On the Development of Fatigue and Damage Tolerance Framework for *Metal* AM Parts

Federal Aviation Administration

Presented at:

NRC Workshop on Advanced Manufacturing Technologies – *Session 4*

December 9, 2020

Presented by:

Dr. Michael Gorelik

FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

BLUF *(bottom line upfront)*

- **All the existing rules apply to AM**
- **Need to consider unique / AM-specific attributes, especially for high-criticality components**
- **Leverage industry and regulatory experience with other relevant material systems**
    - ***More on this topic in Dec. 10th presentation***
- **Leverage public standards**

Example: Moving Towards Safety-critical AM Parts

GO BEYOND

PRODUCTS & SERVICES NEWSROOM COMPANY CARE

Home / Newsroom / News

Pratt & Whitney Teams with Industry Leaders to Test Additively-Manufactured Rotating Parts for Engines

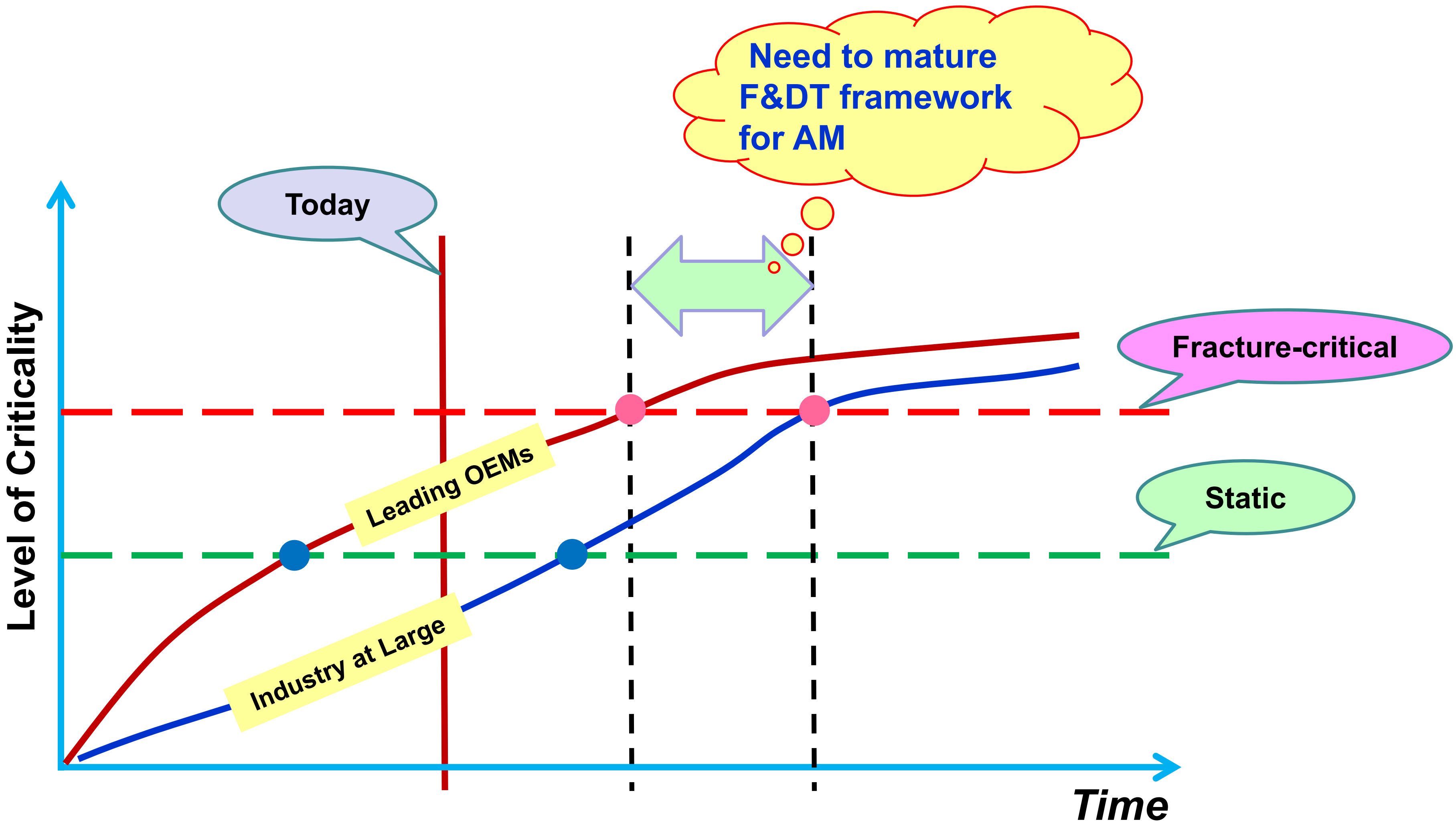
FARNBOROUGH, England, July 17, 2018 /PRNewswire/ — Pratt & Whitney, a division of United Technologies Corp. (NYSE: UTX), today announces its participation in an industry team developing and testing additively manufactured turbomachinery components, including the first additively manufactured rotating part for Pratt & Whitney development programs.

The team includes Norsk Titanium, the Notre Dame Turbomachinery Laboratory (NDTL) and TURBOCAM International.

"We are excited to collaborate on these manufacturing and testing efforts and applications for future engine development," said Dave Carter, senior vice president, Engineering, at Pratt & Whitney. "Pratt & Whitney is a 3D printing leader and has been steadily increasing the use of additive manufacturing techniques for the past 30 years. Working with Norsk, the Notre Dame Turbomachinery Laboratory and TURBOCAM will accelerate already successful efforts to incorporate additively manufactured parts into our production engines."

