Structural Integrity Considerations for Additive Manufacturing

Presented at:

EASA AM Workshop

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Cologne, Germany

Presented by:

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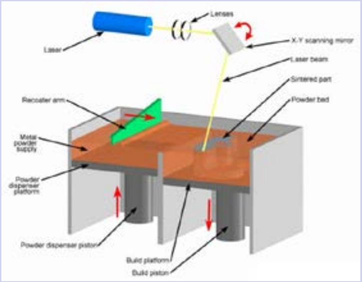
for Fatigue and Damage Tolerance

Disclaimer

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

Additive Manufacturing (AM)



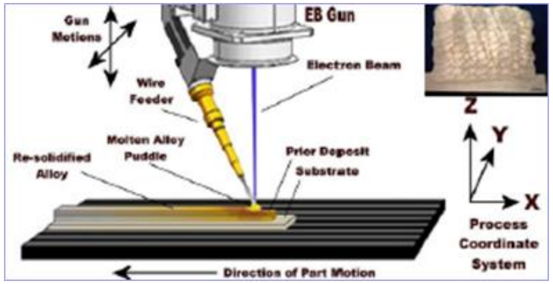
Additive Manufacturing (AM) --

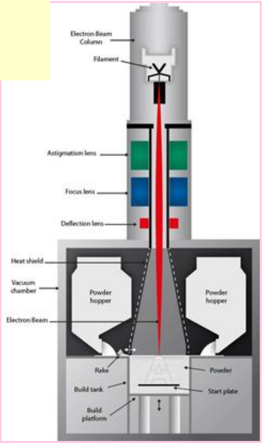
A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to *subtractive manufacturing* methodologies

(***Ref: ASTM F2792 – 12a***)

By Source of Material:
Powder vs. Wire

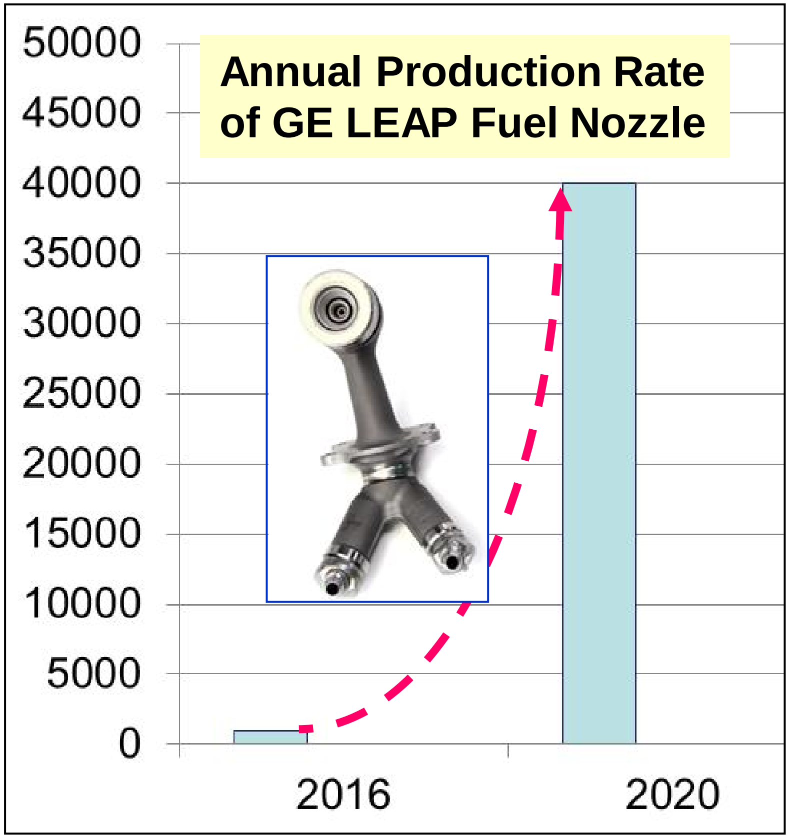
By Source of Energy:
Laser vs. E-Beam





State of Industry

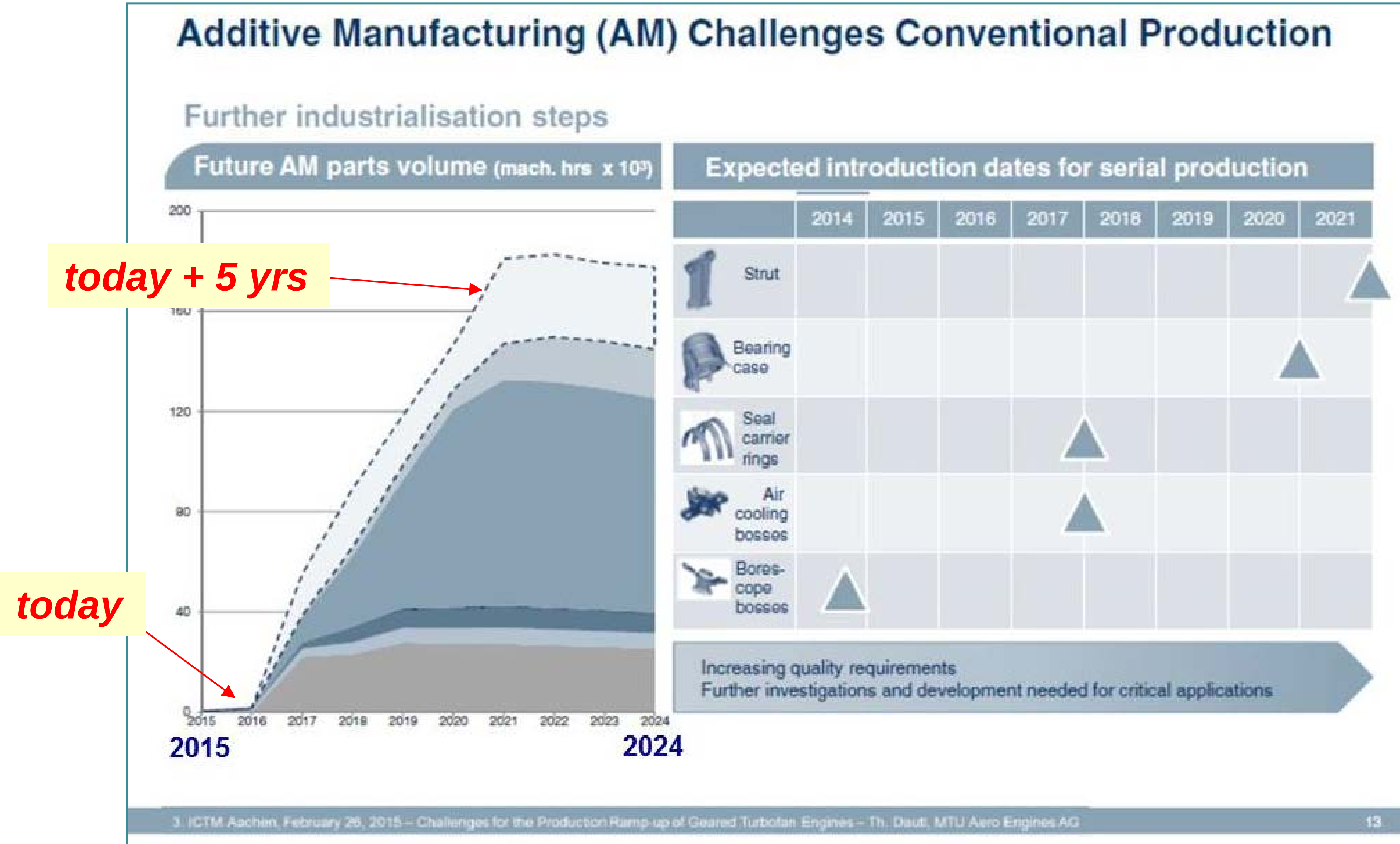
"GE Aviation Selects Auburn, AL for High Volume Additive Manufacturing Facility"



