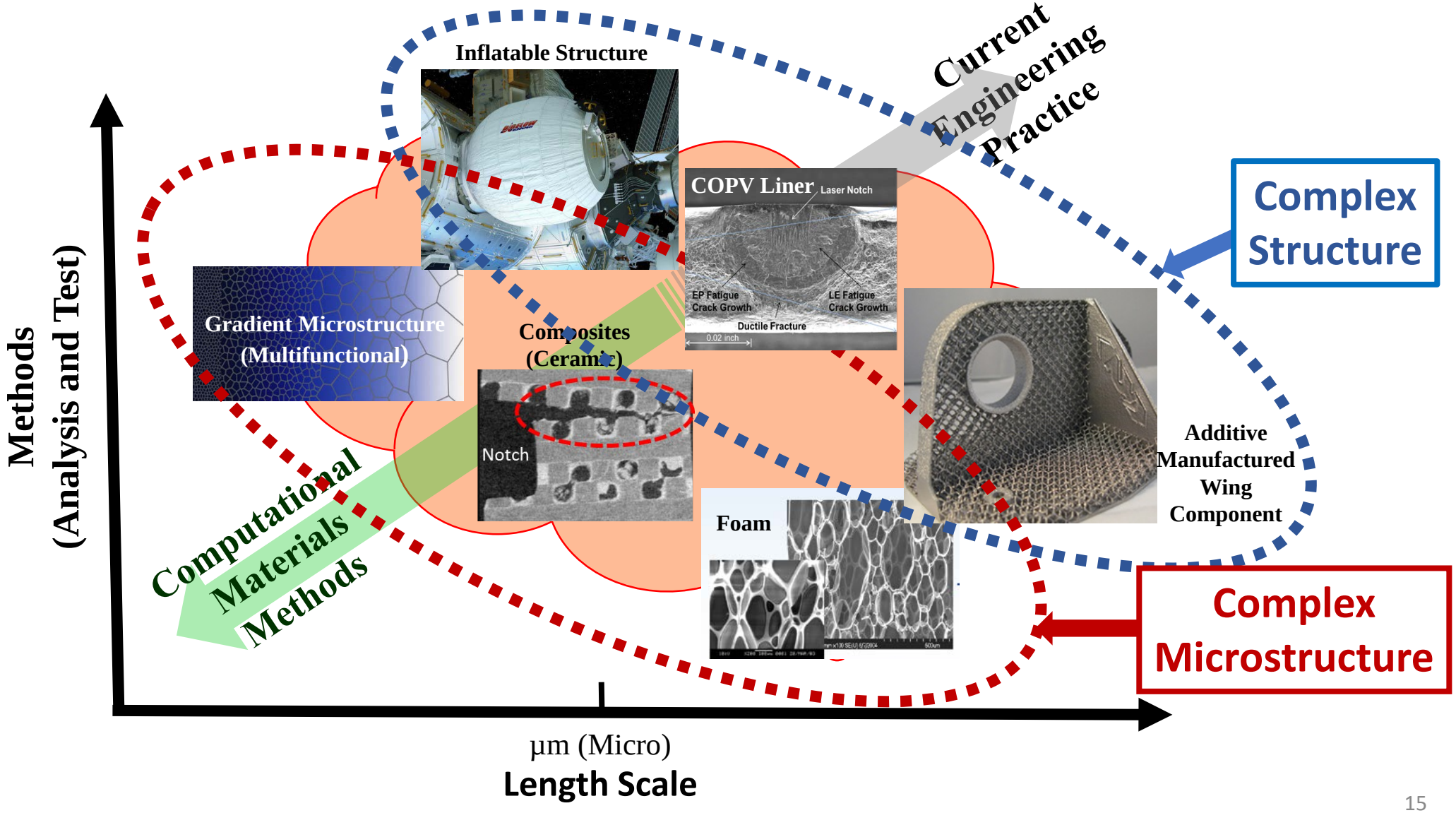
- There is growing concern within NASA that technology gaps are leading to the use of D&DT tools beyond their capabilities (Analysis and Test)
- Many are still using continuum based LEFM in a noncontinuum regime
  - Global properties may not apply
  - Damage growth processes are dependent on local environments
  - Need to understand
    - Local Properties
    - Local Environments
    - Develop new noncontinuum methods

D&DT

- Analysis and Test Methods -

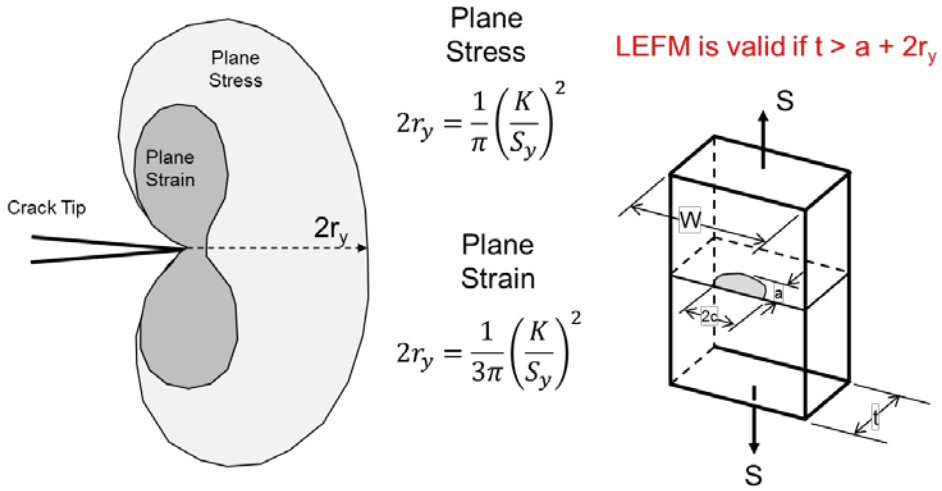


D&DT Analysis and Test Shortfall (Micromechanics Regime)



Thin Walled COPVs - Fracture Control Concern

1. Linear elastic fracture mechanics (LEFM) assumptions at some point will become violated as the liner thickness is reduced
   a) Are the current theories that define the LEFM limitations relative to thickness (e.g., crack depth + plastic zone < remaining ligament, 5 to 10 grains in the remaining ligament) valid?
   b) Can better guidelines be developed to quantify when the use of LEFM is invalidated by decreasing thickness (influenced by applied stress, yield stress, and microstructure)?
2. Safe-life testing procedures or recommendations are not specified



$2r_y = plastic\ zone\ size$

$\frac{K}{S_y} = ratio\ of\ stress\ intensity\ factor\ to\ yield\ stress$

COPV Life Test Assessment

Objectives

1. Evaluate the applicability of linear elastic fracture mechanics (LEFM) based life predictions for metal liners of composite overwrapped pressure vessels (COPVs)
2. Develop a test procedure for experimentally evaluating COPVs when LEFM is not applicable

Justification

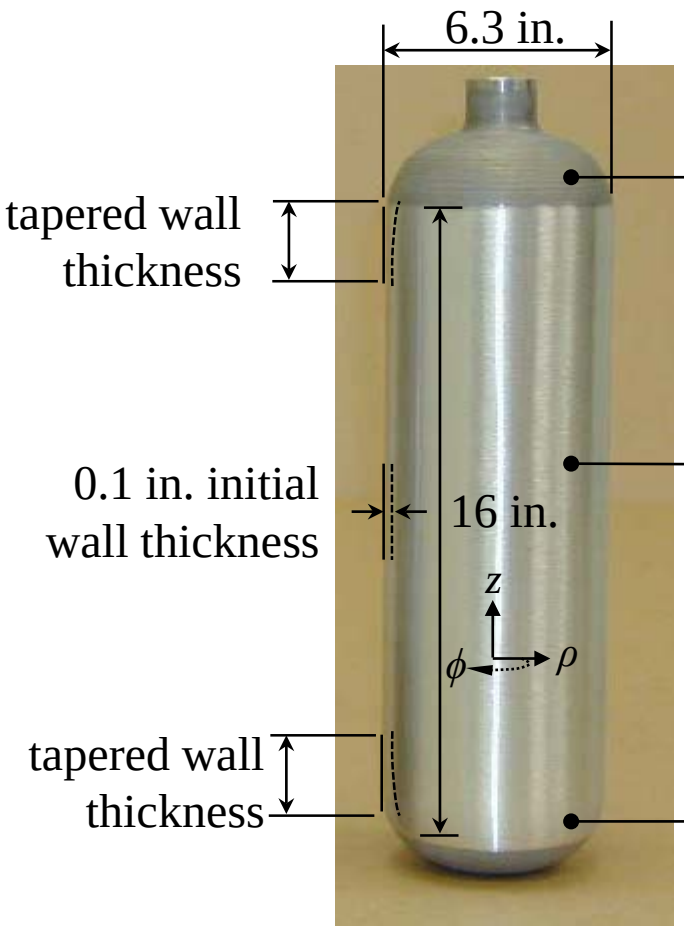
1. Weight considerations are driving the design of COPVs toward thinner liner thicknesses
2. Safe-life requirements can be addressed using LEFM techniques if the liner behaves elastically
3. At what thickness will LEFM assumptions become invalid?
   - Plasticity: the remaining ligament ahead of the crack tip is fully yielded
   - Continuum or microstructural: the number of grains in the ligament is small (<10)

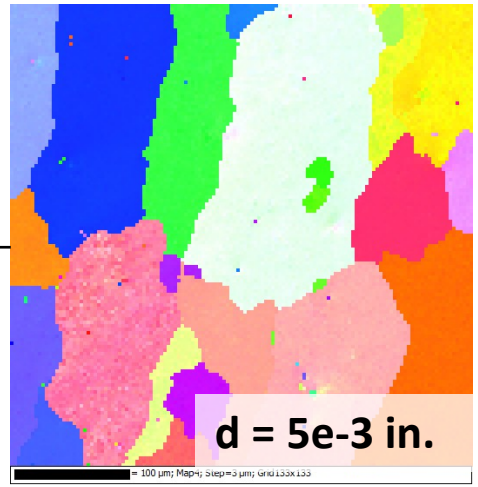
- Three commonly used COPV liner materials will be examined:
  - 6061-T6 aluminum
  - Ti-6-4 –
  - Inconel –
- Sheet materials in various thickness for each alloy will be used
- Spun formed 6061-T6 aluminum liner

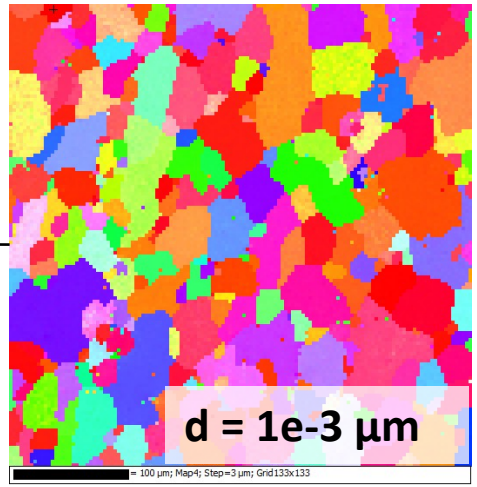
Initial results on 0.09” 6061-T6

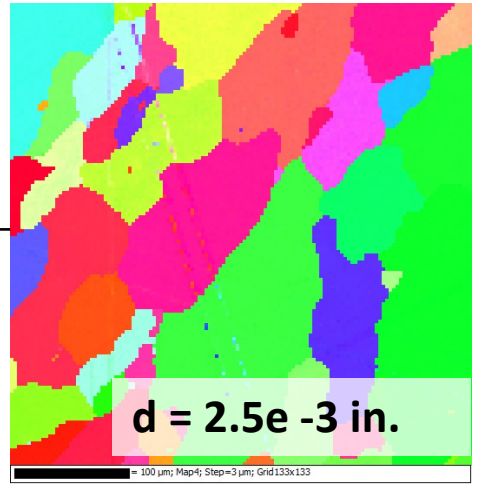
COPV Liner Microstructure Variation

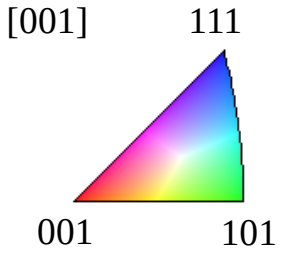
Spin-formed liner











Microstructure inconsistency

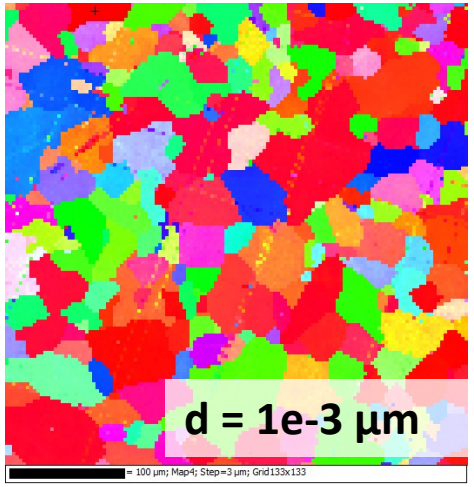
Spin-formed liner:

- follows flow lines
- random texture
- varies along length

Rolled sheet:

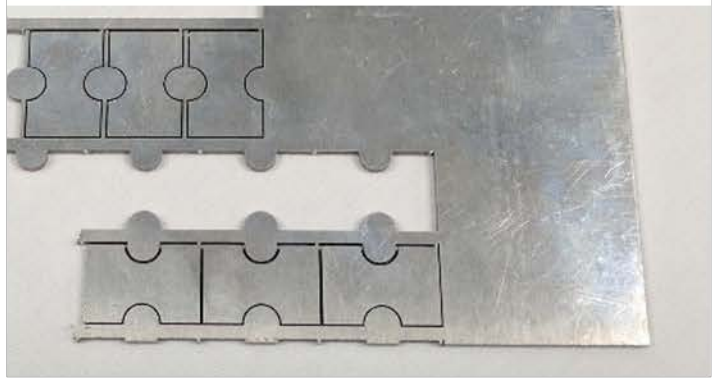
- elongated grains
- rolled texture
- consistent across sheet

Rolled sheet



Small-Scale Testing: Specimen Fabrication

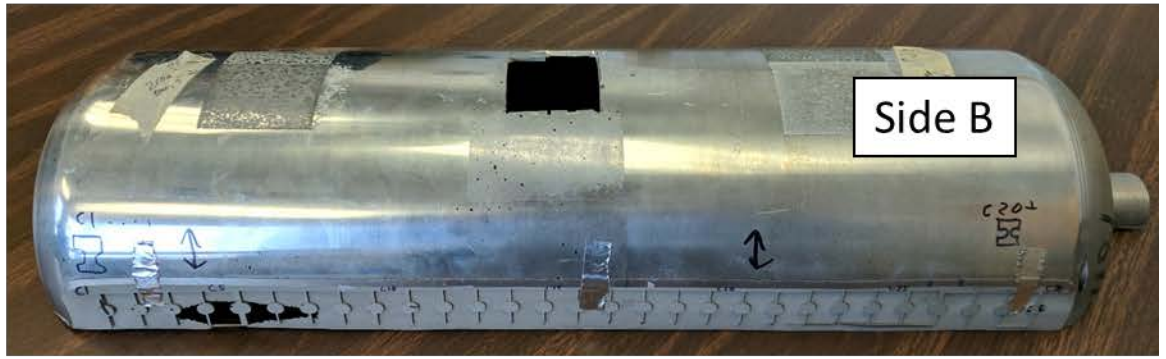
- 0.09” sheet, cut with Electrical Discharge Machining (EDM)
- half were milled to 0.032” thickness
- 10 in each orientation



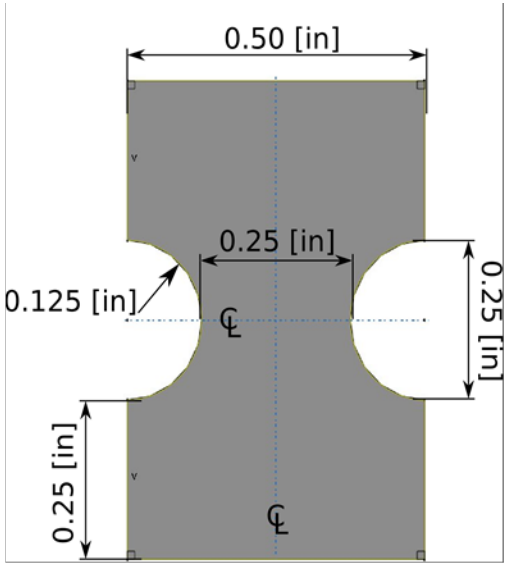
EDM layer removed with 1200 grit paper followed by Never Dull for consistency with long-crack growth tests

- Liner was EDM cut on two sides
- All have 0.032” thickness
- Approx. 20 in each orientation

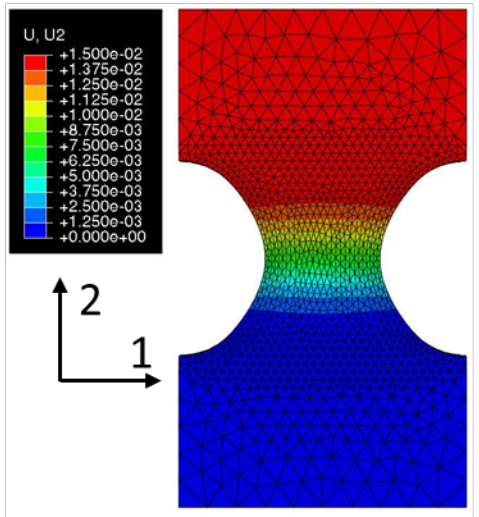




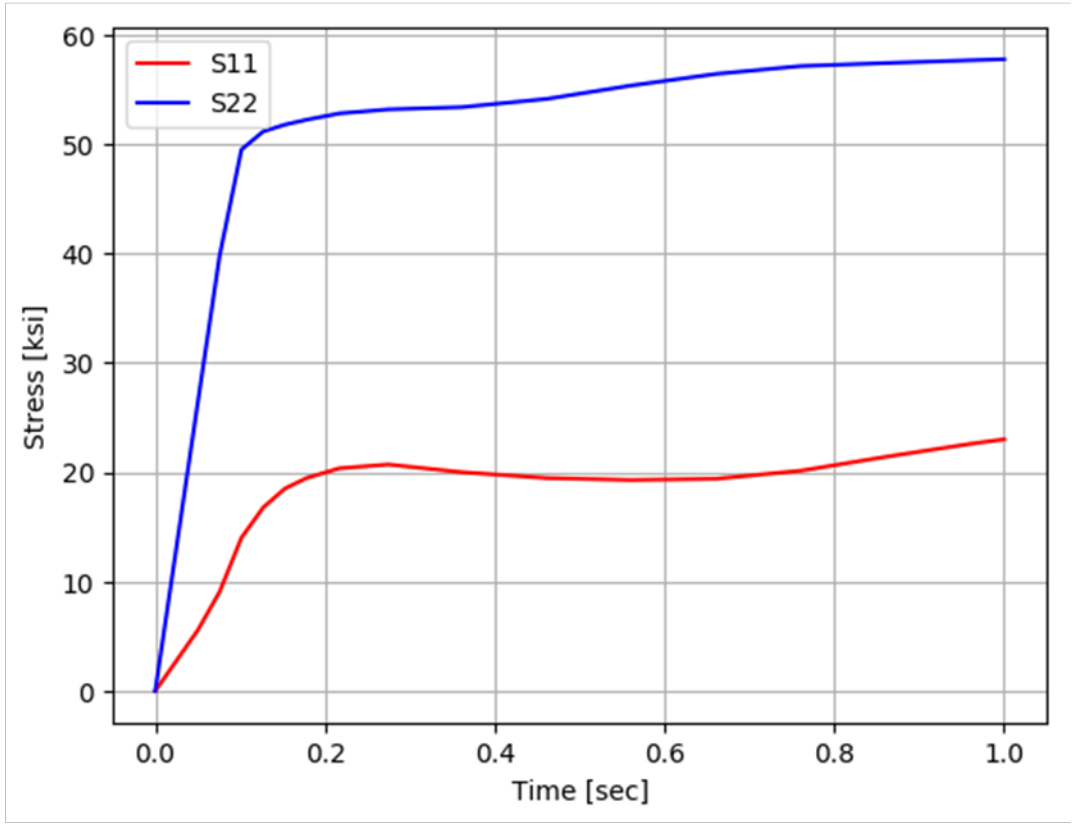
Small-Scale Testing: Specimen Design



Linear ramp to 0.015” displacement

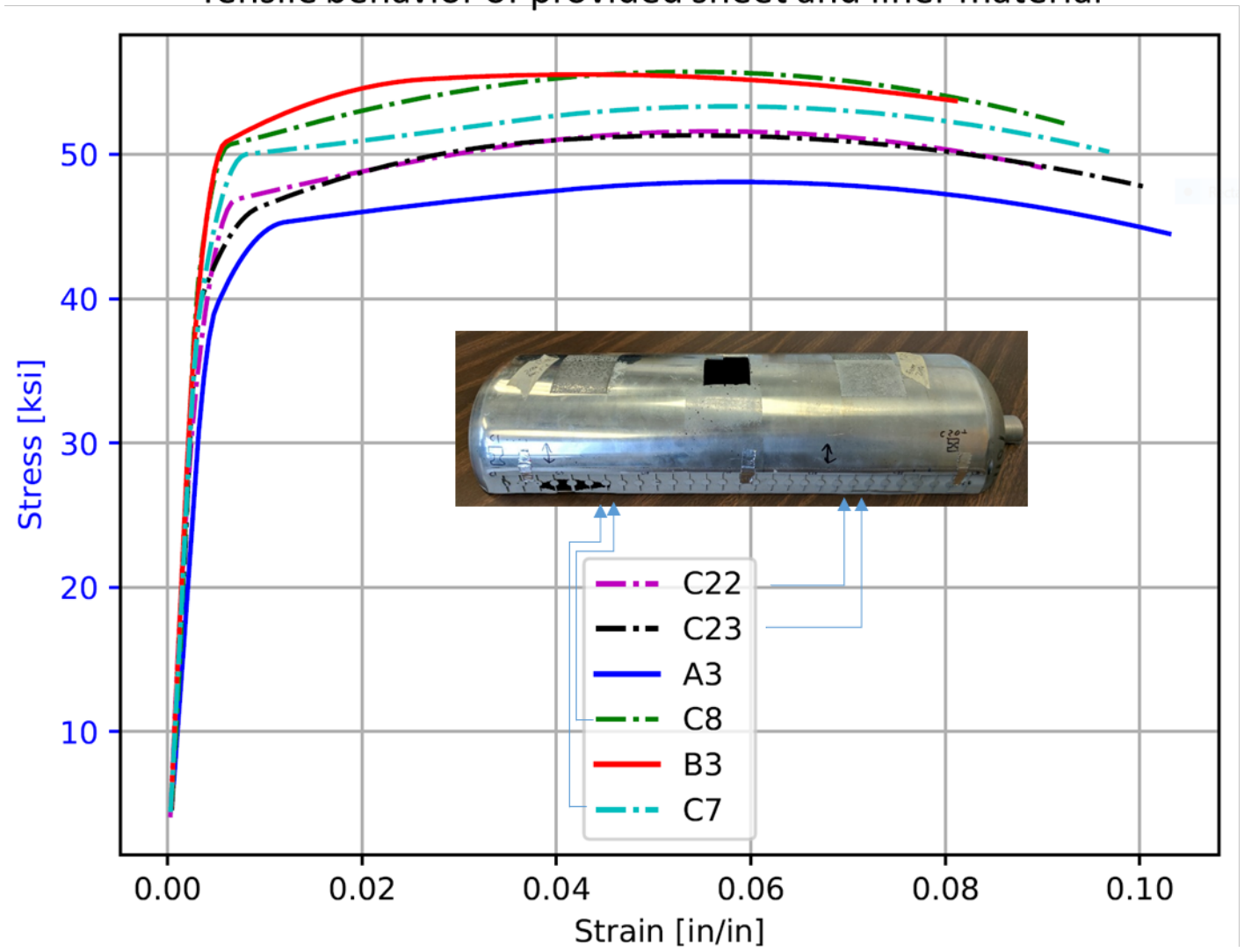


Near 2:1 stress state, more closely emulating service conditions in liner



Small-Scale Testing: Tensile Testing

Tensile behavior of provided sheet and liner material



MAPTIS database (ASM): maptis.ndc.nasa.gov

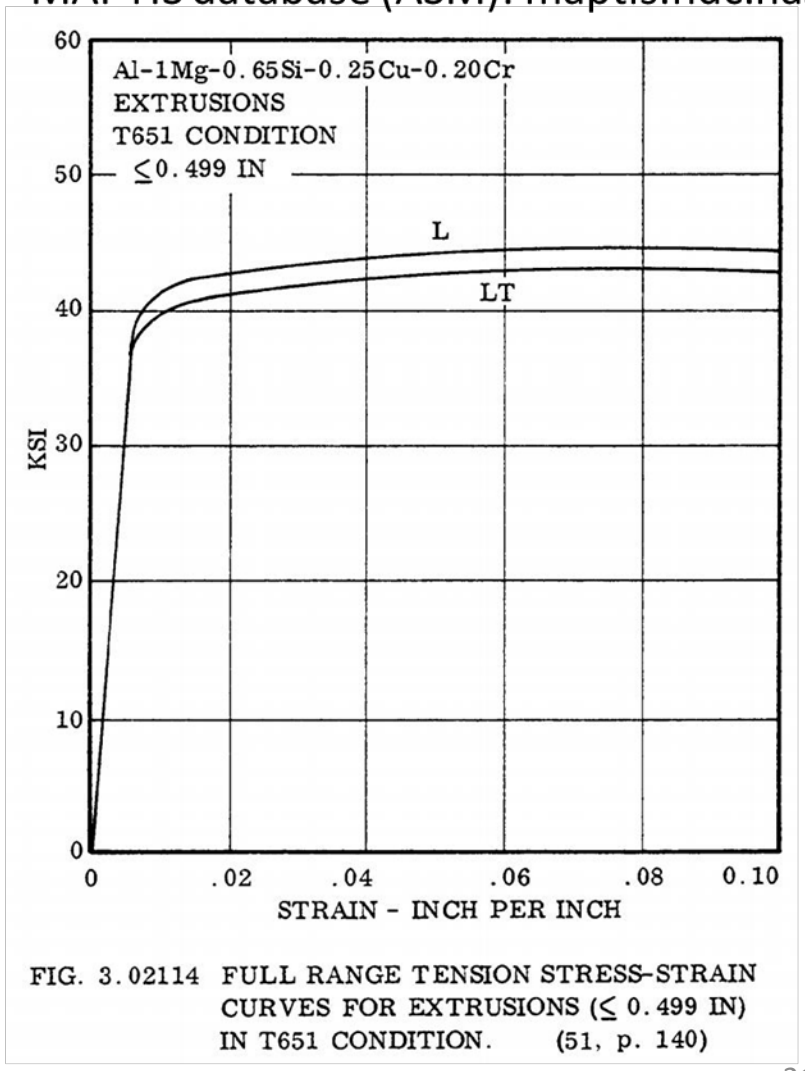
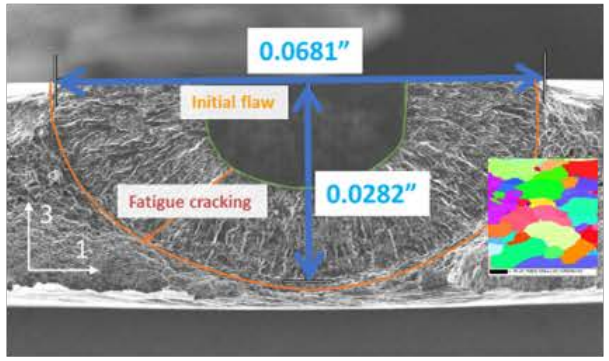
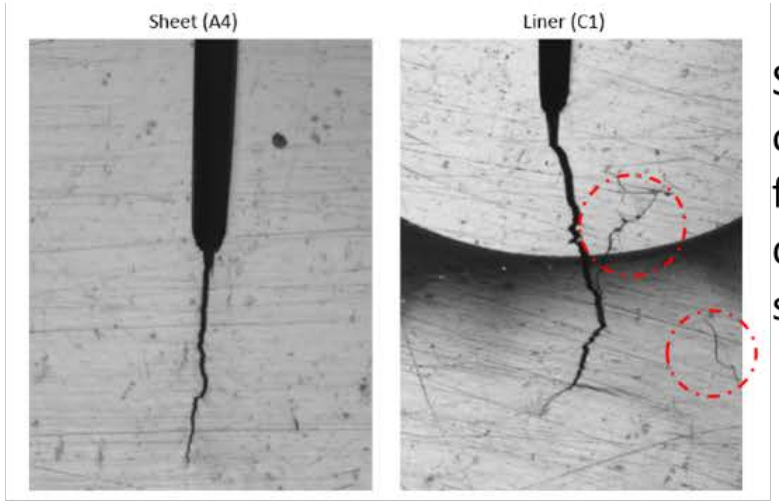


FIG. 3.02114 FULL RANGE TENSION STRESS-STRAIN CURVES FOR EXTRUSIONS (≤ 0.499 IN) IN T651 CONDITION. (51, p. 140)

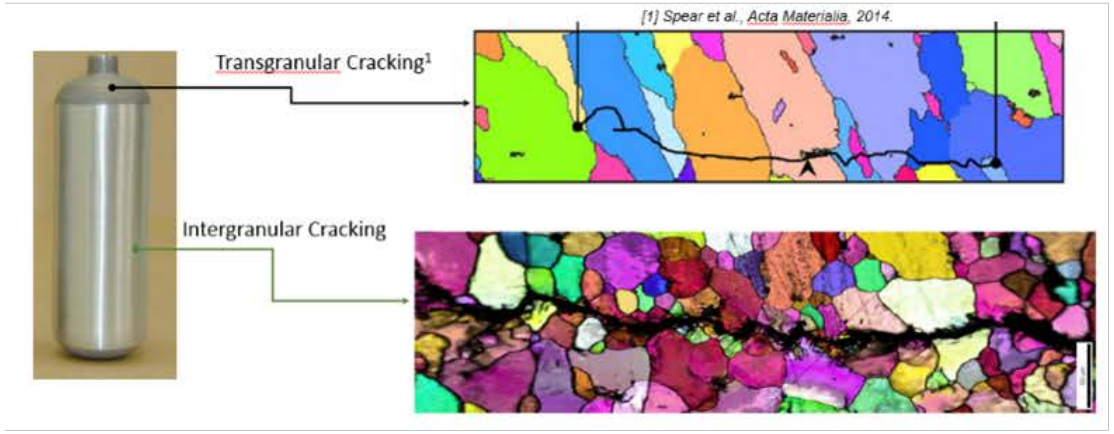
Small-Scale Testing: Fatigue Crack Growth Rates Comparison

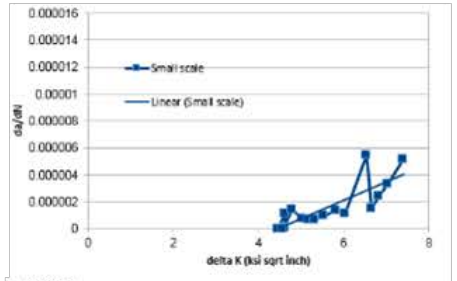


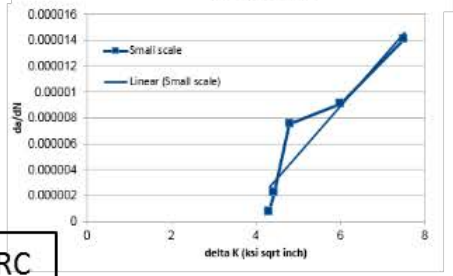
Flaws introduced using PFIB, able to characterize grains with EBSD.



Secondary cracking occurred in spun-formed material that does not form in sheet







FCGR was higher in small grain material due to intergranular nature of crack growth. This grain size/FCGR relationship is not expected and could potentially be effect of spun-formed product.

All data from J. Hochhalter, et al, LaRC

Summary

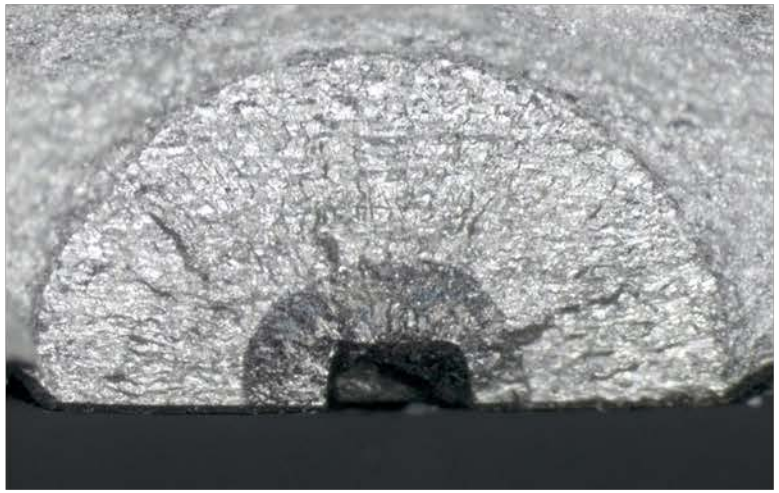
- Microstructure variations are too significant for testing on rolled sheet to be a viable certification method for spin-formed liners.
- Validation of LEFM requires more than plasticity/continuum limitations
- Microstructure variation may, for certain conditions, have a stronger influence than plasticity/continuum effects (and may influence EPFM parameters as well).
- The two liner examined had significant microstructure variation, which appears (with the limited amount of data generated to-date) to have a significant effect on crack growth rates.
- Neither (traditional) LEFM nor EPFM idles consider length scales that can capture the observed microstructural variation

Approach for LEFM Evaluation

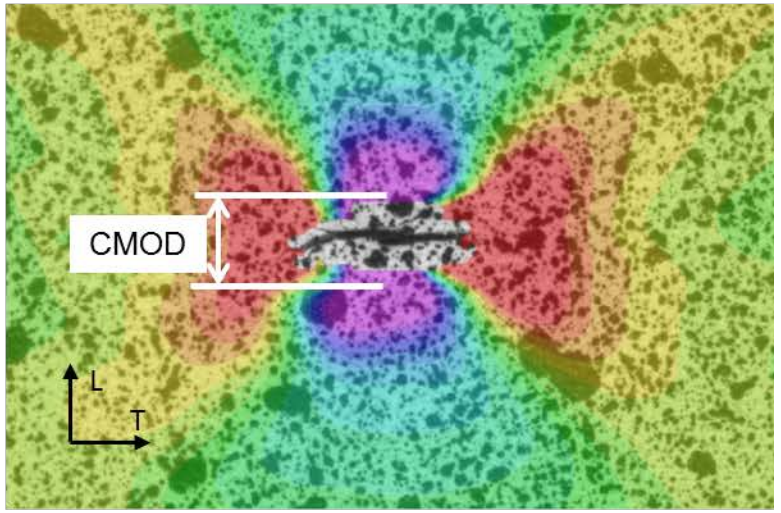
Fatigue Test



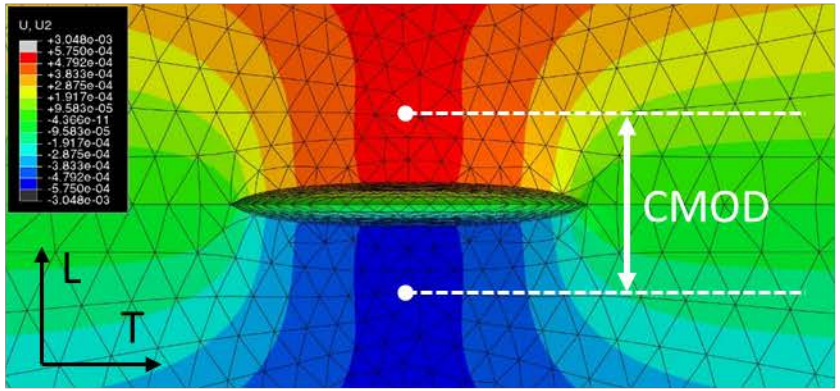
Post-Test Crack Size Measurements



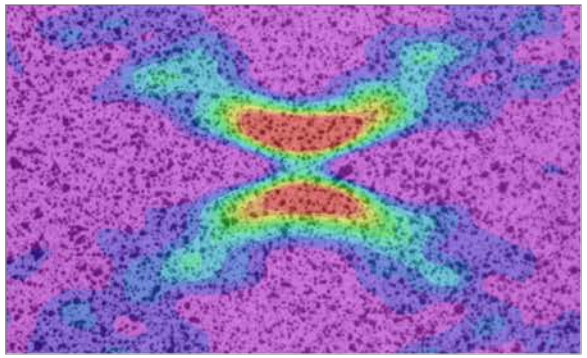
Crack Mouth Opening Displacement (CMOD) Measurements



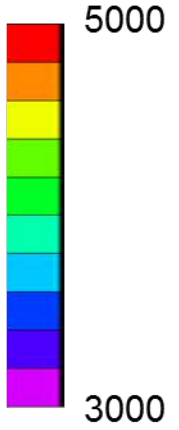
Elastic and Elastic-Plastic FEA



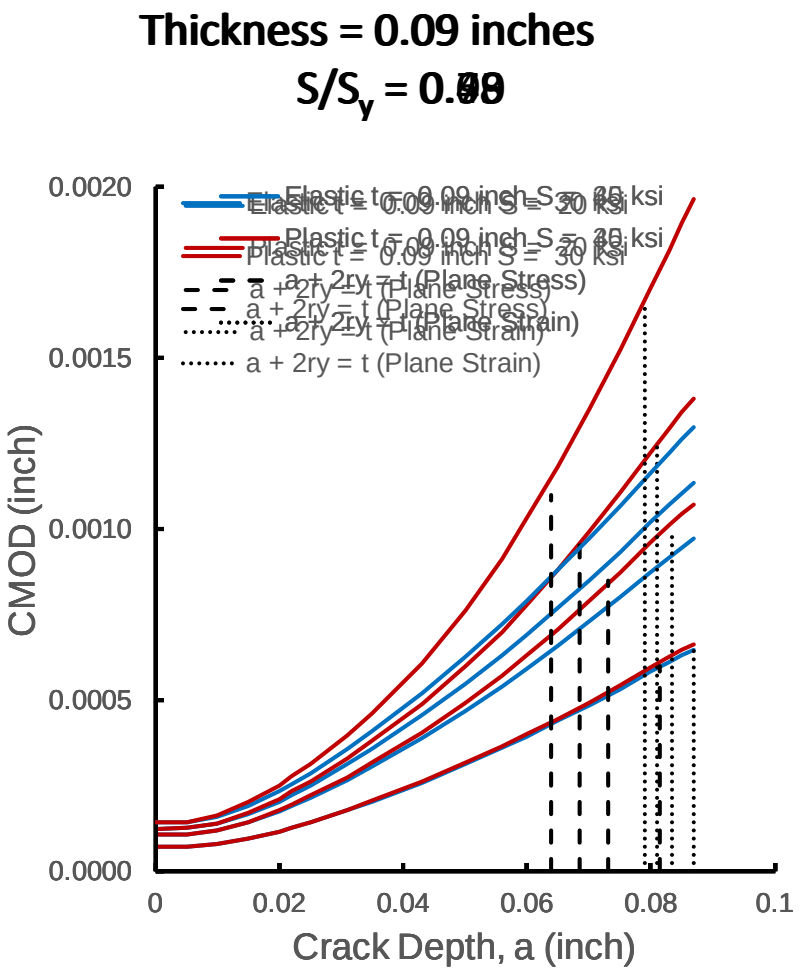
Back Face Strain Measurements



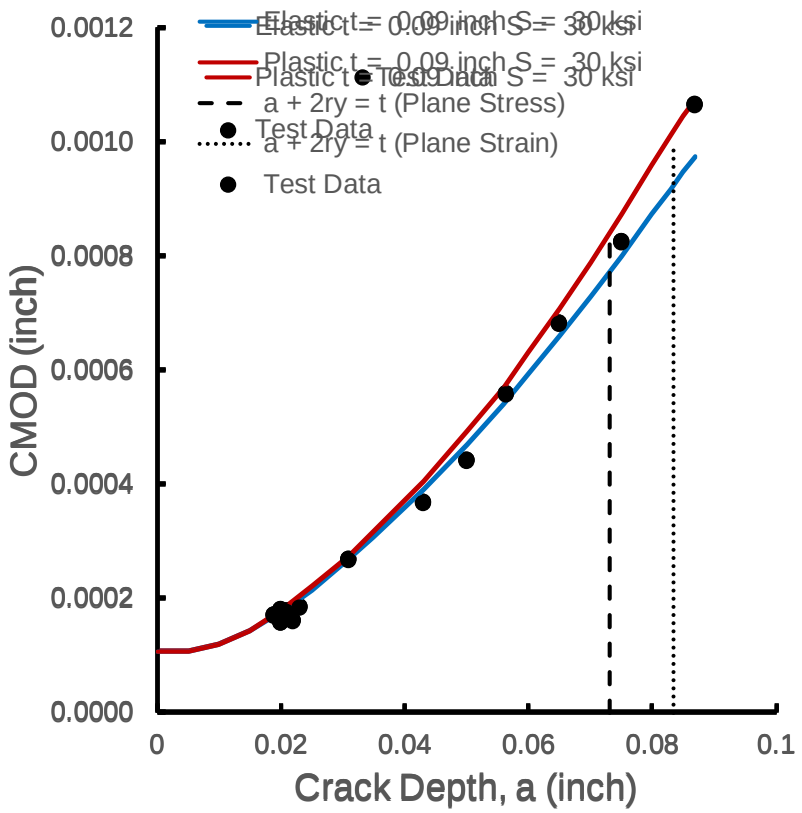
e_y (microstrain)



Finite Element Results

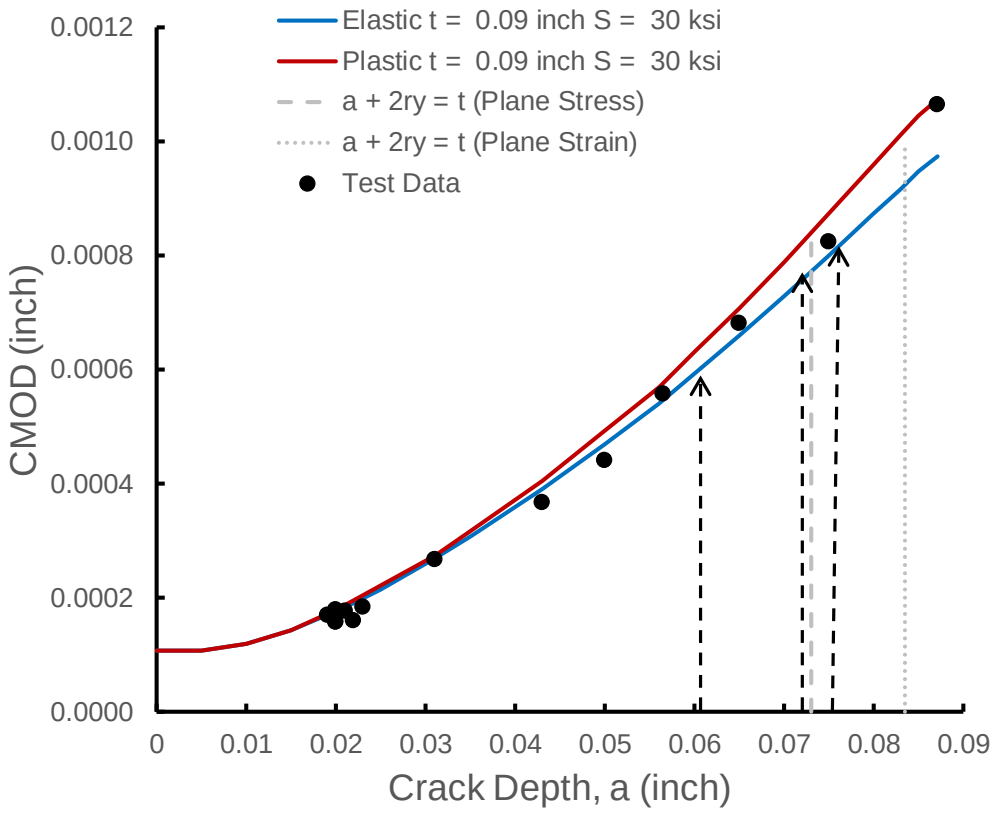


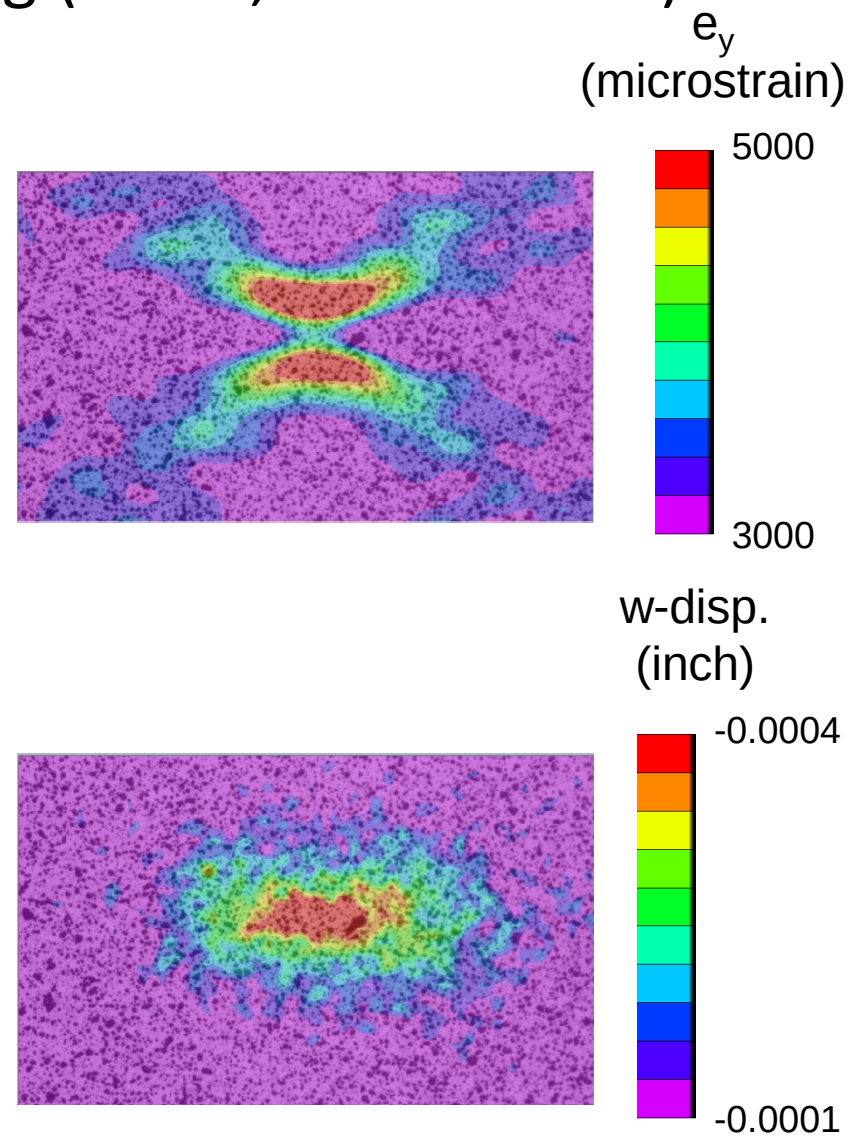
FEA and Measured ΔCMOD (30 ksi, t = 0.09 inch)



- The crack depth is known at the end of precracking (Sharpie stain) and the start of ductile fracture
- The measured ΔCMOD at the known crack depths was plotted as a function of the measured crack depth
- Elastic and elastic-plastic FEA results
- Plastic zone limits

Back Face Strain and Dimpling (30 ksi, t = 0.09 inch)

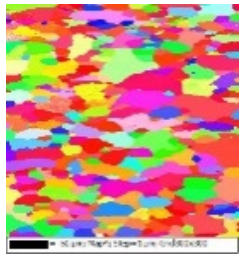




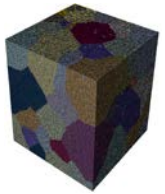
Where do we go next?

- Development of microstructurally informed computational models:
  - Microscale (crystal) plasticity
  - Microstructure-sensitive fatigue crack growth

Development of Microstructurally-Informed D&DT – Big Picture



Characterize Microstructure using Quantitative Measurements



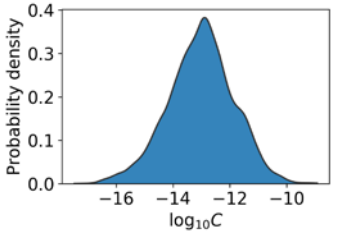
Localized FEA Models and Analyses Exploiting Fitted Measured Data



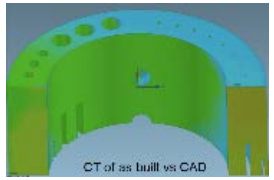
Microstructurally Small Crack Growth Model and Analysis to Understand Local Parameters



Fatigue Crack Growth Parameter Distributions



Global FEA Models and Analyses Subject to Service Environments



D&DT Analysis Tools (NASGRO, LEFM, EPFM, etc)



Today's D&DT Engineering Standard Practice

- Today's standard D&DT standard engineering practice relies on continuum assumptions
- Microstructurally-informed D&DT will consider local length scales, environments and material properties
  - Expanded effort on small-scale testing and physics-based material model calibration
  - Produce distributions of behavior by relying more heavily on modeling and simulation

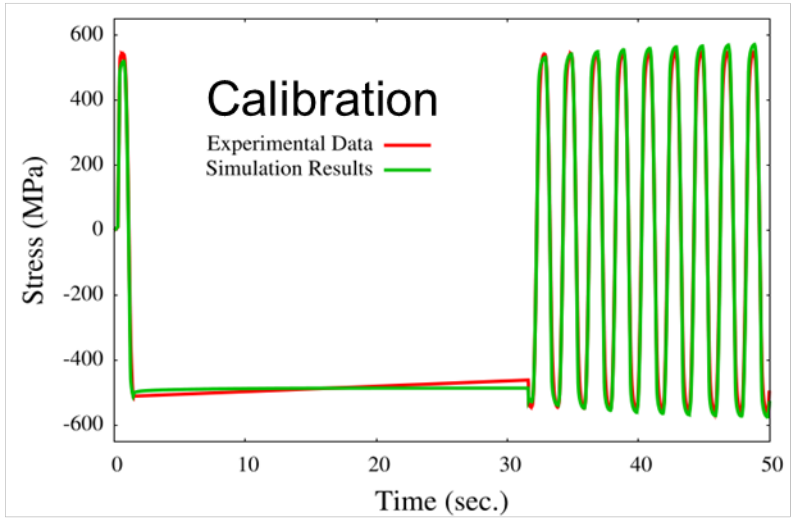
FEA Models with Crystal Plasticity

Plastic velocity gradient: $^{p}\hat{\mathbf{L}} = \sum_{\alpha=1}^{12} \dot{\gamma}^{\alpha}\, \mathbf{P}^{\alpha}$

Schmid tensor: $\mathbf{P}^{\alpha} = \mathbf{s}^{\alpha} \otimes \mathbf{m}^{\alpha}$

Slip rate: $\dot{\gamma}^{\alpha} = \dot{\gamma}_{o} \frac{\tau^{\alpha}}{g^{\alpha}} \left| \frac{\tau^{\alpha}}{g^{\alpha}} \right|^{\frac{1}{m}-1}$

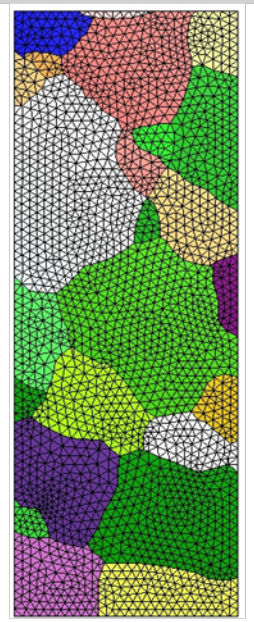
Hardening: $\dot{g}^{\alpha} = G_{o} \left(\frac{g_{o}-g^{\alpha}}{g_{s}-g_{o}} \right) \mathrm{H}^{\alpha\beta} \left| \dot{\gamma}^{\beta} \right|$



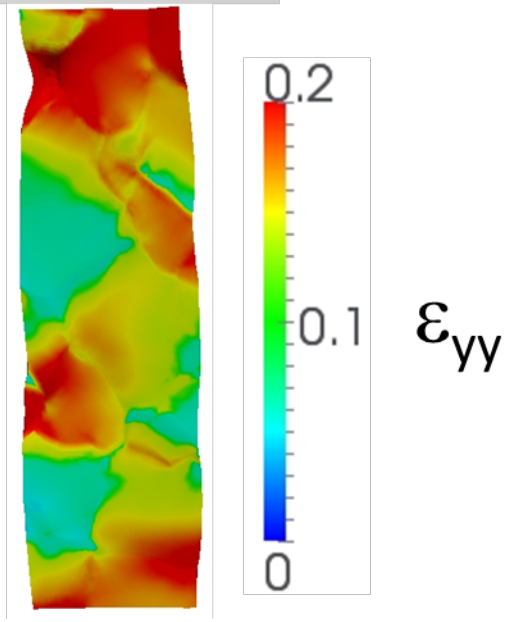
EBSD Orientation Map



Finite Element Model



Computed Strain



Microstructure-sensitive fatigue cracking

Crack growth model using
FIPs (fatigue indicator parameters)

Castellucio (2011), Hennessey (2015)

$$\left.\frac{da}{dN}\right|_{MSC/PSC} = \phi\left(\Delta CTD - \Delta CTD_{th}\right)$$

$$\Delta CTD = A\left(FIP^{\alpha}\right)^{b}$$





Crack initiation

$N_{incu+init} = N_{incu} + N_{init}$

$a_{incu+init} = a_{incu} + avg(GS)$

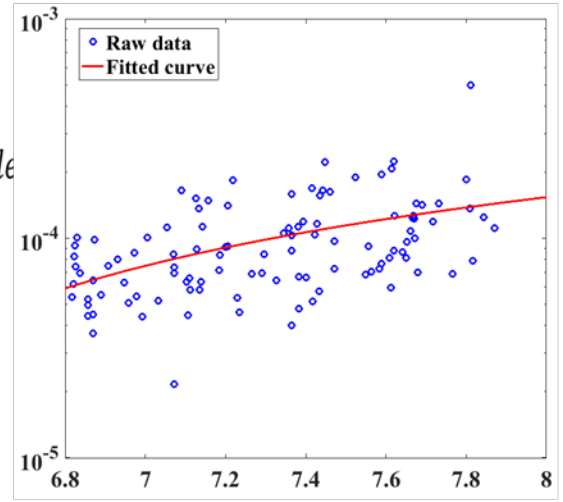
Crack growth (1st step)

$N_{total\ step1} = N_{incu} + N_{init} + N_{MSFC-min-step1}$

$a_{step-1} = a_{incu+init} + avg(GS_{new\ cracked\ grains})$

GS = Grain size

1. Create many (100s) of digital microstructures
2. Compute FIP values throughout each microstructure
3. Use Equations above to predict da/dN for each
4. Plot output of microstructure-sensitive variability (right)



APPENDIX J
RACHAEL ANDRULONIS (NIAR) AND JEFF CONNER (GE)
"SUMMARY AND CONCLUSIONS FROM THE JUNE 2018 EASA WORKSHOP ON AM MACHINE PRODUCERS KNOWLEDGE TRANSFER"

EUROPEAN AVIATION SAFETY AGENCY
AGENCE EUROPÉENNE DE LA SÉCURITÉ AÉRIENNE
EUROPÄISCHE AGENTUR FUR FLUGSICHERHEIT

Summary and Conclusions from the June 2018 EASA Workshop on AM Machine Producers Knowledge Transfer

June 28th & 29th, 2018
Cologne, Germany

Your safety is our mission.

Workshop Details

- Invited Attendees
  - → Group 1: Machine Manufacturers
  - → Group 2: Type Certificate Holders
  - → Group 3A: Operators/MROs/POA Holders/non-TCH DOAs
  - → Group 3B: Standardisation Bodies

- Key Question
  - → What knowledge does each group believe that it needs from the other groups (including the regulators) in order to function more efficiently and better meet its (safety) objectives? (metallic and non-metallic)

- Goal
  - → Identify common knowledge transfer priorities

Group Details

- **Group 1: Machine Manufacturers**
  - → Chair: Richard Grylls, SLM Solutions Group
  - → 13 participants from 8 machine manufacturers
- **Group 2: Type Certificate Holders**
  - → Chair: Jeff Conner, GE Aviation
  - → 10 participants from 5 companies
- **Group 3A: Operator / MRO / POA / non-TCH DOA**
  - → Chairs: Simon Muller, Lufthansa Technik
    Wayne Thomas, Air New Zealand
  - → 13 participants from 7 organizations
- **Group 3B - Standardisation Bodies**
  - → Chair: Rachael Andrulonis, NIAR
  - → 4 participants from 3 organizations

Pre-Meeting Homework

- Each group met PRIOR to the workshop
- Answered the following questions:
  1. Information/knowledge we need from other groups?
  2. Information/knowledge we think that other groups probably need from us?
  3. Ideas on how information and knowledge could be shared?
  4. Information on other activities/organizations that are involved or should be involved in this general area?
  5. Any other information/comments?
- Groups were encouraged to use recent related activities/information (workshops, conferences, etc.)

Opening Comments

Group 2 … Opening Comments

1 TCHs Must Know Established/Frozen Processes Remain Valid Over Time

- *COMMUNICATE* proposed AM Machine changes *PRIOR* to incorporation if the change:
  a) Is being rolled to existing machines, or
  b) Creates a difference in operating software or hardware between previously purchased machines and yet to delivered machines, or
  c) Will drive changes to recommended maintenance or calibration

- *VALIDATE* proposed changes with a “generic test plan” *PRIOR* to incorporating
  - Demonstrate no impact to mechanical properties, feature resolution, and/or anomaly generation with a “generic test plan”

Results by Group

After:

- *Closed group sessions*
- *Large group sessions*
- *Cross group sessions*

Results … Group 1

Relevant Topics ➔ How?

What	How	Question for Today
Change Management	P or D FMEA by machine manufacturers of the impact – how does the change affect the baseline performance. No industry standard is needed. This topic needs to be part of the overall certification training below.	Is an industry standard needed? How to move forward?
Machine capability and consistency test	Industry standard needed. Check if activity already exists, if not, start one	How to move forward?
Certification Training	Awareness overview from TCH and regulators. Including understanding of how our systems and sub-systems (e.g. powder handling methods) affect airworthiness.	How to move forward?
Machine / Process Training	Pre-competitive – LTTS training programs	Who to deliver? POA? Independent 3rd parties? How to move forward?
Key Processes and Machine Parameter definition	AMS7003 list already exists. ISO52944 in progress – to be accepted or not in Singapore in September	Who will assess if current activities meet intent?
Quality Reports	Commercial/competitive activity?	Is an industry standard needed?

Results ... Group 1

Relevant Topics ➔ Prioritization

What	Impact	Difficulty	Priority
Change Management	H	M/H	H
Machine capability and consistency test	H	M	H
Certification Training	H	L	H
Machine / Process Training	M	L	H
Key Processes and Machine Parameter definition	M	L	L
Quality Reports	H	L	M

Results ... Group 2

1 Certification Training ... “the basics” including roles & responsibilities, requirements flow down, traceability, etc.

Owner: EASA

- High level overview of regulatory structure
- Expectations by stakeholder including roles & responsibilities
  - → Machine Producer
  - → Type Certificate Holder
  - → POA Holder
  - → Operator/MRO
  - → Non-TCH DOA Holder

Results ... Group 2

2 Configuration Control ... production processes including AM and classical machines

Owner: TC Holders

- Machine Level Configuration Control (Group 1)
  - → Responsibilities:
    - communicate to TC Holder PRIOR to introducing changes
    - assess proposed change(s) against established baseline
    - address end user identified machine issues
- Process Level Configuration Control (Group 3A)
  - → Responsibilities:
    - communicate to TC Holder PRIOR to introducing changes
    - demonstrate that proposed change(s) ensure required results

Results ... Group 2

3 Performance Standards ... baseline machine capabilities, calibration and maintenance recommendations

Owner: Group 1 & Group 3B

- Leverage existing standards
- Establish “aviation” baseline

Results ... Group 3

Overall Issues

- What are the responsibilities for each group?
- Change management
- Statistical process control - How to adapt/ develop for AM
- Participation in standard development organizations
- Continued collaboration for all – private group (LinkedIn)

Results ... Group 3

Responsibility ➔ Machine Manufacturers

- Baseline data to enable qualification for machines and processes
  - → Catalog of material characteristics/anomalies and how to detect
  - → KPI for process stability
  - → Calibration/maintenance of machine required to remain valid to aerospace standards
  - → Training (applies to all of the above)
- Change management

Results ... Group 3

Responsibility ➔ Type Certificate Holders

- How to find information on how to become AM supplier
  - → Linked to baseline test program? Show production process compliance
- Change Management
- Product Lifecycle Management & Documentation
  - → Replace or repair?

Results ... Group 3

Responsibility ➔ Regulators

- Training/Guidance
  - → AM is a Special Process
    - How to develop and capture KPIs, etc.
    - How do smaller DOAs gain access to an appropriate special process
- Fundamentals of Certification
  - → What and why
  - → Can define own part categories
  - → Who is responsible for what
- How to develop statistical process control
  - → What is acceptable to regulators
  - → How to adapt/develop for AM

Consensus/Final Takeaways

High priority items for all groups:

- Change Management (1,3)
- Certification Training/Responsibilities of Each Group (1,2,3)
- Machine Capability/Baseline Data, Consistency Check (1,2,3)
- Machine and Process Training (1,3)
- Configuration Control (2)
- Performance Standards (2)

Future Plans

- Overall format was successful – *some group members had never had discussions before*
- All groups need to informed of roles and responsibilities
  - Basic information is not well understood – perhaps training/tutorial will be beneficial
- Baseline data for machine reference is needed
- Key characteristics/parameters need to be defined by process
- Regulatory guidance should be proportional to application criticality

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QUESTIONS?

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Snapshot of Pre-Meeting Input

Group 1 - Machine Producers

Category - pick a category from the menu!	Subcategory	Input - write your comments here!
1. Information/knowledge we need from other groups	Facility qualification	How to "quantify" any change to an AM based facility in terms of, if it affects the airworthiness of its products etc.?
1. Information/knowledge we need from other groups	Machine operation / features	Nature/Amount of 'layer level' process monitoring & reliability that would ensure confidence on the end part
1. Information/knowledge we need from other groups	Machine qualification	what levels of flexibility could be afforded software 'versions'/'updates' on AM system for a certified process?
1. Information/knowledge we need from other groups	Organizational	Changes in the DO organizational struc that would be needed (according to EASA) in terms of DCS/DER etc. required to "include" AM in certifications/type certifications - existing DCS for e.g. for metallic matreials & process will be further AM 'educated'? And how can Group1 support this
1. Information/knowledge we need from other groups	Part family qualification	EASA's approach to categorize (AM driven) changes at a part level in terms of Minor or major modification?
1. Information/knowledge we need from other groups	Quality assurance	Amount of manufacturing process tracability & documentation required for parts on in-service aircrafts / what could be 'adequate' configuration control of AM manufactured parts?
1. Information/knowledge we need from other groups	Quality assurance	what kind of Quality escape procedures/strategy is required from the Authority side?
1. Information/knowledge we need from other groups	Roadmap of component qualification	what is EASA's strategy/first ideas to establish "acceptable" quantitive levels of inspection, in an AM based serial production set up, which should lead to confidence on part quality

Group 2 - TCH

Category - pick a category from the menu!	Input - write your comments here!
1. Information/knowledge we need from other groups	MACHINE PRODUCERS Foundational Principle #1 … TCHs must know that established/frozen processes remain valid over time (TCHs own the final responsibility for machine, manufacturing process, and product performance!) Software Changes … 1) Proposed changes to operating software must be communicated to machine owners prior to incorporation if the change (a) is being rolled to existing machines, (b) will create a difference in operating software between previously purchased machines and yet to be delivered machines, or (c) will drive changes to recommended calibration and maintenance. 2) Machine producers should develop a “generic test plan” that demonstrates that changes to machine software do not change resultant mechanical properties, feature resolution and/or anomaly generation as compared to test results from samples produced with the same baseline parameters prior to the software change. Hardware Changes 3) Proposed changes to machine hardware must be communicated to machine owners prior to incorporation if the change (a) will create a difference in hardware configuration between previously purchased machines and yet to be delivered machines, or (b) will drive changes to recommended calibration and maintenance. 4) Machine producers should develop a “generic test plan” that demonstrates that changes to machine hardware do not change resultant mechanical properties, feature resolution and/or anomaly generation as compared to test results from samples produced with the same baseline parameters prior to the hardware change.
1. Information/knowledge we need from other groups	MACHINE PRODUCERS Mechanical Property Understanding … Machine producers need a better understanding of the relationship of key process parameters and material properties for aerospace materials to ensure that ongoing development of machine technology supports continued growth in use of aerospace materials 1) Machine producers should execute basic parametric studies with aerospace materials to develop a better understanding of key process to property correlations … e.g. gas flow rates and coverage, laser parameters, powder re-use and degradation concerns 2) Machine producers should undertake “variability studies” that highlight machine to machine variation for the machines they produce and implement process improvement efforts to reduce variation … goal should be to ensure that frozen parameters established to fabricate a specific part can be used on all “identical” machines from the same machine producer

Snapshot of Pre-Meeting Input

Group 3a - MRO/Operator/POA/non-TCH DOA	
Information/knowledge we need from other groups	**For Which Party**
Is it a mandatory to generate the material design values?	Regulators
For material design values, will it be AM technology specific or machine specific? - For example, company 123 has just generated the material design values using machine A with material X. Now company 123 want to setup another machine B (same model as machine A) in a separate site. Company 123 just use the same process control for machine B with same material X. - Can company 123 just use the design values generated using machine A for parts fabricated using machine B? - Or machine B will need to go through the full cycle of generating its own material design values?	Group 1 & Regulators
Any additional requirements if replacing existing parts with additive manufactured parts?	Regulators
What is the development on in-situ process monitoring?	Group 1
How can in-situ process monitoring system help in part certification?	Group 1
Can the machine manufacturers develop the Process Control Document (PCD) so operators can just adapt to it?	
Can the machine manufacturers list down the recommended finishing techniques for the finished parts?	Group 1
What is the development on generating material design values? (B-basis?)	Group 1
Are there any additional requirements from the TCHs if we replace existing parts with additive manufactured parts?	Group 2
Is the standardisation body developing any new standard testing for polymer and metallic AM parts? (e.g. tensile strength)	Group 3b
Can standardisation body define the standard tests and quantity of the coupons required to generate a basic material design values for AM parts? (B-basis?)	Group 3b

Group 3b - Standardization Body	
Category - pick a category from the menu!	**Input - write your comments here!**
1. Information/knowledge we need from other groups	How do we get on an agree for mimimum set of process control parameters across one AM modality? This has implications on the standards that can specifically be designed around a modality such as PBF or DED, etc.
1. Information/knowledge we need from other groups	Information on training requirements: what are the knowledge, skills and experience expectations for additive manufactuing operators, planners, owners
1. Information/knowledge we need from other groups	Is a practical element to assessment required/desirable?
1. Information/knowledge we need from other groups	To what degree should qualifications be 'required' - as a minimum to perform the process such as with Welding operators and NDT inspectors or as a desired?
1. Information/knowledge we need from other groups	Useful to understand the specific manufacturing consequences of poorly trained and unqualified personnel performing this process.
1. Information/knowledge we need from other groups	Machine Producers: in addition to providing definition to key elements, need to have a min level of training - how can this be achieved?
1. Information/knowledge we need from other groups	Once equivalency requirements are set up, machine producers need to be involved with setting up qualification requirements
2. Information/knowledge we think that other groups probably need from us	Information on how a concensus based standardization process is applicaple to different types of deliverables (e.g. method, guide, spec, report, etc.) regardless of a industry type.
2. Information/knowledge we think that other groups probably need from us	Understanding of how eQualified and other qualification systems have been implemented in other manufacturing areas such as Composite Repair, Heat Treating, Welding etc.
2. Information/knowledge we think that other groups probably need from us	Proposed process flow to show how a qualification system could be rolled out across the industry
2. Information/knowledge we think that other groups probably need from us	Information on how an equivalency approach would work
2. Information/knowledge we think that other groups probably need from us	Information on how the different standardization groups work together (or don't work together) and how each of the SDOs may be applicable to different types of technology/applications

Results … Group 1

Relevant Topics ➔ Starting Point

What	Group 1 Comments	Group 2 Concerns
Change Management	How to manage any hardware and software changes that are made to the machine / process?	Configuration Management of the machine and its impact on the TCH change management process
Machine capability and consistency test	Repeatable coupon level baseline test	Matches baseline standard for machine qualification and acceptance tests
Certification Training		Training on regulatory processes to machine providers
Machine / Process Training	Two parts – precompetitive and competitive	
Key Processes and Machine Parameter definition	Standard list with guide as to why each is important	Sub-topic of machine capability and consistency test
Quality Reports	Standard customizable ways to issue a report that a particular build is okay	Sub-topic of process monitor and key process and machine parameter definition

APPENDIX K
SIMON WAITE, EASA
"EASA REGULATORY UPDATE ON AM"

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Additive Manufacturing (AM)

FAA/EASA Workshop

August 2018

Wichita

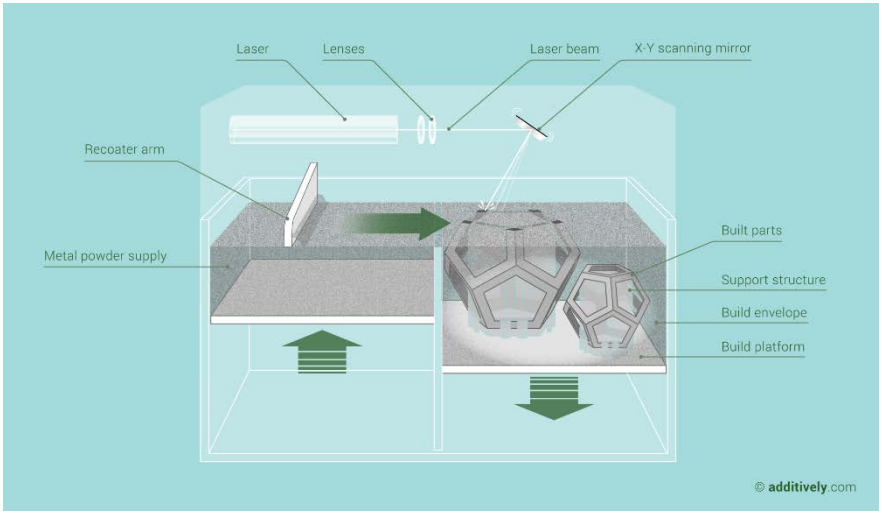
Dr. S.Waite
Senior Expert - Materials
Certification Directorate

Your safety is our mission.

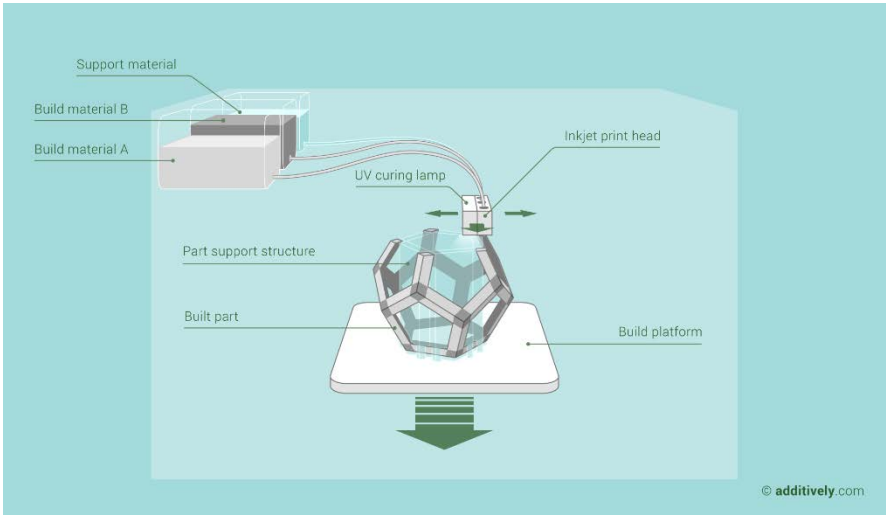
Additive Manufacturing – many methods, and definitions:

'... make objects...layer upon layer...'

