Computational Tools to Accelerate Additive Manufacturing Development

Robert Tryon

Animesh Dey, Robert McDaniels

Ibrahim Awad, Nate Oliver

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Powered by ASME

Presentation Outline

- Introduction
- Role of ICME in AM – rapid certification
- Certification framework
- Computational fatigue model
- Examples
  - AM fatigue certification / prediction

VEXTEC Introduction

Headquarters

Nashville, TN – 20 years in business

VPS-MICRO® Software

Predicting fatigue durability and risk of metallic products and systems

Value Proposition

Supplement physical testing for increased confidence in accelerated qualification of parts

VPS-MICRO is:
Validated by US Government research programs
Utilized globally by commercial industries
Backed by 7 US Patents

Role of ICME (Integrated Computational Materials Engineering)

Save time and money by:

Reducing

physical testing burden for qualification of new materials/sources

Accelerating

push of Additive Manufacturing into standard production

Identifying

causes of component fatigue failure

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Certification Costs

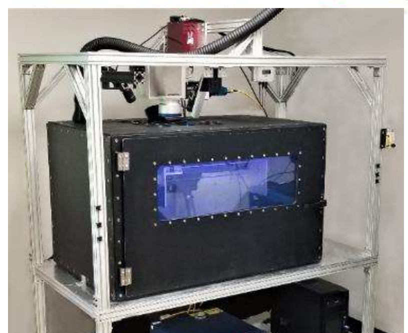
- **Current AM development / validation process is iterative, costly and slow**
  - Build, test, analyze, **repeat**
- **Long lead times and high development costs**
  - Design allowable databases
  - Machine manufacturer specific
  - NDE and post process inspection

Building Block Test Structure Required for Certification (adapted from DARPA/DSO "Open Manufacturing Review", 2016)

Size scale	Level	Specimen Count	Cost ($M)	Time (Years)
Analysis validation	Full-scale	2-3	100-125	4
	Components	10-30	10-20	3
Design-value development	Sub-components	25-50	10-35	3
	Elements	2000-5000	10-35	3
Basic material properties	Test coupons	5000-100,000	8-15	2
	Manufacturing Process (foundation)			

Integrated Computational Material Engineering (ICME) tools can provide up to **50% time/cost savings** for AM process development.

Build it



Test it

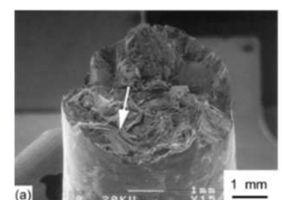
Did it pass?

Yes

Certified

No

Examine failure



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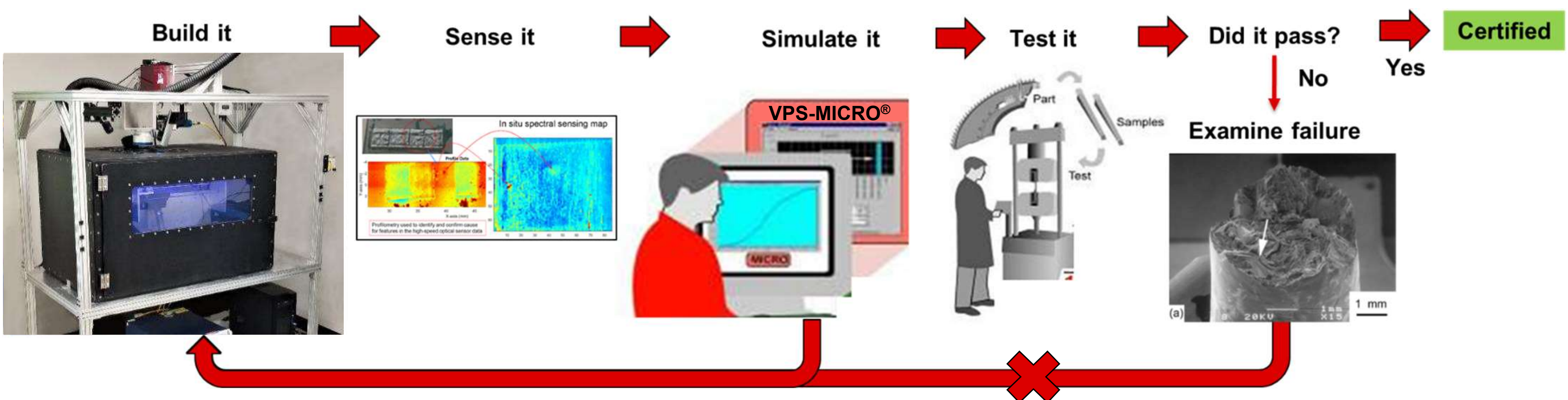
What Do We Mean by ICME-Based Certification?

- We are <u>not changing the required elements</u> of the certification process; we are instead simulating important aspects.
- Build and sense what is happening layer-by-layer, point-by-point, to have a high fidelity 3-D model of local properties.
- Take that model and simulate what would happen if you test it.
- Only test the part when you have high confidence it will pass the test → reducing costly repeats.



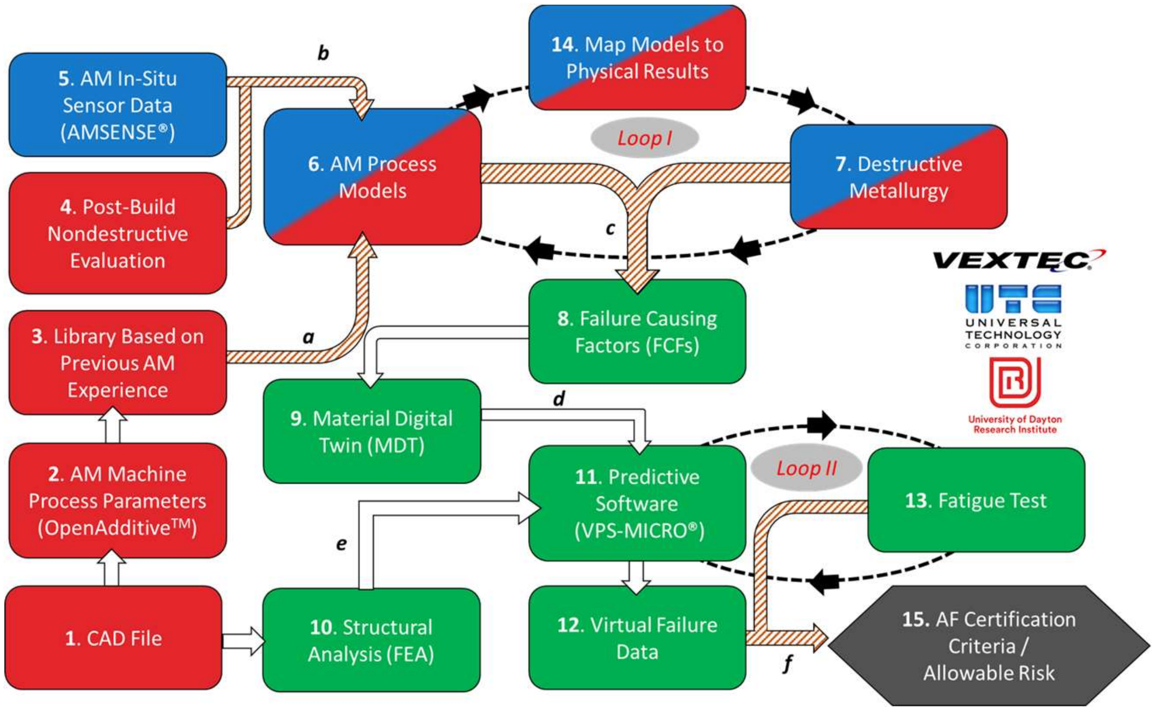
Current USAF Initiatives

- **AFLCMC/RO Rapid Sustainment Office**
  - **Rapid Qualification for Metal Additive Manufactured Parts**
  - **TPOC: Howard Sizek, howard.sizek@us.af.mil**