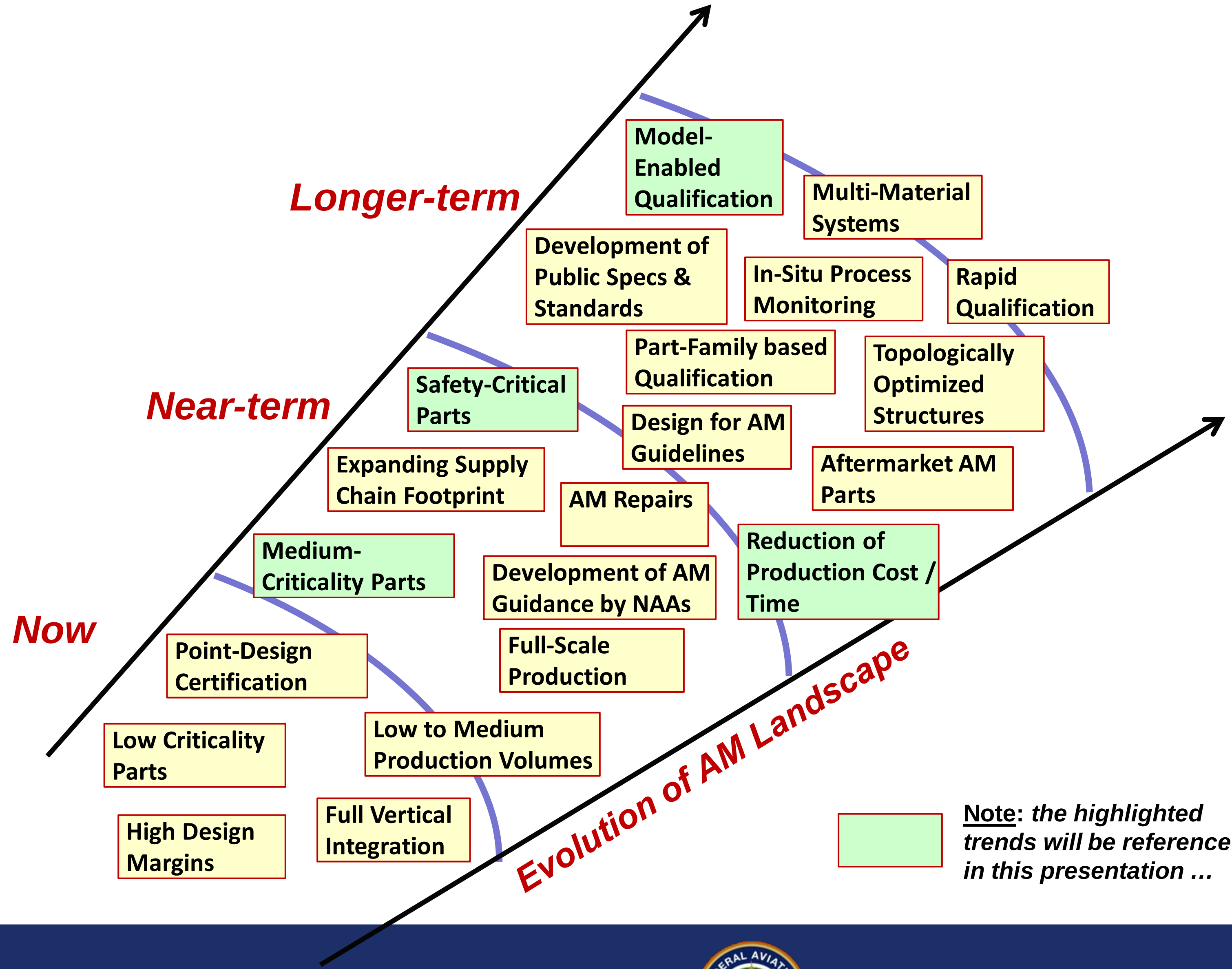
"Production will ramp up quickly over the next five years, going from 1,000 fuel nozzles manufactured annually to more than 40,000 by 2020".

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

State of Industry (cont.)