The jointly managed team is currently exploring the applicability of Norsk Titanium's Rapid Plasma Deposition™ (RPD™) material to turbomachinery applications. As part of this effort, the Notre Dame Turbomachinery Laboratory will test an additively manufactured, integrally bladed rotor (IBR) produced to meet the applicable quality specifications used in Pratt & Whitney's current turbomachinery products. The initial test IBR will be machined by TURBOCAM International. Pratt & Whitney is expected to test the part at the Notre Dame Turbomachinery Laboratory in the second half of 2018

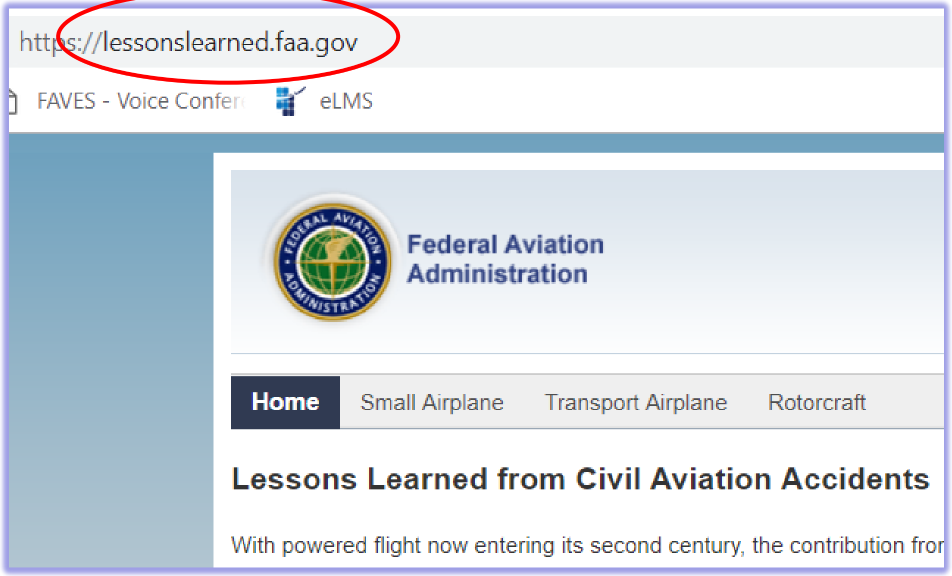
State of Industry



1.1 A CENTURY OF STUDY - - - AND FATIGUE STILL FAILS STRUCTURES

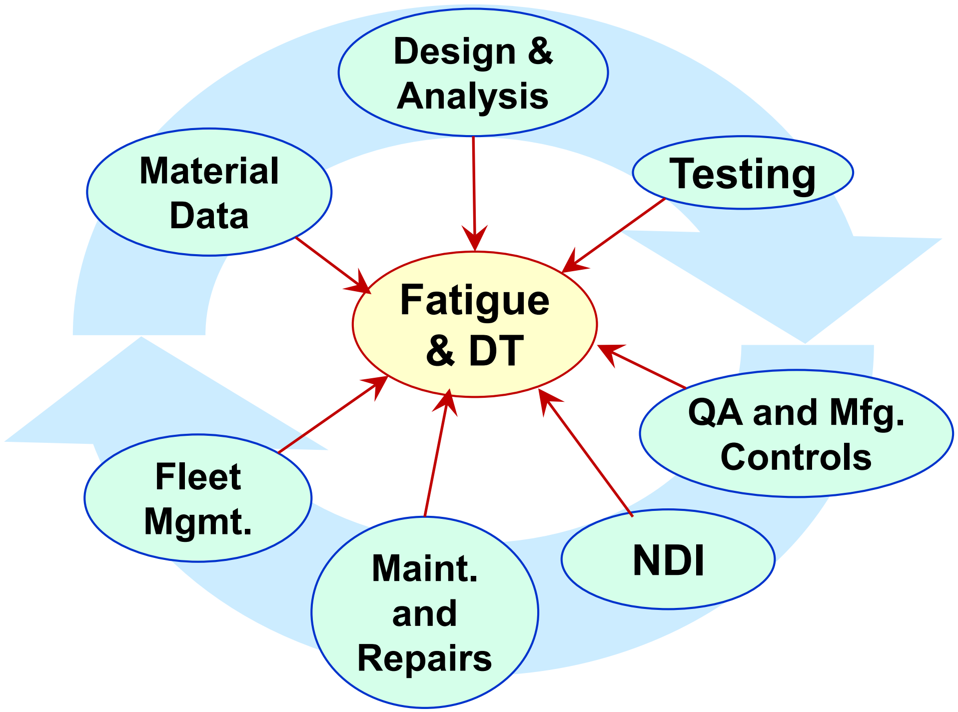
The fatigue problem relating to metals and structures has been investigated experimentally for more than a century. In 1849, Jones and Galton investigated cast iron bars in bending. They found that failure occurred in less than 100,000 cycles if loaded to more than one-third of ultimate bending strength. Similar work on wrought iron built-up girders by Fairborn (1860-1861) showed similar results. Wohler's work for the Prussian State Railways goes back to the 1850's when he made an extensive series of tests of various grades of iron and steel subjected to repeated direct tensile and compressive loads, to repeated bending loads, and to repeated torsional loads. Yet we continue to read about and hear about railroad wrecks, automobile smashups, airliner crashes, and other catastrophes directly attributable to fatigue in metallic structures.

C. R. Smith, "Tips on Fatigue", Dept. of the Navy, 1963



How can we leverage this experience for AM?

System-Level View of F&DT Discipline



All elements of the system are essential to ensure safety …

Two Types of Anomalies

that may result in life debit

Rogue (rare) Anomalies

Examples:

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

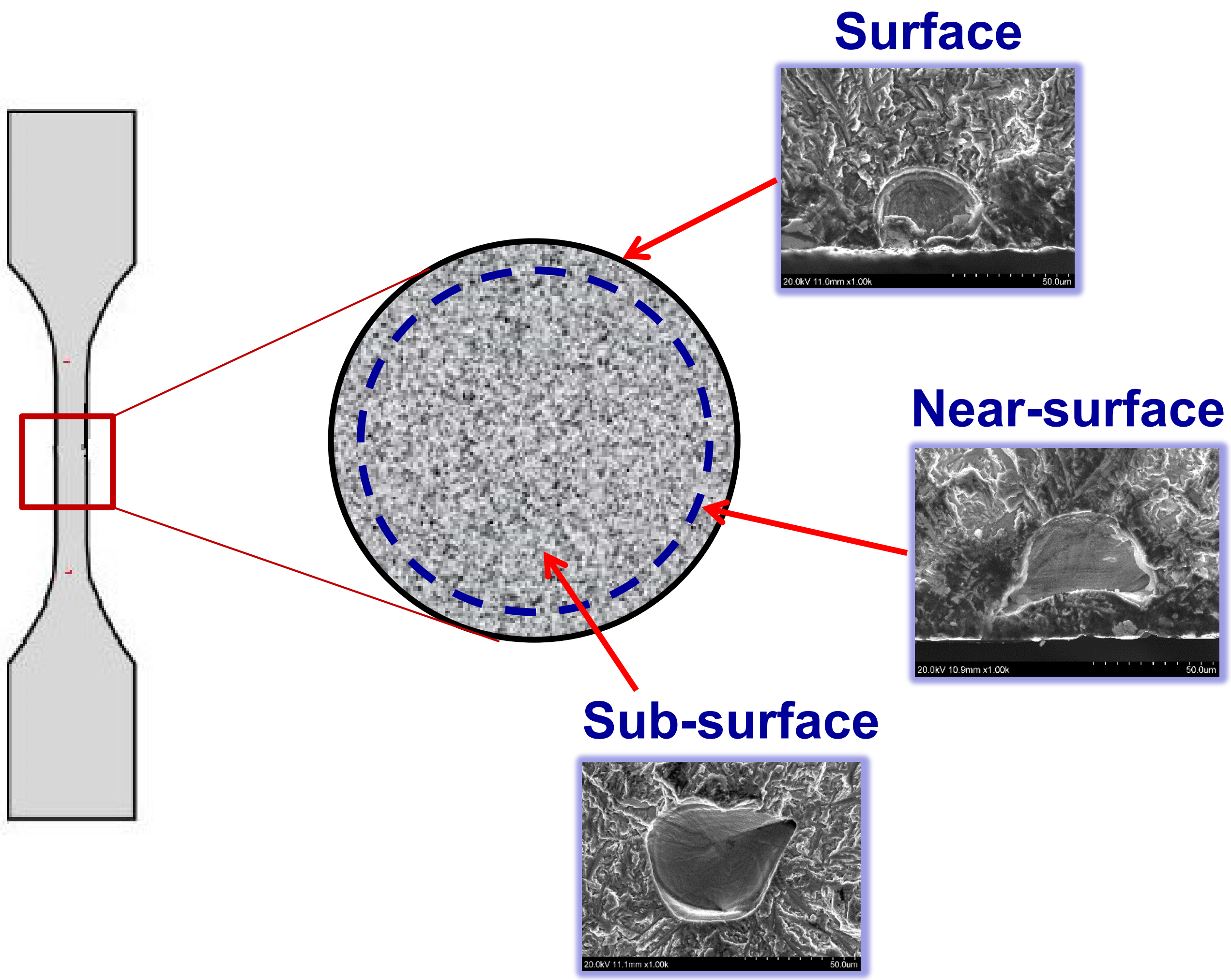
Inherent Anomalies

Examples:

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

Surface vs. Volume

Categories of Anomalies by Location



Considerations

- **Crack initiation vs. propagation**
- **Defect types**
- **NDI detectability**
- **Size distribution**
- **Frequency of occurrence**
- **Effect of post-processing**
- ***Near-surface scan pattern (for PBF)***

Photo credits: S. Jha et al, "*Fatigue Life Prediction OF Additively Manufactured Ti-6Al-4V*", MS&T 2019, Portland, OR.

Example: Porosity vs. Scan Speed

Ref: N.T. Aboulkhair et al, "*Reducing porosity in AlSi10Mg parts processed by selective laser melting*", Additive Manufacturing 1–4 (2014), pp. 77–86

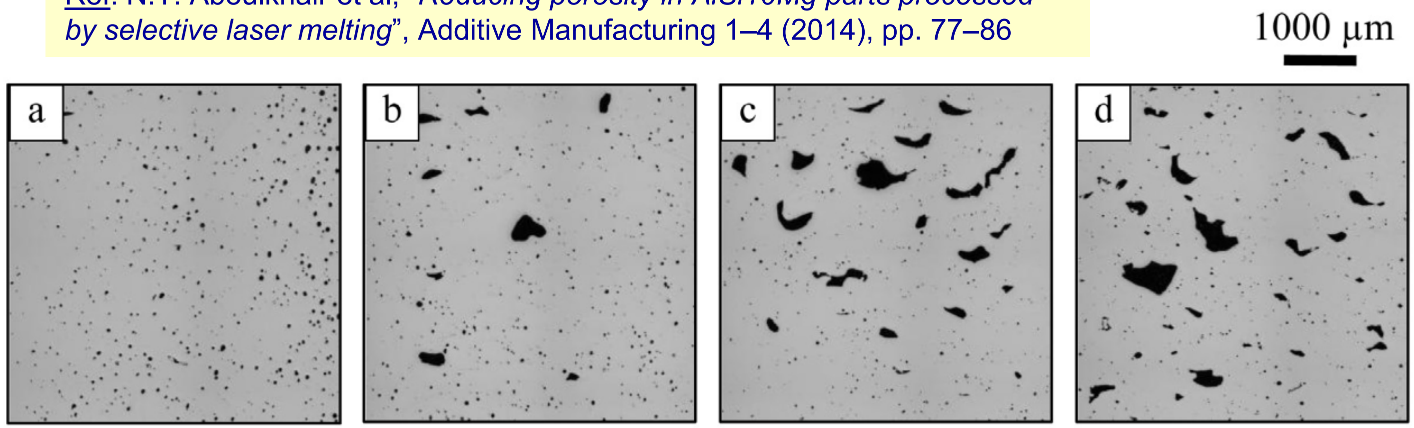


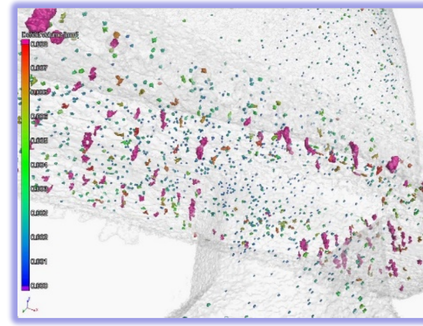
Fig. 5. Evolution of pores with scanning speed: (a) 250 mm/s, (b) 500 mm/s, (c) 750 mm/s, and (d) 1000 mm/s.

