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

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

- 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 ➔ ~ $1M

Equipment acquisition

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 *)**

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>% Failures (Aircraft Components)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>55%</td>
</tr>
<tr>
<td>Corrosion</td>
<td>16%</td>
</tr>
<tr>
<td>Overload</td>
<td>14%</td>
</tr>
<tr>
<td>Stress Corrosion Cracking</td>
<td>7%</td>
</tr>
<tr>
<td>Wear / abrasion / erosion</td>
<td>6%</td>
</tr>
<tr>
<td>High temperature corrosion</td>
<td>2%</td>
</tr>
</tbody>
</table>


- 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

Additive Manufacturing (AM) Challenges Conventional Production

Further industrialisation steps

Future AM parts volume (mach. hrs x 10^3)

Expected introduction dates for serial production

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Strut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seal carrier ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air cooling bosses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borecope bosses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Increasing quality requirements
Further investigations and development needed for critical applications

today + 3 yrs

today

2015 2024
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”.

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’
“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

**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

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...

FAA

America Makes

AMSC

AMC

KART

Next Manufacturing

AIA

SAE

MMPDS

ASTM

AWS
Example: Cross-SDO Collaboration

AMSC – AM Standards Collaborative

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
Committee F42 on Additive Manufacturing Technologies

Multi-Disciplinary Interfaces Are Essential
Examples of *External* Benchmarking

EM20

MSFC TECHNICAL STANDARD

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

America Makes Technology Roadmap 2.0

Final Report

Department of Defense Additive Manufacturing Roadmap

Report Released 30 November 2016
Dr. Jennifer Fielding, Technical Advisor, Structures, Propulsion and Manufacturing Enterprise Branch, Air Force Research Laboratory
AM Certification – Main Strategic Focus Areas

- Engineering Certification
- Production / QA
- Maintenance / MROs
- Continued Operational Safety

Enablers:
- Workforce Education (FAA + Designees + Industry)
- R&D
Initial AM Documents Are Available at:

http://rgl.faa.gov

Search Keyword: Additive

1-100 of 194 results for 'additive'

- AIR100-16-110-GM26: Subject: AS1 Job Aid for Additive Manufactured Parts
- AIR100-16-130-GM39: Subject: Additive Manufacturing Awareness
- AIR100-16-130-GM18: Subject: Engineering Considerations for Powder Bed Fusion Additively Manufactured Parts
- AIR100-16-160-PM09: Subject: DER/ODA Compliance Finding and Approval Authority of Additive Manufactured Parts
• 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

“Critical” Parts (e.g. CFR Part 25 → PSEs, CFR Part 33 → LLPs)

“Critical” Level

“critical”

“major” effect

“minor” effect

“High Value” Parts

Business Value

Time

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)
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

However

<table>
<thead>
<tr>
<th>Development Phase</th>
<th>Development Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modification of an existing material for a noncritical component</td>
<td>2 to 3 years</td>
</tr>
<tr>
<td>Modification of an existing material for a critical structural component</td>
<td>Up to 4 years</td>
</tr>
<tr>
<td>New material within a system for which there is experience</td>
<td>Up to 10 years. Includes time to define the material’s composition and processing parameters.</td>
</tr>
<tr>
<td>New material class</td>
<td>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).</td>
</tr>
</tbody>
</table>

Example

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

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 **high energy debris**

**Reference:** ATSB Transport Safety Report, Final Investigation - In-flight uncontained engine failure Airbus A380-842, VH-OQA
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
§ 25.571 Damage—tolerance and fatigue evaluation of structure

(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
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)

Fatigue Crack from Inherent Ceramic Defect

- 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

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

HIP Effectiveness

Many More Identified by Experts…

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

over 100 process parameters identified
**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)

Anisotropy in SLM Parts

Stress-life approach


Microstructural Challenges: Process control

(location-specific microstructure / properties)

Effect of Size and Geometry

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

<table>
<thead>
<tr>
<th>Yield Stress (MPa)</th>
<th>Single-Built (as-built)</th>
<th>Single-Built (heat treated)</th>
<th>Nine-Built (as-built)</th>
</tr>
</thead>
<tbody>
<tr>
<td>408</td>
<td>307</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>384</td>
<td>306</td>
<td>477</td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>301</td>
<td>475</td>
<td></td>
</tr>
<tr>
<td>390</td>
<td>321</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>410</td>
<td>322</td>
<td>487</td>
<td></td>
</tr>
</tbody>
</table>

LENS 316L SS

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)

location-specific
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**  
  – 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**
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.”

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...”

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?

➢ 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
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
Two small parts of the component were analyzed by CT: QM1 and QM2.

Their volumes are:
- \( V_{QM1} = 15500 \text{ mm}^3 \)
- \( V_{QM2} = 3870 \text{ mm}^3 \)

Application of the previous ‘rules’ was successful.

Question

• How much time / effort / investment does it take to develop an analysis tools that can support zoning-type assessment and 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:
  - Design Data for Q&C
  - Fatigue and Fracture Considerations
  - NDI Inspections and In-situ Process Monitoring

Report and full proceedings will be made available to the public

FAA POC: Dr. Michael Gorelik

- **2017 AM Workshop**

- **2016 AM Workshop**

- **2015 AM Workshop**
Other AM Q&C References

Several concepts reflected in this presentation

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

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