Laser-melting



Photopolymer-jetting



- metallic/non-metallic
- single material, multi-material, + fillers,
- hybrid processes, e.g. icw convention methods

Illustrations courtesy of additively
your access to 3D printing

- significant potential commercial benefits, e.g. rapid prototype evolution, reduced part count, weight reduction etc

EASA - AM

AM – EASA Perspective (see support slides and EASA Workshop presentations and CM*)

- rapidly increasing number of materials, processes, and applications, i.e. baseline applications and repair
- potential safety considerations
  - 'engineering properties', e.g. anisotropic, new and competing damage modes
  - repeatability - many variables (materials, processes, products), etc
  - changes in relationship between design, production, continued airworthiness (CAW), more integrated than many typical metallic processes (some similarities wrt composites)
    - increasing process driven quality (relative to inspection)
    - pressure for utilisation in increasingly critical applications
    - **industry and regulator knowledge base and training**
    - are changes required in rules and/or guidance?

*EASA Workshop 2016: http://www.easa.europa.eu/system/files/dfu/WORKSHOP%20Additive%20Manufacturing%20-%20Presentations.zip
EASA Safety Conference 2016: https://www.easa.europa.eu/event-type/annual-safety-conference
EASA Workshop 2017: http://www.easa.europa.eu/newsroom-and-events/events/2017-easa-workshop-additive-manufacturing
EASA Certification Memo: https://www.easa.europa.eu/sites/default/files/dfu/EASA%20CM-S-008%20Additive%20Manufacturing.pdf
EASA Knowledge Transfer Workshop 2018: https://www.easa.europa.eu/newsroom-and-events/events/additive-manufacturing-workshop-machine-knowledge-and-training

EASA - AM

➢ EC No 216/2008 annex 1.a.**Structures and materials**: the **integrity of the structure must be ensured throughout, and sufficiently beyond, the operational envelope for the aircraft, including its propulsion system**, and maintained for the operational life of the aircraft.
1.c.3. Systems and equipment…

egulatory Framework (moving towards **performance based regulations**)

Basic Regulation

(EC) No 216/2008

EU Parliament
EU Council

.Binding

➢**21A.31 Type design …** shall consist of:
➢2. Information on **materials and processes** and on **methods of manufacture and assembly** of the product necessary to ensure the conformity of the product

ing rules

Regulation No 1702/2003

For the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations.

EU Commission

GM 21.A.147(a) Changes to the approved production organisation – Significant changes
1 …to be approved by the competent authority include:
- significant changes to production capacity or methods…

Acceptable Means of Compliance (AMC) and Guidance Material (GM) for

PART 21

Certification Specifications

Airworthiness Codes, e.g. CS 23, 25, 27, 29 et

PART 145 – Maintenance organisation approvals

PART 66 – Certifying staff

Part 147 – Training organisations requirements

EASA

.Non-Binding

➢ **Certification Specifications: Limited 'Material and Process', e.g.**
CS 25.603: Materials… 'suitability and durability … based upon experience/test… conform to specifications… consider environment
CS 25.613: Mechanical Strength Properties and Design Values
Materials. (a) … design values based upon a statistical basis

AM relative to The Regulations – EASA priorities and resources:

- **priority is safety**… 'do not reduce the existing level of safety'
- **prioritise activities with respect to novelty and criticality**

e.g. AM within scope of LOI (NPA 2015-03)

21.B.100 Level of Involvement

….(b) The Agency shall establish its **level of involvement** at the level of compliance demonstration items, or groups thereof, following a **safety and environmental risk assessment, taking into account** but not limited to:

1. the **novel or unusual features** of the certification project, including operational, organisational and knowledge management aspects;

2. the **criticality of the design or technology** and the related safety and environmental risks, including those identified on similar designs; 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.**

(b) Each **new aircraft fabrication method must be substantiated by a test programme**

CS 25.613: Mechanical Strength Properties and Design Values Materials

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

EASA Composite Materials Safety

baseline structures **and repairs**

Example: Key Specification applicable to baseline structure **and repairs**….

CS25.571*: Damage-tolerance & fatigue evaluation*

Note: Recent Amendments CS25 amdt.19

*'(a) General. An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, **manufacturing defects**, **environmental deterioration**, or accidental damage will avoided throughout the operational life of the aeroplane…'*

'(3)…..inspections or other procedures must be established as necessary to prevent catastrophic failure, and must be included in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness required by CS 25.1529'

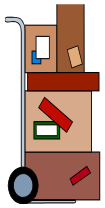
Does not need to be visual,
…or an inspection
Note: 80-90% of inspections are visual
ref. also CS25.611

need to find, define, and bound damage…

EASA - AM

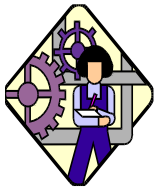
Material properties built into part, or repair…

Manufacturing Processes



Material Purchased

+



Internal Manufacturing Processes Controlled by site specific Process Documents

=



Production Certification (PC)

+ **Material & Processing Standards**

Material Specification

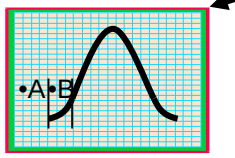


Process Specification



- close link between DOA, POA, and suppliers, mostly via specifications

Engineering Processes



Prediction of Material Behavior

(Design Values)

+



Prediction of Structural Behavior

(Design Analysis)

+



Verification & Certification Tests

=



Note: slide from a CMH-17 composite tutorial – similar for AM

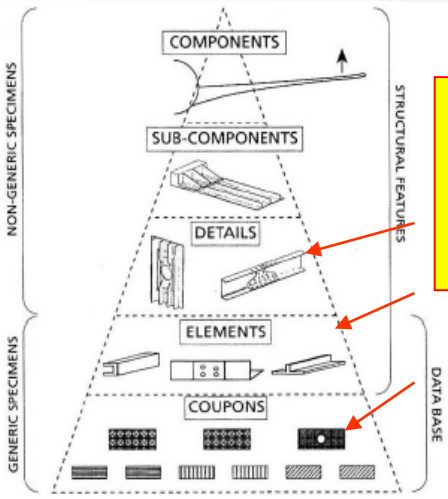
EASA - AM

AM 'Engineering Properties' are:

- defined by the 'material and process'
- built directly into the part or repair

a challenge:

- 'complex parts' – base pyramid coupon data may not represent the complex part properties (although stable simple base pyramid data is essential…otherwise, how can the higher pyramid work be trusted?)
- 'sensitive processes' – a major challenge if completing production activities in a more challenging maintenance environment



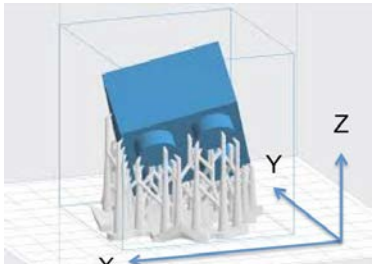
representative 'engineering properties' developed here?

Figure 1 - Schematic diagram of building block tests for a fixed wing.

e.g. AM, composites, bonded joints



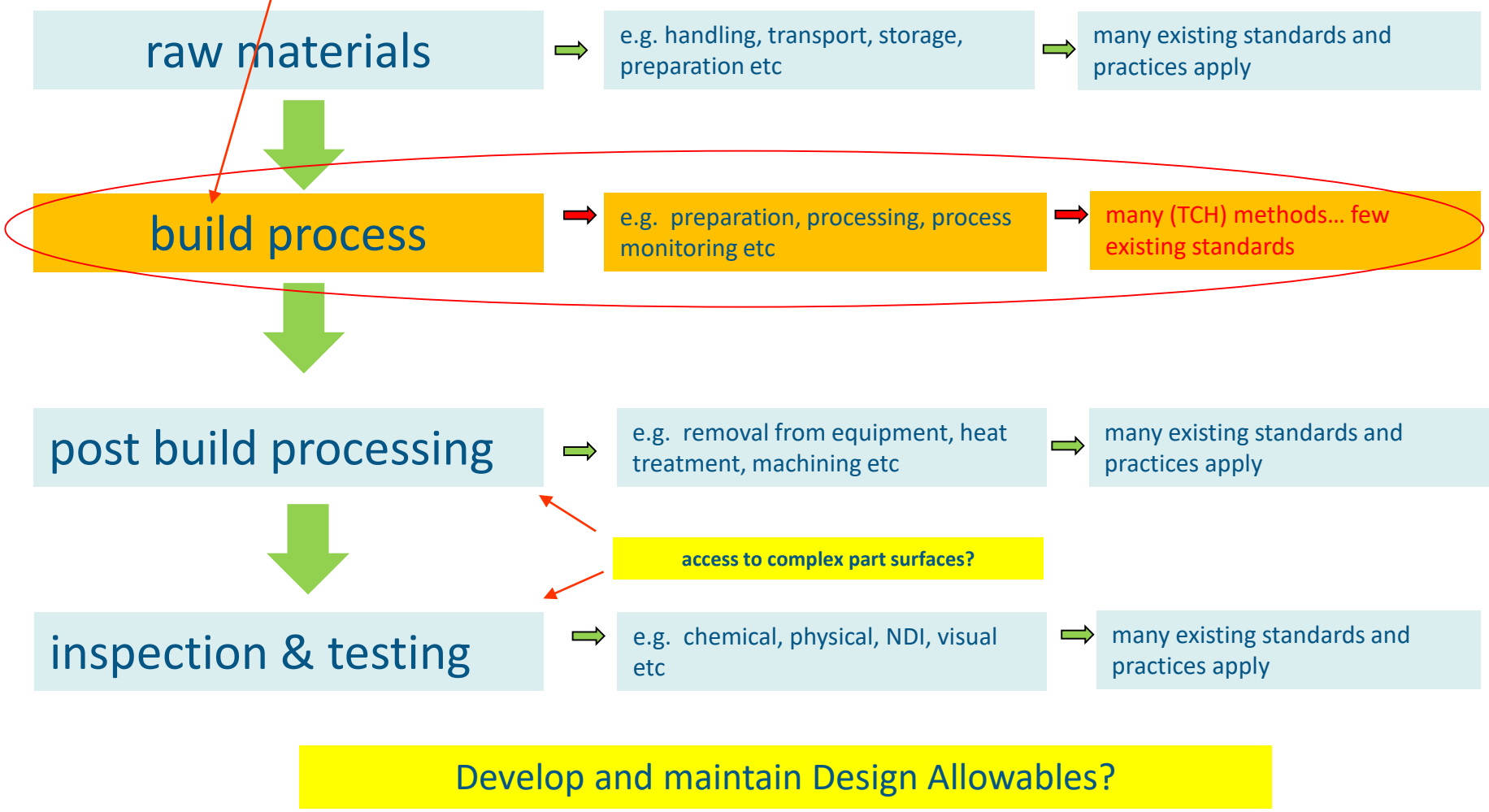
e.g. no access to free edges – fatigue issue?



e.g. support structure on the build platform

…. limited to specific machine serial number
… avoid using different materials in the same machine until variability/equivalence is better understood

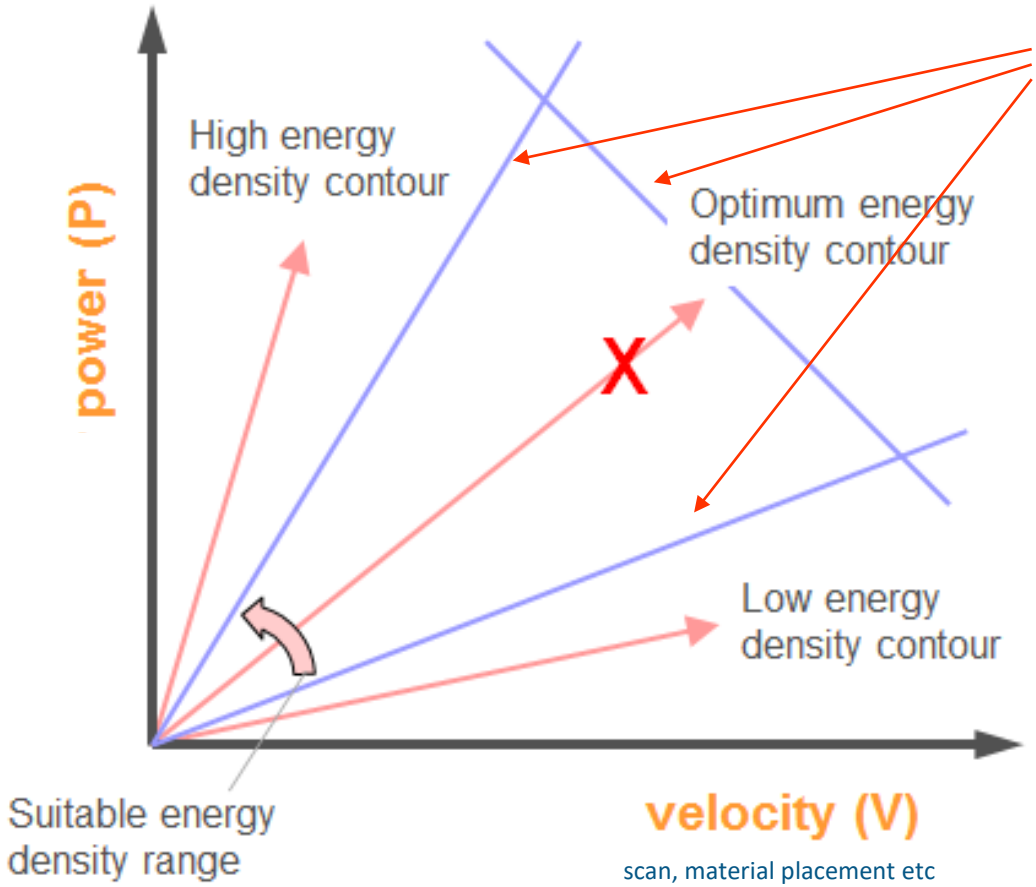
Additive Manufacturing: What is new to manufacturing regarding AM?



Develop and maintain Design Allowables?

- Many materials and processes…

What needs to be understood? P-V diagrams etc:



Metallic/non-metallic and many processes generalisations:

Boundary definitions:
- Key parameter definition?
- Competing defect/damage modes?
- Statistical credentials (A, B-Basis etc)?
- Sensitivity (% change in 'engineering properties' wrt boundaries and key parameters?)

- 100+ control parameters
20, 30, 40….'key parameters'?

What is a ‘key parameter/characteristic’*?

- large ‘engineering property’ change relative to a parameter range (relative to machine operation tolerances/capabilities?)?

- defect/damage mode change relative to a parameter range (relative to machine operation tolerances/capabilities?)?

Many materials and processes…
How do we regulate this…

e.g. does a static part remain a static part if produced using AM?

* ‘key characteristic’ used in SAE

What is a ‘key parameter/characteristic’? – in a real engineering world

- marginal property data management - acceptance v criticality? (‘statistical equivalence’ v ‘engineering judgement’?)

‘Statistics’ are intended to help engineers make decisions…

- are the marginal property values associated with design drivers and/or low margins and/or competing damage modes?

EASA - AM

Writing guidance for the many materials and processes will be a **resource challenge**…

Guidance documents…

Example AM challenge - Guidance (what is the appropriate level of detail)?

- FAA *Memorandum AIR100-16-130-GM18 'Engineering Considerations for Powder Bed Fusion (PBF) Additively Manufactured Parts'

*…addresses one method, PBF, which refers to (but does not address in detail) '100 control parameters… '**

many variables – materials, process, configurations…
Who is going to do this for each material and process…? What level of detail?

- *need to standardise strategy to identify **key parameters and manage sensitivity**?*
- *failure modes wrt hazard analysis?*
- *other mitigating factors?… e.g. batch mixing in multi-load path structure etc*



* one of a number of useful developing FAA AM documents

EASA - AM

Recent Regulator AM activities:

- Further to industry feedback from previous FAA and EASA annual AM Workshops:
  - FAA and EASA requested to work more closely
  - many large global AM meetings challenging resourses
    (many common organisations)

Regulator Response:

- alternate hosting annual joint large FAA/EASA AM Workshops

- develop more smaller detailed/themed discussions and ‘working’ Workshops with industry (partly to help progress and to provide supporting content at the large Workshops)

EASA - AM

Recent Regulator AM activities:

- Further to industry feedback from previous FAA and EASA annual AM Workshops:

Regulator Response:

- First smaller complimentary 'working' Workshop hosted by EASA June 2018 - Machine Knowledge Transfer, and Training
- 2018 Regulator AM Workshop to be hosted by FAA August 2018
- 2019 Regulator AM Workshop to be hosted by EASA
- other smaller complimentary 'working' Workshops to be defined…

EASA AM Strategy - current activities: Certification Memo (CM)

EASA CM–S-008 Issue 01: Additive Manufacturing:

- simple message to industry… share intent early with EASA in order to support integration within existing regulatory framework
- Shared responsibilities within EASA via subject contacts, identified in CM
- **c**o-ordinated through internal EASA AM WG meetings etc

- Cert. Directorate (Chief Expert - Airframe)	R. Minter – richard.minter@easa.Europa.eu
- Structures	S. Waite (AM WG chair) – simon.waite@easa.europ.eu
	W. Hoffmann - wolfgang.hoffmann@easa.europa.eu
- Propulsion	M. Mercy - matthew.mercy@easa.europa.eu
	O. Kastanis - omiros.kastanis@easa.europa.eu
- Systems	**M. Weiler - michael.weiler@easa.europa.eu**
- Cabin Safety	T. Ohnimus - thomas.ohnimus@easa.europa.eu
- DOA	A. Enache - alexandru.enache@easa.europa.eu
	O. Tribout - olivier.tribout@easa.europa.eu
- POA	D. Lamothe - dominique.lamothe@easa.europa.eu
	S. Pernet - samuel.pernet@easa.europa.eu
- Maintenance	R. Tajas - rosa.tajes@easa.europa.eu
- ETSO	TBD

* changes in progress since CM published – new subject contacts ‘red text’

AM relative to The Regulations – EASA priorities and resources:

EASA Risk Matrix (RM) elements:

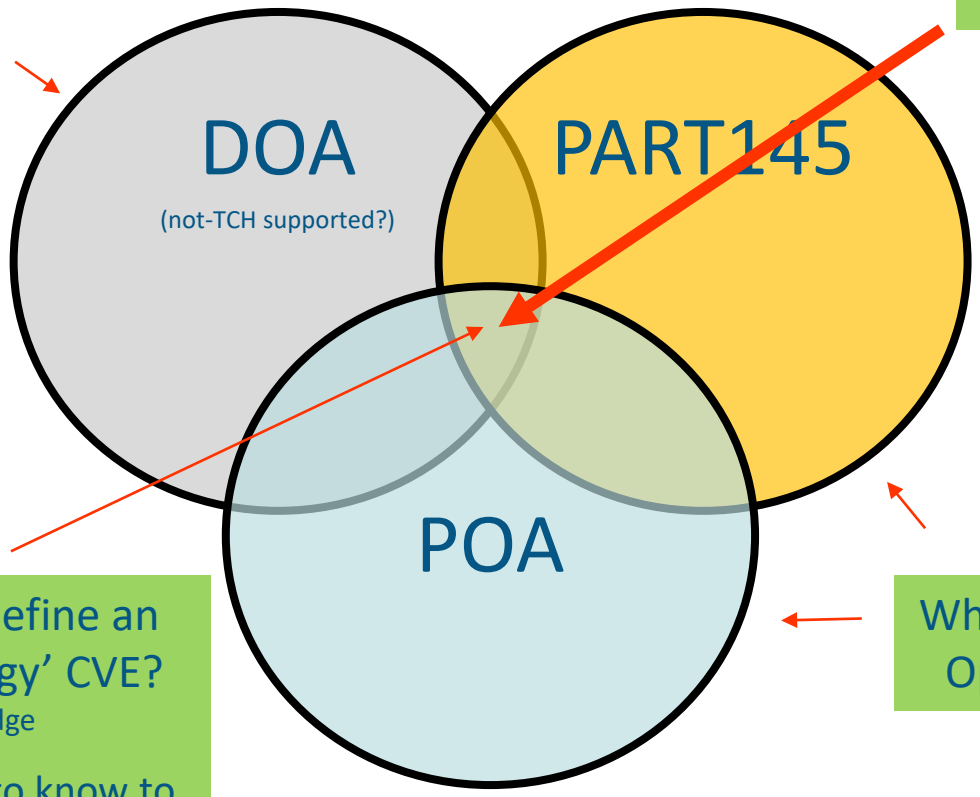
- Scope, definition, and associated AM terminology not standardised
- Current RULES ineffective (Low risk… existing rules are high level and generic)
- Current GUIDANCE ineffective (Low risk… however some additional supporting guidance is expected to be necessary)
- Design Certification - Engineering Properties
- DOA related
- POA related
- Repairs and Maintenance
- DOA/POA/Maintenance and Cert interfaces
- EASA DESIGN CERT interface with EASA DOA, POA, Maintenance
  - DOA - POA interface
  - DOA - Maintenance interface
  - POA - Maintenance interface
  - EASA - Industry interface
- Bogus Parts/Non-Compliant parts

Common RM elements:
- *Knowledge transfer*
- *Training*
- *Workforce awareness*

Knowledge Transfer – What needs to be transferred to whom in order to support defining appropriate training?:

What does an AM Design Engineer need to understand about the machine and its operation wrt design allowables/values?

- The AM Machine…



Large TCH needs and organisation process different to MRO!

Does EASA need to define an 'Integrated Technology' CVE?
…Materials, POA, DOA knowledge

What does EASA need to know to fairly regulate the industry?

What does an AM Machine Operator need to know?

EASA - AM

Existing regulation does not help at any useful detailed level… example composites

Note: Existing Part 66 'Certifying Staff' … very limited wrt Composites:

PART 66 'Certifying Staff': 66.A.45 Type/task training and ratings

no further information!

'6.3 Aircraft Materials — Composite and Non-Metallic
6.3.1 Composite and non-metallic other than wood and fabric'

Issue recognised:

- EASA intent to add some/all of SAE AIR 5719 'Teaching Points for an Awareness Class on Critical Issues in Composite Maintenance and Repair'' to PART 66

- supported by various 'airworthiness' training activities (on-line and hands-on)

Is an AM equivalent to AIR 5719 appropriate?

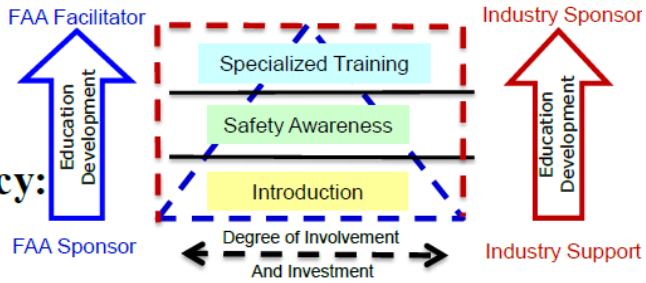
Knowledge Transfer – What needs to be transferred to whom in order to support appropriate training?:

Is this an appropriate support model for AM? If not, why not?

Composite Educational Initiatives

FAA AVS Composite Training

- **FAA composite training strategy established** [Sept., 2009]
  - Courses to support airframe structural engineering, manufacturing, and maintenance functional disciplines



Incl. three levels of competency:

I) Introduction (common to all functional disciplines)
Self-study intro content for composite basics/terminology
CMH-17 Tutorial for composite certification & compliance [Aug, 2008]

II) Safety Awareness (courses for each functional discipline)
Skills needed for FAA workforce supporting composite applications (including industry focal involved in safety and certification oversight)

III) Specific Skills Building (most courses developed by the industry)
Specialized skills needed in the industry & some FAA experts
Currently dominated by industry on-the-job training/mentoring

e.g. Level II:
Composite Engineering (CSET)
Composite Manufacturing (CMfgT)
Composite Maintenance (CMT)

EASA AM Workshop 28-29/6/18 - Machine Knowledge Transfer, and Training

- Invited attendees (50) - 3 groups (based upon different knowledge/different needs):
- Group 1: Machine Manufacturers
- Group 2: TCHs
- Group 3: Operator/MRO/POA/non-TCH DOA & Standardisation bodies
- closed group discussion and open cross group discussions:
- possible themes suggested in the invitation (repeated in support slides)
- deliberately not constrained to a matrix question/feedback format in order to allow easier identification of any issues. However, one constraint is to address the **key question**:

/Q/ What knowledge* does each group believe that it needs from the other groups (including the regulators) in order to function more efficiently and better meet its (safety) objectives?

* themes, level of detail etc, also see invitation and support slides

Maybe we will identify some common knowledge transfer priorities…

Group 1

GROUP 1: Machine Producer Chair: Richard GRYLLS, SLM Solutions Group AG (richard.grylls@slm-solutions.us)					
First name	**Family Name**	**Job Title**	**Organisation**	**TCH, machine producer, regulator, standardisation body etc**	**E-mail address**
Niccoló	GIANNELLI	Aerospace Application and Account Manager EMEA	Stratasys	machine producer	Niccolo.Giannelli@stratasys.com
Rachael	Brandt	Associate Application Engineer Manufacturing SBU.	Stratasys	machine producer	Rachael.Brandt@stratasys.com
Vinu Chaprayil	VIJAYAN	Business Development Manager – Aerospace	EOS GmbH	machine producer	vinu.vijayan@eos.info
Lucas	FUCHS	Business development manager - turbo machinery	EOS GmbH	machine producer	Lukas.Fuchs@eos.info
Jonathan	ORTNER		Concept Laser	machine producer	jonathan.ortner@ge.com
Matthieu	PETELET	Industrialization Expert Aerospace	ARCAM EBM	machine producer	Matthieu.Petelet@ge.com
Andreas	SOLBACH	Application Engineer Aerospace	SLM Solutions Group AG	machine producer	Andreas.Solbach@slm-solutions.com
Richard	GRYLLS	Technical Director SLM Solutions NA	SLM Solutions Group AG	machine producer	richard.grylls@slm-solutions.us
Simon	MERKT-SCHIPPERS	Industry Manager Additive Manufacturing for	Trumpf Laser und Systemtechnik GmbH	machine producer	simon.merkt@de.trumpf.com
Julia	MOLL	Application Engineer Aerospace / Energy	Trumpf Laser und Systemtechnik GmbH	machine producer	Julia.Moll@de.trumpf.com
Jono	MUNDAY	Customer Projects Manager	Renishaw PLC	machine producer	Jono.munday@renishaw.com
Mark	VAES	CTO	Additive Industries b.v.	machine producer	m.vaes@additiveindustries.com
Harry	KLEIJNEN		Additive Industries b.v.	machine producer	h.kleijnen@additiveindustries.com

Group 2

GROUP 2: TCH Chair: Jeffrey CONNER, GE Aviation (jeff.conner@ge.com)				
First name	**Family Name**	**Job Title**	**Organisation**	**TCH, machine producer, regulator, standardisation body etc**
Holger	LOGES	Manufacturing Technologies Development Engineer	Airbus	TCH
Philippe	EMILE	Additive Manufacturing Expert	Airbus	TCH
Neil	MANTLE	Head of Centre of Competence – Additive Layer Manufacturing	Rolls-Royce	TCH
Jeffrey	CONNER	Chief Consulting Engineer – Fielded Product Integrity	GE Aviation	TCH
Mark	SHAW	Qualifications & Certification Leader	GE Aviation	TCH
Anne	THÉNAISIE		SAFRAN AIRCRAFT ENGINES	TCH
Yann	DANIS	Safran HE additive manufacturing expert	SAFRAN HELICOPTER ENGINES	TCH
Bruno	MACQUAIRE	Head of R&T Additive Manufacturing plateform	Safran	TCH
Dominique	BOUVIER		SAFRAN HELICOPTER ENGINES	TCH
**MR Bouvier will attend only on 29 June*				
Sophie	FERRENDIER	Vehicle Airworthiness Expert	AIRBUS Helicopters	TCH

Group 3a

Sub-group 3a: MRO/Operator/POA/non-TCH DOA

Sub-group chair: Simon MÜLLER, Lufthansa Technik AG (simon.mueller@lht.dlh.de) & Wayne THOMAS, Air New Zealand (wayne.thomas@airnz.co.nz)

First name	Family Name	Job Title	Organisation	TCH, machine producer, regulator, standardisation body etc
Wayne	THOMAS	3D Printing and Advanced Manufacturing Project Manager	Air New Zealand	Operator
Joseph	CHONG	Vice President, Aircraft Engineering	ST Engineering Aerospace Ltd.	DOA
Wen Ming	TAN	Assistant Principal Engineer, Aircraft Engineering	ST Engineering Aerospace Ltd.	DOA
Guo Ying	ZHENG		ST Engineering Aerospace Ltd.	DOA
Simon	FEICKS	Project Manager Additive Manufacturing	Lufthansa Technik AG	DOA
Simon	MÜLLER	Additive Manufacturing Engineer	Lufthansa Technik AG	DOA
Clemens	MIASKOWSKI		Lufthansa Technik AG	DOA
Geert	APPELTANS	Quality Manager Polymers	Materialise NV	Industries
Jörn	WERITZ	Quality Manager Metals	Materialize GmbH	Industries
Éric	BAUSTERT	R&T Manager	Volume-e	Industries
Utkarsha	ANKALKHOPE	Senior Research Engineer, National Centre for Additive Manufacturing	MTC UK	Industry Support
Martin	DURY	Training Operations Manager, Training Services	MTC(AMTC) UK	Industry Support
Thorsten	WESENDRUP		Premium AEROTEC GmbH	Industries

Group 3b

First name	Family Name	Job Title	Organisation	TCH, machine producer, regulator, standardisation body etc
Hannah	GODREY	General Manager, PRI Europe and Professional Development Manager	Performance Review Institute (PRI) Europe	Standardisation body
Ian	SIMPSON	Nadcap Program Manager - Welding	Performance Review Institute (PRI) Europe	Standardisation body
Sara	GOBBI	Director of European Affairs	ASTM International	Standardisation body
Rachael	ANDRULONIS	Senior Research Engineer	National Institute for Aviation Research, Wichita State University (NIAR)	Standardisation body

Recent related activities:

PRI: Bodies of knowledge:

- *Process Operator/Technician*
- *Process Planner*
- *Process Owner*

FAA Workshop 2017:

http://www.tc.faa.gov/its/worldpac/techrpt/tc18-3.pdf

SAE ('operator training' – Norway April 2018)

EASA - AM

Welcome:

EASA welcomes you to Koeln to discuss AM Machine Knowledge Transfer and Training (metallic and non-metallic)**, with the objective of identifying the challenges, process gaps, and possible solutions relating to knowledge transfer and training**

EASA Certification:

It will be important for the **regulators to understand the machine technologies and that appropriate knowledge is being transferred between the TCHs*, machine producers, and other sub-contractors, such that the TCHs and STCHs* have full and appropriate knowledge to demonstrate to the regulators full control and responsibility for their products, including maintenance considerations**.

* Type Certificate Holders
**Supplementary Type Certificate Holders

This Workshop: Machine Producer/Knowledge Transfer/Training

Meeting format:

- closed group
- mixed group
- across group
- all group

EASA European Aviation Safety Agency

EASA AM Machine Producer –
- Knowledge Transfer - Training Meeting

Cologne, 28-29 June 2018

AGENDA

DAY 1, 28/06/2018, Jugendherberge Köln-Deutz (Siegesstr. 5, D-50679 Köln)

TIME	MEETING ROOM	TITLE, SPEAKER
12:30 H – 13:00 H	LOBBY, RECEPTION DESK	REGISTRATION
		I. ALL-HANDS MEETING: INITIAL GROUP PRESENTATIONS (20 MIN PER GROUP)
13:00 H – 15:00 H	Wolgograd	Introductory Words EASA
		Group 2 presentation (Chair: Mr Jeffrey CONNER, GE Aviation) TCHs
		Sub-group 3a presentation (Chairs: Mr Simon MÜLLER, Lufthansa Technik & Mr Wayne THOMAS, Air New Zealand) Operator/MRO/POA/ non-TCH DOA
		Sub-group 3b presentation (Chair: Ms Rachael ANDRULONIS, NIAR) Standardisation Bodies
		Group 1 presentation (Chair: Mr Richard GRYLLS, SLM Solutions Group AG) Machine Producers
15:00 H – 15:30 H	CANTEEN ROOM (SEPARATE, ON THE LEFT)	NETWORKING BREAK
		II. GROUPS MEETINGS
15:30 H – 17:30 H	Turku	Group 1
	Indianapolis	Group 2
	Tunis	Group 3 (a&b)
17:30 H		CLOSING OF 1ST DAY

This Workshop: Machine Producer/Knowledge Transfer/Training

EASA
European Aviation Safety Agency

EASA AM Machine Producer –
- Knowledge Transfer - Training Meeting

Cologne, 28-29 June 2018

10:00 H – 10:30 H	TURKU/ INDIANOPOLIS/ TUNIS	NETWORKING BREAK
[..continue] II. GROUPS MEETINGS		
10:30 H – 12:30 H	Turku	Group 1
	Indianapolis	Group 2
	Tunis	Group 3 (a&b)
12:30 H – 13:30 H	CANTEEN ROOM (SEPARATE, ON THE LEFT)	LUNCH BREAK
III. ALL-HANDS MEETING: CONCLUSIONS (20 MIN PER GROUP)		
13:30 H – 14:30 H	Wolgograd	**Group 1 presentation (Chair: Mr Richard GRYLLS, SLM Solutions Group AG)** Machine Producers
		Group 2 presentation (Chair: Mr Jeffrey CONNER, GE Aviation) TCHs
		Sub-group 3a presentation (Chairs: Mr Simon MÜLLER, Lufthansa Technik & Mr Wayne THOMAS, Air New Zealand) Operator/MRO/POA/ non-TCH DOA
		Sub-group 3b presentation (Chair: Ms Rachael ANDRULONIS, NIAR) Standardisation Bodies
14:30 H – 15:00 H	CANTEEN ROOM (SEPARATE, ON THE LEFT)	NETWORKING BREAK
15:00 H – 16:30 H		IV. DISCUSSION
17:00 H		CLOSING

Initial main outcomes:

- each stakeholder group produced:
- an opening presentation and spreadsheet questions/comments* identifying expectations and perceptions relating to the other groups activities:
  - What they thought others needed to know about their function
  - What they believed they needed from others…

* each group prepared well for the meeting (essential!)

Initial main outcomes:

- Following closed, mixed, and across group discussion, each stakeholder group produced:
- a closing presentation and spreadsheet questions/comments

  - opening meeting presentation refined based upon meeting discussions

EACH GROUP TO PRESENT ITS SUMMARY AT THIS MEETING

Initial main outcomes (EASA perspective):

- successful open discussion
  - feedback – some ‘light bulb’ moments for some group members (good!)
  - first time all major AM Machine Manufacturers had been together at a ‘working’ workshop
- need for all stakeholders to be informed of roles and responsibilities in certification process
  - need for basic certification tutorial similar to composites CMH-17 ‘level 1’? (supplied by regulators icw TCHs?)
  - TCHs also to cascade responsibility message to sub-contractors

Initial main outcomes (EASA perspective):

- need for baseline machine reference builds
  - confidence building…not design allowables….
- need to define ‘key characteristics’
  - definition?
  - define for each material/process?
  - prioritise knowledge transfer/training wrt ‘key characteristics’?

Initial main outcomes (EASA perspective):

- need to manage applications in proportion to criticality
  - appropriate guidelines (e.g. ‘low criticality AM products’ EASA Cert Memo)
- need to further process output from the Knowledge Transfer Workshop 2018:

https://www.easa.europa.eu/newsroom-and-events/events/additive-manufacturing-workshop-machine-knowledge-and-training

Questions?

Support Slides

Possible knowledge transfer themes might include (see invitation):

- Who are the key functionaries, e.g. machine operator, CVE, design staff, production staff, training staff, etc. and where does the technical knowledge exist,
  - what background knowledge do they need (theory/practical)
  - what do they need to know?
- what timescales are expected for training of each functionary?

- Knowledge base for CVEs (and/or other key staff members) addressing AM? (EASA understands that knowledge relating to materials, POA, DOA, systems etc may all be necessary to appropriately address the integrated link between design, production, and maintenance)

- Machine producer interface with industry (from the TCH, machine manufacturer, MRO, or other sub-contractor basis)
  - what does the TCH/STCH need to know from the machine producer to clearly demonstrate control and responsibility for the product
  - how does this change in the maintenance environment

Possible knowledge transfer themes might include (see invitation):

- Understanding/training relating to machine issues
  - Maintenance practices and impact upon key variables/sensitivities (how are key variables/sensitives identified)
  - Calibration practices
  - Software management
  - Cyber security issues
- Training strategy
  - How was the training strategy developed in your organisation?
  - Initial strategy – lessons learned?
  - Current training strategy – lessons learned?
  - Future training strategy and the planned link between the machine manufacturer, the DOA, and the POA or PART145 organisation
- Development of a common industry lead training strategy?

Possible knowledge transfer themes might include (see invitation):

- Development of a common industry lead training strategy?
- Is there a need for a high level training ‘teaching points’ guideline, similar to SAE AIR 5719 as used for composites ?
- Is there a need to adopt a training strategy similar to composites, e.g. level 1,2, and 3 etc (no need to reinvent the wheel etc)
- How can standardization bodies support the above activities?

EASA – AM WG Subject Contacts

EASA AM Strategy - current activities:

- EASA AM WG – subject contacts (as identified in CM*):

- Shared responsibilities via subject contacts
- Co-ordinated through EASA AM WG, e.g. internal meetings etc

- Cert. Directorate (Chief Expert - Airframe)	R. Minter – richard.minter@easa.Europa.eu
- Structures	S. Waite (AM WG chair) – simon.waite@easa.europ.eu
	W. Hoffmann - wolfgang.hoffmann@easa.europa.eu
- Propulsion	M. Mercy - matthew.mercy@easa.europa.eu
	O. Kastanis - omiros.kastanis@easa.europa.eu
- Systems	**M. Weiler - michael.weiler@easa.europa.eu**
- Cabin Safety	T. Ohnimus - thomas.ohnimus@easa.europa.eu
- DOA	A. Enache - alexandru.enache@easa.europa.eu
	O. Tribout - olivier.tribout@easa.europa.eu
- POA	D. Lamothe - dominique.lamothe@easa.europa.eu
	S. Pernet - samuel.pernet@easa.europa.eu
- Maintenance	R. Tajas - rosa.tajes@easa.europa.eu
- ETSO	TBD

* changes in progress since CM published – new subject contacts 'red text'

EASA - AM

EASA AM Strategy - current activities:

- EASA AM WG:

- Risk and Mitigation Matrix
- Workshops (first meeting - September 2016)
- Regular communication with other regulators

EASA - AM

Certification Memo: **EASA CM–S-008 Issue 01: Additive Manufacturing***

Requirements: **CS X.571, CS X.603, CS X.605, CS X.613, CS-E 70, CS-E 100 (a), CS-P 170, CS-P 240, CS-APU 60, GM 21.A.91, 21.A.101, 21.A.133, 21.A.433, GM 21.A.435, 21.A.437, 21.A.447, 21.A.805, AMC 145.A.42(c)**

Purpose/Scope: …provide guidance regarding regulator expectations relating to the usage of AM technologies in products (Aircraft, Rotorcraft and Propulsion) subject to EASA Type Certification

simple 'early engagement' message…

EASA Certification Policy and Guidance for DOA and POA Holders

- is a change of material or/and process iaw GM 21A.91
- in repair, repair design would normally be classified Major, applicants are advised to consult EASA when introducing AM in repairs, including cases where they hold a privilege for repair approval.

not intended to make everything Major…
'case by case' approach…

*https://www.easa.europa.eu/system/files/dfu/EASA%20CM-S-008%20Additive%20Manufacturing.pdf

EASA - AM

CM: EASA Certification Policy and Guidance for DOA and POA Holders

- Design Organisation Approval Holders are advised to involve the Agency at the earliest opportunity during the development and implementation of AM. ….AM will be subject to increased oversight by the agency and that specific audits will be scheduled to examine the introduction and use of AM within the scope of the design organisation audit cycle. … audits may take place concurrently with the review of AM applications rather than post approval.

- Production Organisation Approval holders are advised to inform their respective competent authorities at the earliest opportunity before the implementation of AM processes. ...implementation of a new AM process by a POA holder is a change which may be identified as a significant change in accordance with Part 21.A.147 + GM

simple 'early engagement' message…

PART145s typically have no access to TCH hazard analysis, damage modes, criticality etc – which AM might change

EASA - AM

potential need for more guidance regarding expectations proportional to criticality recognised

CM: Maintenance/Operators: Existing DOA, POA, PART145 regulations apply…

PART 145.A.42 Acceptance of components:

'…organisation may fabricate a restricted range of parts to be used in the course of undergoing work within its own facilities… procedures are identified in the exposition.'

'All necessary data to fabricate the part …approved by the competent authority, TC holder, or Part-21 design organisation approval holder, or supplemental STC holder;'

'Para.7. Examples of fabrication under the scope of an Part-145…:

a) Fabrication of bushes, sleeves and shims… b) …secondary structural elements and skin panels… etc

All the above fabricated parts, should be in accordance with data provided in overhaul or repair manuals, modification schemes and service bulletins, drawings or otherwise approved by the competent authority. Note: It is not acceptable to fabricate any item to pattern unless an engineering drawing of the item is produced which includes any necessary fabrication processes and which is acceptable to the competent authority.'

EASA - AM

Certification Memo (lessons learned):

- working well with large TCHs, e.g. Airbus, Rolls Royce, Safran (see 2016 Workshop Slides)
  - evolution towards more critical applications in progress

e.g. DRAFT AMS 7003 – agree upon 'Significant Process Characteristics' SPCs

- need strategy to better identify and understand 'key parameters', e.g. machine parameters, statistical strategy, enable shared databases (e.g. SAE AM-P, NIAR work) etc

- some challenges to be addressed regarding optimisation of evolving use in maintenance/operator environment
  - less critical interior part applications….
    - strength, fire, failure modes (sharp edges preventing evacuation, fatigue), statistics etc

- rapid technology integration…
  - knowledge base/training for industry/regulators is likely to be a challenge

New! support CM

EASA – NAA activities: NAA Materials Network (NAAMN)*

- improve communication/standardisation between NAA and EASA regarding broader 'material and process' issues

NAAMN – Terms of Reference:

To identify, and address as necessary, common **Materials and Process** (metallic, non-metallic, ceramic, Additive Manufacturing (AM) etc) issues with **potential safety implications** from an **European NAA perspective**.

To consider all aspects of Materials and Processes in the context of all activities, including design, supply, production, and maintenance.

To consider Materials and Processes issues ranging from detailed technical issues (airframe, propulsion, systems, cabin safety, maintenance etc) through to organisational and regulatory structural issues, including certification, material qualification, complex part substantiation, training, standardisation, R&D, and rulemaking.

* see support slide for current membership (all European NAAs invited, currently 11 NAAs)

EASA - AM

Conclusions – 2017 (see 2016 presentation): AM is rapidly evolving:

- EASA does not approve materials or processes, but accepts them as part of a project - provided that they are shown to be validated, applicable, and repeatable

- Technology, and technology application, changes must not reduce the existing 'acceptable' level of safety

- EASA AM Working Group in place to review and assess risk, and risk mitigation, and to work with other regulators and industry (CM) to help ensure safe integration of the evolving technologies into aviation

- EASA AM CM in place CM approach seems to work

  - additional NAA communication path established to support process (NAAMN)

EASA - AM

Conclusions: AM is rapidly evolving:

Rules: limited/possibly no rule change expected by EASA…

Guidance: some guidance development expected (level of content/detail unclear), a function of:

- criticality of applications
- identification of any common underlying philosophy development* associated with maturing technologies e.g. icw international standards bodies etc, e.g. SAE, ASTM.
- would an AM equivalent to AMC 20-29 'Composite Structures' potentially useful?

R&D: EASA increasingly working with EU funded projects

Workforce knowledge base and training (industry and regulators)

– likely to be a limiting factor in this rapidly developing technology

* it is understood that IP will not be shared. However, applicants are required to meet the requirements, e.g. show stable process, repeatable 'engineering properties' etc

Questions?

Support Slides

EASA - AM

➢ EC No 216/2008 annex 1.a.**Structures and materials**: the **integrity of the structure must be ensured throughout, and sufficiently beyond, the operational envelope for the aircraft, including its propulsion system**, and maintained for the operational life of the aircraft.
1.c.3. Systems and equipment…

egulatory Framework (moving towards **performance based regulations**)

Basic Regulation

(EC) No 216/2008

EU Parliament
EU Council

.Binding

➢**21A.31 Type design …** shall consist of:
➢2. Information on **materials and processes** and on **methods of manufacture and assembly** of the product necessary to ensure the conformity of the product

ing rules

Regulation No 1702/2003

For the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations.

EU Commission

GM 21.A.147(a) Changes to the approved production organisation – Significant changes
1 …to be approved by the competent authority include:
- significant changes to production capacity or methods…

Acceptable Means of Compliance (AMC) and Guidance Material (GM) for

PART 21

Certification Specifications

Airworthiness Codes, e.g. CS 23, 25, 27, 29 et

PART 145 – Maintenance organisation approvals

PART 66 – Certifying staff

Part 147 – Training organisations requirements

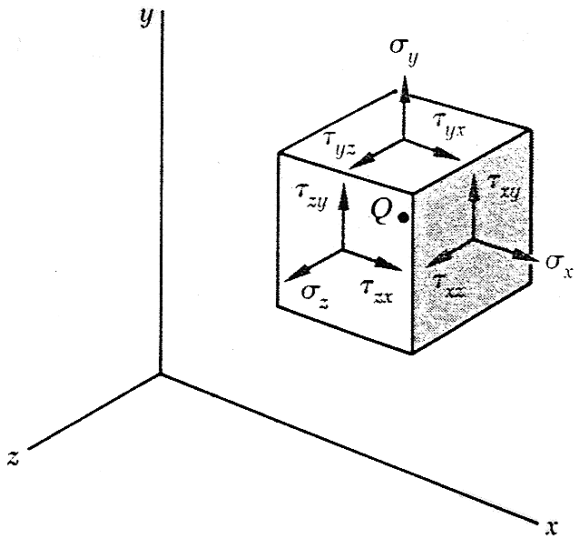
EASA

.Non-Binding

➢ **Certification Specifications: Limited 'Material and Process', e.g.**
CS 25.603: Materials… 'suitability and durability … based upon experience/test… conform to specifications… consider environment
CS 25.613: Mechanical Strength Properties and Design Values
Materials. (a) … design values based upon a statistical basis

'Engineering Properties'*: '… historically, many materials used in aviation are isotropic

- properties similar in all directions of load application, e.g. mechanical, thermal etc (+ similar/limited damage modes)



Isotropic: similar strength in X,Y, and Z directions

Anisotropic: different strengths in X and/or Y and/or Z directions

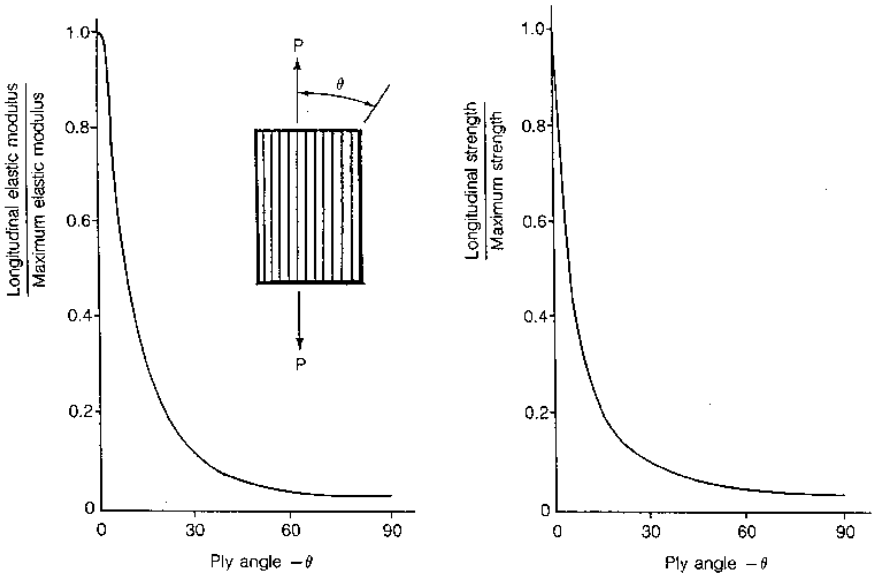
* 'engineering properties', e.g. strength + stiffness (local and global buckling) which define the structure performance

intentional or unintentional!

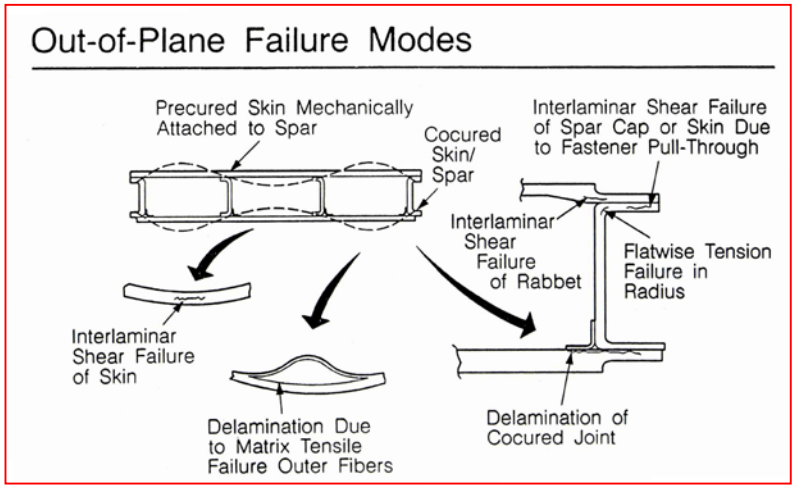
'Engineering Properties': '... make objects...layer upon layer...'

- initially assume AM potentially anisotropic – properties change with direction of load application (+ competing damage modes)

Anisotropy: Significant strength/stiffness reduction with orientation relative to load



Strength/Stiffness v Ply Angle
(non-dimensionalised)



Anisotropy: potentially difficult to predict:

- **failure loads**
- **damage modes**
- **damage locations**
- **damage sequence**

Identification and control of key process steps essential… look for substantiated tolerance sensitivity data

Example AM challenge…*

CS 25.613: Mechanical Strength Properties and Design Values Materials

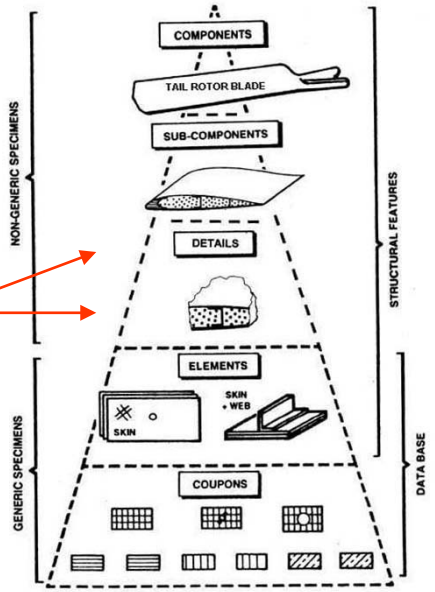
How do we statistically manage inaccessible free edges in complex laser melt parts?

- *free edge coupons produced in parallel with parts*
- *coupons produced from part cut-up*
- *use higher pyramid component testing (small data set statistics?)*

Non-TCH DOA unlikely to have this information…
e.g. acceptable free edge details etc



Free Edge – fatigue issue?



AMC 20-29 Figure 2 - Schematic diagram of building block tests for a tail rotor blade

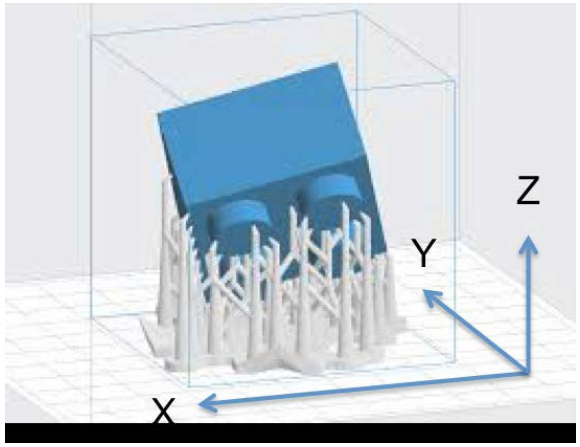
** similarities to how castings are addressed in CS25.621 'Castings Factors'?*

Identification and control of key process steps essential… look for substantiated tolerance sensitivity data

Example AM challenge…

CS 25.613: Mechanical Strength Properties and Design Values Materials

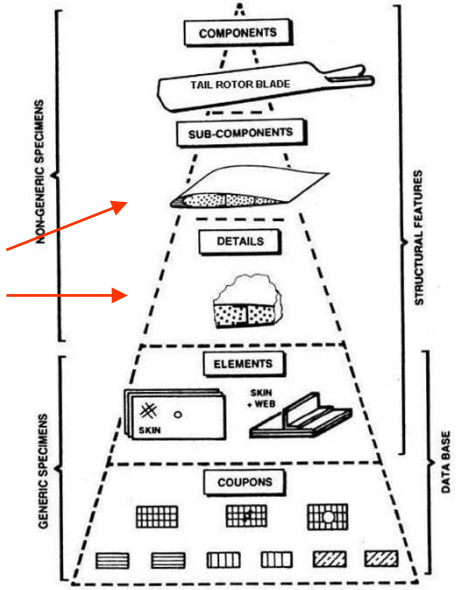
How do we statistically manage complex supported parts?*



PBF part (blue) and Support Structure (white) on the Build Platform



Unsupported "roof"



AMC 20-29 Figure 2 - Schematic diagram of building block tests for a tail rotor blade

* *support provides physical support and/or thermal management*

EASA AM: Strategy:

1 - Understand the technology / process / product and its actual, planned or potential uses.

2 - Identify potential safety / environmental risks.

3 - Define and implement means to mitigate risks working closely with industry and NAAs.

4 - Monitor evolution of technology / product / process and effectiveness of mitigation.

5 - Review and revise implementation of strategy as necessary.

CM:

EASA Certification Policy and Guidance for DOA and POA Holders

applicants to demonstrate:

- complies with appropriate CS's
- suitable for intended use
- source materials purchased to spec
- produce consistent product to process spec
- statistically significant design values wrt defined facilities/equipment
- control of equipment/process

Risk and Mitigations Matrix:

Preliminary (initial) areas of risk list (under EASA AM WG review/development*):

Scope and definition of AM not standardised
New materials
Many process parameters to control (see Appendix)
Anisotropic properties of finished part
Variation in the types of AM equipment / processes and lack of standardization
Limited understanding of acceptable ranges of variation for key manufacturing parameters
Limited understanding of key failure mechanisms
Transfer from small scale manufacture to high levels of production
Lack of broad industry databases / allowables (each implementation is unique)
Development of capable NDI methods
Repairs
Current rules: Note: ARAC Composite and Metallics group also has to consider new technology in F&DT recommendations)
Insufficient guidance (Likely)
POA related
DOA related
DOA and POA link
Certification related
Higher risk of bogus parts

* including identification of existing mitigations and the need for new additional actions

NAA Materials Network (NAAMN): Current Members

Organisation	Focal First Name	Focal Family Name	Focal Function within NAA	e-mail address
CAA-NL	Bart	Abbes	Aircraft Structures Specialist	bart.abbes@ilent.nl
CAA-CZ	Tomaz	Franc	Specialist - Aircraft Design Section	franc@caa.cz
CAA-CH	Andreas	Boss	Inspector	Andreas.boss@bazl.admin.ch
LBA 1	Dietmar	Goldschmidt		dietmar.goldschmidt@lba.de
LBA 2	Karen	Mueller	National Standardisation Coordinator (NSC) Luftfahrt-Bundesamt	Karen.Mueller@LBA.DE
CAA-SI	Bostjan	Palcic	Airworthiness Inspector	bostjan.palcic@caa.si
CAA-RO	Alexandru George	Musat	Airworthiness Inspector	alexandru.musat@caa.ro
ECAA-EE	Margus	Keerman	Senior Inspector Airworthiness	margus.keerman@ecaa.ee
Austro Control	Flrian	Glatzl	Airworthiness and Certification Surveyor	Florian.Glatzl@austrocontrol.at
Trafi (Finland)	Jyrki	Laitila	Head of Unit, Airworthiness	jyrki.laitila@trafi.fi
CAA- Poland - Institute of Aviation	Małgorzata (Margaret)	Zalewska	Composites Testing Laboratory Manager in the Institute of Aviation	malgorzata.zalewska@ilot.edu.pl
CAA-UK	Ted	Blacklay	Airworthiness Survey - Subject Matter Expert for Materials, Special Processes and NDT	ted.blacklay@caa.co.uk

Standardisation of Certification Requirements Applicable to AM

- limited material specific specific rules/guidance
  (although significant to design and throughout CSs)

- governing rule is CS 2x.603:

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…..'

- *be based upon experience/test*
- *conform to specifications (meeting design data)*
- *consider environmental effect (temperature, moisture etc)*

*AMC 20-29 - harmonised with FAA AC20-107B

CS- E – different words, similar intent as CS 2x-603, 605

CS-E 70 Materials and Manufacturing Methods (See AMC E 70)

(a) The suitability and durability of materials used in the Engine must be established on the basis of experience or tests. The assumed design values of properties of materials must be suitably related to the minimum properties stated in the material specification.

(b) Manufacturing methods and processes must be such as to produce sound structure and mechanisms which retain the original mechanical properties under reasonable service conditions.

CS- E – different words, similar intent as CS 2x-613 (statistical credibility - safe-life - metal assumption)

CS-E 515 Engine Critical Parts

…the factors used to account for scatter should be justified. In order to utilise this approach the test should be designed to be representative of the critical engine conditions in terms of the temperature and stress at the specific features…

…test data should be reduced statistically in order to express the results in terms of minimum LCF capability (1/1000 or alternately -3 sigma). The fatigue life should be determined as a minimum life to initiation of a fatigue crack, defined typically as a crack length of 0.75mm.

CS25.571: ***Damage-tolerance & fatigue evaluation of structure***

'(a) General. An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, or accidental damage, will be avoided throughout the operational life of the aeroplane…'

Environmental Damage - ED

Accidental Damage - AD

Historically: metal/fatigue/corrosion focused

Existing CS25 Structures Regulations of particular interest and potential relevance include:

CS 25.571: Damage Tolerance and Fatigue Evaluation of Structure:

'(3).....inspections or other procedures must be established as necessary to prevent catastrophic failure, and must be included in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness required by CS 25.1529'

Does not need to be visual,
Note: 80-90% of inspections are visual
ref. also CS25.611

Does not need to be an 'inspection'

Notes:

1/ EASA does not approve inspection standards, but accepts them as part of a process, project etc - provided that they are shown to be validated, applicable, and repeatable

2/ technology and technology application changes must not reduce the existing 'acceptable level of safety'

EASA - AM

AM - Maintenance/Operating Environment:

Example AM challenge – existing requirements/awareness**…*

PART 145.A.42 Acceptance of components:

'…organisation may fabricate a restricted range of parts to be used in the course of undergoing work within its own facilities provided procedures are identified in the exposition.'

AMC 145.A.42 Acceptance of components:

'All necessary data to fabricate the part should be approved either by the competent authority or the type certificate (TC) holder or Part-21 design organisation approval holder, or supplemental type certificate (STC) holder;'

* *AM similarities wrt composites*

** *applies to industry and regulators*

AM - Maintenance/Operating Environment:

*Example AM challenge – existing requirements/awareness***

PART 145.A.42 Acceptance of components:

'7. Examples of fabrication under the scope of an Part-145 approval can include but are not limited to the following:

a) Fabrication of bushes, sleeves and shims.

b) Fabrication of secondary structural elements and skin panels.

c) Fabrication of control cables.

d) Fabrication of flexible and rigid pipes.

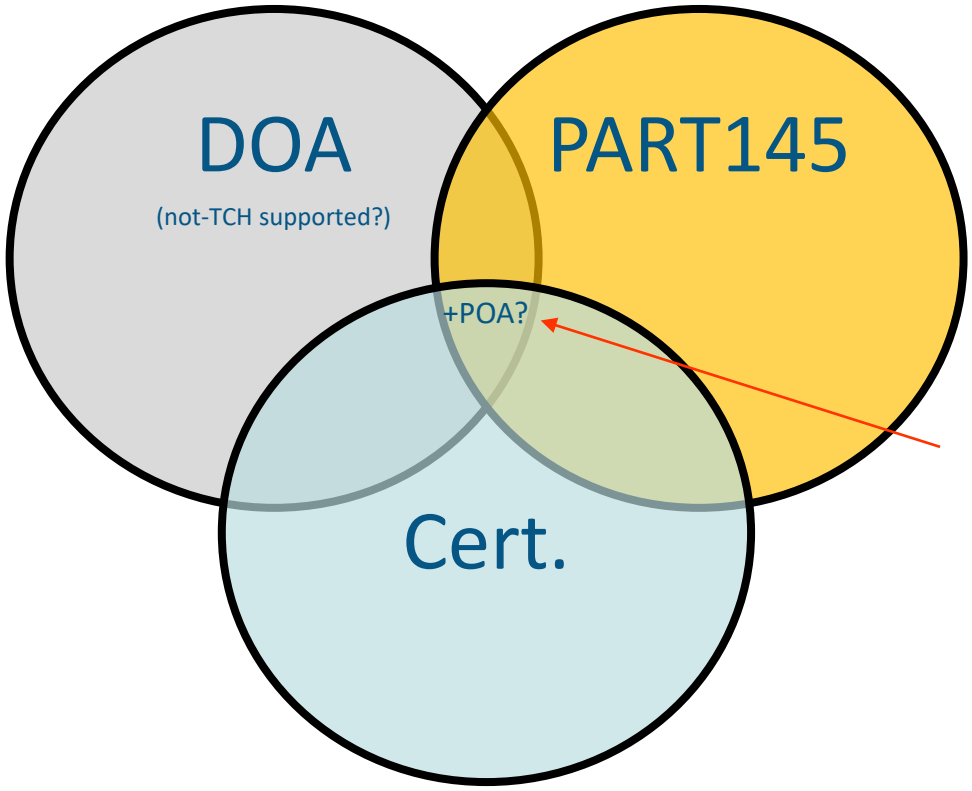
e) Fabrication of electrical cable looms and assemblies.

f) Formed or machined sheet metal panels for repairs.

changed material:
changed damage mode/debris?
- consider downstream critical part consequences…

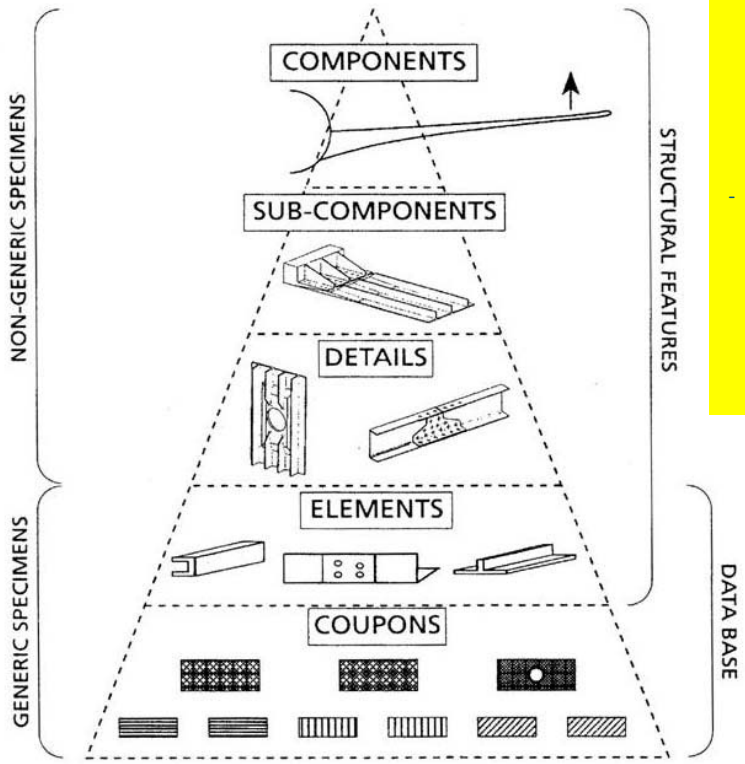
All the above fabricated parts, should be in accordance with data provided in overhaul or repair manuals, modification schemes and service bulletins, drawings or otherwise approved by the competent authority. Note: It is not acceptable to fabricate any item to pattern unless an engineering drawing of the item is produced which includes any necessary fabrication processes and which is acceptable to the competent authority.'

AM - Maintenance/Operating Environment:



Existing rules:
- POA?
- Improve links between EASA and NAAs

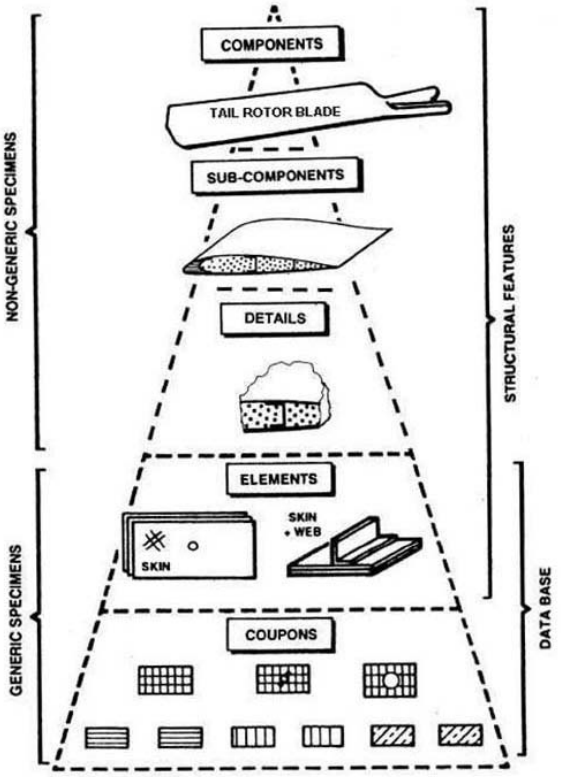
Substantiation: Test/Analysis Pyramid (Building Block)?



AMC 20-29 Figure 1 - Schematic diagram of building block tests for a fixed wing.

Static and F&DT substantiation in mid-upper test/analysis pyramid

- typically, representative Boundary Conditions are essential



AMC 20-29 Figure 2 - Schematic diagram of building block tests for a tail rotor blade

Design Philosophy: robust design concept, e.g. Large Damage Capability (LDC)

- to be similar to established metallic structure except:
  - potentially different/more competing damage modes,
  - some damage modes not so readily detected

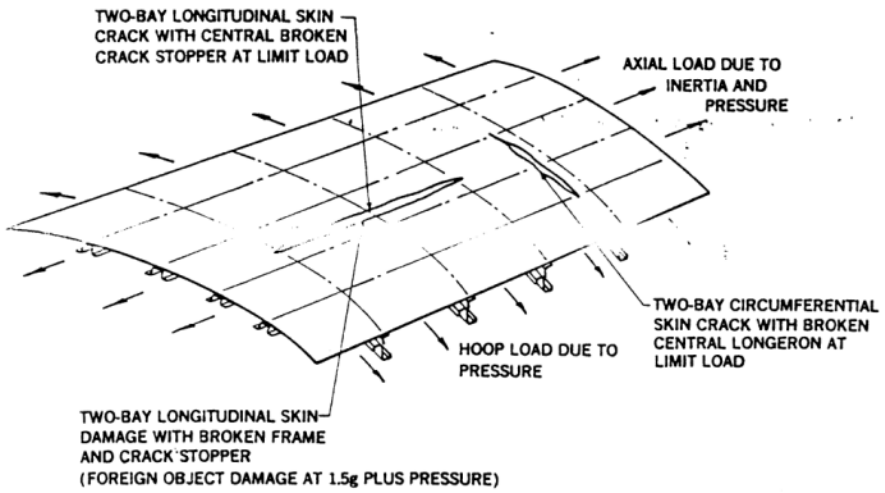


FIGURE 2. FUSELAGE DAMAGE TOLERANCE SIZES FOR STRUCTURAL DESIGN

Metal Design - Design for Redundant Structures' - T. Swift

- additional consideration may be required for technologies which change design concepts

Design philosophy changes:

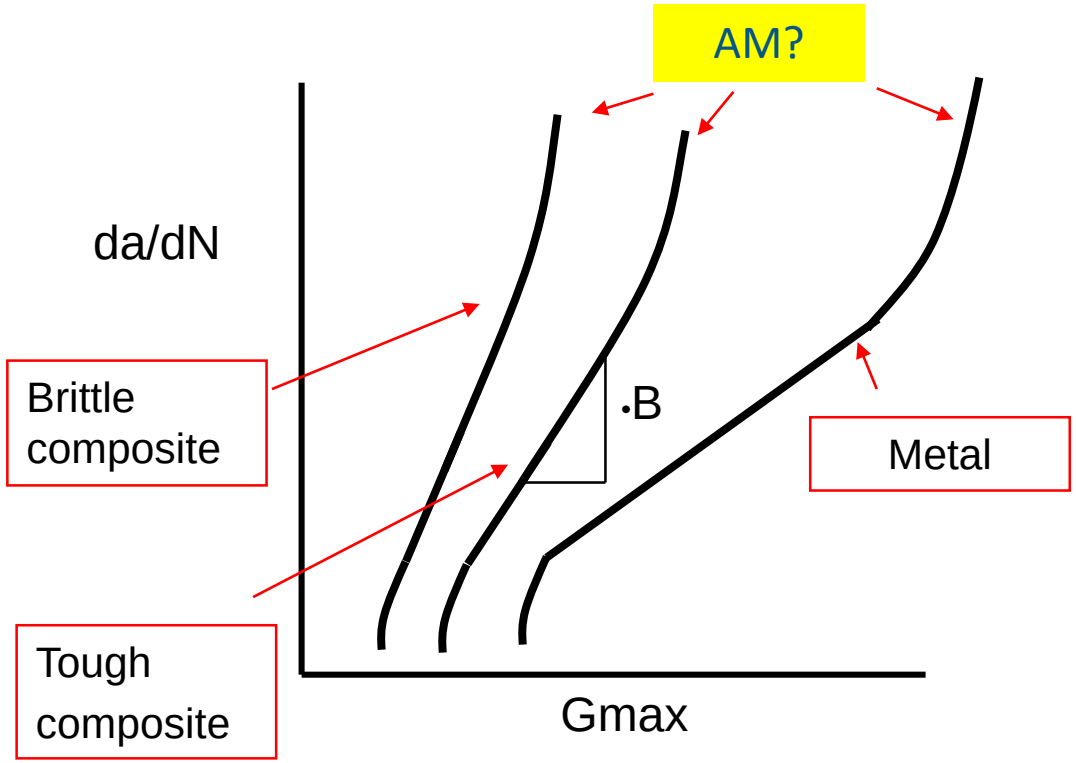
Do not reduce the existing Level of Safety

- show ‘equivalence’ to existing technologies
- result of: experience, R&D, ‘engineering judgement’, reaction to incidents and accidents, and regulations existing at the time of certification, Type Certificate Holder in-house design practice

Maintain robust ‘aircraft level’ design concept

- address all identified threats, e.g. manufacture, in-service
- similar to established metallic structure, e.g. T. Swift philosophy etc
- local damage may be different, but structural level failure may be driven by the similar failure mode, e.g. buckling

Damage – Inspection and Damage Tolerance:



$$\frac{da}{dN} = AG^B \qquad G \propto P^2$$

$$\Rightarrow \frac{da}{dN} \propto P^{2B}$$

Material	B
Steel	1.6
Aluminium	2.2
Carbon/Thermoplastic	6.1
Carbon/Epoxy	12.2

Solution :- ensure that when damage is present, G is below a threshold value for crack growth

AM – potential for a broad range of Fatigue and Damage Tolerance philosophies
- safe life, flaw tolerant safe life, fail-safe, damage tolerant?

Composite Safety Issues

AMC 20-29 - Composites:

3. APPLICABILITY

This AMC provides Acceptable Means of Compliance with the provisions of CS-23, CS-25, CS- 27 and CS-29. Many of the concepts included in this AMC may also be applicable in part or in full to other CSs. However, when using this AMC as an Acceptable Means of Compliance for these other CSs, appropriate engineering judgement should be exercised and early agreement with the Agency sought.

This AMC applies to: applicants for a type-certificate, restricted type-certificate or supplemental type-certificate; certificate/approval holders; parts manufacturers; material suppliers; and maintenance and repair organisations.

– similar for AM

Composite Safety Issues

Standardisation of Certification Requirements for Composites

Composite Certification - existing rules and guidance

EASA AMC 20-29/FAA AC20-107B – 'COMPOSITE AIRFRAME STRUCTURE'

CONTENTS (expanded 12 to 36 pages, new sections – red)

1. PURPOSE
2. CANCELLATION
3. TO WHOM THIS AMC APPLIES
4. RELATED REGULATIONS AND GUIDANCE
5. GENERAL
6. **MATERIAL AND FABRICATION DEVELOPMENT**
7. PROOF OF STRUCTURE – STATIC
8. **PROOF OF STRUCTURE – FATIGUE AND DAMAGE TOLERANCE**
9. PROOF OF STRUCTURE – FLUTTER
10. CONTINUED AIRWORTHINESS
11. ADDITIONAL CONSIDERATIONS (crashworthiness, fire/flammability, lightning)

APPENDIX 1 Requirement Table
APPENDIX 2 Definitions
APPENDIX 3 Material Change

1984 document

applicable to PMC composite fan blade

– similar for AM



Composite Safety Issues

Safety Management System

Standardisation of Certification Requirements for Composites:

AMC 20-29 includes clear linkage between design requirements and many material, production, and continued airworthiness related requirements...

