Fatigue and Damage Tolerance Considerations for *Metal* Additively Manufactured Parts

Federal Aviation Administration

Presented at:

18th Annual MARPA Conference

October 24-25, 2018

Orlando, FL

Presented by:

Dr. Michael Gorelik

FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

Presentation Outline

- **Introduction**
- **Industry Trends**
- **FAA Updates and AM Standardization**
- **Parts Criticality**
- **Regulatory Considerations**
- **Risk Factors for AM**
- **Lessons Learned**
- **"Special Topic" – Zoning Considerations**
  - ***if time permits***
- **Appendix:** *Misc. Q&C References*

Disclaimer

The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration position, rules interpretation or policy

- **Introduction**
- **Industry Trends**
- **FAA Updates and AM Standardization**
- **Parts Criticality**
- **Regulatory Considerations**
- **Risk Factors for AM**
- **Lessons Learned**
- **“Special Topic” – Zoning Considerations**
- **Appendix:** *Misc. References*

AM is Not a Single Process…

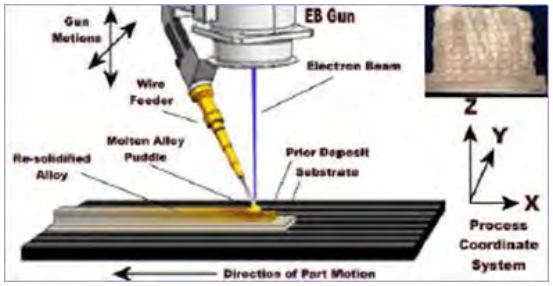
… a *partial* list of metal AM technologies

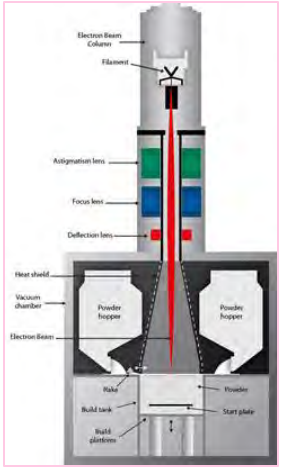
- 3-D Printing
- Powder Bed Fusion (PBF)
- Electron Beam Melting (EBM)
- Additive Layer Manufacturing (ALM)
- Directed Energy Deposition (DED)
- Direct Metal Laser Sintering (DMLS)
- Selective Laser Melting (SLM)
- Rapid Plasma Deposition (RPD)
- Laser Engineered Net Shaping (LENS)
- Laser Freeform Manufacturing Technology (LFMT)
- Laser Cladding Technology (LCT)
- Laser Deposition Technology (LDT)
- Wire + Arc AM (WAAM)
- Ultrasonic Additive Manufacturing (UAM)

- **Different physics → different Q&C considerations**
- **Lack of common terminology (*e.g. L-PBF / SLM / DMLM / DMLS*)**

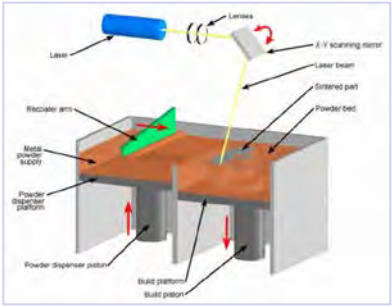
Diversity of AM Processes and Certification Domains

By Source of Material:
Powder vs. Wire





By Source of Energy:
Laser vs. e-Beam vs. Plasma Arc



New Type and Production Certificates

Repair and Overhaul (MROs)

Aftermarket Parts (PMAs)

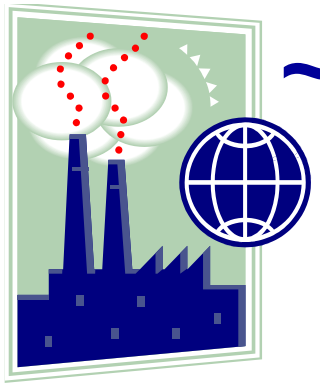
AM - “Barrier to Entry”

Optimistic →

Equipment acquisition

~ $1M

Realistic →



~ $10’s of M

- **Process development**
- **Process qualification**
- **Process controls**
- **Material characterization**
- **Design data**
- **QA / NDI**
- **etc.**

> Everything should be made as simple as possible, but not simpler.
>
> Albert Einstein

Structural Integrity

- Structural integrity is the condition which exists when a structure is sound and unimpaired in providing the desired level of structural ***safety***, performance, ***durability***, and supportability

Reference: MIL-STD-1530C

areas of primary interest to the FAA

What Causes Failures?

Frequency of Failure Mechanisms *)

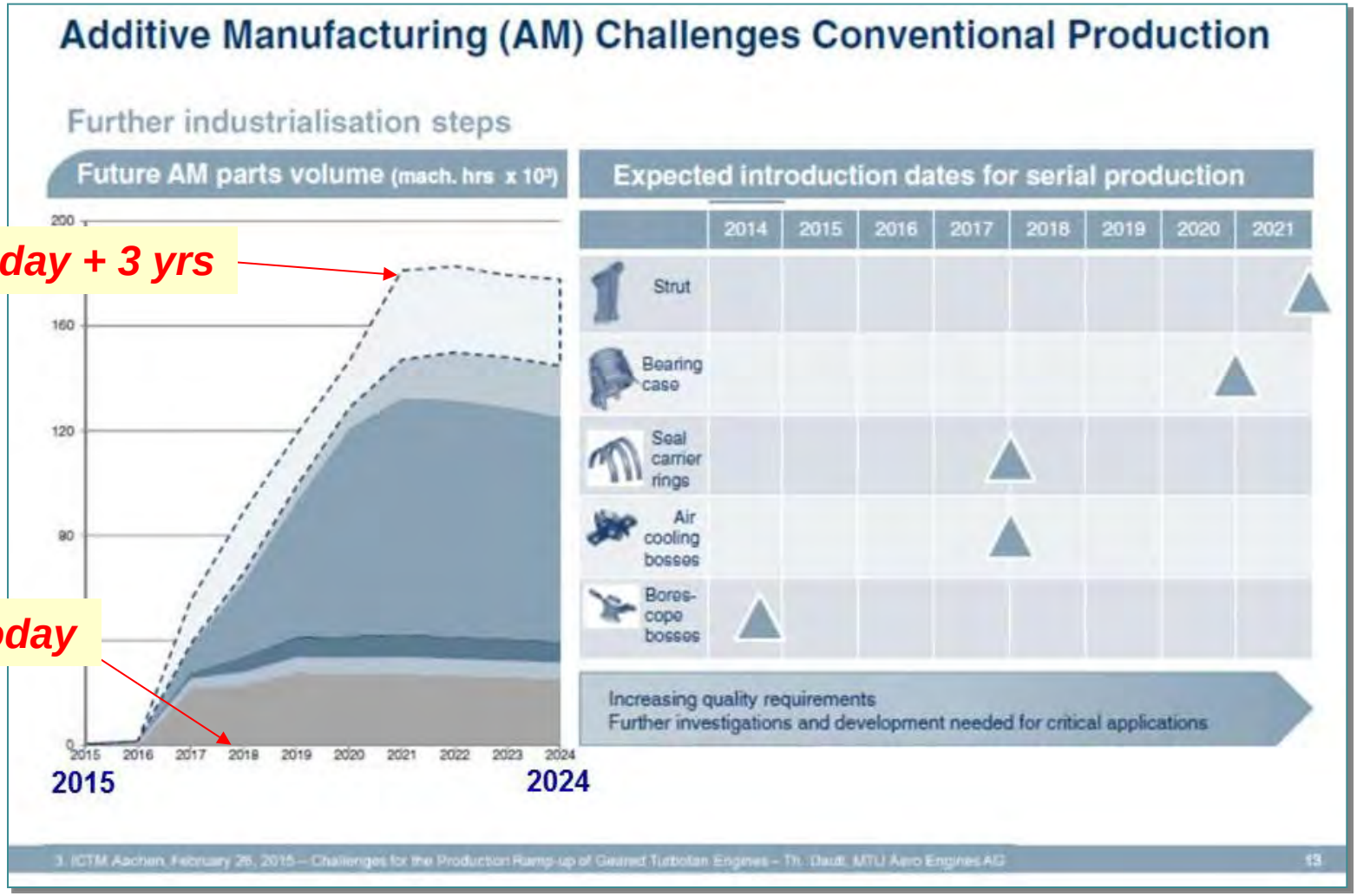
Failure Mechanism	% Failures *(Aircraft Components)*
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

**) Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Expect this trend to continue for metallic materials**
- **Some of the most challenging Q&C requirements *for new material systems* are related to F&DT**

- Introduction
- **Industry Trends**
- FAA Updates and AM Standardization
- Parts Criticality
- Regulatory Considerations
- Risk Factors for AM
- Lessons Learned
- "Special Topic" – Zoning Considerations
- Appendix: *Misc. References*