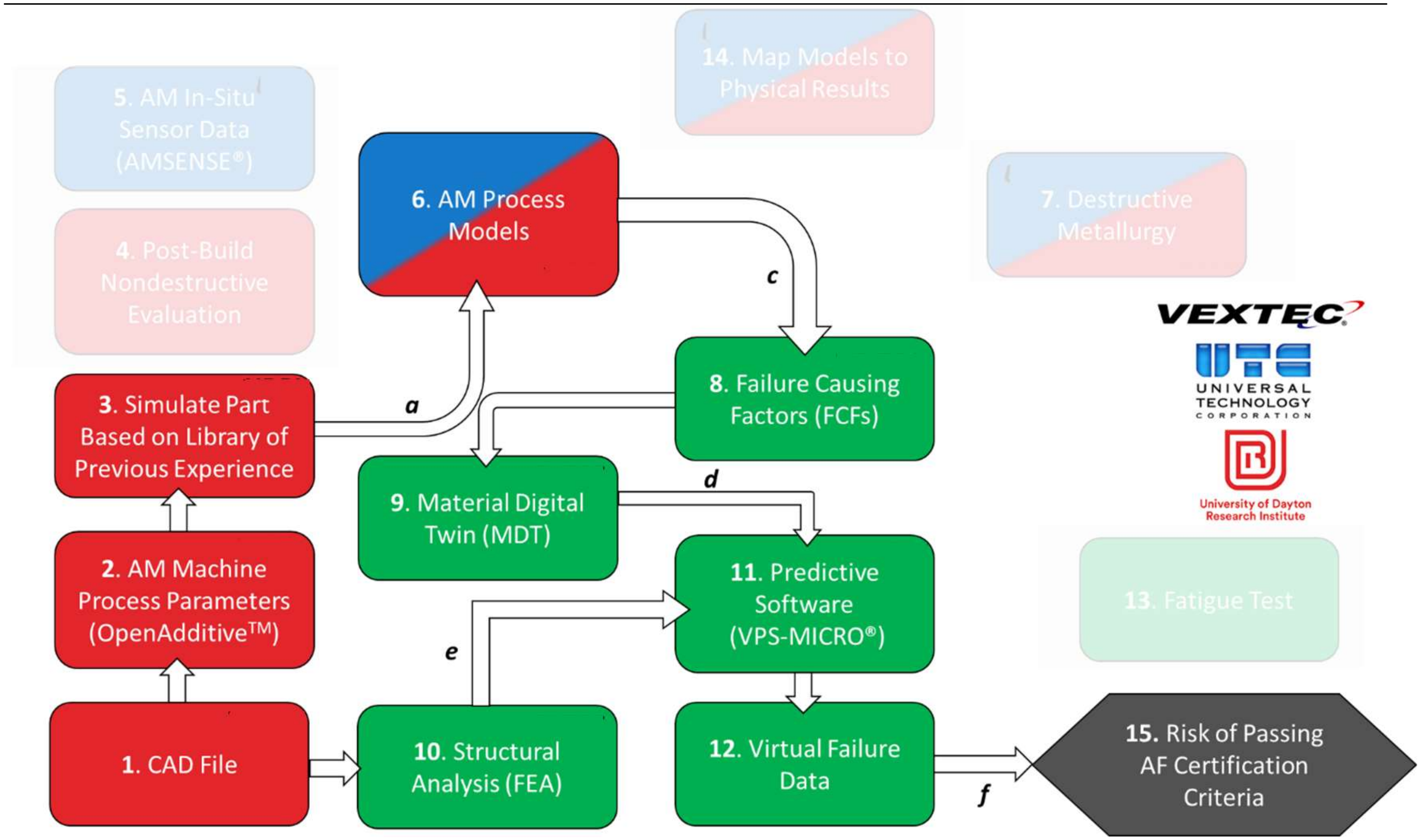
- **AFRL/RX**
  - **Computational Simulation Software for Improved Fatigue Prediction of Additive Manufactured Components**
  - **TPOC: Pat Golden, patrick.golden@us.af.mil**

Certification Solution for AM Needs

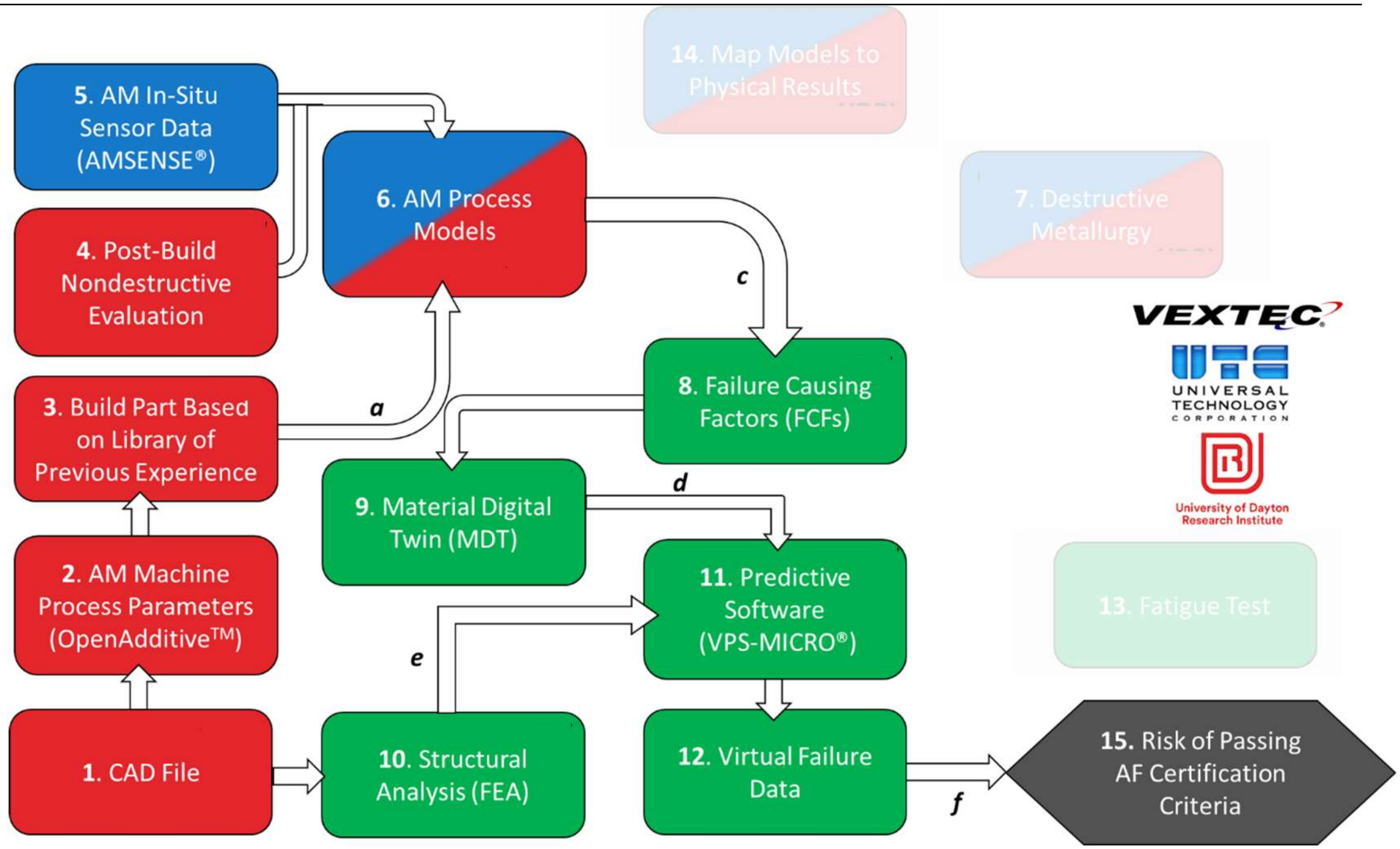
- Tight integration of these ICME toolsets that link microstructure to the properties to the performance.
- Deliver an affordable, rapid solution with the following benefits:
  - Reduction in AM process development time, testing, and cost
  - Quantification of ‘effects of defects’ impact on fatigue life - including microstructural defects
- Working with University of Dayton Research Institute and UTC-ARTOS