Regulations:	CS23	CS25	CS27*	CS29*
Material and Fabrication	603 613 619	603 613 619	603 613 619	603 613 619
Proof of Structure – Static	305 307(a)	305 307(a)	305 307(a)	305 307(a)
Proof of Structure – F&DT	573**	571	573	573
Proof of Structure – Flight	629	629	629	629
Additional Considerations				
Impact Dynamics	561	561	561	561

Works for CS-P CS-E

table continues with other requirements linked to flammability, lightning strike, production specifications, continued airworthiness etc.

* Rotorcraft

** Many similar code numbers, but some differences in content

– similar for AM

Production Organisation Approval PART 21, Sub. G:

21.A.147 Changes to the approved production organisation

(a) ….each change to the approved production organisation … significant to the showing of conformity or to the airworthiness … particularly changes to the quality system, shall be approved by the competent authority

GM 21.A.147(a) Changes to the approved production organisation – Significant changes

1 Changes to be approved by the competent authority include:

- significant changes to production capacity or methods…
- changes in the production or quality systems …important impact on the conformity/airworthiness of each product, part or appliance.

2 …ensure that changes do not result in non-compliance … competent authority and approval holder to establish a relationship … will permit the necessary evaluation work to be conducted before the implementation of a change

EASA - AM

Conclusions: AM is rapidly evolving:

Rules: limited/possibly no rule change expected by EASA…

Guidance: some guidance change expected (level of content/detail unclear), a function of:

- criticality of applications
- identification of any common underlying philosophy development* associated with maturing technologies e.g. icw international standards bodies etc, e.g. SAE, ASTM.
- would an AM equivalent to AMC 20-29 'Composite Structures' potentially useful?

R&D: EASA increasingly working with EU funded projects

Workforce knowledge base and training: Need

* it is understood that IP will not be shared. However, applicants are required to meet the requirements, e.g. show stable process, repeatable 'engineering properties' etc

Conclusions:

POA/DOA/Maintenance:

- need to increase awareness of closer relationship between design, production, continued airworthiness (CAW), more integrated than many typical metallic processes (some similarities wrt composites)
- need to increase awareness of existing rules, particularly at interfaces between design, production, and maintenance, e.g. link between non-TCH DOA, PART 145 (AMC 145.A.42 para.7), and the need for TCH data for extensive repair and 'replacement' (also similarities wrt composites)

R&D:

EASA strategy to work with EU funded projects and industry to ensure regulatory resource is efficiently focused upon maturing methods and applications

- Test/analysis pyramid statistical credibility issue within scope of next EU FP - TBD

EASA AM Workshop

June 2018

CLOSE

Next EASA AM Workshop
… 2019 date TBD

Thank you for your interest and support

Particular thanks to: The Presenters

and

Lily Kamburova and Erika Amrhein for organising the agenda and managing this Workshop

APPENDIX L
STEPHANE BIANCO, AIRBUS
“AIRBUS EXPERIENCES IN QUALIFICATION OF AM PRODUCTS”



AIRBUS experience in Qualification of AM Products

Stephane BIANCO
H/O Additive Manufacturing Materials and Processes

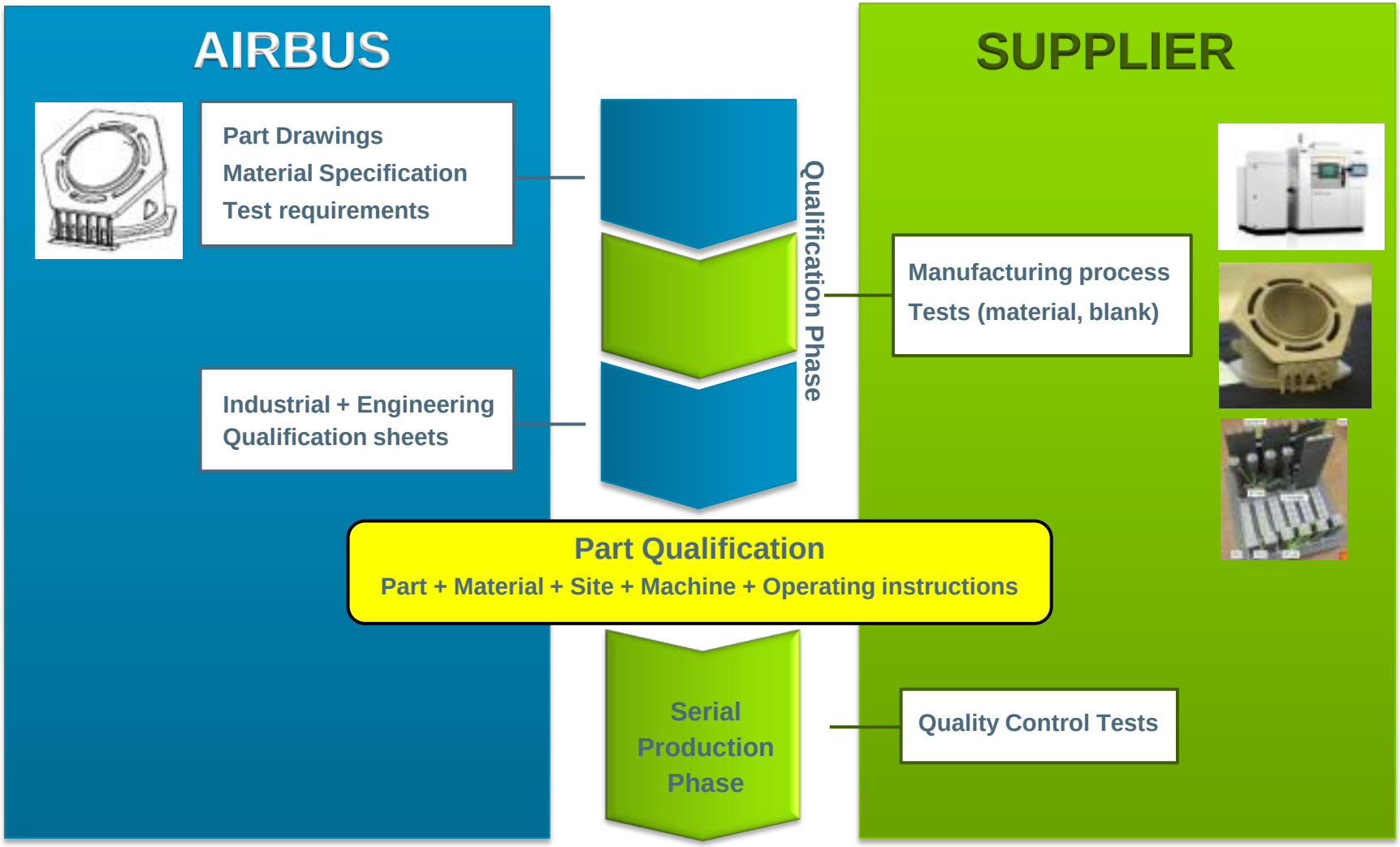
August 2018

AIRBUS

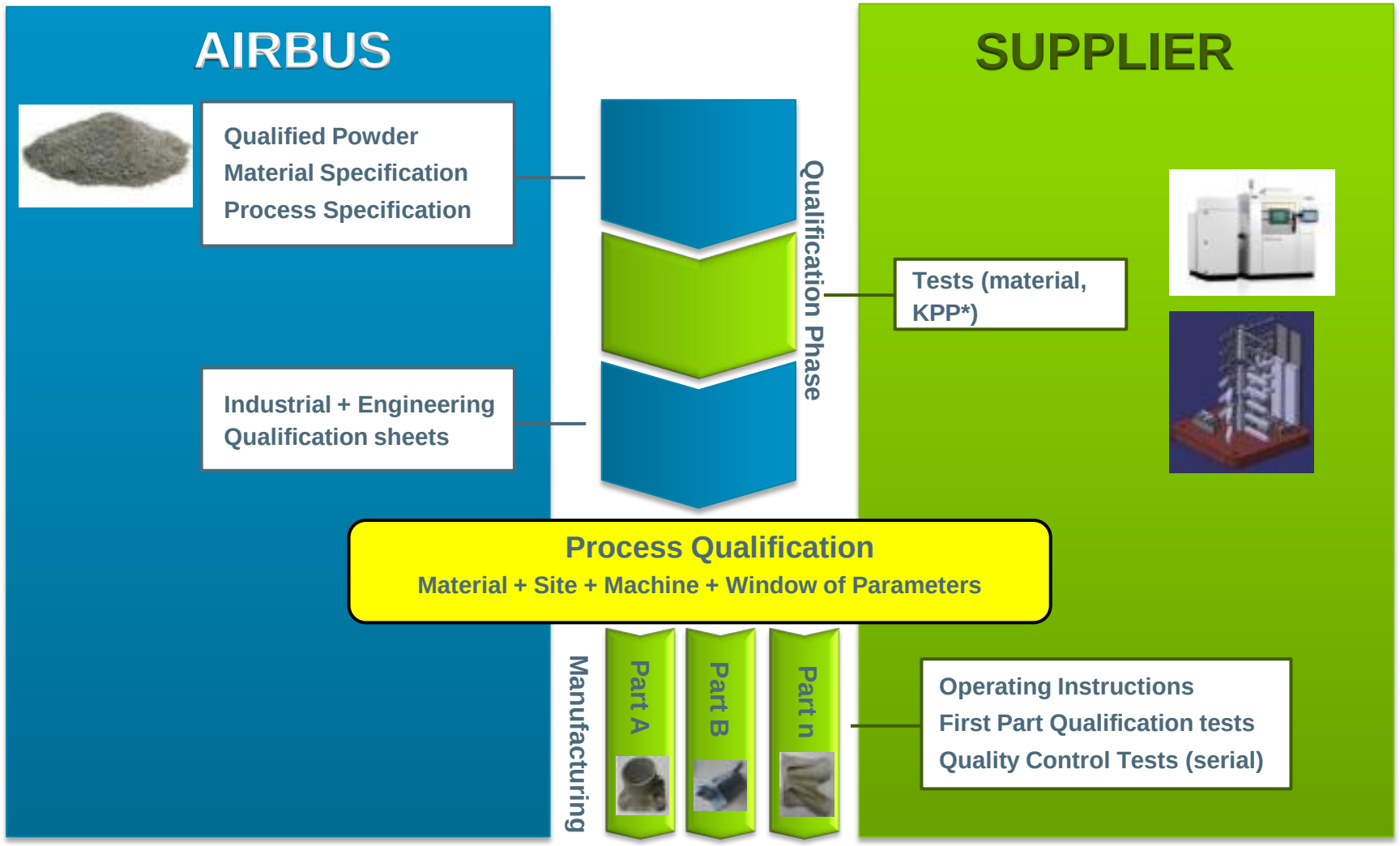
Content

- AIRBUS qualification protocol
- Feedback from first serial applications
- Conclusion

Airbus Qualification Protocol: Single Part Qualification



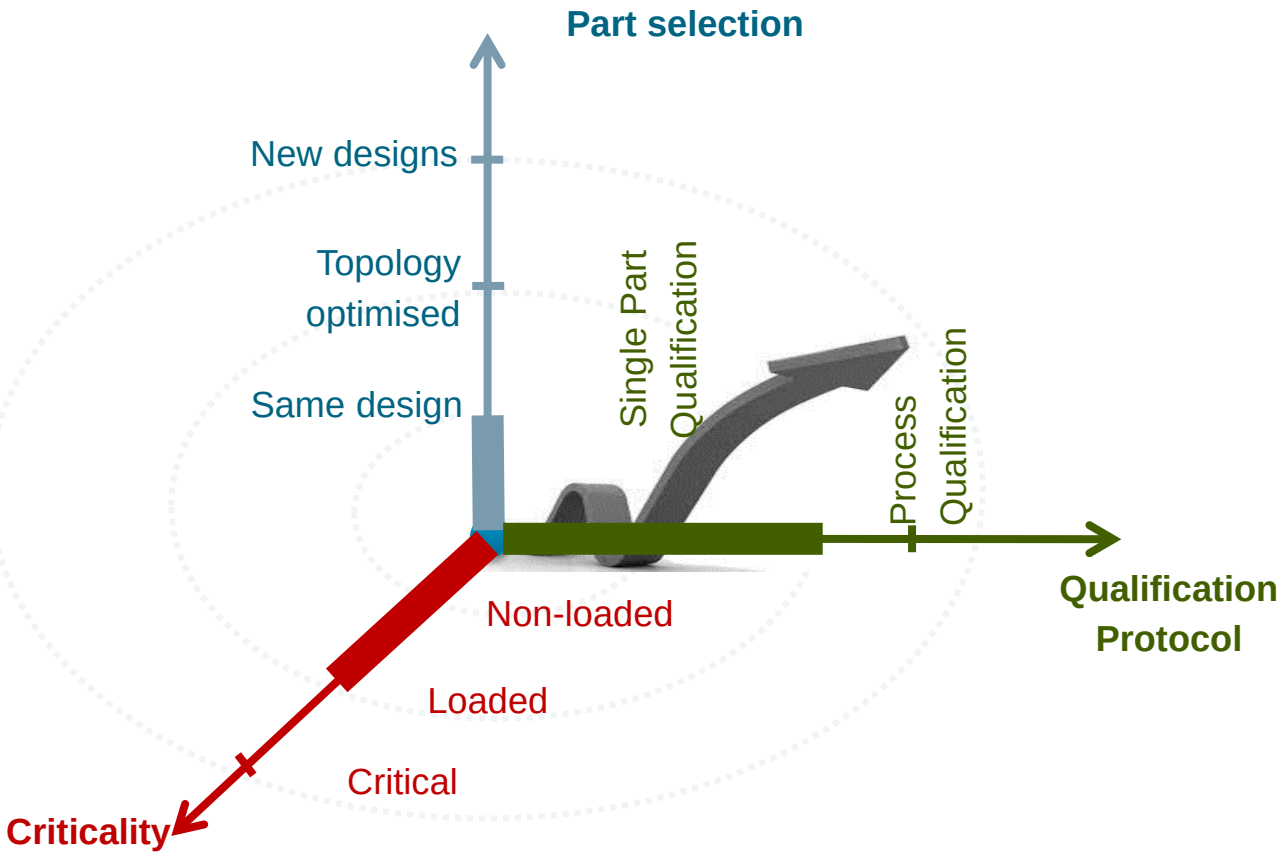
Airbus Qualification Protocol: Process Qualification



*KPP = Key Process Parameters

AIRBUS

Airbus Qualification Protocol: Stepwise introduction – Where are we?



Feedback from first serial manufacturing

Several Part Numbers already qualified using part qualification approach:

- From several suppliers
- From different machines
- From several grades

Airbus has **qualified and certified first serial AM Powder bed part**



A350 pylon Pyramid bracket



Qualified & Certified

AIRBUS

Feedback from first serial manufacturing

- **Machine maturity/stability**
- **Machine configuration management** (hardware, software)
- **Machine to machine variability**
- **Parameters setting: balance between quality and productivity**
- **NDI:**
  - Acceptable internal defect size
  - Detectability with high roughness
- **Powder feedstock management**
- **Thermal management** during printing and distortion during post processing (Heat treatment)

Covered in the Airbus qualification approach by:

- Manufacturing route frozen
- Extensive qualification with frozen parameters + Serial tests / inspections
- Systematic machine qualification
- Extensive work performed on typical AM surface to ensure external defect detection
- Feedstock and AM product specification that integrates the adequate level of inspection
- Residual Stresses managed by systematic stress relieve and/or heat treatment
- Demonstration of distortions during First Article Inspection

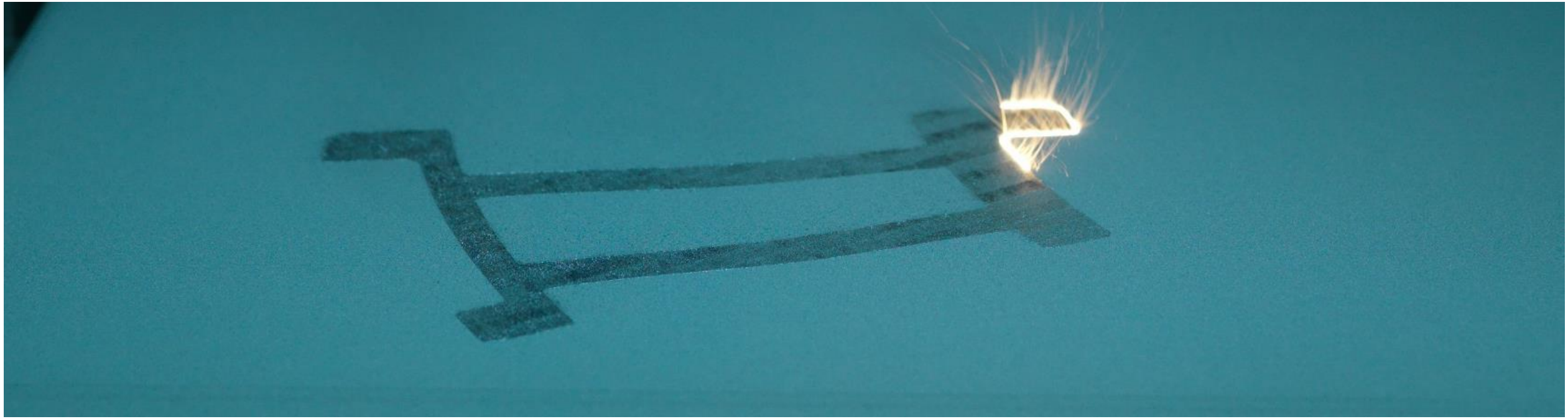
Conclusions

- Successful Progressive introduction of AM
- Qualification approach forced Supply chain to increase maturity and quality at an appropriate level
- Efficient AIRBUS qualification processes to identify and fix issues
- Qualification approach still heavy …
- Once stability of the process demonstrated, a tailoring of the requirements will be applied

Thank you!

AIRBUS

APPENDIX M
ALEXANDER LADEWIG, MTU AERO ENGINES
“QUALITY ASSESSMENT DURING LPBF-PROCESS BY OPTICAL TOMOGRAPHY INSPECTION OF SYSTEMATIC AND LOCAL DEVIATIONS”



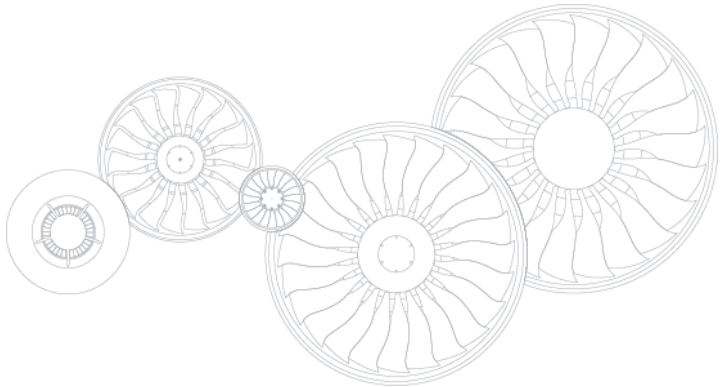
Quality Assessment during LPBF-Process by Optical Tomography

Inspection of systematic an local deviations

Wichita, KS

8/21/2018 - Alexander Ladewig, Hans-Uwe Baron, Joachim Bamberg, Anian Goegelein, Günter Zenzinger

- AM @ MTU
- Quality Assurance - Why Optical Tomography?
- OT - Systematic Deviations
- OT - Local Deviations
- Summary



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MTU Aero Engines' business model

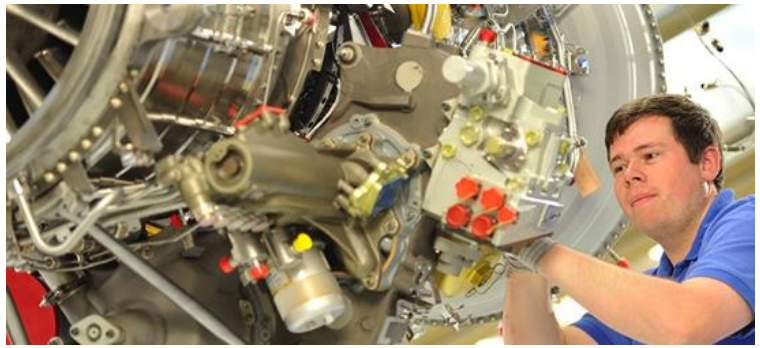
Commercial engine business



Share in sales: ~ 48%

- Balanced portfolio of products in all thrust categories
- Partnerships with OEMs going back decades

Military engine business



Share in sales: ~ 8%

- European and U.S. engine programs
- Lead industrial partner to the German Armed Forces

Commercial maintenance



Share in sales: ~ 44%

- Access to high-growth segments
- Provider of services to airlines worldwide

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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 „PW1100G-JM Boroscope boss“





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



2018
Start AM@MTU III
Focus on new design



Continuous development of manufacturing expertise and range of applications

© MTU Aero Engines AG.

AM @ MTU
Facilities



Equipment
- 6x M280 machines
- 2x M290 machines
- 1x M400-4 machine

  → **total of 9 machines**

Materials
- **IN718**
- MAR-M509
- stainless steel 316L
- Hastelloy X

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

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AM @ MTU - Parts Portfolio

Parts Class 3 in Serial Production and Class 2 in Preparation



Boroscope Boss



Sealing Carrier



Brackets

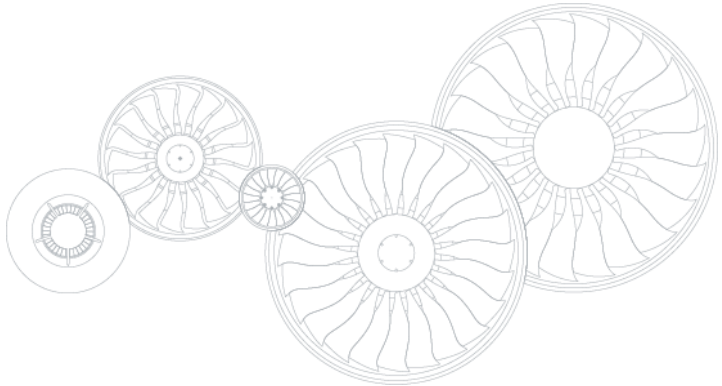


Bearing Casings

Parts portfolio with stepwise increasing criticality level

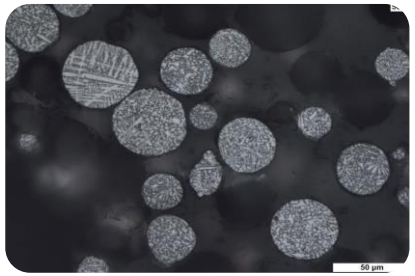
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- AM @ MTU
- Quality Assurance - Why Optical Tomography?
- OT - Systematic Deviations
- OT - Local Deviations
- Summary



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Quality Assurance
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
- CMM / blue light
- Test bars
- Cut-ups

Quality control system has to cover full range of process chain

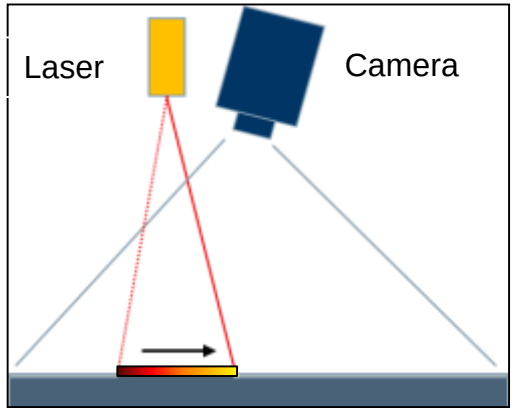
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Quality Control
Optical Tomography Principle



Long time exposure of urban traffic

→ traffic volume



Brightness in the picture equals radiation integrated over time

→ Measurement of energy per length



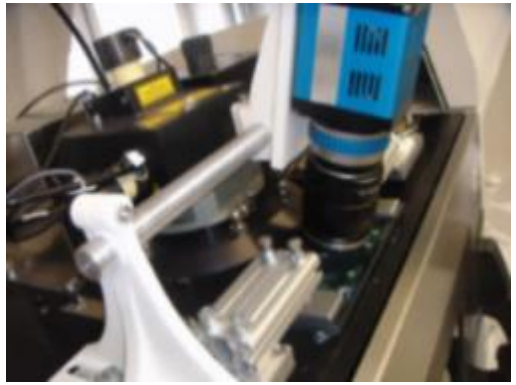
Long time exposure in additive manufacturing

→ radiation density

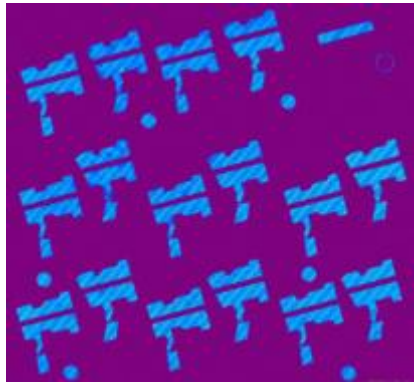
Optical Tomography is an inseparable part of MTU's machining process

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Quality Control
Optical Tomography Principle



Camera installation
for OT-System



Process surveillance for
each layer

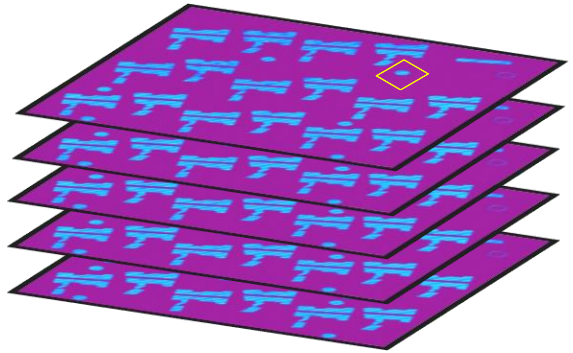
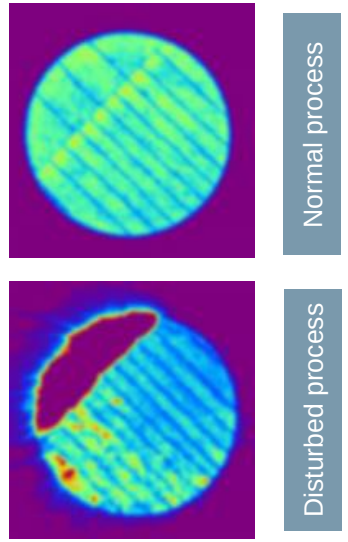


Image stack of
entire build job



Analysis and classification
based on existing correlations

- Complete monitoring of every single layer
- OT has been successfully introduced for the first serial production parts

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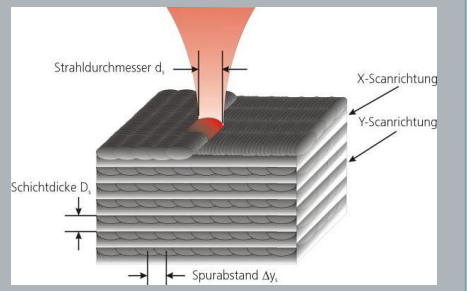
Optical Tomography

Deviation Types

Systematic Deviations

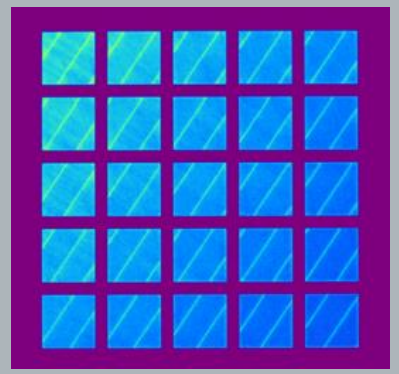
Key parameters do not conform to the specification:

- Laser power
- Scan speed
- Hatch distance
- ….



Conventional alternative to OT:

- Testing of samples (DT/NDT)
- Sacrifice parts



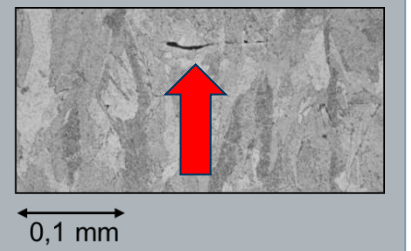
Advantage of OT:

- Significant cost reduction
- Possibility to monitor every part on all building positions

Local Deviations

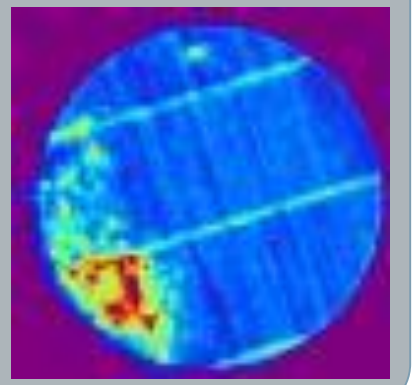
Local (random) disturbances lead to deviations:

- Removal of process by-products
- Disturbance of guided gas flow
- Powder contamination
- ….



Conventional alternative to OT:

- NDT (not for small lack of fusion)

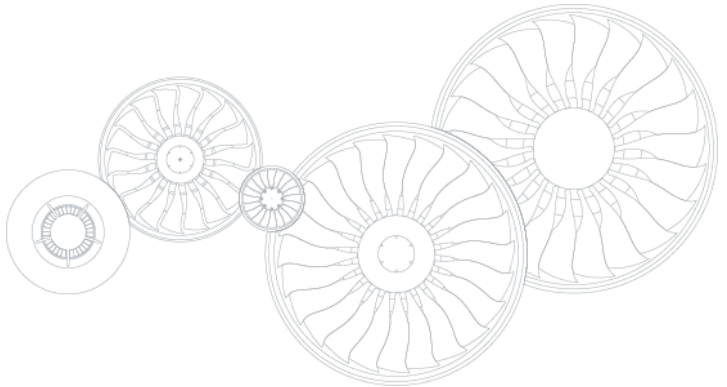


Advantage of OT:

- Significant cost reduction
- Possibility to monitor even small defects

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- AM @ MTU
- Quality Assurance - Why Optical Tomography?
- OT - Systematic Deviations
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- Summary



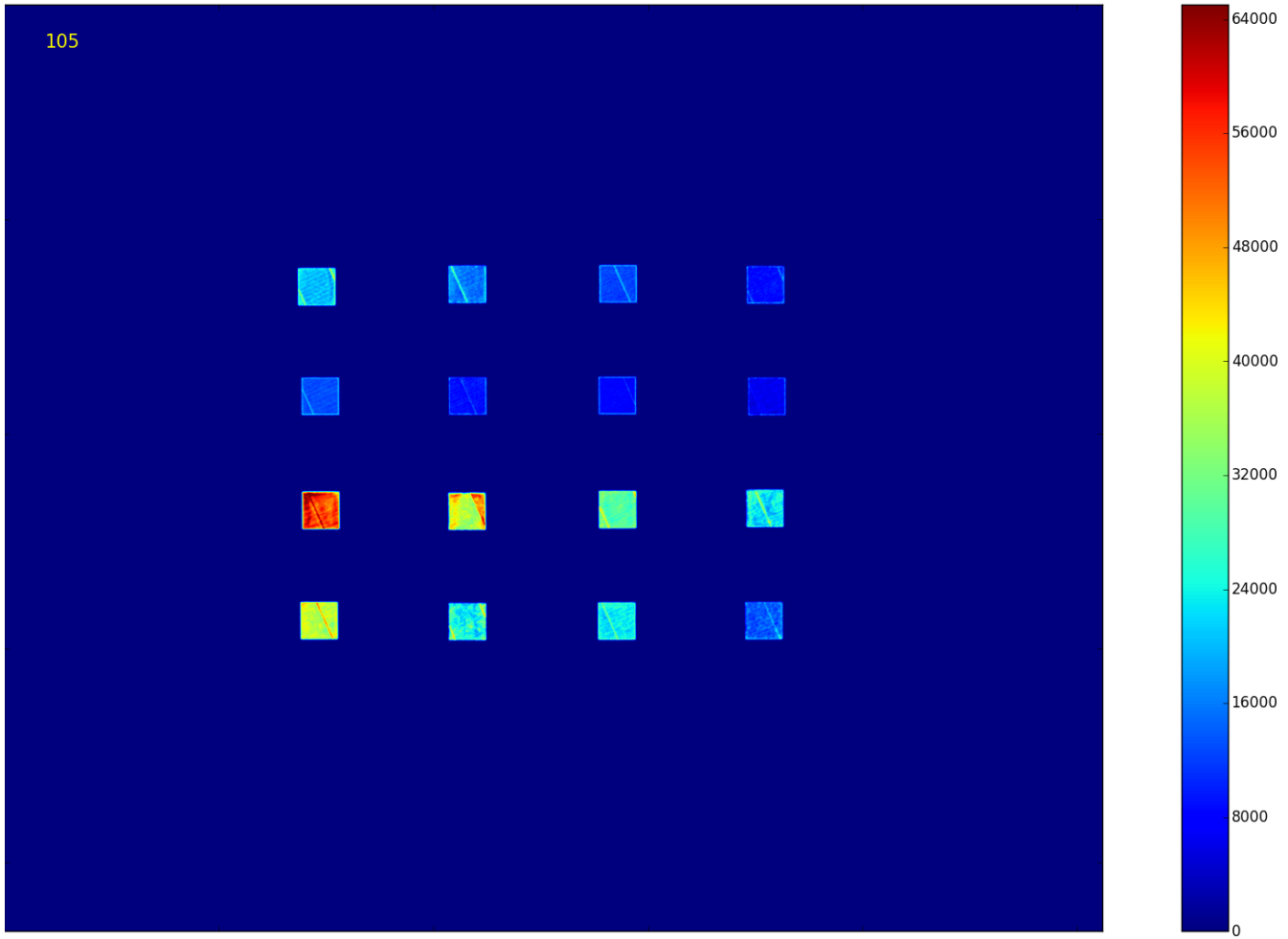
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Optical Tomography – Systematic Deviations

Evaluation of Sensitivity

Full factorial DOE

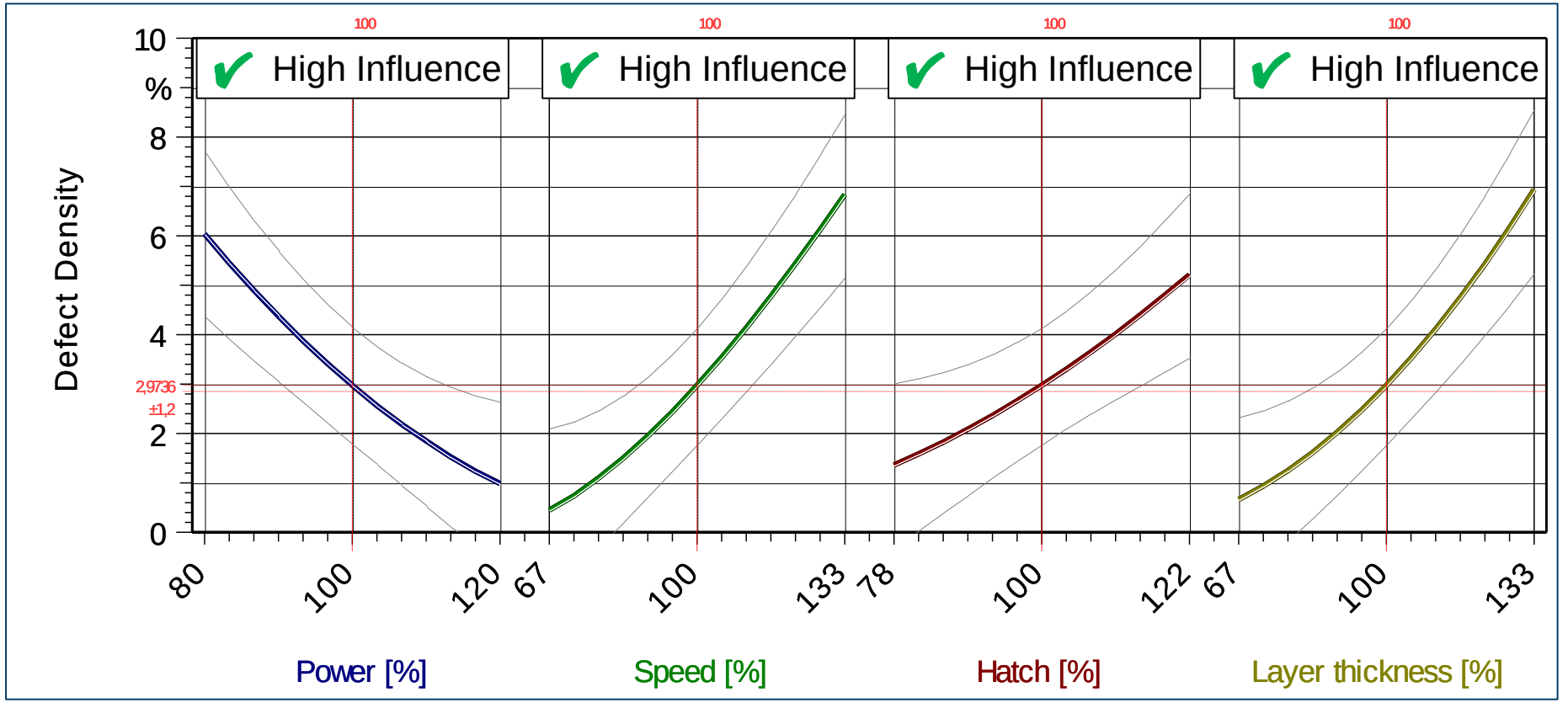
- 2 Stage variation of key parameters:
  - Laser Power, Scan Speed, Hatch, Layer Thickness
- 2 command variables
  - Defect Density – the rate of defect areas to areas with dense material measured in multiple cross sections
  - OT Average – the average greyvalue measured over multiple layers
- High Coefficient of Determination R^2:
  - OT average: 0.99
  - Defect density: 0.97



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Optical Tomography – Systematic Deviations

Evaluation of Sensitivity

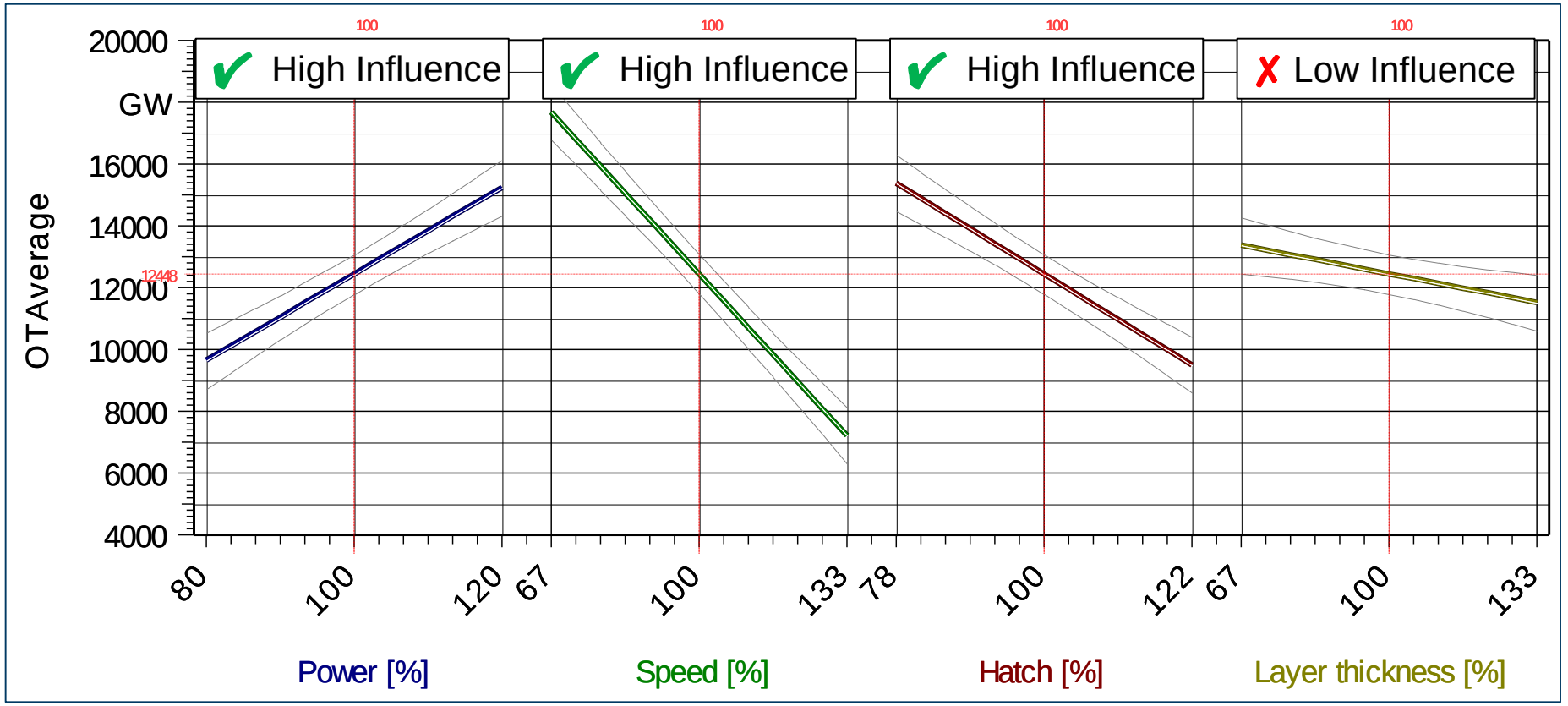


- All parameter variations show a high impact on material quality
- Defect density increases with a reduction of laser power or an increase in scan speed, hatch distance and layer thickness

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Optical Tomography – Systematic Deviations

Evaluation of Sensitivity



- The parameters Power, Speed, Hatch have high influence on the measured OT value → Monitoring is possible
- Layer thickness has only poor influence → has to be monitored by a separate system

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Optical Tomography – Systematic Deviations

OT-Signature

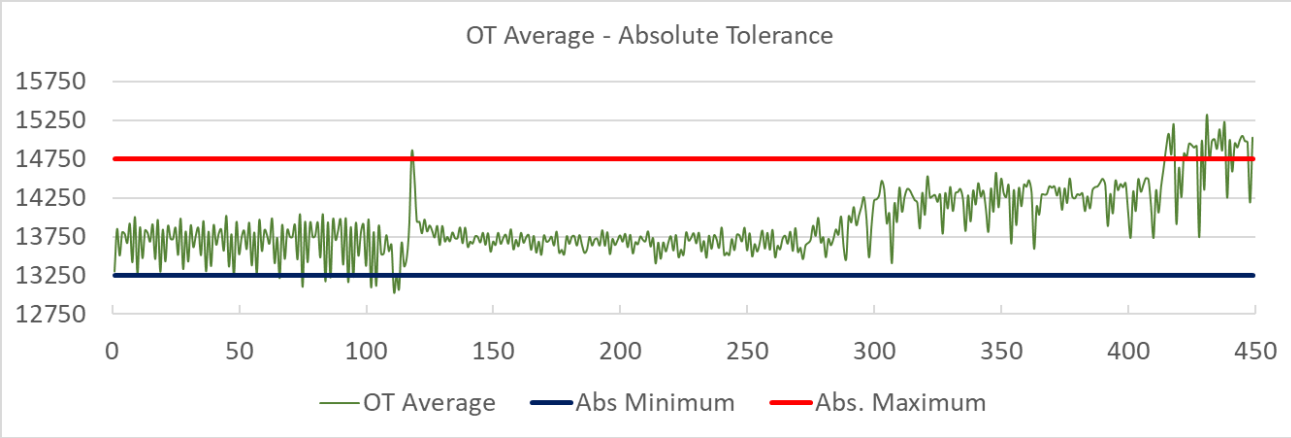
Additional factors influence the OT value such as:

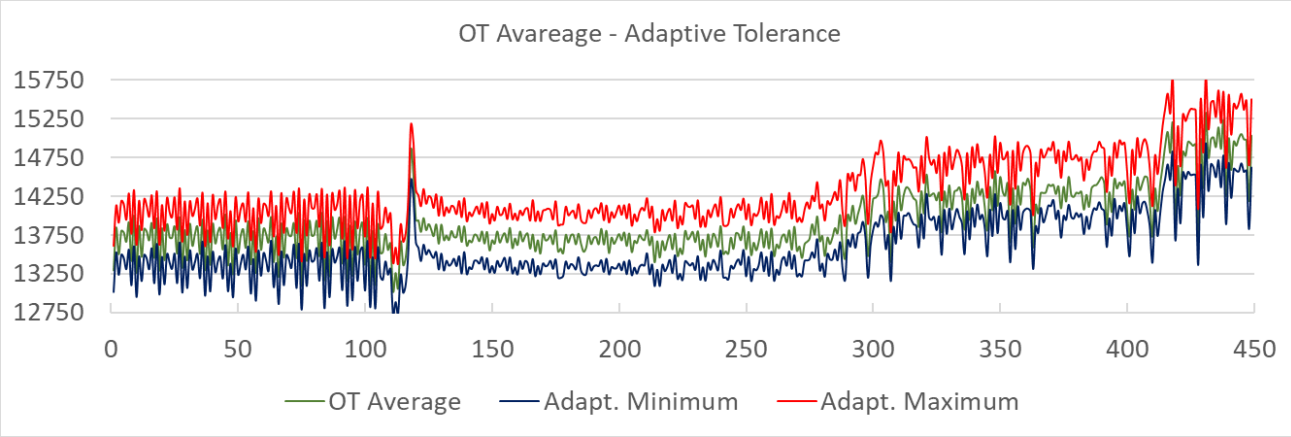
- Building height
- Overhanging structures
- Hatch Strategy
- Hatch Angle

  → every job has a specific signature

Different possibilities for evaluation in production:

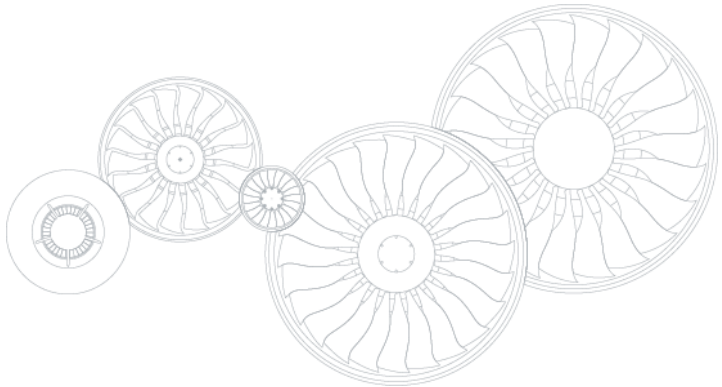
- Defined absolute range applied on all layers
- Experimental evaluation of tolerances for every layer
- Simulation of tolerances for every layer





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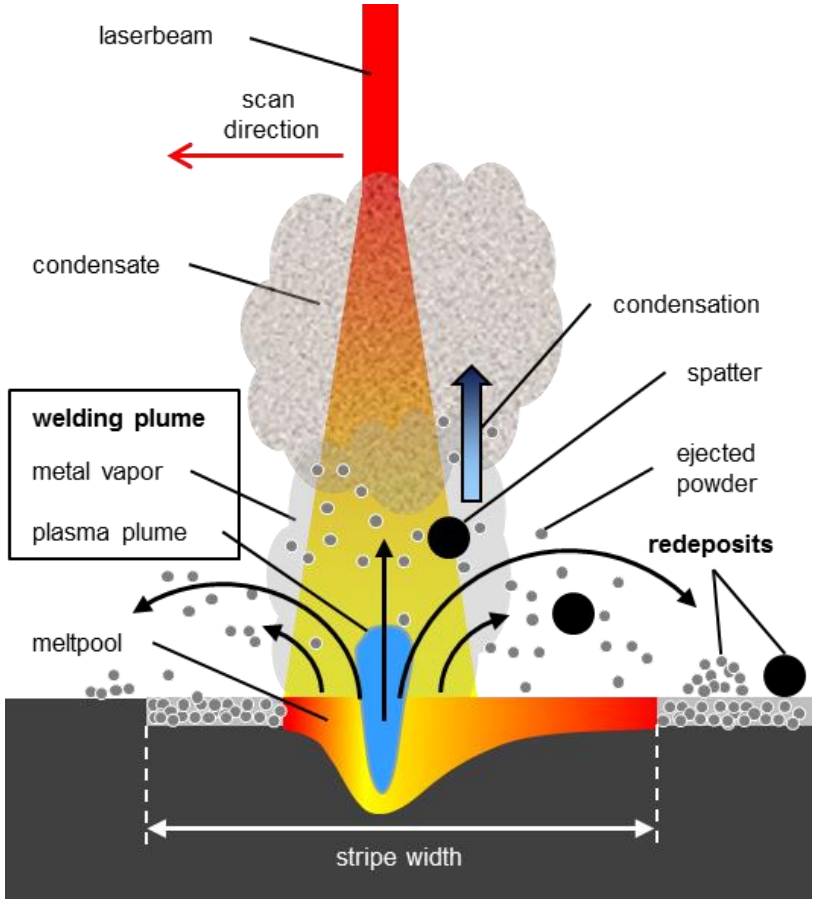


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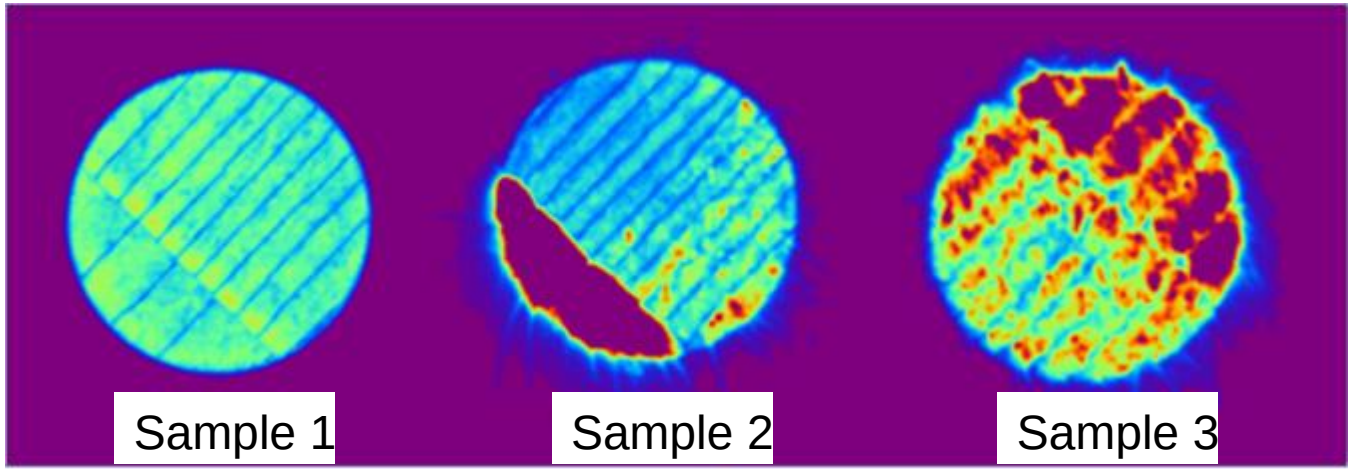
Optical Tomography – Local Deviations

Local Deviations induced by process by-products

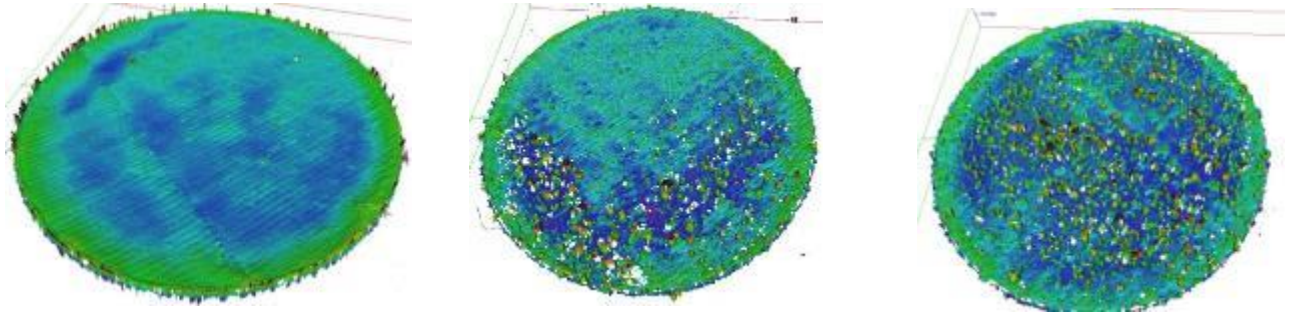
Process by-products during LPBF



OT Images without (1) and with indications (2 and 3)



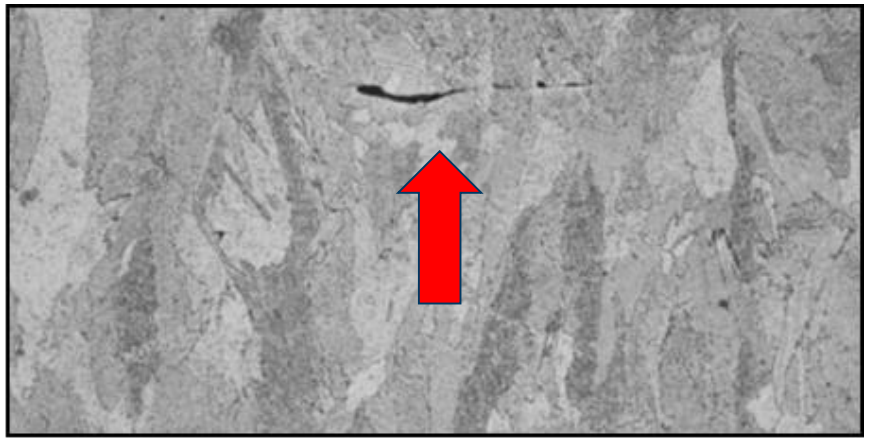
Resulting Surface Topography



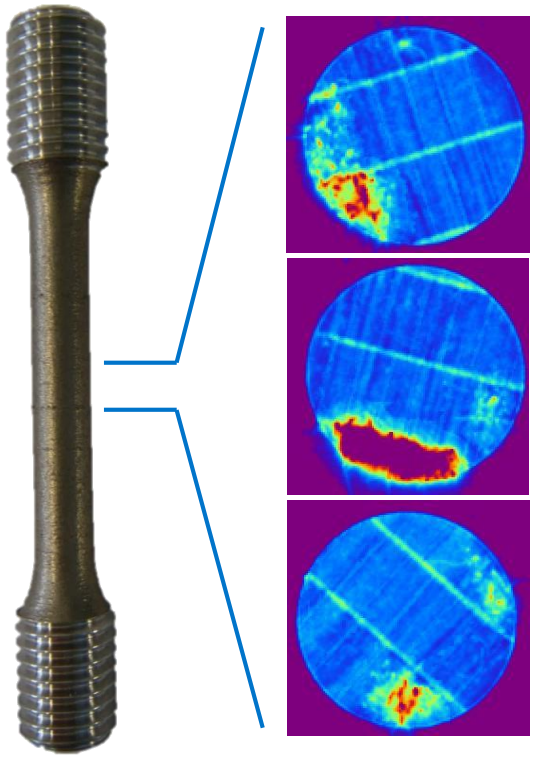
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Optical Tomography – Local Deviations

Local Deviations lead to lack of fusion defects

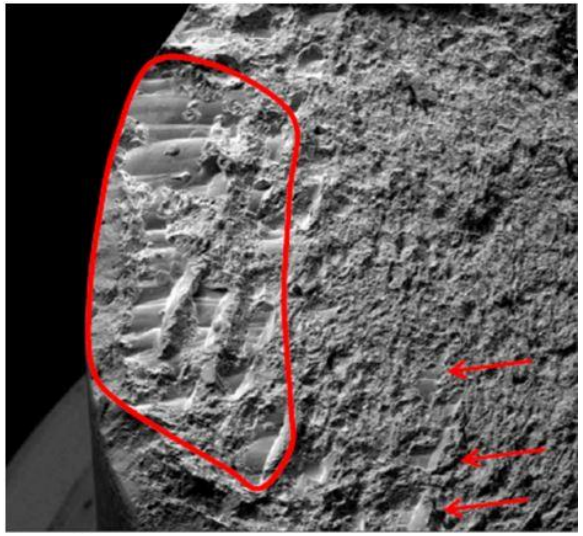


Metallographic Cross-section



Tensile specimen

OT-Images



fracture pattern

Internal defect → NO FPI

3D part geometry → NO UT

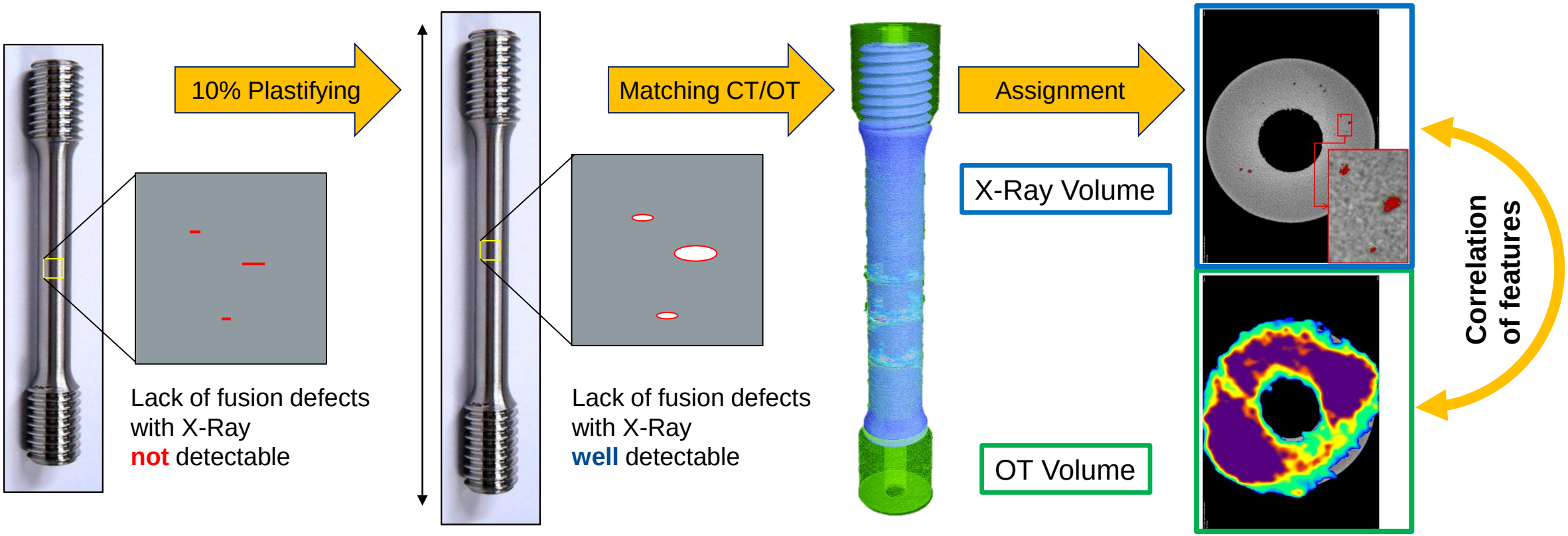
Too small compared to part thickness → NO X-Ray

- Small lack of fusion defects are very difficult to detect by conventional NDT
- Their negative effect on fatigue life is severe

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Optical Tomography – Local Deviations

Building up a correlation between OT-indication and defect size

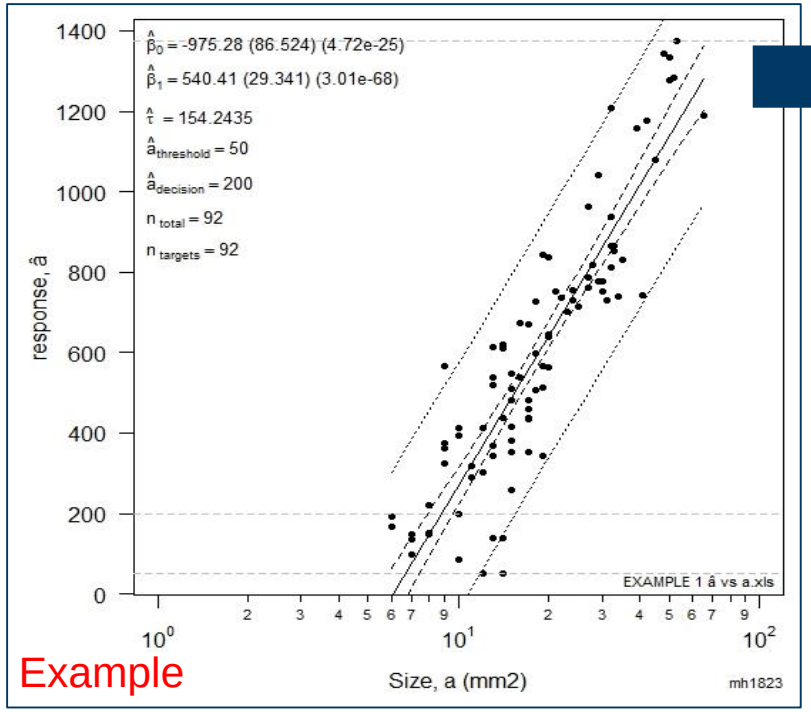


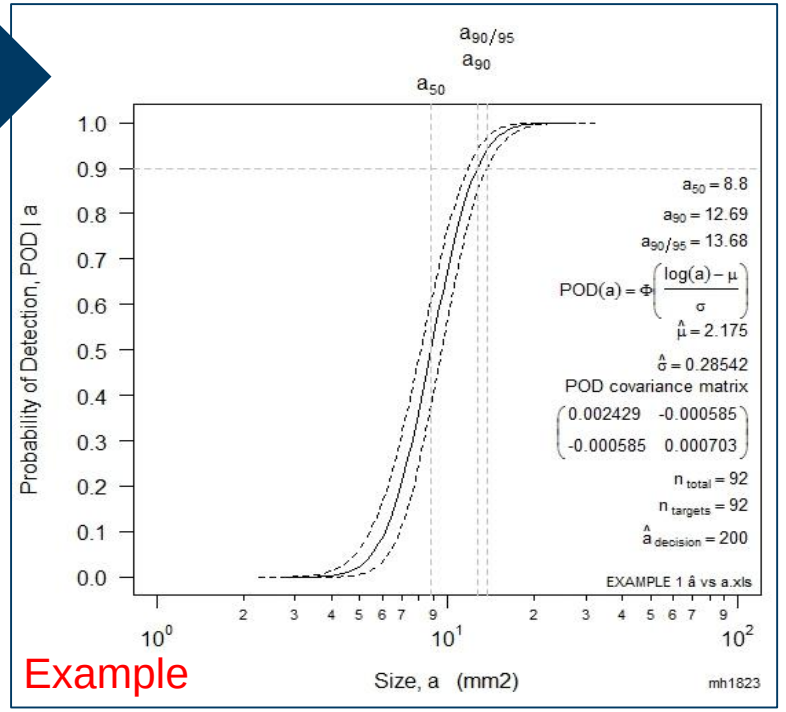
- Correlation between lack of fusion defects and OT-Indication is possible by “PlastiX” method

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Optical Tomography – Local Deviations

From Online Monitoring to Online Inspection – POD for lack of fusion caused by defocussing





POD for OT:

- More than 150 data pairs as base for the POD
- No false negative observed (defect without OT-Indication)
- a90/95 POD for defect size <300 µm reached

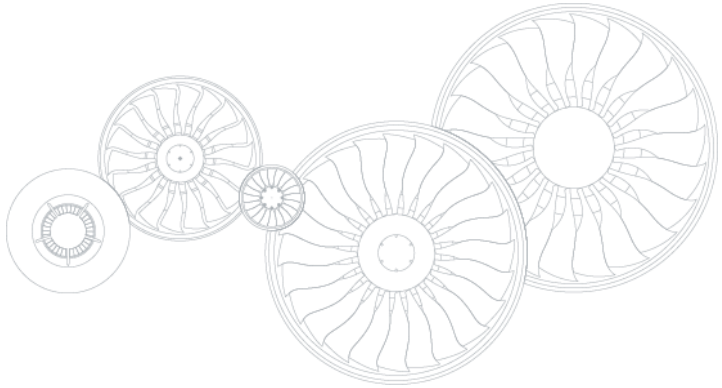
→ Goal: Approve OT as inspection system for defined defect types

â = Feature of OT-Indication
a = Real defect size

← determined by OT evaluation software
← measured from X-Ray data

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- AM @ MTU
- Quality Assurance - Why Optical Tomography?
- OT - Systematic Deviations
- OT - Local Deviations
- Summary



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Summary and Outlook

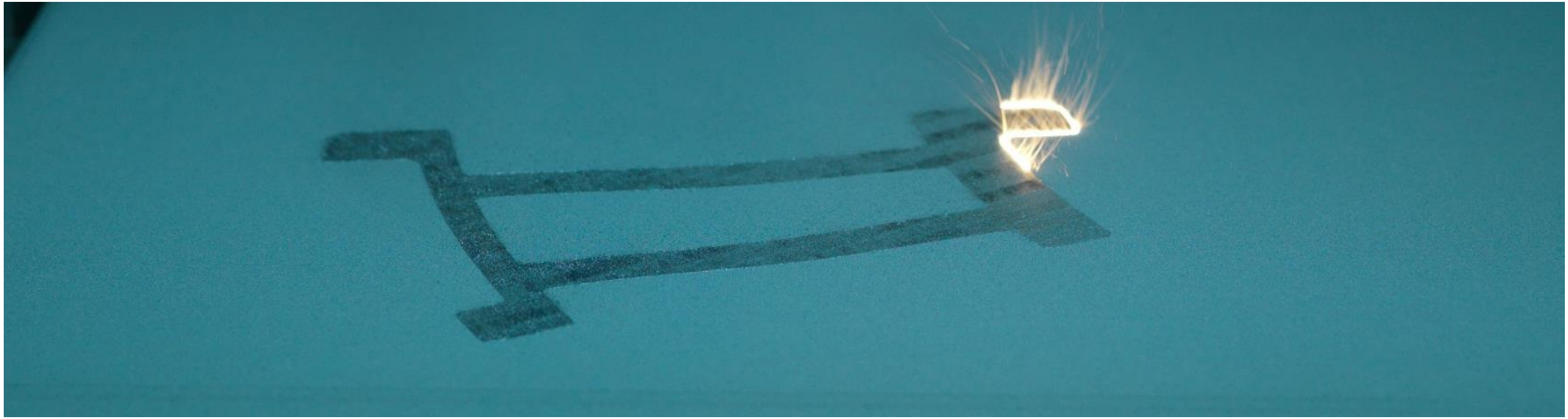
Current state:

- OT is applied on all machines at MTU (M400-4 upcoming)
- As monitoring system successfully introduced for production parts (borescope bosses)
- Enables monitoring of key parameters and therefore systematic deviations
- Local deviations can be correlated to defect sizes which enables the creation of PODs
- The System is commercially available for M290 machines of EOS

Outlook:

- Further development of the OT data analysis algorithms
- POD studies for other OT Indications
- Application of OT for other SLM systems
- OT approval as a non-destructive testing method

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Thank you for your attention!

APPENDIX N
MICHAEL GORELIK AND MARK FREISTHLER, FAA
“FAA REGULATORY UPDATE ON AM”

Update on FAA *Metal* AM Activities

Federal Aviation Administration



Presented at:

Joint FAA – EASA AM Workshop

August 21, 2018

Wichita, KS

Update on FAA AM Activities

- **AM Roadmap draft – completed first round of senior management reviews.**
  - Timescale overlapped with significant FAA reorganization in 2017/2018 (a.k.a. *AIR Transformation*).
  - Being reviewed through the prism of the new organizational vision
- **Several documents in the works**
  - Engineering, manufacturing, maintenance certification considerations
  - Work in progress – various levels of maturity and/or internal approvals
- **Active engagement with SDOs**
  - SAE, ASTM, AWS, AMSC, …
- **Development and initiation of a multi-year R&D plan**
- **Re-chartering of AM National Team (AMNT) – *in progress***
- **Continuing engagement with government agencies**

Update on FAA AM Activities (cont.)

- ***Draft* Advisory Circular: AC 33.15-4**
  - "*Guidance Material for Turbine Engine Parts and Repairs Produced by Powder Bed Fusion Additive Manufacturing*"
  - ➢ ***Tim Mouzakis, FAA***

- **Update on AM-related MMPDS activities**
  - ➢ ***Mark Freisthler, FAA***

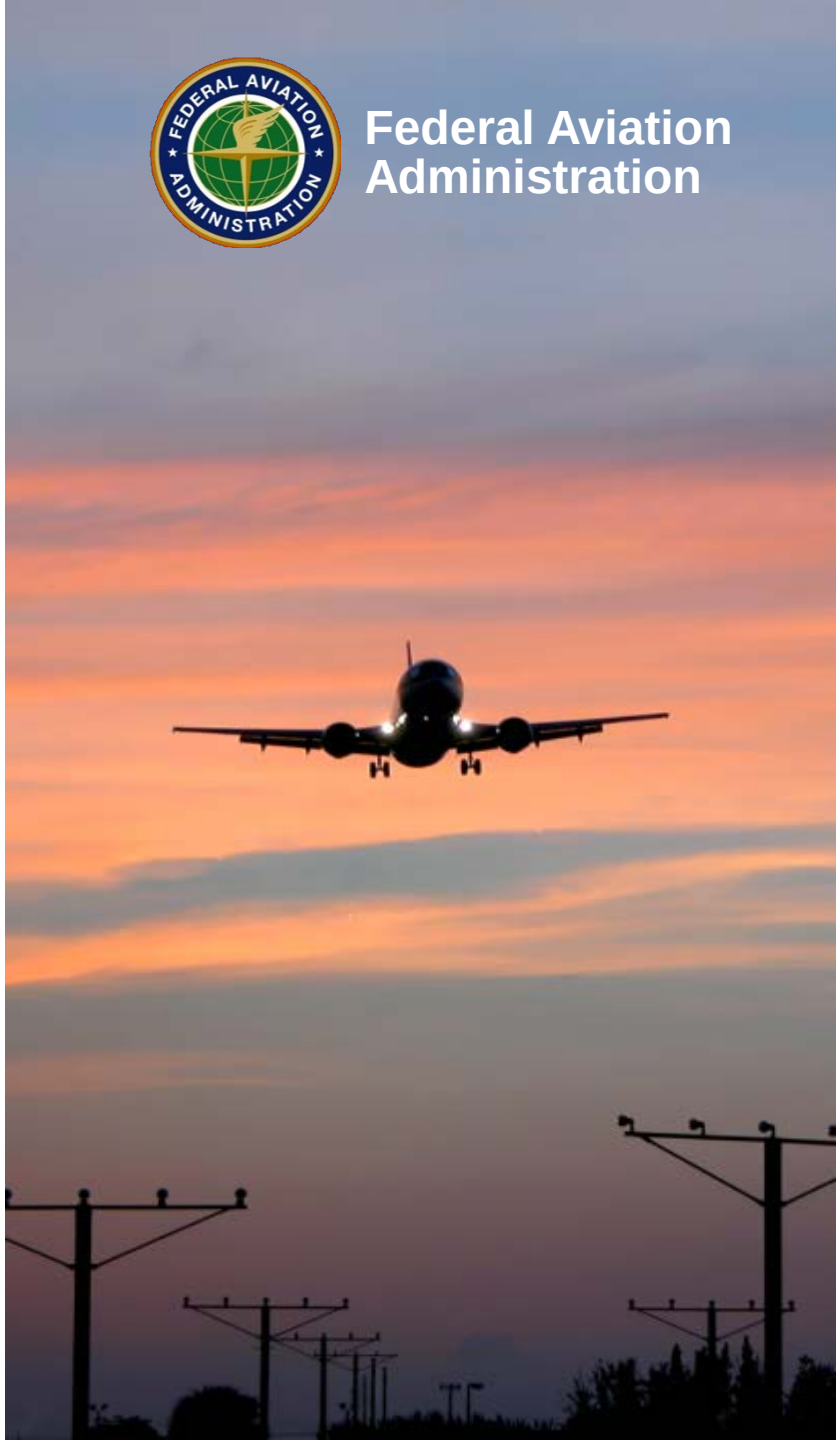
Draft Advisory Circular 33.15-4

Guidance Material for Turbine Engine Parts and Repairs Produced by Powder Bed Fusion Additive Manufacturing Process

Presenter: Tim Mouzakis, AIR-6A0

Date: August 21 2018

Federal Aviation Administration



Advisory Circular 33.15-4

Background:

- General Memo No. AIR100-15-130-GM39, *Additive Manufacturing Awareness*
- General Memo No. AIR100-16-130-GM18, *Engineering Considerations for Powder Bed Fusion Additively Manufactured Parts*
- 15 industry specifications already issued related to various aspects of additive manufacturing … many more under development

Advisory Circular 33.15-4

Objective: Describe acceptable means for demonstrating compliance with 14 CFR 33.15 requirements

§ 33.15 Materials

The suitability and durability of materials used in the engine must—

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

(b) Conform to approved specifications (such as industry or military specifications) that ensure their having the strength and other properties assumed in the design data.