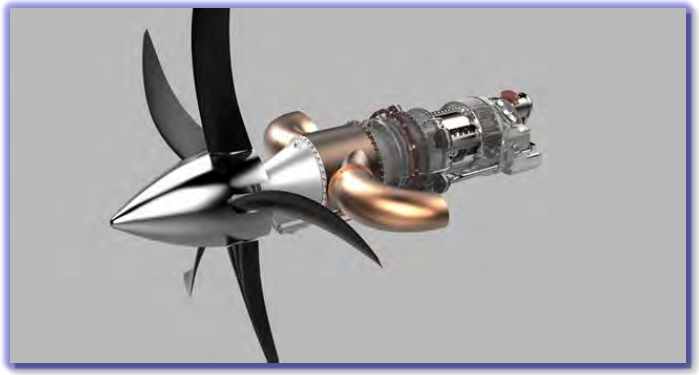
State of Industry



Examples of Expanding Use of AM

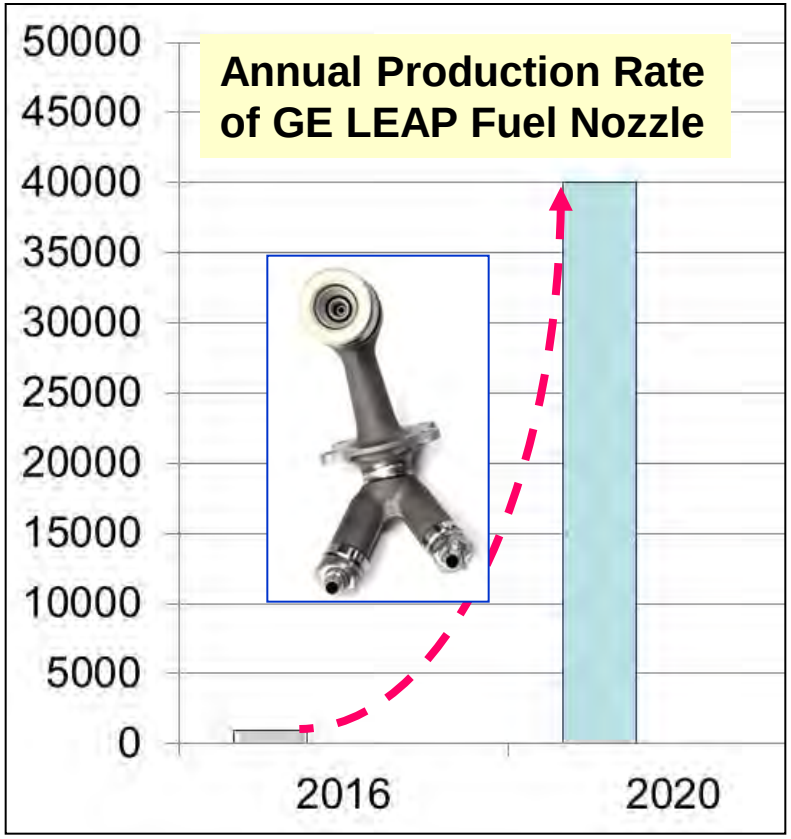
- **"GE *Advanced Turboprop* is the first Aviation product to fully utilize additive tools…"**
  - **It has 30% fewer parts (from 800+ to *12 parts*), and will be completed with a 50% reduction in cycle time**

From GE 2016 Annual Report



Example: Moving Towards Full-Scale Production

"GE Aviation Selects Auburn, AL for High Volume Additive Manufacturing Facility"



"Production will ramp up quickly over the next five years, going from 1,000 fuel nozzles manufactured annually to more than 40,000 by 2020".

Reference: http://www.geaviation.com/press/other/other_20140715.html

Example: Moving Towards "Part Family" Qualification

Families for qualification

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

Separate qualification of each AM part is not necessary.

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

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

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

15 29th August 2017 AIRBUS

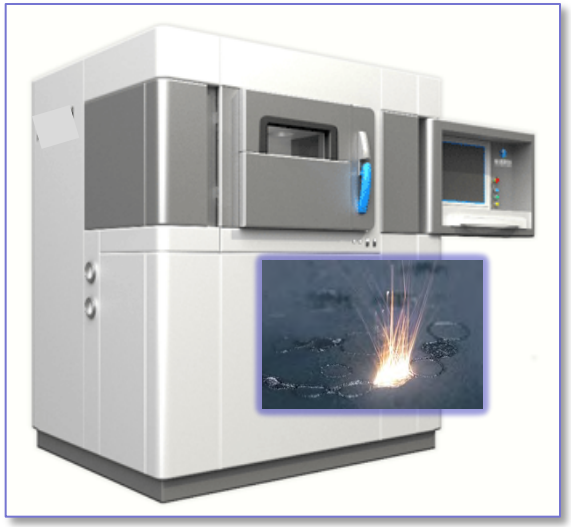
Presented by J. van Doeselaar (Airbus) at the 2017 Joint FAA – AFRL AM Qual & Cert Workshop, Dayton, OH.

Additive Manufacturing – New Paradigm:

Manufacturing Capabilities Ahead of Design Vision..?

"Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…"

Mr. David Joyce, GE Aviation President and CEO

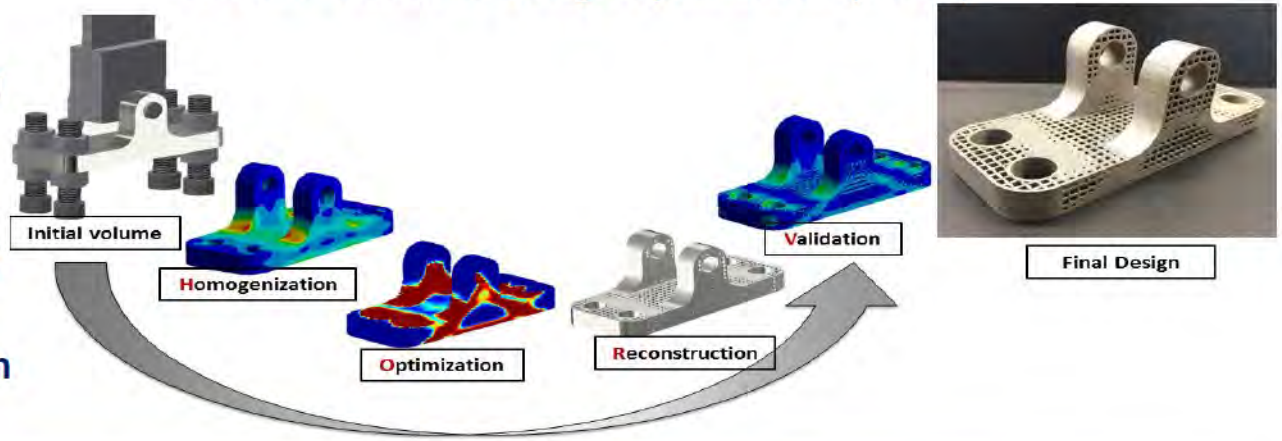


Example: AM Structure Design Optimization

Objectives

- Extend CSDO to other physics (i.e. thermal cooling, natural frequency)
- Implement CSDO algorithms into ANSYS Topo Opt module
- Apply CSDO to real design problems
- Develop AM design aides in SpaceClaim

Cellular Structure Design Optimization (CSDO)



Project Benefits

- The proposed integrated design suite will help minimize time of the design phase, lower manufacturing cost, and reduce time to market for new AM product development

Approved for Public Release

AmericaMakes.us

Albert C. To, Integrated Design Tool Development for High Potential Additive Manufacturing Applications, America Makes, 2016.

Location-specific properties (*include fatigue*) need to be considered during design *and optimization*

AM Technology Trends to Watch

(partial list)

- **Transition to full-scale production**
- **Use of less expensive raw materials (*e.g. lower-grade powders*)**
- **More aggressive machine settings (*speed, layer thickness, …)***
- **Use of multi-laser systems**
- **Larger build envelopes**
- **Introduction of safety-critical parts**
- **Topological optimization**

Longer-Term

- ***Tailored* location-specific microstructure / properties**
- **Replacement of conventional QA / NDI with in-situ process monitoring and adaptive controls**
- **Increased use of modeling and simulation in Q&C**

- Introduction
- Industry Trends
- **FAA Updates and AM Standardization**
- Parts Criticality
- Regulatory Considerations
- Risk Factors for AM
- Lessons Learned
- "Special Topic" – Zoning Considerations
- Appendix: *Misc. References*

Examples of FAA-approved Metal AM Parts

T-25 Sensor Housing (GE-90)

14 CFR Part 33

Fuel Nozzle (LEAP Engine)

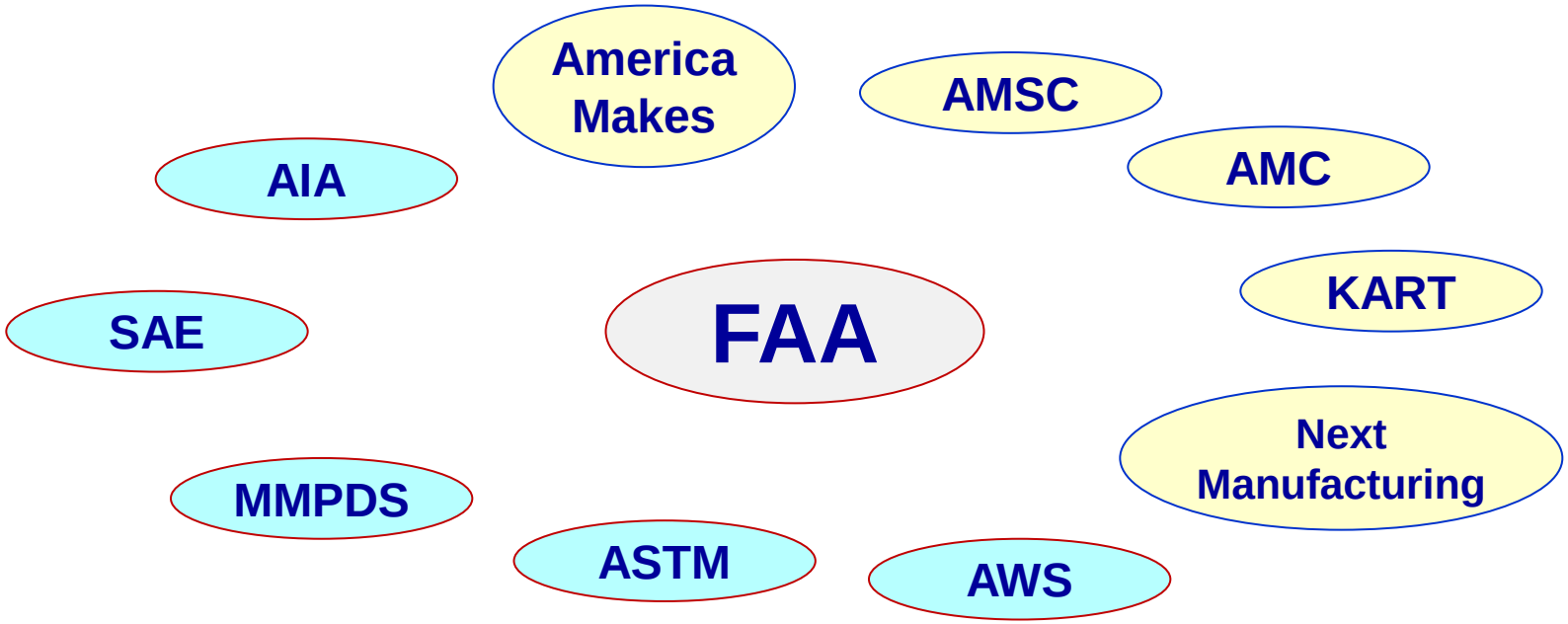
14 CFR Part 33

Galley Floor Bracket (B-787)