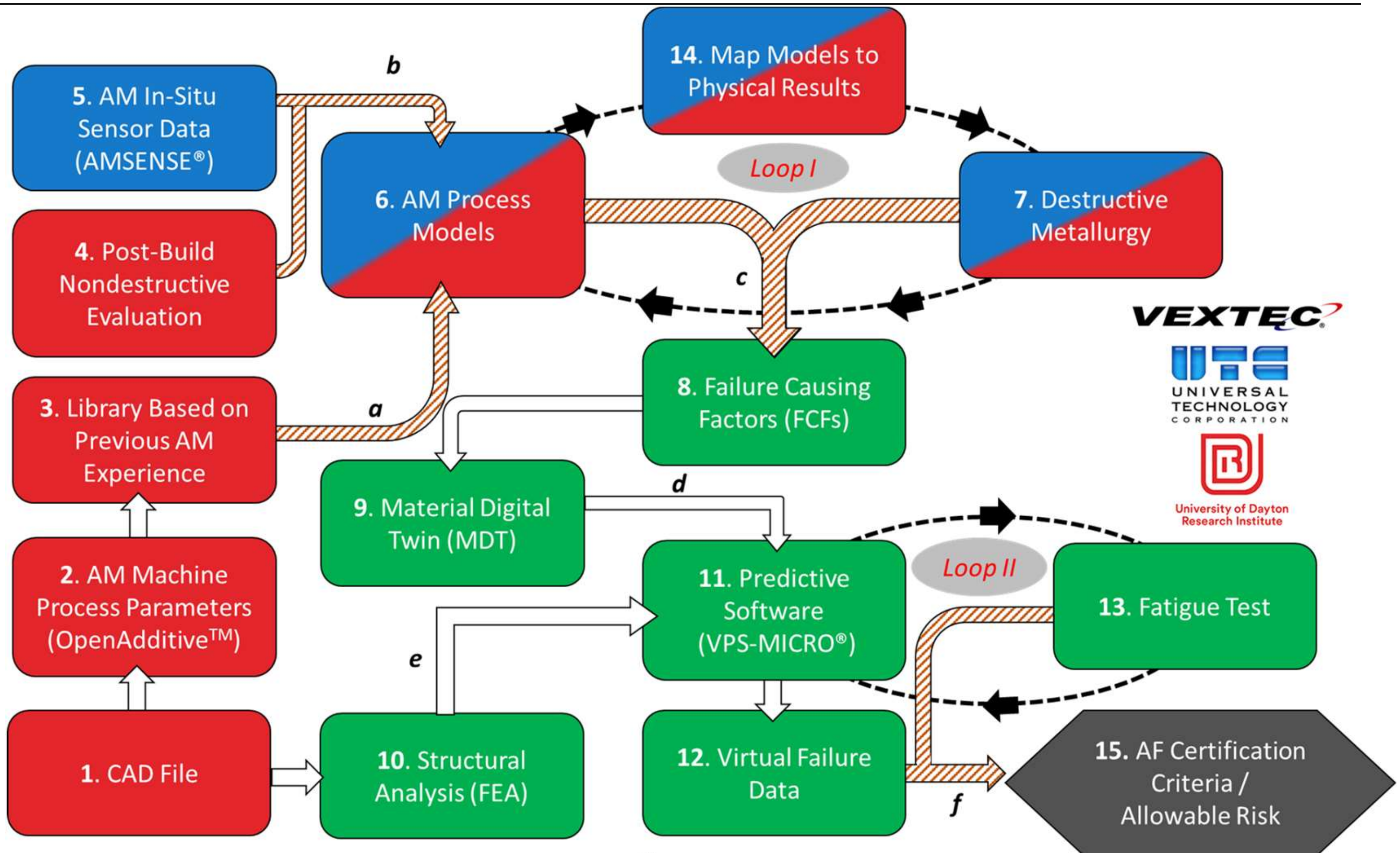
AM ICME Framework: Simulate the Build



AM ICME Framework: Build the Part

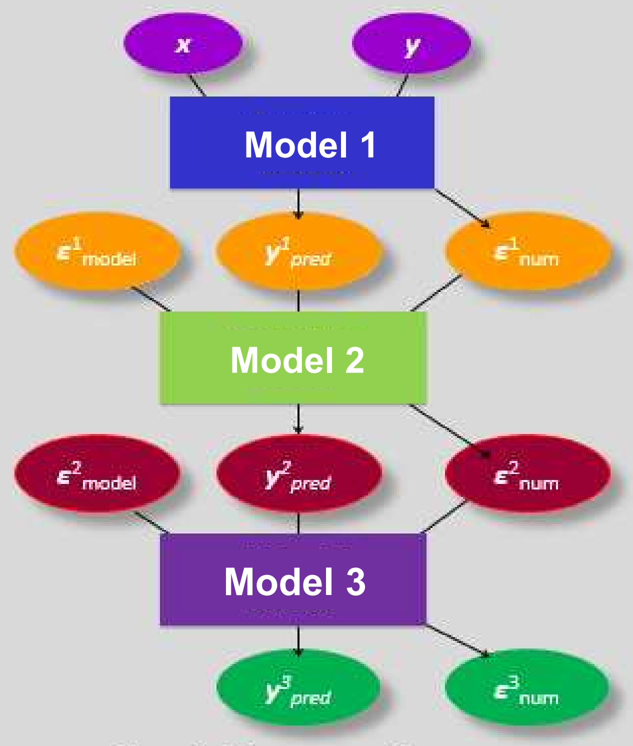


AM ICME Framework: Calibrate the Models



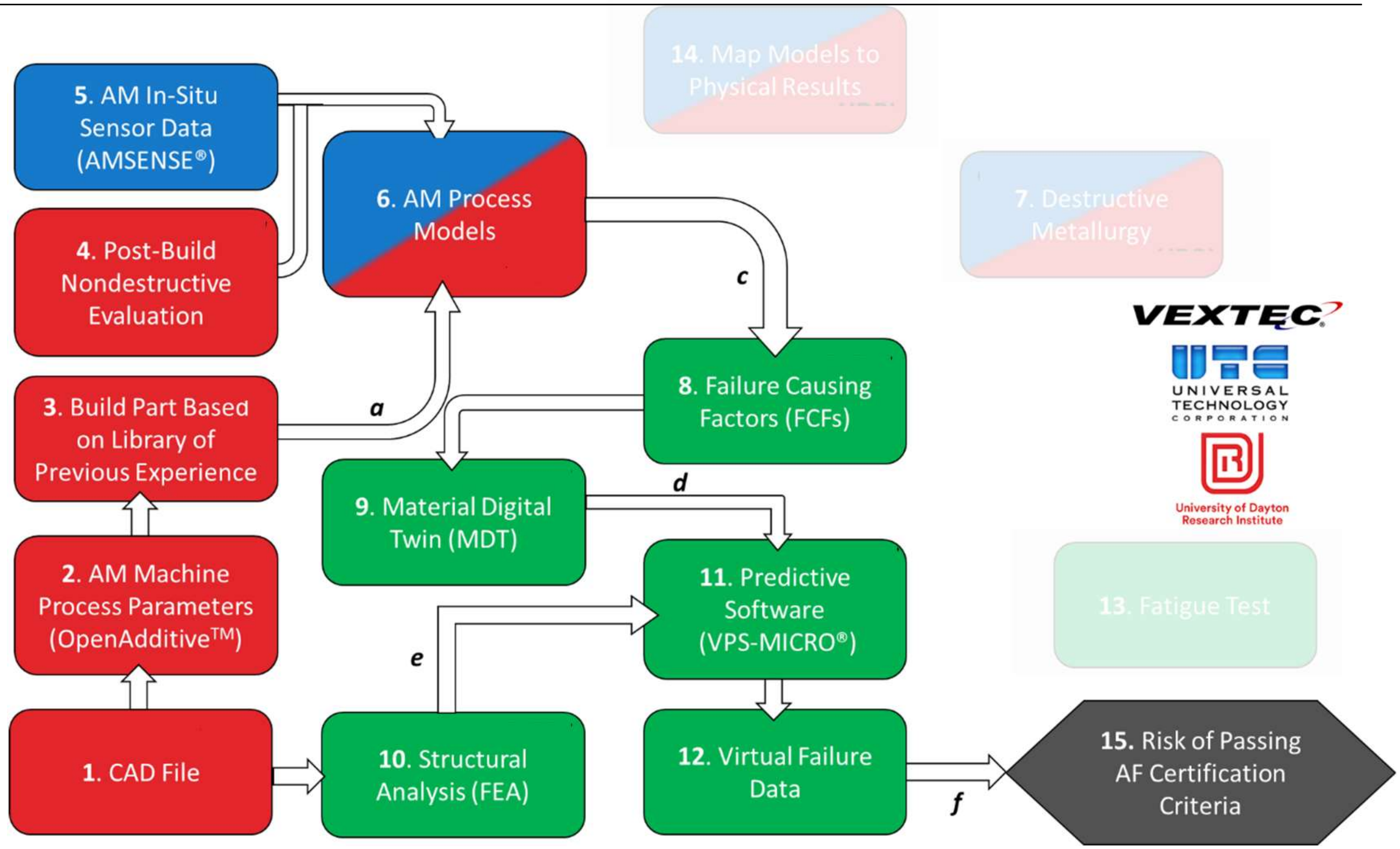
Uncertainty Propagation

- Use all available data and knowledge.
- Use physics-based computational analysis.
- Use probabilistic analysis to explicitly propagate statistical uncertainty.
- Update when new data/knowledge becomes available.