Advisory Circular 33.15-4 (cont.)

PUBLIC COMMENT PHASE

U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: Guidance Material for Turbine Engine Parts and Repairs Produced by Powder Bed Fusion Additive Manufacturing Process

Date: MM/DD/YY **AC No:** 33.15-4
Initiated By: AIR-6A1

1 **PURPOSE.**

This advisory circular (AC) describes an acceptable means for demonstrating compliance with Title 14, Code of Federal Regulations (14 CFR) 33.15 for turbine engine parts and repairs with materials produced by the powder bed fusion (PBF) additive manufacturing (AM) process. Guidance is also presented on closely related design and manufacturing aspects associated with AM.

https://www.faa.gov/aircraft/draft_docs/ac/

Advisory Circular 33.15-4 (cont.)

Key Focus Areas:

- Establishing Robust Material Design Allowable Values
  - Must reflect the variability of feedstock materials AND variability associated with the manufacturing process
  - Must represent part features that can impact design allowables
- Highlighting Related Design and Manufacturing Aspects
  - Part design considerations (e.g. thermal exposures, part feature debits)
  - Part orientation considerations (e.g. overhanging surfaces, anisotropy)
  - Post processing considerations (e.g. support removal, residual stress relaxation)

Advisory Circular 33.15-4 (cont.)

Key Focus Areas (cont.):

- Inspection Methods Considerations
  - Placement of NDI within the manufacturing process sequence
  - Selection of NDI techniques to be used
  - Inspection of rough surfaces, complex geometries & internal features
- Part Qualification Considerations
  - Establishing a “fixed” process
  - Qualifying multiple machines
  - Periodic destructive evaluation of parts
  - Changes to significant process characteristics

Status and Next Steps

- **AC is currently out for public comments.**
  - Comments period closes on 22-08-18
- **Next steps:**
  - Disposition of internal comments
  - Disposition of public comments
  - Legal review
- ***Expected* publication date – Q2 2019**

MMPDS Emerging Technology Working Group

Mark Freisthler
August 21, 2018



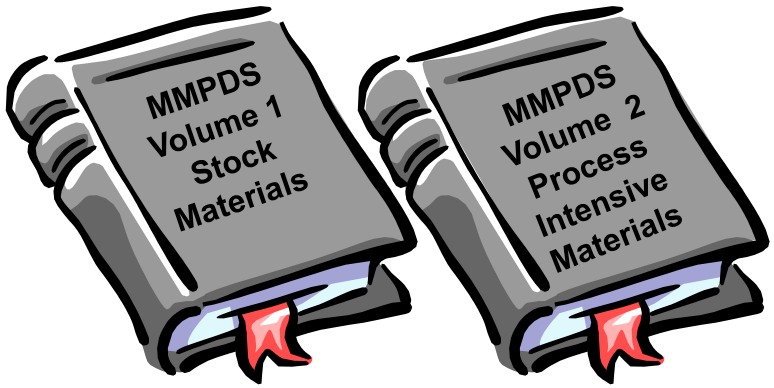
ETWG Scope

- **The Emerging Technology Working Group (ETWG) is focused on:**
  - Development of processes and procedures best suited to derive and publish design information for process intensive materials such as Additive Manufacturing
  - Assess the validity of public material specifications, establish data submission requirements and determine information to be published in material data tables
  - Determine the limitations of data published, along with guidance to data users on the use of data tables.

- **Active ETWG members are sought from all segments of the aerospace industry and government, representing AM suppliers and users throughout the world. Users and Suppliers from other industries are welcome to participate in the group's discussions.**

ETWG Vision
Create Separate Document for PIM

- General agreement within the MMPDS to split the current Handbook into two Volumes,
  - Traditionally produced Materials.
  - Process intensive materials (PIM).
    - ✓ New process intensive and associated guidance would be contained in Volume 2



ETWG Challenges

- **MMPDS is exploring the publication of document containing guidance and material properties for PIM (namely additive manufacturing), however:**
  - Industry standards are limited.
  - Need to develop approved processes and procedures for using statistical based tools for “equivalency”
  - A lot of guidance needs to be developed before a new companion document for PIM is published.
  - PIM will not be integrated in the current MMPDS volumes (special guidance will be needed and the integrity of currently published values must be maintained.)

Sample of ETWG Questions

- **Given the development of SAE process specifications for additive materials, does MMPDS need to define some required processing requirements for data generations?**
- **Assuming that MMPDS adopts the "shared database" approach to AM properties, (similar to what is done for composites for CMH-17), do we want to limit our initial work to "B" basis only?**
- **Based on our review on SAE specification, can we reach an agreement on the data submission requirements?**
  - Will we accept "purpose built test specimens" or require specimens extracted from representative parts?
- **What guidance will we needed to put in place for potential data users in order to follow the "shared database" approach?**

APPENDIX O
DON PALMER, BOEING
“CERTIFICATION AND QUALIFICATION OF AM PARTS”



Engineering, Operations & Technology
Boeing Research & Technology

Qualification and Certification (and NDE) of Additive Manufacturing

FAA – EASA AM Workshop

Don Palmer, Rigo Perez, Kevin Slattery

21-Aug-2018

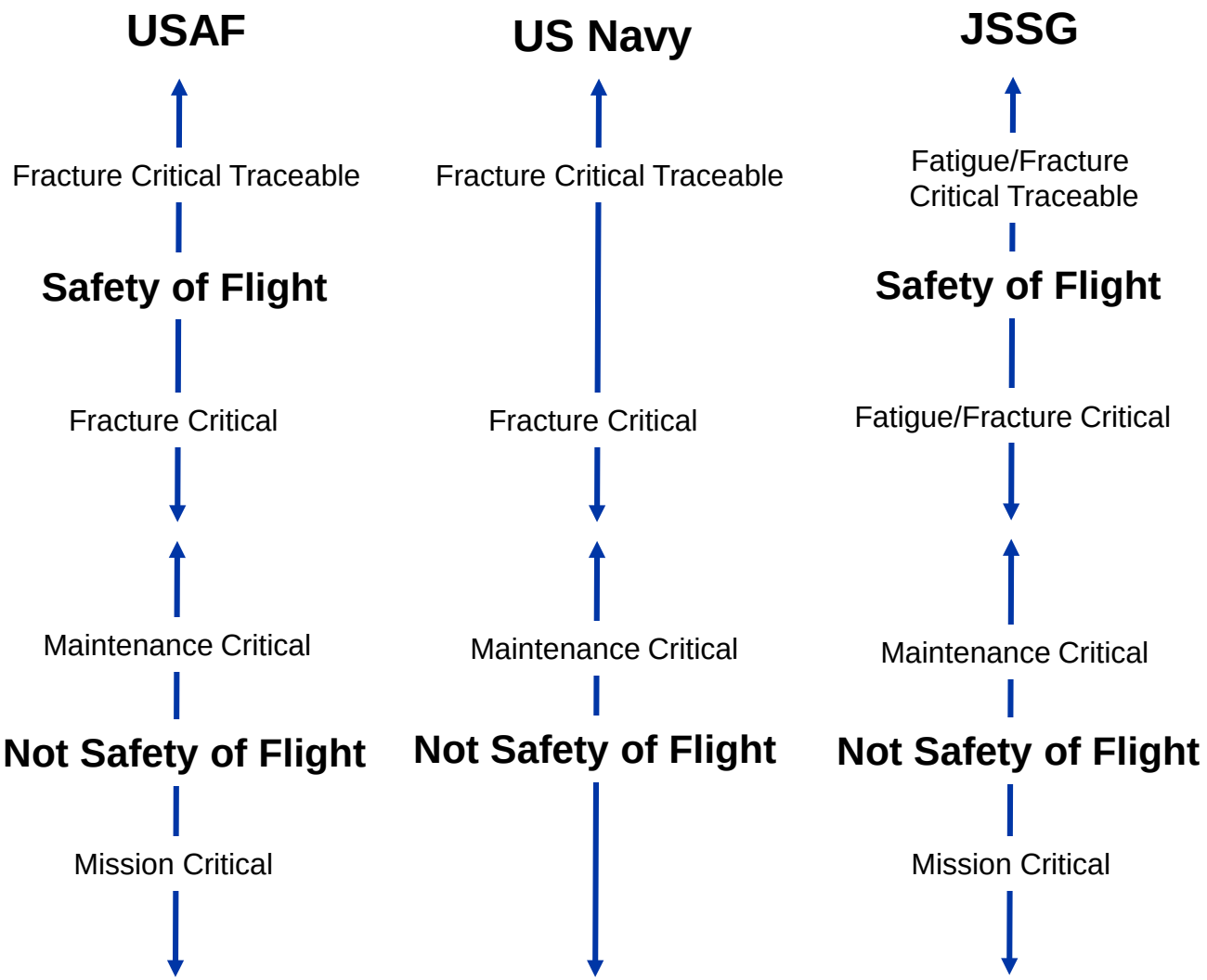
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Overview

- Part Criticality Terminology
- Definition of Risk
- Certification and Qualification Program Elements
- Case Study Summary
- NDE Considerations
- Future Vision for Additive Manufacturing NDE
- Conclusions

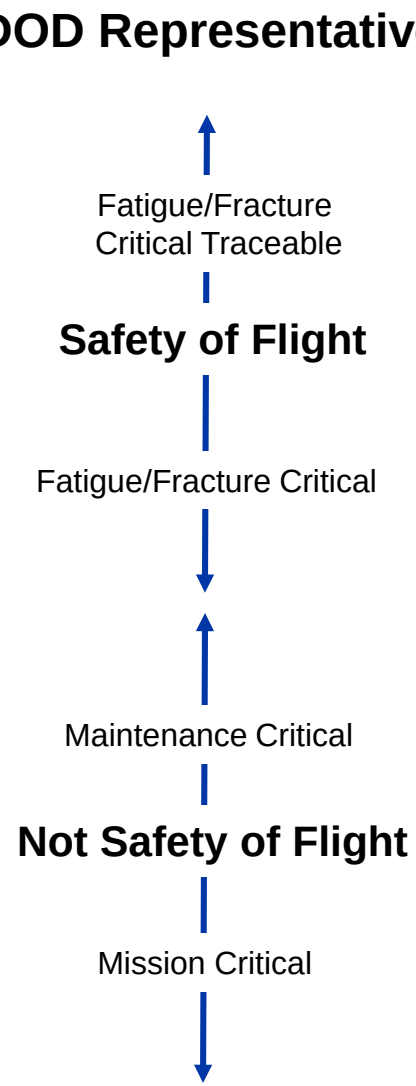
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Part Criticality – DOD Terminology Comparison



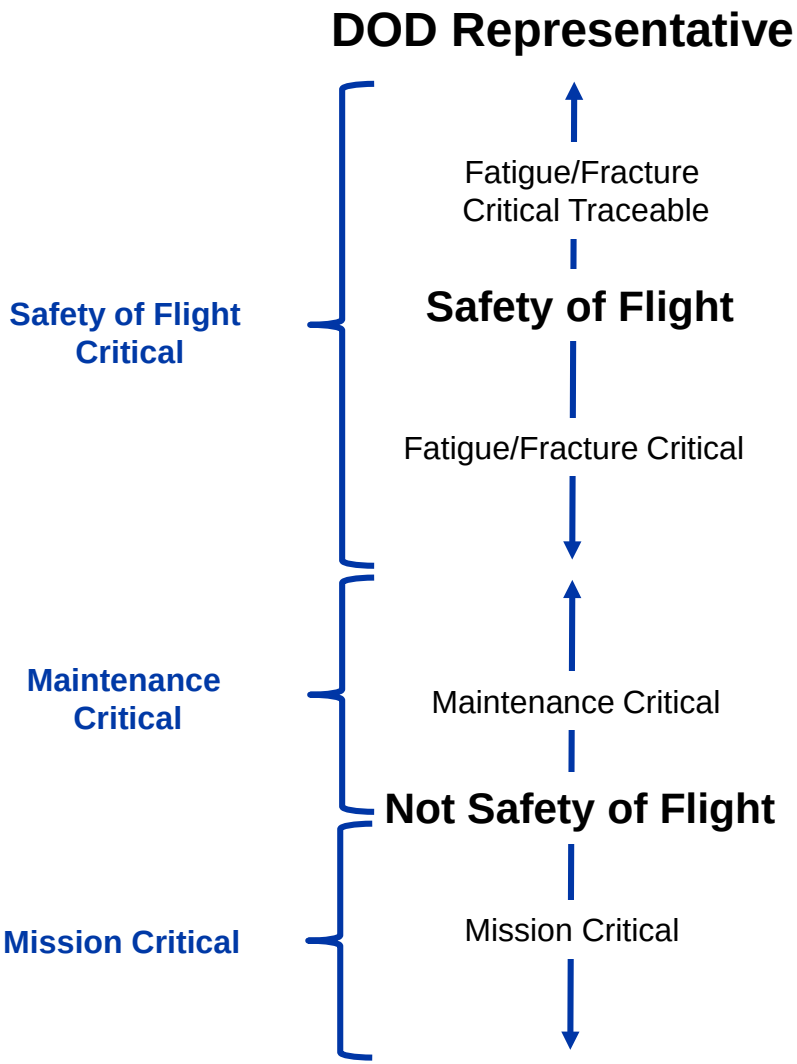
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Part Criticality – Representative DOD Terminology



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Part Criticality – Concise DOD Terminology



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Definition of Risk

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Definition of Risk

Life Cases
- Production – Full Life
- Short Run – Long Life
- Short Run – Limited Life

Criticality
- Safety of Flight Critical
- Maintenance Critical
- Mission Critical
- Not Critical

Loading
- Ti – Replace Ti
- Al – Replace Al
- HSA – Replace LSA (e.g., Ti Replace Al)

HSA – Higher Strength Alloy
LSA – Lower Strength Alloy

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Definition of Risk

Increasing Risk



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Increasing Role of NDI

HSA – Higher Strength Alloy
LSA – Lower Strength Alloy

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Definition of Risk

Increasing Risk

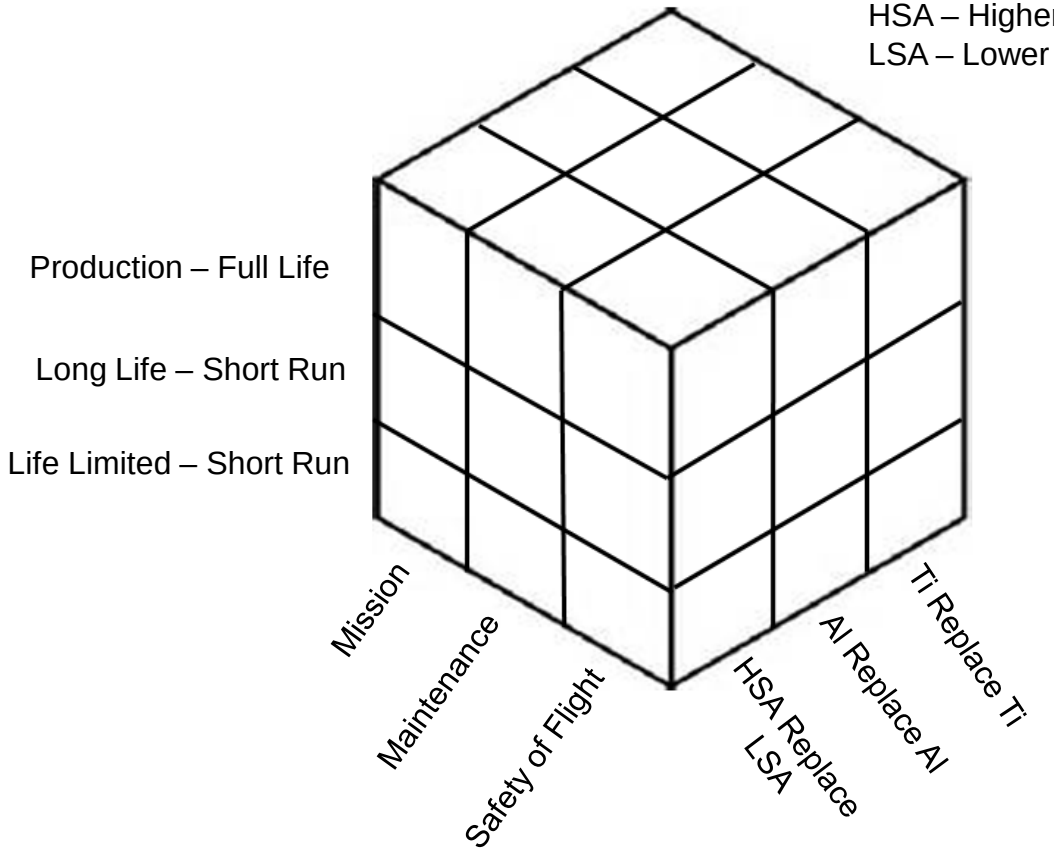
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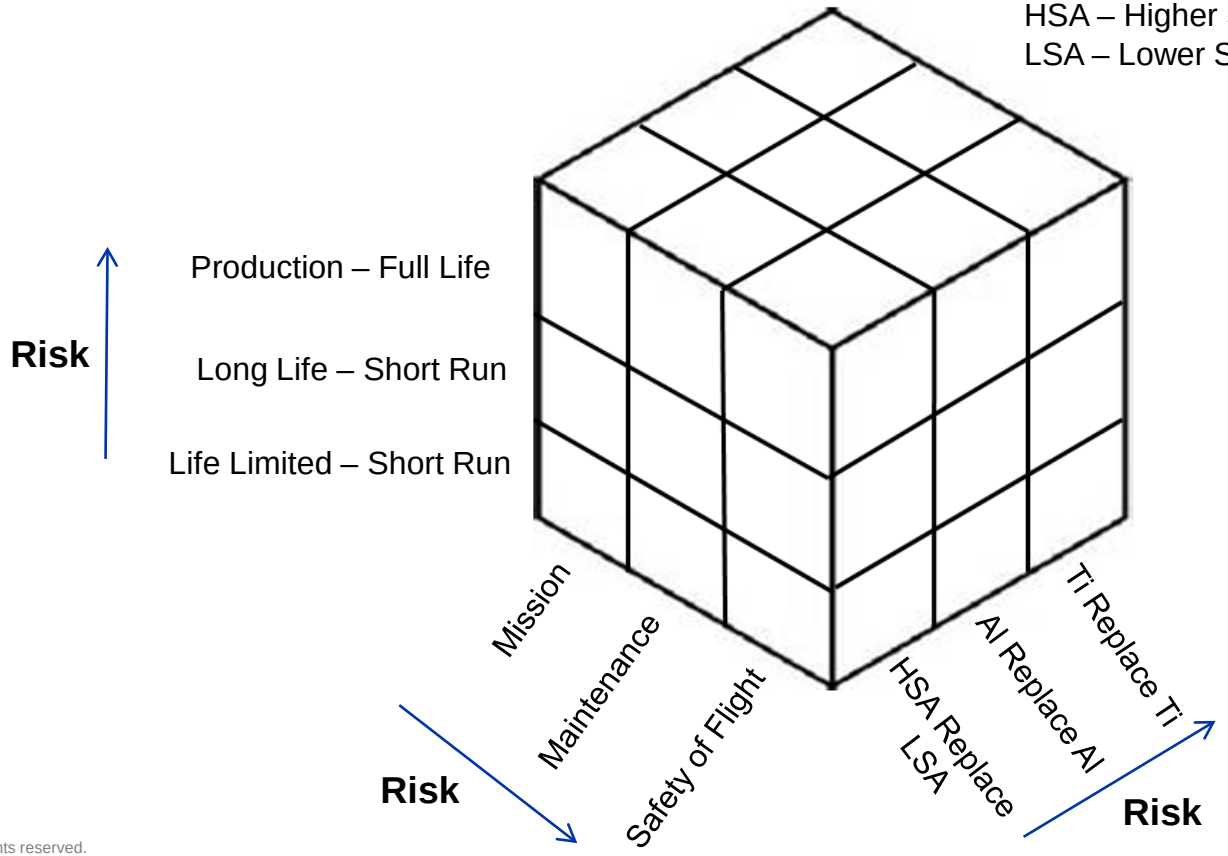
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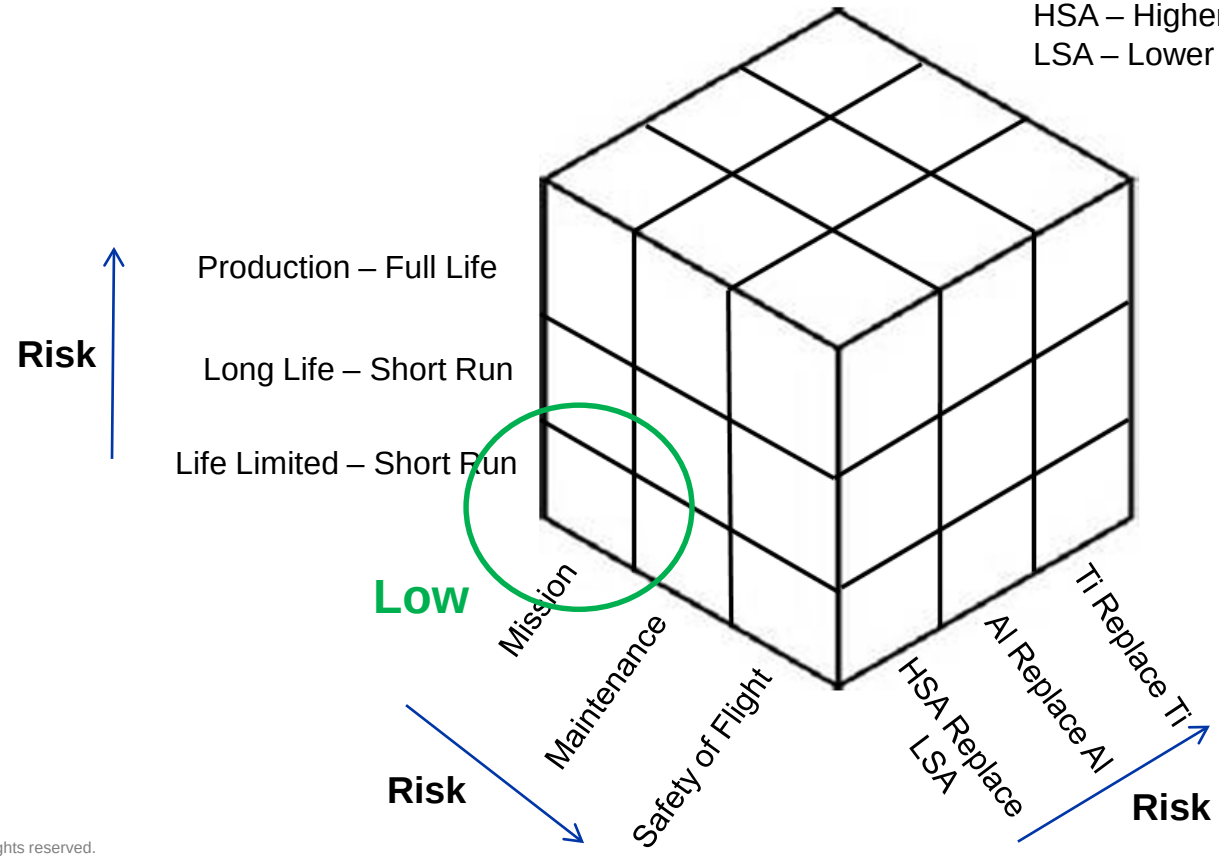
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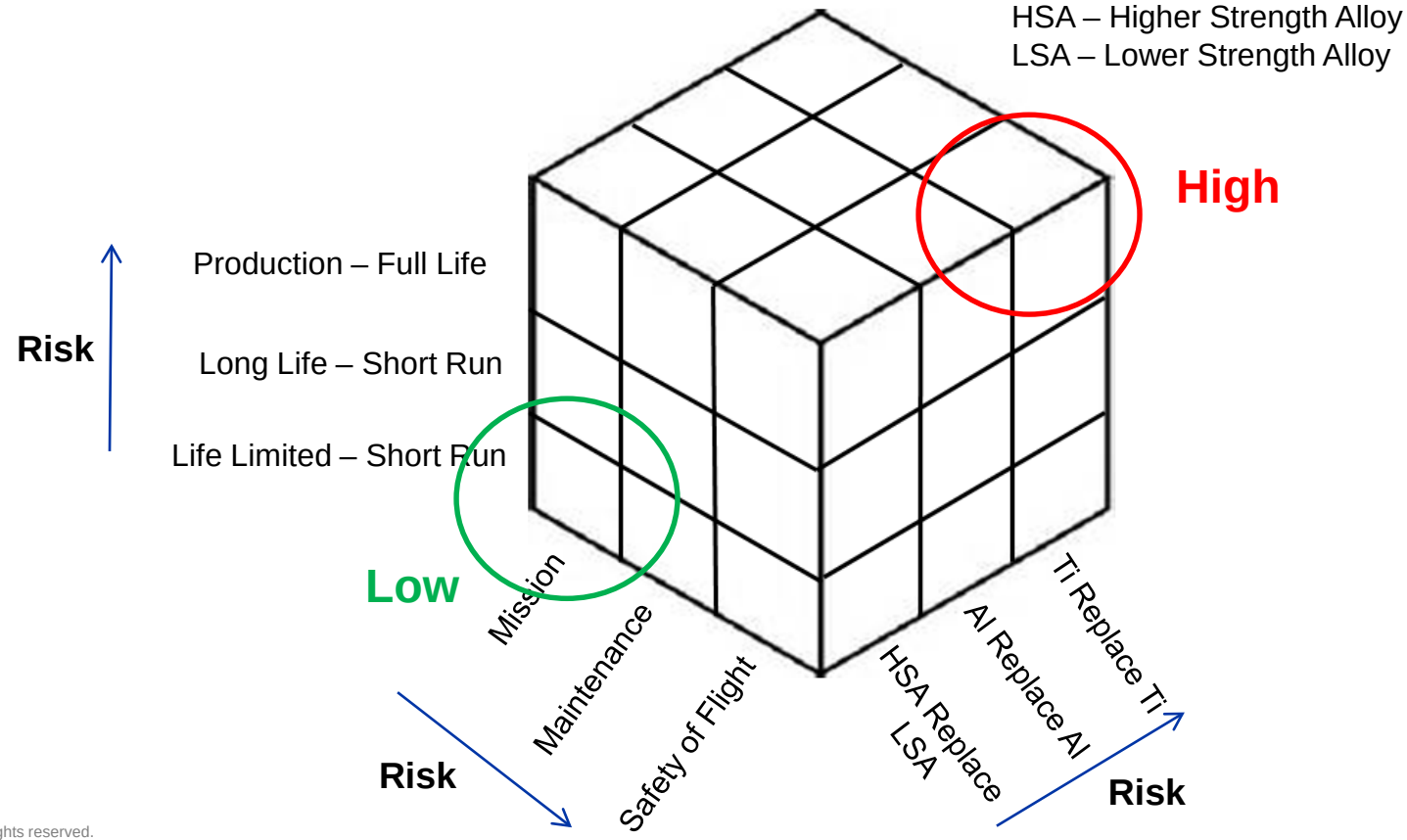
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Definitions of Risk

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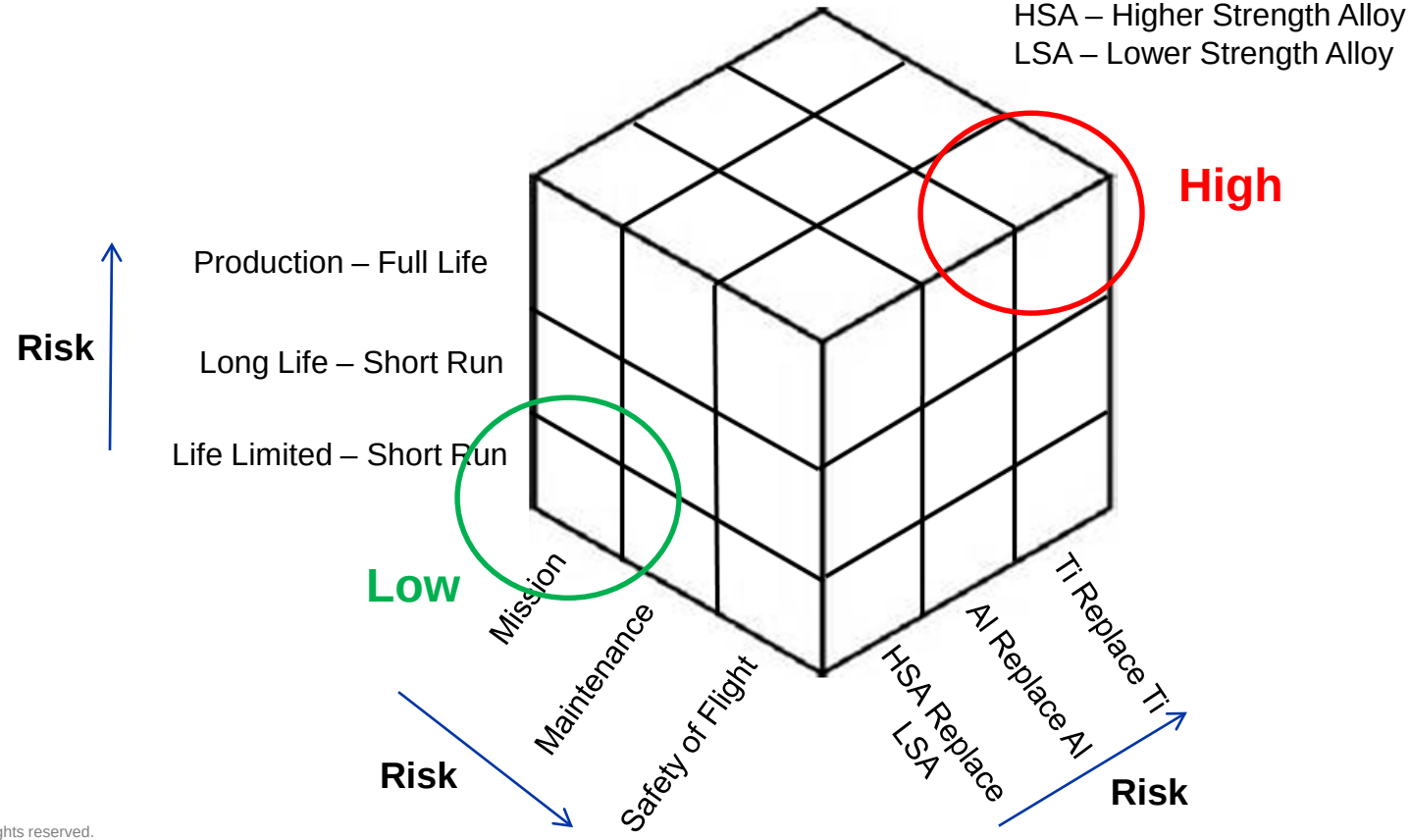
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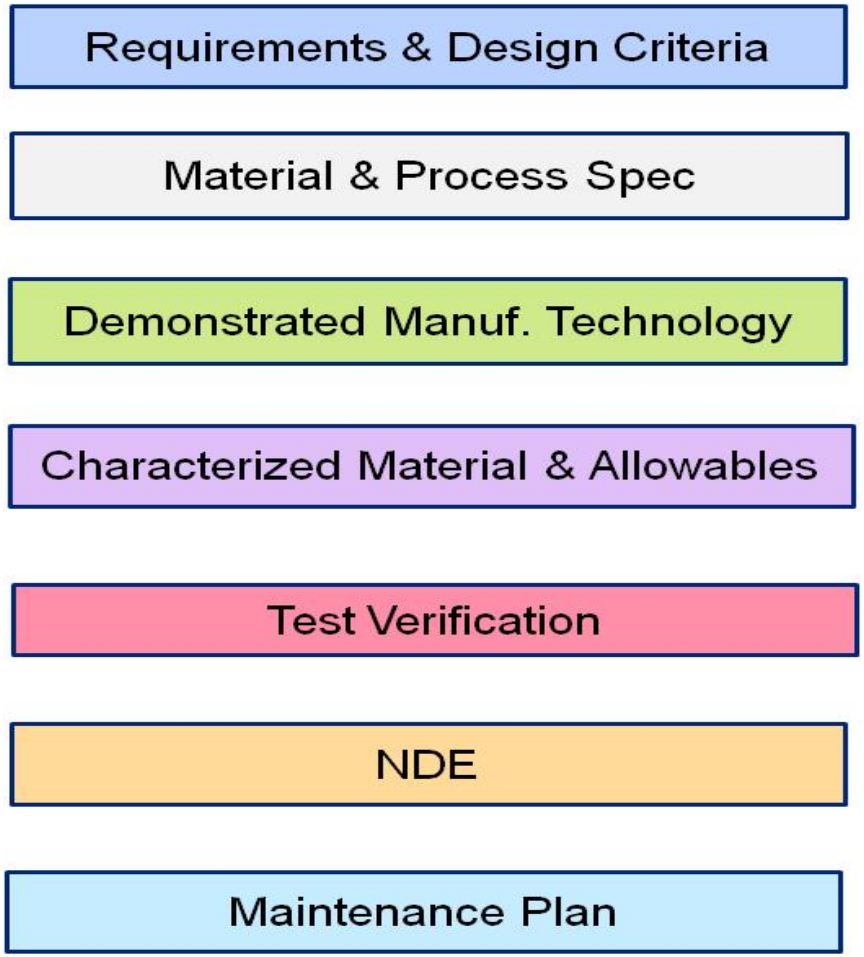
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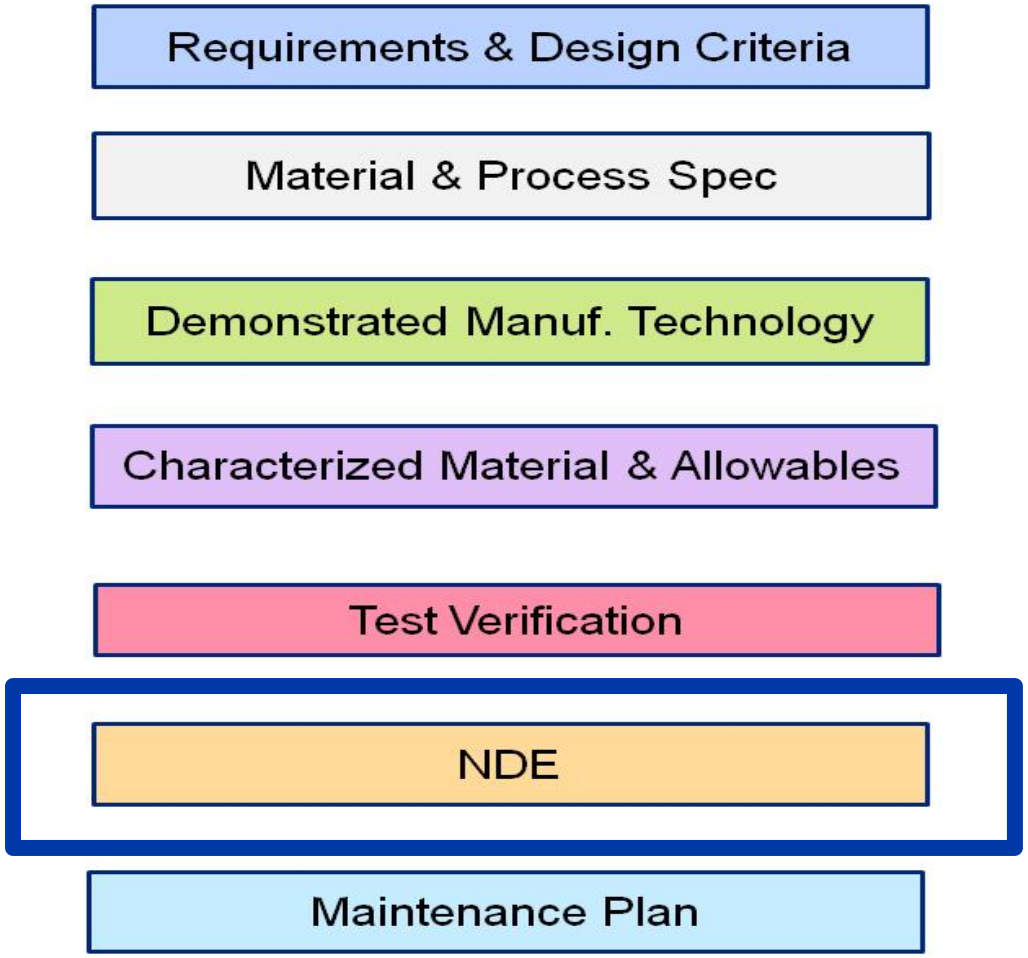
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General Structural Certification Steps:



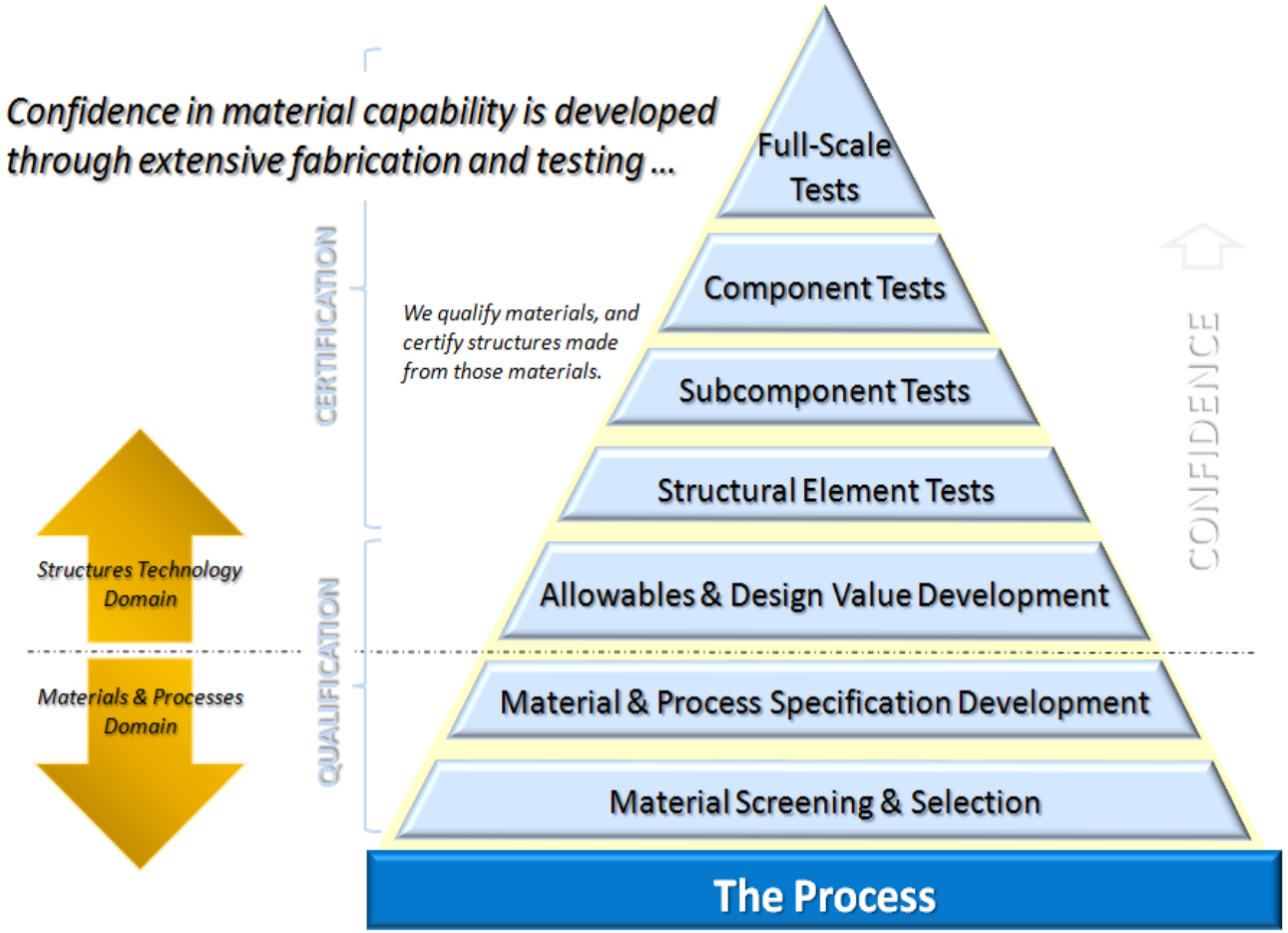
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General Structural Certification Steps:



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Building Block Test Pyramid



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Open Manufacturing Transition Study

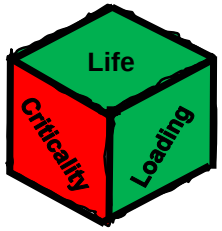
Looked at 3 Cases

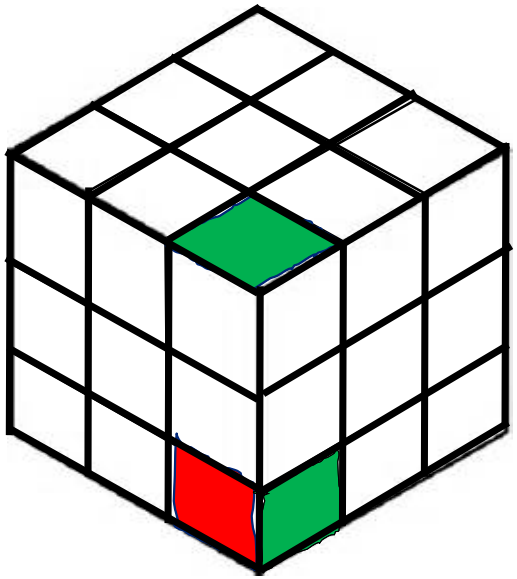
- Short-Run Spares (Pylon Rib)
- Long Run Aircraft Production (Component of FAR Part 25)
- Short Run Prototype (Conceptual)

Use of Risk Cube for Pylon Rib

- Limited Life, Short Run
- Safety of Flight Critical
- Ti-6Al-4V Replacing Aluminum







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Castings Overview – Class & Grade

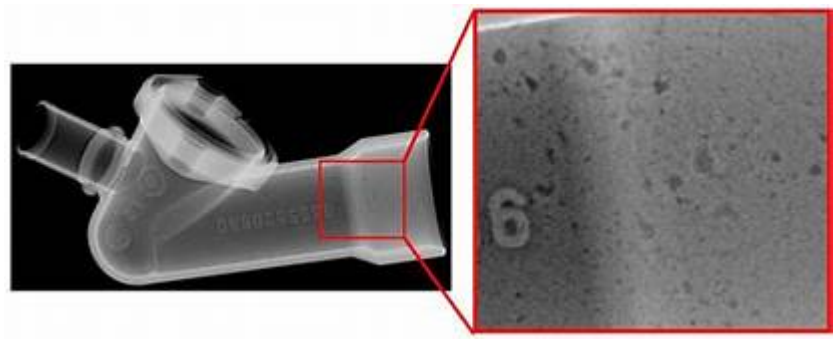
Class	Description
1	A casting, the single failure of which would endanger the lives of operating personnel, or cause the loss of a missile, aircraft, or other vehicle
2	A casting, the single failure of which would result in a significant operational penalty. In the case of missiles, aircraft, and other vehicles, this includes loss of major components, unintentional release or inability to release armament stores, or failure of weapon installation components
3	Castings not included in Class 1 or Class 2 and having a margin of safety of 200 percent or less
4	Castings not included in Class 1 or Class 2 and having a margin of safety greater than 200 percent

Grade	Description
A	The highest quality grade of casting, or area of a casting, with minimum allowable discontinuities and very difficult to produce except in local areas
B	The second highest quality grade of casting, or area of a casting, which allows slightly more discontinuities than grade A, and difficult to produce, except in local areas
C	A high quality grade of casting, or area of a casting, that can be consistently produced
D	The lowest quality grade of a casting, or area of a casting, that is easily produced and is used primarily for low stress or noncritical areas adjacent to the higher graded areas.

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Castings Inspection Requirements Summary

Class	Inspection Requirements
1	• 100% Visual Inspection • 100% Penetrant or Magnetic Particle Inspection • 100% Radiographic Inspection • Ultrasonic Inspection Required for Section Thicknesses of 4.50” or Greater
2	• 100% Visual Inspection • 100% Penetrant or Magnetic Particle Inspection • Radiographic Inspection – Sampling (Table I) • Ultrasonic Inspection Required for Section Thicknesses of 4.50” or Greater
3	• 100% Visual Inspection • 100% Penetrant or Magnetic Particle Inspection • Radiographic Inspection – Sampling (Table II)
4	• 100% Visual Inspection • Penetrant or Magnetic Particle Inspection – Sampling (Table I) • No Radiographic Inspection Unless Otherwise Specified





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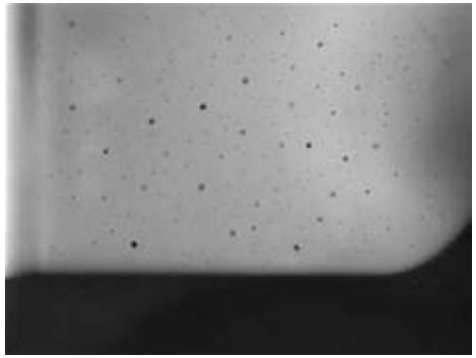
Casting Acceptance Criteria – RT, PT, MT

Discontinuity	Grade A Inch		Grade B Inch		Grade C Inch		Grade D Inch	
	1/4	3/4	1/4	3/4	1/4	3/4	1/4	3/4
Gas Holes	None	None	1	1	2	2	5	5
Gas Porosity, Round	None	None	1	1	3	3	7	7
Gas Porosity, Elongated	None	None	1	2	3	4	5	5
Shrinkage Cavity	None	None	1	3 [2]	2	4 [2]	3	5 [2]
Shrinkage Sponge	None	None	1	1	2	2	4	3
Foreign Material, Less Dense	None	None	1	1	2	2	4	4
Foreign Material, More Dense	None	None	1	1	2	1	4	3
Cracks [1]	---------- None ----------							
Cold Shuts [1]	---------- None ----------							
Surface Irregularity [1]	---------- Not to exceed drawing tolerance ----------							
Core Shift [1]	---------- Not to exceed drawing tolerance ----------							

Notes:

[1] Reference radiographic plates are not available for this type of discontinuity.
[2] A 3/4 inch shrinkage cavity plate is not available in ASTM E 155. For section thicknesses greater than 1/2 inch, use the 1/4 inch shrinkage cavity plate and the following limits: Grade A = none, Grade B = 3, Grade C = 4, Grade D = 5.
[3] Use ASTM E 155 Volume 1 reference radiographic plates for film methods and use ASTM E 2422 digital reference images for non-film methods.
[4] For feature thicknesses greater than two inches, the 3/4 inch reference radiographic plates may be used.
[5] See Table 5 for additional notes that apply to this table.
[6] Segregation is acceptable if it meets the magnesium reference radiographs for the specified Grade in accordance with Table 7.





Discontinuity Type		Grade A	Grade B	Grade C	Grade D
Random Individual Discontinuities (Gas Holes, Inclusions, Discrete Shrinkage Cavities), Nonlinear [5] [6]		1/4 T or the sizes shown below, whichever is less:	1/3 T or the sizes shown below, whichever is less:	1/3 T or the sizes shown below, whichever is less:	1/2 T or the sizes shown below, whichever is less:
Surface		0.03 dia	0.05 dia	0.09 dia	0.12 dia
Subsurface (Magnetic Particle only)		0.05 dia	0.09 dia	0.12 dia	0.15 dia
Cracks, Hot Tears, Cold Shuts, or Through-Wall Discontinuities		None	None	None	None
Microshrinkage or Shrinkage Sponge, Nonlinear [7]		0	0.12 dia	0.38 dia	0.75 dia
Microshrinkage or Shrinkage Sponge, Linear [1] [4]		0	0	0.12	0.25
Number of Discontinuities Allowed Within a 2 x 2 Inch Area	Random Individual Discontinuities [8]	2	3	4	4
	Microshrinkage or Shrinkage Sponge	0	1	1	1

Notes:

[1] Linear discontinuities (length to width ratio of 3 to 1 or greater) are not allowed except under the following circumstances:
  a) Linear dendritic shrinkage or linear shrinkage sponge indications shall be evaluated in accordance with this table and shall not be allowed to break over an edge, extend through a wall, or be located in internal corners of fillet radii.
  b) In magnetic particle inspection, discontinuities 0.030 inches or less in length need not be evaluated for linearity. In penetrant inspection, discontinuities 0.015 inches or less in length need not be evaluated for linearity.
[2] Discontinuities that are visible under white light without the use of penetrant or magnetic particles may be evaluated to the criteria of this table.
[3] Size limits shown are for actual discontinuity size as opposed to bleed out from penetrant inspection. Indications may be inspected by measuring their size after wiping with a solvent dampened cloth, cotton swab, or brush. Immediately evaluate the discontinuity for size as soon as the solvent has evaporated.
[4] For rounded indications exhibiting bleedout in excess of discontinuity limits in Table 4, or for doubtful indications of microshrinkage or sponge shrinkage, disposition may be based on the radiographic acceptance criteria after radiographing the part. Linear microshrinkage or linear sponge shrinkage shall only be acceptable after verification by radiography.
[5] For random individual discontinuities, the minimum resolvable size shall be 0.030 inches for magnetic particle inspection and 0.015 inches for penetrant inspection. Discontinuities smaller than these sizes shall be considered non-interpretable.
[6] For Grade A, any two random individual discontinuities shall be separated by a distance of at least three times the maximum dimension of the larger discontinuity. For Grades B, C, and D, random individual discontinuities shall be separated by a distance equal to twice the maximum dimension of the larger discontinuity. However, if the total length of the discontinuities that violate this spacing requirement does not exceed the maximum length permitted for a single discontinuity, then these discontinuities shall be considered as one and shall not be cause for rejection.
[7] Microshrinkage is also called dendritic shrinkage.
[8] The limits for random individual discontinuities do not apply if the discontinuities are smaller than one-half their maximum allowable size and they meet the minimum spacing requirement of Note [6].
[9] "T" is the casting section thickness.

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Transition to Additive Manufacturing

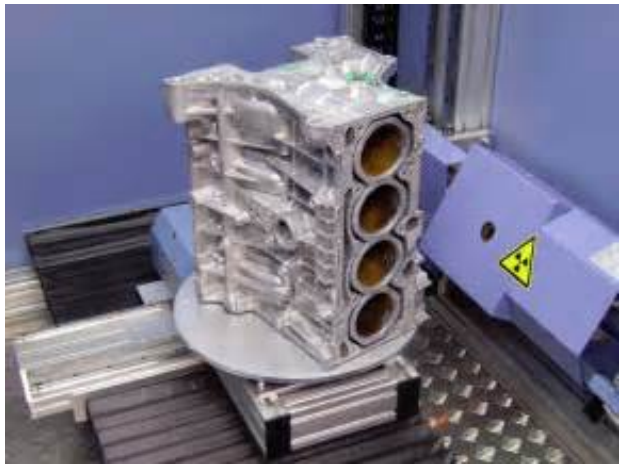
- Methods used to inspect castings applicable to additive manufacturing

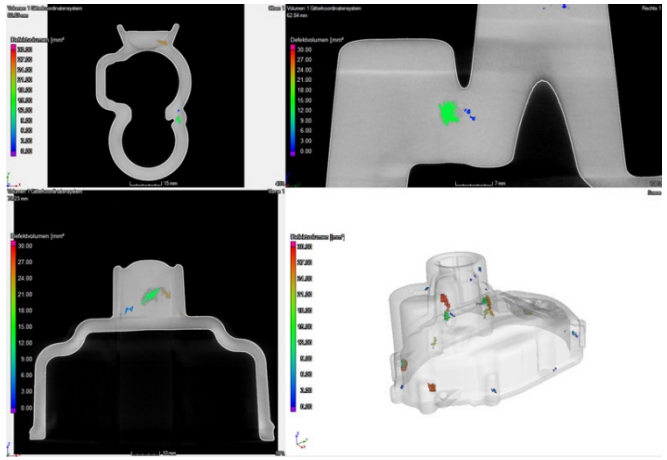
- Issues with surface conditions in as-manufactured state
  - Degradation in radiographic image quality
  - Inability to perform penetrant or magnetic particle inspection
  - Ultrasonic inspection not practical due to coupling issues and signal loss

- All methods possible with machined surfaces

- X-ray computed tomography may be required due to complex geometry
  - “Artifacting” may mask indications in highly contoured areas

- Casting acceptance criteria should be refined based on allowables data

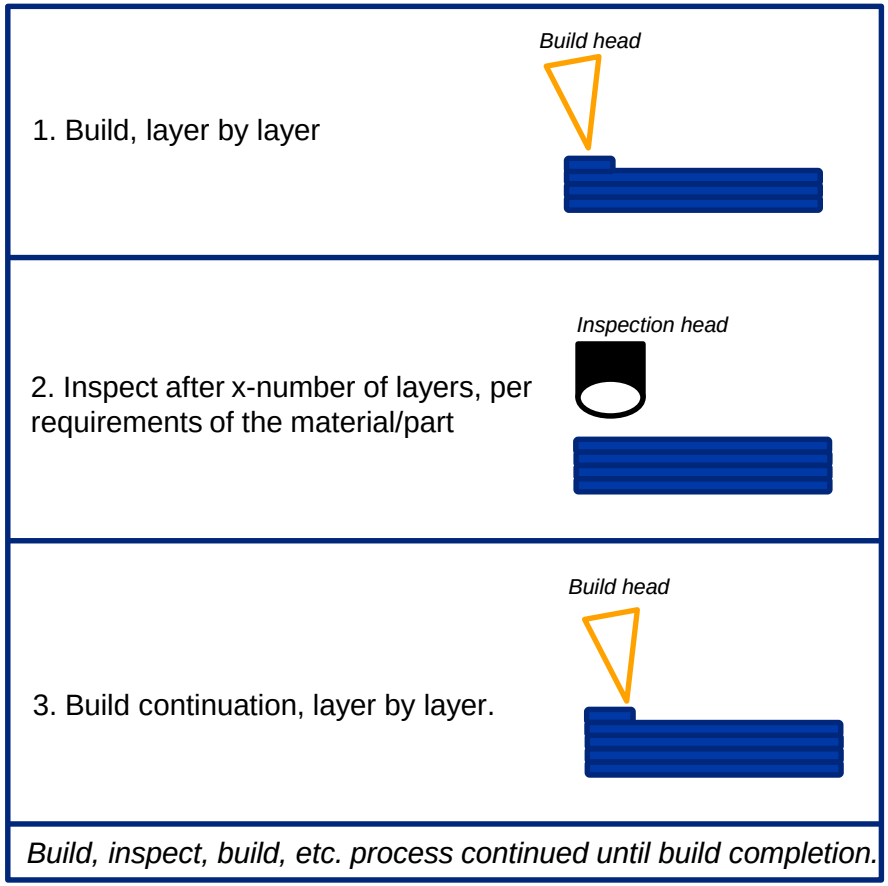




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In-Process NDE

In-Process NDE Concept



Why In-Process NDE?

Mitigates risk of increased post-processing inspection time and cost by enabling…

- **100% replacement of post-process inspection (secondary structure)**
- **“Zoned” approach for post-process inspection (primary structure)**
- **Sampling plan for post-process inspection (primary structure)**

Key challenge: Achieving high enough signal-to-noise ratio in order to detect critical flaw sizes

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Weld Inspection Criteria (Friction Welding)

Discontinuity	Size
Cracks or Crack-like (surface and/or embedded, lack of penetration)	None allowed [2]
Surface flaw (open voids)	0.300 inch x 0.030 inch [2] 0.130 inch x 0.065 inch [2]
Embedded flaw (voids, inclusions, wormholes, lack of adequate forging	0.078 inch x 0.078 inch [2] 0.174 inch x 0.034 inch [2]
Multiple surface flaws within 1 inch (open voids, galling)	None allowed [1]
Multiple embedded flaws within 1 inch (voids, inclusions, wormholes, lack of adequate forging)	None allowed [1]

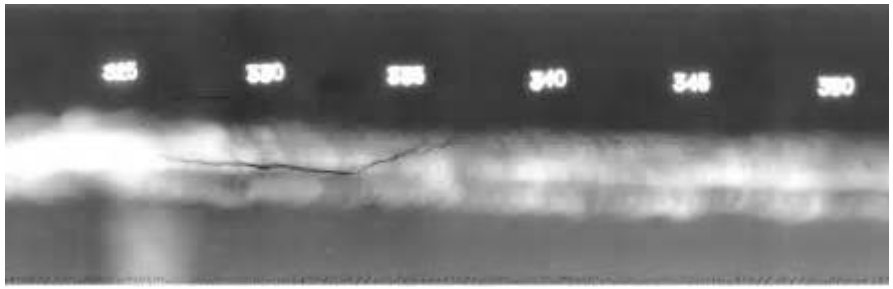
[1] Any non-crack-like multiple flaw contained (encompassed) within the equivalent area of a Single elliptical flaw, shall be interpreted as a single flaw.

[2] Indications with an amplitude greater than or equal to15% will be evaluated. Indications with an amplitude less than 15% will be disregarded.

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Weld Inspection – Traditional NDE Approaches

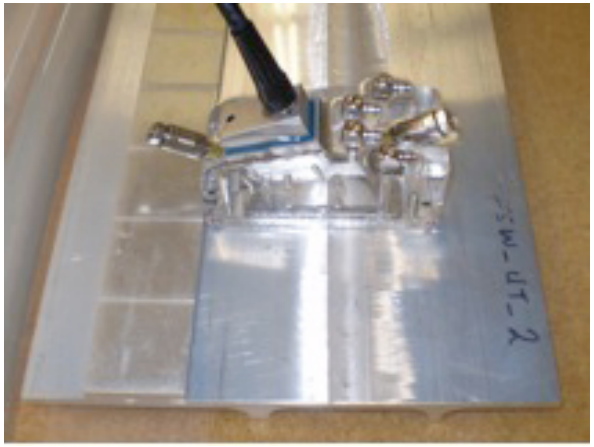
- **Penetrant Inspection**
- **Radiographic Inspection**
- **Ultrasonic Inspection**





Penetrant Inspection





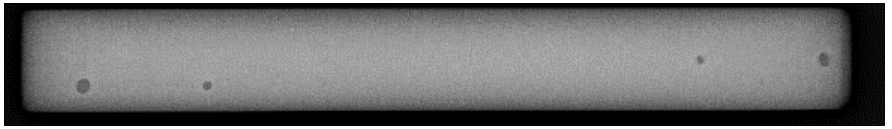
Ultrasonic Inspection

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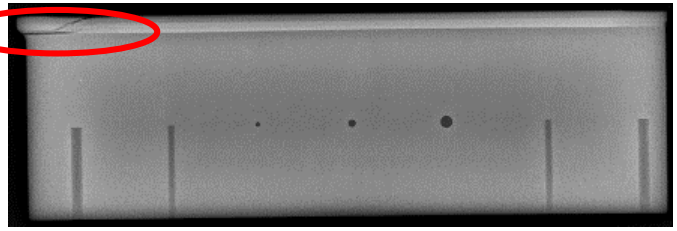
Representative Defects from Powder Feed Process

Lack of Adhesion Between Substrate and Build



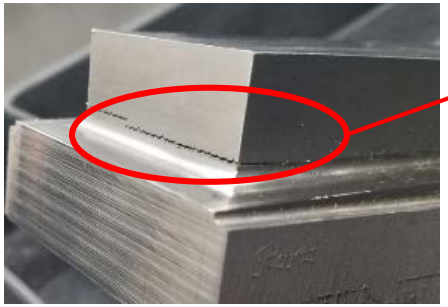


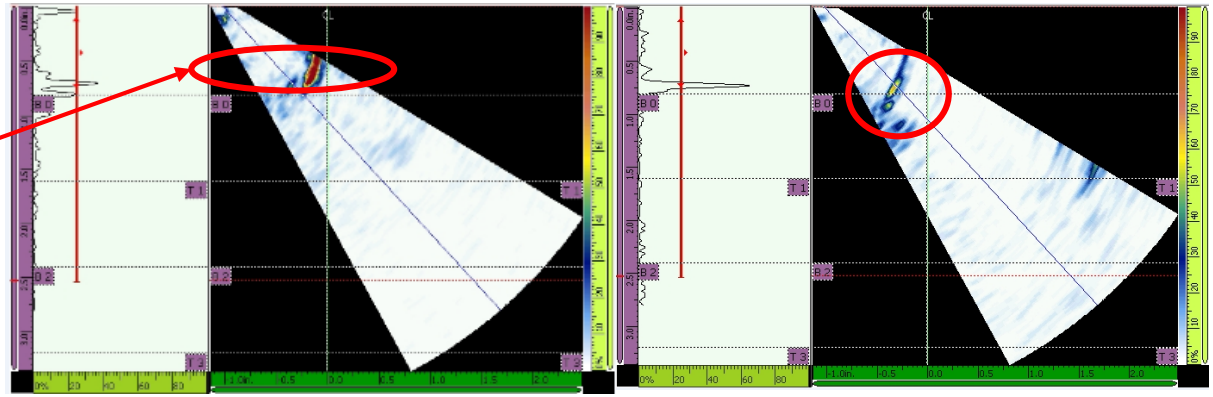
Top Down View



Side View

Radiographic Inspection





Example of crack at corner edge.

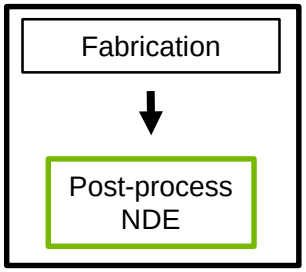
Example of edge reflection.

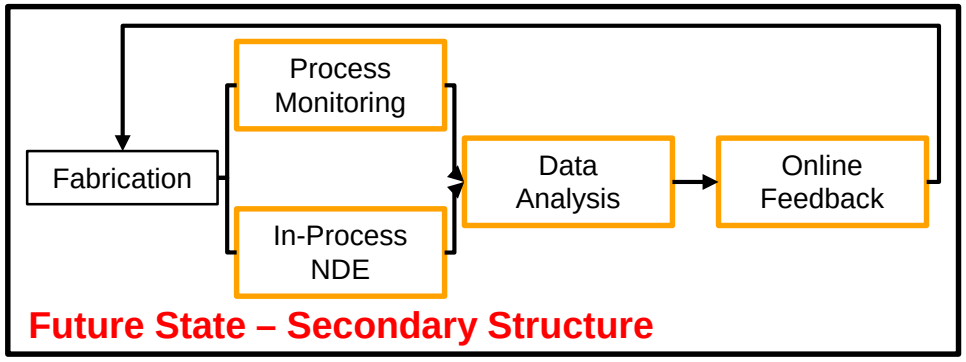
Ultrasonic Phased Array Inspection

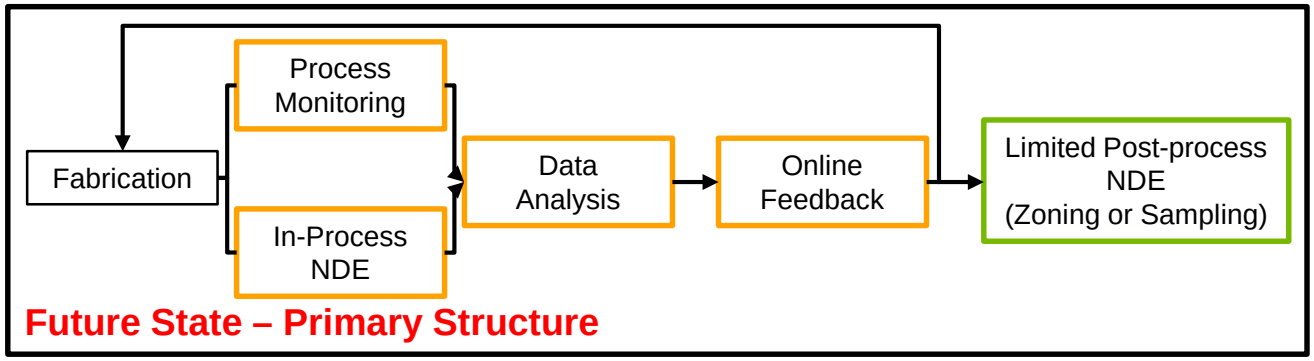
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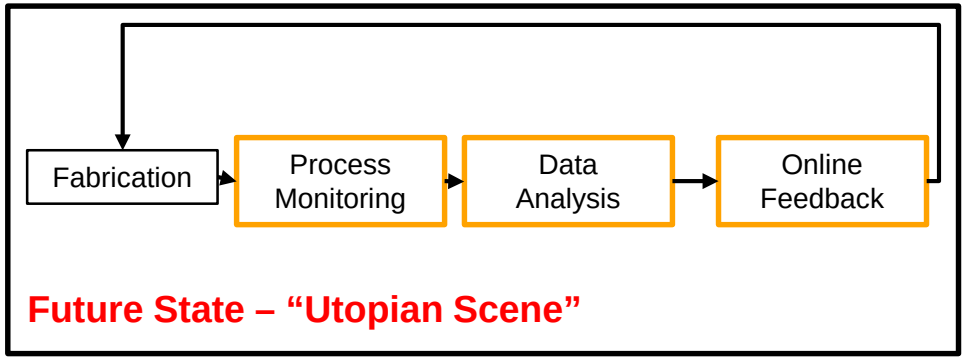
Future Vision for Additive Manufacturing NDE

Current State (All Structures)





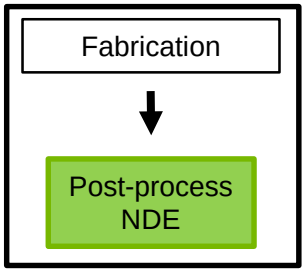


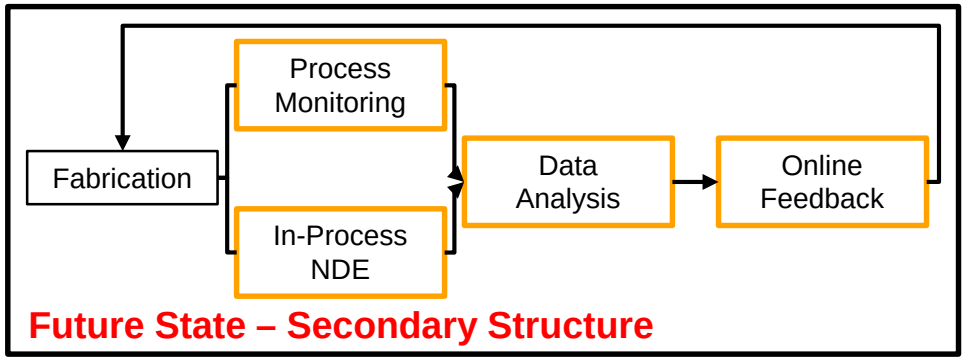


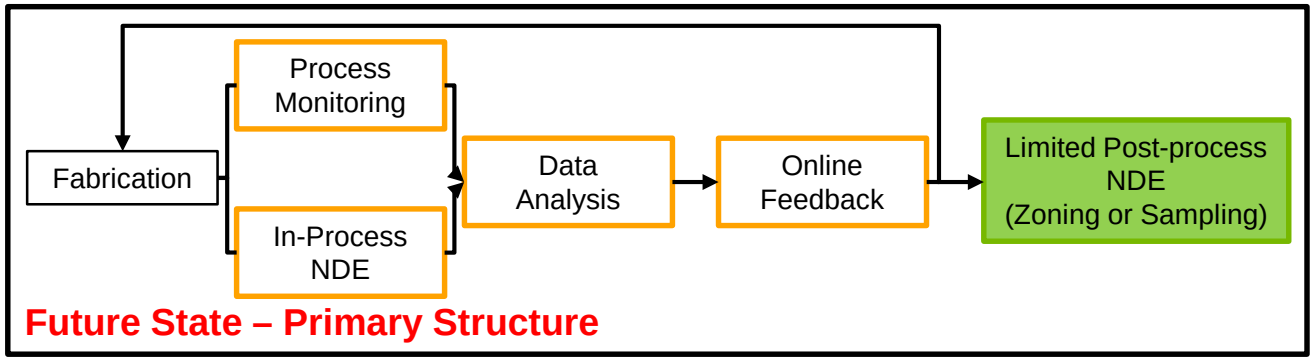
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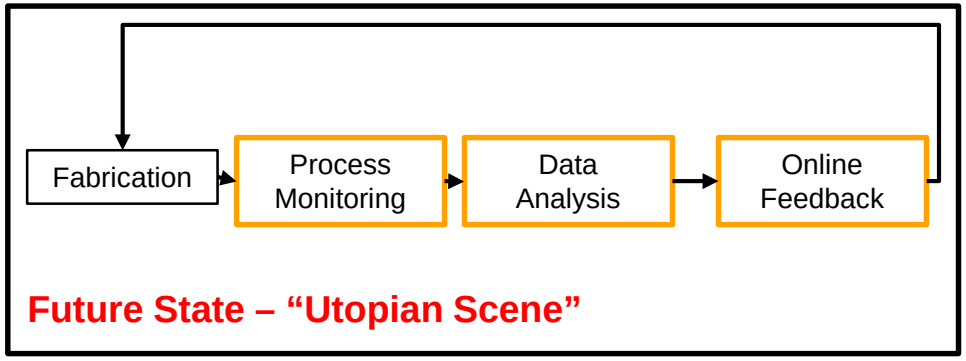
Research & Development Focus – Post-Process NDE Optimization

Current State (All Structures)





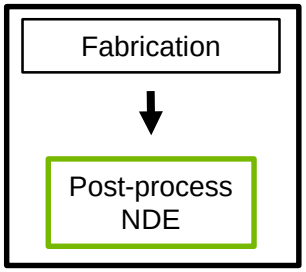


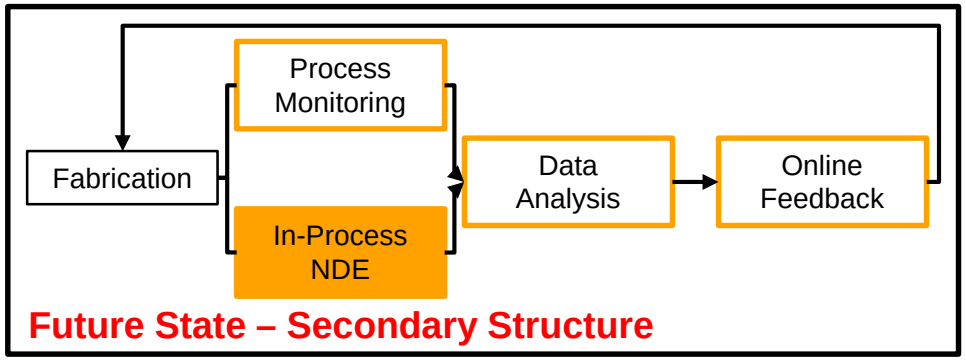


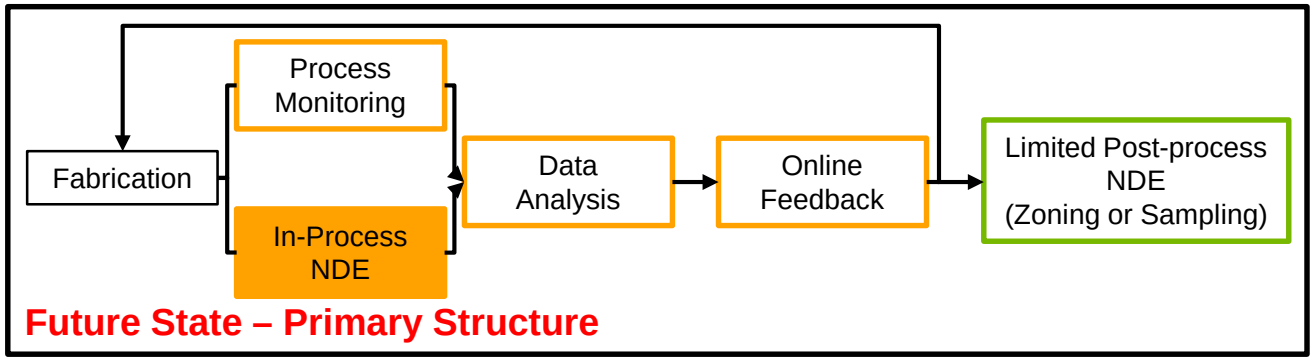
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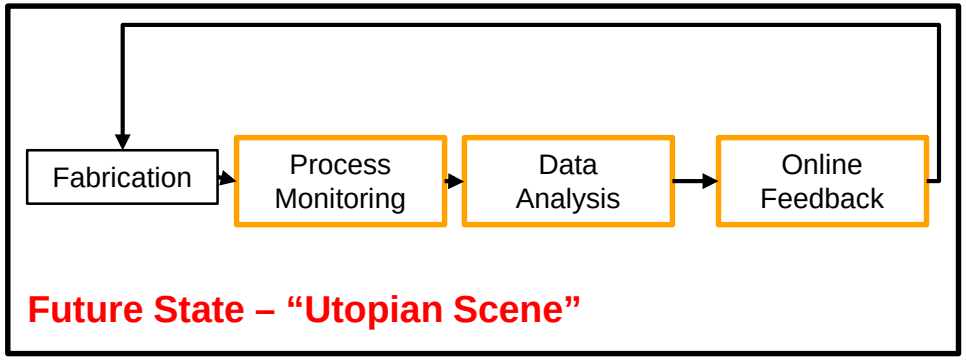
Research & Development Focus – In-Process NDE