14 CFR Part 25

Engagement with SDOs and Consortia

A partial list…



Example: Cross-SDO Collaboration

AMSC – *AM Standards Collaborative*

America Makes

ANSI
American National Standards Institute

Can be downloaded at: https://www.ansi.org/standards_activities/standards_boards_panels/amsc/

Standardization Roadmap for Additive Manufacturing

VERSION 2.0

Example: Cross-Committee Collaboration *(SDO-level)*

Committee E08 on Fatigue and Fracture

Committee E07 on Nondestructive Testing

ASTM INTERNATIONAL

Committee F42 on Additive Manufacturing Technologies

Multi-Disciplinary Interfaces Are Essential

Examples of *External* Benchmarking

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

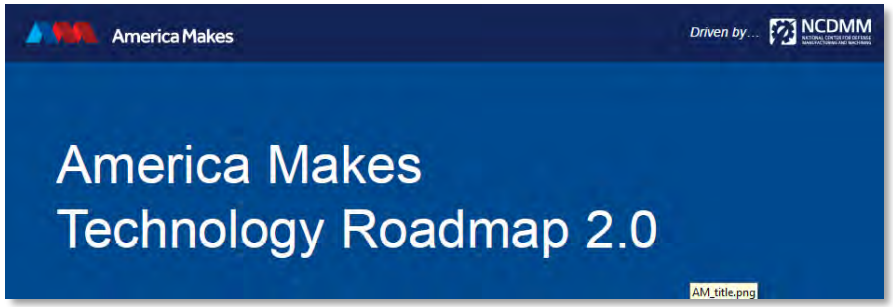
MSFC-STD-3716
BASELINE
EFFECTIVE DATE: October 18, 2017

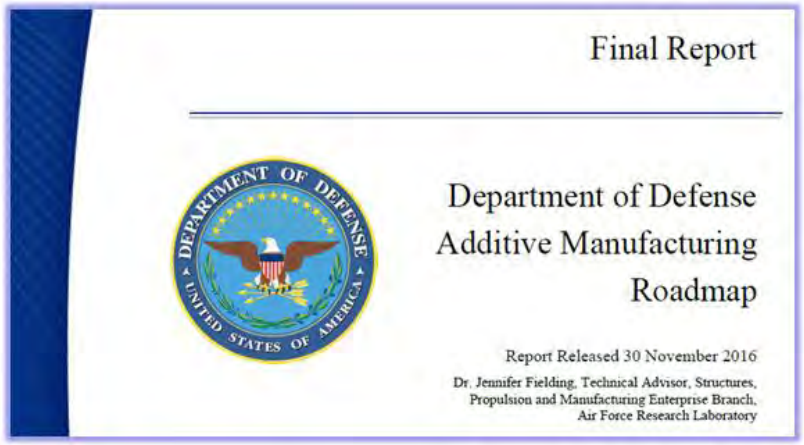
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS





AM Certification – Main Strategic Focus Areas

Engineering Certification

Production / QA

Maintenance / MROs

Continued Operational Safety

"regulatory"

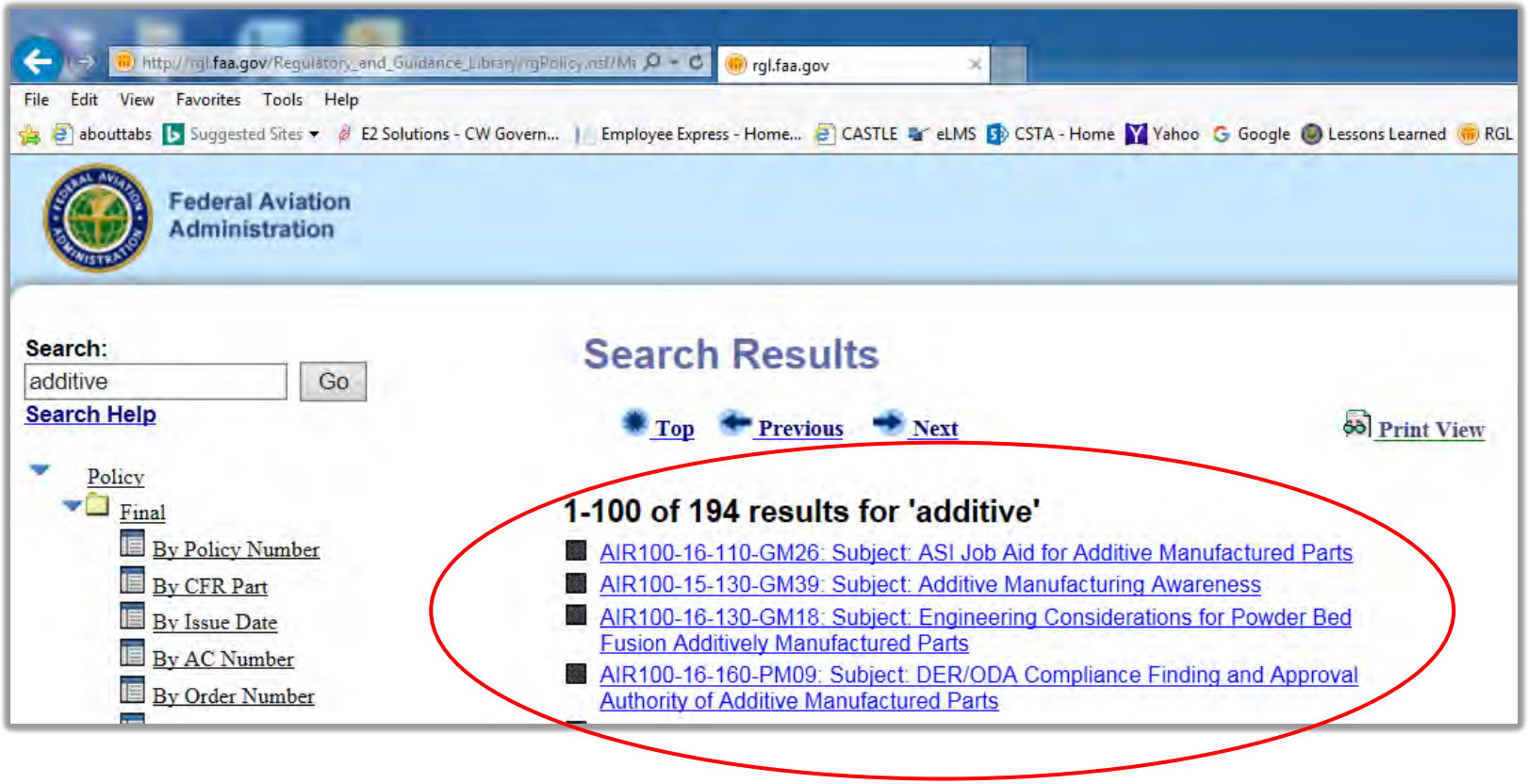
Enablers:

Workforce Education (FAA + Designees + Industry)

R&D

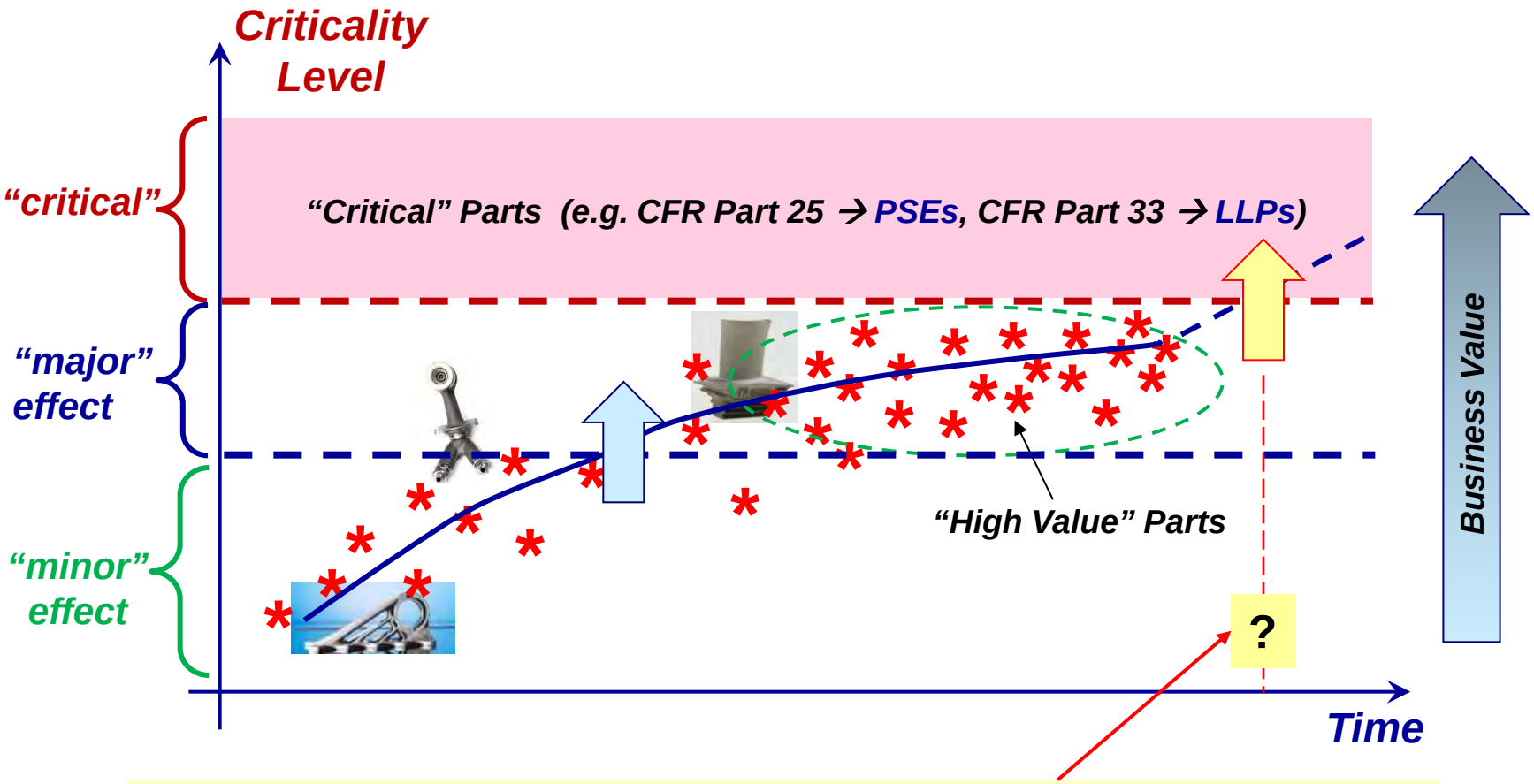
Initial AM Documents Are Available at:

http://rgl.faa.gov → **Policy** → Search Keyword: *Additive*



- Introduction
- Industry Trends
- FAA Updates and AM Standardization
- **Parts Criticality**
- Regulatory Considerations
- Risk Factors for AM
- Lessons Learned
- "Special Topic" – Zoning Considerations
- Appendix: *Misc. References*