Uncertainty propagation across multiple levels in the Virtual Twin®

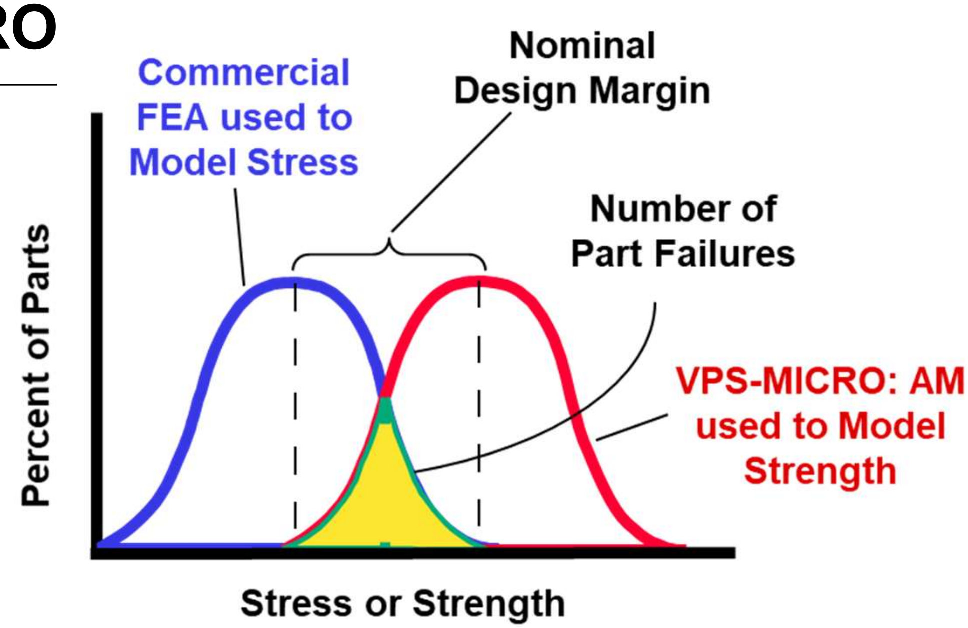
AM ICME Framework: Confident the Build will Pass

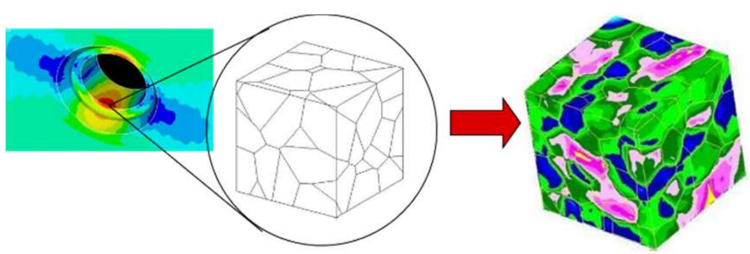


ICME Fatigue Software VPS-MICRO

- Just as FEA uses a digital representation of the part to model the stresses, VPS-MICRO uses a digital representation of the material to model strength.
  - Fatigue strength is the big cost driver and is governed by the material microstructure.
  - Software addresses fatigue strength.
  - Software creates digital models of the material microstructure.
  - Software simulates effect of surface roughness.

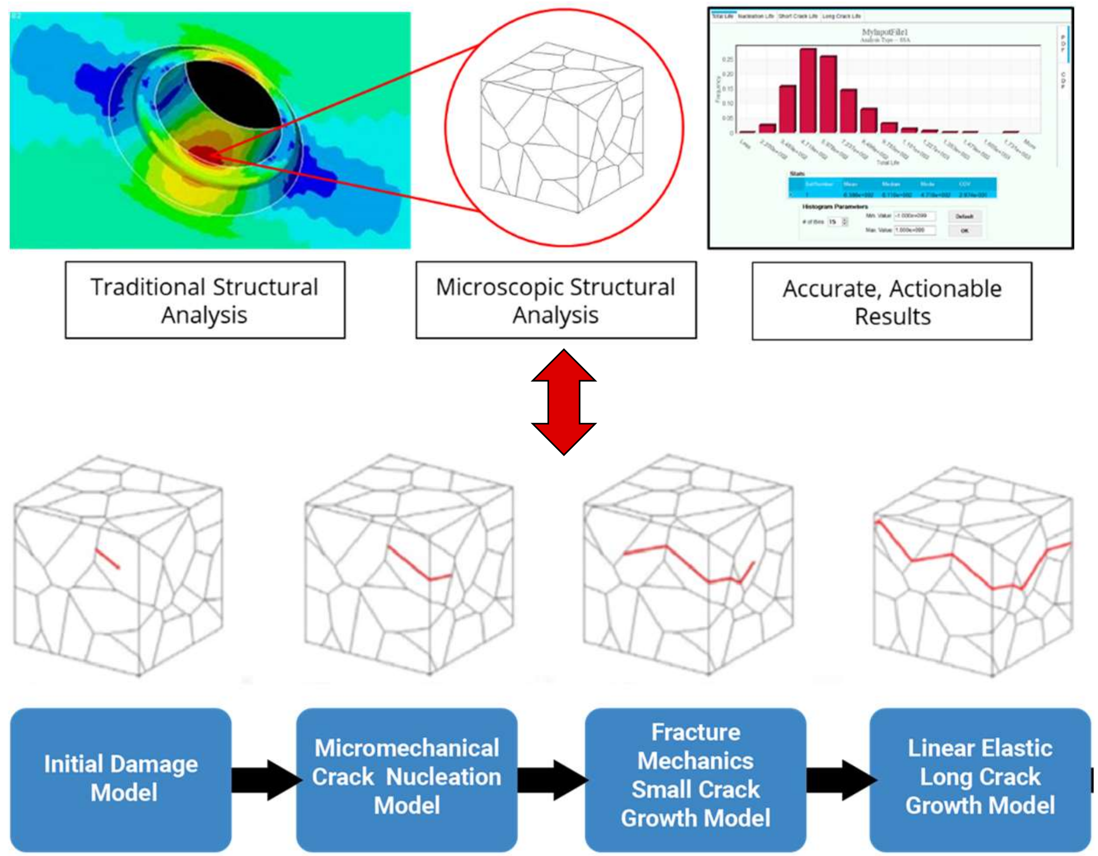
With AM, the need for analysis software is even more urgent because of the difficult-to-test-for internal surface roughness of complex geometries.



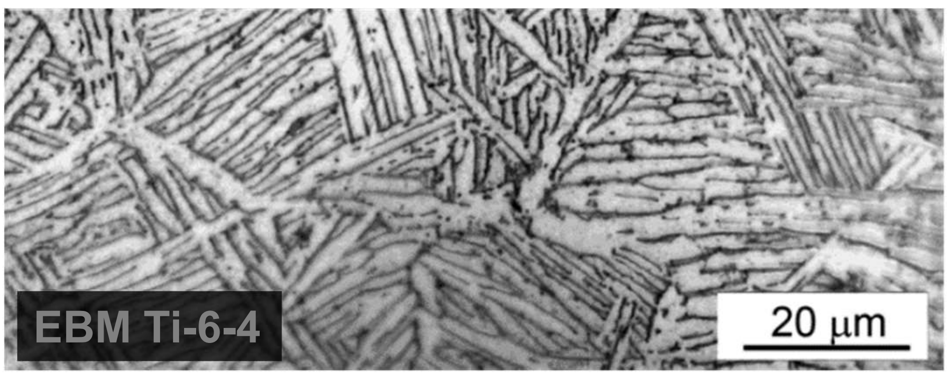


Computational Fatigue Software

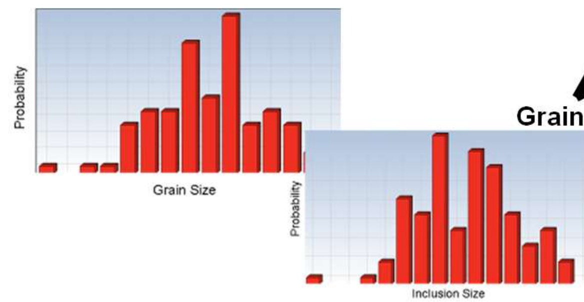
- Links microstructure to macrostructural FEA to:
  - Predict scatter in fatigue.
  - Predict complex part failure rates.
  - ID allowable microstructural tolerances in manufacturing process.
- Uses physics-of-failure modeling to analytically predict the cause and extent of fatigue failure.