Current State (All Structures)





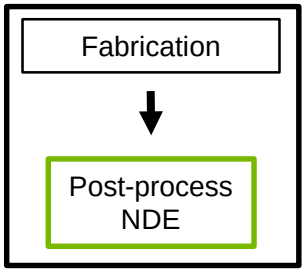


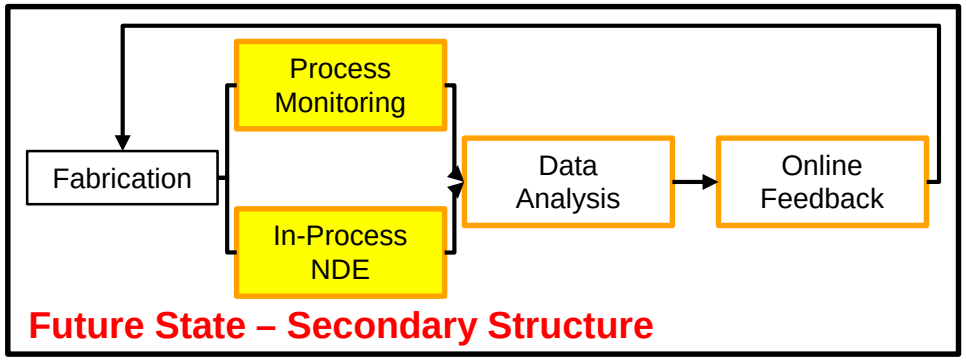


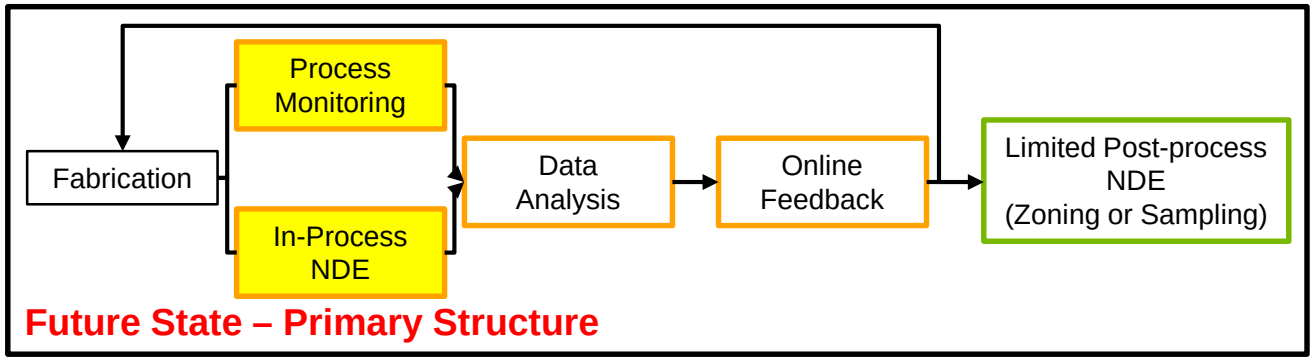
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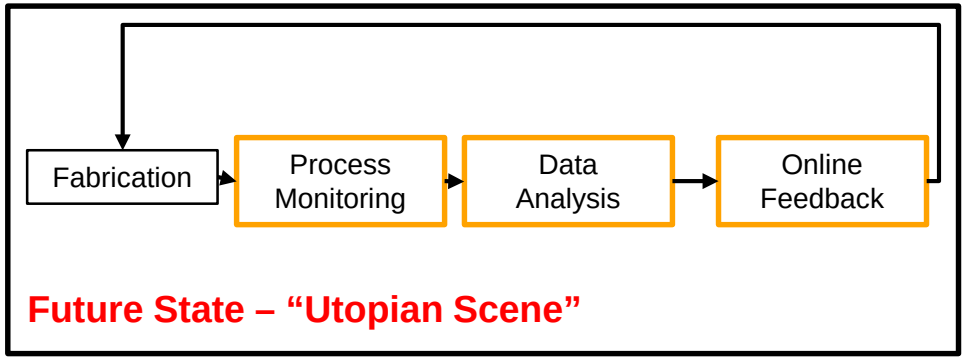
Research & Development Focus – NDE/Process Control Correlation

Current State (All Structures)





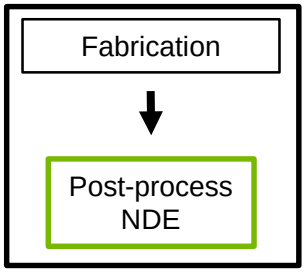


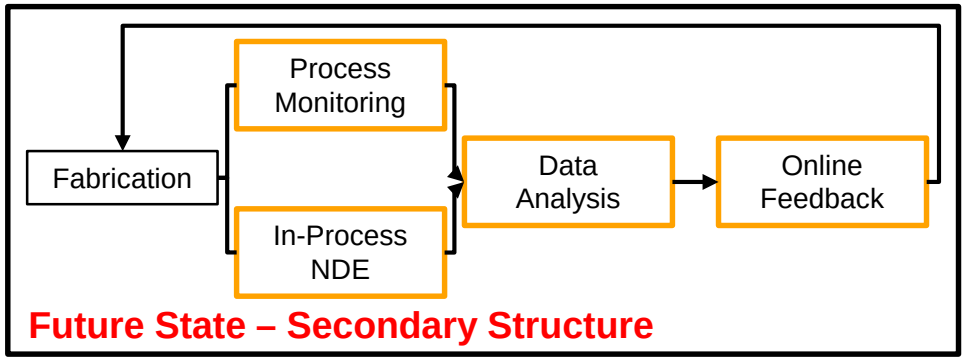


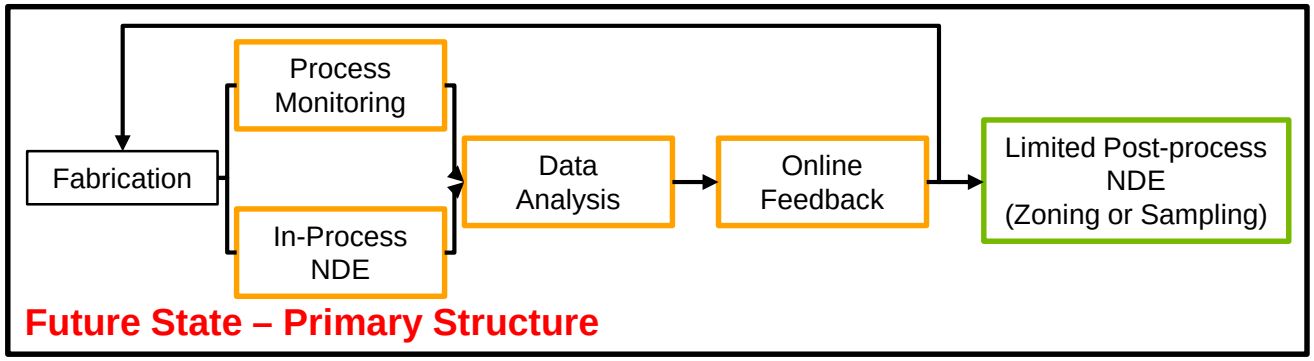
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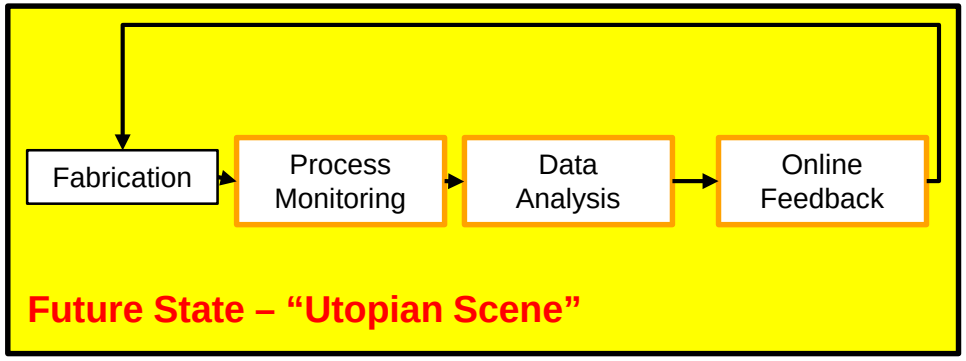
Research & Development Focus – Desired End-State

Current State (All Structures)









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Summary

- Need uniform definitions for different levels of criticality.
- Wide variety of AM processes makes it more challenging to establish a more general method of certification and qualification
- Research and development and prototype development efforts have revealed limitations associated with post-processing NDE approaches
- In-process NDE designed to reduce extent of post-process inspection – but is not a direct replacement for primary structural applications
- Future vision of NDE for metals additive manufacturing focuses on optimized quality approach including NDE and process control
- NDE research and development for metals additive manufacturing focused on:
  - Optimization of post-processing NDE approaches
  - Development of in-process NDE technology
  - Relationship between process control measurements and NDE results

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APPENDIX P
BRANDON WEGGE, BOEING
“UPDATE ON ADDITIVE MANUFACTURING AT BOEING”

2018

Boeing Additive Manufacturing

Brandon Wegge
Chief Engineer

About Boeing

COMMERCIAL AIRPLANES

Boeing 7-series family of airplanes leads the industry

DEFENSE, SPACE & SECURITY

World's largest manufacturer of military aircraft and satellites and major service provider to NASA

Large-scale systems integration, networking technology and solutions provider

GLOBAL SERVICES

A dedicated services business focused on the needs of global defense, space and commercial customers

$93.4 BILLION

in 2017 revenues

Products and services support to customers in more than **150 COUNTRIES**

Manufacturing, service and technology partnerships with companies around the world

Contracts with more than **20,000** suppliers and partners globally

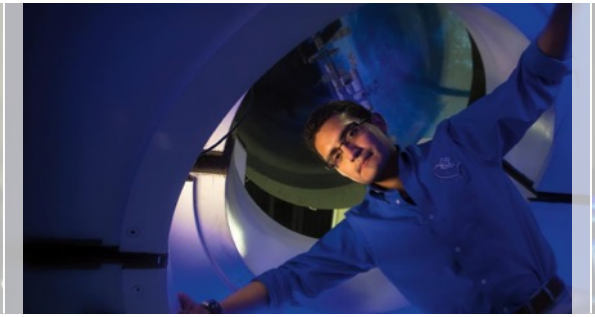
Approximately **140,000 BOEING EMPLOYEES**

across the United States and in more than **65 COUNTRIES**

Research, design and technology-development centers and programs in multiple countries

70% of commercial airplane revenue historically from customers outside the United States







Partnering across the planet for mutual prosperity – and to change the world

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Boeing **Additive** Manufacturing by the Numbers

20

Number of Boeing sites worldwide
With 3-D printing facilities (U.S., Canada, Australia & U.K.)



17 **U.S. Site Locations**

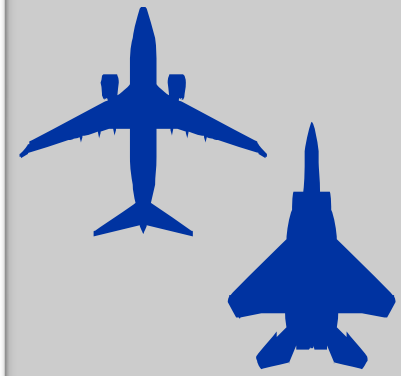


3 Focus Areas



60,000+

3D-printed parts flying on both commercial and defense programs



Over 20 Years of Experience in Additive Manufacturing

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Boeing Additive Manufacturing
Metallic



2001

X-37A

- First Flying Laser Additive Manufacturing Part (LAM)



2003

F15 Pylon Rib

- Additively Manufactured Ti replacement (LAM)
- Implemented on 15 Aircrafts



2004

C17 Pylon Panels

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



2011

MAI Satellite Components

- Launched August 5th, 2011



2016

702 MP Satellite

- Receive Antenna Deployment Actuator (RADA) Cage



June 2017

787-9 Passenger Floor Galley Diagonal Fittings

- First Flying Ti Wire Feed Additive Manufacturing Part

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Boeing Additive Manufacturing

Vision

Aerospace **Leader** in Additive Manufacturing

Mission

Leverage & Accelerate Additive Manufacturing in the design & manufacture of parts & tools across the enterprise to transform the production system & support growth

Strategic Goals



Operational Priorities

- Prioritize Cost Opportunities
- Design for Performance
- Right – Size Capacity
- Global Competitive Benchmarking
- Capture Value

Leverage Intellectual Capital of our Talented Global Team

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Boeing Additive Manufacturing
Supply Chain Opportunities



Structures
- Major assemblies
- Body sections
- Movable wing sections
- Doors
- Flight control surfaces
- Fuselage



Systems
- Avionics
- Flight systems
- Hydraulics
- Wheels and brakes
- Landing gear
- Environmental control systems
- Electrical systems



Interiors
- Passenger seats
- Cabin systems
- Galley inserts
- Interiors
- Cargo systems



Services
- Spares
- Technical & Engineering services
- Customer support
- Internal
- Non-production



Common Commodities
- Machined parts
- Sheet metal parts
- Assemblies
- Tubing
- Wiring
- Tooling
- Raw materials
- Standards



Propulsion
- Engines
- Struts
- Nacelles

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APPENDIX Q
MARTIN WHITE, GKN AEROSPACE
"THE CERTIFICATION TOOLBOX APPROACH AND FUTURE OPPORTUNITIES FOR QUALIFICATION"

The Certification Toolbox Approach and Future Opportunities for Qualification

Dr Martin White, Chief Engineer | August 2018

No Technical Data contained in this presentation

Introduction

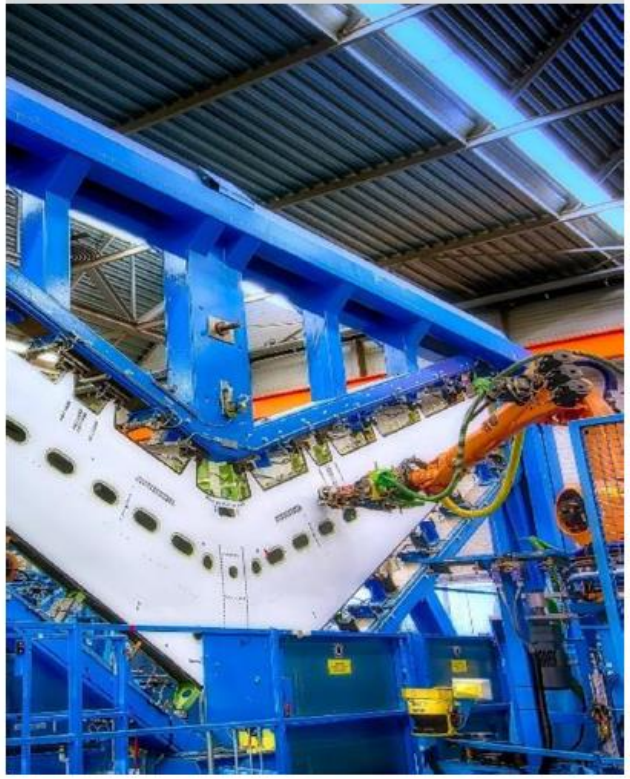
- **Who am I?**
  - Chief Engineer, GKN Aerospace – Additive Manufacturing.
  - Background:
    - Landing Gear Structures – Materials & Methods R&T, Certification of A350-900 MLG
    - High Temperature Materials – Gas Turbine Material Characterisation, Nickel Superalloys
    - Nuclear Consultancy – Through-Life Materials Performance in UK AGR, Management of Failed Nuclear Fuel
- **GKN Aerospace**
  - What are we doing in Additive Manufacturing?
  - What do our customers say?
- **Certification Overview & Experiences**
  - The ‘Certification Toolbox’ approach
  - Focus on Low Safety Classification Components – The Pathfinder Principle
- **Future Opportunities & Challenges…**
  - How do we help to accelerate AM?



GKN: Leading Global Tier One Aerospace Supplier

A strong focused business, with sales of £3.6billion in 14 countries

Aerostructures
49% £1.8 billion



Engine Systems
37% £1.3 billion



Special Technologies
14% £0.5 billion

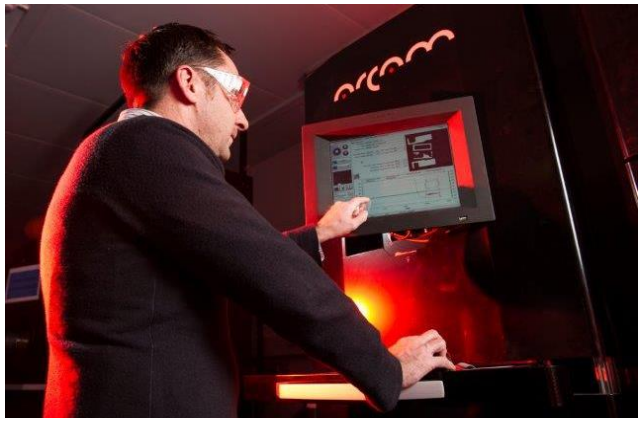


GKN TECHNOLOGY: MAKING THINGS FLY

GKN Additive, Bristol







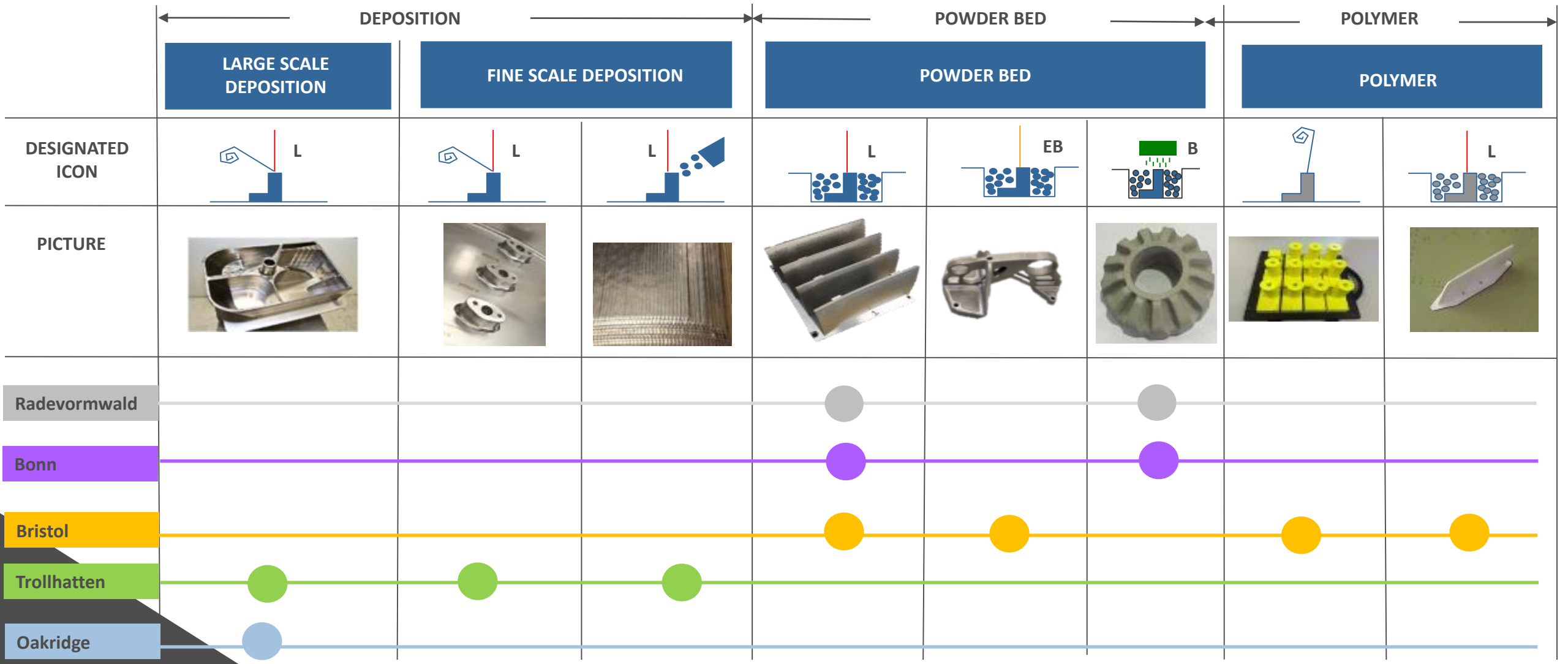
The GKN Additive Manufacturing Centre in Filton :

- Substantial R&D Capability developed over a number of years
  - 25 people, about to grow with new R&T projects
- Newly formed Industrialisation Team
  - Rapid growth… from 4 to 28 people over 18 months
- Electron Beam Melting (EBM); Development and Production
- Laser Powder Bed (LPB);
  - Production Facility now commissioned
- Polymer / Indirect AM (FDM/SLS)
- Multi-functional team:
  - Materials PhDs, Process Specialists, Manufacturing Engineers



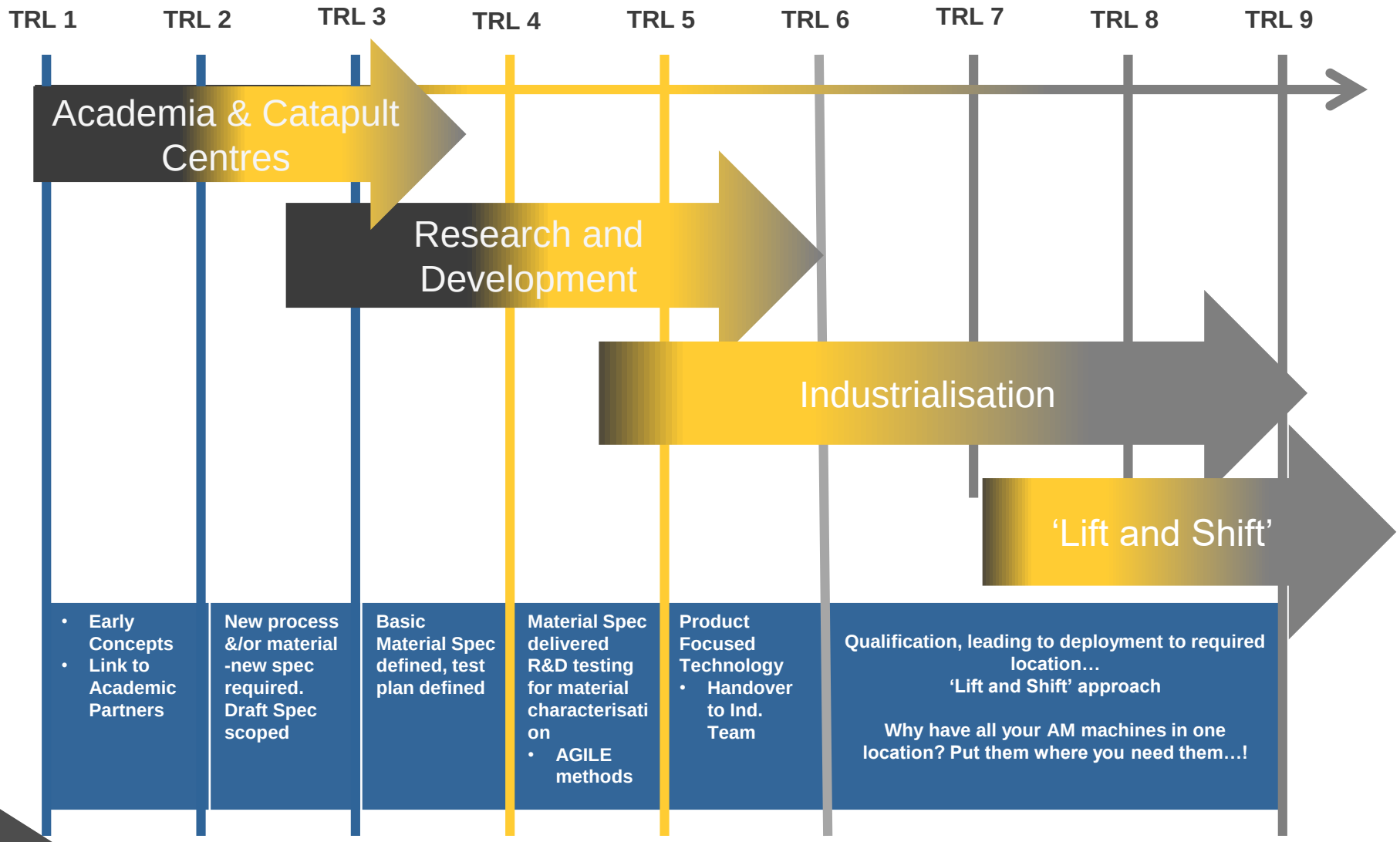
GKN TECHNOLOGY: MAKING THINGS FLY

GKN Additive - Worldwide



GKN TECHNOLOGY: MAKING THINGS FLY

The AM ‘Valley of Death’ – Technology Readiness Levels

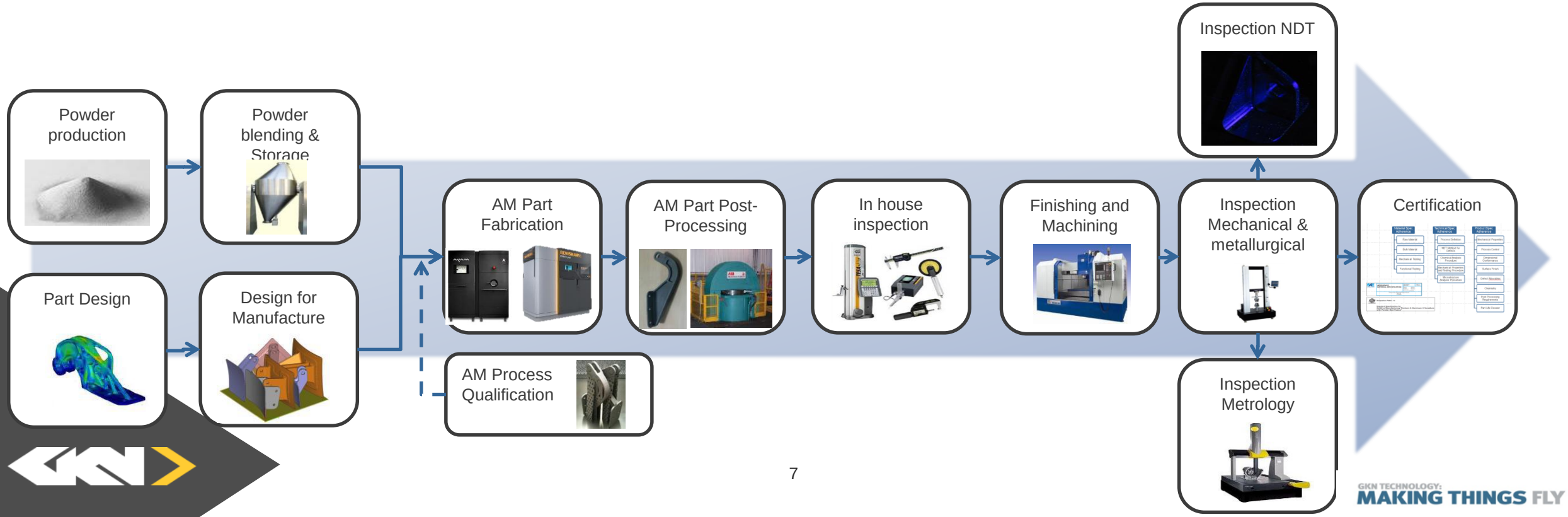


6

GKN TECHNOLOGY: MAKING THINGS FLY

Product Lifecycle

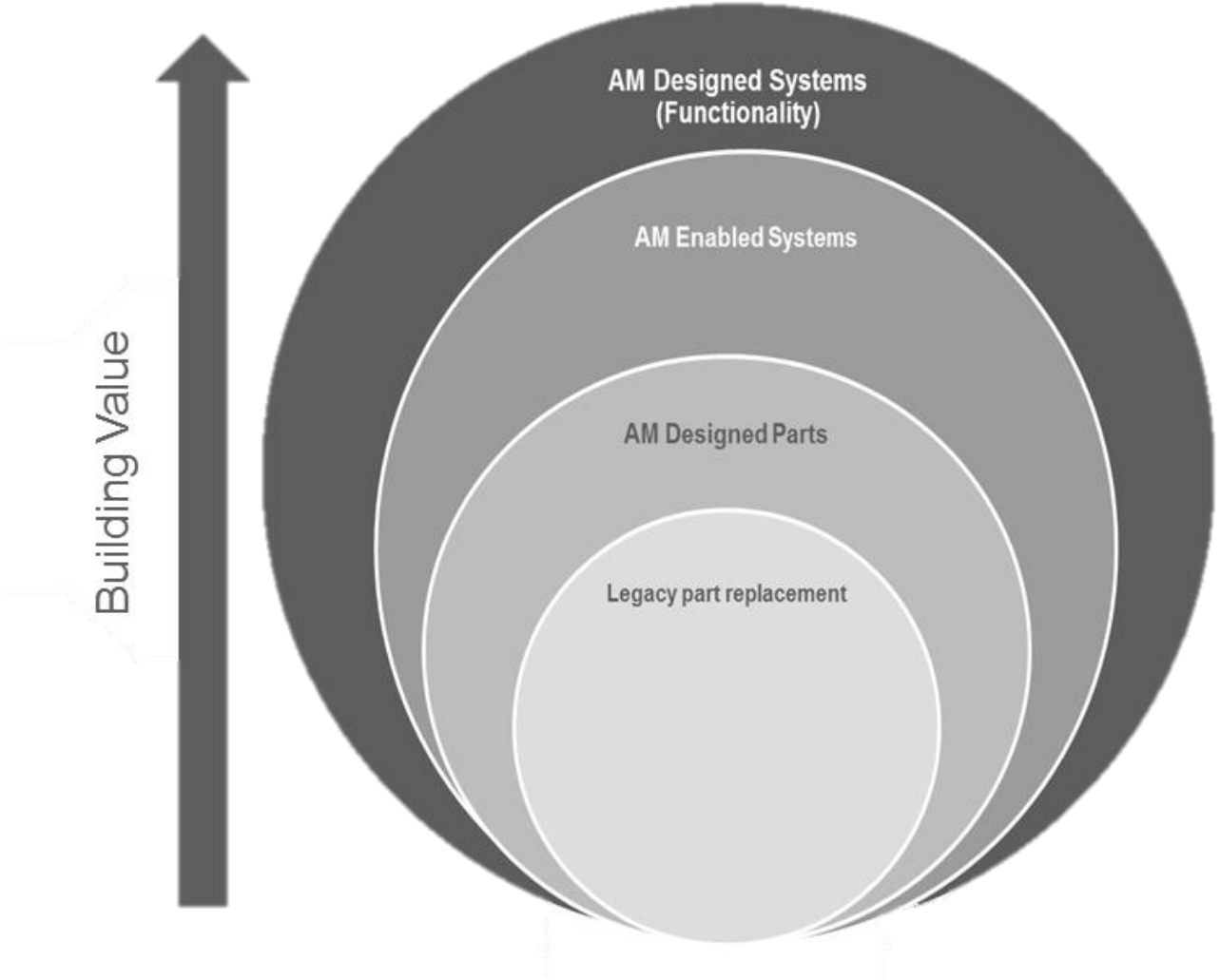
Function	Benefit
• Vertically integrated AM solution	GKN can tailor our solutions to meet our customers needs with complete control over all processes in the supply chain.
• Design capability	Allows us to maximise functionality realising the full benefits of 3D printing
• Process and Part certification	Our customers gain complete confidence in material properties and process robustness
• Industrialisation	Allowing AM to be quickly implemented to deliver real economic benefits to your business



GKN TECHNOLOGY: MAKING THINGS FLY

What do we want to gain from introducing a product?

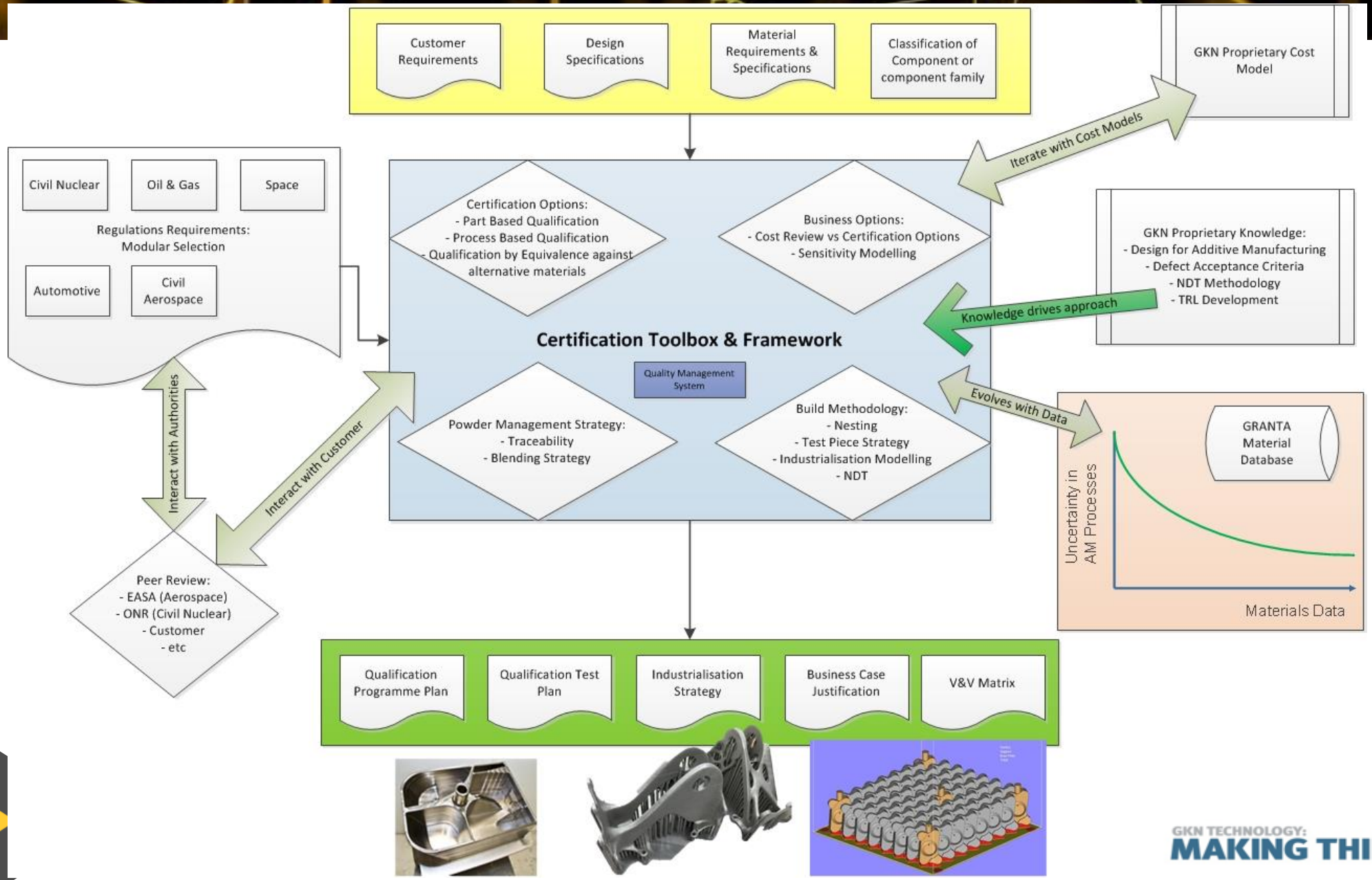
- **“Why are we picking this product?”**
  - Will we make money?
    - Can we develop a business case?
  - What will we learn?
    - Certification
    - Design for AM
    - Industrialisation
  - Generate Material Understanding
    - Generation of Allowables
    - Increase Technology Readiness Levels
  - How does a product allow us to move up the ‘value proposition of AM’?
    - How do we link to a longer-term strategy?
  - Will the knowledge we gain be transferrable?



Voice of the Customer

- **Consistent Points:**
  - “We are deciding whether to develop our own AM capability, or offload to a supplier. Either way, we need to learn more”
    - i.e. – “Why should we use GKN, instead of buying our own machines & cracking on?”
  - “How do you know that a part won’t just turn back to powder?”
  - “What are your allowables? We need to know what to design with”
  - “Who are you making parts for?”
  - “What Class 1-2 parts do you have flying today?”
  - “How many products do you have flying?”
  - “What makes a good AM part?”
  - “Why do I have to machine all over?”
  - “What is the route to certification?”
  - “What do the Airworthiness Authorities think about additive?”
  - “Can you tell us how to build a facility?”
  - “Can you transfer all of your knowledge to us?”
  - “Can we have your process specifications?”
  - “Will CT save the world?”

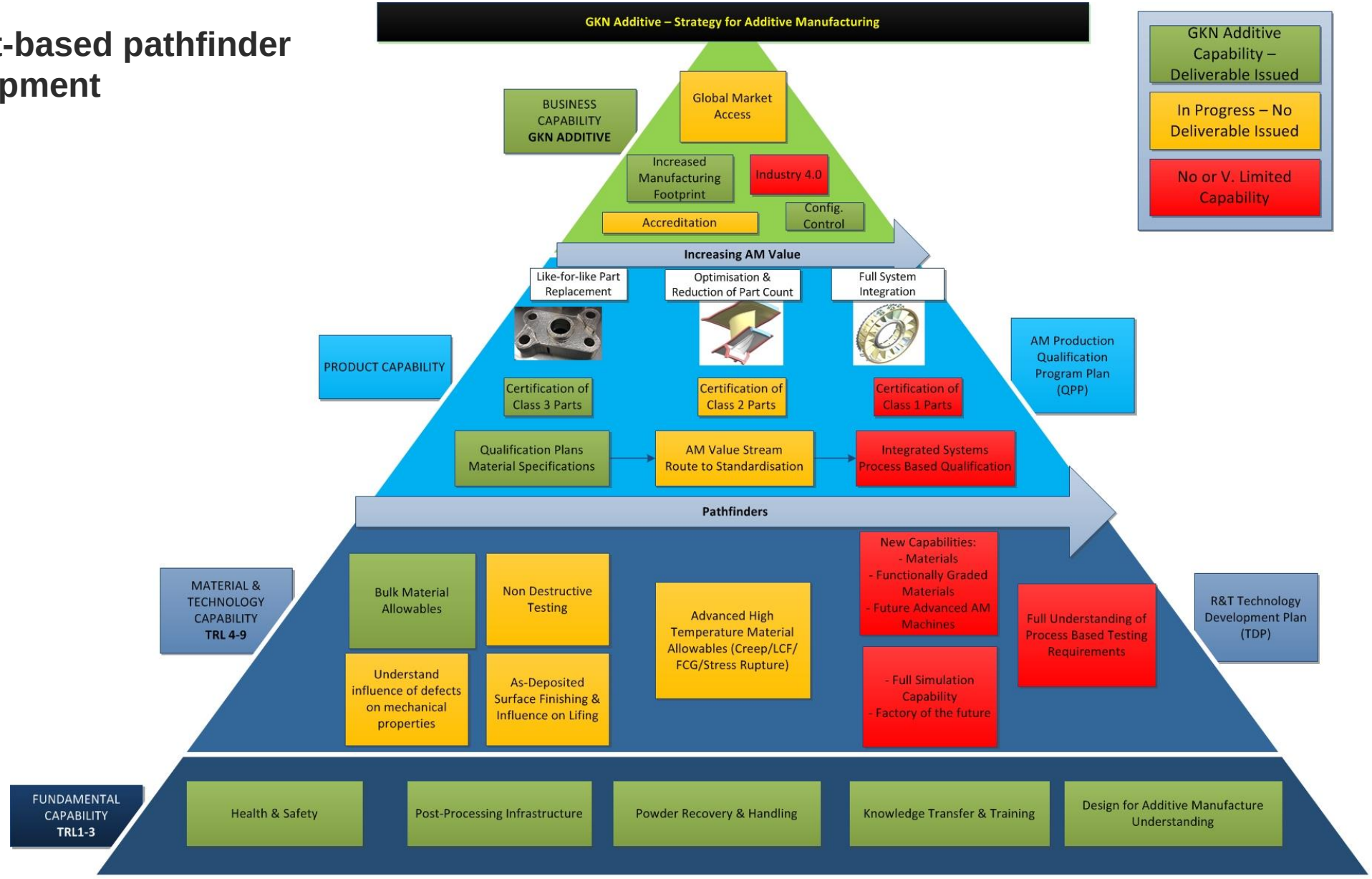
Certification Toolbox & Framework



GKN – Approach to Product Introduction & Certification

GKN will use the Product-based pathfinder approach to drive development

1. Process Development
2. Material Capability
3. Certification
4. Industrialisation



Route to Certification

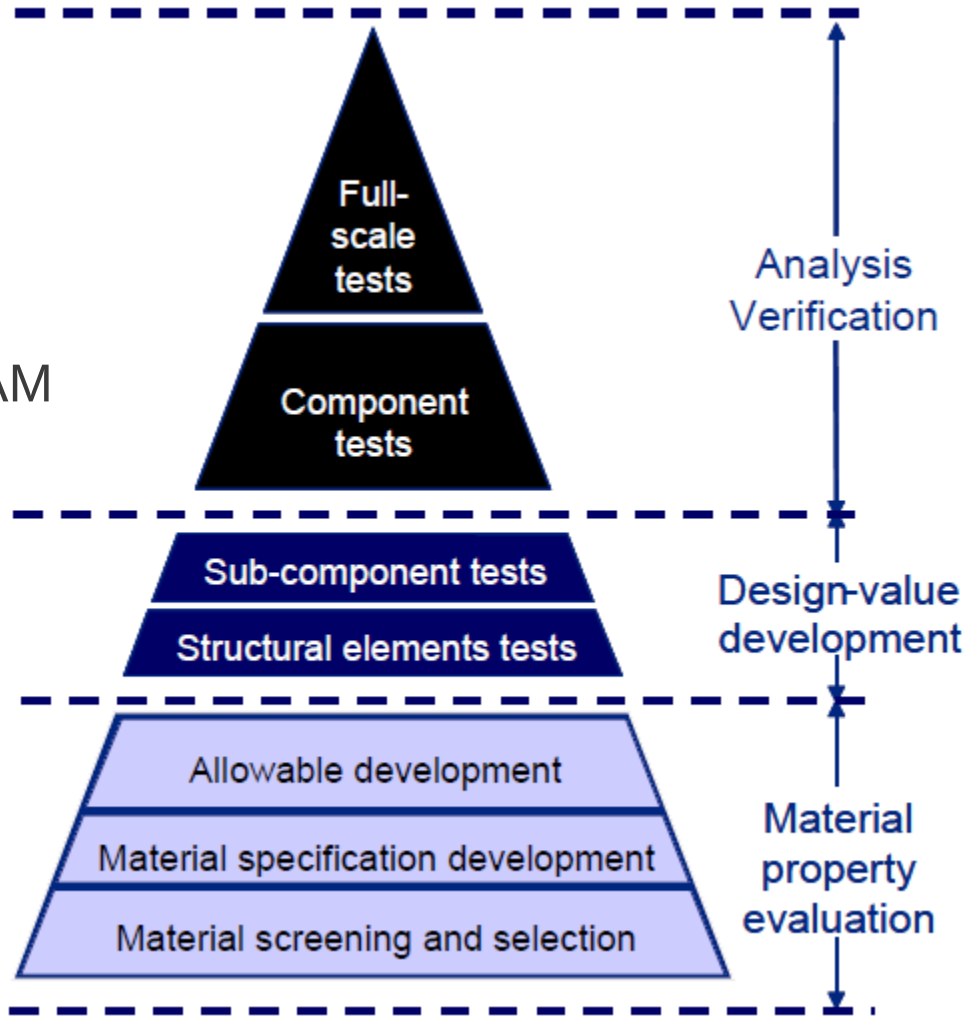
How do we Certify?

- Various Routes are available
- AM Industry still learning best routes
  - New standards becoming available
  - ‘Route to Standardisation’

- **Classification of Parts**
  - Safety Critical Components are the target for AM
    - Important to **walk before we run!**
    - **‘Pathfinder’ Principle**

- Certification must consider:
  - Technology Readiness Levels (TRL)
  - Product Readiness Levels
  - Process Readiness Levels

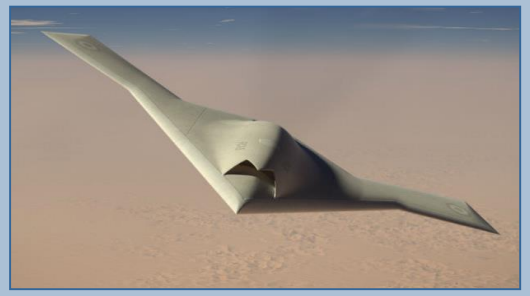
- GKN Certification Toolbox used to help define approach



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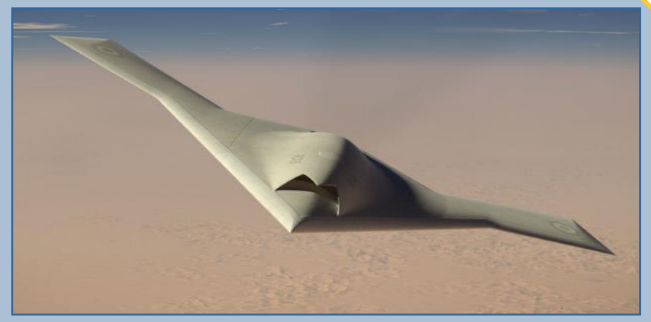
The *Product* being qualified defines the approach

EQUIVALENCE BASED QUALIFICATION



- Compare AM vs Cast Material… Or wrought!
- Demonstrate Large Reserve Factor vs Existing Dataset
- Reduces benefit of AM Material Potential
- Empirical Qualification – Aggressive Schedule

PART BASED QUALIFICATION



- Development parts & Low Volume
- Part specific process parameters
- Qualification only valid for tested parts
- ‘Short’ schedule

PROCESS BASED QUALIFICATION

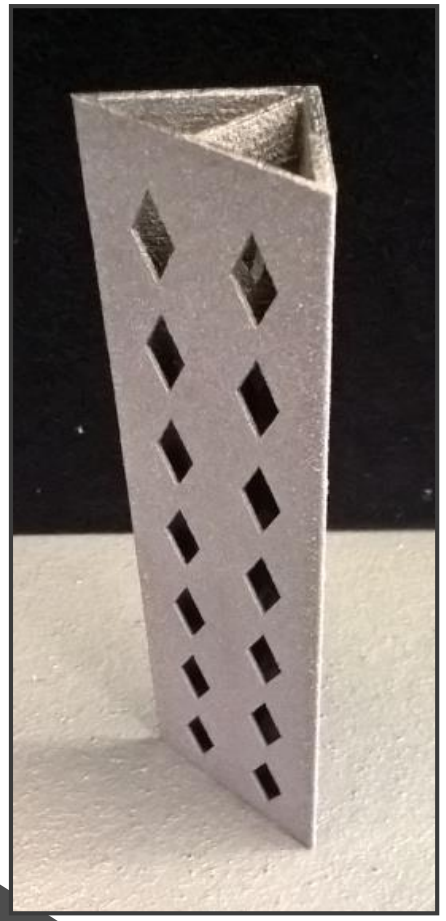


- Production run
- Population specific process parameters
- Qualification applicable to a defined population
- Longer timescale

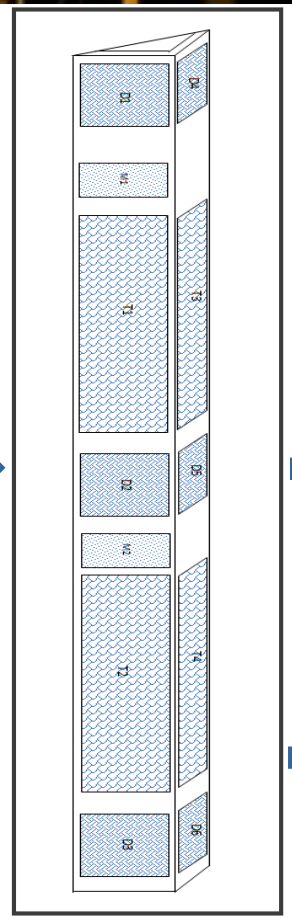
Today’s approaches — **Evolution of Approach to Certification** — **Future approach**

GKN TECHNOLOGY: MAKING THINGS FLY

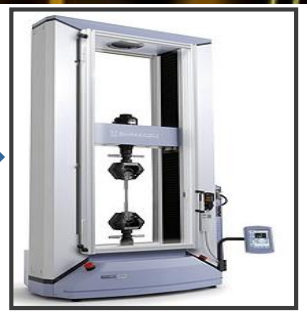
Traveller specimens – ‘Non-Critical’ Part Based Qualification



Traveller specimen included in the build



Split into coupons





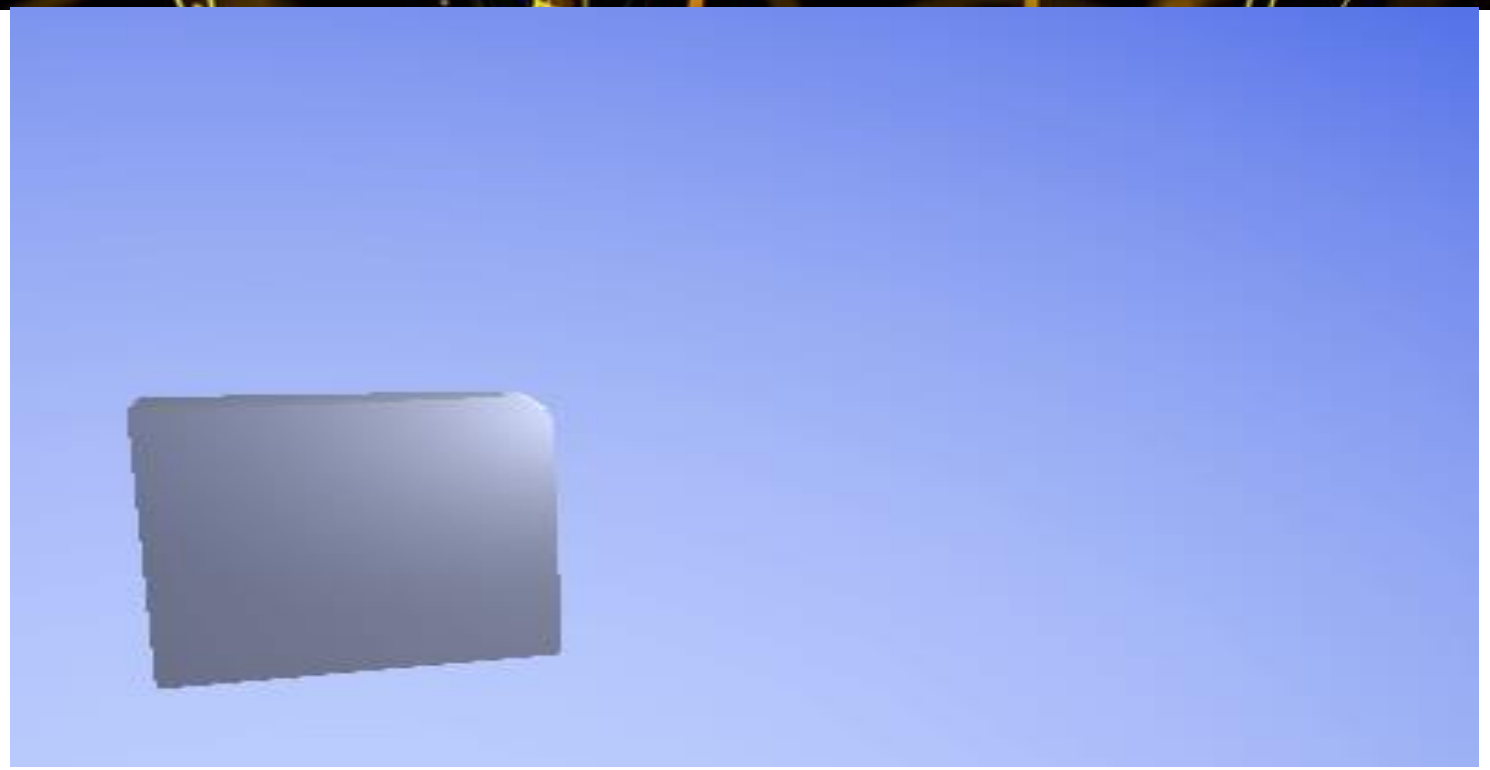


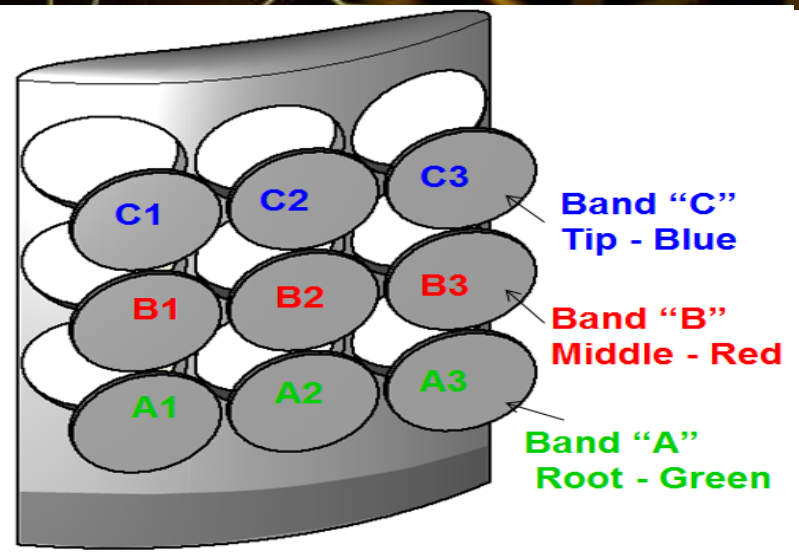
Testing

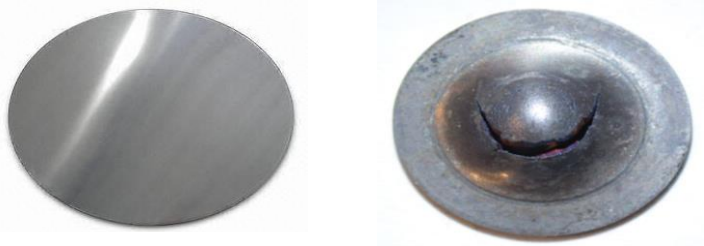
- Intent is to demonstrate a successful AM build
  - Used for low safety classification, thin-walled, EBM components
  - Linked to a Qualification Campaign
- Testing defined by the requirements
  - Static
  - Chemical composition
  - Internal Defect Analysis
    - Pass/Fail Criteria?
  - Microstructure
- Traveller specimen designed to represent the component
  - Wall thickness
  - Build direction
  - No fatigue or creep requirements currently on this type of part classification

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Future Work – Small Punch Testing, Swansea University

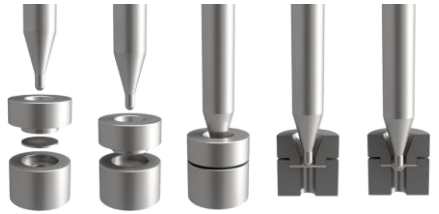






Before

After

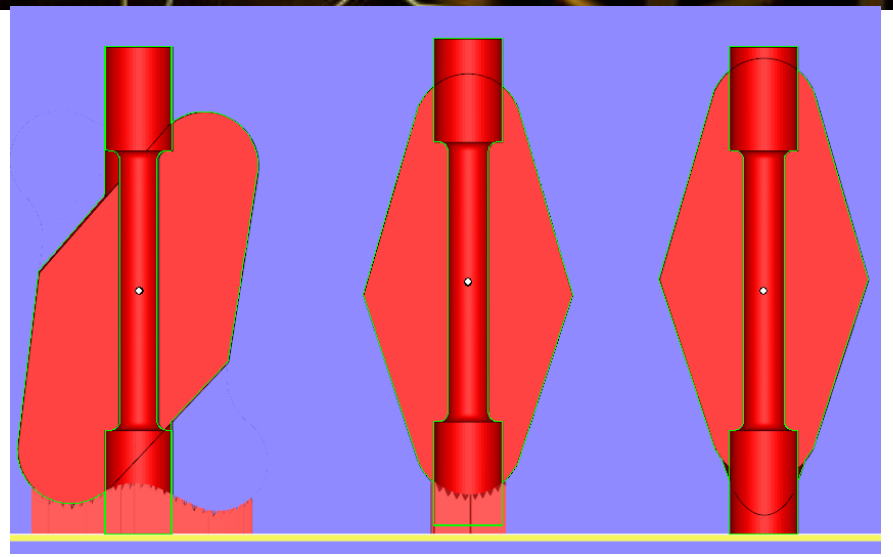


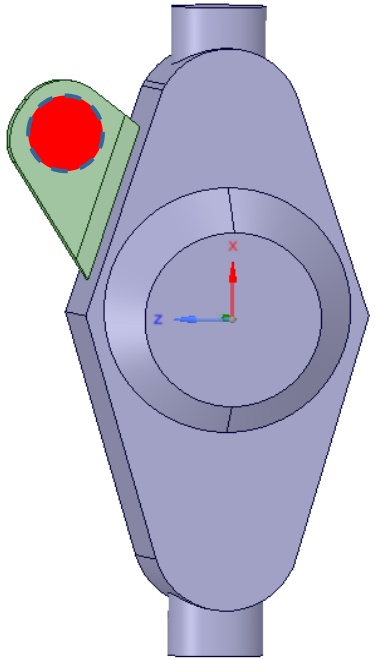
- Currently progressing towards an EN test standardisation
- Specimen Dimensions: 500µm ± 5µm thick & 8-9.5mm diameter
- Approach will compliment & eventually replace the traveller specimen approach
- Tensile methods well established
- Also possible to Fatigue & Creep test

GKN TECHNOLOGY: MAKING THINGS FLY

Evolution of the Traveller Specimen

- Can we use the parts themselves as the ‘traveller’?
- Work underway to evaluate whether SPT can be successfully be implemented in Production



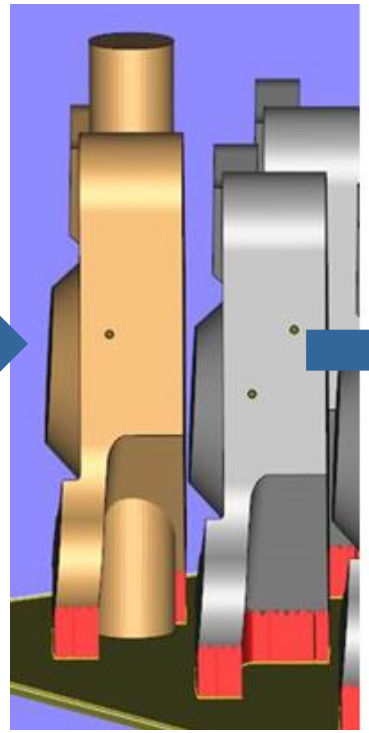


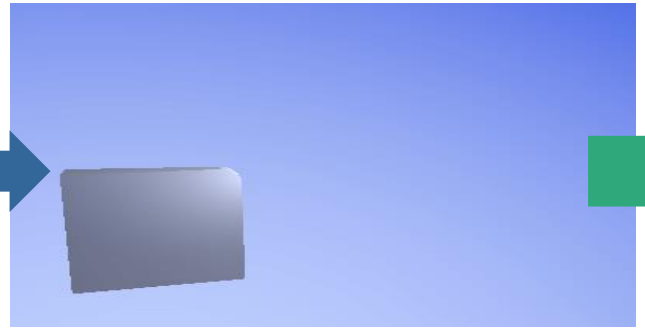


Summary - Evolution of Approach to Certification

Approaches will change – we will benefit from more data, operational experience, and understanding of cost









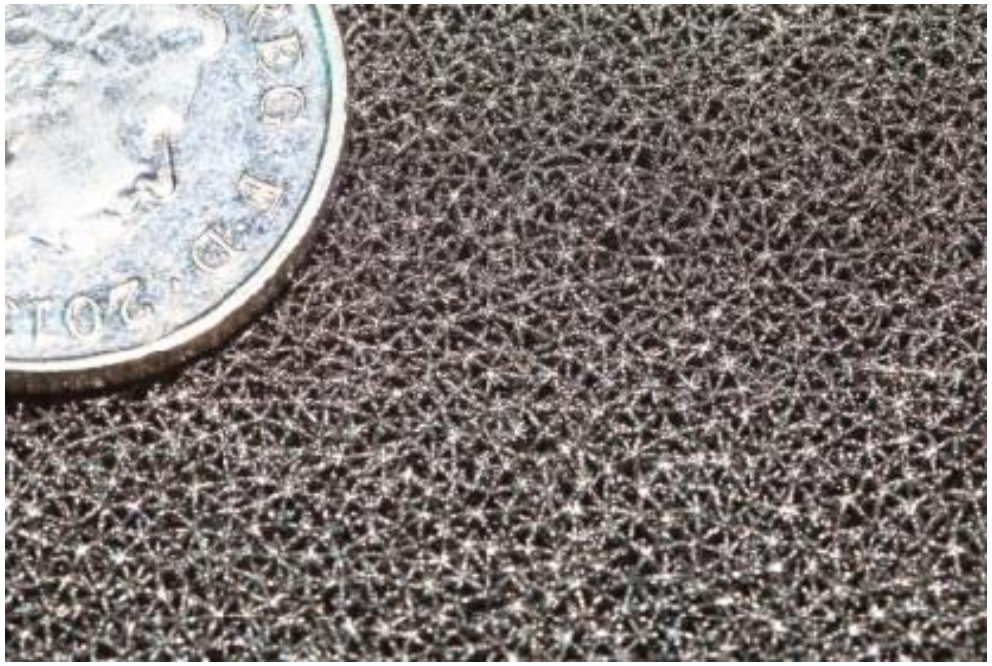
Part Qualification — Evolution of Approach to Certification — Process Qualification

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Future Challenges - The Next Generation of AM Materials

Future Challenges for Certification:

- Functionally Graded Materials
- Effect of defects
- NDT tailored to part criticality
- Machine OEM buy in to new standards (e.g. AMS7003)
- DfAM
  - Design the Material!
- How do we test and provide allowables for Metallic Foams?
- How do we get to Certification by Analysis, Supported by Test?
- R&T vs Production Mentality…
  - “Look at this cool stuff we can do!”
  - “How do we actually get that on an aircraft?”
- This will be our next 4 years…



GKN TECHNOLOGY: MAKING THINGS FLY

AIRLIFT and DAM

AIRLIFT - Additive IndustRiaLIsation for Future Technology

A technology industrialisation programme which uses industry 4.0 and simulation competencies to develop LMD-w & powder bed

Industrialisation and large scale



Digital twin for AM



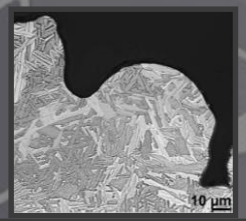
LMD wire factory pilot line



DAM - Developing Design for Additive Manufacturing

Develop the next generation of design tools, methods and people to exploit AM using a data driven material centric approach

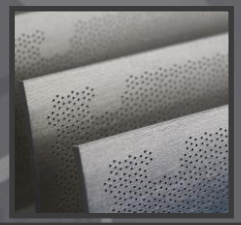
Material Centric Design



Generative Design

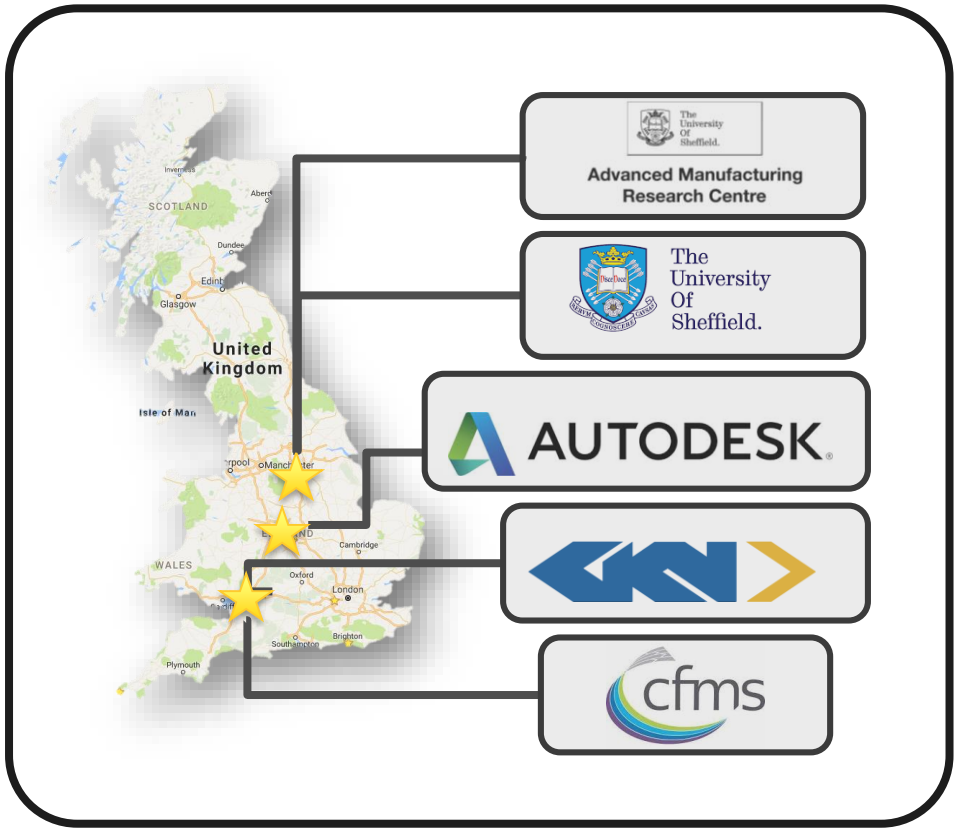


Functional systems



GKN TECHNOLOGY: MAKING THINGS FLY

DAM & AIRLIFT Programme Overview



- 4 year collaborative R&D projects
- Funded by the Aerospace Technology institute (ATI)
- Bringing together partners with unique skillsets from industry, research and technology institutes, catapults and academia
- Total value of both projects across all partners is £32M

Thank you for listening!



Any Questions?

Dr Martin White

martin.white2@gknaerospace.com

APPENDIX R
STUART JACKSON, RENISHAW PLC
“INFLUENCE OF ATMOSPHERIC CONTROL ON LPBF PART QUALITY & POWDER LIFE”

Influence of Atmospheric Control on LPBF Part Quality & Powder Life



Presented by Stuart Jackson

Prepared by Youssef Gaber

Renishaw Plc - AMPD

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Introduction

Industrialisation Economics of AM

- Early adopters of LBPF are currently qualifying parts
- Market focus on machine productivity and reducing the cost / part
- Powder usage philosophy has a significant impact on cost
- Are you taking the correct approach?

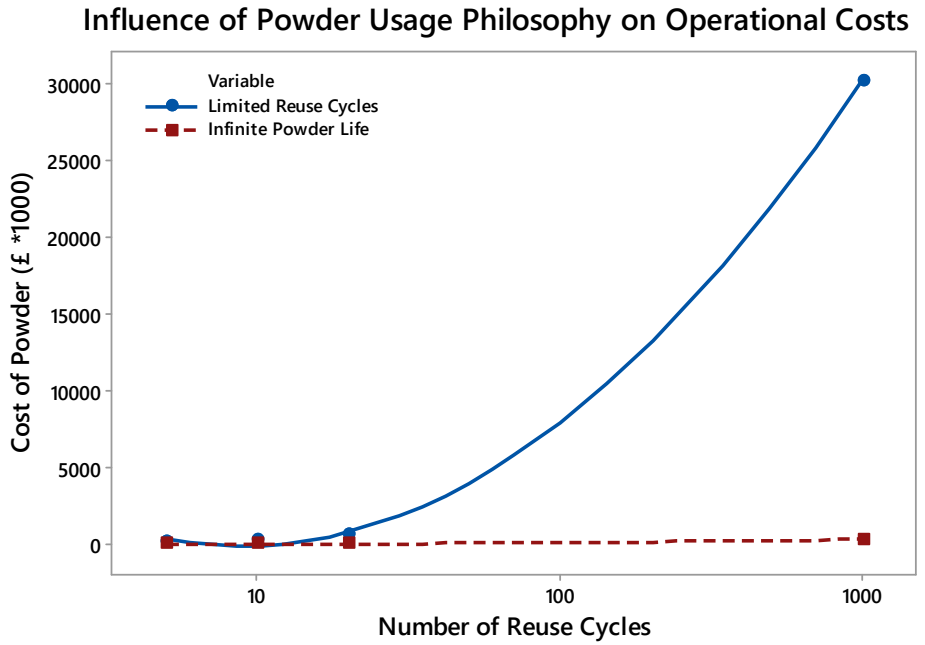


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Introduction

Industrialisation Economics of AM

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- Are you taking the correct approach?