Evolution of Criticality of AM Parts



Transition to "safety-critical" applications in aviation will occur sooner than initially expected

NAVAIR News Release
NAVAIR Headquarters
Patuxent River, MD

July 29, 2016

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

An MV-22B Osprey equipped with a 3-D printed titanium link and fitting inside an engine nacelle maintains a hover as part of a July 29 demonstration at Patuxent River Naval Air Station, Maryland. The flight marked Naval Air System Command's first successful flight demonstration of a flight critical aircraft component built using additive manufacturing techniques. (U.S. Navy photo)

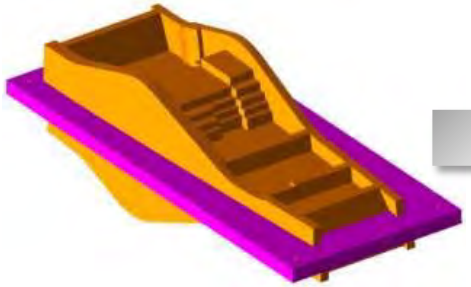
Courtesy of AFRL

F-15 Pylon Rib Insertion Success Story

Issue: -7075 Al Forging, Pylon Rib, Corrosion Fatigue Cracking
-Decision to move to Ti 6-4 forging already made
Long lead time for Ti forging ~1 year

Solution: -Replace with Ti 6Al-4V Additive
-To meet urgent need for aircraft in depot
- Quality issues lessened because of high margin for Ti in this application.

RX Role: -Provided Technical Leadership to Acquisition
-Executed Technology Demonstration Project
-Worked Attachment Issues (bushings, fasteners,etc...)



First structural AM part introduced in 2003

From Non-Critical to Critical

- **Typical new aerospace alloy development and introduction timeline – *10 to 15 years***

➢ **<u>However</u>**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural components	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

<u>Example</u>

"The *outcome* of Rawfeed (*an R&D program*) will be a *<u>specification for a process to additively manufacture Class 1 titanium structures</u>*, such as engine hangers, wing spars and gear ribs… expensive, critical parts…"

<u>Reference</u>: *Rolling Key To Additive-Manufacture Of Critical Structures*, Aviation Week & Space Technology, Nov 10, 2014.

Parts Criticality

Ref: AC 33-8 ***"Guidance for PMA of Turbine Engine and APU Parts under Test and Computation"***

- **"…test and substantiation plan applicants submit as part of their data package to show compliance *should reflect the criticality* or complexity of their proposed PMA part design to ensure the part meets the airworthiness requirements"**

- **"This AC categorizes parts based on their *most severe potential failure effect* using various methods for assessing malfunctions and failure modes…"**

“History is a Vast Early Warning System”

Norman Cousins

Part Criticality – a Case Study

The ATSB found that the engine failure was the result of a *fatigue crack in an oil feed pipe*

- **The crack allowed the release of oil that resulted in an *internal oil fire***
  - **The oil fire led to *one of the engine's turbine discs separating from the drive shaft***
    - **The *disc then over-accelerated and broke apart*, bursting through the engine casing and releasing other <u>high energy debris</u>**

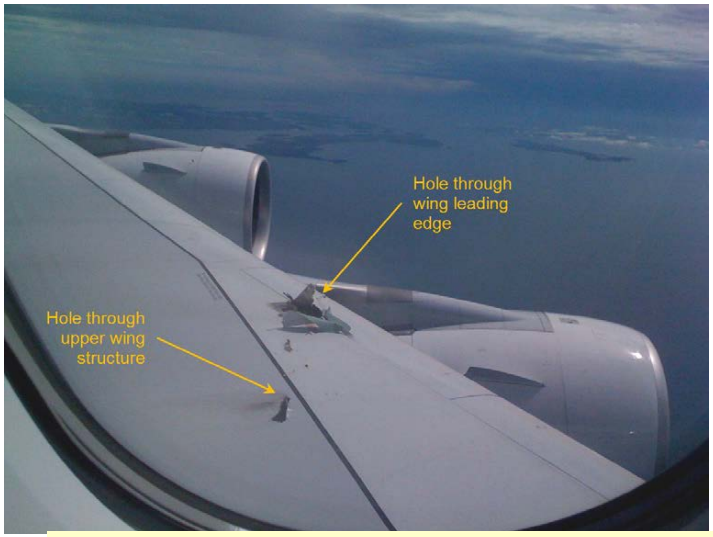


Image source: Supplied by a passenger (!)

Property damage from a section of the No. 2 engine turbine disc

<u>Reference</u>: ATSB Transport Safety Report, Final Investigation - In-flight uncontained engine failure Airbus A380-842, VH-OQA

Part Criticality – a Case Study (cont.)

Root cause: the ATSB found that *a number of* oil feed stub pipes … were manufactured with *thin wall sections* that *did not conform to the design specifications*

Manufacturing deviation of non-critical part nearly brought down A-380 a/c

- **These are the *types of parts* considered by OEMs for initial entry into AM**
- ***System-level risk assessment* is an important consideration (FMEA / FMECA / etc.)**

Reference: ATSB Transport Safety Report, Final Investigation - In-flight uncontained engine failure Airbus A380-842, VH-OQA

- Introduction
- Industry Trends
- FAA Updates and AM Standardization
- Parts Criticality
- **Regulatory Considerations**
- Risk Factors for AM
- Lessons Learned
- “Special Topic” – Zoning Considerations
- Appendix: *Misc. References*

Regulatory Considerations for AM

- **New Material and Process Space**
  - *Common consideration for new material or manufacturing technology introduction*
- **New Design Space**
  - *Unique to Additive Manufacturing..?*

Diverse Regulatory Environment

(driven by different product types)

Transport Airplanes
(14 CFR Part 25)

Small Airplanes
(14 CFR Part 23)

Engines and Propellers
(14 CFR Parts 33, 35)

Rotorcraft
(14 CFR Parts 27, 29)

Part Rules Comparison - *General Observations*

- **Detailed material related requirements are Part rule dependent**
  - **Various levels of requirements' details by Part**
- **Some of the most critical material requirements (Fatigue / Damage Tolerance) are closely linked to OEMs design / analysis system**
  - **Typically approved on OEM-specific basis (means of compliance)**
- **Differences by product type tend to be more pronounced in F&DT certification requirements**
  - ***One common theme – strong dependence on part criticality***

Excerpts from FAR 25.571

<u>§ 25.571 Damage—tolerance and fatigue evaluation of structure</u>

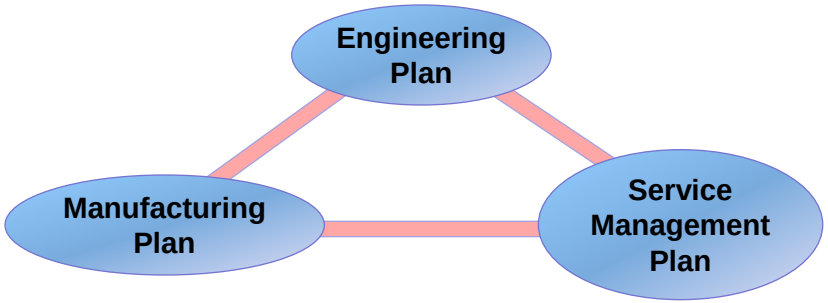
(a) General. **An evaluation of the strength, detail design, and fabrication must show that *catastrophic failure* due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane.**

"…identification of *principal structural elements* (PSE) **and detail design points, the failure of which could cause *catastrophic failure* of the airplane…"**

Excerpts from FAR 33.70

- **WHY: Industry data has shown that manufacturing-induced anomalies have caused about 40% of rotor cracking and failure events**
- **WHAT: 33.70 rule requires applicants to develop coordinated engineering, manufacturing, and service management plans for each life-limited part**
  - **This will ensure the attributes of a part that determine its life are identified and controlled so that the part will be consistently manufactured and properly maintained during service operation**

Engine life-limited parts (LLPs) are rotor and major static structural parts whose primary failure is likely to result in a *hazardous engine effect*



What Did Historically Work Well to Address "Known Unknowns"?

- **Effective manufacturing process controls**
- ***Damage tolerance (DT) framework***
- ***QA / NDI methods***
- **Sharing of lessons learned across the industry**

Success story – rotor-grade Titanium alloys

(Reference: proceedings of AIA RISC Working Group)

Two Types of Anomalies

that may result in life debit

Rogue (rare) Anomalies

Examples:

- **Melt-related defects (hard alpha) in Ti**
- **Machining induced**

Inherent Anomalies

Examples:

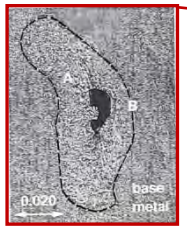
- **Porosity in castings**
- **NMEs (non-metallic inclusions) in PM alloys**