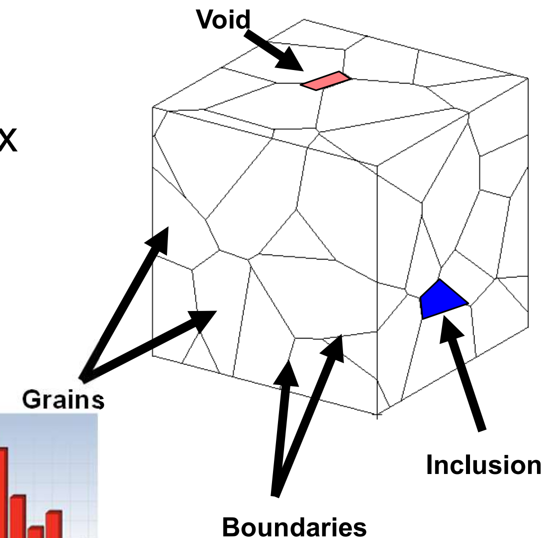


Microstructural Definition



Microstructural Volume Element
- Microscale matrix material model
- Voids and NMIs

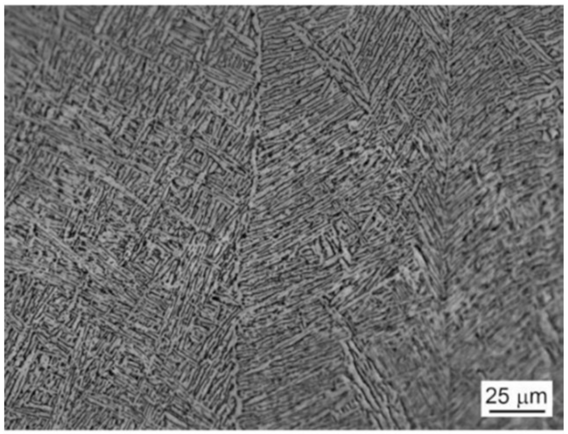




Build Orientation vs. Damage Mechanism

Horizontal Specimens

Load direction



Build direction

Vertical Specimens

Load direction

Build direction

- Slightly higher tensile strength due to absence of build defects.
- Smooth fatigue fracture surface.

- Slightly lower tensile strength due to build defects.
- Rough fatigue fracture surface.

Gong PhD Thesis, University of Louisville (2013)

Material Property Comparison (Forged vs. EBM)

†Additional model parameters (not listed) were unchanged between forged & EBM conditions

††"Grain size" is the size of the α-lamellar colonies within prior β grains

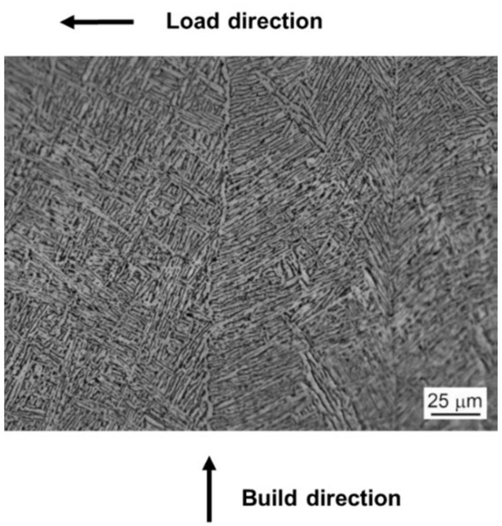
	Material Properties Influenced by Mfg. Technique†		Ti-6Al-4V Forged + β-Annealed		Ti-6Al-4V EBM (Horizontal)		Ti-6Al-4V EBM (Vertical)	
	Description	Distribution	Mean Value	COV	Mean Value	COV	Mean Value	COV
Probabilistic	Grain size††	Lognormal	0.025 in	0.3	0.0034 in	0.3	0.0034 in	0.3
Probabilistic	Frictional strength	Weibull	113 ksi	0.3	83 ksi	0.3	83 ksi	0.3
	Specific fracture energy	Deterministic	7500 lbs/in	N/A	7700 lbs/in	N/A	7700 lbs/in	N/A
Probabilistic	Defect size (population density)	Lognormal	None	N/A	None	N/A	0.004 in ($200/in^2$)	0.3
	Asperity factors	Deterministic	0.01,1,0.1,1	N/A	None	N/A	0.014,1,1,1	N/A

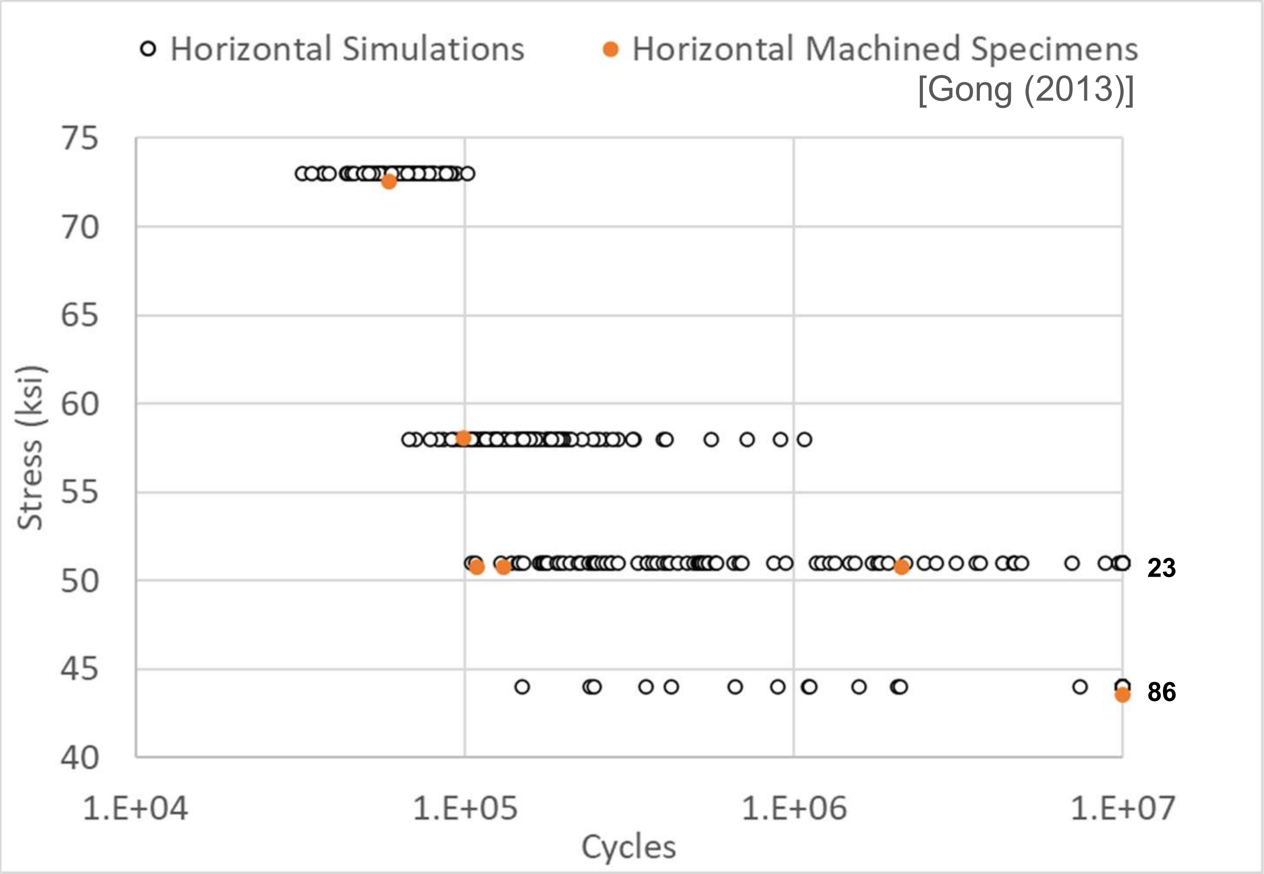
Simulation Compared to Test Data

- Forged specimens
- 100 specimens simulated per loading level

Simulation Compared to Test Data

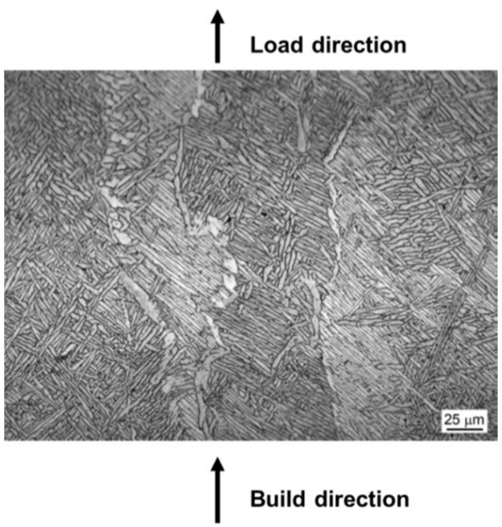
- Horizontal built specimens
- 100 specimens simulated per loading level