Number of Reuse Cycles	**Limited Reuse** Powder Quantity Required	**Infinite Life** Powder Quantity Required
5	505	105
10	1010	110
20	2020	120
1000	101,1000	1100

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Context of Presented Data

- Collaborative research within Renishaw's UK solutions centre
- Commercially sensitive case studies
- Results obtained after 18 months of powder reuse following Aerospace standards and procedures
- We are not able to comment on the material used or exact values for mechanical properties
- Demonstrate the results achieved by benchmarking against standards
- Please be courteous and do not take photos of the slides

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Sources of Oxidation

1. Process
   - Process chamber oxygen content
   - Oxygen content of Ar supply
   - Moisture content of Ar supply
2. Powder
   - Moisture Content of Powder
   - Oxygen Content of Powder
3. Moisture anywhere else in the system

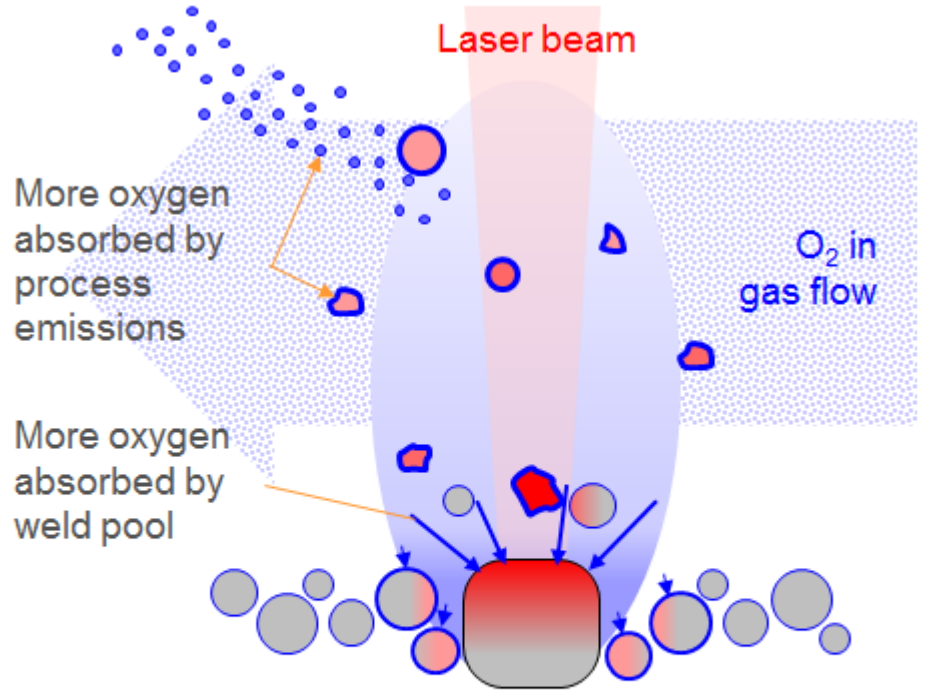
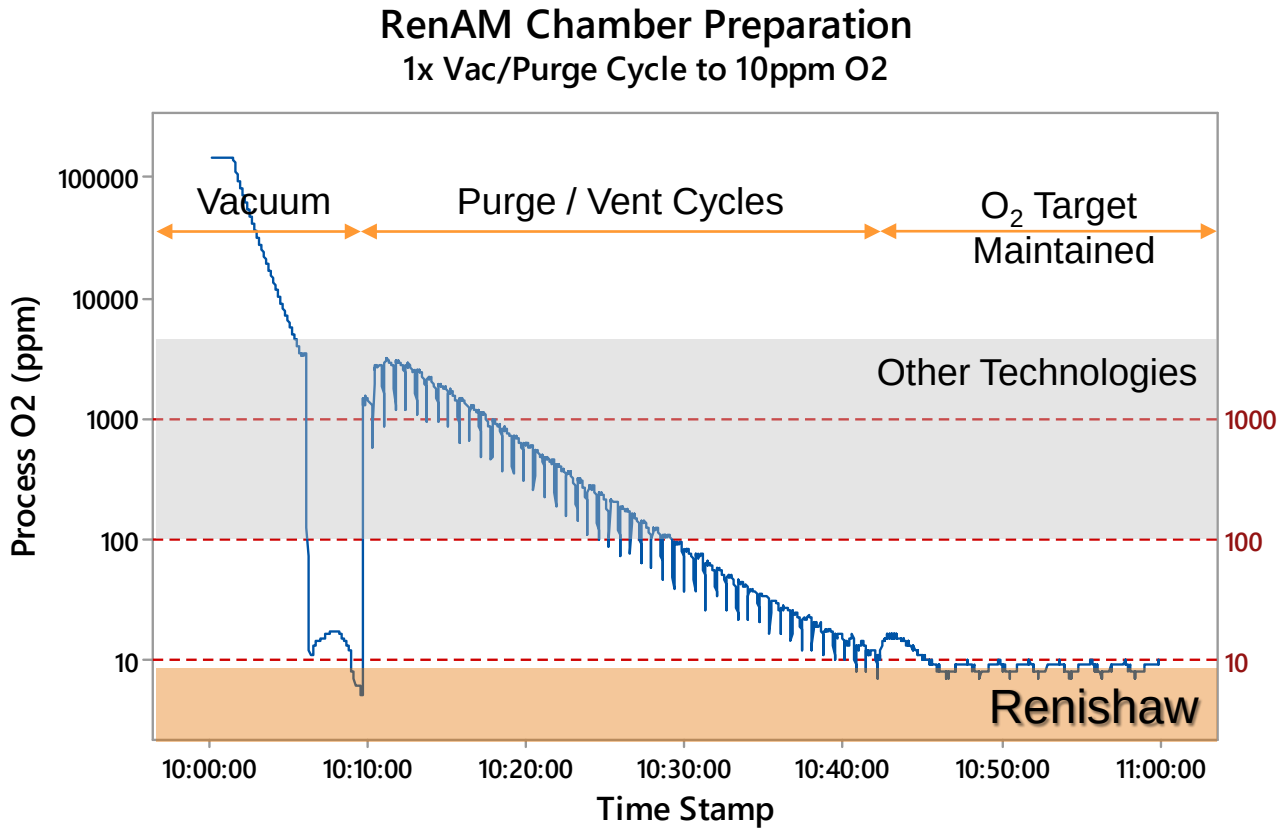


Image above - the hot weld pool, spatter and condensate all attract oxygen liberated from the powder and from the passing gas flow

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Atmospheric Control

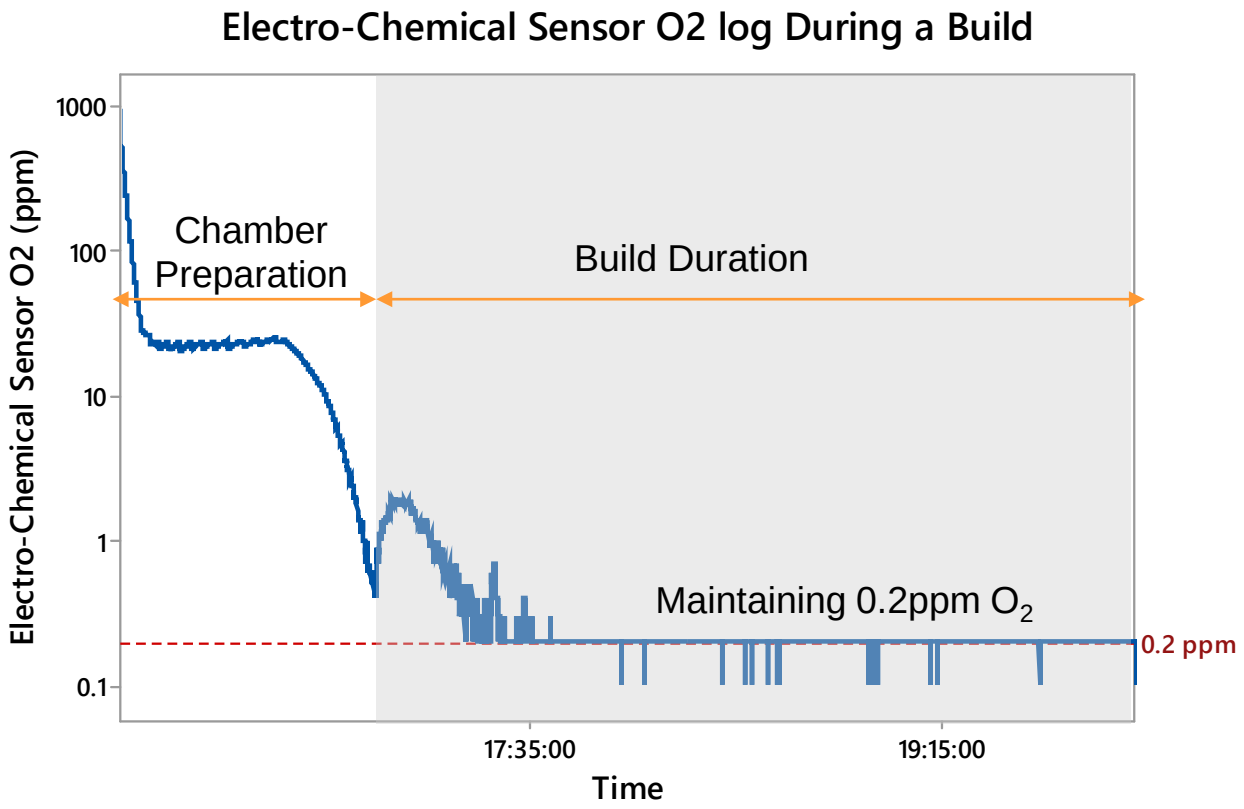
- Renishaw employs a novel inerting technique (vacuum & purge sequence) to achieve a set O_2 target level
- This differs from other technologies using an O_2 content in excess of 1000ppm
- We start a build at 10ppm O_2 for reactive powders but capable of achieving 0.2ppm O_2 if required
- Different sensors in ascending order of accuracy at low O2 levels:
  - Lambda Sensors – Usually calibrated for a very wide range
  - Zirconia Sensors– More accurate down to 2ppm O_2
  - **Electrochemical Sensors**– Most accurate <2ppm O_2



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Atmospheric Control

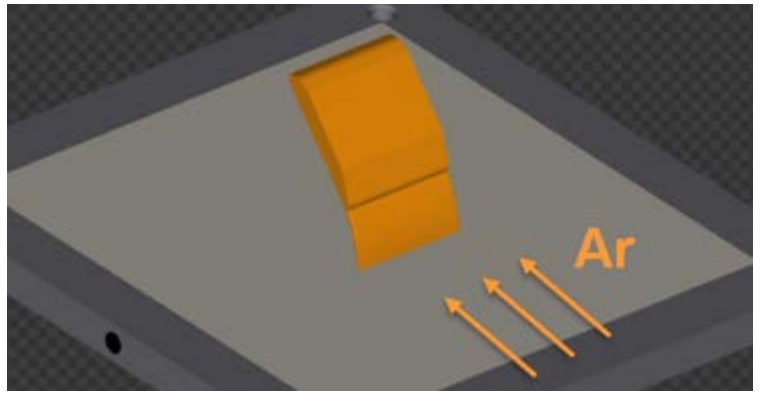
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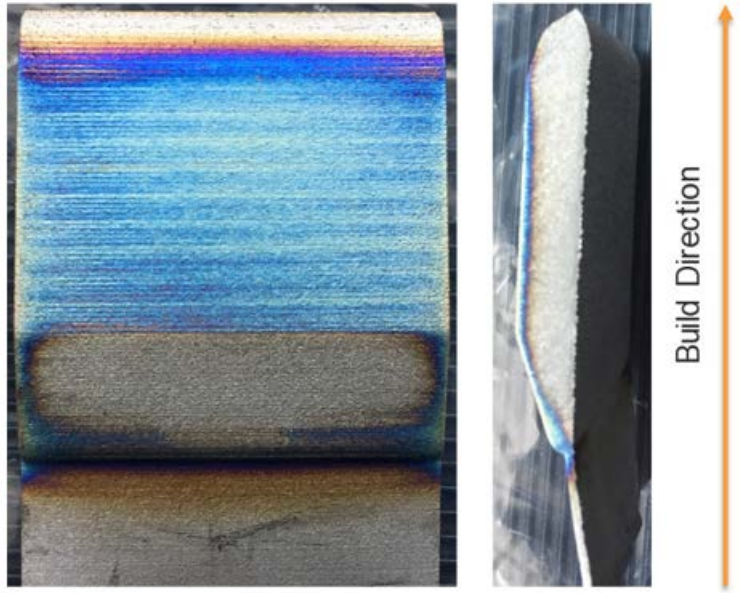


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Atmospheric Control

- Eliminating O2 from the system uncovered other sources of Oxidation
- This test piece grows from 0.9mm to 6mm in thickness and thereby allowing the temperature to rise significantly
- Clear oxidation observed on the upskin layer, directly facing the incoming Ar stream
- This meant that moisture in the system may have been the cause

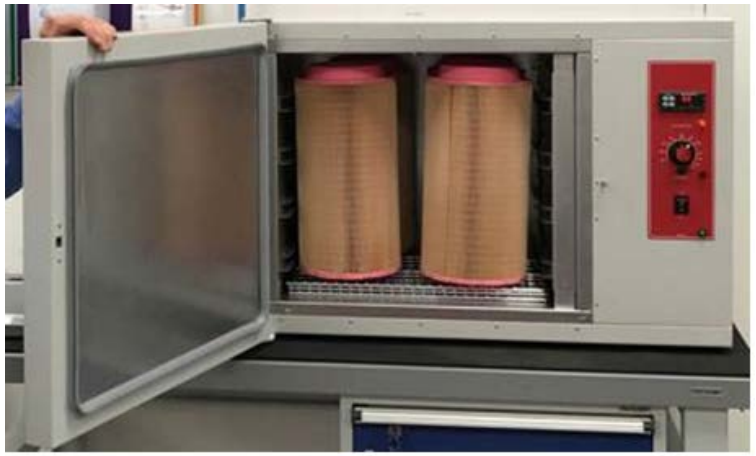




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Moisture Control

- Possible sources of moisture: powder, filter and / or inert gas
- Filters were dried to act as a desiccant to remove moisture from the system



Filter preparation procedure

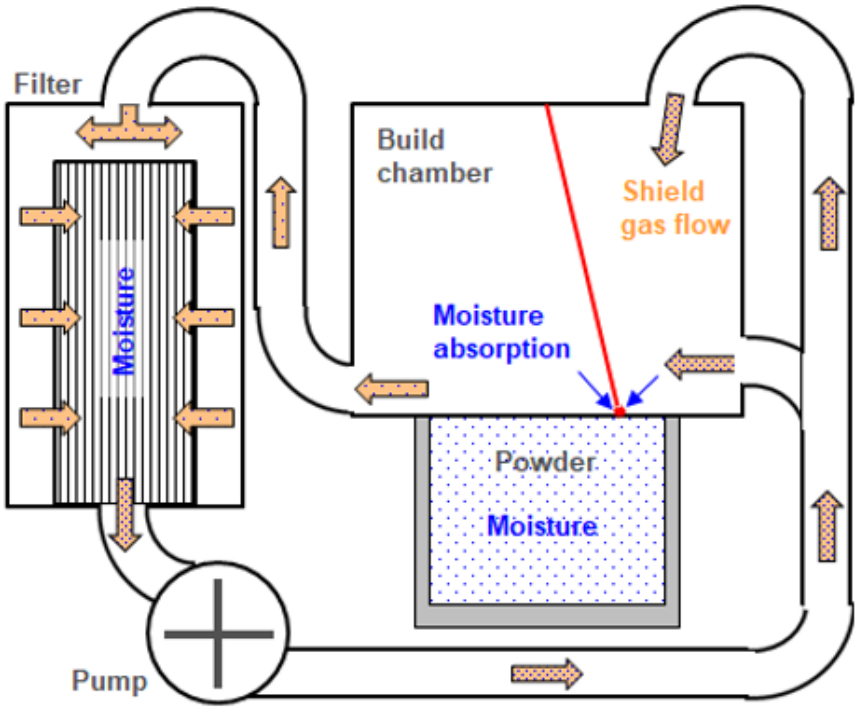
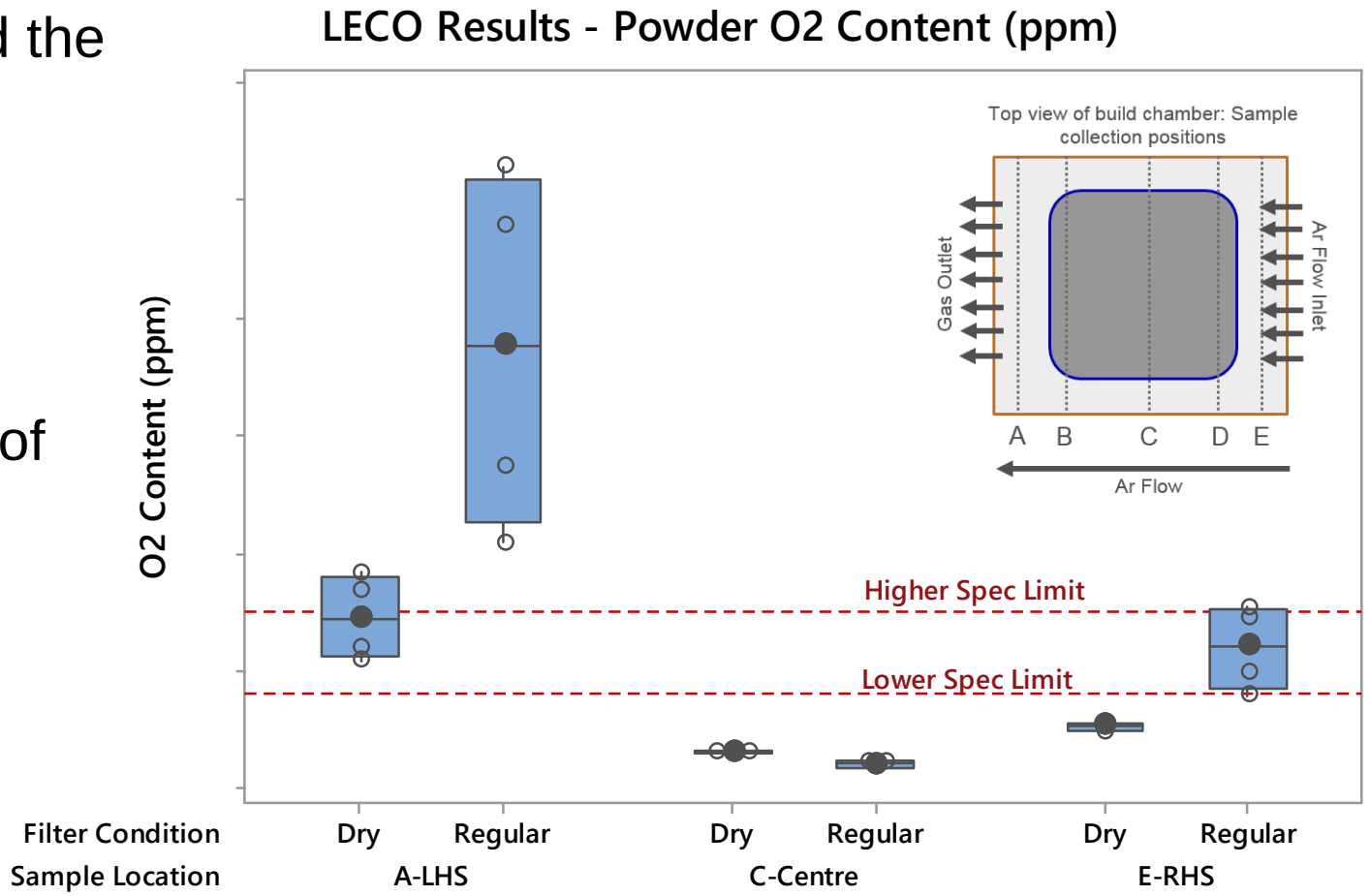


Image above - shield gas re-circulation cycle in an LPBF machine. Gas is pumped across the powder bed, out of the build chamber and through a filter cartridge, where fine condensate is removed. The gas can pick up moisture from the powder bed and the filter as it re-circulates. This airborne moisture is in turn absorbed by the molten metal alloy.

Moisture Control

- The dry filters successfully reduced the moisture from system resulting in improved flowability and reduced oxidation
- 47% reduction in O_2 pickup
- 29% reduction in moisture content of powder (Titration results)

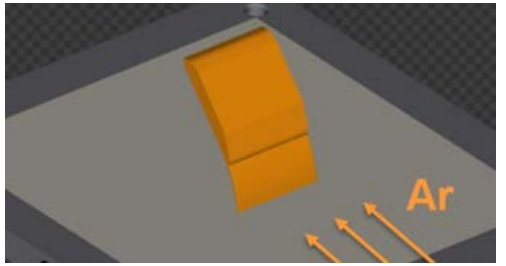
Titration Results	Moisture (ppm)
Used Powder	18.5
Virgin Powder	26.0

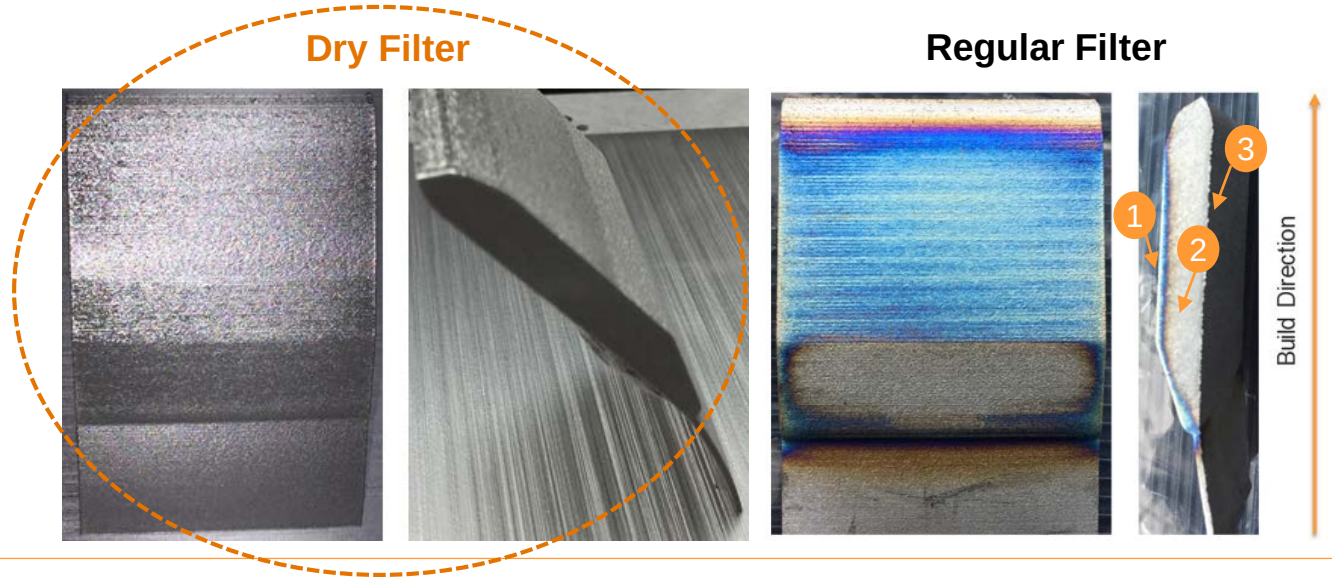


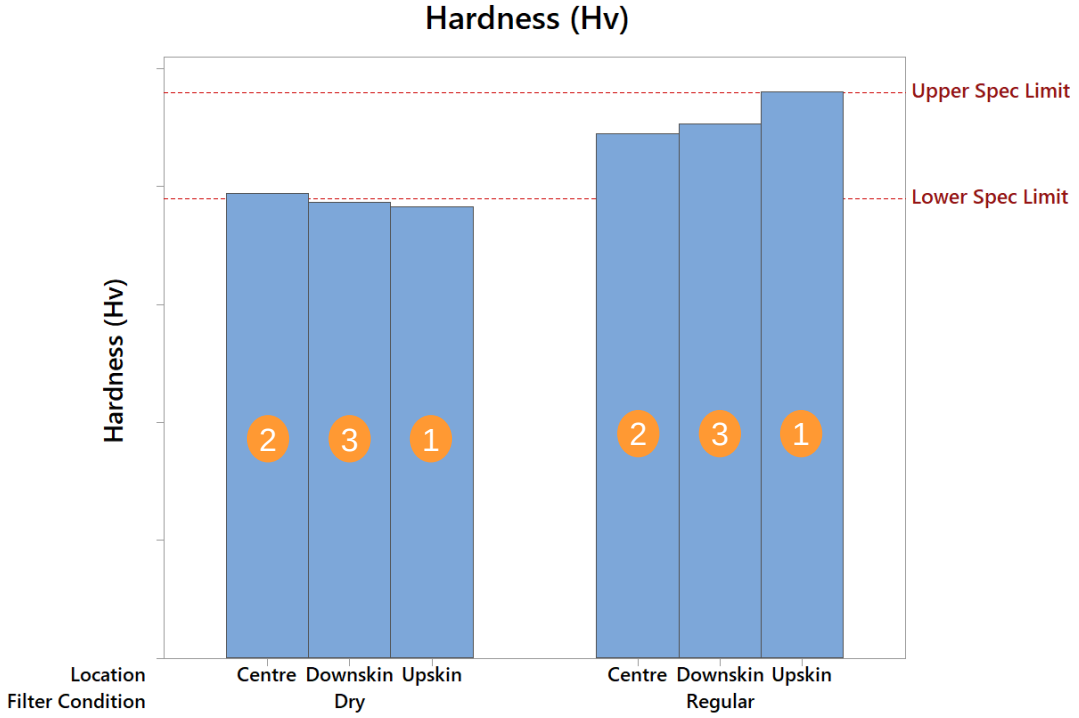
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Moisture Control

- No oxidation was observed when the filter was used as a desiccant during the build
- Hardness values in all 3 regions were below the lower specification limit which directly reflects on oxygen content of the part



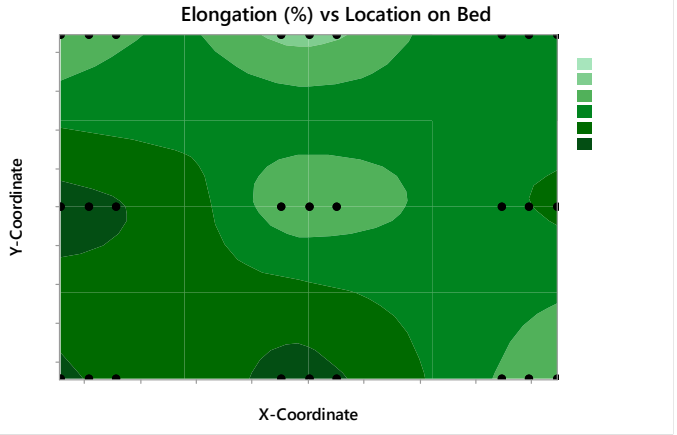


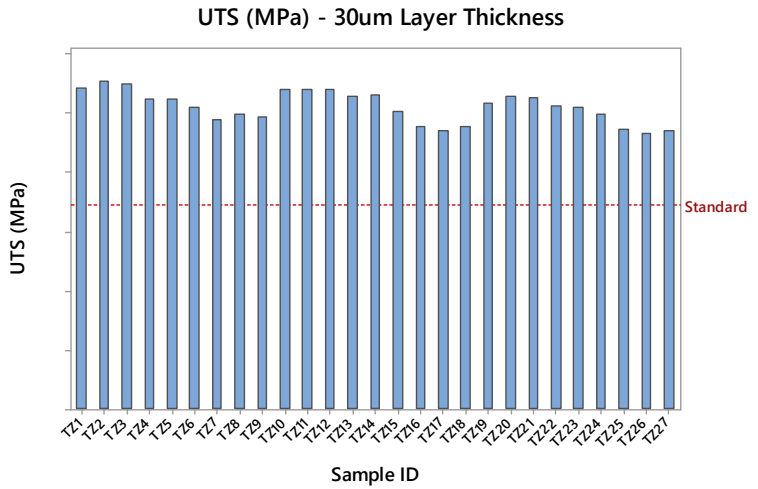


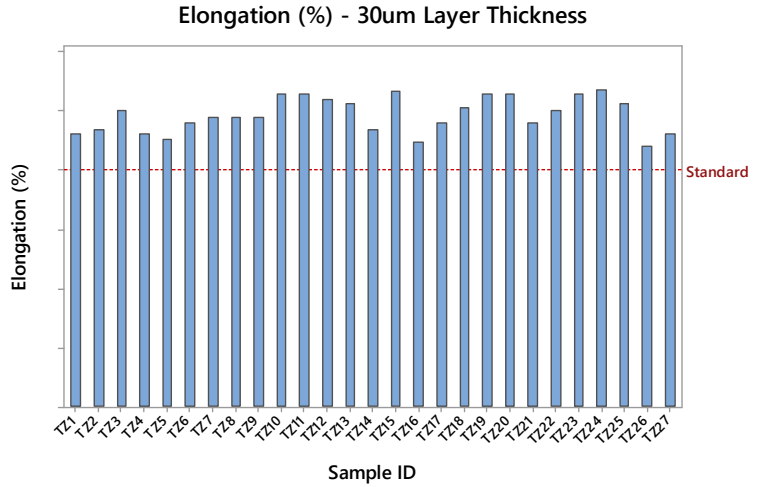
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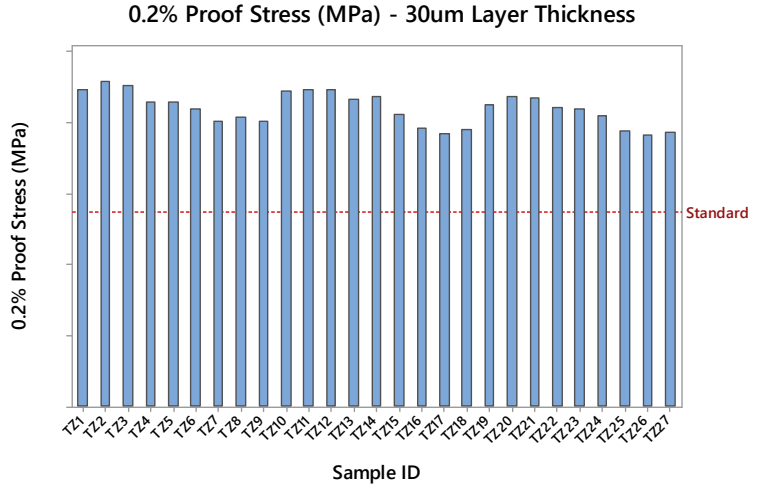
Mechanical Properties

- Results from one build carried out using Oxygen and moisture control procedures and **powder reused for more than 18 months**
- Elongation, 0.2% proof stress and UTS surpassed the specifications of wrought material
- Excellent consistency across the build plate – Max 4% variation in elongation at fracture
- Timeseries data showing change overtime is not presented as it was obtained during parameter development activities





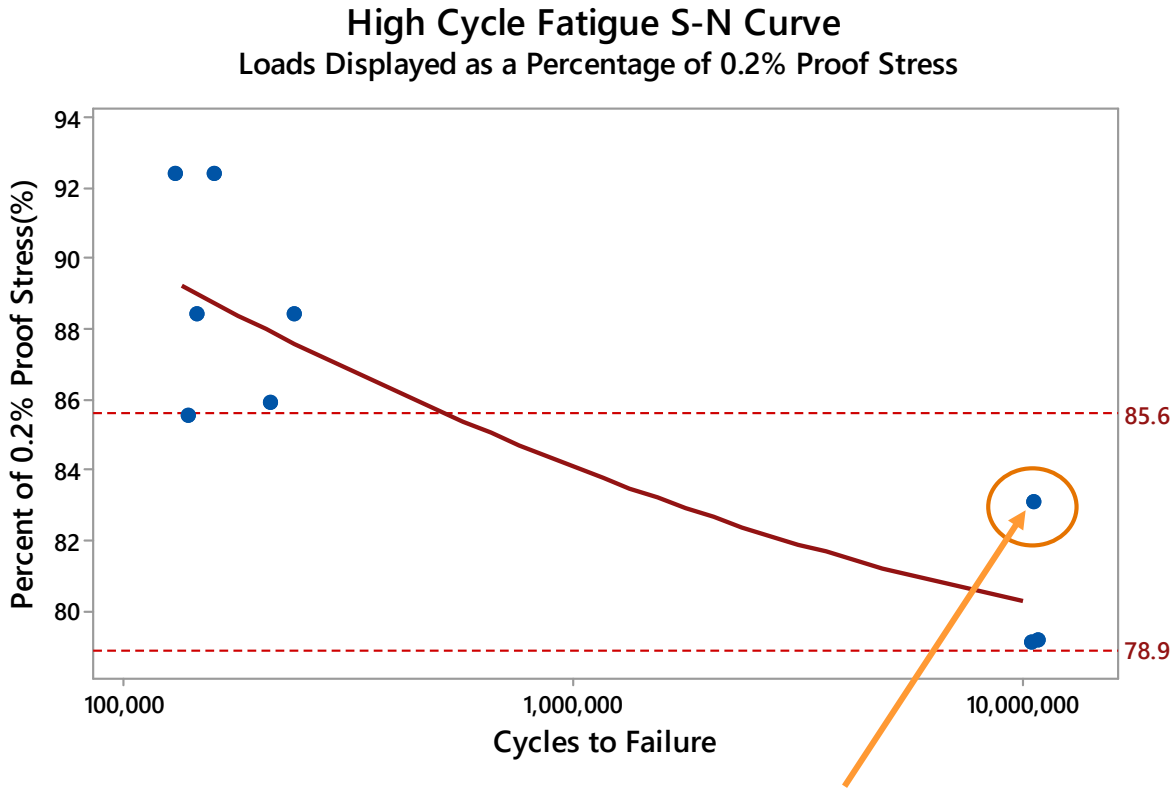




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Mechanical Properties

- High cycle fatigue data for a build carried out the same procedures and reused powder
- 10,000,000 Cycles achieved at a load level equal to 83% of the Yield Strength
- Variability was shown to be due to the machining of the test pieces
- This work is ongoing and more data points are being obtained



121% of the Standard's Requirement for Yield Strength

RENISHAW
apply innovation™

Concluding Remarks

- The source and magnitude of the moisture content is yet to be determined
- Heat treatment procedures could be an ideal place oxidation, for e.g. if an inert gas quench is used where the inert gas had a high moisture content
- These procedures may not be relevant to some less reactive alloys and user judgement is required to balance process economics vs part quality and powder life
- Acknowledgements

BAE SYSTEMS

NTRON Gas Measurement

APPENDIX S
ADAM RYBA, USAF AFLCMC
“USAF ADDITIVE MANUFACTURING”



USAF Additive Manufacturing

Adam Ryba
AFLCMC/EZP
22 August 2018

Additive Manufacturing Vision

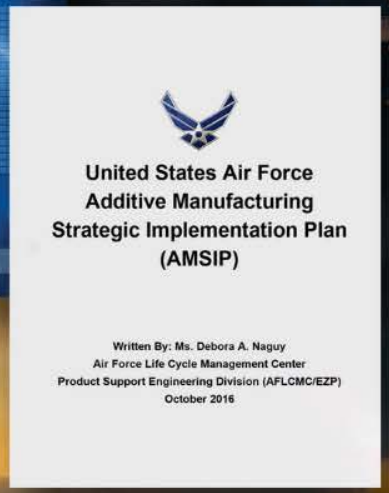
U.S. AIR FORCE

AIR FORCE LCMC

Laying the Foundation of AM

- Standardized processes & equipment
- Certified operators & machines
- Skilled technicians & engineers
- Cyber secure, centralized technical data
- Enterprise Network





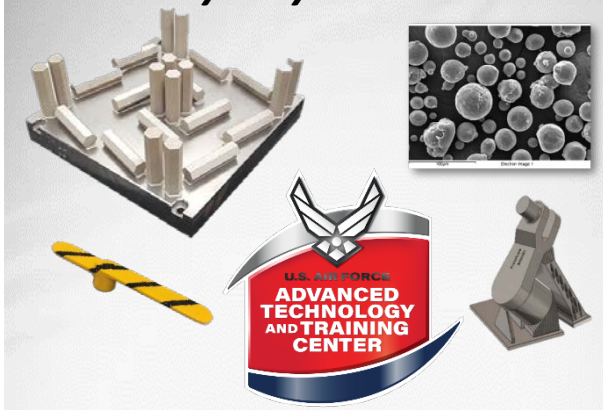
Agile Manufacturing
Additive Manufacturing (AM)

U.S. AIR FORCE

AIR FORCE LCMC

Today

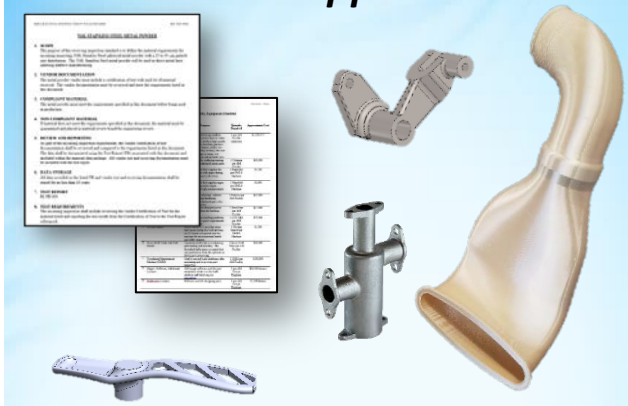
Mainly Polymer Based



- **Printing polymer training aids, fixtures, & low criticality parts**
- **Materials data for stainless steel, titanium, & Ultem™**
- **Metal & polymer components currently flying on 5 airframes**
- **Advanced Technology & Training Centers (ATTC)**
- **Educating leaders, engineers & technicians**

Tomorrow

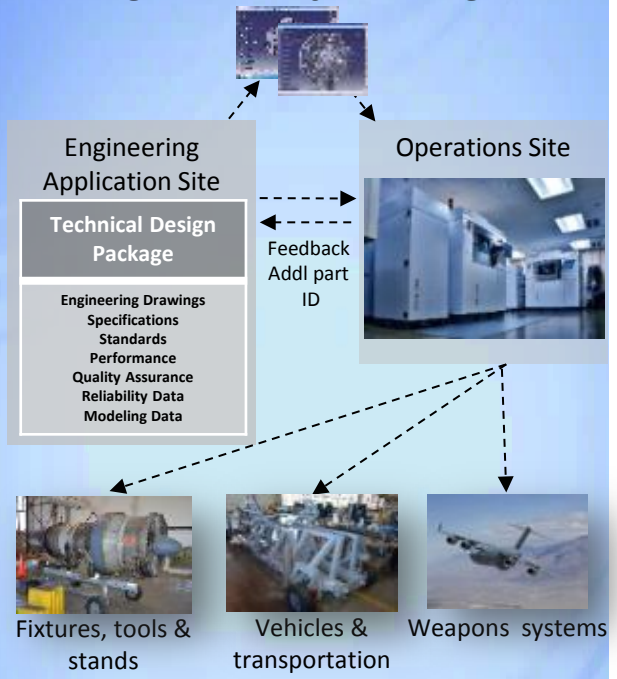
Centralized Applications



- **Qualify higher criticality parts**
- **Expand materials database to high strength/temp alloys**
- **Standard AF documentation**
- **Qualified operators/machines**
- **Implement digital thread/twin**
- **Expand ATTCs**
- **Implement initial qualified field level capability**

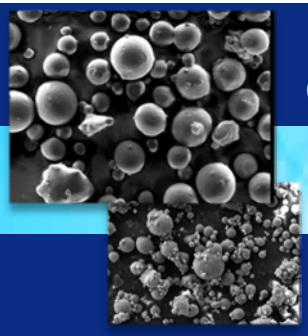
Future

Agile Manufacturing



- **Global manufacturing network using digital thread**
- **Cyber secure parts library**
- **Print on demand, any time, any machine**

USAF AM Challenges



Materials & Standards …Creating DoD specs & expanding material properties database to employ solutions faster across part families

Part Selection …Creating, validating and implementing automated part selection and cost benefit analysis tools

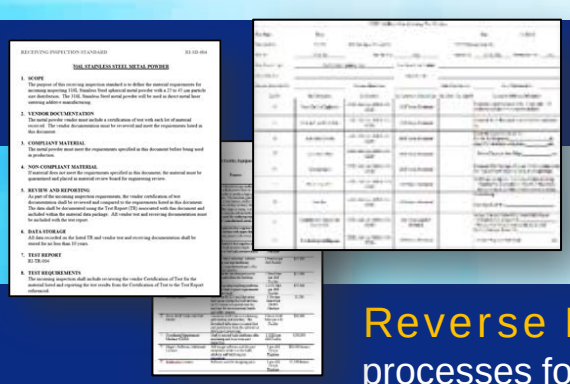
Skillset Development… Developing and exporting training for engineers and operators to leverage technology faster

Configuration Control …Establishing centralized library, standard TDPs, standard process and policies for facility layout, quality control, and material evaluation



Process Qualification …Determining and managing machine and process controls for reducing manufacturing variations between builds

Digital Thread/Digital Twin …Beta testing digital thread and PLM capabilities throughout the AM process from design to fielding



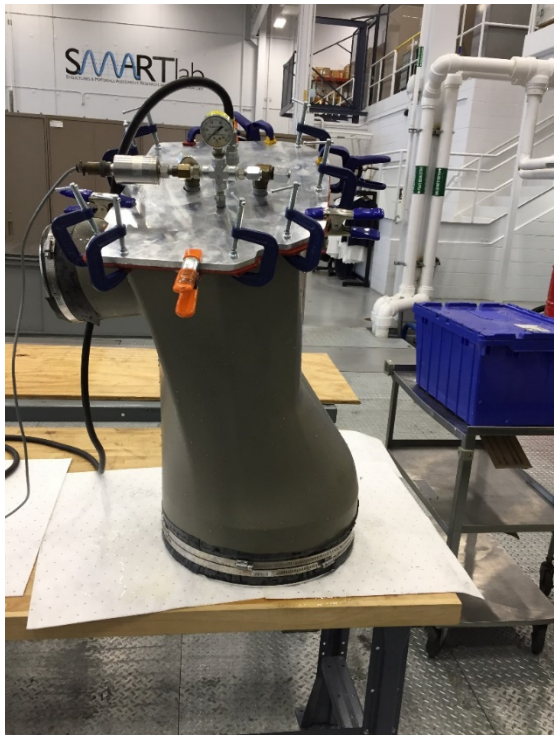
Part Qualification …Leveraging technologies to qualify parts faster across part families (NDI, In situ monitoring)

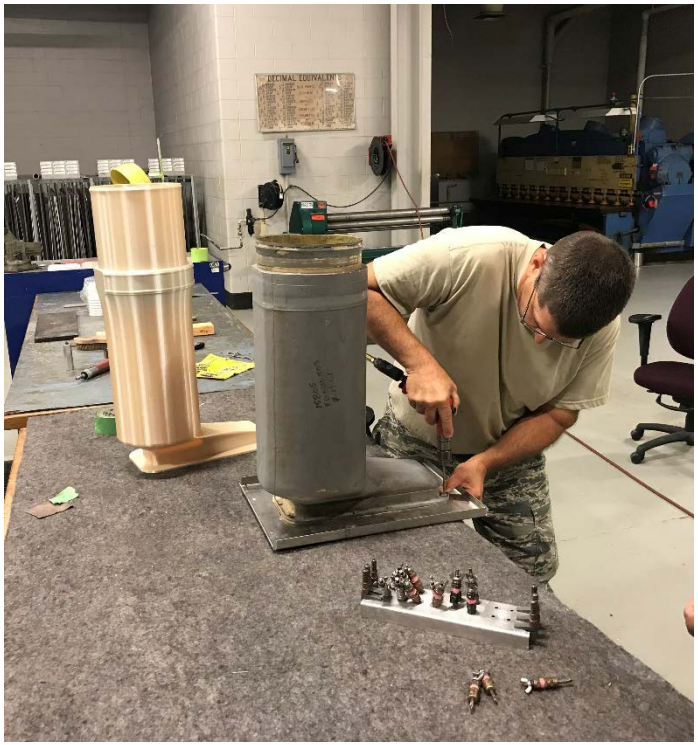
Quality Assurance …Establishing quality assurance controls necessary for machine certification

Reverse Engineering … Developing, validating, and implementing repeatable processes for faster implementation

Polymers - Family of Parts
Cooling Ducts







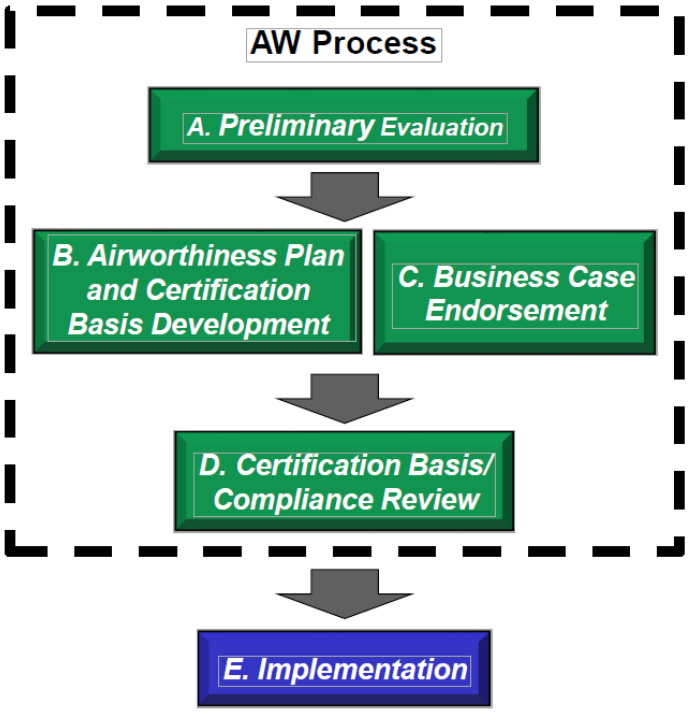
Standard…

- …**Process** – Tech Orders, Predictable and Consistent Quality
- …**Machine** – COTS Equipment, Proven Repeatability
- …**Material** – Certified Material, Traceable, Material Specification
- …**Operators** – Training Courses for Qualification Complete Aug 2018

→ Airworthiness Bulletin 1015

AWB-1015 Process

- **Applies to all new/substitute materials, processes and products on currently certified platforms**
  - **Reduces duplication**
  - **Ensures technology is mature and ready for implementation**
  - **Ensures airworthiness requirements are addressed**
  - **Faster implementation of technology across the enterprise**
- **Review artifacts, develop baseline requirements and initial qualification plan for safely deploying new/substitute materials, processes or product forms**



Technology Maturity Evaluation

- "Five Factors" of maturity
  - Stability
  - Producibility
  - Characterized Mechanical & Physical Properties
  - Predictability of Performance
  - Supportability
- Structures Bulletin EZ-SB-13-001 as applicable

Technology maturity ≠ Full qualification

Qualifying Metals AM Present Efforts

- **Fatigue Testing**
- **Repeatability Studies**
- **Powder Characterization and Alternate Source Selection**
  - →*MIL-DTL specifications*
- **Print Parameter Optimization**
- **Heat Treatment Optimization**
- **Releasing Tech Orders for EOS M290**
  - →*Machine and operator qualification procedures*
  - →*Step by step process controls and periodic maintenance*
- **DoE's for Quality Control**
  - →*Pairing AI & Robomet with in-situ monitoring*
- **Releasing Training for Operators and Engineers**
  - →*Online and in-residence*
  - →*Suite of videos for operators and maintainers*
  - →*Augmented Reality – Capturing "tribal knowledge"*

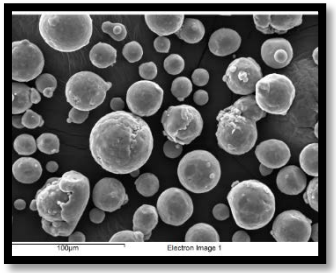
MIL-DTL Powder Specification Status

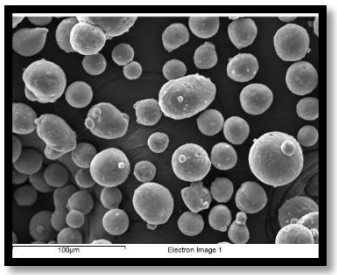
U.S. AIR FORCE

AIR FORCE LCMC

Sections

- Material Characterization
  - Chemical Composition
  - Particle Size Distribution
  - Quality/Agglomerates
  - Apparent Density
- Manufacturing Process
- Packaging and Storage
- Acquisition Requirements





Powder Type	Release Date for Final Collaboration (ASSIST)
Ti-6Al-4V	September 2018
AlSi10Mg	October 2018
17-4PH SS	November 2018
IN 718	
CoCrMo	December 2019
High Strength Aluminum	

Team Approach



Leveraging pockets of excellence to champion the enterprise approach


AIR FORCE LCMC

APPENDIX T
MOHSEN SEIFI, ASTM INTERNATIONAL
“ASTM AM COE”

CENTER of EXCELLENCE



ASTM AM CoE:

FAA/EASA Q&C Workshop

Mohsen Seifi, Ph.D.
Director, Global Additive Manufacturing Programs
ASTM International

August 21st, 2018,
NIAR, Wichita, KS

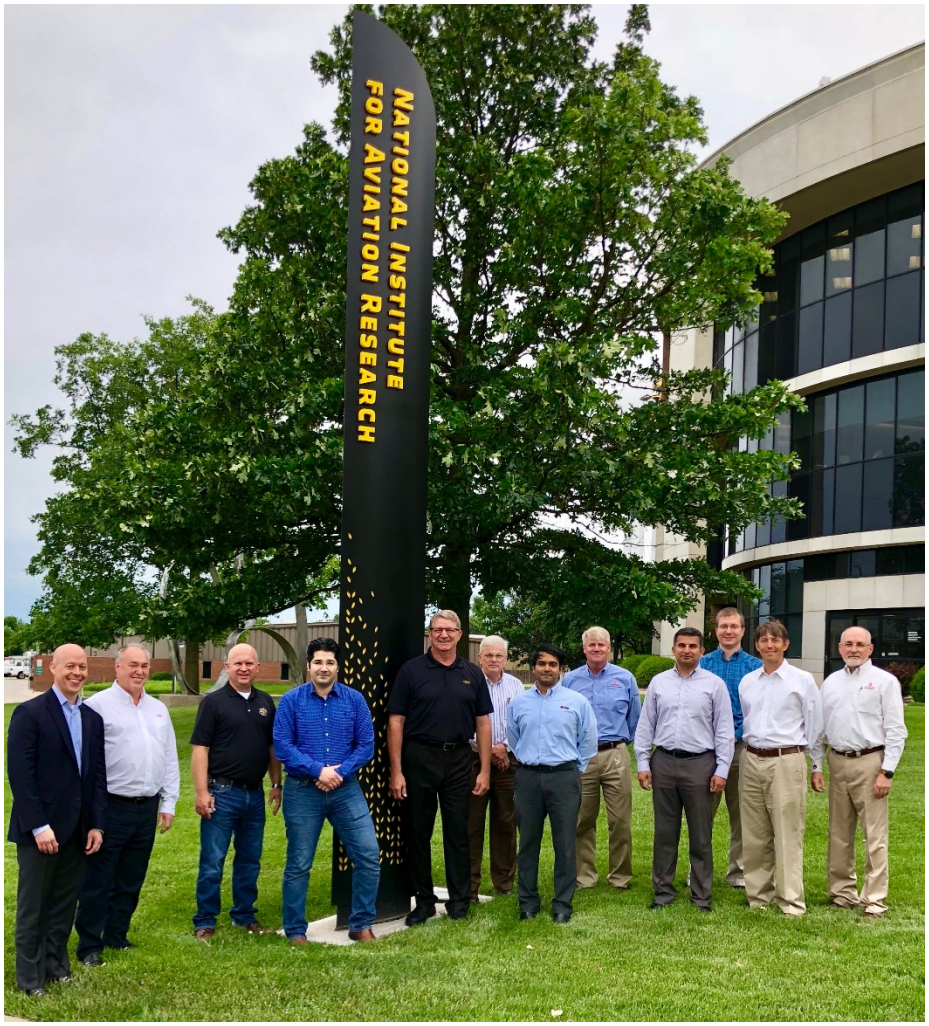
www.amcoe.org

Special Announcement

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

- **June, 7th 2019** – ASTM AM CoE team had a one day visit of NIAR facilities to discuss partnership opportunities.

- **Today**, we are proud to announce that NIAR is joining AM CoE as a first strategic partner.



In audience from CoE (9 people):

NIAR: John Tomblin, Rachael Andrulonis, Paul Jonas, other NIAR folks
MTC: Utkarsha Ankalkhope
EWI: Ian Harris
Auburn: Steve Taylor, Mike Ogles
NASA: Rick Russell, Doug Wells

AM standards advancement is a time consuming process and innovative solutions are needed to keep up with rapid pace of AM technology development.

Current ad hoc approach results in:

- Standards gaps and duplications of efforts
- Inconsistent standards R&D across industries globally
- No dedicated workforce to drive R&D for standards
- Lack of global acceptance of standards

How do we overcome these challenges?

© ASTM International

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

ASTM INTERNATIONAL
Helping our world work better

ASTM Additive Manufacturing Center of Excellence

A Hybrid Industry-Academic AM CoE:

- 5 years program
- 1st time in the history of a Standard Developer
- Conduct of Competition / Selection of Partners from applicants across 15 countries

ASTM AM Center of Excellence

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

Bridges standards development with R&D and Innovation Community to better enable efficient **development of standards**, education and training, certification, and proficiency testing programs to **support AM commercialization and adoption**.



CoE conducts R&D to advance technical standards across all aspects of AM and AM markets

Standards published **FASTER**

Accelerated and cost-efficient AM

CoE founding/strategic partners

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

- **March 2019** – ASTM International Selects EWI and Auburn University/NASA for New Additive Manufacturing Center of Excellence

- **May 2019** – ASTM International Selects UK-based Manufacturing Technology Centre (MTC) as New Additive Manufacturing Center of Excellence Partner

- **August 2019** – ASTM International welcomes National Institute for Aviation Research (NIAR) as first strategic partner of AM CoE.

EWI
We Manufacture Innovation

AUBURN UNIVERSITY

NASA

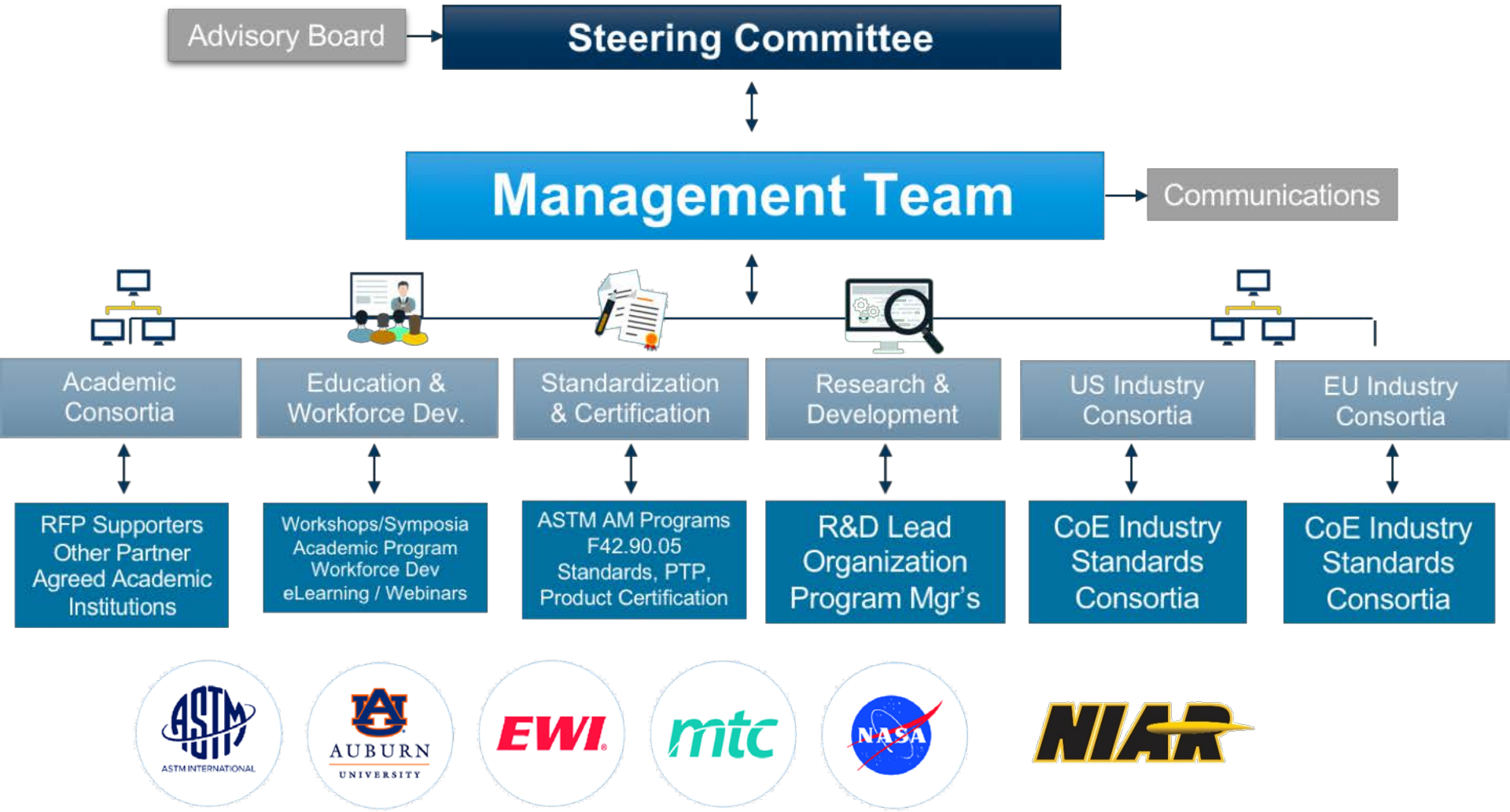
mtc
Manufacturing Technology Centre

NIAR

ASTM INTERNATIONAL
Helping our world work better

ASTM AM CoE Structure & Roles

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing



ASTM AM CoE Advisory Board

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing



John Vickers
Principal Technologist
NASA



Mike Molnar
Director
Advanced Manufacturing NIST



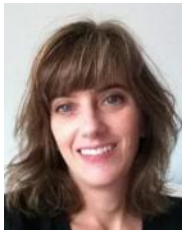
Adele Ratcliff
Director of Manufacturing
DoD



William Frazier
Chief Scientist
NAVAIR



Hany Demian
Standards Executive
FDA



Cindy Ashforth
Senior Technical Specialist
FAA



Ralph Resnick
Founder
America Makes



Robin Wilson
Innovation Lead, Manufacturing
Innovate UK



Filip Geerts
Director General
CECIMO



Jonathan Meyer
AM Technology Roadmap Owner
Airbus



Mohammad Ehteshami
VP and General Manager
GE Additive



Jeff Haynes
Program Manager
Aerojet Rocketdyne



Eddie Kavanagh
Principal Engineer
3D Printing CoE
Johnson & Johnson



Anil Sachdev
Lab Group Manager
General Motors



Terry Wohlers
Principal Consultant & President
Wohlres Associate Inc.

Research and Development (R&D) Team

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing



Doug Wells
Senior Research Engineer
NASA



Richard Russell
Technical Fellow
NASA



John Vickers
Principal
NASA



Michael Gorelik
Chief Scientist
FAA



John Bakuckas
Structural Integrity Manager
FAA



Matthew DiPrima
Research Scientist
FDA



Kevin Jurens
Deputy Chief
NIST



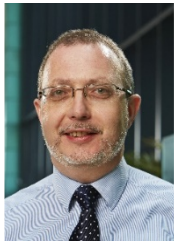
Matthew Donovan
ASTM F42 Vice Chair
Oerlikon



Rutuja Samant
Application Engineer
EWI



Nima Shamsaei
Director
Auburn University



David Wimpenny
Chief Technologist
The MTC



Christopher Holshous
Technical Director
NIAR



Mohsen Seifi
Director
ASTM International

US Industry Consortia – Invite only: Founding members

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

Objective:

Rapid development of AM standards that address consortia identified gaps within the consortia theme by:

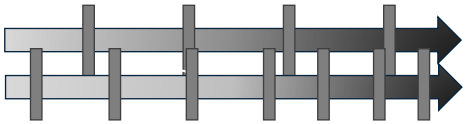
- Performing non-redundant, industry-defined R&D that leverages industry consortia, EWI, Auburn and NASA capabilities
- Creating fast track standards (via rapid balloting process)
- Directly linking to committee F42 for the creation of ASTM standards

Notes:

- 7 founding members working to define the consortia theme. Companies involved at this stage:
  - **Moog, Honeywell, GE Additive, GM, Praxair, Oerlikon, Raytheon**
- Representation from Aero, Auto, Defense, Medical, feedstock manufacturers
- Funding mechanism: 50% in kind and 50% cash (total of $100 K per membership)

Roadmap Core Theme: How R&D become standards

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RESEARCH TO STANDARDS
Additive Manufacturing



Tight coupling between "AM R&D" processes and "AM standards" development processes

- ASTM
- Industry Consortia
- Government

Direct Funding

Plan R&D

+ other partners

CoE

+ other partners

Conduct R&D

Standards Development

- Industry use
- Certification
- Training
- Proficiency testing

Implementation

Benchmarking materials, testing, processes, and machinery for standards development



1st meeting on ASTM CoE R&D planning May 15/16th, 2018 at Auburn University

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RESEARCH TO STANDARDS
Additive Manufacturing

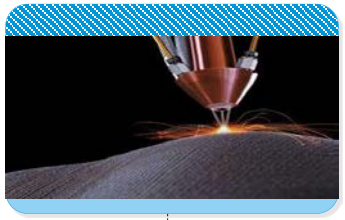
- Presentation made by NASA, FAA, FDA, NIST,F42 co-chair, CoE partners on possible R&D topics that CoE can prioritize to conduct
- Ideas consolidated and voted
- Short internal R&D roadmap is under development
- Scope of projects is being coordinated with F42



Participation:
NASA (Doug Wells, Rick Russell, John Vickers)
FAA (Michael Gorelik)
FDA (Matthew DiPrima, James Coburn)
NIST (Kevin Jurens)
Oerlikon (Matt Donovan, Vice Chair ASTM F42)
EWI (Frank Medina, Alex Kitt)
The MTC (David Wimpenny, Ben Dutton)
Auburn University (Nima Shamsaei)
ASTM International (Mohsen Seifi)

R&D Themes

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Additive Manufacturing



Transitioning R&D into standards development

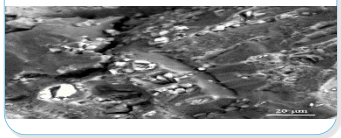
Feedstock materials (Testing, Reuse)



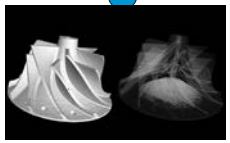
AM processes /Post Process



Design & Testing



Qualification (NDT, etc.)



1st round R&D Projects to support AMSC gaps

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RESEARCH TO STANDARDS
Additive Manufacturing

- R&D Team Established
  - GVT: FAA, FDA, NASA, NIST
  - Industry: MTC, EWI, Oerlikon
  - Academia: AU, NIAR
- Connectivity with F42.90.05 Research and Innovation
- 5 Initial projects
- Resulting in 5-7 standards

Project Areas and Lead

News Releases

ASTM International Additive Manufacturing Center of Excellence Announces First Round of R&D Projects

Yesterday, global standards developer ASTM International announced its first round of funding to support research that will help catalyze the development of needed standards in additive manufacturing, also known as 3D printing. This investment of $300,000 and in-kind contributions will help partners in the ASTM International Additive Manufacturing Center of Excellence address pressing technical information needs in this fast-growing area.

Organization	MTC	NASA	EWI	Auburn	NIAR
Focus Area	Feedstock	Process-Qualification	Post-Processing	Metallic AM Testing	Non-metallic AM Testing
AMSC Gaps	PM1-4, PM7	QC2, QC3	D7, D28, P4	D9, FMP1, FMP2	FMP1

3rd Symposium on Structural Integrity of Additive Manufactured Materials and Components (E08, F42, E07):

https://www.astm.org/SYMPOSIA/filtrexx40.cgi?+-P+EVENT_ID+3548+callforpapers.frm

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

Topics to be addressed include:

- Applicability of existing fatigue and fracture test
- Development of new fatigue and fracture test methods
- Fatigue and fracture behavior of components fabricated using AM
- Residual stress effects
- Effects of process and design parameters on fatigue and fracture behavior

Chairs:

- Dr. Nima Shamsaei, *Auburn Univ.*
- Dr. Steve Daniewicz, *Univ. of Alabama*
- Dr. Nik Hrabe, *NIST*
- Dr. Stefano Beretta, *Polimi, Italy*
- Dr. Jess Waller, *NASA*
- Dr. Mohsen Seifi, *ASTM International*

Dates:
Nov. 6-8th, 2018

Location:
Washington, DC, USA



The ASTM International
Additive Manufacturing Center of Excellence



Founding partners

ASTM INTERNATIONAL

AUBURN UNIVERSITY

EWI

mtc

NASA

Strategic partners

NIAR

A synergistic, collaborative, and efficient environment in which R&D advances technical standards, helping all aspects of additive manufacturing flourish.

www.amcoe.org | amcoe@astm.org

APPENDIX U
MARK SHAW, GE ADDITIVE

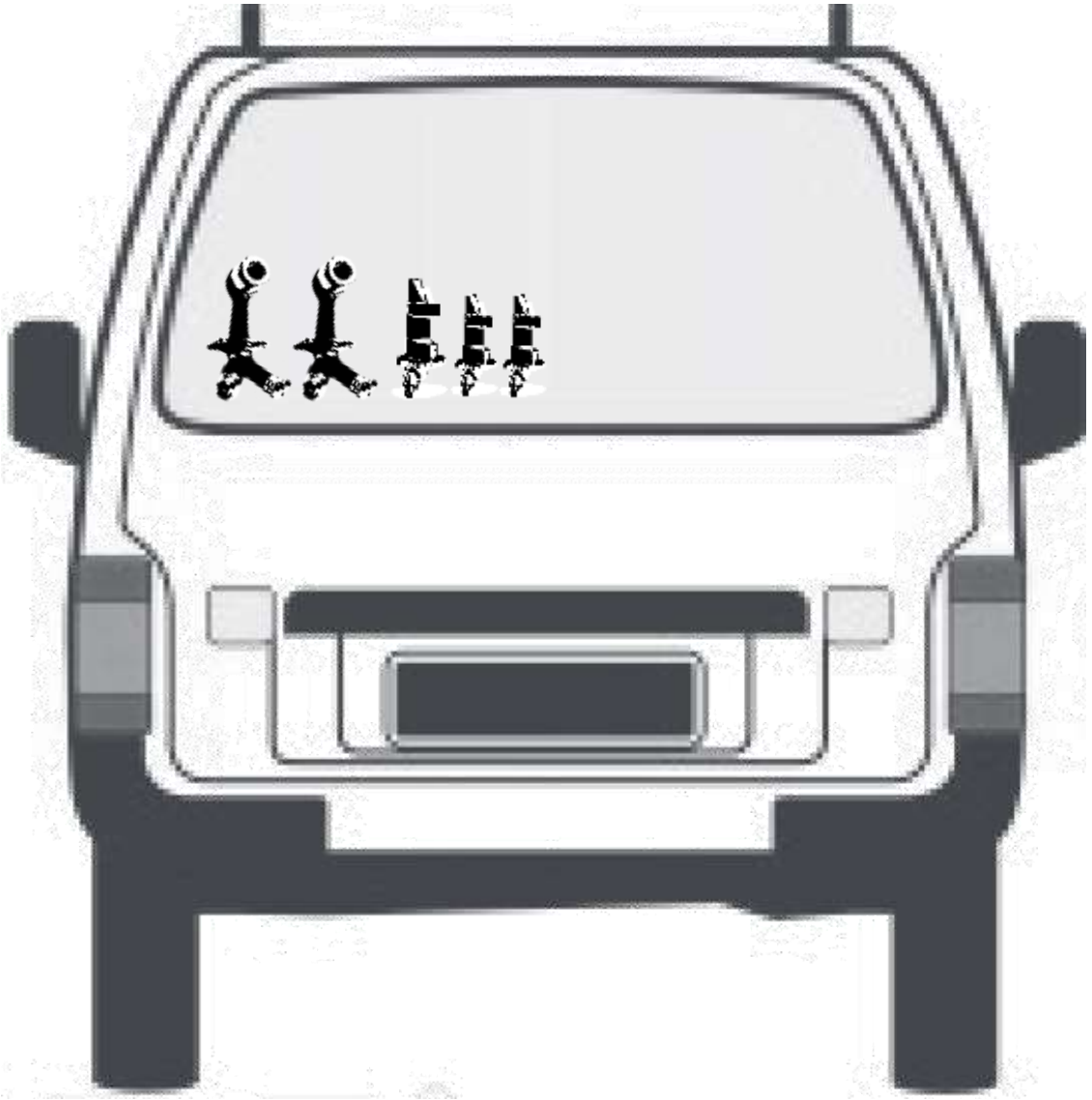
GE Part Family Approach

2018 FAA-EASA Metal Additive Manufacturing Workshop

2018

Mark Shaw

GE’s First Part Family…





LEAP Fuel Nozzle



GE90 T25 Sensor

What is in a Part Family?

Repair – AC No: 33-9 (e.g. HPT, LPC, HPT, Combustor, Externals…)

Quality – GE S1002, *"A group of parts with similar processes, materials, complex form, and tolerances, which have been produced by similar manufacturing methods"*

Material – GE Design Practice (Part type, Part criticality, Material property)

Design – GE Design Practice (Part criticality)

Supply Chain (Sustainment) – Part Qualification (Machine, Material, Process)

Certification – Part Certification (Type, Material, Criticality)

Industry – Standard (Part type, Part criticality, Material, Material Basis, Process, Part Feature, Tolerances, Anomalies Allowables…)

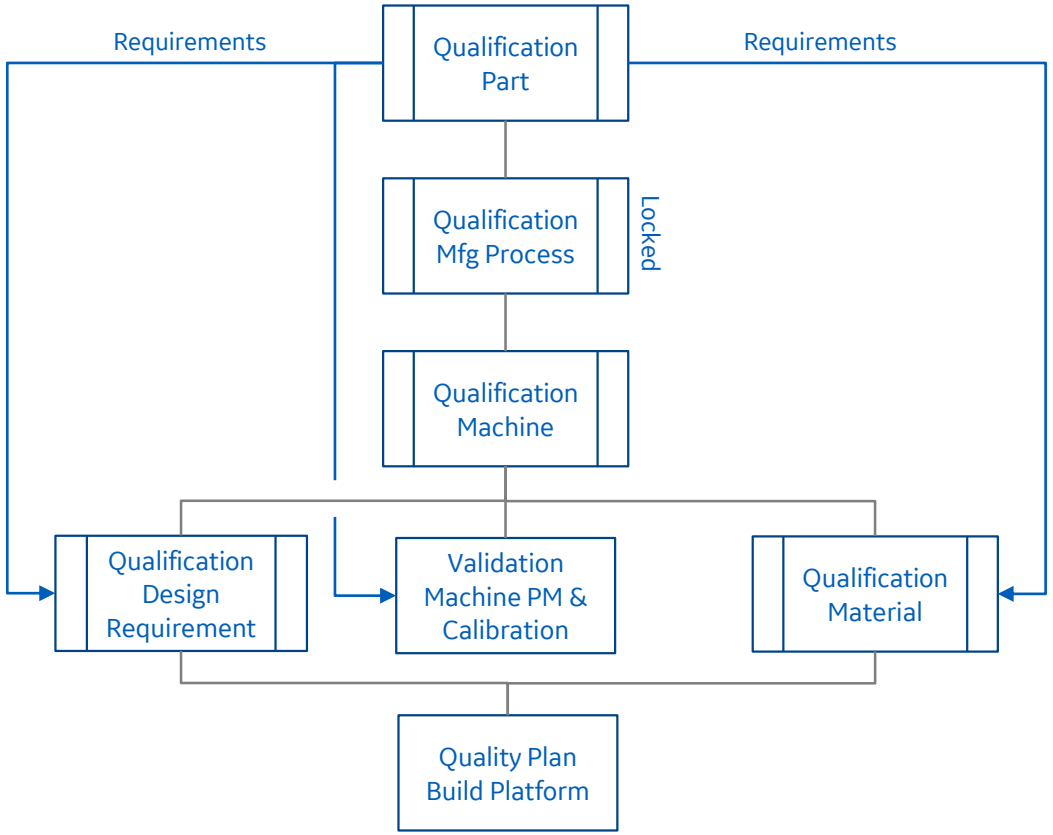
GE Additive Supply Chain Example:

A group of components which by the nature of their attributes can be manufactured within a common manufacturing cell.