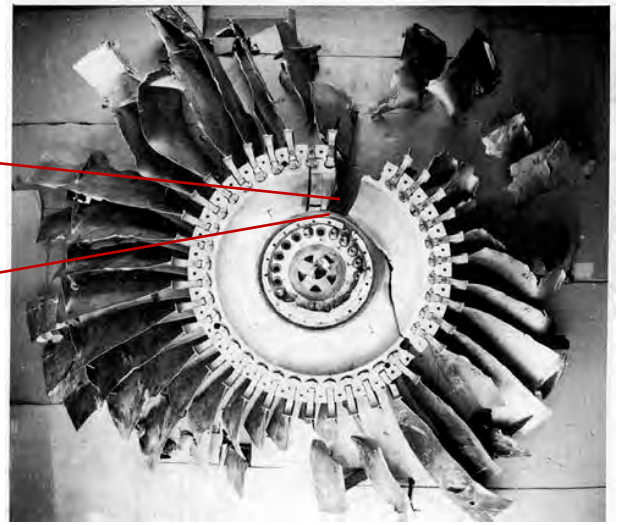
Surface vs. Volume

Courtesy of AIA RISC

Example of *Rogue* Anomalies

Titanium Hard Alpha DT Methodology





U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

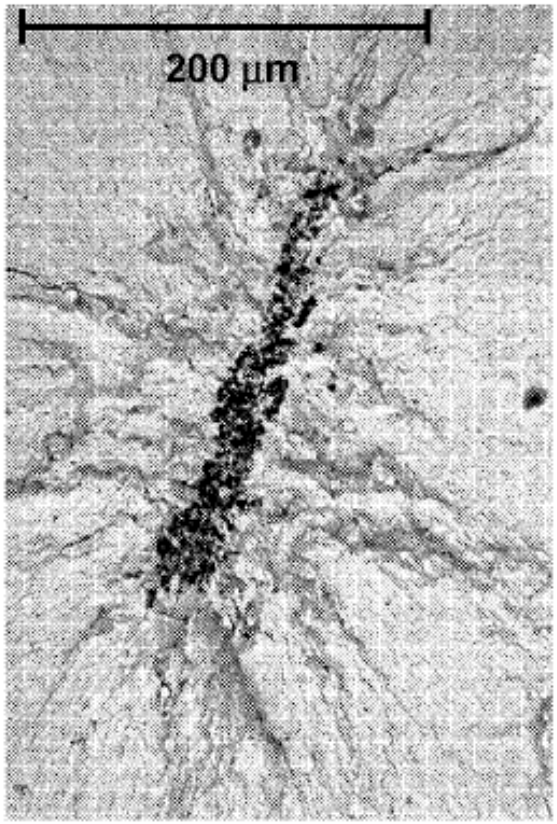
Subject: Damage Tolerance for High Energy Turbine Engine Rotors	**Date:** 1/8/01 **Initiated By:** ANE-110	**AC No:** AC 33.14-1 **Change:**

b. Use of the enhanced life management process depicted in FIGURE S2-1, will result in damage tolerance assessments being conducted on critical titanium alloy rotor designs. These will be fracture-mechanics based probabilistic risk assessments, the results of which will be compared to the agreed upon design target risk (DTR) values. Designs that satisfy these DTR values will be considered to comply with the requirements of § 33.14. The engine manufacturer

Example of *Inherent* Anomalies (PM Alloys)

FAA AC is being developed (with input from AIA RISC WG)

Fatigue Crack from Inherent Ceramic Defect



P. Bonacuse et al, NASA CP-2002-211682

- Inherent to powder process (unavoidable)
- Can cause significant life debit
- Large inclusions exceedingly rare
- Cost prohibitive to study the effect of naturally occurring inclusions on life

AFRL-RX-WP-TP-2009-4152

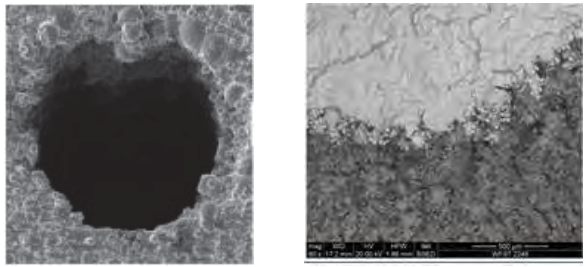
MEAN VS. LIFE-LIMITING FATIGUE BEHAVIOR OF A NICKEL-BASED SUPERALLOY (POSTPRINT)

S.K. Jha, M.J. Caton, and J.M. Larsen

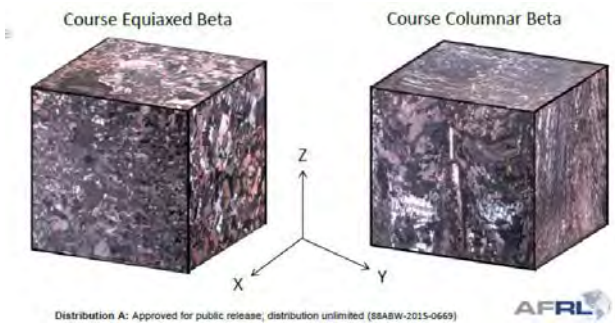
Metals Branch
Metals, Ceramics, and NDE Division

- Introduction
- Industry Trends
- FAA Updates and AM Standardization
- Parts Criticality
- Regulatory Considerations
- **Risk Factors for AM**
- Lessons Learned
- “Special Topic” – Zoning Considerations
- Appendix: *Misc. References*

Examples of Risk Factors for AM



Surface Quality



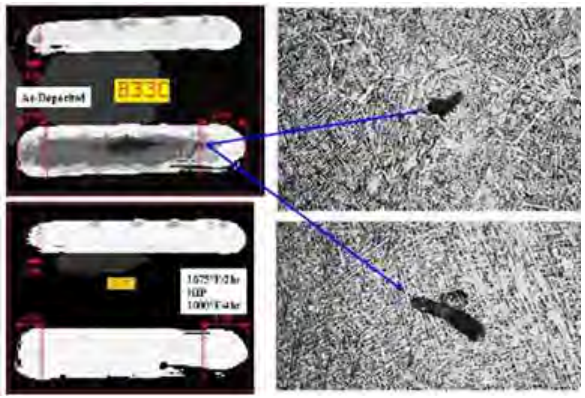
Microstructure Variability

Powder Control

Powder feed rate (g/min)
Laser Power (W)
Scan speed (in/min)
Laser spot size (in)
Substrate temp (ºF)
Hatch spacing (% of calculated)

over 100 process parameters identified

Process Controls

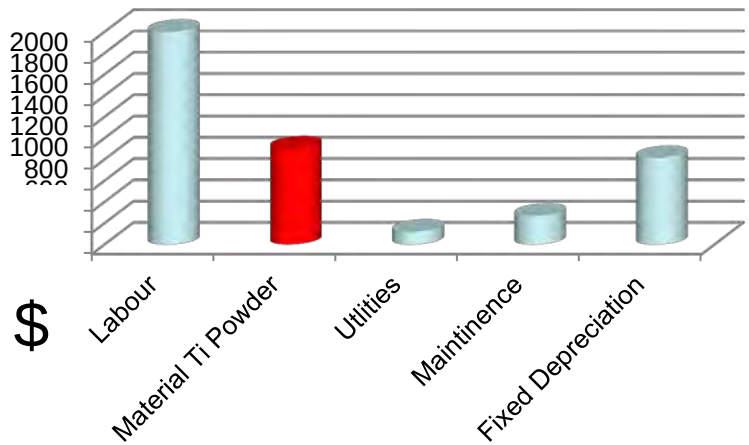


HIP Effectiveness

Many More Identified by Experts…

Powder Reuse

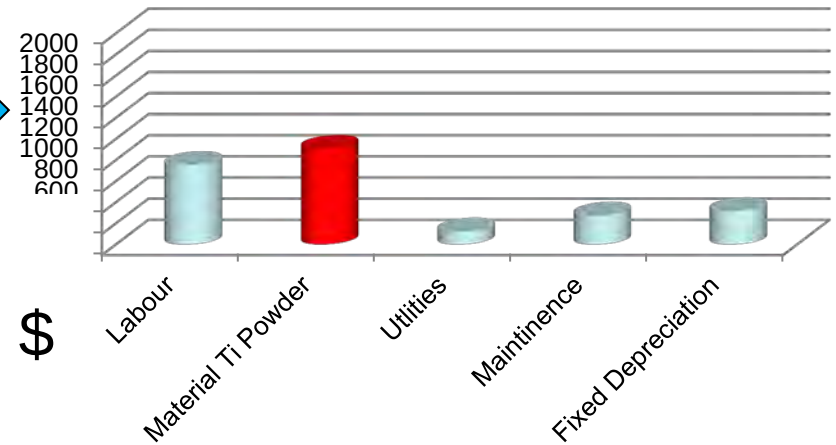
Today



50% of the cost in operation is labour

20% is depreciation (i.e. cost of the unit)

Future



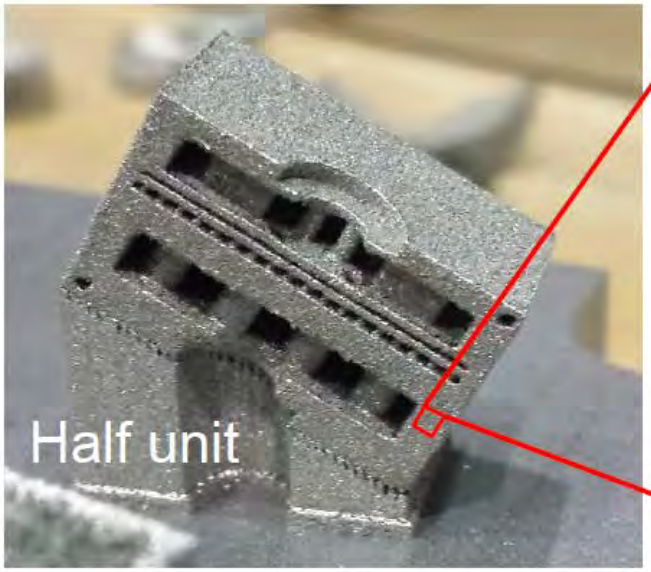
As the equipment costs come down and labour gets more productive (affordable), *powder becomes the most costly component of AM*

"… it is highly likely you can reuse IN718 powder at least 14 times with no significant degradation from its initial quality…"

"… There was also no evidence of the quality degradation of final parts made with reused powder, despite *some minor changes in the powder properties relating to its particle size distribution and chemistry*."