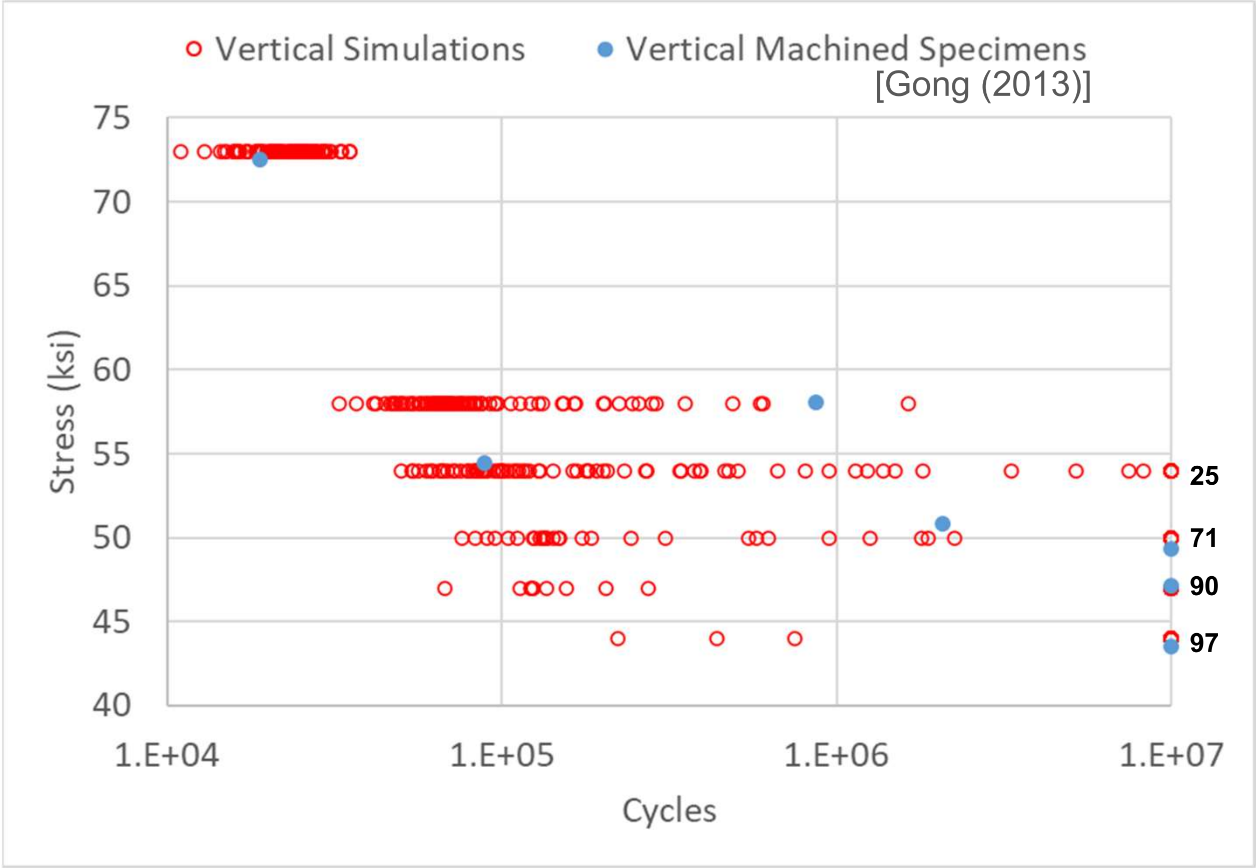




Simulation Compared to Test Data

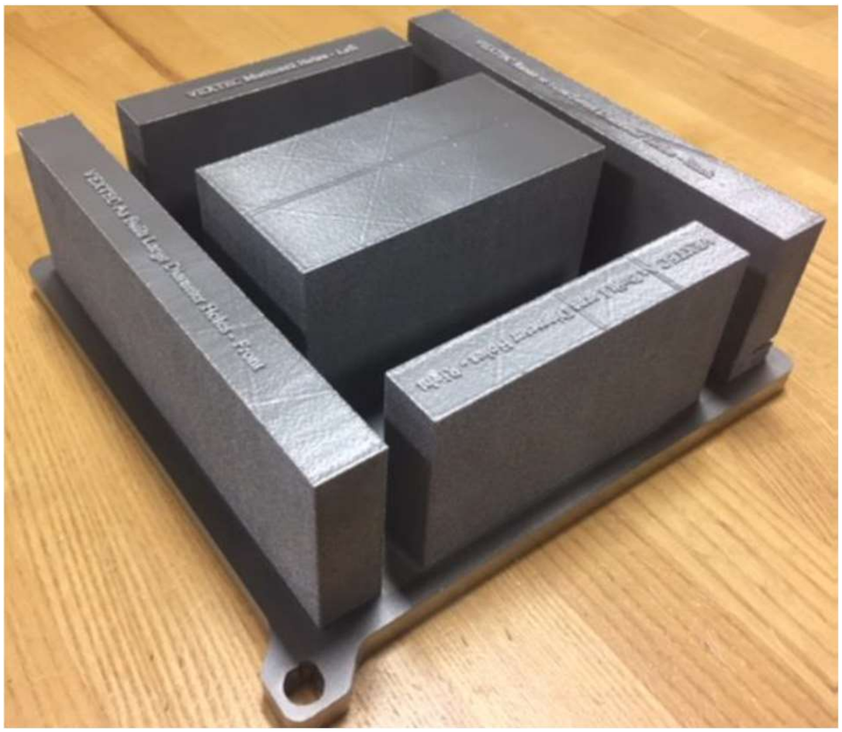
- Vertical built specimens
- 100 specimens simulated per loading level