Common attributes are:

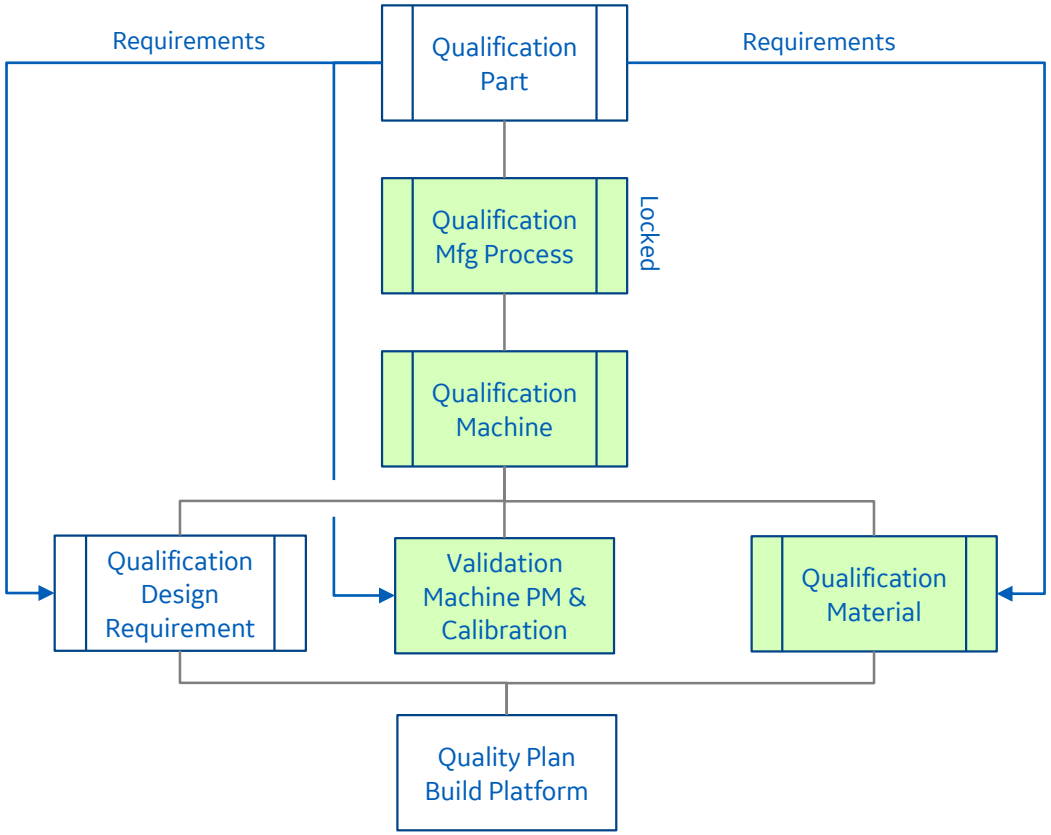
- Manufacturing process such as casting, forging, or additive
- Machine type such as Concept Laser M2 or Arcam Spectra H
- Material such as Inconel 718, stainless steel 321, or titanium 6Al4V
  - Material class, such as GE Class 1, or MMPDS A-Basis

Part Qualification Process



Part Qualification Process

*…What attributes must be **common** for part families?*





Machine Qualification

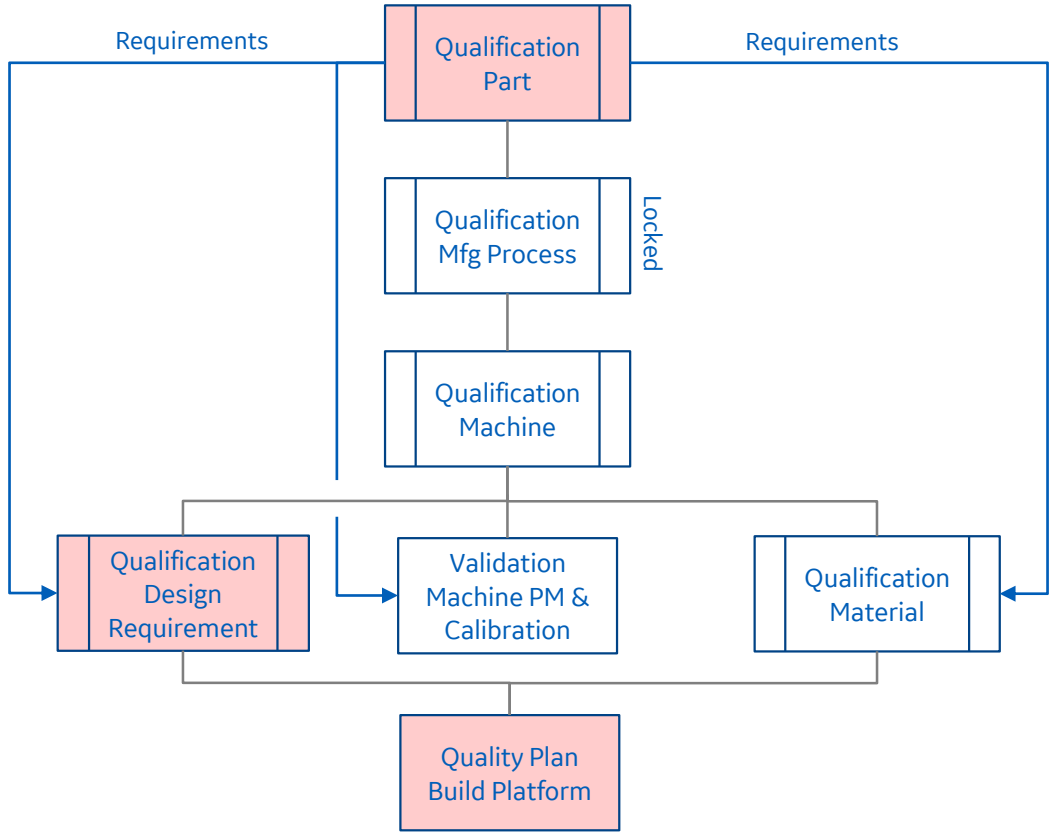
- Validation Build
- Material Qualification

Process Qualification

- Locked Process

Part Qualification Process

*…What attributes can be **unique** within part families?*





Part Qualification

- Unique analysis and test

Design Requirement Qualification

- Unique part requirements

Quality Plan, Build Platform

- Unique part requirements

Establishing the Build Platform Quality Control Plan

Considerations:
- Part criticality
- High stress / lowest margin areas
- Higher probability defect areas
- Inspection gage accuracy
- Inspection efficiency
- Company quality system policy

Participants:
- Design
- Manufacturing (development & production)
- Quality
- Inspection technology expert
- Certifying Agent (process expert)



CT scan



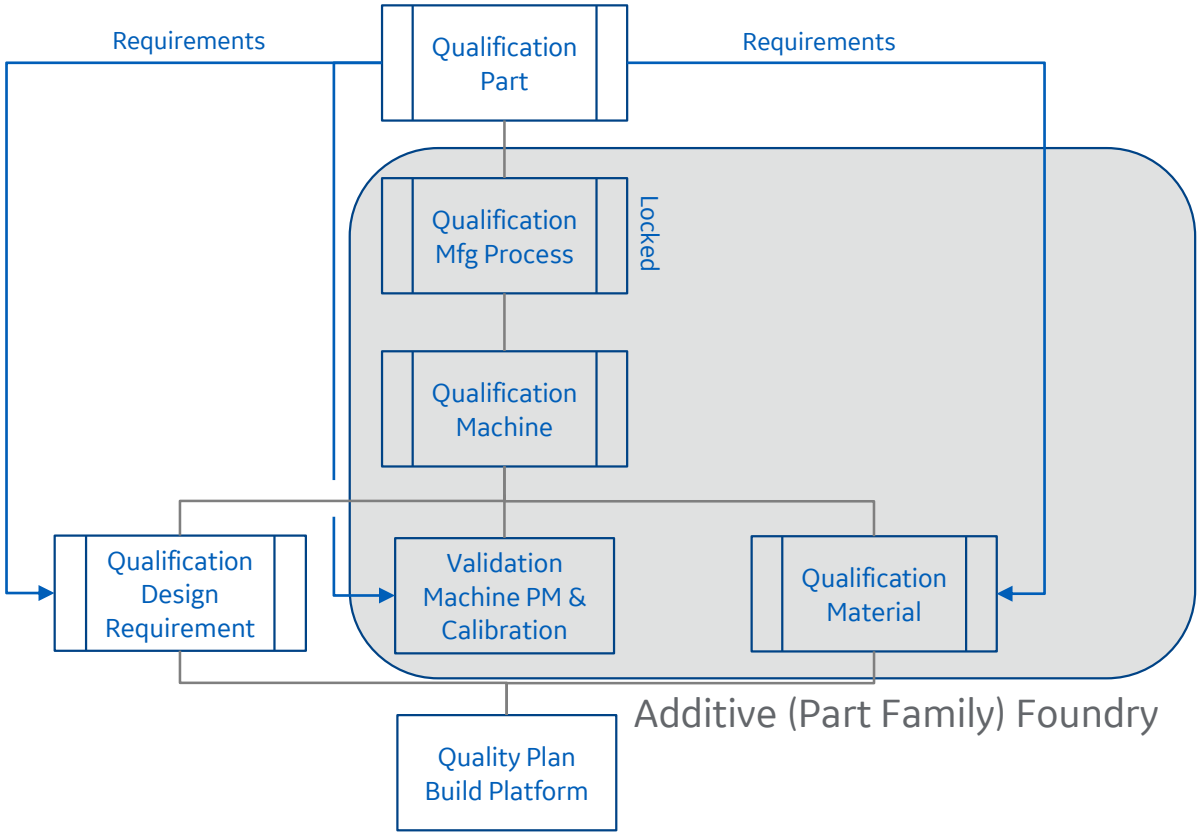
FPI



- Material Properties
- Tensile Bars
- Full Z-Height Bars
- Bar location
- Bar direction
- Bar geometry
- Thin wall
- Part cut-up plan
- X-Ray
- CT scan
- FPI
- Other NDI
- Geometric accountability
- Long term storage

Identifying Part Families

for the "additive foundry"



GE90



CoCr, 250mm, CL2 material

LEAP



CoCr, 250mm, CL2 material

GE9X









CoCr, 250mm, CL2 material

Catalyst





CoCr, 250mm, CL2 material

Catalyst

Not in part family



F357, 250mm, CL2 material

Part Family Considerations…

No Common Definition of Criticality Levels… *FAA, EASA, USAF, NAVAIR, TCHs*

- *Certification considerations… criticality, part type, material*
- *Process Agnostics… not unique to AM*

Many “Part Family” Definitions… *this is OK, but can be confusing*

Certification: Basis of evaluation has not changed
Supply Chain: based on process, is useful for economic manufacturing



APPENDIX V
DAVID POLLAND, BOEING



Breakout Session #1: Design Data for Qualification & Certification
Framing the Problem: One OEM's Perspective

David Polland, Chief Structures Engineer - Boeing Commercial Airplanes

Presented at Joint FAA – EASA Workshop on Qualification / Certification of Metal Additively Manufactured Parts
22 August 2018

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Key Additive Manufacturing Challenges

- **Material, process repeatability & robustness to ensure consistently sound structure**
  - Understanding material feedstock, fabrication process effects
  - Identification of critical process parameters
  - Protocols to establish process parameter ranges resulting in desired part performance
  - Systems-level view of process reliability & repeatability
- **Performance specification approaches**
  - Qualification requirements – material, machine, process, part, system
  - Potential path to qualifying multiple AM process types
  - Industry standards - will they be sufficiently robust?
- **Cost-effective post-processing techniques**
  - Surface treatment; Stress relieve, heat treatment, HIP; non-destructive inspection
- **Part design & analysis**
  - Predictive capability - complex shapes, material/process simulation
  - Coupon-based design values – are they representative of part performance?
  - Industry standard design values – is it possible?
  - Fatigue & damage tolerance – possible to bridge from static strength?

Challenges increase as function of part criticality

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Design Approaches

- **Structural substantiation combines:**

Manufacturing Process Controls + **Material Design Values** + **Analysis Methods**

  - These elements must be in balance – a ‘deficit’ in one area can be compensated by appropriate conservatism in one or both of the other elements
- **Three approaches to material design values:**
  - General material design values
    - common approach for wide range of materials
  - Part-specific material design values
    - e.g., forgings
  - Part acceptance test approach
    - e.g., fasteners
    - While material design values are not used for certification, are needed to develop design
    - Two primary options
      - Proof test every production part
      - Conduct sufficient part testing at beginning of production to demonstrate capability
        - Requires adequate process control to ensure future production will have comparable capability
        - May require periodic sampling testing to confirm process capability has not drifted

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Spiral Development

Rational Implementation Based on Expanding Process Knowledge

Today → Tomorrow → The Day After

Pathfinders • Learn by doing

- material & process specifications
- machine, process, part qualification
- static material databases
- process proofing, production experience
- process window robustness
- understand value

Expanded use, more challenging applications • Leverage value/benefits

- serial production stability
- expand material databases
- optimize post processing, surface treatments
- process improvements, NDT development, in-process monitoring
- cost reduction

Broad use – safety-critical parts

- Mature production-ready processes
  - fatigue/fracture material databases
  - design for additive – integrated, multi-functional components
  - optimum performance

Part-specific | **Part family, feature-based** | **General design values**

Pathfinder applications to mature technology, foundation for broader implementation

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APPENDIX W
BÉNÉDICTE VALETTE, SAFRAN

BREAKOUT SESSION#1

DESIGN DATA FOR QUALIFICATION &CERTIFICATION

Joint FAA-EASA workshop on Qualification / Certification of Metal Additively Manufactured Parts
August 21-23, 2018, Wichita KS

Bénédicte Valette– Safran Additive Manufacturing

SAFRAN

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Understanding/Meaning of «Design data for Q&C »

- Develop robust design values in order to establish the capability of a component to meet design intent (PART21J)
- Put the process under control in order to demonstrate the capability of the process to ensure “serial” part compliance with the FAI (“First Article Inspection”) & therefore with the design intent (PART21G)

Back to basic!

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« Design data for Q&C »: global approach

- **Robust design values:**

AM material design values are taking into account for both, “feedstock” materials and process variability used to manufacture the AM part.

Data used to derive design values are obtained from stable and repeatable feedstock material procured per a controlled material specification.

Material are processed with a stable and repeatable process per a representative process specification.

Part design features and processing (including but not limited to thermal effects, environmental effects, and geometric features) that impact material properties are addressed as well.

In particularly, the representativity of the test piece vs AM part is adressed with a direct comparison of microstructure and mechanical properties.

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« Design data for Q&C »: global approach

- **Production repeatability:**

The AM process, as per special process requirements, is properly qualified & monitored to produce stable and reproducible AM parts.

Process characteristics that have a direct influence on the final AM part mechanical properties and physical attributes are frozen.

Process requalification is performed in the case of at least one of the significant process characteristics is changed.

Significant process characteristics are controlled/monitored according to the part quality control plan in order to prove that AM parts are produced in a stable and repeatable manner (yield capability).

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APPENDIX X
BREAKOUT SESSION #1 DEBRIEF

Design Data for Q&C

Starting point for discussion was “Part Family Considerations”

- Through debate, we discovered that the definition and implication of a “Part Family” approach has various meanings, for example:
  - “part family” could include everything beyond “point design”
  - “part family” could imply the use of common design values that are not part-specific
  - “part family” could mean qualification of parts by similarity to avoid repeated requalification of very similar parts
  - Therefore, the term “part family” needs standardization before policy can be negotiated
- In addition, the consensus was strong that better definition of the design data requirements for qualification/certification of individual parts is needed before “part family” considerations are appropriate, i.e., we’ll get to part families, but we can’t start there
  - As a precursor to “part family” approaches, considerations requalification methodologies following major / minor changes needs definition

The conclusion to defer considerations for the “part family” approach does NOT imply the industry should remain at a “point design” methodology for AM. There is consensus that if every AM part is treated as fully unique, the certification burden is simply unsustainable.

The Industry is ready to move beyond the point design scenario. Establishing an accepted framework that enables the use of common design values is the key first step to lessoning certification burden.

Design Data for Q&C

Discussions led to a potential framework for AM Q&C design data based on the following concepts:

STEP 1: AM Process Qualification (part agnostic, with some exceptions)

A. Define a baseline, locked AM candidate process by machine serial number
    - Candidate process refined to produce high material and build quality under nominal conditions
    - Candidate process “well-centered” in the AM process box
    - Candidate process definition includes all “key parameters” influential to material performance
        - Feedstock, AM machine conditions/settings, post-build thermal treatments

B. Qualify the candidate process using commonly accepted metrics (no standards yet) to an accepted and understood state of inherent, yet acceptable “discontinuities” (defect state)

C. Characterize material performance of qualified baseline process as required for Q&C

D. Identify AM-specific “influence factors” that may alter material performance.
    - (Thermal history, thin sections, surface finish, orientation, etc.)
    - Characterize the effects of influence factors in a bounding, containable fashion based on understanding of process physics
    - Define standard methods of application of “influence factors” to baseline data

Design Data for Q&C

STEP 2: Establish common design value properties based upon baseline process and influence factors

- Maintain both design values and supporting data characteristics used in their development
- Nominal material performance definitions eventually become part of industry handbooks

STEP 3: Establish statistical process controls that maintain material quality and performance standards throughout production

- SPC metrics are likely required on a variety of factors to achieve control to defend design values

STEP 4: Demonstrate Equivalent AM Material Performance

- Use statistical equivalence methods to demonstrate additional qualified processes (machines) may justifiably use the established common material properties (with prerequisites).
- Nominal equivalence methods eventually become part of industry handbooks, enabling use of handbook design values
- Equivalence does not mean equal or better, but equivalent in fundamental material aspects including feedstock/chemistry controls, microstructure, properties and performance on multiple metrics

STEP 5: Maintain a strong Part Qualification process that ensures each implementation of the qualified AM process and application of properties (and influence factors) has been successful relative to the assumed material performance standards. (1st Article cut-ups)

APPENDIX Y
DOUG WELLS, NASA

Framework for Enabling Additive Manufacturing Design Values Suitable to the Qualification and Certification of Aerospace Quality Hardware

Douglas N. Wells
NASA MSFC
Damage Tolerance Assessment Branch

A five-step system is proposed as a foundation for establishing design values suitable for the qualification and certification of additively manufactured, aerospace quality hardware. This discussion is based upon the laser powder bed fusion (L-PBF) additive manufacturing (AM) process in metals, but the concepts may be adapted to other AM processes. The concepts reflect the intent of the requirements in AM technical standards published by NASA Marshall Space Flight Center: MSFC-STD-3716 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals[1]" and MSFC-SPEC-3717 "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes[2]." The intent of this framework is to bridge the gap between a "point design" approach to design values where material property data is developed specifically in the context of a given AM part, and the traditional approach to design data "allowables" as developed and tabulated in resources such as the MMPDS. As noted above, the point design approach is not sustainable for any meaningful quantity of AM hardware and the traditional concept of design data allowables is not considered appropriate or applicable for materials from AM processes given their sensitivity to process and current state of maturity. The proposed framework presented here is a compromise with significant advantages over the burdens of point design, but with added encumbrance compared to the traditional allowables approach where design data are generated once and assumed applicable to all future material produced to the governing specification. The enabling concept in the proposed framework is reoccurring evaluations that demonstrate material equivalency for purpose of qualifying AM processes and monitoring the health of the AM process continuously through statistical process control (SPC).

STEP 1: AM Process Qualification

This framework begins with an assumption that each AM machine is unique and capable of independent variability and process failure modes; therefore, each AM machine is qualified individually by serial number. There are economies to be gained for qualification of multiple machines with identical configurations, but each machine requires independent substantiation of the quality of its process. In this context the machine and defined AM process are indelibly linked—they are interdependent and qualified simultaneously. *Importantly, this machine/process qualification procedure is not to be confused with the state of AM machine calibration. This methodology relies upon the underlying assumption that each AM machine is independently maintained and calibrated such that its functionality and response to commands is proper.*

[1] https://standards.nasa.gov/standard/msfc/msfc-std-3716
[2] https://standards.nasa.gov/standard/msfc/msfc-spec-3717

Before qualification can begin, the candidate process requires clear definition. In the context of L-PBF and MSFC-STD-3716, this is referred to as a Candidate Qualified Metallurgical Process (Candidate QMP). This candidate process definition necessarily includes all "key parameters" influential to the final material performance: feedstock specification and controls, complete definition of machine configuration and all fusion parameter settings, and all post-build thermal treatments. An AM process definition that lacks any of these constituents cannot be used to govern material performance and thus cannot achieve the goal of substantiated design values.

The defined Candidate QMP is intended to be agnostic to part geometry although some exceptions are possible, such as a Candidate QMP tuned for building parts with very thin walls. The candidate QMP is refined such that under nominal conditions, the process produces AM material of high quality with a diminishingly small inherent defect state and high quality build characteristics regarding surface condition and detail rendering. Most importantly, the candidate QMP is defined to be "well-centered" in the AM process box, meaning that the process is robust against changes in process conditions that will occur due to varying demands of part geometry, build platform content, and other influences that affect the thermal history of the AM process throughout the build.

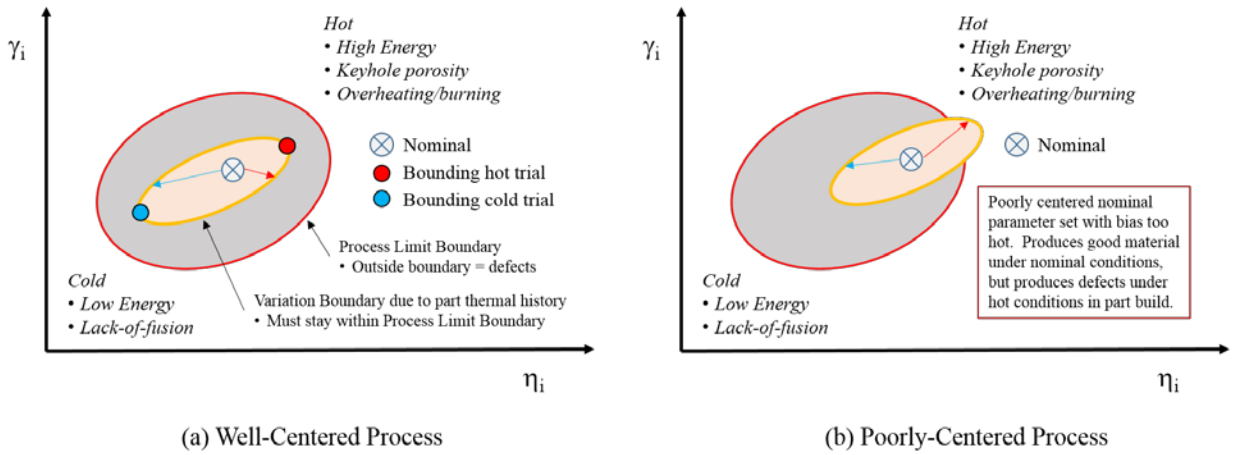


Figure 1. (a) Thermal tolerance for a well-centered nominal process. (b) Poorly centered nominal process that tends toward overheating defects under hot process conditions.

As schematically illustrated in Figure 1, nominal process parameters render variations in the local fusion process conditions throughout the part build process due to thermal and geometric variation. This expected process variation is represented by the yellow "Variation Boundary" in Figure 1(a). The extent of the "Variation Boundary" is verified by evaluation of anticipated bounding hot and cold part build conditions. If the nominal process parameters are well-centered, the "Variation Boundary" will not cross the "Process Limit Boundary" represented by the red line. Operating conditions outside the "Process Limit Boundary" are associated with a significant increase in inherent defects. Figure 1(b) represents a nominal process definition that produces good quality material under nominal conditions, but tends toward the hot side of the process box; therefore,

during hot process conditions of a part build defects are likely because the “Process Limit Boundary” is crossed.

Once the definition of Candidate QMP is finalized and documented, no further changes to the definition are permitted and the qualification procedure begins. There are currently no open industry standards defining qualification procedures for AM processes. MSFC-SPEC-3717 provides a qualification procedure for L-PBF that requires three forms of AM material evaluation: (1) microstructure (grain structure and defect state, such as porosity/density, or lack of fusion), (2) quality of surface texture and detail rendering, and (3) mechanical and/or physical properties. To substantiate the use of design values from the QMP, an assessment of equivalency is required between the material characteristics and performance rendered by this QMP relative to a nominal performance reference state. This process, called Registration, is discussed further in STEP 4 Equivalence Methodologies. Note that there is a precedence issue that must be handled by engineering judgement when AM processes are to be qualified prior to having sufficient data to establish the nominal performance reference state. In this scenario, the qualification of process and establishment of reference data occur simultaneously and can be considered a form of “bootstrapping” the process.

Following qualification, the nominal material performance may be further characterized to meet the needs of the qualification and certification objectives. The necessary design data typically vary with the expected hardware applications. Generation of design data from the qualified AM process is more tractable if the nominal material condition (machined coupons from AM blanks) is considered independently from the complications of Influence Factors. An Influence Factor is defined as any aspect of the AM process and resulting material that has an influence on material (or part) performance relative to associated material property design data. Identifying relevant Influence Factors and characterizing their effects represent the most significant engineering challenge arising in AM material characterization. Examples of influence factors include: effects of as-built surface texture on fatigue performance, effects of microstructure variation due to thermal history or scan strategies, effect of thin-section performance with as-built surfaces, or the effects of process interruption and re-start. Characterization of Influence Factors for AM design data immediately becomes an endeavor in engineering risk management to balance material knowledge, data rigor, safety, cost, and schedule.

As AM processes are qualified and material performance characterized, a central repository is required to organize and manage the resulting influx of data. This repository of data has multiple specific purposes in the AM design data framework and is the subject of STEP 2: Material Property Suite.

STEP 2: Material Property Suite

The Material Property Suite (MPS) is the name assigned in MSFC-STD-3716 to the data repository for AM materials. An MPS typically exists for each unique AM material and heat treat condition, much the way individual entries exist on this same basis for materials in handbooks such as the MMPDS. The MPS marks the first major step away from the point design methodology. The intent is that most QMPs for the same alloy and heat treat will be registered to the same MPS. This

commonality in design data is enabled through equivalence evaluations from both QMP Registrations and the application of SPC of witness sampling in part production. The MPS is unique from traditional material databases in that it consists of three specific parts: (1) an actively maintained database of material property values, (2) a sub-set of that database used to derive and implement a Process Control Reference Distribution (PCRD) that is used for enforcing process control, and (3) an actively maintained set of design values used to support part design. Each of these aspects of the MPS are briefly discussed.

The first part of the MPS is simply an active collection of all appropriate and relevant material data produced under the auspices of Registered QMPs. Primarily this collection consists of mechanical properties, but relevant microstructural data and physical properties are also included. The sources of data in this collection include data from successful process qualifications, data from dedicated material characterization efforts, data from witness specimen testing from builds, and data from mechanical property evaluations directly from parts (See STEP 5: Part qualification—pre-production article evaluations). In a departure from current practice in metals, these various sources of data are viewed as continuous data streams into the database and are maintained and organized accordingly.

The second part of the MPS selects specific data from the database, primarily data from witness testing of AM builds, and develops a set of PCRDs. For a given alloy and condition, a PCRD typically exists for tensile strength, yield strength, ductility, and fatigue life. The PCRD is an example of the previously mentioned "nominal performance reference state." It describes the nominal performance of material generated by QMPs that are registered to the MPS and provides acceptance criteria for evaluating the equivalence of new data from process qualifications or part witness testing. For example, a PCRD for tensile strength may be merely the mean and standard deviation from an appropriate statistical model of the data with acceptance values defined for use in process control (STEP 3). Again, the objective of the set of PCRDs is simply to define the nominal performance range of the material on a variety of metrics to be used in process control.

The third part of the MPS is the collection of design values. Design values are based on all relevant data in the MPS and must include all appropriate sources of variability; therefore, controls on the minimum number of feedstock lots, heat treatment lots, build lots and so forth are required to achieve a valid set of design values. The design values must account for nominal cases as well as the effects of Influence Factors. Data taken from direct evaluation of AM part materials should also be incorporated into the assessment of design values. When sources of variability in the database are limited, the design values are to incorporate additional margin (based on observed coefficients of variation) that helps mitigate the significant programmatic risk of making downward revisions to published design values. It can be noted that under the integrated design value framework described herein, the burden of screening parts with unexpected variability that endangers design values is partially carried by process controls such as the witness testing and equivalency methods used through the PCRD to accept parts, as opposed to relying on the questionable assumption that all variability potentially present in parts is actually represented in the database.

STEP 3: Statistical Process Controls

Maintaining the validity of design values over time and across a variety of AM machines (QMPs) requires the implementation of strict process controls and quality management throughout the AM process. The list of required controls is daunting: feedstock, equipment, facilities, heat treating process, operating procedures, and so forth. The most direct control related to defending design value assumptions is enforced through SPC in witness specimen testing for each build using the PCRD or an equivalent measure of process consistency. Meaningful SPC can be obtained on a case-by-case basis (independent AM builds) with sufficient witness sampling to assess to the PCRD. For scenarios with machines in continuous production using the same QMP, methods of tracking nominal process performance over time through control charts is preferable.

Successful witness test acceptance provides evidence for the overall health and consistency of the AM process during the build they witness. For critical parts, additional evidence (non-destructive inspections, proof testing, etc.) is generally required to extend that confidence to the part itself, as discussed in Step 5.

This framework rejects the idea that design values in AM can be defended with the common acceptance test used for metals: a single tensile test data point that falls above the specification minimum or design value. Such an acceptance method has insufficient leverage to adequately determine if and when the AM process has changed. Given the number of opportunities for process disruption in AM and that each individual AM machine operates as its own independent "foundry" with independent process failure modes, such simplistic acceptance methods are incompatible with the process control requirements. Significant changes in the AM process can occur prior to being identified by a single (or one of two) witness data points falling below the minimum. This situation is exacerbated if the acceptance minimums are set low under the mistaken consideration this would be conservative. It is critical that the witness acceptance criteria and design values be treated independently. The design values are based upon the data population of the MPS. To affect process control and defend the design values, witness acceptance criteria must require witness data be in family with the data population of the MPS. This is the basis for the concept of Equivalence Methodologies.

STEP 4: Equivalence Methodologies

The descriptions of Steps 1 through 3 have already made a case for the need of methods to show one set of data equivalent to a master set of data. This concept is key to the implementation of this framework for design values. If this framework is considered in the context of the familiar building block approach pyramid used to describe the development of design values in composite materials, reasonable comparisons can be drawn. In Figure 2, Steps 1, 2, and 3 are shown stacked from the base of the pyramid. This forth step, equivalence methodologies, is best represented as what enables adding layer upon layer up the pyramid—it is the mortar holding the framework together.

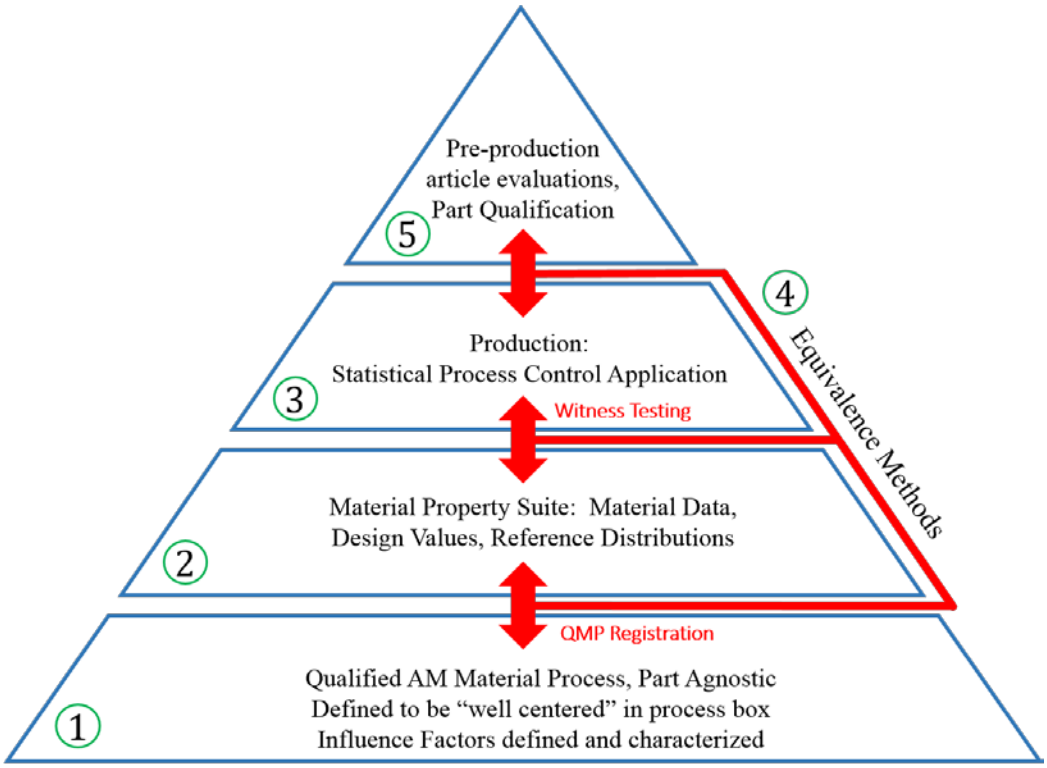


Figure 2. A building-block analogy to the design value framework in five steps.

As the enabling technology of the framework, the role of equivalence methodologies is simple in concept: provide assurance that material performance remains consistent. When leveraged, the notion facilitates engineering solutions to many issues in AM that relate to material integrity and performance and the use of common design values, such as consistent process qualification, machine re-qualification, determining adequate equivalency across machine platforms, makes and models, and comparisons of part material to test coupon material performance.

As shown in Figure 2 and discussed above, there are two primary applications for equivalence methodologies in the framework. The first is the registration of a QMP to the database of an MPS. The second is the application of SPC on witness specimen data during AM part production.

The QMP registration process provides the necessary evidence to consider the QMP data equivalent to the database of the MPS, which in turn enables the use of the MPS design values for parts produced to the QMP. In the case of QMP registration, equivalency is based upon multiple factors. The following criteria are typically involved in the equivalency evaluations across each QMP registered to the MPS:

a) Consistency of feedstock controls,
b) Consistency in metallurgical and microstructural characteristics,
c) Tensile strengths and ductility meeting MPS PCRD criteria,
d) High cycle fatigue life meeting MPS PCRD criteria,
e) High cycle fatigue life $>10^6$ cycles in family with MPS data,
f) Low cycle fatigue life in family with MPS data,

g) Fracture toughness in family with MPS data,
h) Tensile properties at temperature in family with MPS data.

The use of statistics is important to the development of a rigorous method for determining equivalence in QMP registration, however, the specific methods are not nearly settled consensus. Outside of the cases using the defined PCRDs, the quantities of available data do not allow a rigorous statistical approach. The methodology leverages the idea of getting smaller quantities of data that interrogate a variety of material failure mechanisms to reach a broader determination of equivalence. This a emerging subject of active technical development and debate. Engineering judgement on the part of materials and process engineers is likely to remain a key part of this determination of equivalence.

The use of equivalence methods for SPC of the AM build process is simpler than the QMP registration process, made so primarily through the necessity of cost control. However, to maintain equivalence arguments and the requisite level of SPC, the quantity of witness specimens is larger. For build-to-build acceptance the tensile and fatigue PCRDs are used with 6 and 2 specimens respectively. Structural parts will commonly also include microstructural criteria for equivalence. Based upon part risk classification and circumstances, further witness criteria may be applied. For cases of continuous production, the SPC may be applied through the use of control charts that monitor mean and variability in witness specimens with appropriate criteria for acceptance compatible with the PCRD. Each machine (QMP) is monitored and tracked independently and there are specific criteria that must be in place for a machine to qualify as being in a continuous production state. The continuous production criteria trades fewer witness tests per build (generally only 4 tensile, with metallography on critical parts) for the benefit of history tracking and data trending. The SPC criteria are further bolstered with a periodic (60 day) SPC qualification build that refreshes aspects of the QMP qualification and tests additional properties that are evaluated through equivalence to the MPS database.

STEP 5: Part qualification—pre-production article evaluations

The argument for substantiated design values applicable to AM parts produced to a valid and registered QMP has been developed through discussion of Steps 1 through 4. Restated in a different light, the framework centers on a consistent definition of nominal material property performance contained in the MPS, against which processes are qualified and post-build SPC is enforced through equivalence methodologies. This consistent definition of nominal material performance is also the primary source for developing material design values. There remains one final, critical connection necessary to complete the substantiation of design values sufficient for qualification and certification—corroboration of equivalent part material quality.

There are two aspects to the corroboration of equivalent part material quality. The first is a comprehensive evaluation of a pre-production article (first article), which is integral to the AM part qualification process. The second is the ongoing part acceptance inspections required for each part as it is produced.

As discussed in Step 1, the development of the QMP includes assurances that the nominal process is well-centered in the process box such that expected variations in part build conditions do not cross the Process Limit Boundary of Figure 1 to create defects. While this procedure is intended to establish a QMP with high likelihood of successfully building most parts, this cannot be construed as assurance that all parts will build successfully. This assumption must be confirmed directly on each pre-production article. To provide this confirmation, a form of equivalence evaluation is performed on the pre-production article typically through sectioning the part to provide both microstructural and mechanical property verification. Due to the variety of circumstances presented by various parts and their geometry, the framework does not specify the application of specific equivalence methodologies to the pre-production article evaluation. The evaluation requirements acknowledge that direct mechanical property evaluations may be limited and in such cases additional burden is placed on evaluation of microstructural consistency to the reference micrographs documented in the MPS. Given this variety, the corroboration of part material equivalence typically requires adaptation of the equivalence methodologies to suit the situation; thus, the exercise requires application of judgement and is not without risk.

Once the pre-production article has been evaluated and determined to have sufficiently equivalent material quality, the part production process is qualified and considered a “locked” or “frozen” process that is not to be changed. The qualified AM part process establishes sufficient evidence that the AM process is capable of producing a part of necessary quality to substantiate the application of the MPS design values. This still leaves a necessary substantiation of material quality in each part produced to the QMP in the future. Each build process is independent and vulnerable to the multitude of potential process failure modes. The entirety of the framework discussed provides strong process control rationale against systemic process failures, but lacks a direct connection to each individual part. This substantiation is the responsibility of the part acceptance tests levied on each part. Part acceptance criteria are tailored to the part criticality and include all available options such as surface and volumetric inspections, proof testing, leak testing, simulated service acceptance testing, and so forth. The rigor of part acceptance testing is highest for safety-critical (fracture critical) parts and will typically consist of combination of non-destructive inspections and physical acceptance tests. In such cases, the efficacy of non-destructive inspections requires substantiation.

The substantiation of part to part consistency and quality is likely the first application of AM process in situ monitoring. If set up as a passive system, not interfering or intervening in the process, this form of in situ non-destructive inspection can be expected to add to the part acceptance rationale, though not likely replace post-build acceptance tests for some time to come. Movement toward relying on in situ processes will require the certification of these techniques through a process analogous to the certification of other non-destructive inspection techniques.

APPENDIX Z
MARKUS HEINIMANN, ARCONIC

Fatigue and Damage Tolerance Considerations for AM Parts

Markus Heinimann, Vice President – Engineered Product and Process Technology

ARCONIC

Innovation, engineered.



General Fatigue and Damage Tolerance (F&DT) Principles

Successful application of F&DT Principles to ensure Structural Integrity requires understanding of:

- ❑ Local static & cyclic loads (stresses, strains, thermal, etc.)
- ❑ Material behavior under cyclic loading (S-N, ε-N, da/dN – ΔK, etc.)
- ❑ Initial defect population (size, orientation, distribution, etc.)
- ❑ Failure mechanism
- ❑ Environmental effects (humidity, temperature, etc.)
- ❑ NDT Inspection (POD, largest defect missed, etc.)
- ❑ Structure Classification (PSE, CSE, etc.)
- ❑ Certification Approach

Challenges of Applying F&DT Principles to AM Parts

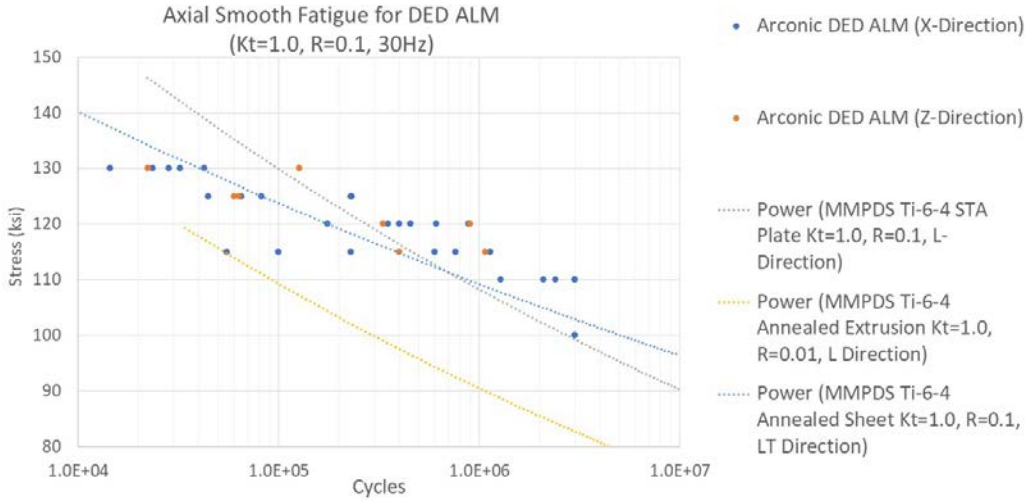
Key ASIP Principles Remain Unchanged

Successful application of F&DT Principles to ensure Structural Integrity requires understanding of:

- Local static & cyclic loads (stresses, strains, thermal, etc.)
  - ✗ Topology optimized parts required more detailed analysis to capture local stresses/strains
  - ✗ Residual stresses need to be considered



- Material behavior under cyclic loading (S-N, ε-N, da/dN – ΔK, etc.)
  - ✗ Limited understanding of impact of build orientation, section thickness, etc.
- Initial defect population (size, orientation, distribution, etc.)
  - ✗ Limited understanding of defect size, distribution, effect of defects, surface quality

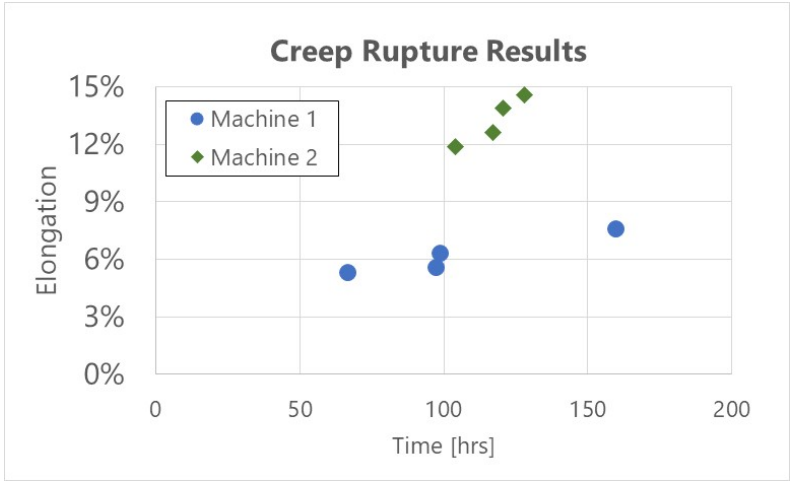


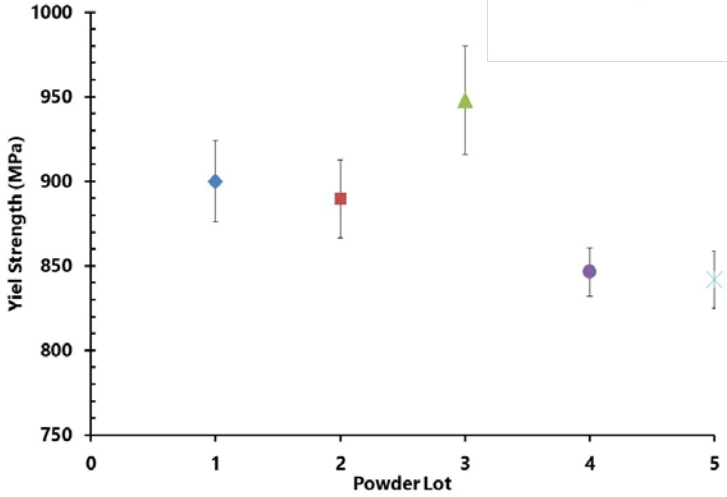
Challenges of Applying F&DT Principles to AM Parts

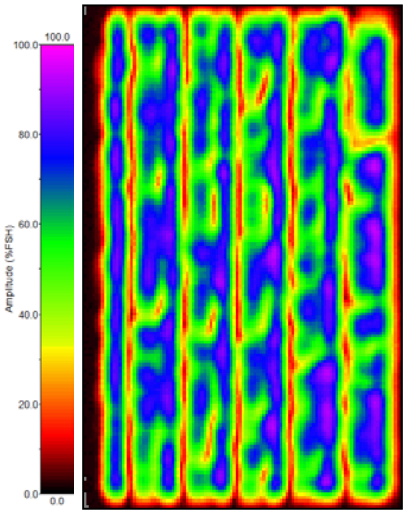
Key ASIP Principles Remain Unchanged

Successful application of F&DT Principles to ensure Structural Integrity requires understanding of:

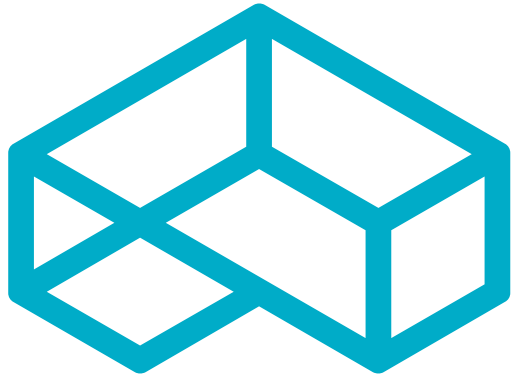
- Failure mechanism
  - ✗ Build orientation effects fracture properties
  - ✗ Machine dependence
- Environmental effects (humidity, temperature, etc.)
  - ✗ Impact on powder and build properties
- NDT Inspection (POD, largest defect missed, etc.)
  - ✗ Build features or defect?
- Structure Classification (PSE, CSE, etc.)
  - ✓ To-date only used for non critical structures
- Certification Approach
  - ✗ ✓ Existing approaches ok?







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Innovation, engineered.

APPENDIX AA
CRAIG MCCLUNG, SWRI

Zone-Based Probabilistic Damage Tolerance Methods for Additive Manufacturing

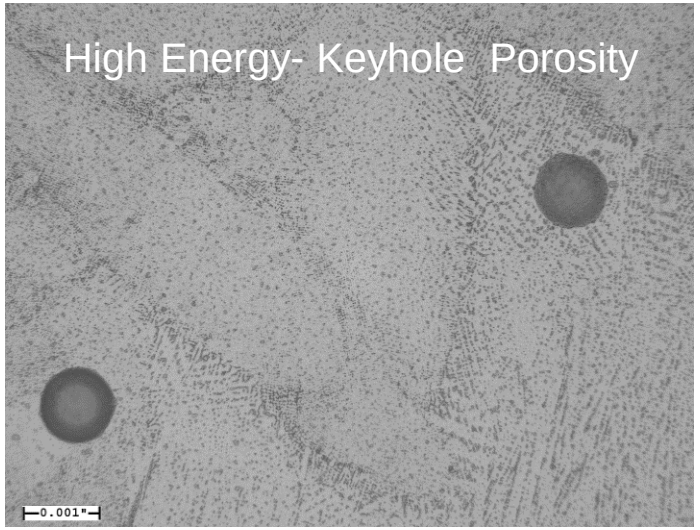
Joint FAA – EASA Workshop on
Qualification/Certification of Additive Manufactured Parts
Wichita, Kansas
August 2018

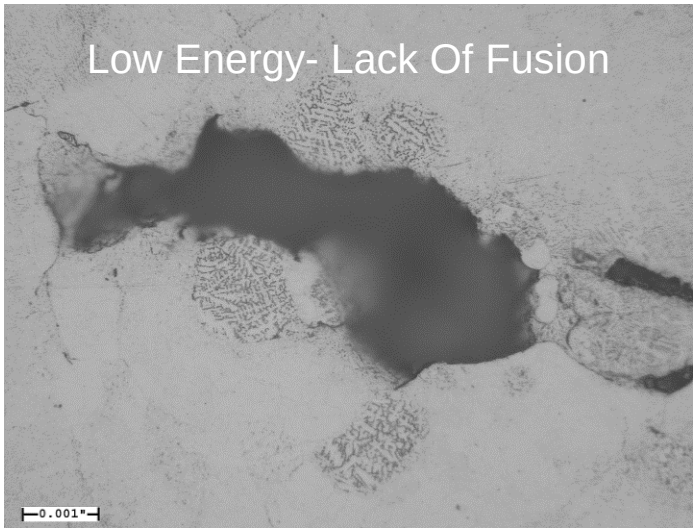


R. Craig McClung
Southwest Research Institute
San Antonio, Texas, USA

Structural Integrity Challenges for Additive Manufacturing

- A variety of potential material anomalies can occur anywhere in the volume (or on surface) of an AM part
  - Post-processing may or may not eliminate these anomalies
- Anomalies can lead to crack formation and fracture, depending on the local stresses in the part
- Material properties are uncertain and can vary from location to location in the part
- Geometric complexity can lead to significant variability in inspectability
- Manufacturing methods are immature and field experience is limited





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Proposed Approach to AM Structural Integrity

- Gorelik (*Int. J. Fatigue*, 2017) has proposed a zone-based probabilistic damage tolerance approach to ensuring the structural integrity of AM components of higher criticality
- Analogies: structural castings, powder metallurgy, titanium hard alpha

International Journal of Fatigue 94 (2017) 168–177

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue



Additive manufacturing in the context of structural integrity

Michael Gorelik

Federal Aviation Administration, Scottsdale, AZ, United States

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Probabilistic Damage Tolerance Methods

- Traditional fatigue design depends on baseline fatigue testing that does NOT account for random/rogue material anomalies (only nominal material condition)
- Traditional damage tolerance design typically focuses on cracks forming on the surface at stress hot spots (significant stress concentrations) or design features
- Materials/components susceptible to inherent material anomalies can potentially form a fatal crack anywhere that a significant anomaly occurs in a significant stress field and is not detected by NDI
- Probabilistic damage tolerance (PDT) can integrate the risk over a large volume (or surface area) considering all of these (uncertain) factors

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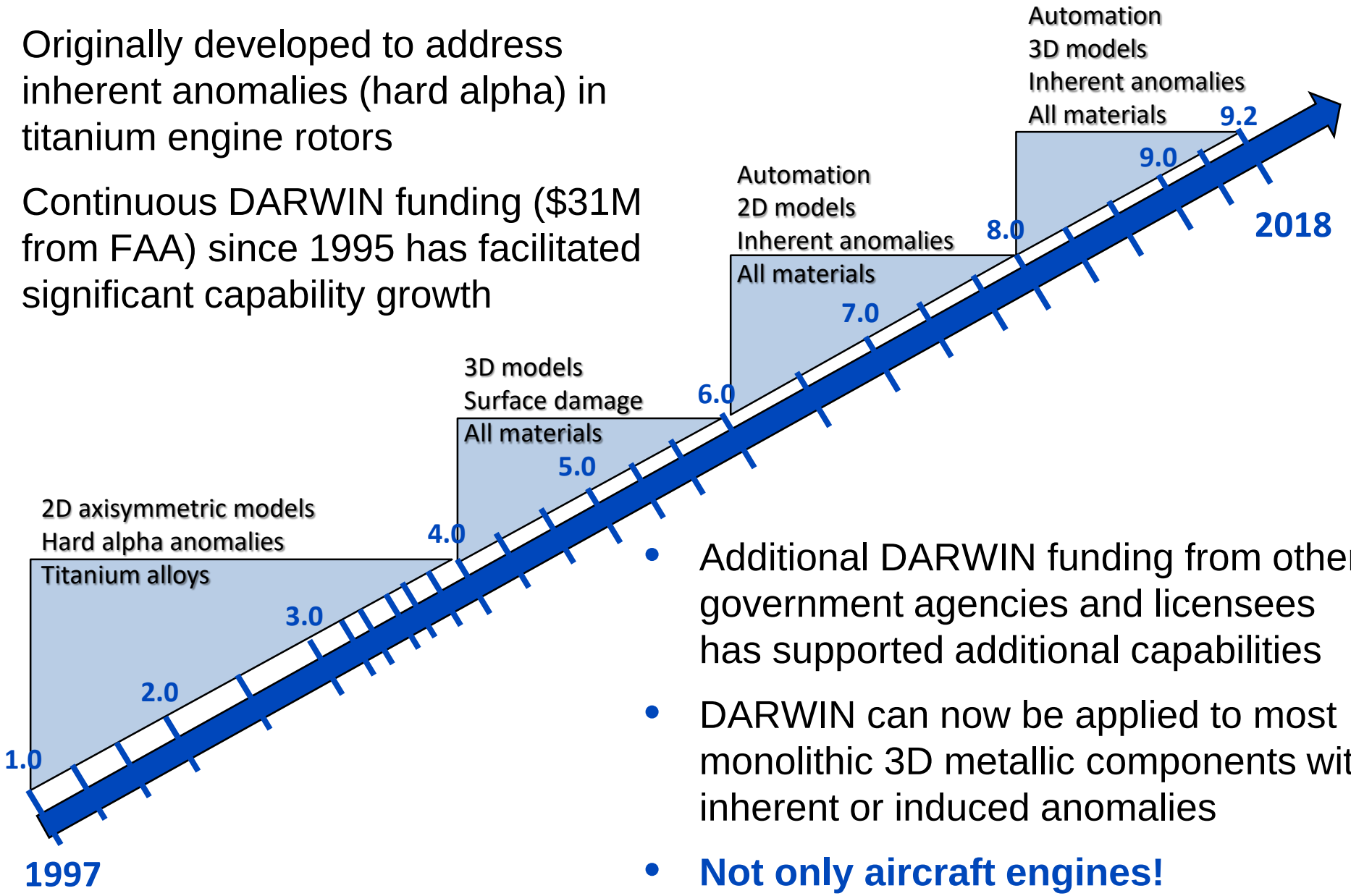
“Zone-Based” Methods

- Gorelik: Define the following attributes for each zone:
  - Frequency and size distribution for significant anomalies
  - Material properties (including anisotropy)
  - Stress distribution and mission cycle information
  - Residual stress distribution
  - NDI inspections and acceptance/rejection criteria
  - Acceptable zone-level probability of failure
- Level of analysis (for each zone) may vary from simplified / conservative (e.g., safety factors) approach to more accurate / less conservative (e.g., probabilistic damage tolerance) for higher criticality parts/zones
- Two main attributes of the approach:
  - Flexibility (use only necessary level of complexity)
  - Ability to perform quantitative assessment (when/as needed)

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The Example of DARWIN:
A Tool for Zone-Based PDT

- Originally developed to address inherent anomalies (hard alpha) in titanium engine rotors
- Continuous DARWIN funding ($31M from FAA) since 1995 has facilitated significant capability growth

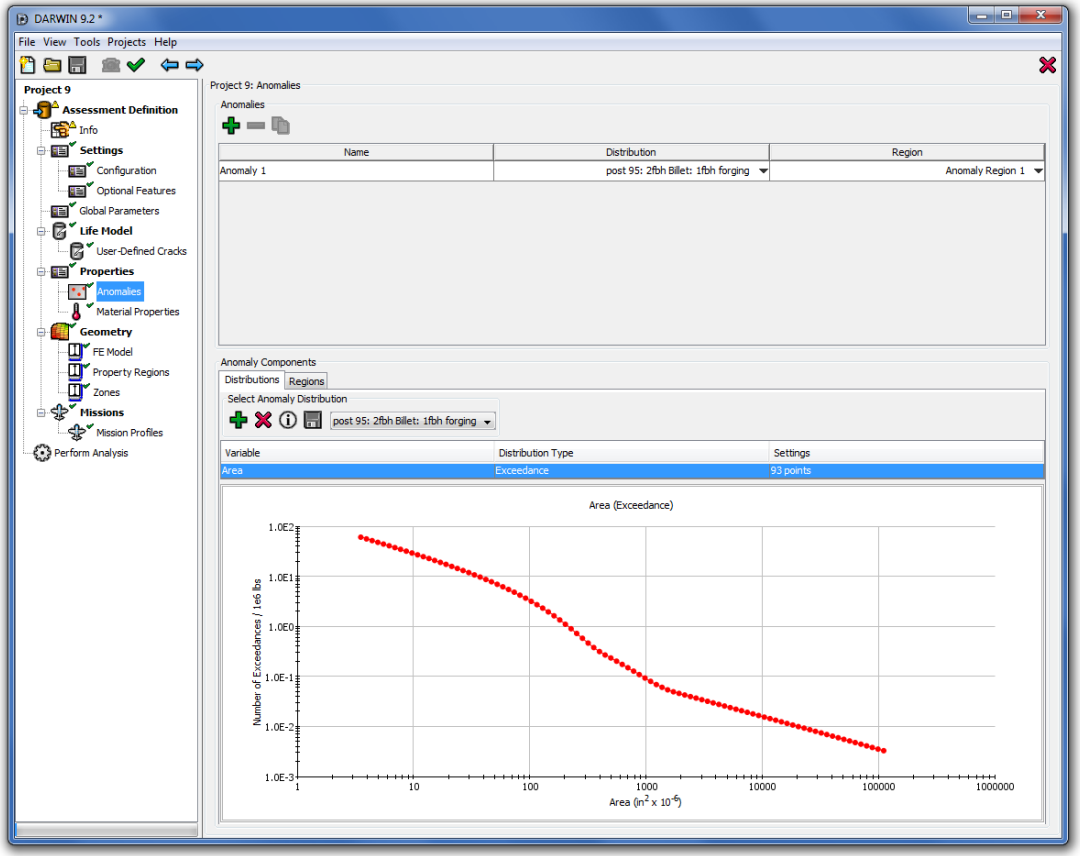


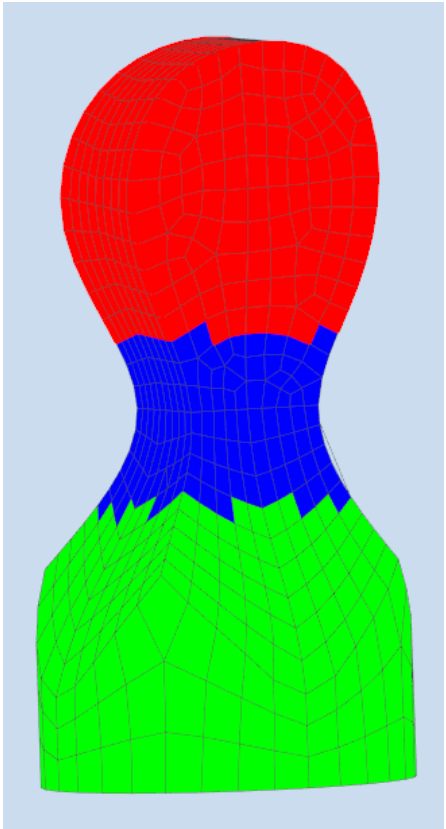
- Additional DARWIN funding from other government agencies and licensees has supported additional capabilities
- DARWIN can now be applied to most monolithic 3D metallic components with inherent or induced anomalies
- **Not only aircraft engines!**

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“Zone-Based” Methods in DARWIN

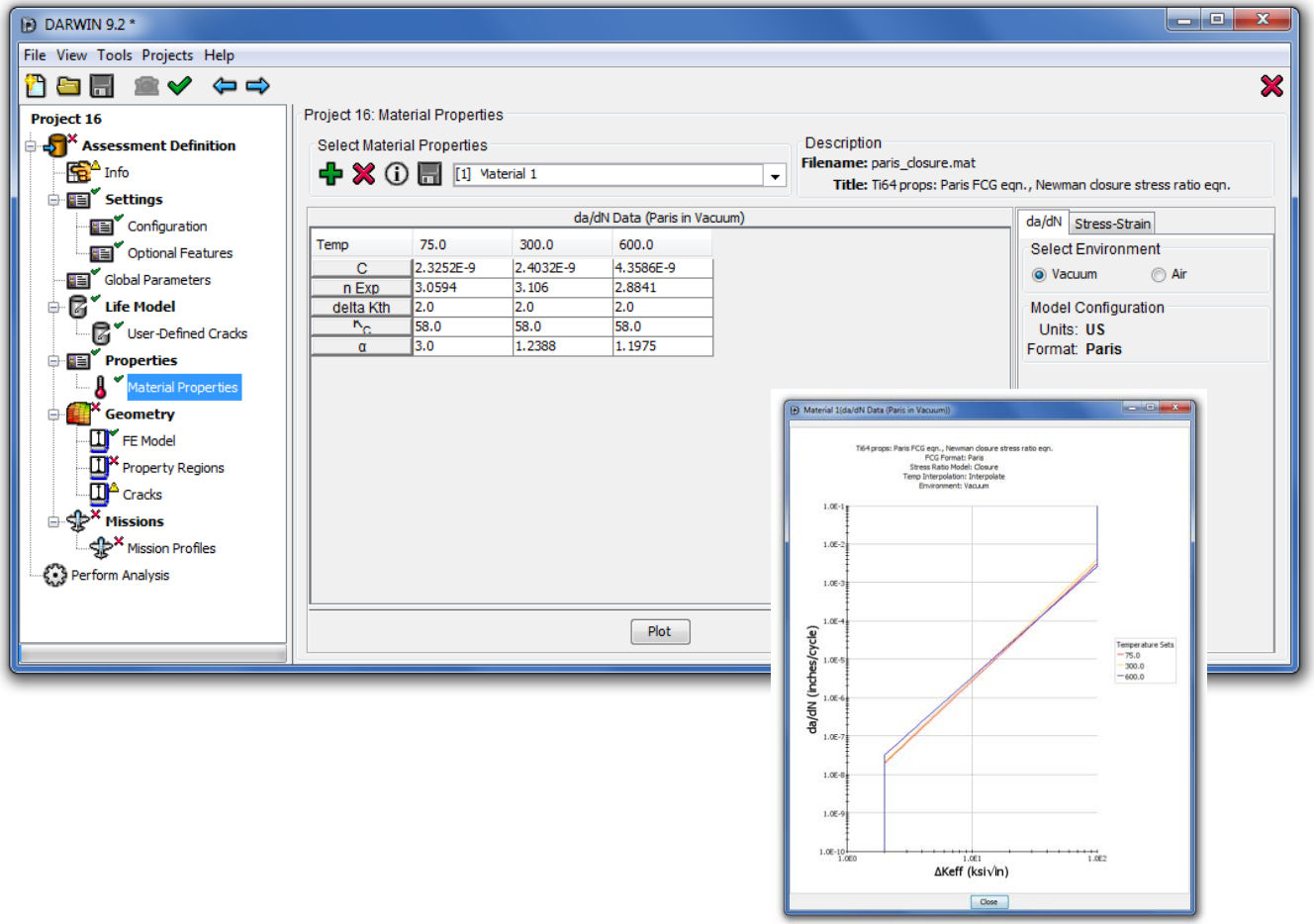
- Define the following attributes for each zone
  - Frequency and size distribution for significant anomalies (internal and surface) (DARWIN anomaly regions)

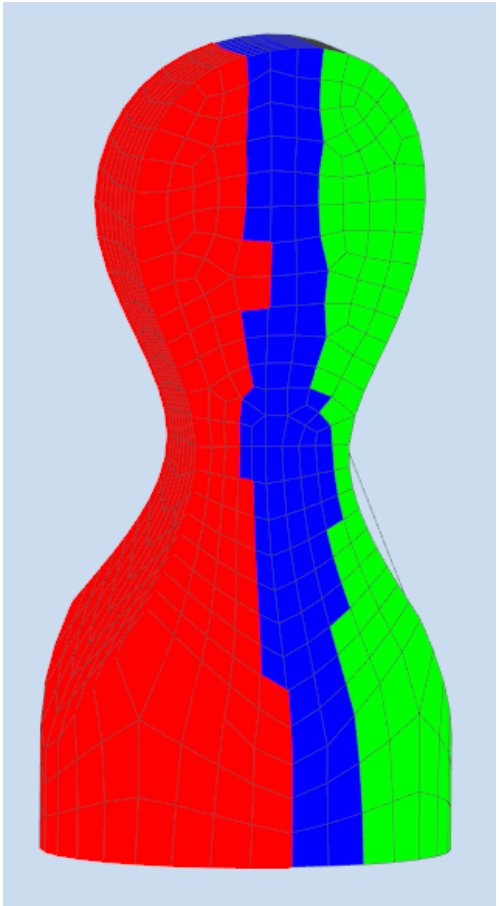




“Zone-Based” Methods in DARWIN

- Define the following attributes for each zone
  - Material properties (DARWIN material property regions)

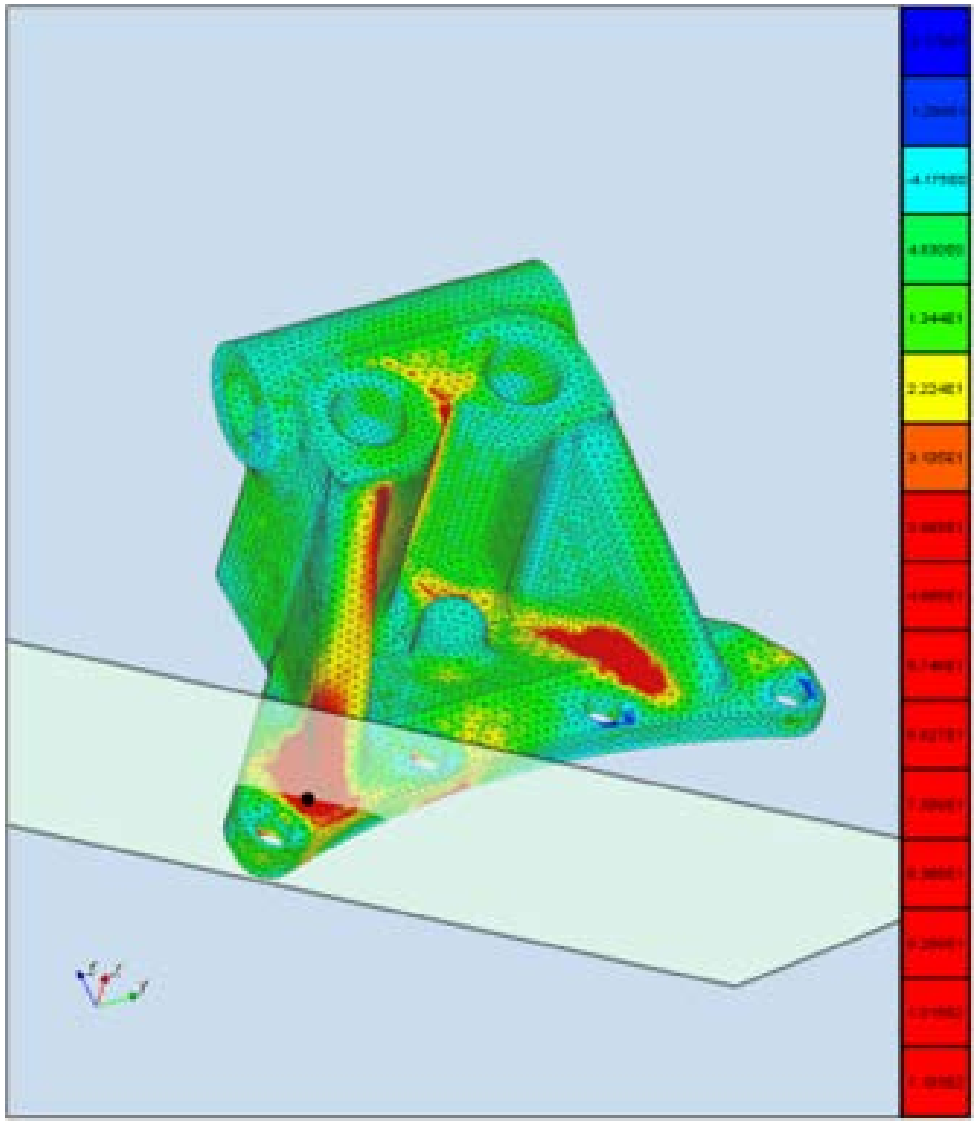




“Zone-Based” Methods in DARWIN

- Define the following attributes for each zone
  - Stress distribution and mission cycle information

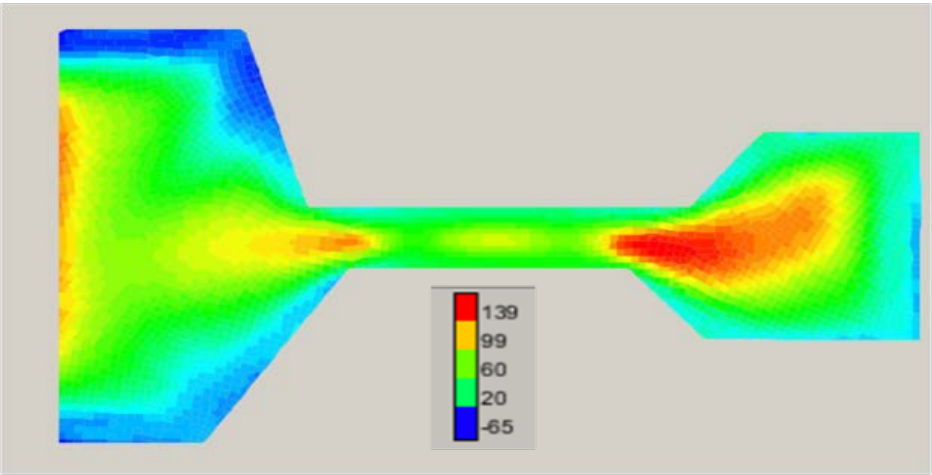
  (DARWIN import of 3D FE models/results)

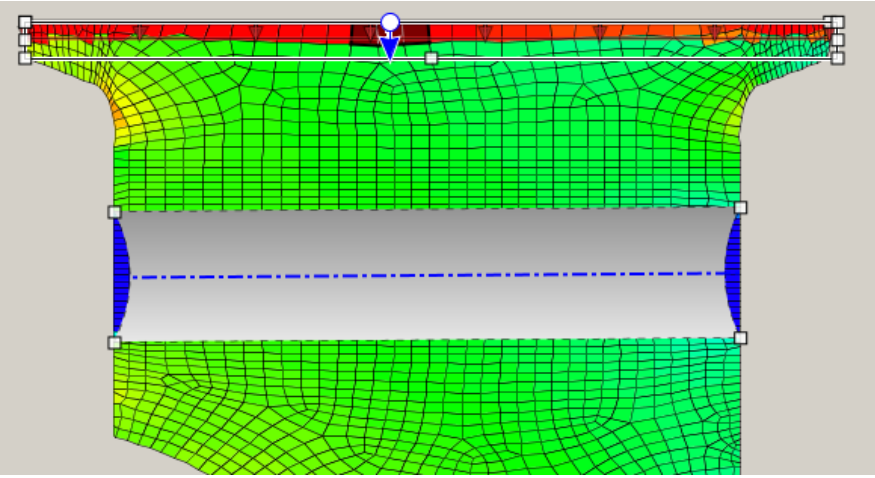


“Zone-Based” Methods in DARWIN

- Define the following attributes for each zone
  - Residual stress distribution

  (DARWIN import of 3D bulk residual stress results or local residual stress profiles)

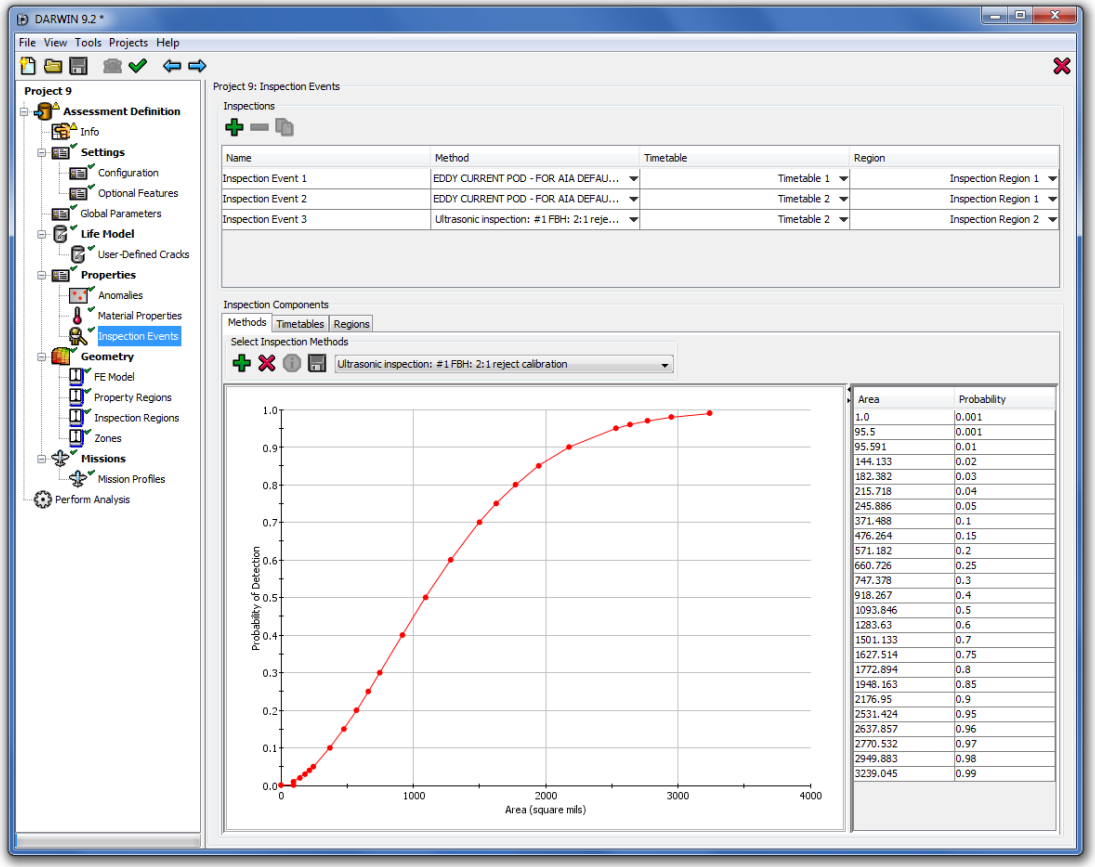




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“Zone-Based” Methods in DARWIN

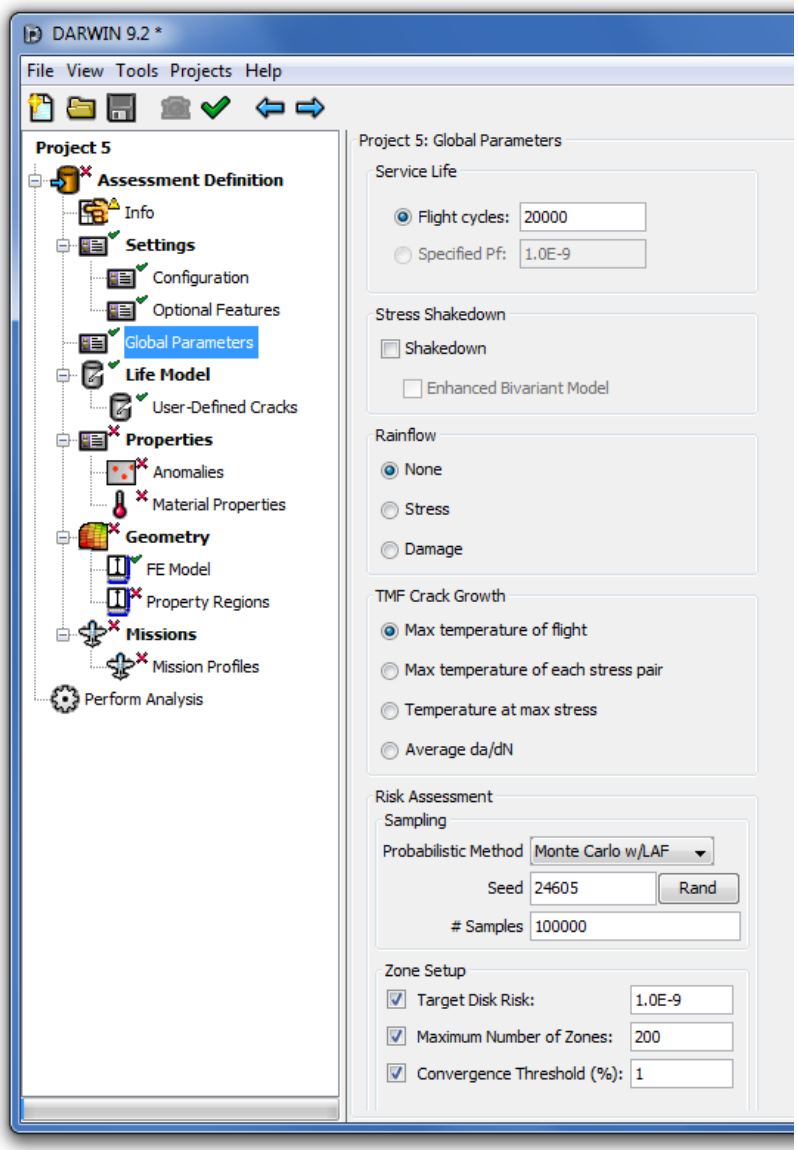
- Define the following attributes for each zone
  - NDI inspections and acceptance/rejection criteria (DARWIN inspection regions)



“Zone-Based” Methods in DARWIN

- Define the following attributes for each zone
  - Acceptable zone-level probability of failure

  (DARWIN target fracture risk)



"Zone-Based" Methods in DARWIN: Summary

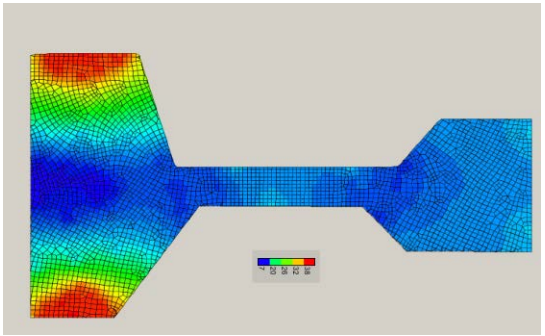
- Define the following attributes for each zone
  - Frequency and size distribution for significant anomalies (DARWIN anomaly regions)
  - Material properties (DARWIN material property regions)
  - Stress distribution and mission cycle information (DARWIN import of 3D finite element models/results)
  - Residual stress distribution (DARWIN import of 3D bulk residual stress results or local residual stress regions)
  - NDI inspections and acceptance/rejection criteria (DARWIN inspection regions)
  - Acceptable zone-level probability of failure (DARWIN target fracture risk)

Note: Gorelik "zone" is similar to a DARWIN "property region". The intersection of DARWIN property regions is the initial DARWIN zone breakup, which is further refined to aid the speed/accuracy of risk calculations.