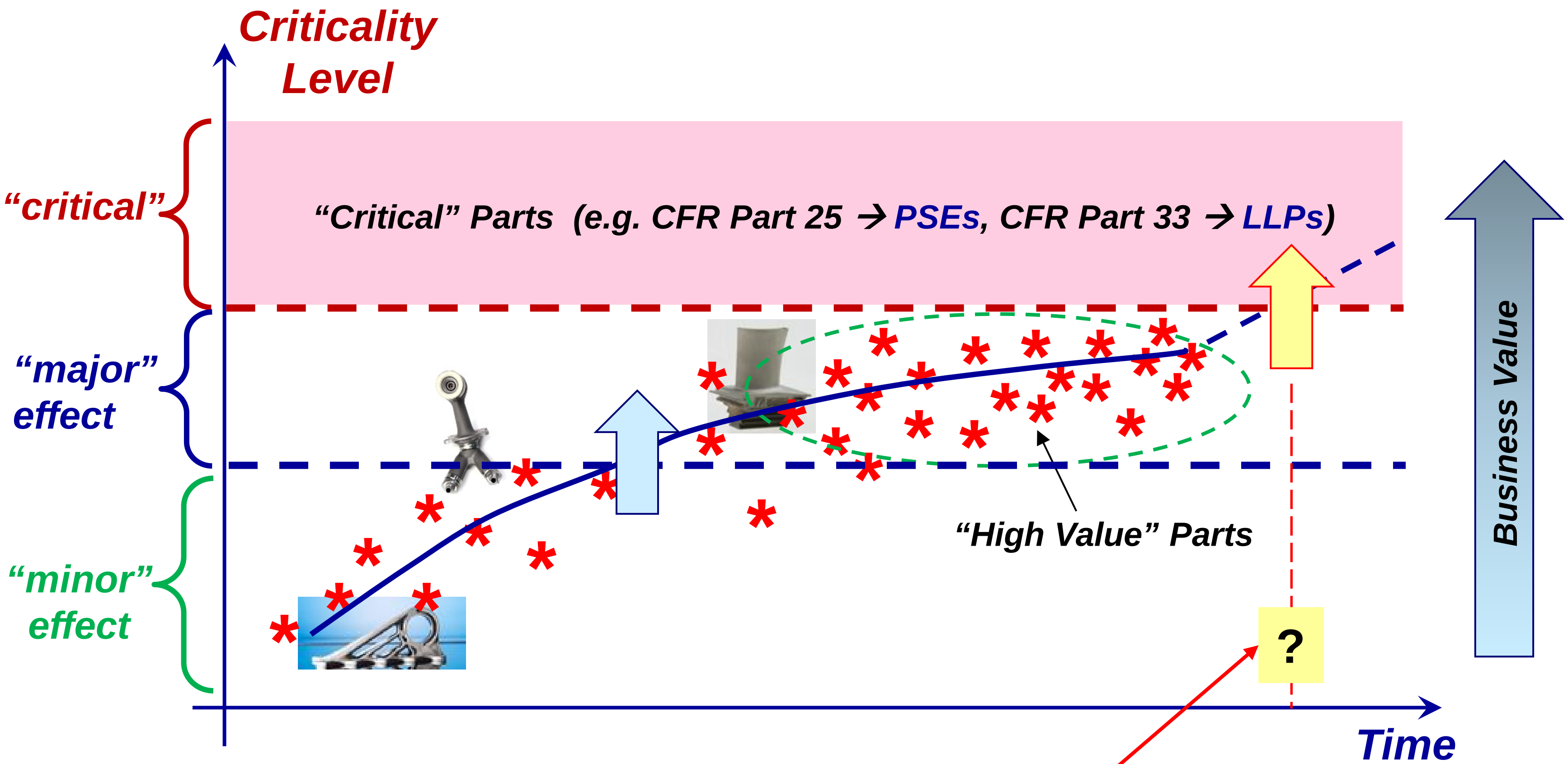


Changing AM Landscape



<u>Note</u>: *the highlighted trends will be referenced in this presentation …*

Evolution of Criticality of AM Parts



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

From Non-Critical to Critical

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

➢ **However**

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).

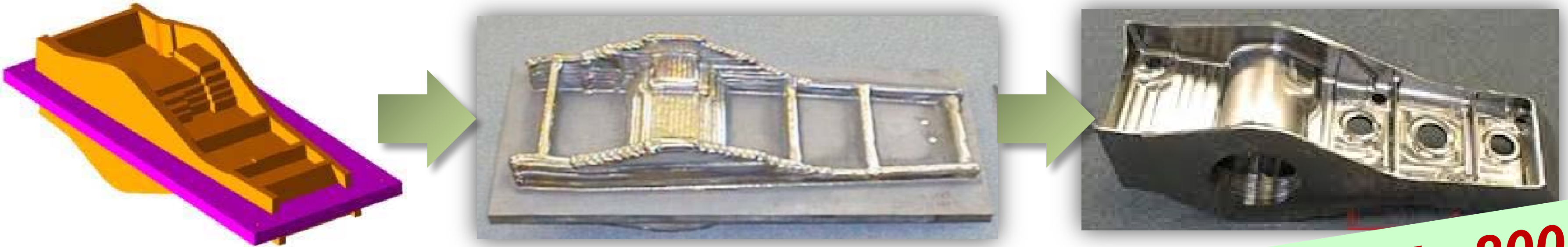
SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

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...)



Results: -Additive Substitution Certified for use in Structur
-Parts Manufactured and Qualifi
-Prior to Insertion or Provided Forgings
-Ti forging cost redu due to competition

First structural part introduced in 2003

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)

What Causes Failures?