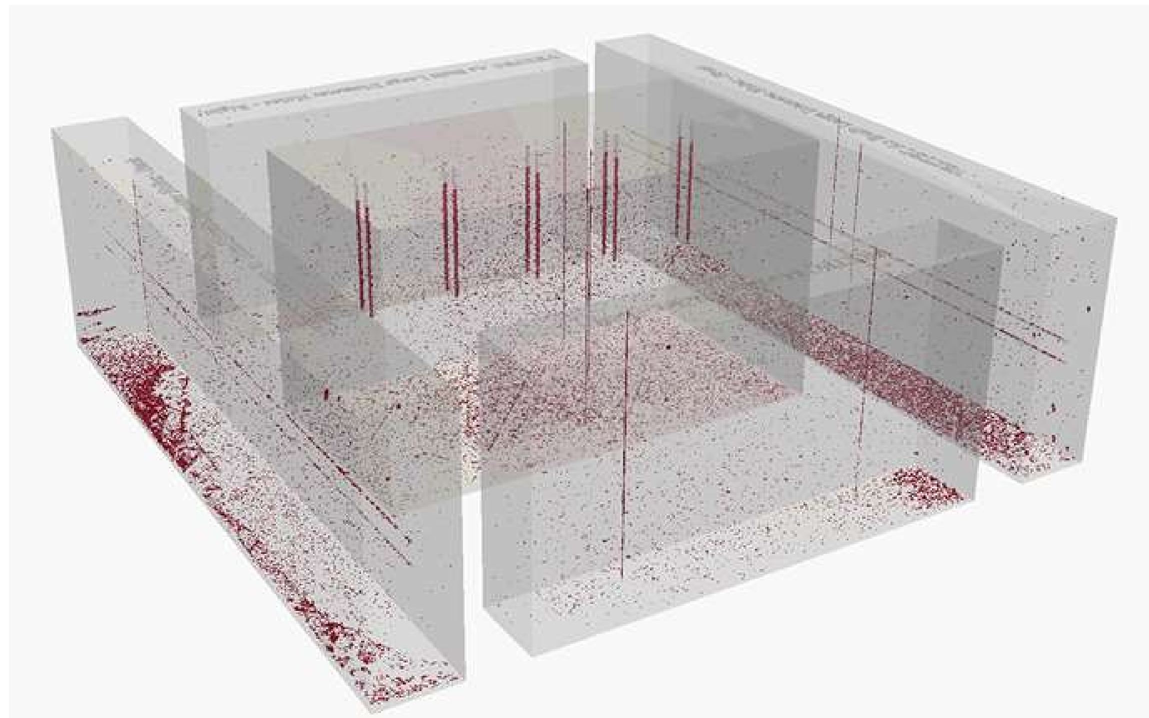


Sensed Defects

Build Blocks



Defect Size and Location



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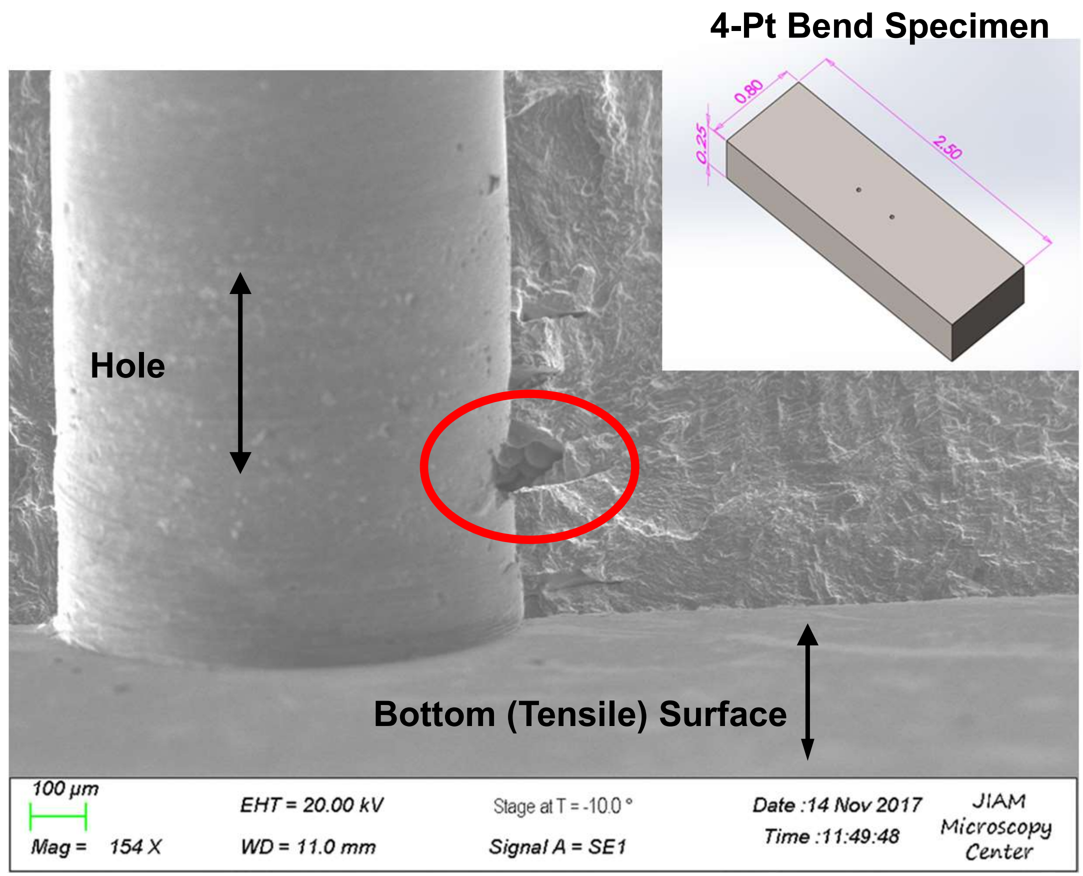
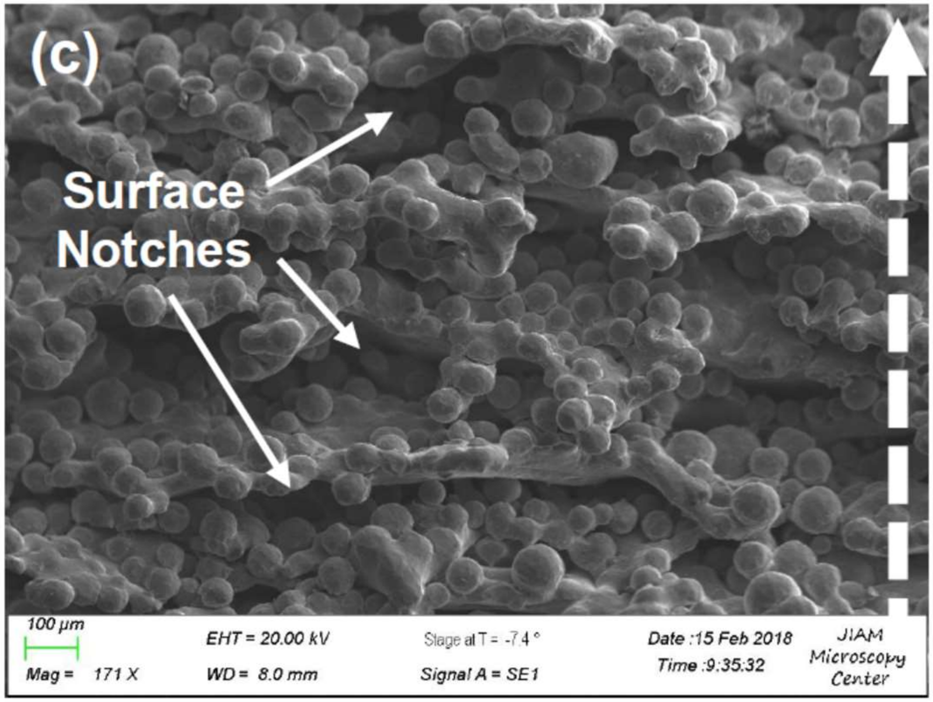
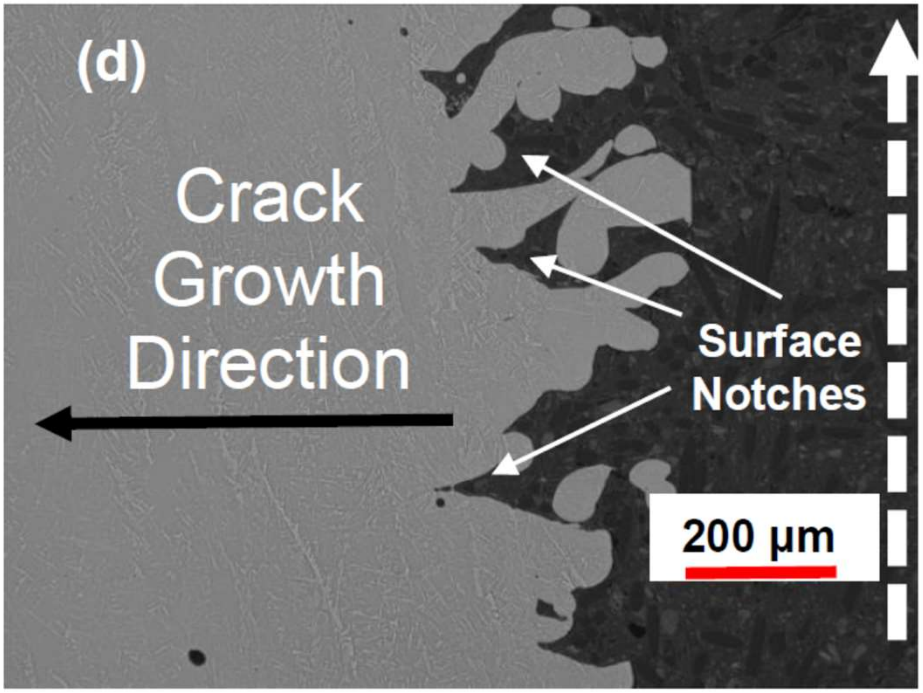
Defect Fatigue Initiation Mechanism

- Defect observed in NDE initiated fatigue cracks
  - 4 point bending specimens with holes machined to expose interior defects
  - Fatigue testing showed that the defects in the high tensile stress regions initiated fatigue cracks