"Printing jet engines" by James Perkins, Materials World, March 2015

Microstructural Challenges: Defects



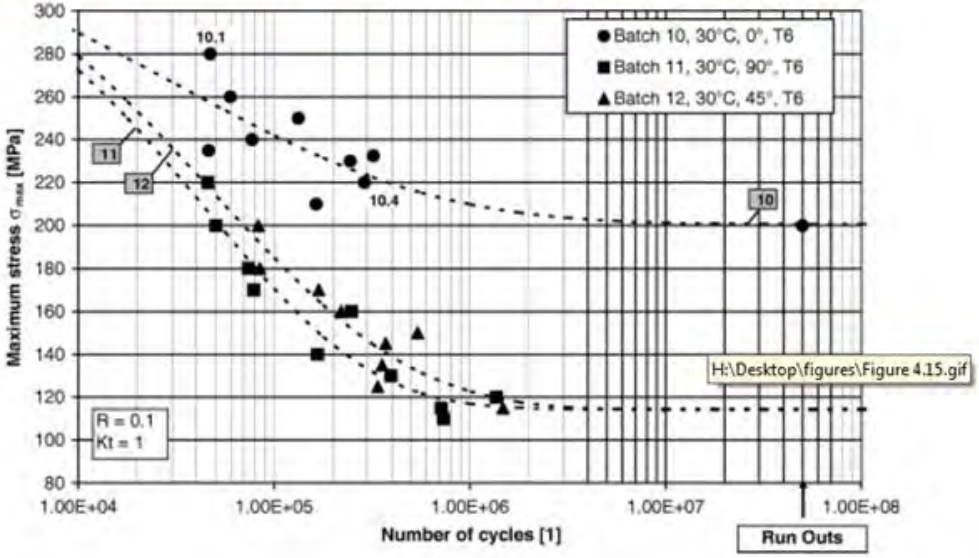
Prototype heat exchanger for high temperature service (> 700 ° C)

Reference: A. Rollett, DOT/FAA/TC-16/15, "*Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts*".

Reference: S. Daniewicz, DOT/FAA/TC-16/15, "*Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts*".

Anisotropy in SLM Parts

Stress-life approach



Brandl, E., Heckenberger, U., Holzinger, V., & Buchbinder, D. (2012). Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design, 34, 159-169.

MISSISSIPPI STATE UNIVERSITY

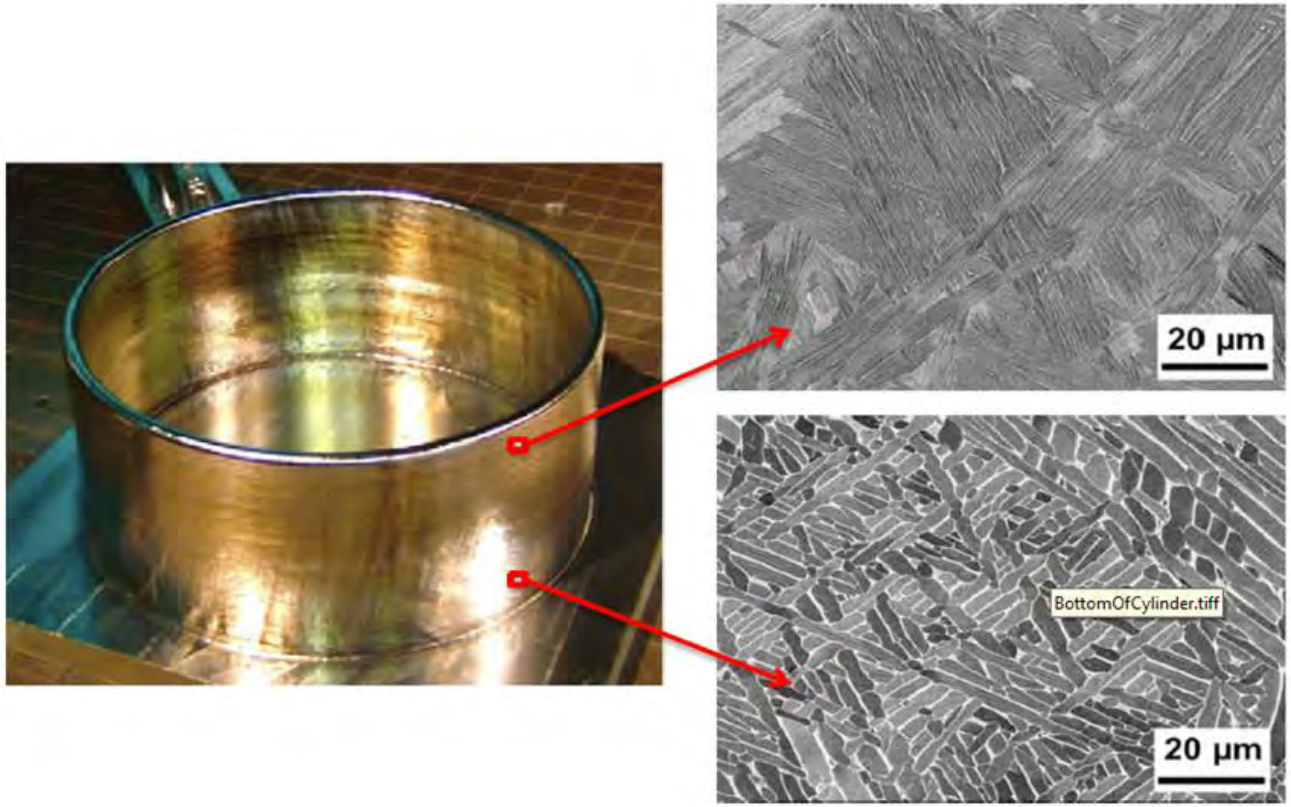
14

CAVS

Federal Aviation Administration

Microstructural Challenges: Process control

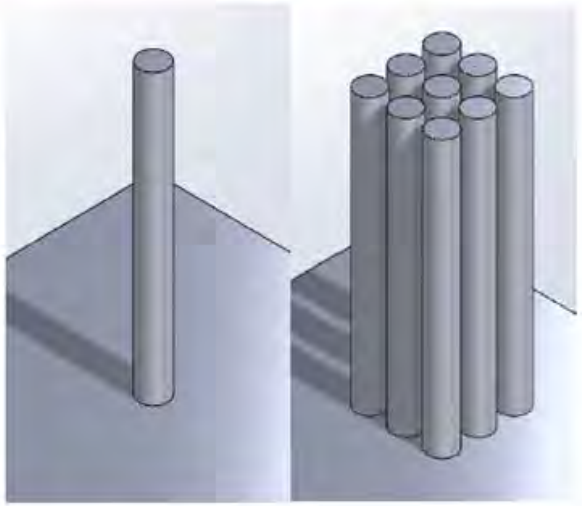
(location-specific microstructure / properties)

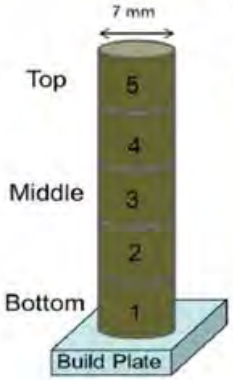


Reference: A. Rollett, DOT/FAA/TC-16/15, "*Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts*".

Effect of Size and Geometry

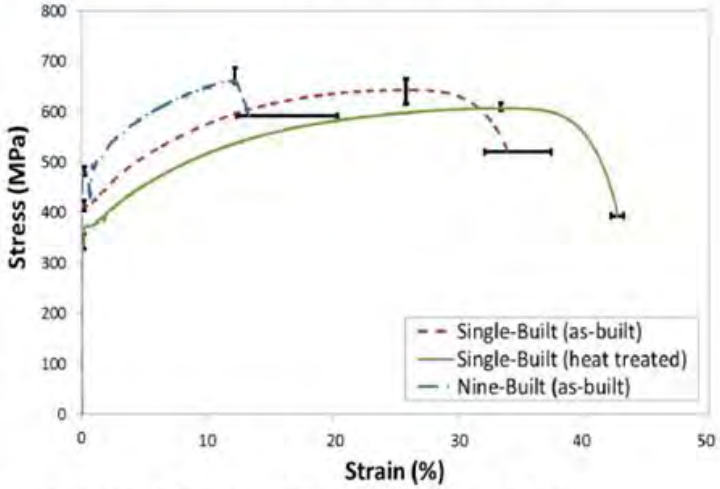
Reference: S. Daniewicz, DOT/FAA/TC-16/15, *"Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts"*.





Yield Stress (MPa)		
Single-Built (as-built)	Single-Built (heat treated)	Nine-Built (as-built)
408	307	480
384	306	477
350	301	475
390	321	485
410	322	487

LENS 316L SS



- Process and design parameters should be adjusted depending on part's dimensions/geometry
- Mechanical properties vary within the parts

Yadollahi, A., Shamsaei, N., Thompson, S.M., Seely, D., 2015, "Effects of Time Interval and Heat Treatment on the Mechanical and Microstructural Properties of Direct Laser Deposited 316L Stainless Steel," *Materials Science and Engineering A*, **644**, pp. 171-183.