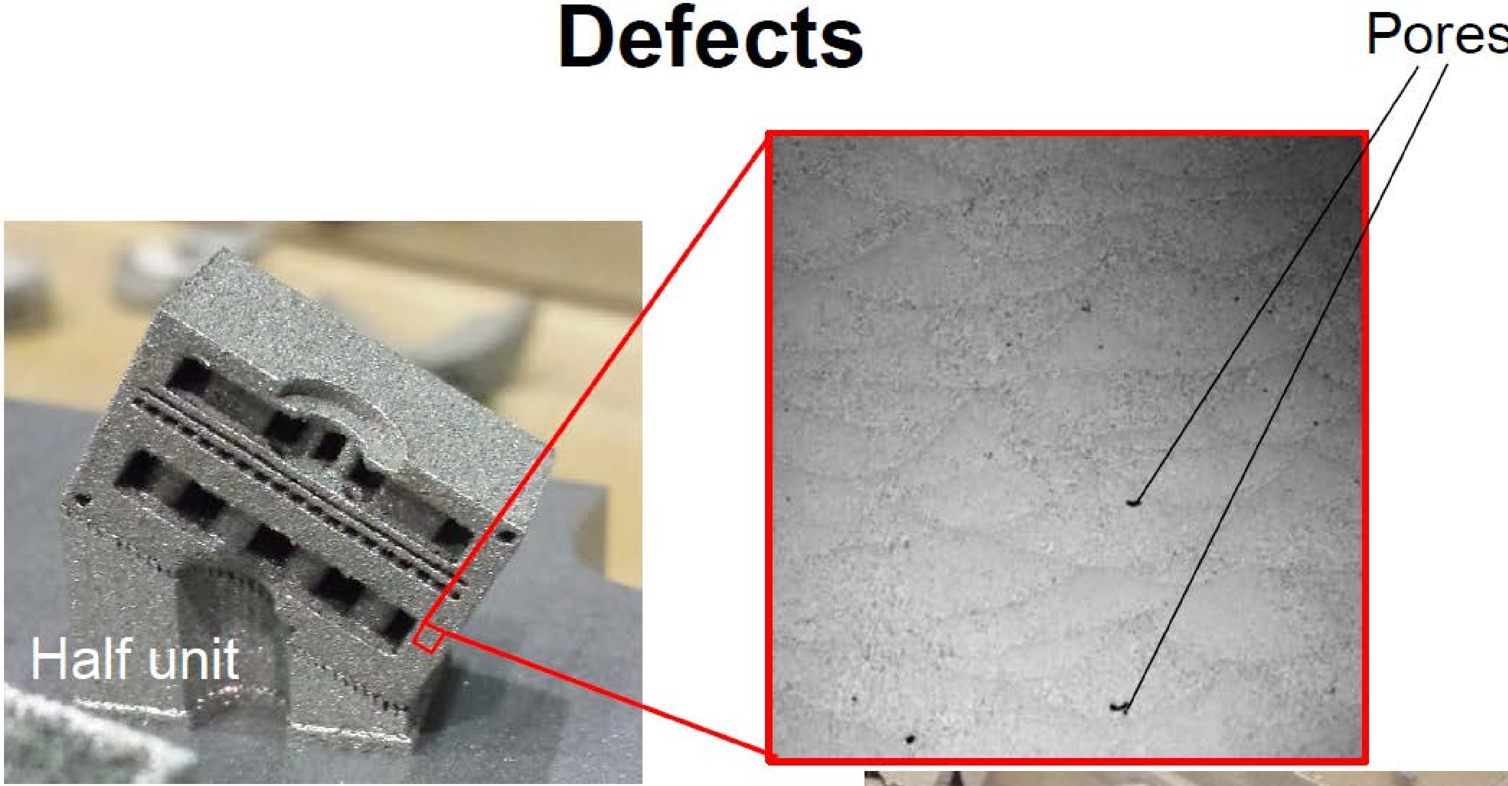
Frequency of Failure Mechanisms *)

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

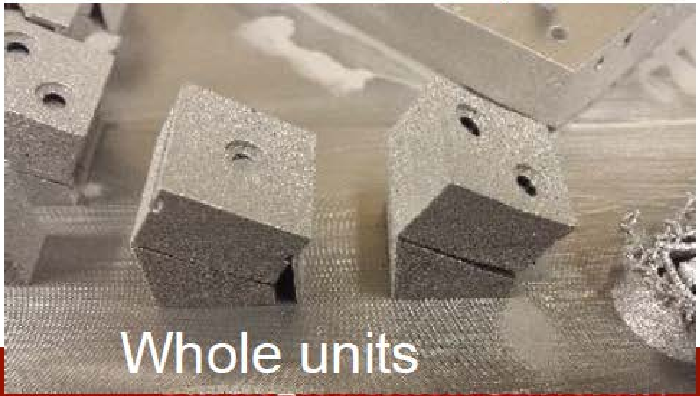
**) Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Fatigue is the Predominant Failure Mode in Service**
- **Expect this trend to continue for metallic materials**
- **Some of the most challenging requirements *for new material systems* are related to F&DT**