Scanning speed →

Populations of AM defects can be a strong function of process parameters, and may need to be re-assessed if the process has changed

Anomalies Characterization Methods

- **NDI (CT, Digital X-ray, UT)**
- **Fractography**
- **Serial sectioning**



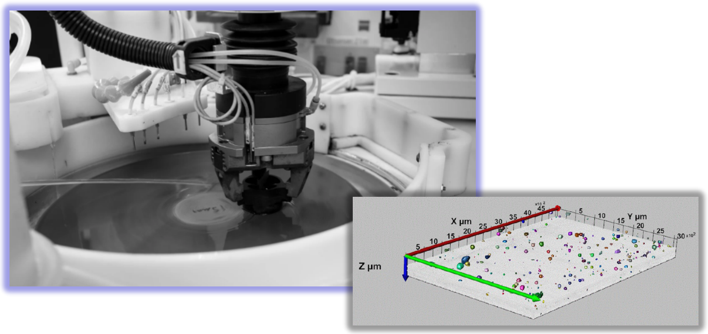
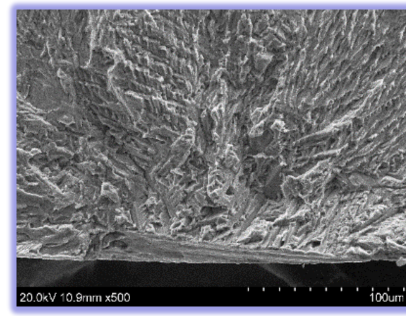


Photo credits: V. Sundar et al, Microsc. Microanalysis 24 (Suppl 1), 2018, pp.554-555.



Key Outputs:

- **Size Distribution**
- **Frequency of occurrence*)**

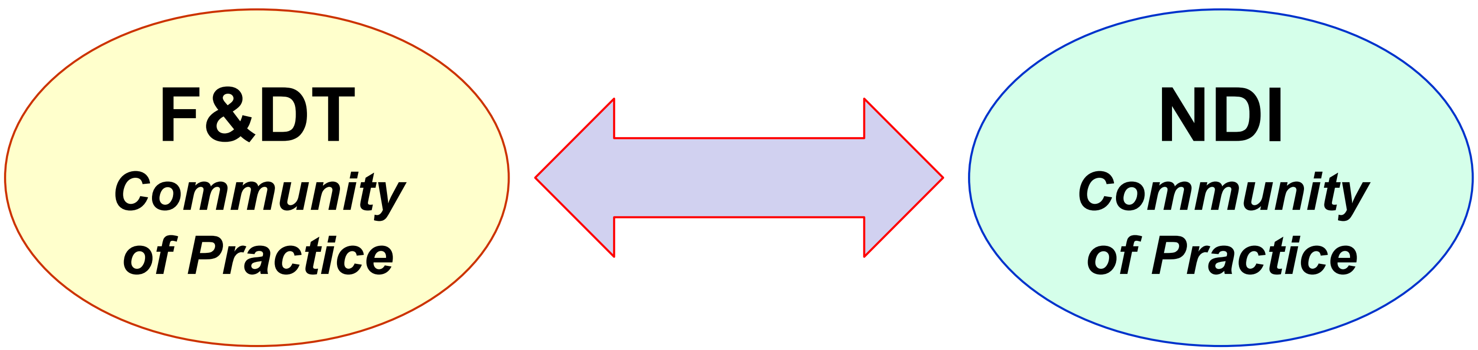
*) *Typically, more challenging to quantify*

Can be combined in the form of *exceedance curves*
(see, for example, FAA AC 33.14-1 or AC 33.70-2)

NDI Considerations for AM

- **Current lack of validated and quantified NDI capabilities for flaw detection in metal AM parts**
- **Effective two-way dialogue is needed between the NDI and F&DT (fatigue and damage tolerance) communities of practice**

➢ **Focus on the largest flaw that can be missed, not the smallest flaw that can be found…**



- **What types of defects need to be detected?**
- **What is the range of defect sizes that need to be *reliably* detected?**

- **What are the *quantifiable* detection capabilities for a given class of defects (QNDI)?**