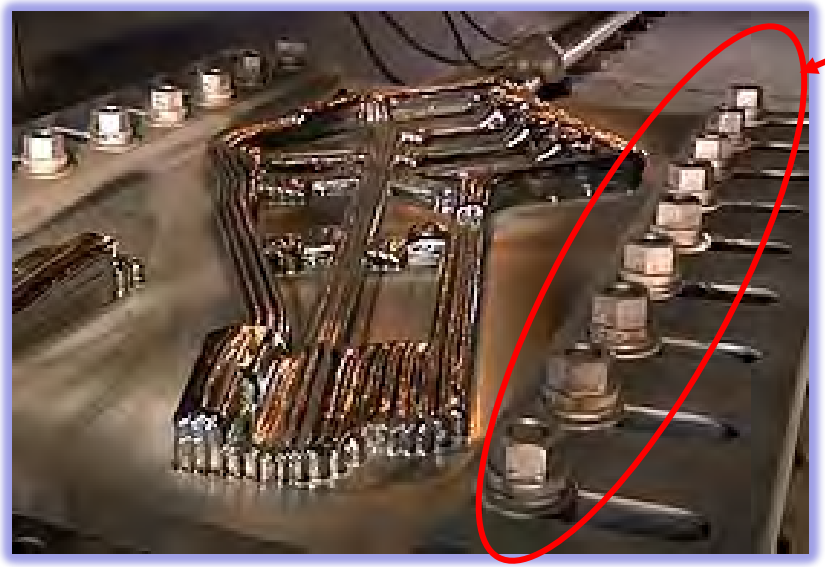
MISSISSIPPI STATE UNIVERSITY

6

CAVS

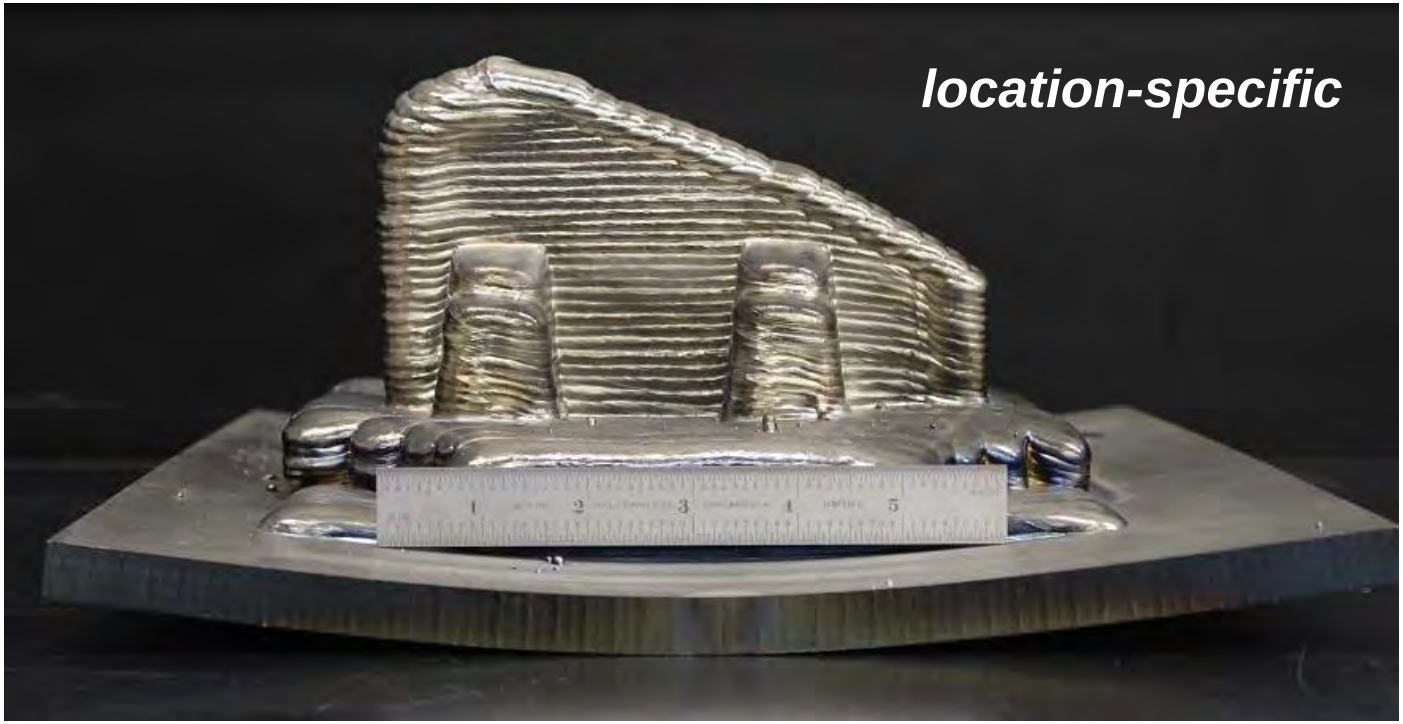
Residual Stresses in AM Parts

- **Effect on crack initiation and crack propagation**
- **May be location-specific**
- **May be significant in AM parts**



Why are these bolts so big..?

Residual Stresses in AM Parts

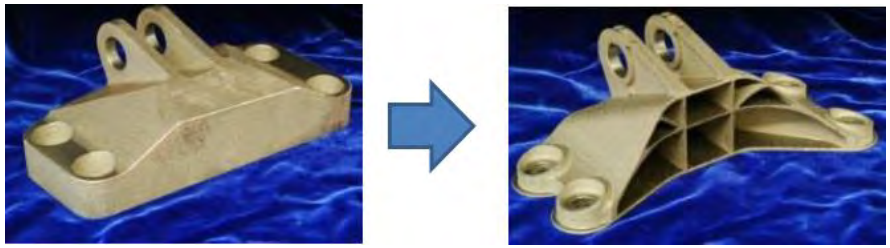


Crack Initiation (LCF)

Crack Propagation (DT)

Topological Optimization Using AM

"*Complexity is Free…*"



- ***… But is it really?***
  - **High number of Kt features**
  - **Inspectability challenges**
  - **Location-specific properties**
  - **Surface quality of hard-to-access areas**
    - **may need to live with as-produced surface**

Need a Realistic Assessment of Technical Challenges / Risks Associated with a Business Case

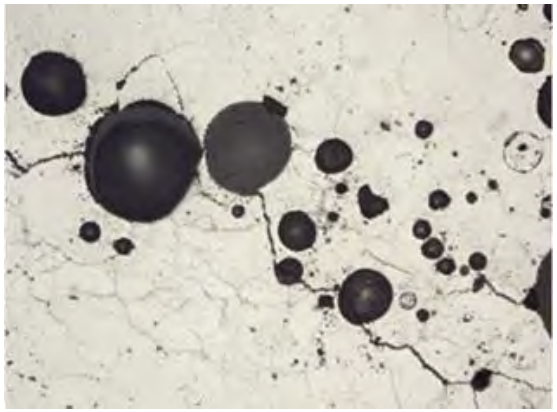
- Introduction
- Industry Trends
- FAA Updates and AM Standardization
- Parts Criticality
- Regulatory Considerations
- Risk Factors for AM
- **Lessons Learned**
- "Special Topic" – Zoning Considerations
- Appendix: *Misc. References*

Lessons Learned - *Examples*

- **Structural Castings** → *See next 3 slides…*
  - Effect of material anomalies not well quantified
  - Empirical life management system (design knock-downs, NDI acceptance criteria etc.)
- **Powder Metallurgy (PM)**
  - Gave rise to PM-specific fatigue and DT methodologies, explicitly accounting for material anomalies
- **Composites**
  - Location-specific and anisotropic properties → unique process control and regulatory considerations
  - Defects detectability challenges

Lessons Learned – Structural Castings

- ***Prone to manufacturing variability, material anomalies and resulting variation in material properties*, including fatigue**
- **Range of material anomalies intrinsic to castings, including gas and shrinkage porosity, inclusions, micro-cracking etc.**



Examples of Material Anomalies in Cast Alloys

Effect on debit in material properties is well documented …*but not necessarily well quantified*

Lessons Learned – Structural Castings (cont.)

- **Historically, and in part due to the *lack of modeling capabilities*, an *empirical framework* was developed to mitigate the risk of the above factors**
- **It consists of the following key elements:**
  - **Class of Casting (1 through 4) - determined by application criticality**
  - **Casting Grade (A through D) - defines acceptable levels of NDI indications, either for the entire part or for a specified area (zone)**
  - **Casting Factor - a safety factor originating from uncertainties in material properties**

5.2.1 "… The application of factors of safety to castings is based on the fact that the casting process can be inconsistent …"

5.2.2 "… Since the mechanical properties of a casting depend on the casting design, the design values established … for one casting might not be applicable to another casting made to the same specification."

Reference: FAA Advisory Circular 25.621-1 "Casting Factors", Oct. 2014.

Lessons Learned – Structural Castings (cont.)

Challenges

- **Empirical – effects of material anomalies are not well understood or quantified → *no explicit feedback loop to process controls and QA***
- **No means to assess / quantify risk**
- **May be too conservative in some cases**

"…by taking every deleterious variable imaginable, it was found that average strengths were still well above minimum requirements…"

Reference: "Modern Castings", D. McLellan, ISSN: 0026-7562, May 1994.

Question →

Can we do better for AM..?

Quantitative relationship between location-specific part attributes (including anomalies distribution) and part's probability of failure ..?

- Introduction
- Industry Trends
- FAA Updates and AM Standardization
- Parts Criticality
- Regulatory Considerations
- Risk Factors for AM
- Lessons Learned
- **“Special Topic” – Zoning Considerations**
- Appendix: *Misc. References*

“Business” Considerations

- **Qualification and certification considerations for AM parts of high criticality**
  - ***Flexible approach → variable levels of conservatism***
- **OEMs moving to full-scale production**
  - **Usual business pressures will apply**
    - **How to build a part faster?**
    - **How to reduce cost?**

see next slide

- ***Need effective analysis tool that can support trade-off studies and quantify risk***

AM "Knobs" Affecting Cost and Cycle Time

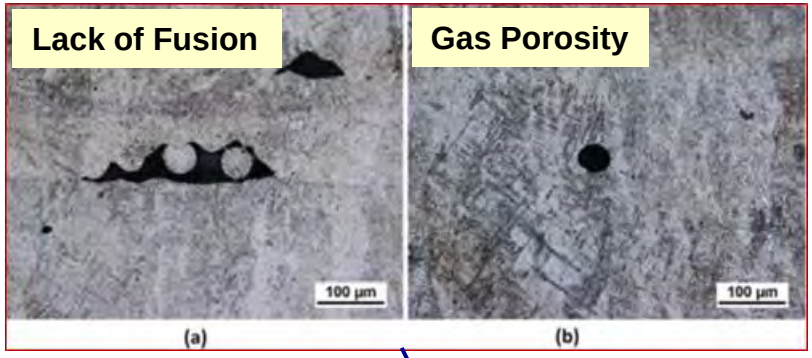
- **Raw material quality (*examples - powder*)**
  - **Powder size distribution / sphericity**
  - **Acceptable level of inclusions**
- **Process settings (*examples*)**
  - **Build layer thickness**
  - **Scan speed and energy density**
  - **Extent of support structure**
- **Post processing steps (*examples*)**
  - **Machining / surface enhancements**
  - **HIP / Heat treatment**
- **NDI inspections**
  - **CT / UT / EC / …**

Each of these factors has a potential of influencing fatigue properties, residual stresses, material anomalies formation etc.