Microstructural Challenges: Defects



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



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

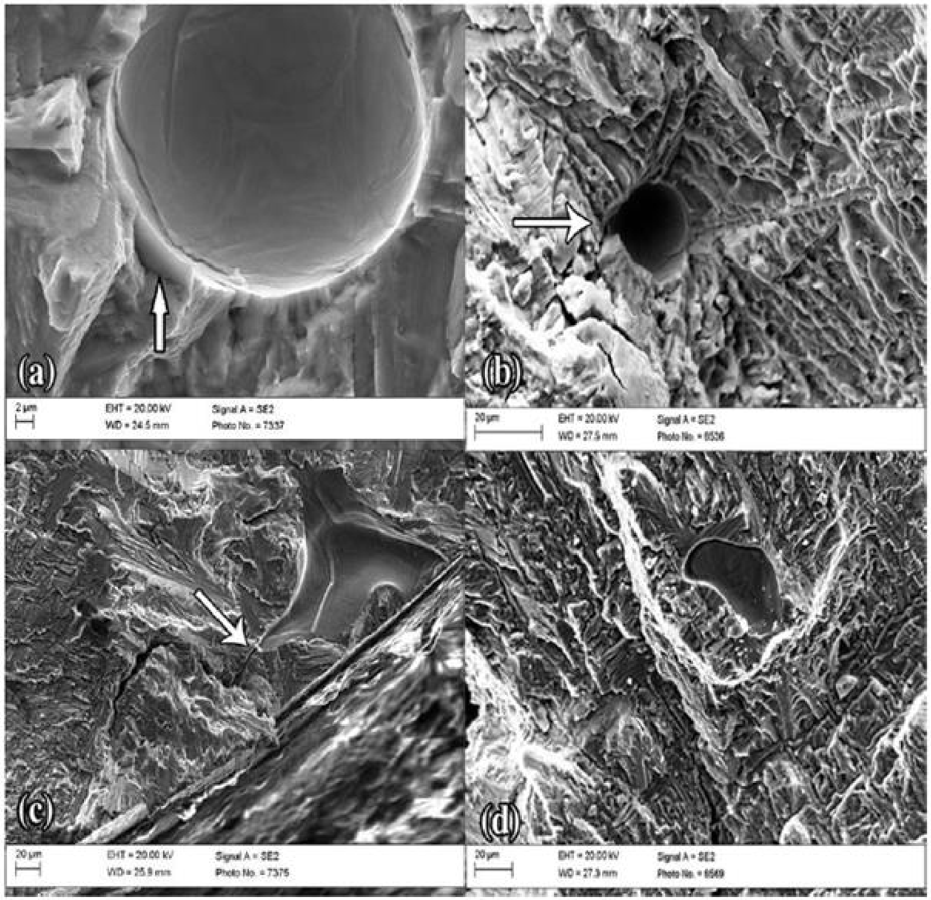
Porosity in AM Ti-6Al-4V

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

Fatigue life decreases with presence of:

- Larger pores
- Near-surface pores
- Closely-packed pores (pore density)
- More irregularly-shaped pores

- Some porosity introduced by partially melted (un-melted) particles
- Very little correlation was found between the number of pores and fatigue life of specimens

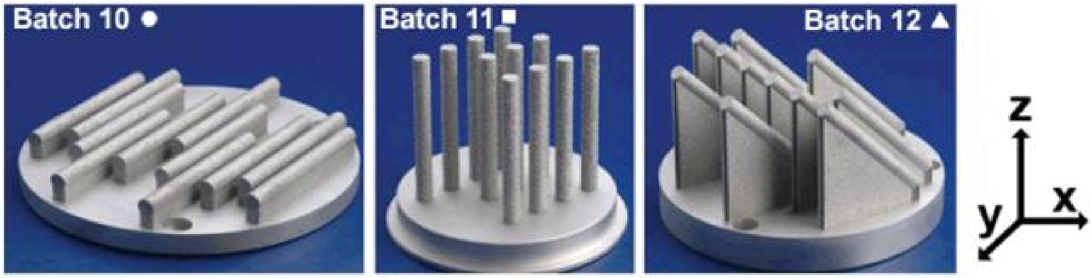


C:\Users\Brian\Downloads\IJF Paper\Figure11_8_2_2015.jpg

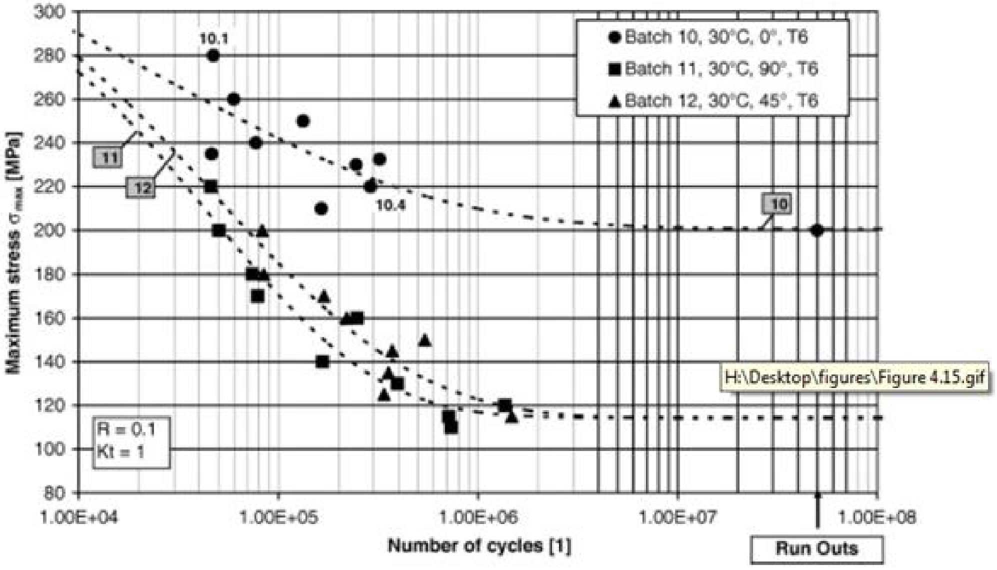
Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* Kissimmee, FL.