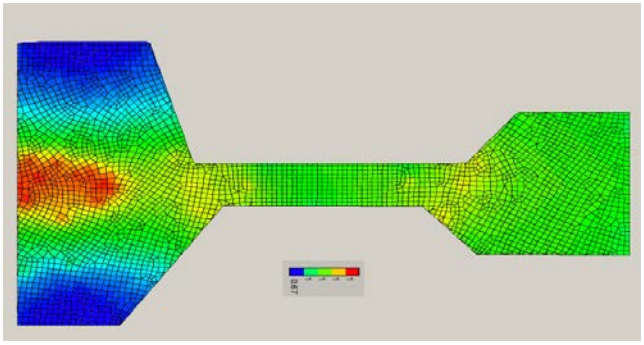
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Location-Specific Attributes in DARWIN

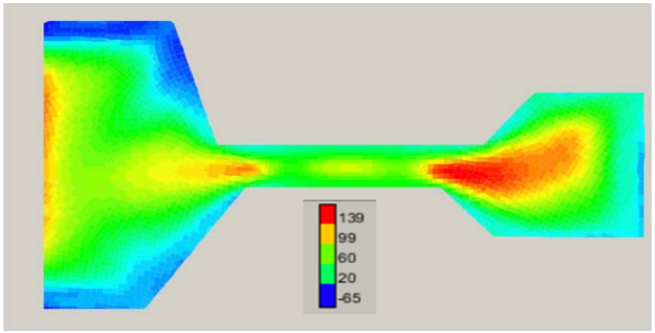
- (Optional) Calculate and import location-specific attributes from (AM) manufacturing process simulation software and/or sensors
  - Location-specific microstructure
  - Location-specific material properties
  - Location-specific anomaly distributions
  - Location-specific bulk residual stress



grain size contours



FCG property contours

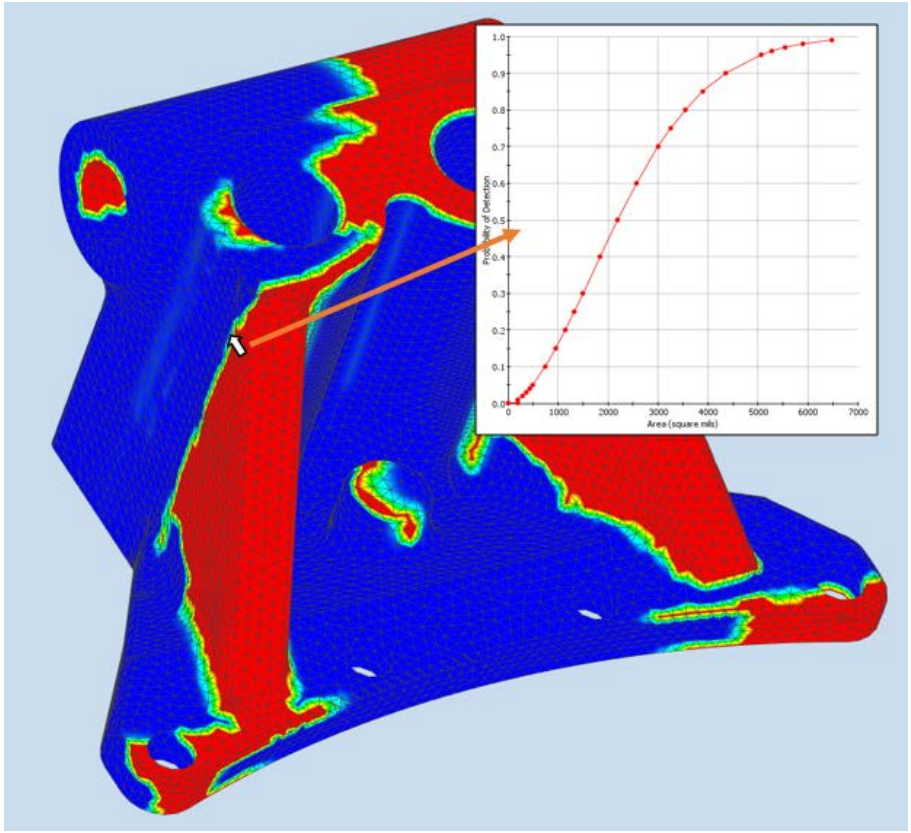


residual stress contours

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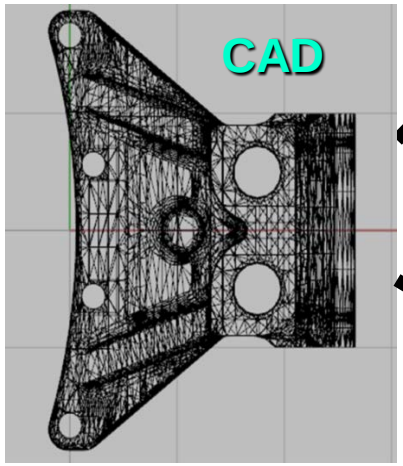
Location-Specific Attributes in DARWIN

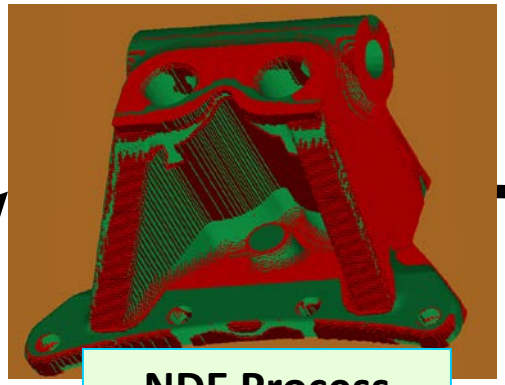
- (Optional) Calculate and import location-specific attributes from NDI simulation software
  - Location-specific probability of detection curves



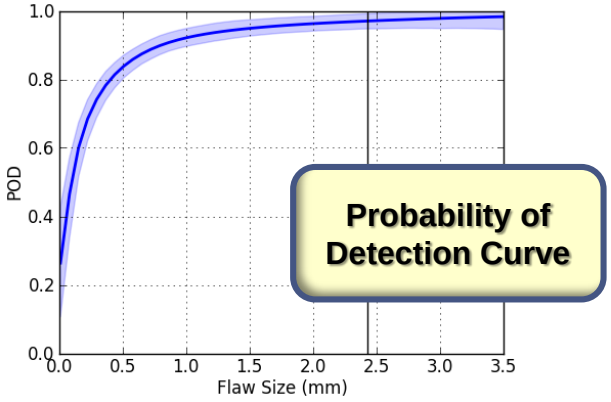
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Integration of NDE and Fracture Risk Models

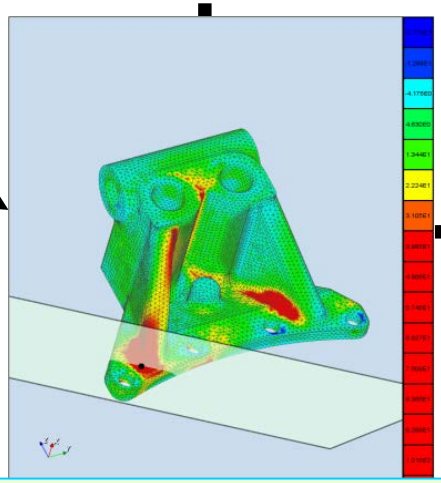




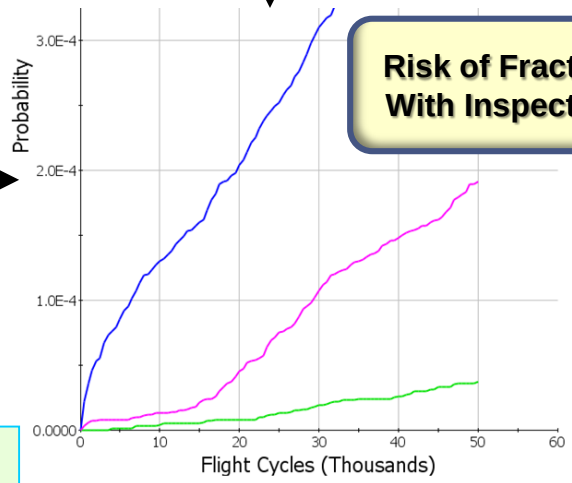
NDE Process Simulation



Probability of Detection Curve



Stress and Fracture Mechanics Analysis

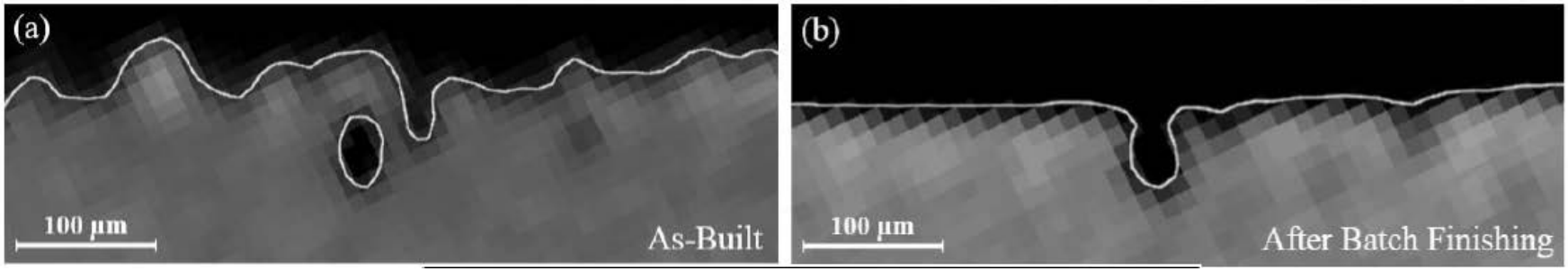


Risk of Fracture With Inspection

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The Question of Crack Formation

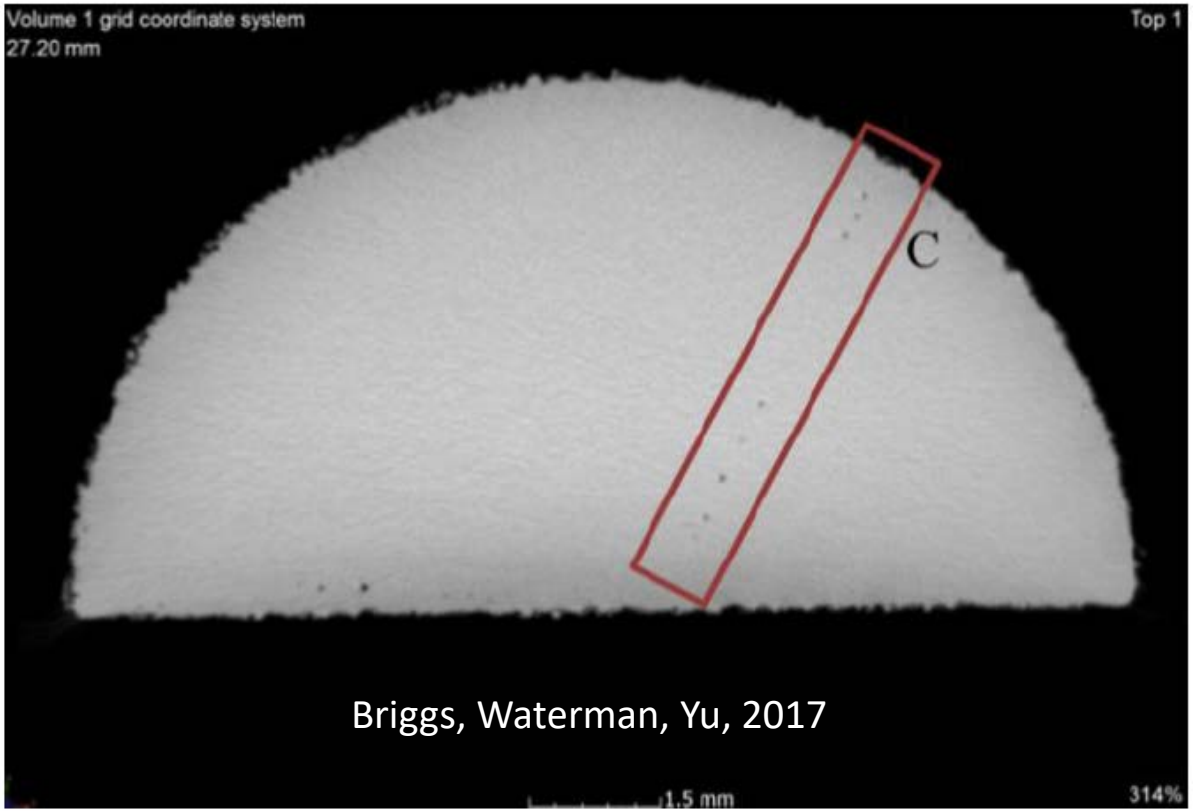
- PDT sometimes assumes an anomaly immediately forms a growing fatigue crack (crack formation life = 0)
- This may be too pessimistic for some types of AM anomalies
- DARWIN already has the architecture to perform crack formation life calculations at each anomaly
- Severe surface roughness (and surface-connected porosity) are also potential crack formation mechanisms in AM
- Work is ongoing to implement several specific crack formation models for internal and surface anomalies



W.F. Mitchell et al., 2017

Additional Issues for Internal Anomalies

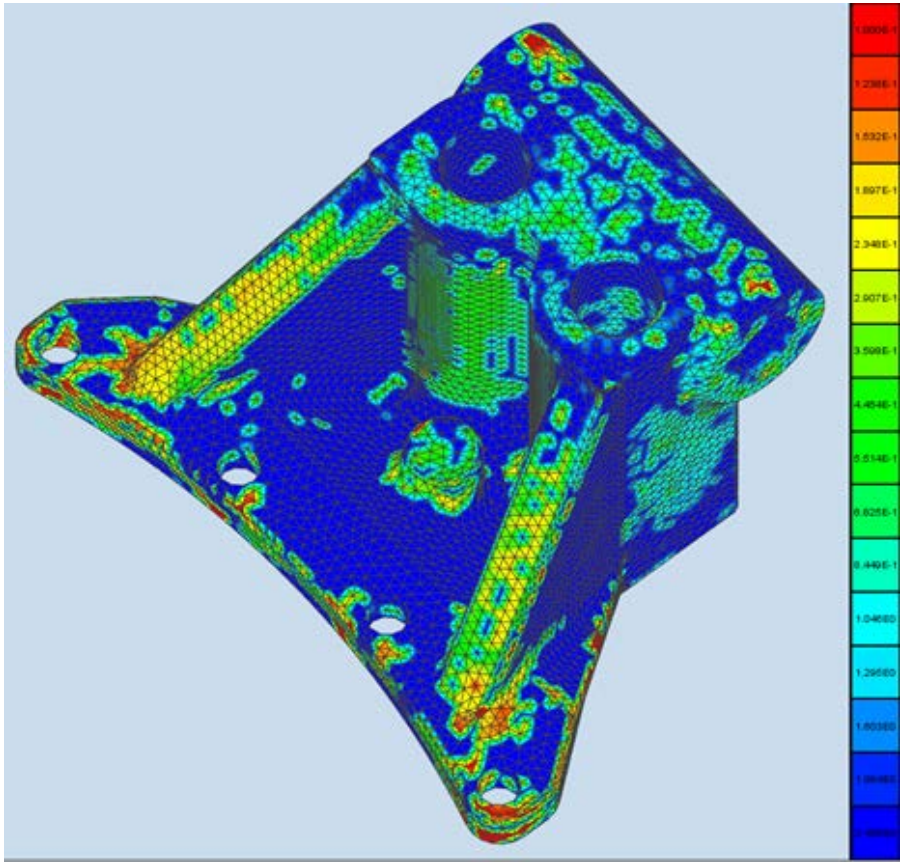
- Several different types of (competing) internal anomalies may occur
- Internal cracks grow in “vacuum” (→ different FCG properties)
- Some anomaly types may be preferentially located
- Multiple aligned pores may offer special fracture mechanics challenges



Briggs, Waterman, Yu, 2017

DARWIN CICS Contours

- DARWIN can calculate Critical Initial Crack Size (CICS) contours
  - At any given location, what initial crack size will just grow to failure during a desired service life?
- This information can be used to support development of
  - Build strategies that will avoid putting anomalies at undesirable locations
  - Inspection strategies that will find critical anomalies



Red = small CICS, Blue = large CICS

Enabling Data

- **What basic data are needed to support zone-based probabilistic damage tolerance methods for AM?**
  - Stress distribution and mission cycle information
    - Finite element models of (uncracked) components
  - Anomaly distributions
  - Material properties (esp. FCG properties)
  - Bulk residual stresses
  - NDE POD curves

- May be informed by experience, sensors, or simulations
- May be zone-specific or location-specific

APPENDIX BB
BREAKOUT SESSION #2, DEBRIEF

Aug. 22, 2018

Breakout Session #2 (Rm. S210)

Co-chairs: M. Gorelik (FAA) and S. Waite (EASA)

"**Fatigue and Fracture Considerations** – effect of defects, characterization of defects, characterization of F&DT properties, zoning considerations for F&DT".

Hosted by NIAR

NIAR Wichita State University National Institute for Aviation Research

Discussion Scope

- **Main focus on *safety critical parts* (PSEs, LLPs)**
- **Recognize representation of several product segments (airframes, engines, rotorcraft) and agencies**
  - ***Tried to focus on product-neutral and agency-neutral considerations when practical***
- ***Non-regulatory discussion* – focus on underlying technical issues**

Opening Remarks → *level-setting the Session*

Presentation 1	Presentation 2	Presentation 3	Presentation 4
M. Heinimann	*K. Tenneti*	*C. McClung*	*J. Schirra*
Arconic	LMCO	SwRI	P&W

Discussion Topics

1. **Characterization of AM defects**
   - **Size distribution and frequency (2D or 3D?)**
   - **Inherent vs. rogue anomalies**
   - **How to use this information in life prediction / life management process?**
   - **Characterization techniques / development of best practices**
     - **Is it worth benchmarking other material systems?**
2. **Characterization of effect of defects**
   - **Conventional S-N curves; use of feature-based knock-down factors?**
   - **Inherent vs. rogue – same or different framework?**
   - **Deterministic DT**
   - **Probabilistic DT**
3. **Role of Fatigue and Fracture Data in Process Qualification**
   - **Any considerations that are different from conventional process**

Discussion Topics (cont.)

4. **Expectations from regulators relative to F&DT guidance for AM**
5. **Recommendations for AM F&DT research topics *in the context of Q&C***

Topic 1

- **Should as-built surfaces be included in consideration – YES**
  - **Need to consider scan strategy (PBF) for exposed surfaces - may influence level of defects**
- **Sub-surface defects very close to the surface may need a special considerations**
- **Surface treatment may smear pre-existing surface defects**
- **How to build notched fatigue specimens tailored to AM?**
  - **Machined notches, as-built notches, …**
- **Consider potential for *defects interaction* (e.g. porosity near LOF)**
- **Are conventional measures of roughness in AM adequate for correlating to fatigue debits?**
- **What is the pre-requisite / level of process readiness for generating detailed defect data?**
  - **Process maturity, but for inherent anomalies – don't expect data sharing in the foreseeable future (too many company-specific proprietary settings)**
  - **Note: the answer will likely be different for rogue defects (data sharing may be required; at the moment – an Unknown Unknown for AM)**
    - **Ref: RISC / RoMan activities**

Topic 1 (cont.)

- **How do we define rogue defects? (in ref. to previous bullet)**
- **External reference: ASTM draft document – "catalog of defects"**
  - **WK47031**
- **Need to distinguish between as-built vs. post-processing defects**
- **Types of defects for LPBF / EPBF:**
  - **LOF, gas porosity, keyholing, contamination, inclusions, micro-cracks, surface roughness / surface connected features, localized Alpha post-HIP (Ti64), unmelted particles, abnormal microstructure (e.g. abnormal grain growth, ALA grains), support structure "interaction" with part's surface, software-induced defects, cross-layer and layer defects (collinear arrays of defects linked to scan strategy), local non-uniform chemistry**
- **Types of defects for Wire DED:**
  - **LOF, interface defects, gas porosity, contamination, inclusions, residual surface defects (not fully removed by machining), cracks, abnormal microstructure (e.g. abnormal grain growth, ALA grains)**

Topic 1 (cont.)

- **Characterization of inherent defects / anomalies**
  - **Need to understand the range of practical interest (min size)**
  - **Methods: CT + image analysis s/w (e.g. VolumeGraphics), metallography / sectioning, fractography, EBSD (contamination), profilometry, digital X-ray**
  - **Frequency charact. – mostly CT, potentially in-situ monitoring**
  - **3D characterization may be needed, depending on the application , defect types, criticality, …**
  - **Starting with 1-parameter (1D) size distribution may be adequate, but may need to treat it as location-specific property**

Topic 2

- **Effect of as-built roughness on fatigue – similar or different from other conventional alloy forms?**

S-N Curves

- **If using conventional S-N curve approach, will have high scatter due to *potential variability* in material properties and defect rates / population; may need to consider alternative methods**
  - **May depend on how S-N curves are used; consider that we create material and part at the same time.**
- **With so many machines, configurations, etc. – how many S-N curves would we need?**
- **Need to consider specimen size effect.**
- **Can't address rogue defects**
- **For inherent anomalies – should be adequate, if the frequency is such that we have representative set of anomalies within the gage section volume**

Topic 2 (cont.)

S-N Curves (cont.)

- **May get anti-conservative assessment if fatigue bar's volume is too small compared to parts**
- **Need to generate significant volumes of data to better understand fatigue and fracture behavior (in public domain)**
- **Getting the right pedigree data may be more challenging for AM**
- **Challenge area – highly topologically optimized parts (not enough representative volume)**

Alternative methods to quantify effect of defects

- **DT assessment, probabilistic approach allows to account for size distribution and frequency of defects**
  - **Don't need to use *probabilistic* approach if we don't have to – deterministic DT is much faster and less expensive**
- **Benchmarking of PM – inherent defects (NMIs) that are not detectable by NDI**

Topic 2 (cont.)

Conventional (regulatory) DT assessment – any changes for AM?

- **Need to modify the approach for topologically optimized parts**
- **Do we need a higher level of FCG material characterization for AM?**
  - **Depends on the framework the company uses for conventional materials**
  - **Potential for location-specific properties, but may be similar to other material systems**
  - **May need new test procedures for special features, e.g. thin walls**
- **Can quantify effect of defects (e.g. on K_{th} and LCF) by artificially generating defects in test coupons**
- **May need to revisit initial flaw size assumptions (for some cases)**
  - **Deterministic or probabilistic approach?**
- **Need to consider residual stresses**

Topic 3

- **Fatigue and fracture data are more sensitive to process variation, harder to hit acceptable window**
  - **Process changes are easier to detect than with static properties**
  - **Fatigue properties may be different for the same static properties (not unique to AM)**
  - **FCG properties are less sensitive to process variation than LCF**
  - **Anisotropy – no different than for other materials (e.g. single crystal blades)**

Topic 4

- **Configuration control is a MUST for safety-critical hardware**
  - **Q: By default, it's OEMs responsibility. How can regulators help?**
- **Guidance for owner-produced parts?**
  - **New FAA policy for ASIs is in the works. Plan is to educate ASIs and DERs.**
- **What would be regulatory response to discovering a rogue flaw in AM critical part?**

Topic 5

- **Defect populations and sizes – needs to be developed as a structured study**
- **Seeded defects study (leveraging process maps, e.g. P-V maps) – to understand process boundaries and fatigue behavior of defects**
- **Understanding of the fatigue behavior of defects below the NDI detectability threshold**
- **Understanding of crack nucleation mechanisms for key types of AM anomalies**
- **Correlating in-situ process monitoring with actual defects formation** *(need to cross-reference w/NDI and Process Monitoring Session)*

Note: need to capture different process families in the above research areas

Parking Lot Items

- **Use of sub-scale part models for evaluating full-scale part integrity?**
  - **May not work for all cases (process scaling issue)**
- **Can manufacturing credits (similar to AC 33.70-2) be defined for AM?**
- **How sensitive is near-threshold FCG behavior to AM-specific materials attributes?**
- **R&D topic – probabilistics based process optimization**
- **R&D in support of the feasibility of static AM factors**

APPENDIX CC
ERIC LINDGREN, AFRL

Air Force Research Laboratory



Challenges in NDE of Additively Manufactured Metallic Structures

23-25 AUG 2018

Eric A. Lindgren
NDE Technology Lead
Materials State Awareness Branch
Materials and Manufacturing Directorate
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

AFRL

88ABW-2018-4009

BLUF

- **Applications have been realized, largely dependent on 100% CT for part acceptance**
- **Challenges remain for NDE of Additively Manufactured Metal Aerospace Components**
- **Severity of Challenge depends on multiple factors**
  - **E.g.: intended application, geometry, access, location of assessment, repeated assessment requirements, and more**
- **Defining NDE requirements depends on effect of defects**
  - **Remains a R&D topic**

AM Applications / Materials

- **Focus on metal AM, range of applications: critical structure to tooling**
  - **Safety, Availability, Cost**

NDE requirements (from critical to supporting):

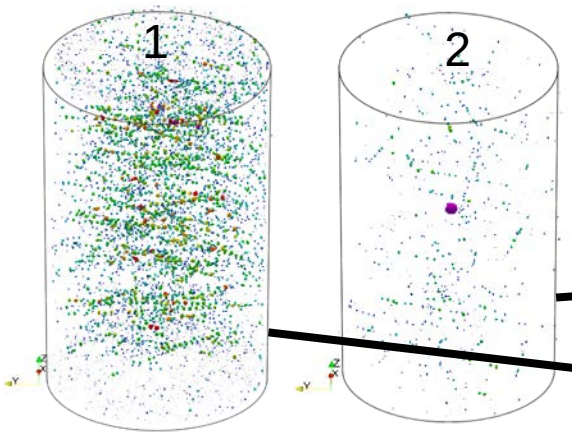
- **ASIP MIL STD 1530Dc1 – Critical Structure**
  - **Requires POD curve to calculate risk and 90/95 detection capability to set inspection intervals**
- **Tooling: NDE depends on cost / failure impact**

Certification process drives NDE Requirements

Representative Challenge: Variability via Porosity

Spatial / Temporal Variations in Build Process:

- **Causes porosity variations:**



CT reconstruction

Cylinder 1
Pore V_f = 0.51%
Pore Max = 253 μm
Pore Avg = 100 μm
Processed in isolation

Cylinder 2
Pore V_f = 0.031%
Pore Max = 176 μm
Pore Avg = 96 μm
Processed with other objects



Laser Powder Bed Fusion (LPBF) of Ti-6Al-4V

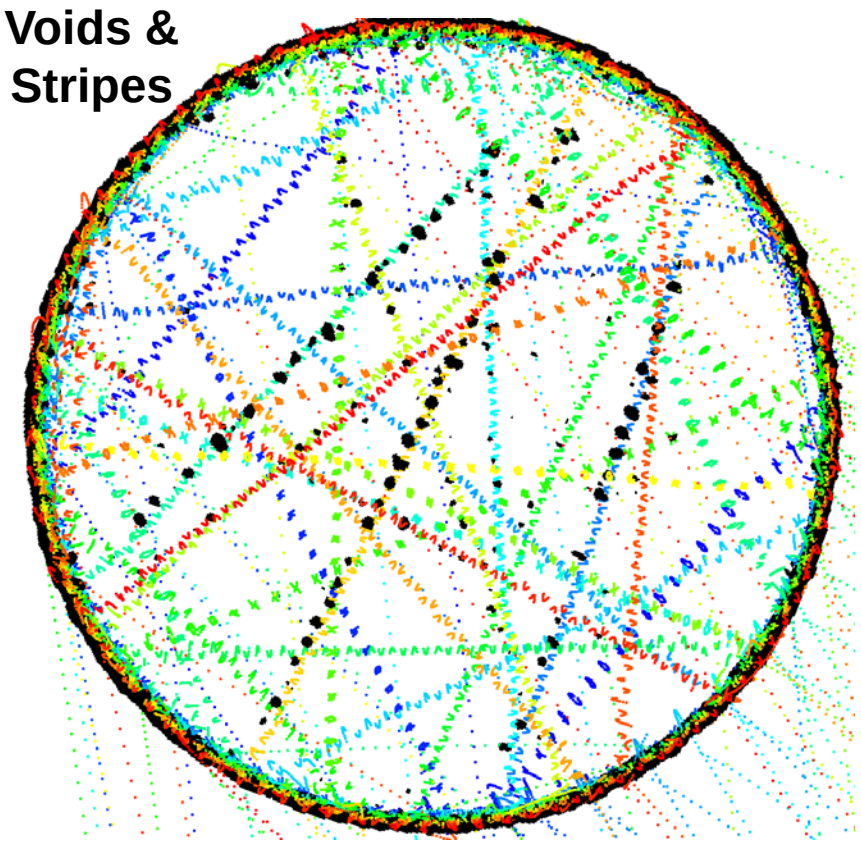
- "Identical" cylinders, but minor change in build strategy results in significant differences in porosity
- Similar challenges in wire-fed, e.g. porosity and anisotropy

Flaw Alignment vs. Size

Questions:

- **Aligned critical?**
- **Size critical?**
- **Shape affects detection?**
- **Rejection criteria?**
- **Testing requirements?**

Development of proper NDE process depends on answers to these and additional questions



Common NDE Factors Affecting Validated NDE Capability

- **Critical flaw size, location, and morphology**
  - Currently on case-by-case basis
  - Effects of defects studies initiated
- **Access, geometry, surface condition, etc.**
  - Many unknowns result in case-by-case solutions
- **NDE method as a function of part geometry and flaw morphology**
  - Even CT cannot readily detect flattened voids
- **Time / cost of NDE vs. value of part**
  - Impact of flaw on safety
  - Recurring inspections for fracture critical parts

BLUF

- **Applications have been realized, largely dependent on 100% CT for part acceptance**
- **Challenges remain for NDE of Additively Manufactured Metal Aerospace Components**
- **Severity of Challenge depends on multiple factors**
  - **E.g.: intended application, geometry, access, location of assessment, repeated assessment requirements, and more**
- **Defining NDE requirements depends on effect of defects**
  - **Remains a R&D topic**

APPENDIX DD
MICHAEL LANDER, UNIVERSAL TECHNOLOGY CORP.



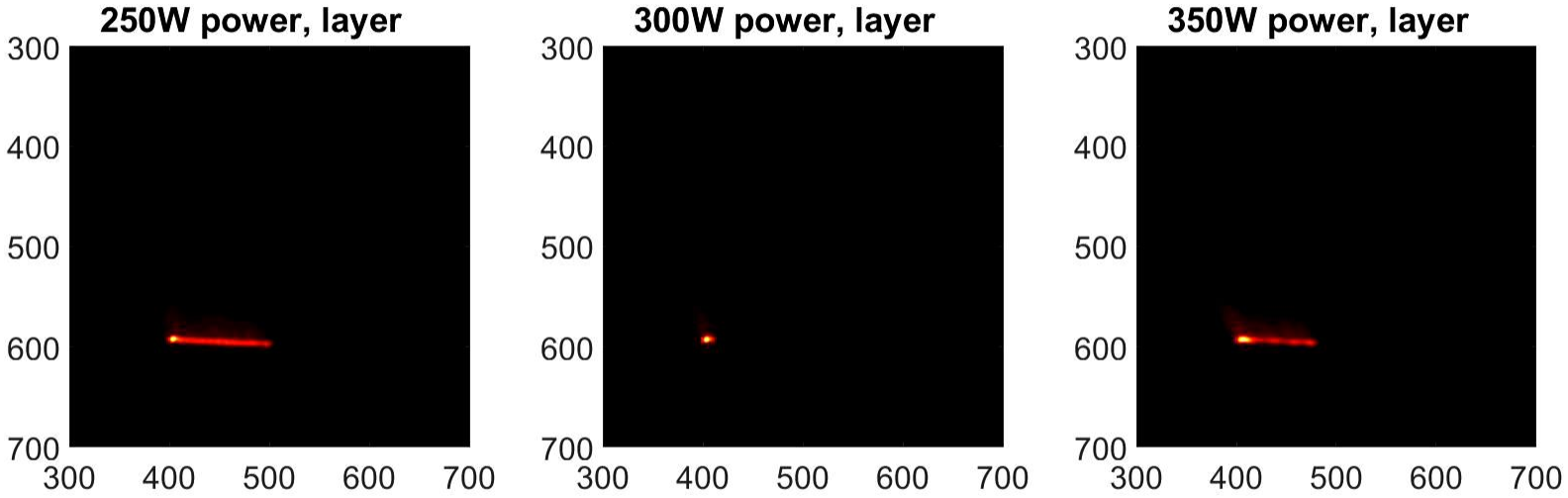
Sensing Methods for In-Process Monitoring of Metals AM

Mike Lander
Senior Scientist – Electro-Optics

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AMSENSE™ - In-Situ AM Process Monitoring

Process Data → **System Performance** → **Part Properties**



Sensor Modalities:

- Visible Imaging
- High-Speed Spectroscopy
- Thermal Imaging
- Surface Profilometry

What can we see?
How can we collect it?
How can we use it?
Validate – Via NDE!

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About UTC

www.utcdayton.com

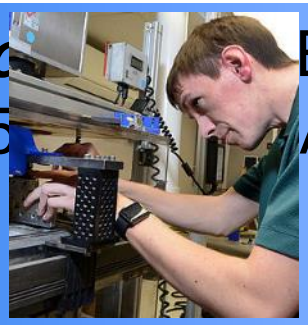
- **Employee-owned <u>small business</u>**
  - ***Established:*** 1961 in Dayton
  - ***Focus Areas:*** Defense R&D, Additive Manufacturing, Data Analytics, Sensors Integration, Commercial Ventures
  - ***Other Services:*** STEM Programs, Meetings, A&AS
  - ***Major Customers:*** AFRL, NASA, other DoD, industry
  - ***Contract Vehicles:*** IDIQs, SBIR/STTR, Consortia…



Joe Sciabica
UTC President

Proud member of America Makes








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3D INNOVATION LAB

Towards Versatile, Validated, and Affordable AM

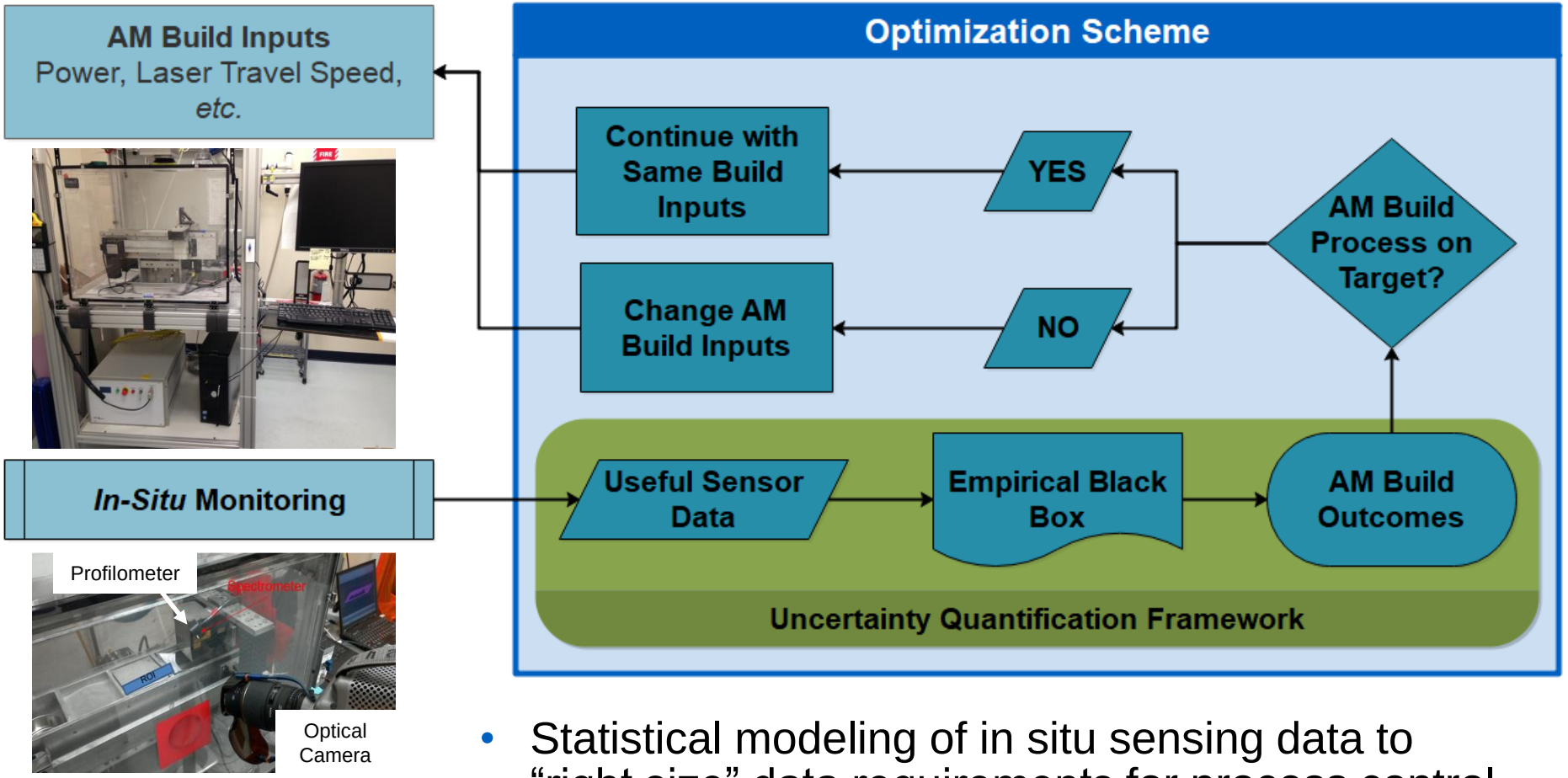
Open-Architecture AM	Laser Powder Bed Systems | Hybrid Additive / Subtractive | Multi-Material
In-Process Monitoring	Novel & Off-the-Shelf Sensors | Sensor Fusion | Sensor Data-to-Defect Correlation
Lasers & Optics	Laser Micromachining | Beam Shaping | Embedded Fiber Optics | Laser Sources
Data Analytics	Data Visualization | Machine Learning | Variability Analysis | Data Integrity & Sharing
Process Validation	Process Optimization | Build Normalization | Standards Development
Material Development	Multi-Material Processes | Tailored Compositions | Exotic Materials

Sponsors:

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SBIR Highlight: *Empirical Optimization*

NASA Phase II



- Statistical modeling of in situ sensing data to "right size" data requirements for process control
- Collecting/analyzing data across various AM systems (EOS, Concept Laser, OPENSLM™)

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Visible imaging

SBIR Phase II and Phase II-X research has demonstrated that visible imaging of ejected powder particles is effective for determining build performance.

- **This project is developing low-cost methods to obtaining the data**
- **Video is proving to be a great medium for data analytics**

Visible imagery can track ejected particles to judge weld quality



Low laser power



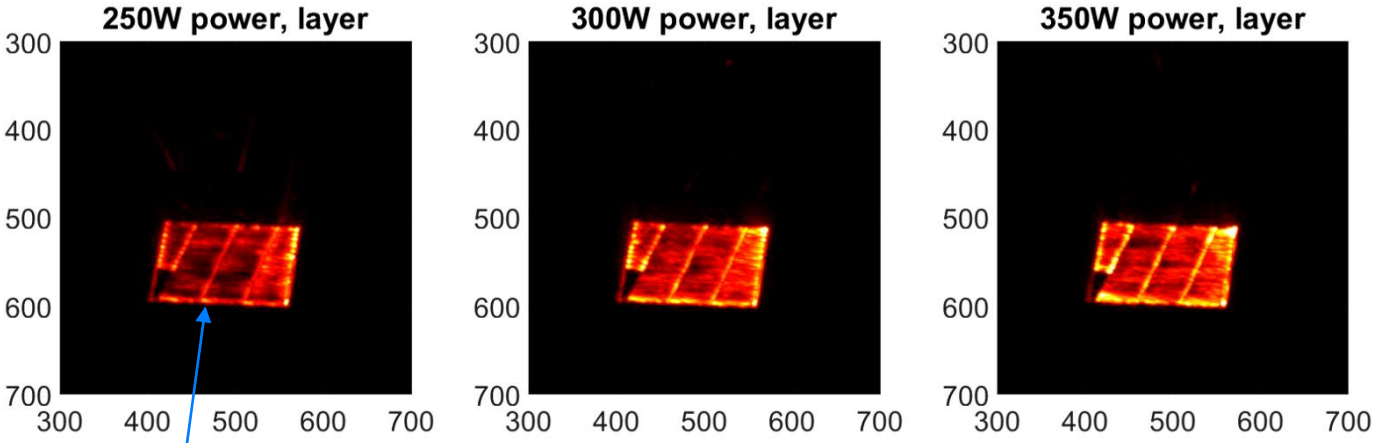
Defocused laser



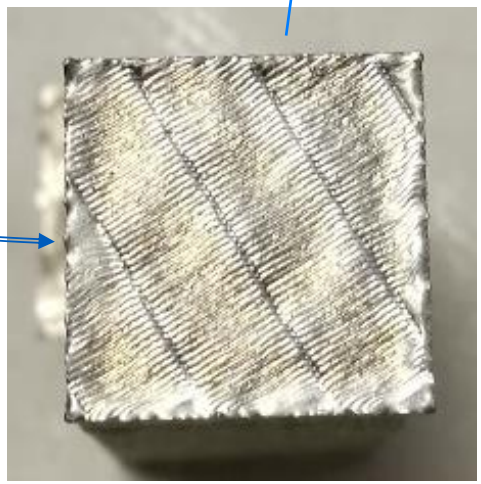
Good (nominal) parameters

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Thermal Imaging



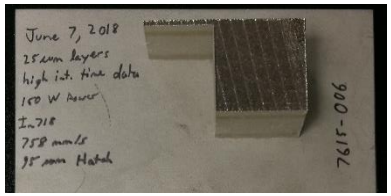
Notice the rings on the surface, they show up in the data

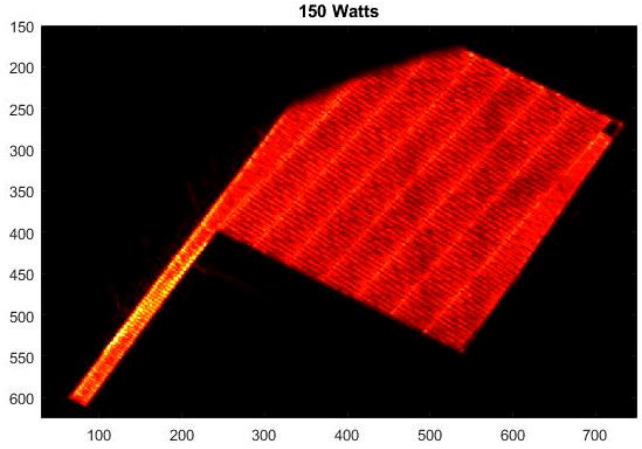


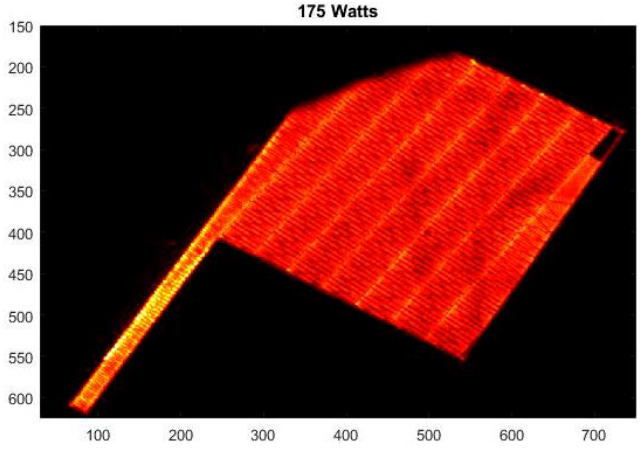
- This video is in situ imagery specifically looking at surface morphology
- There are thermal effects in the data as well, but they are convoluted with surface morphology
- Several interesting features are present, including: layer thickness information, heat build up, stripe overlap information, strike uniformity and shape, etc.

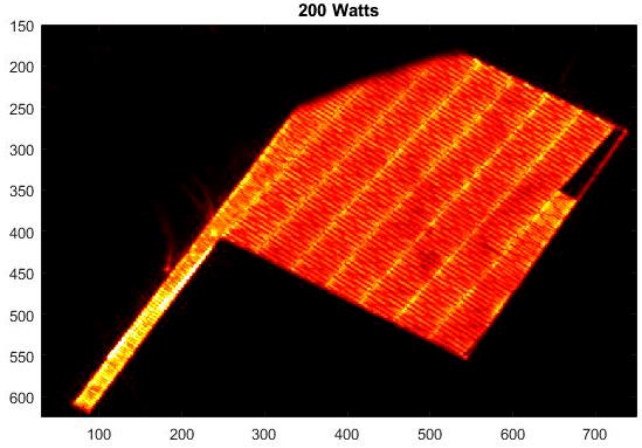
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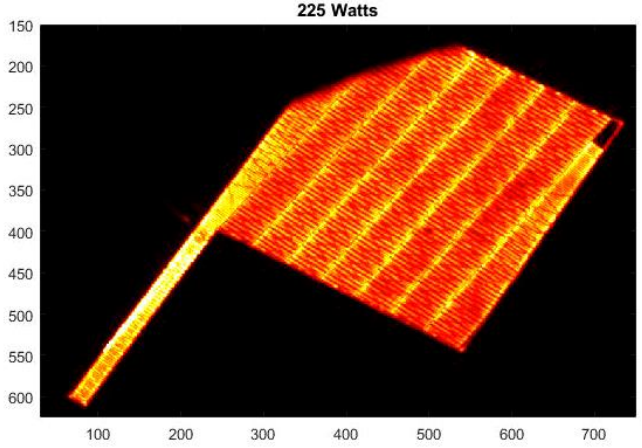
Thermal Imaging







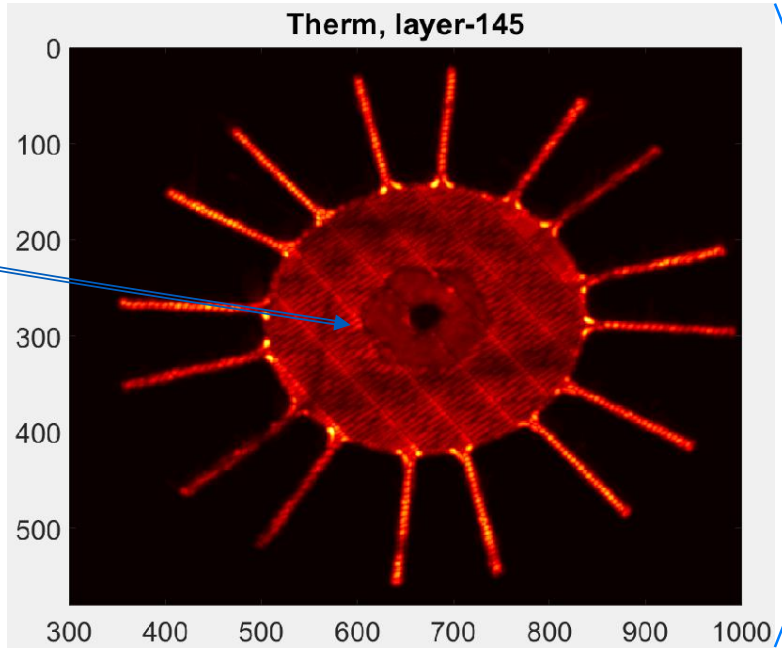


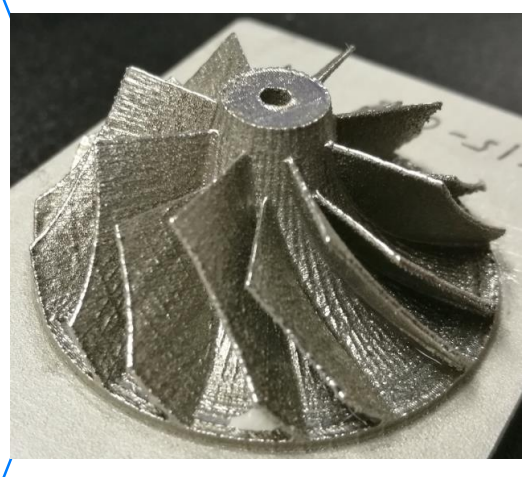


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Thermal Mapping

Shows an overhang on this layer near the middle (where a nut is supposed to go in the part)

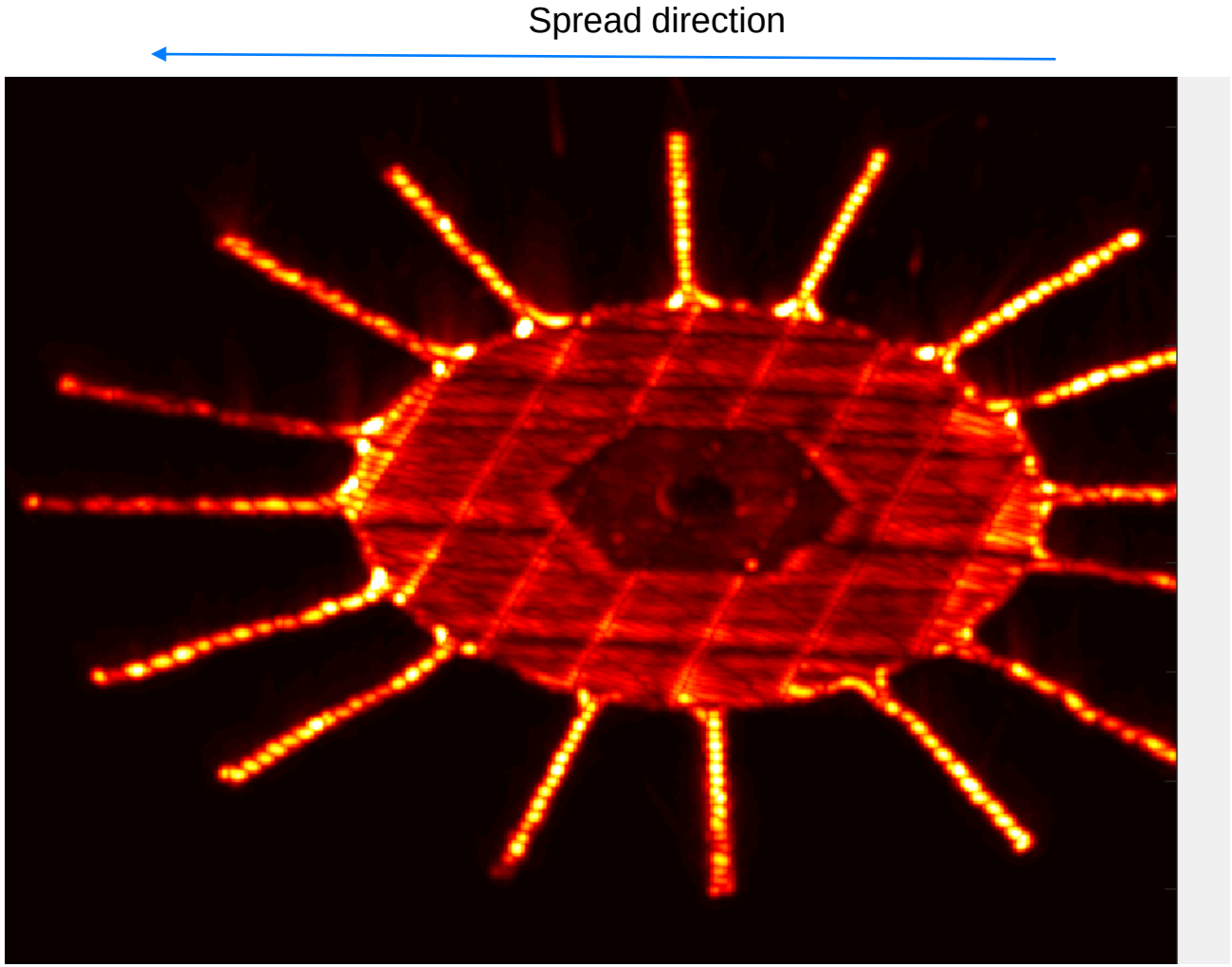




In Situ Thermal mapping

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Thermal Mapping



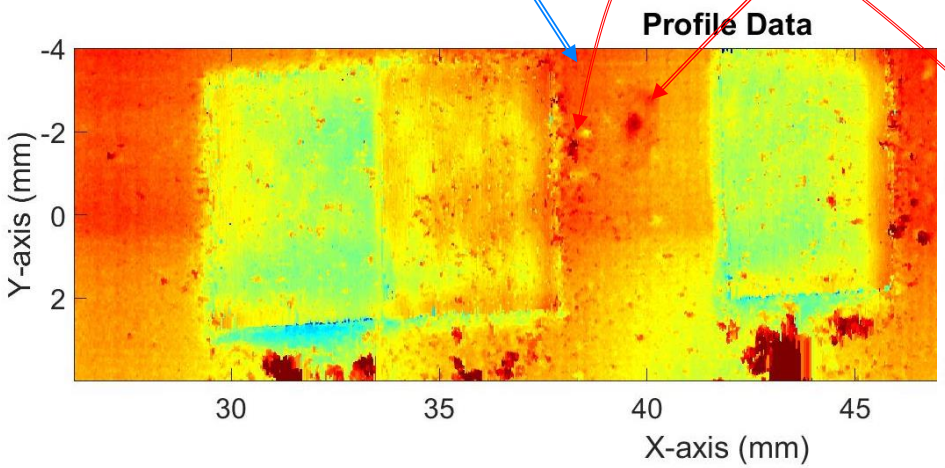
Showing how spreader defects show up in the build

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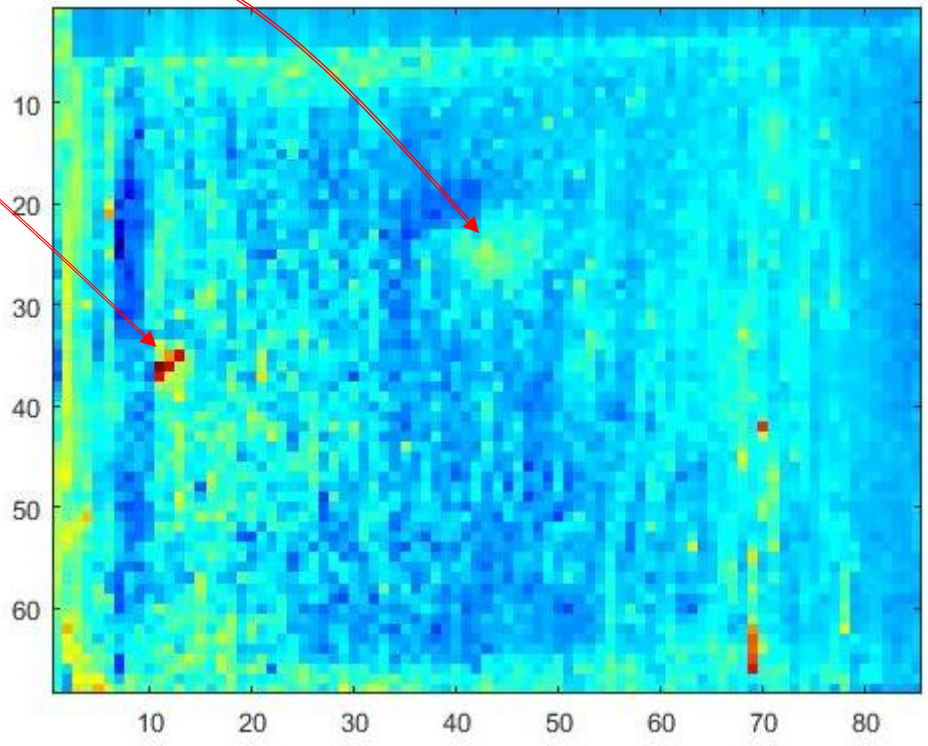
High-Speed Spectroscopy

- **UTCs in situ spectroscopy sensor identifies defects in the powder bed (confirmed with profilometry) and differences in powder layer thickness (denoted by the darker blue vs. teal areas in the image).**
- **This data is well suited for image processing-based data analytics and identifies a large number of build events**





In situ spectral sensing map



Profilometry used to identify and confirm cause for features in the high-speed optical sensor data

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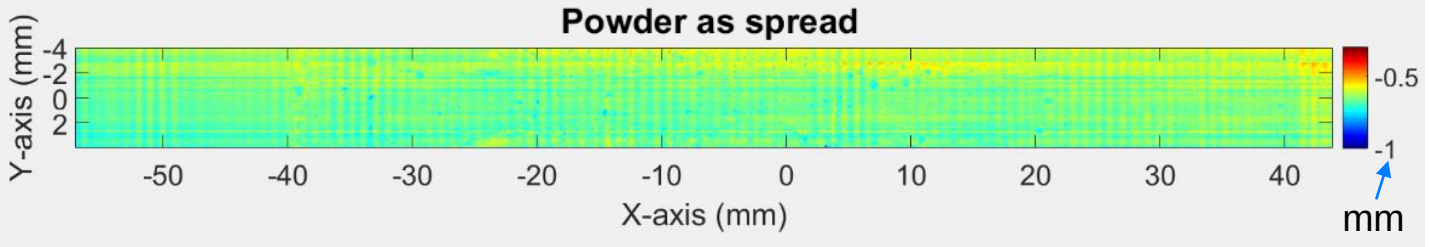
In-Situ Profilometry

Keyence Laser Line Scanner

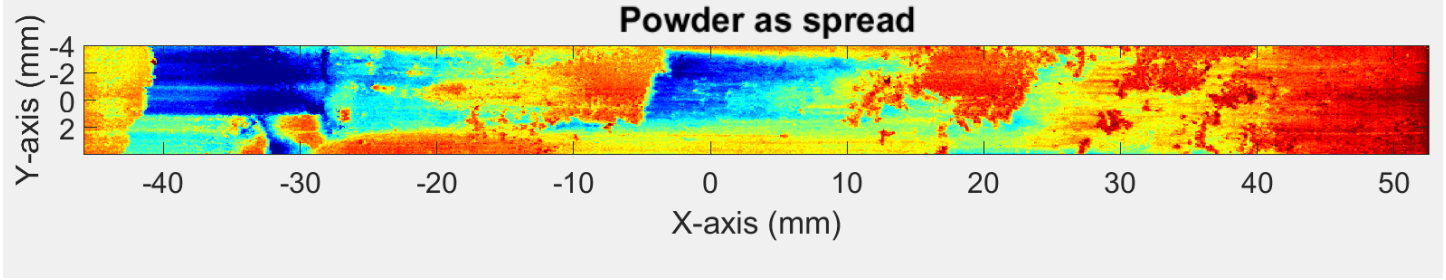
In Situ profilometry is capable of detecting poor powder spreading processes

- **May be caused by bad powder (bottom image)**
- **Could be caused by a vibration**

A nominal powder spread during fabrication of horizontal dog bone specimens



In this case, poorly sieved, used powder caused a bad powder spread in a subsequent build





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In-Situ Profilometry

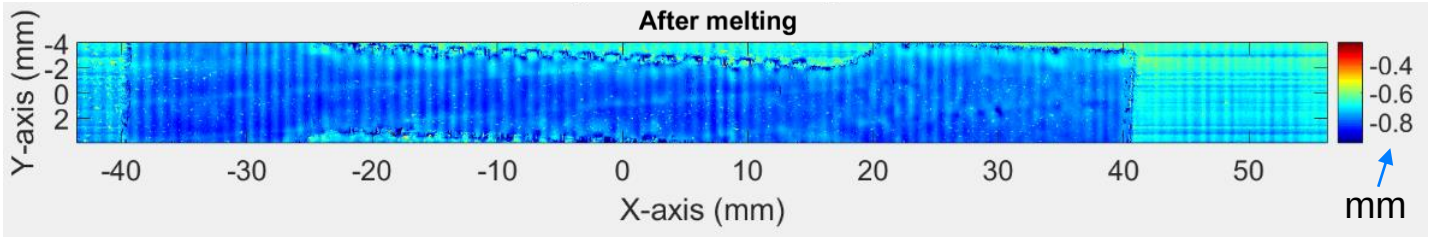
3D INNOVATION LAB

Melting performance is also measured

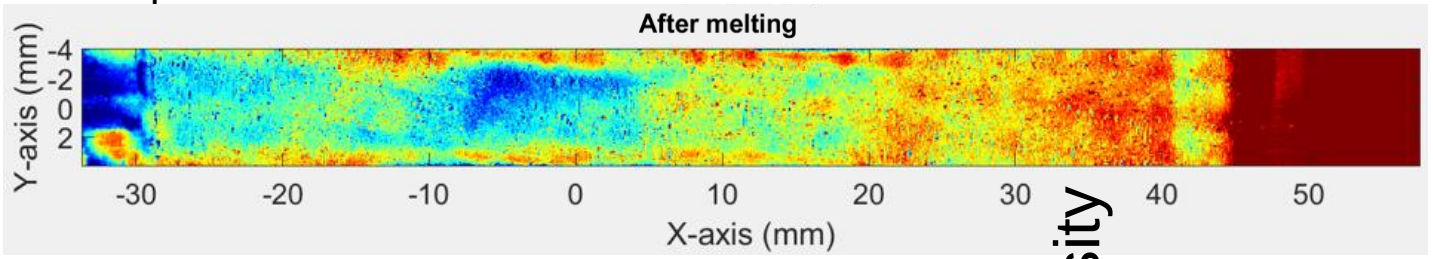
- **Good, dense parts are typically smooth and uniform**
- **Different surface roughness metrics can be used to identify various defect modes**

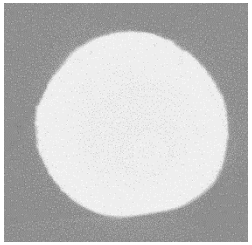


The melt corresponding to the nominal spread on the previous slide



The bad powder leads to an uneven and rough melt, and likely a less dense part

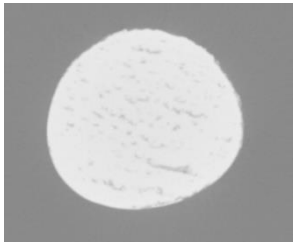




Nominal

Much of the profilometry is accompanied by CT-scanning to validate results

Low density

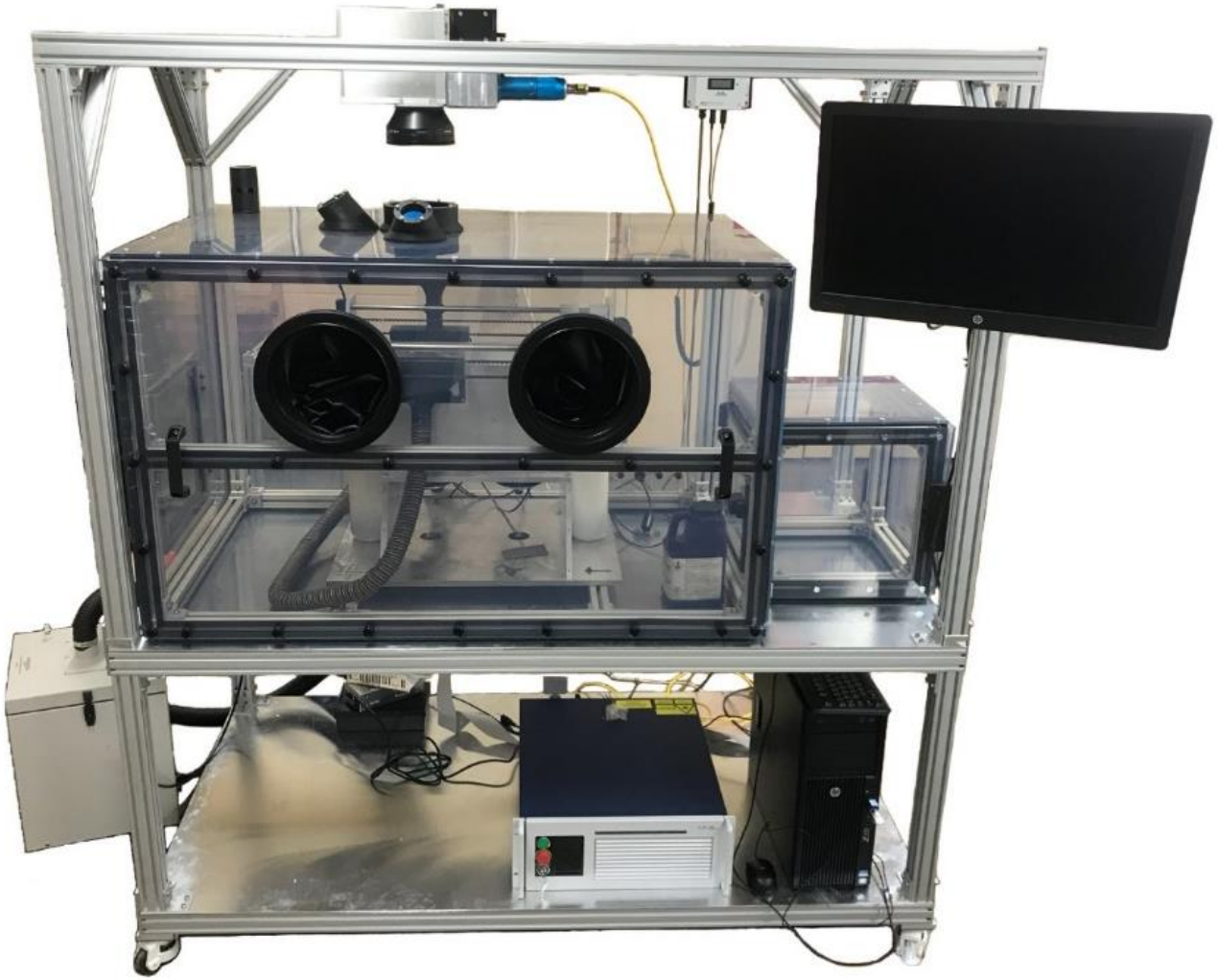


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OPENSLM™

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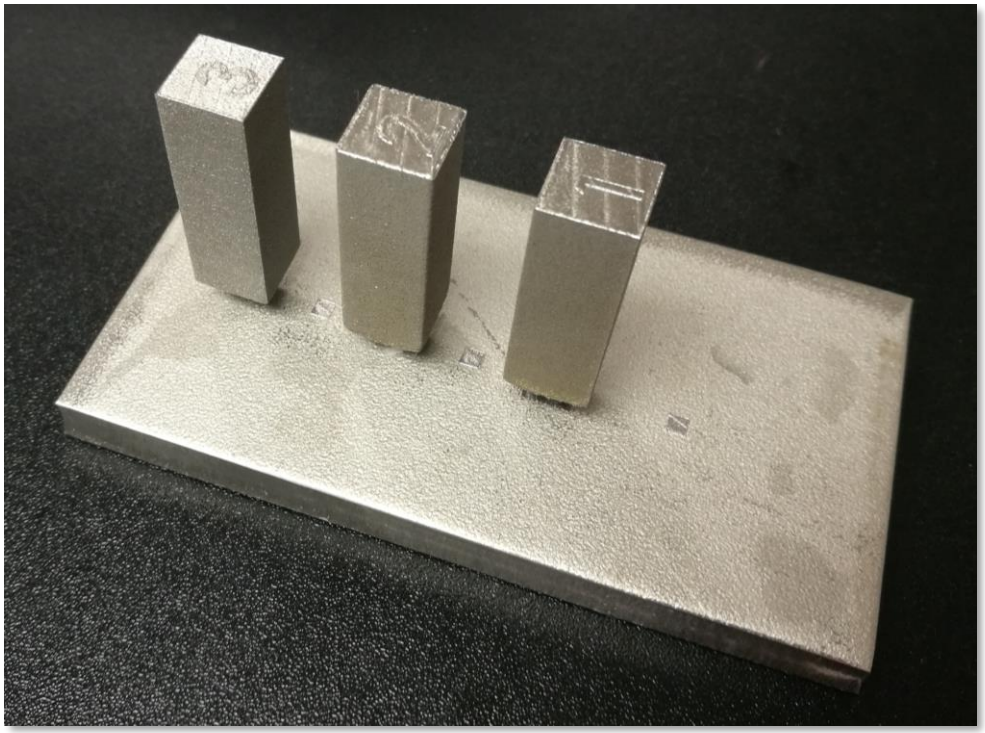


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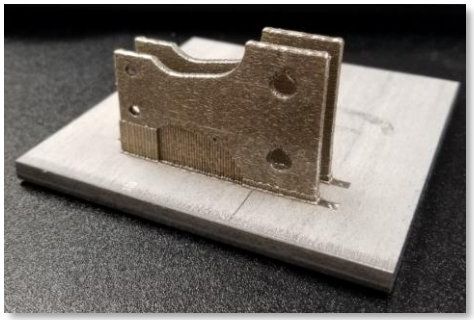
Example OPENSLM™ Builds (As Built)













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APPENDIX EE
BREAKOUT SESSION #3 DEBRIEF

NDE & Process Monitoring in Defect Management



- Design for AM – best practise and design rules
  - Part geometry can limit inspection capability
  - Design with inspection in mind

- Machine validation and process baseline - starting point for capturing potential defects of concern, more effective use of NDE / Process Monitoring

Facilitators

- Min baseline standard for machines (defect capability)
  - More uniform processes and defect behaviour, known variability between machines
- Process parameters identified with tolerance (there will be process variance)
- Preventative maintenance programme, pre and post run health check, maintain system in control

- Decrease variability, but ……
- Will not eliminate the occasional rogue defect!

A Structured Approach using NDE / Process Modelling/Process Monitoring

- Defect characterisation (stochastic and rogue)
  - source of anomalies (key process parameters and influencers)
  - Impact of anomalies (e.g. lack of fusion, residual stress)

- Mitigate your anomalies types based upon part criticality and product requirements

- Anticipate defects through process modelling & residual stress modelling
  - Capture accepted operation and measure manufacturing deviations
  - Predictive indication of variance
- In situ NDE
- Post process NDE –
  - leveraging technologies from casting and welding
  - Existing technologies may have limitations (surface condition)

Combination
1 size does not fit all

- Customised coupons representative of part features (not NDE, but ……)
  - Destructive evaluation to infer part behaviour

Areas for future NDE development, group perspective……

- Cost effective defect resolution during the build
- For as deposited parts NDE limitations exist
  - As built, as machined, as delivered….
- Need for AM specific standards
- CT time constraints
- Better understanding of anomaly effects
- Conversion of in-situ data measurements (e. g. melt pool) into effective diagnostic / preventative tools

- Transfer functions
  - Between defects and measurables
  - Seeded defect and naturally occurring defects

- Structured analysis / decomposition of gaps and / or needs for certification
  - System blockers to progress this area