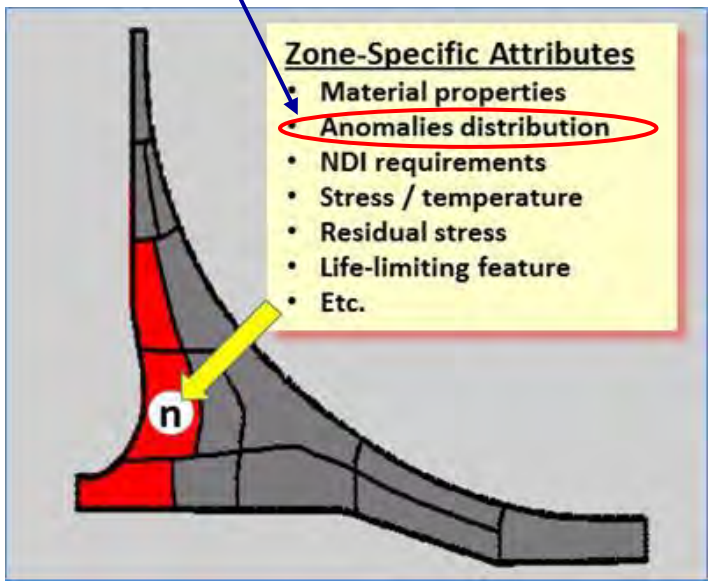
Part Zoning Considerations

- **Many Interpretations exist…**
- **Zones can be defined based on:**
  - **Criticality of failure mode, inspectability, population of defect species, design "margin", microstructure, residual stress, etc.**
- **Number of zones: 1 to N …**
- **Level of analysis (for each zone) may vary from simplified / conservative (e.g. safety factors) approach to more accurate / less conservative (e.g. probabilistic DT) assessment for higher criticality parts / zones**
- **Two main attributes of the approach:**
  - **Flexibility (only use necessary level of complexity)**
  - **Ability of perform *quantitative assessment* (when/as needed)**
    - **see next page**

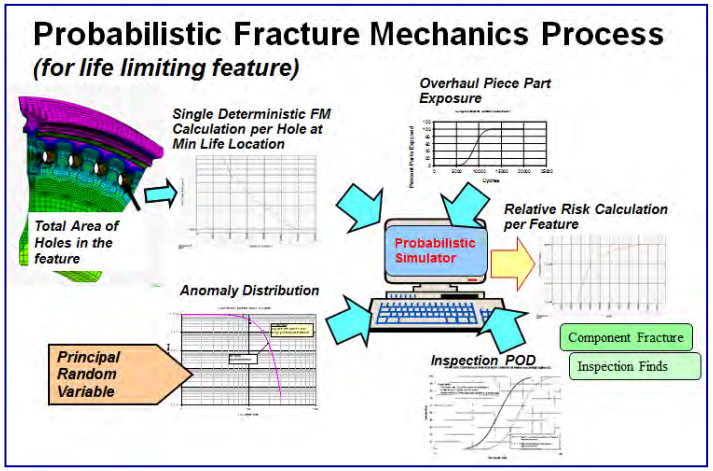
Part Zoning Considerations (cont.)



- **AM parts are uniquely suited for *zone-based evaluation***
- **Concept is similar to zoning considerations for castings…**
- **… however, modeling represents a viable *alternative to empirical* "casting factors"**

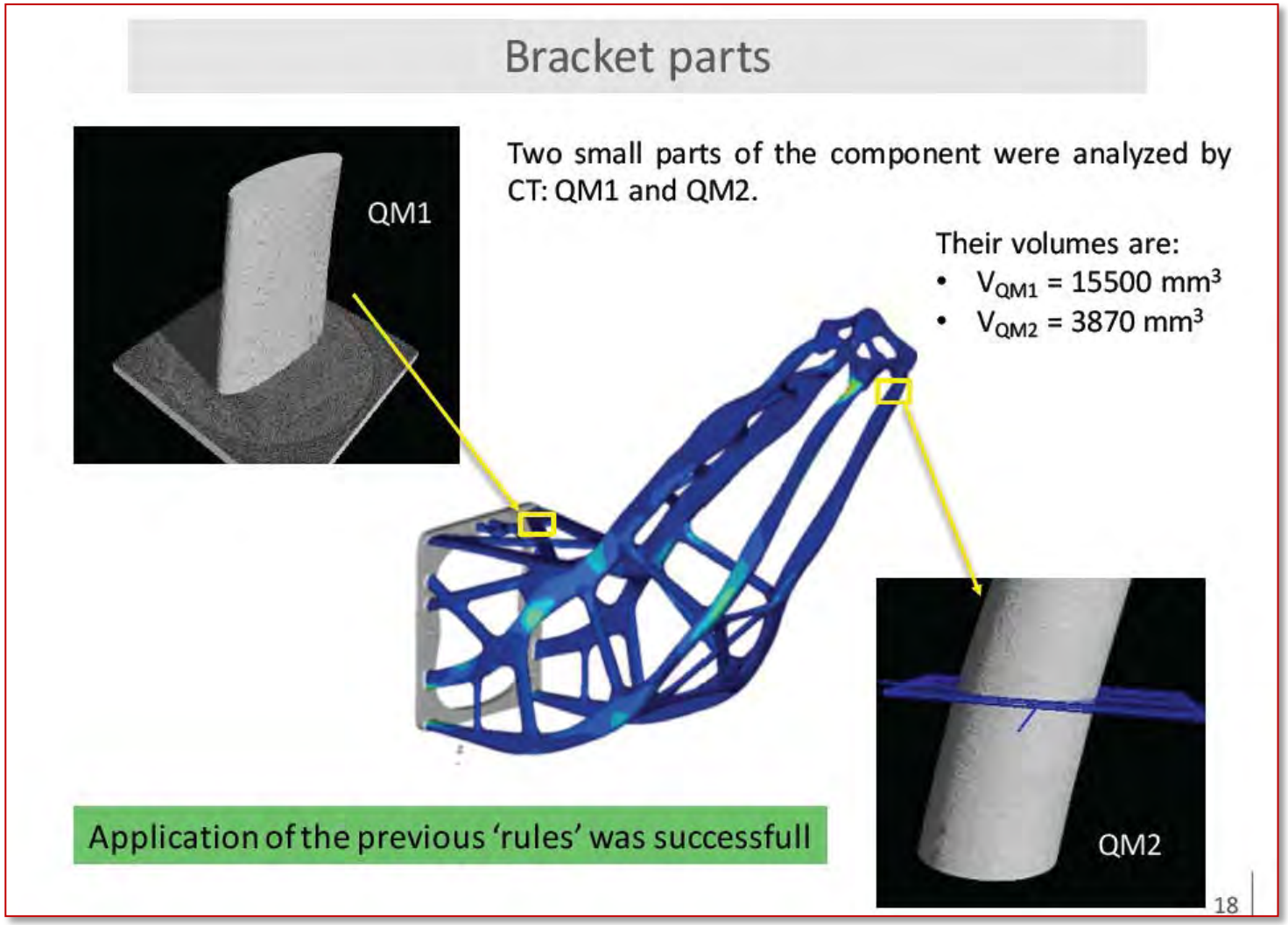


One Assessment Option – PFM *)



***) PFM - Probabilistic Fracture Mechanics**

Zoning Also Works for Complex Structures



S. Beretta et al, EXTREME VALUE ANALYSIS OF DEFECTS ON AM PARTS, ASTM-NIST Workshop, 2016.

Question →

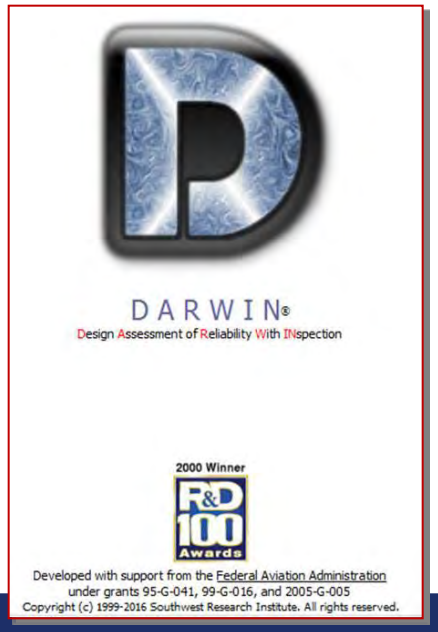
- **How much time / effort / investment does it take to develop an analysis tools that *can support zoning-type assessment* <u>and</u> is:**
  - **Validated by industry**
  - **Accepted by multiple companies and regulators**
  - **Commercial grade**
  - **Can account for:**
    - **Various populations of anomalies**
    - **Inspectability (POD)**
    - **Local DT attributes**
    - **Residual stresses**
    - **Location-specific properties**
    - **Risk targets**

Hint: see next slide… →

Potential Enabler

- **Analysis framework (and software code) that can assess a component with a known population of anomalies / defects and location-specific properties.**
- **Represents *~20 years of R&D work and over $30M of investment* by the FAA, Industry, Air Force, NAVAIR, etc.**
- **Has all the attributes listed on the previous slide**

s/w features can be customized for AM with relatively moderate incremental R&D investment



Discussion

Dr. Michael Gorelik, PMP

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

michael.gorelik@faa.gov

(480) 419-0330, x.258

APPENDIX

AM Q&C References

2018 FAA – EASA AM Q&C Workshop

- **Focus on Q&C of *metal* AM parts**
- **First joint FAA - EASA AM workshop**
- **130+ attendees from industry, government, academia and SDOs from 9 countries**
- **Keynotes:**
  - Director of Advance Repairs (Delta TechOps)
  - VP of Product and Process Technology (Arconic)
- **3 breakout working sessions:**
  - o Design Data for Q&C
  - o Fatigue and Fracture Considerations
  - o NDI Inspections and In-situ Process Monitoring

➢ **Report and full proceedings will be made available to the public**

FAA POC: ***Dr. Michael Gorelik***

“Legacy” Proceedings of FAA - USAF AM Workshops (*2015 - 2017*)

DOT/FAA/TC-18/3

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

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

- **2017 AM Workshop**
  - **External report:** http://www.tc.faa.gov/its/worldpac/techrpt/tc18-3.pdf
- **2016 AM Workshop**
  - **External report:** http://www.tc.faa.gov/its/worldpac/techrpt/tc17-35.pdf
- **2015 AM Workshop**
  - **External report:** http://www.tc.faa.gov/its/worldpac/techrpt/tc16-15.pdf

Other AM Q&C References

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

https://doi.org/10.1016/j.ijfatigue.2016.07.005

Several concepts reflected in this presentation

Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification

Mohsen Seifi, Michael Gorelik, Jess Waller, Nik Hrabe, Nima Shamsaei, Steve Daniewicz & John J. Lewandowski

JOM
The Journal of The Minerals, Metals & Materials Society (TMS)

ISSN 1047-4838
Volume 69
Number 3

JOM (2017) 69:439-455
DOI 10.1007/s11837-017-2265-2

JOM

Additive Manufacturing

https://link.springer.com/article/10.1007/s11837-017-2265-2