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



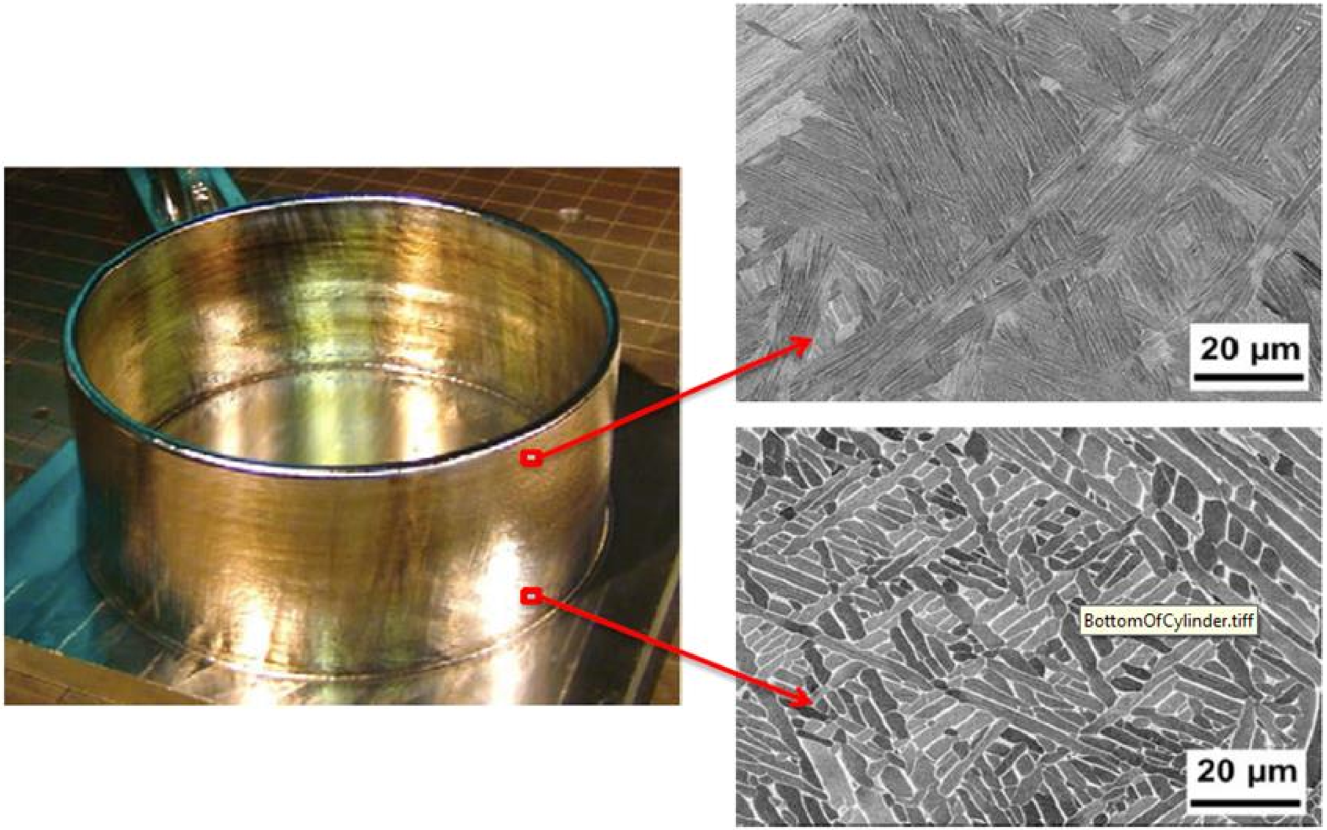
Brandl, E., Heckenberger, U., Holzinger, V., & Buchbinder, D. (2012). Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design, 34, 159-169.

MISSISSIPPI STATE UNIVERSITY

Federal Aviation Administration

M. Gorelik

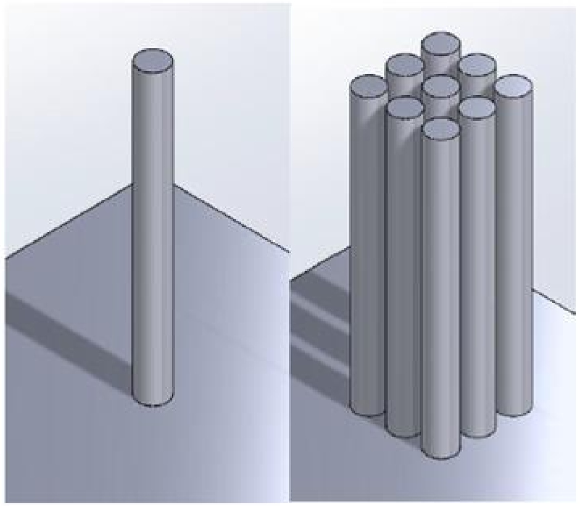
Microstructural Challenges: Process control

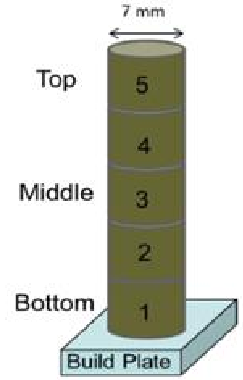


<u>Reference</u>: A. Rollett, DOT/FAA/TC-16/15, "*Summary Report: Joint FAA – Air Force Workshop on Qualification/Certification of AM Parts*".

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

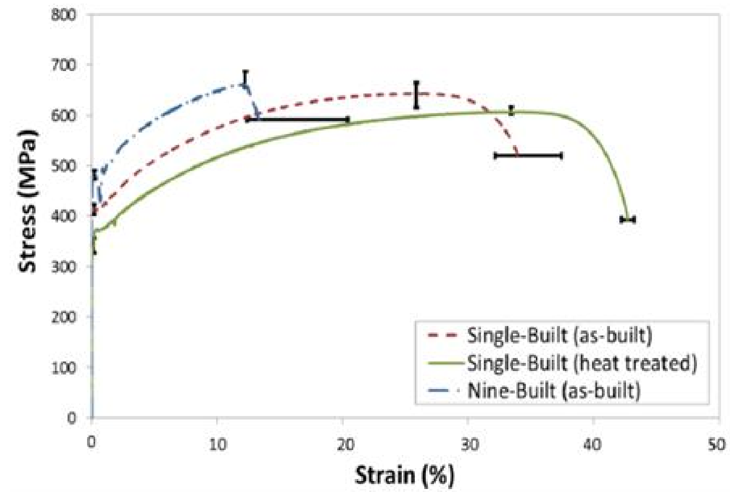
Effect of Size and Geometry





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

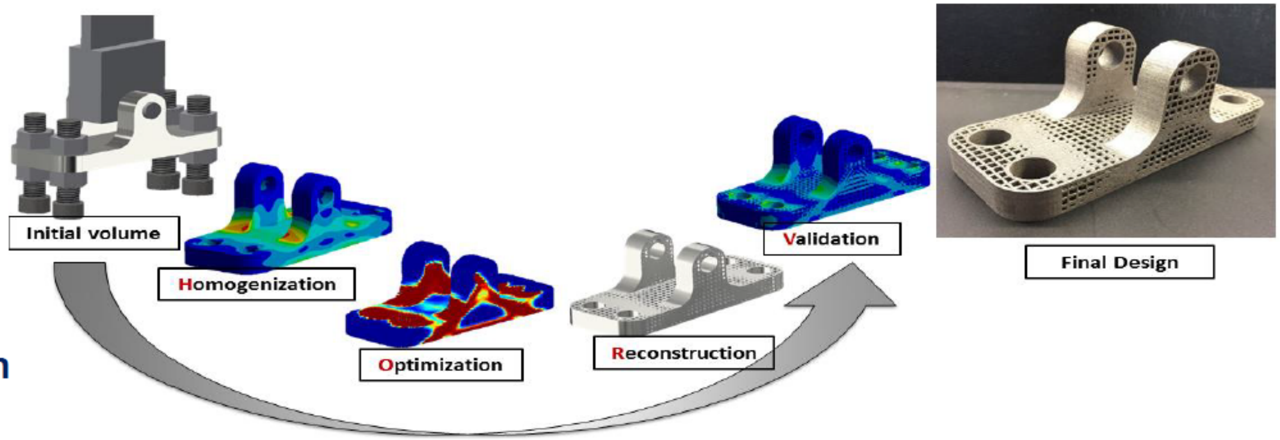
Yadollahi, A., Shamsaei, N., Thompson, S.M., Seely, D., 2015, "Effects of Time Interval and Heat Treatment on the Mechanical and Microstructural Properties of Direct Laser Deposited 316L Stainless Steel," *Materials Science and Engineering A*, **644**, pp. 171-183.