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

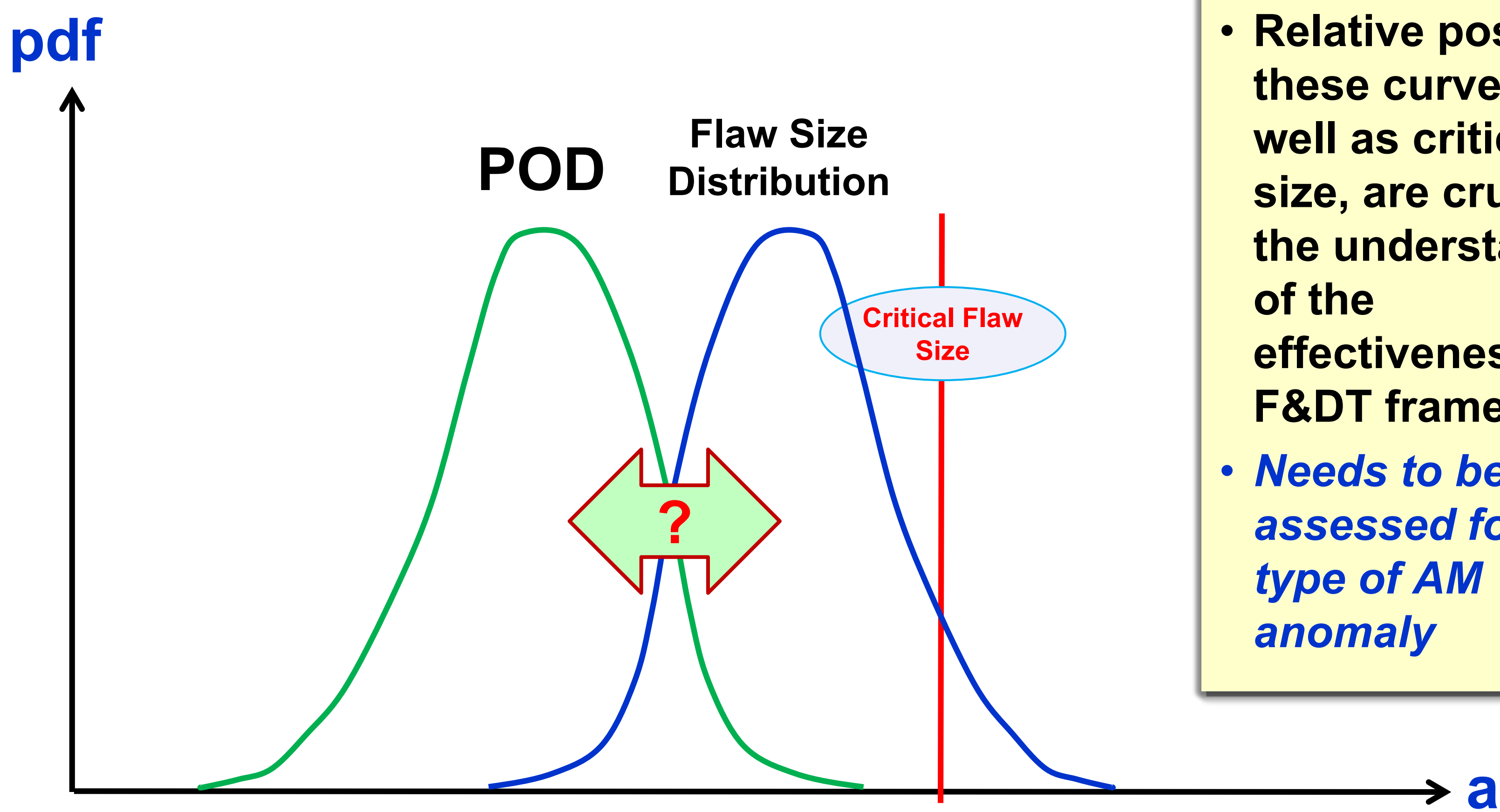
Committee E08 on Fatigue and Fracture

Committee E07 on Nondestructive Testing

ASTM INTERNATIONAL

Committee F42 on Additive Manufacturing Technologies

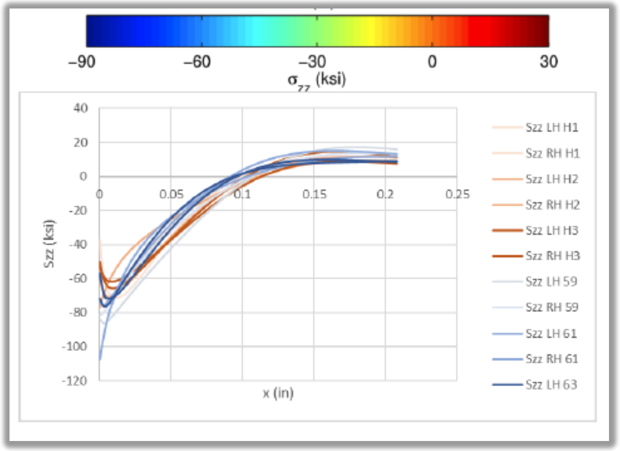
Detection Capability vs. Flaw Size Distribution



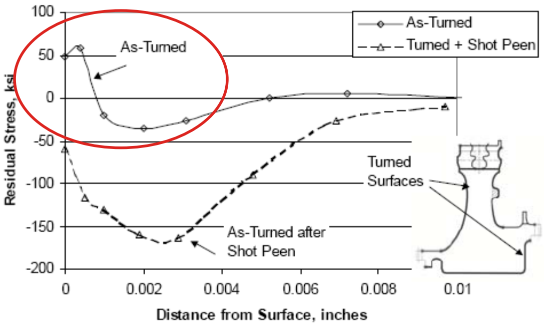
- **Relative position of these curves, as well as critical flaw size, are crucial to the understanding of the effectiveness of F&DT framework**
- ***Needs to be assessed for each type of AM anomaly***

Residual Stress (RS) Considerations

Measurement / modeling capabilities for beneficial *engineered residual stresses* continue to advance



Unfavorable residual stresses *resulting from manufacturing process* may significantly reduce component's safe life (by 10x or more), as well as DT capabilities



Near surface residual stress gradient for a turned surface before and after shot peening.

Existing F&DT assessment tools can largely account for the presence of residual stresses

Example: RS in Aluminum Forgings

SciTech 2015
Kissimmee, Florida, 5-9 January 2015

The Impact of Forging Residual Stress on Fatigue in Aluminum

Dale L. Ball[1]
Lockheed Martin Aeronautics Co., Fort Worth, Texas, 76101

Mark A. James[2], Robert J. Bucci[3] and John D. Watton[4]
Alcoa Technical Center, Alcoa Center, PA, 15069

Adrian T. DeWald[5] and Michael R. Hill[6]
Hill Engineering LLC, Rancho Cordova, CA, 95670

and

Carl F. Popelar[7], Vikram Bhamidipati[8] and R. Craig McClung[9]
Southwest Research Institute, San Antonio, TX, 78238

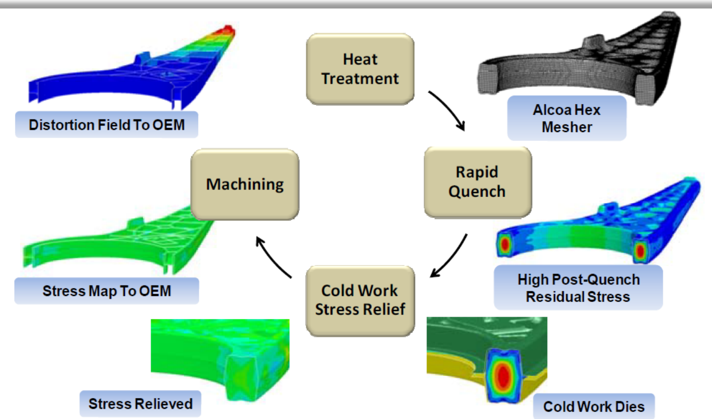
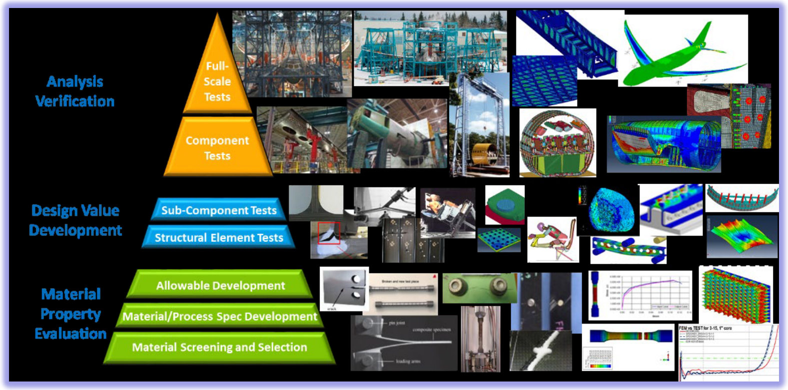


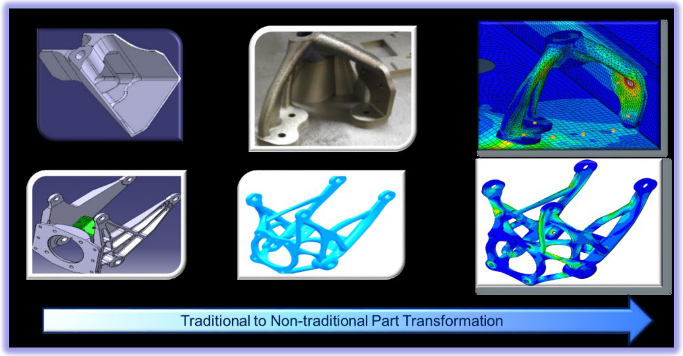
Figure 1. Alcoa's forging process model: 1) solution heat treatment, 2) quench, 3) cold work stress relief, and 4) machining. The capability includes material models for 7050 and 7085, Watton[11].