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

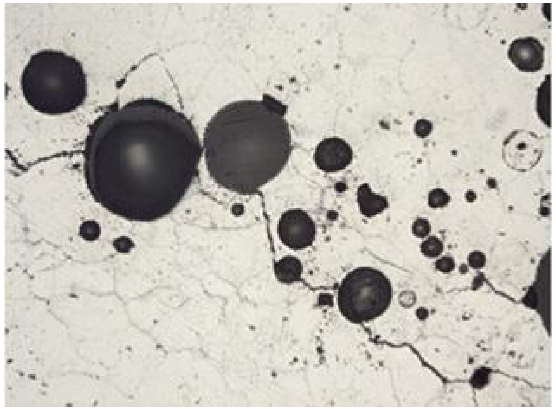
AmericaMakes.us

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*

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 a number of 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.

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

(<u>Reference</u>: 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**

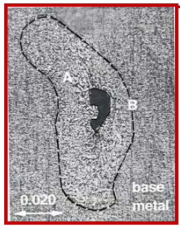
Inherent Anomalies

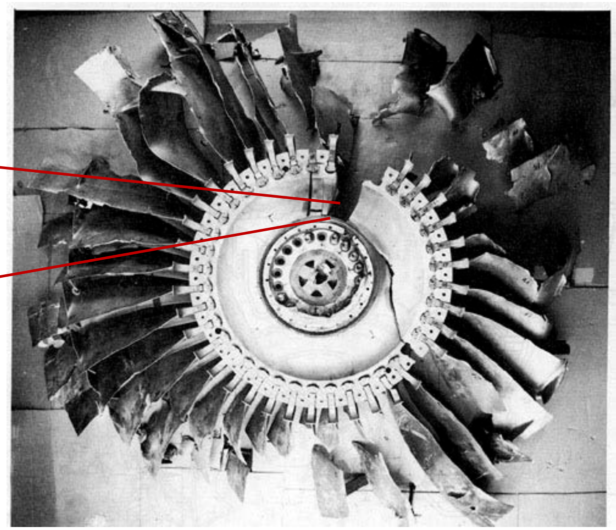
Examples:

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

Surface vs. Volume

Titanium Hard Alpha
Damage Tolerance Methodology





U.S. Department of Transportation
Federal Aviation Administration

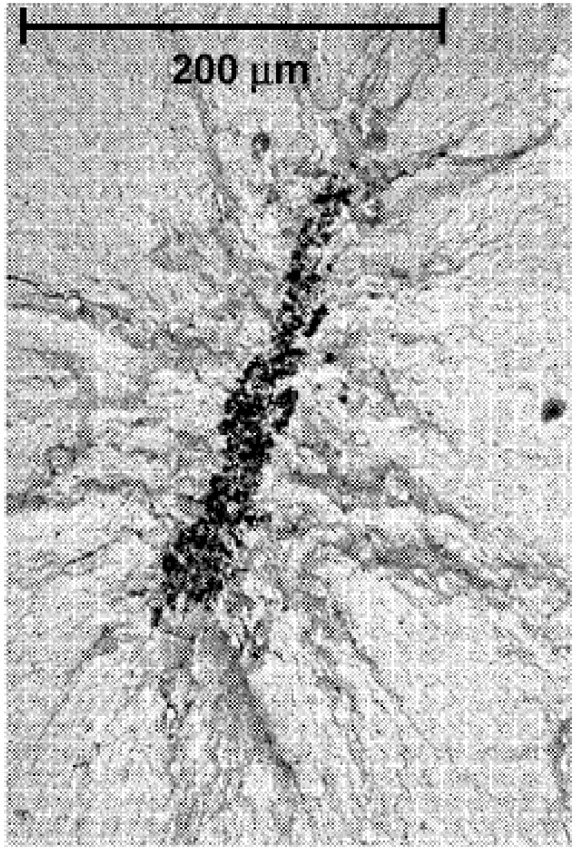
Advisory Circular

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)