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

Example - "Smarter Testing" (BCA)

"Use of advanced analysis techniques using fundamental (coupon-derived) inputs can lead to reduced quantities of program-led mid-level structural tests, reducing airplane development costs and risks".

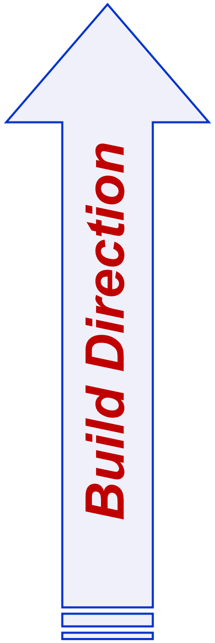




"…AM presents new challenges for certification in that there are no traditional validated analysis methods suited to the arbitrary and organic nature of many AM parts…"

<u>Credits</u>: S. Chisholm et al, "*Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance*", Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

Example: Location-Specific Properties



Each area encircled in red has a different orientation with respect to the build direction, and thus *may* have different local properties

Part Zoning Considerations for AM

- **Many Interpretations exist…**
- **Zones can be defined based on:**
  - **Criticality of failure mode, inspectability, population of defect species, design “margin”, microstructure, residual stress, etc.**
  - ***Somewhat similar to zoning of structural castings***
- **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 proposed approach:**
  - **Flexibility (only use necessary level of complexity)**
  - **Ability of perform *quantitative assessment* (when needed)**

<u>*Example*</u>: "Smarter Testing" (BCA) – *cont.*

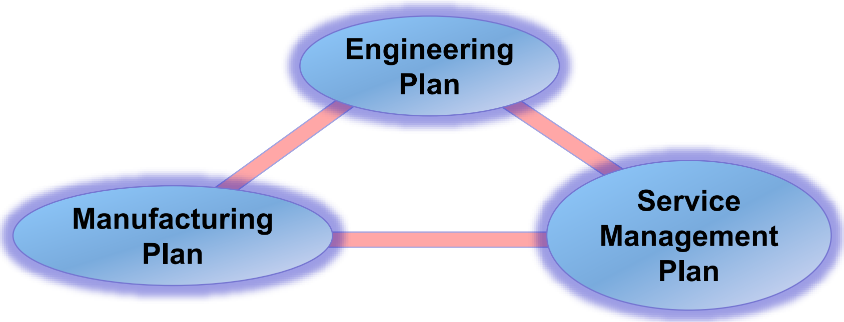
- **"…Fatigue and damage tolerance considerations currently pose significant challenges to the use of AM parts on airplane structures".**
- **"The presence of *inherent material defects* randomly distributed throughout the volume, which may be *below the threshold of detectability*, means that due consideration has to be given to size effects and the *possibility of cracks not always nucleating where they would ordinarily be expected*…"**
- **"The solution to these challenges for AM structural applications may lie in the *application of probabilistic fatigue analysis methods*…"**

<u>Credits</u>: S. Chisholm et al, "*Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance*", Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

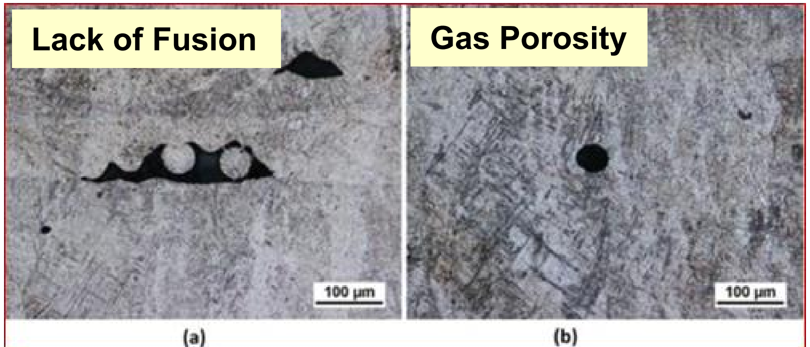
Excerpts from 14 CFR 33.70

- **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

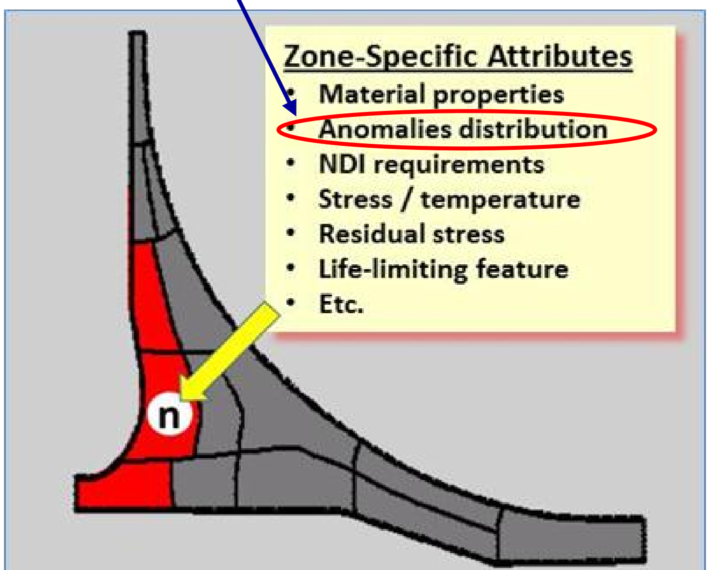
> **"The *probabilistic approach to damage tolerance* assessment is one of two elements necessary to appropriately assess damage tolerance".**
>
> ***AC 33.70-1, GUIDANCE MATERIAL FOR AIRCRAFT ENGINE LIFE-LIMITED PARTS REQUIREMENTS, 7/31/2009.***



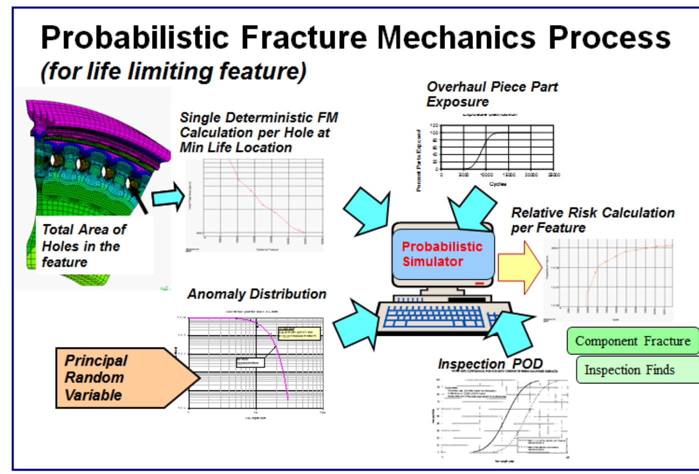
AM Part Zoning and Probabilistic DT



- 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

Reference: M. Gorelik, "Additive Manufacturing in the Context of Structural Integrity", International Journal of Fatigue 94 (2017), pp. 168–177.