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

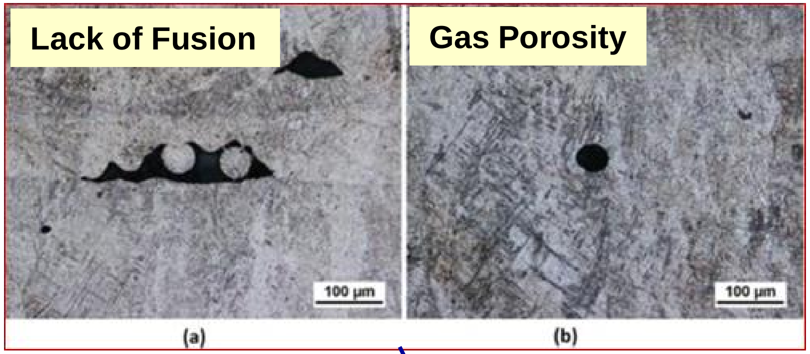
AFRL-RX-WP-TP-2009-4152

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

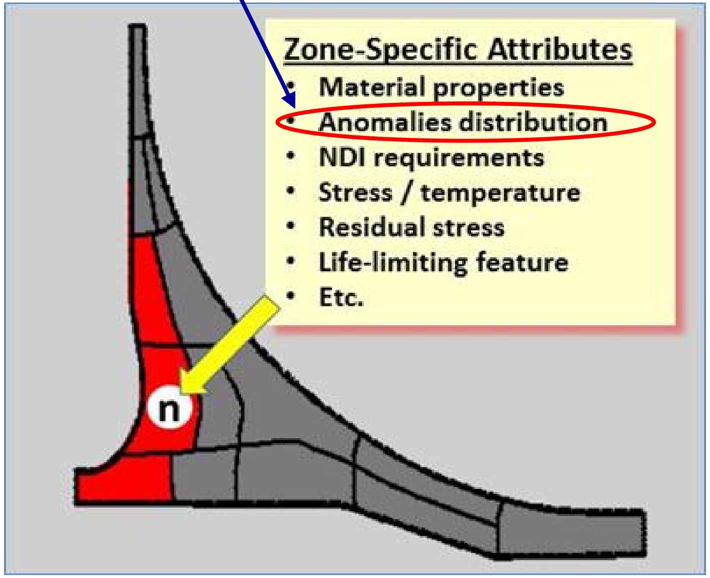
S.K. Jha, M.J. Caton, and J.M. Larsen

Metals Branch
Metals, Ceramics, and NDE Division

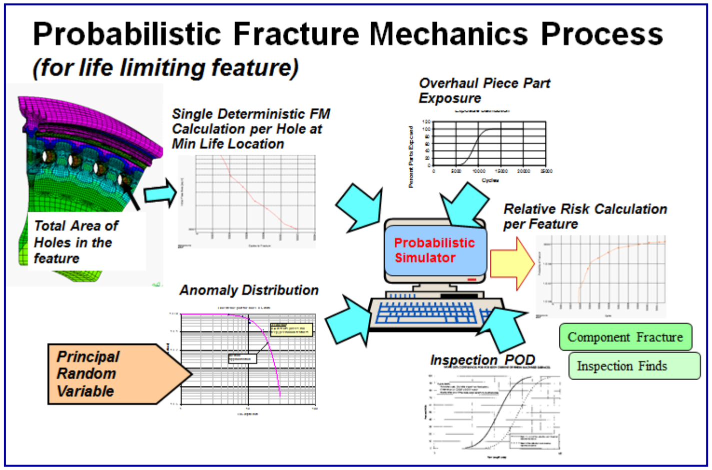
Part Zoning Considerations



- 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**

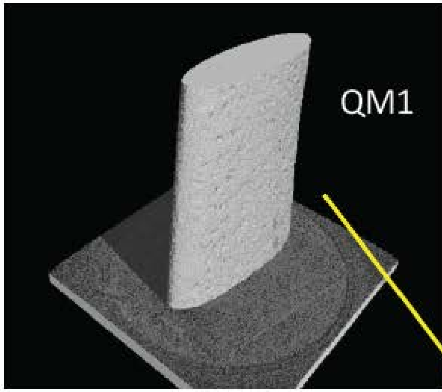
(see next page)

Part Zoning Considerations (cont.)

- **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)**

Zoning Also Works for Complex Structures

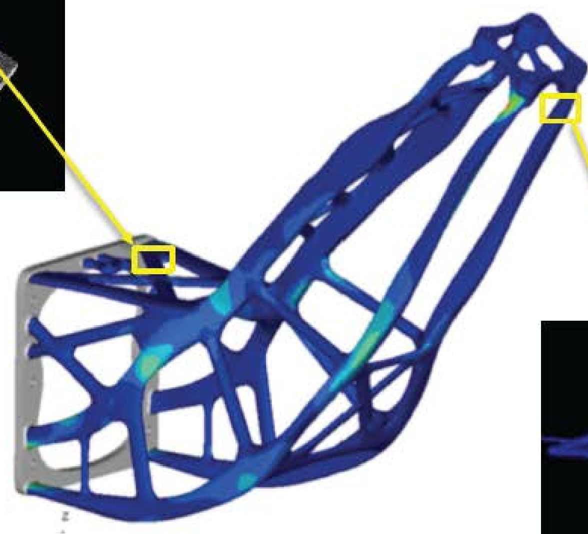
Bracket parts

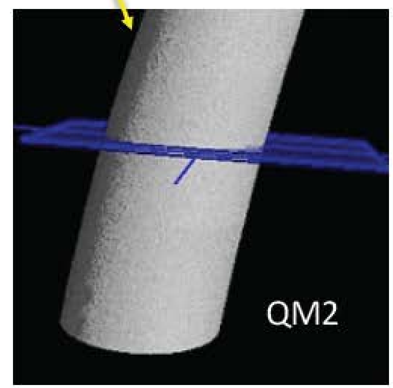


Two small parts of the component were analyzed by CT: QM1 and QM2.

Their volumes are:

- $V_{QM1} = 15500\ mm^3$
- $V_{QM2} = 3870\ mm^3$





Application of the previous ‘rules’ was successfull

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

“Business” Considerations

- **OEMs moving to full-scale production**
- **Usual business pressures will apply**
  - How to build a part faster?
  - How to reduce cost?
    - Feedstock
    - Post-processing
    - Level of QA
    - Level of material characterization
    - Etc.

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

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**

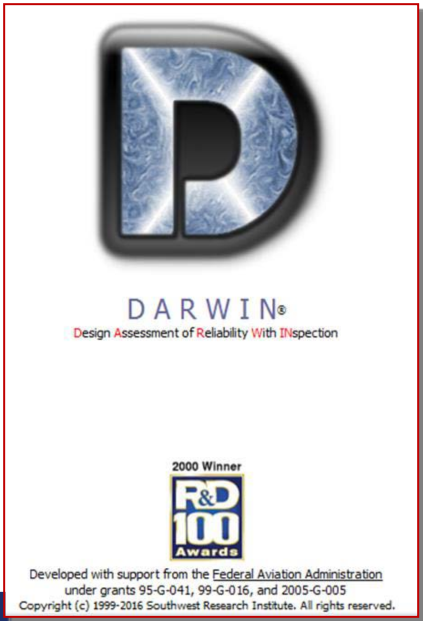
Hint: see next slide… →

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 investment

- ***specific plan still needs to be developed***



Questions…

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