Increasing Recognition of the Probabilistic DT for AM…

Lessons learnt

– Defect distribution is a key parameter (as expected) and potential non-homogeneity across part to be considered

…

– Probabilistic approaches give more realistic predictions
  – More accurate consideration of defect variability and criticality

“Special Topics”

- **Seeded defects studies**
- **Bi-modal fatigue distributions in AM**

Example: "Seeded" Defects Study in Weldments *(circa 1975)*

AD-A013 923

EXPLORATORY DEVELOPMENT OF WELD QUALITY DEFINITION AND CORRELATION WITH FATIGUE PROPERTIES

Robert Witt, et al

Grumman Aerospace Corporation

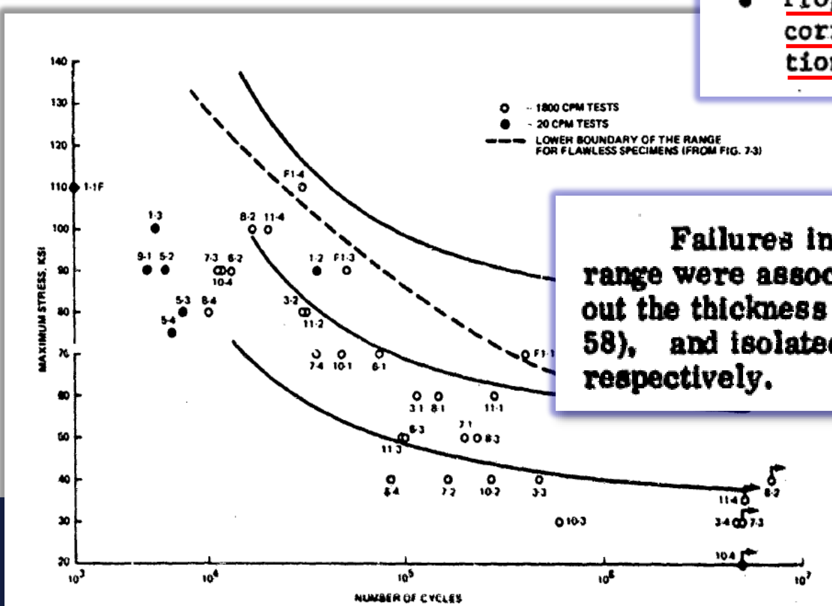
Prepared for:

Air Force Materials Laboratory

April 1975

The program objectives were as follows:

- Determine the feasibility of producing typical defects in Ti-6Al-4V titanium alloy weldments by intentional variation of processing parameters. Ti-6Al-4V (STOA) plates were utilized as base materials.
- Evaluate the effect of flaws produced intentionally in experimental welds by electron-beam (EB), plasma-arc (PA), gas-tungsten-arc (GTA), and gas-metal-arc (GMA) welding on fatigue endurance.
- Propose acceptance criteria for titanium fusion weldments based on correlation of fatigue test results with both nondestructive inspection and fractographic findings.

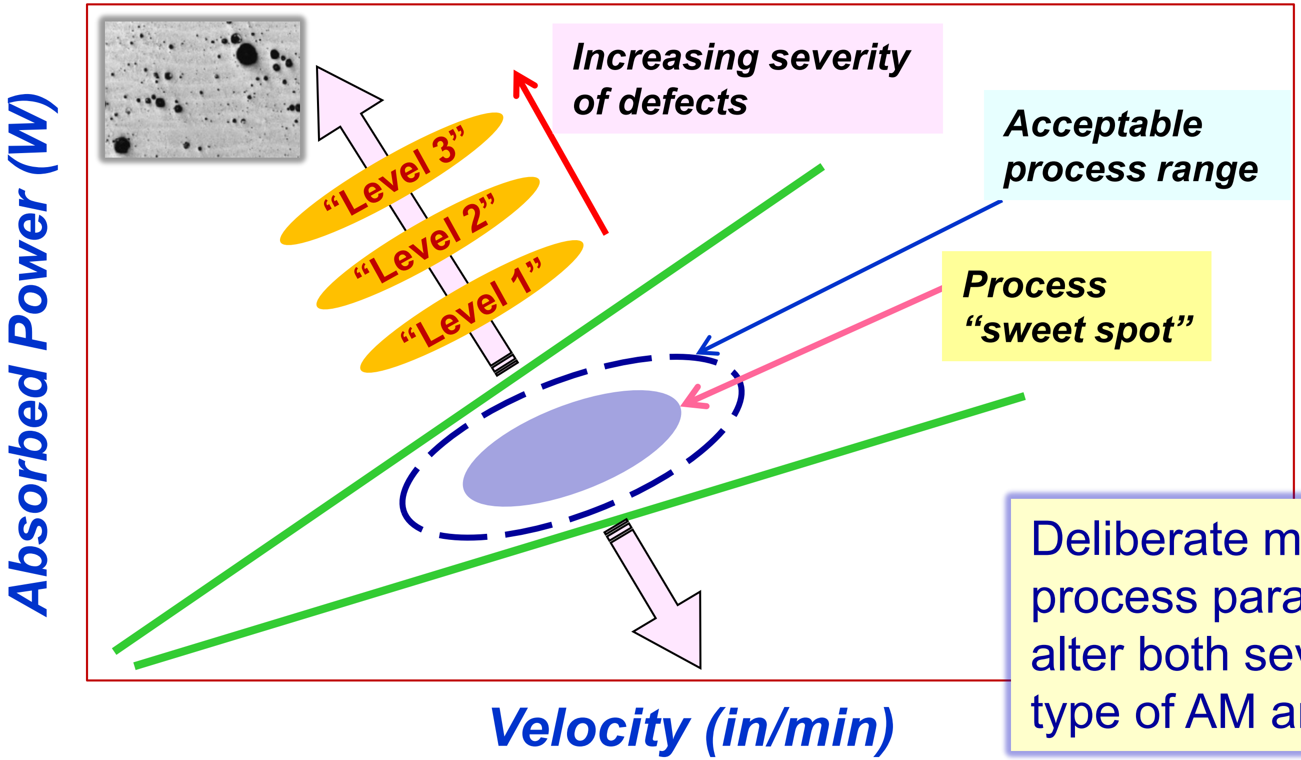


Failures in specimens with fatigue endurance values in the $K_t = 2$ to $K_t = 3$ range were associated typically with 0.010 to 0.035 inch porosity scattered throughout the thickness of the specimens which caused multiple failure initiations (Figure 58), and isolated surface or subsurface porosity, as shown in Figures 59 and 60, respectively.

Generation of "Seeded" Defects in AM Coupons

J. Beuth et al, "Process mapping for qualification across multiple direct metal additive manufacturing processes", *24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013*.

Notional P-V Map

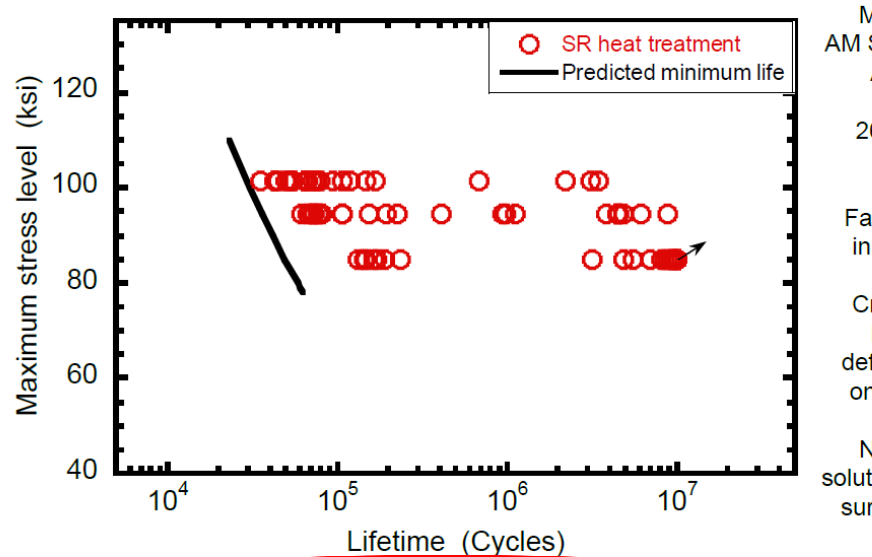


Deliberate manipulation of process parameters can alter both severity and type of AM anomalies

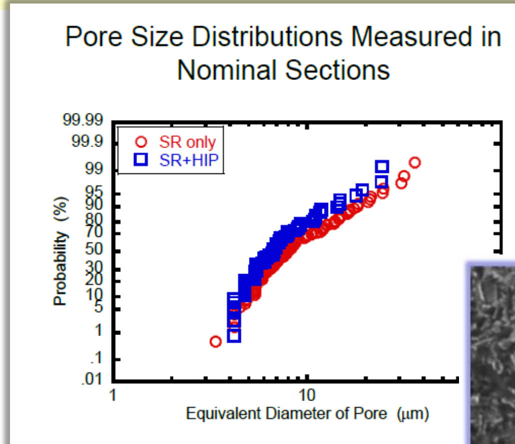
Ref: M. Gorelik, "*Considerations for Qualification of AM Aircraft Components of High Criticality*", ASTM Symposium on Fatigue and Fracture of AM Materials, Nov. 2017, Atlanta, GA.

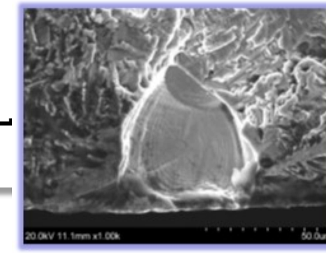
On the Bi-Modal Fatigue Distributions

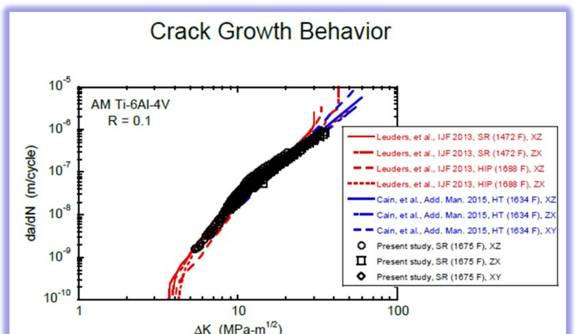
Credits: S. Jha et al, "*Fatigue Life Prediction OF Additively Manufactured Ti-6Al-4V*", MS&T 2019, Portland, OR.



- **Predicted minimum life bound based on crack growth life from maximum defect size measured at crack-initiation sites**







Challenge – availability of "small crack" data for AM

Summary

U.S. AIR FORCE

AFLCMC… Providing the Warfighter's Edge

- **Fracture – mechanics based method to predict the minimum life bounds for fatigue – critical AM parts is proposed and applied to three cases**
  - **Machined surface, SR only**
  - **Machined surface, SR + HIP**
  - **As-printed surface, SR only**
- **Above AM induced variables have significantly stronger effect on the mean life than the minimum life**
- **Minimum life in all three cases is bounded by the crack growth life starting from the controlling microstructural feature**

Summary

- **Expect rapid expansion of AM in Aviation and increase in the levels of AM parts criticality**
- **Good progress is being made by the F&DT community of practice in application to metal AM**
  - ***However, most areas are still "work in progress"***
- **Continued focus is important, through a combination of funded R&D, standardization, technical interchange meetings, and collaborative efforts**
- ***Potential areas* for collaborative efforts:**
  - **Development of public standards for F&DT and NDI of AM**
  - **Seeded defects studies → "*effect of defects*"**
    - *Reference: M. Gorelik's ASTM 2017 AM Symposium presentation*
  - **Development of "Lessons Learned" best practice documents and databases (longer-term)**

Discussion

Dr. Michael Gorelik

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

michael.gorelik@faa.gov

(480) 284-7968