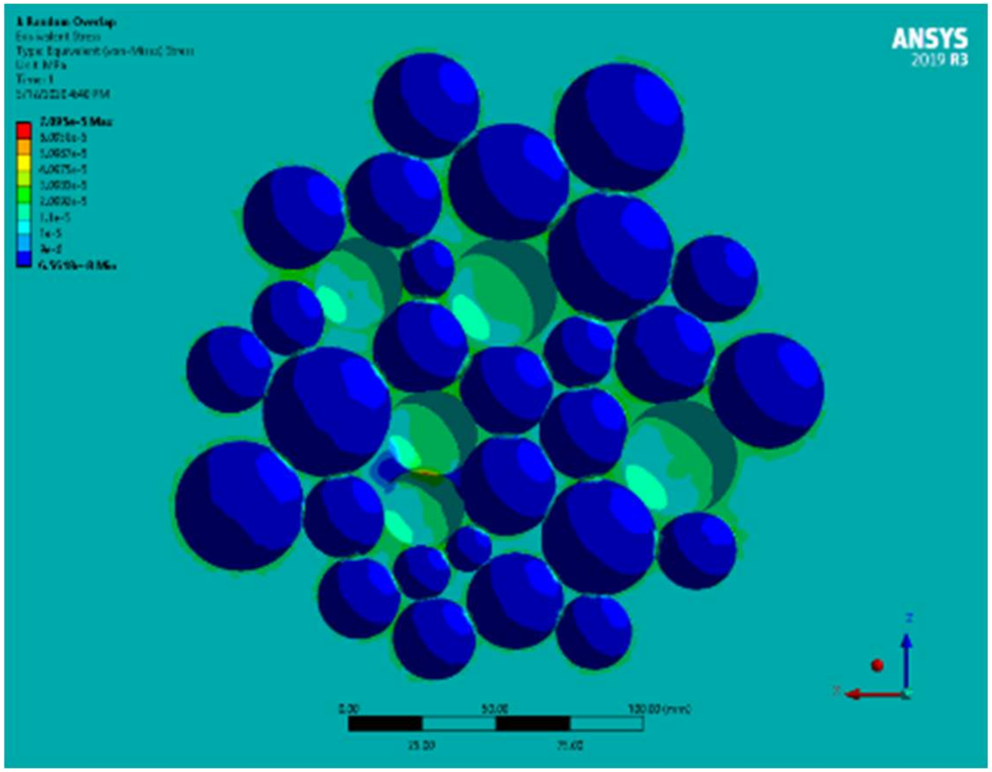


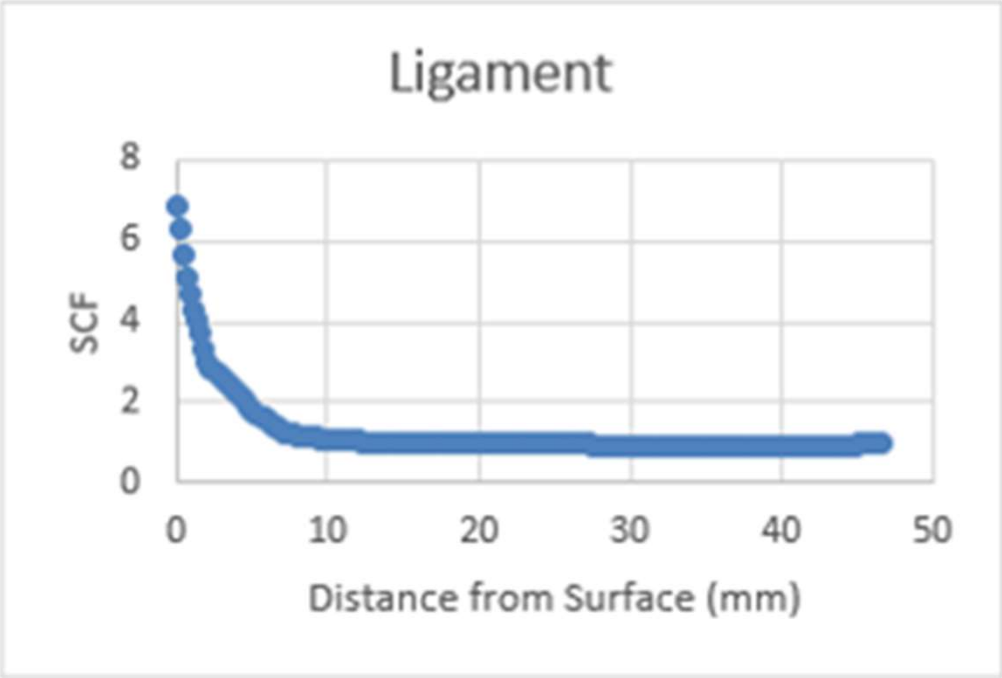
As-Built Surface Morphology



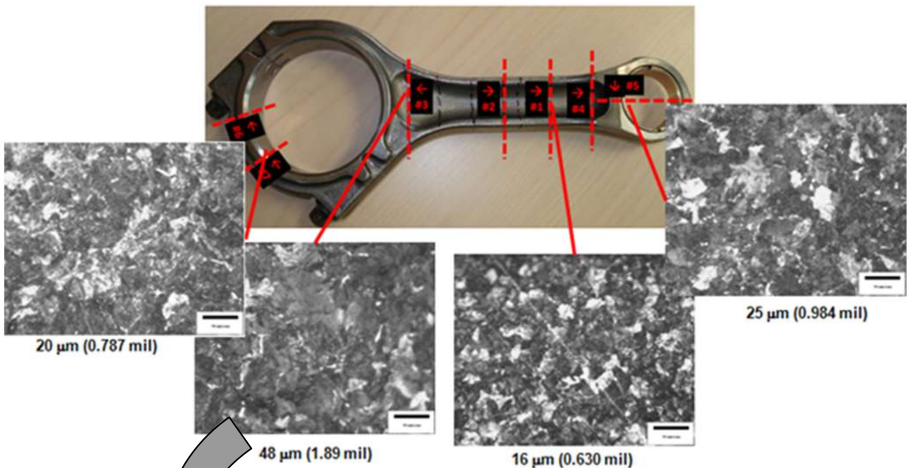


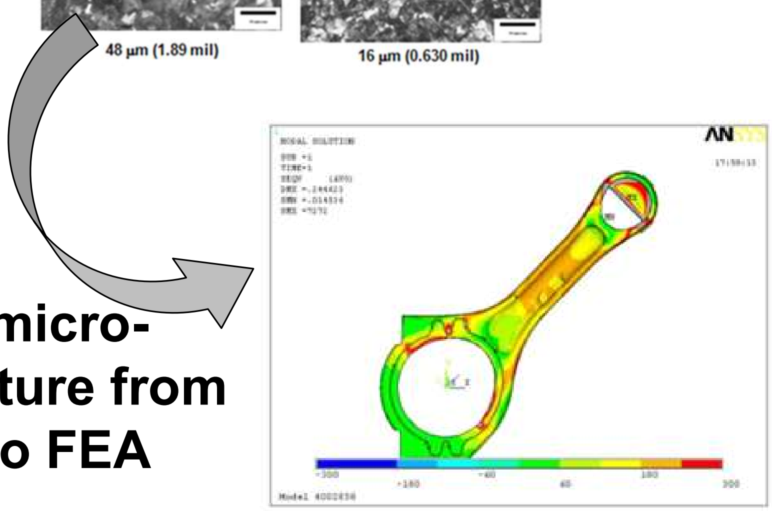
FEA Model of Surface Features





Application to the Component





Map micro-structure from part to FEA

Computational micro*structural* fatigue software.

- Each element in a FE model can have a different distribution of micro-structural properties.
- Virtual fatigue analysis simulation grain → element → component.
- Proven technology on forgings, castings, weldments (2 decades).
- Now being validated on AM parts.

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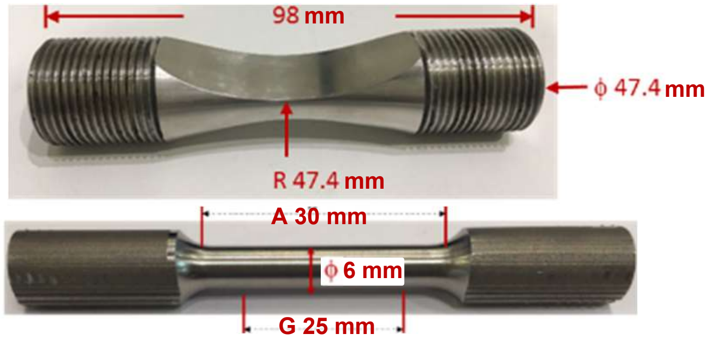
Advanced Remanufacturing and Technology Centre

A*STAR

Additive Manufacturing of IN-718

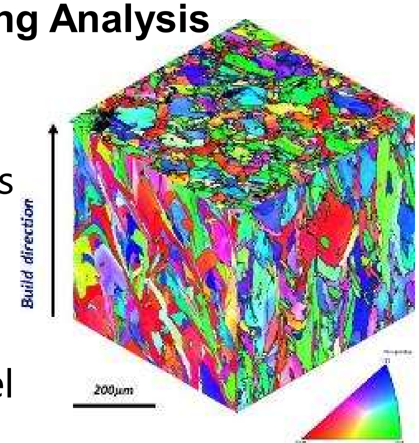
SLM → Heat Treated & Hardened IN-718



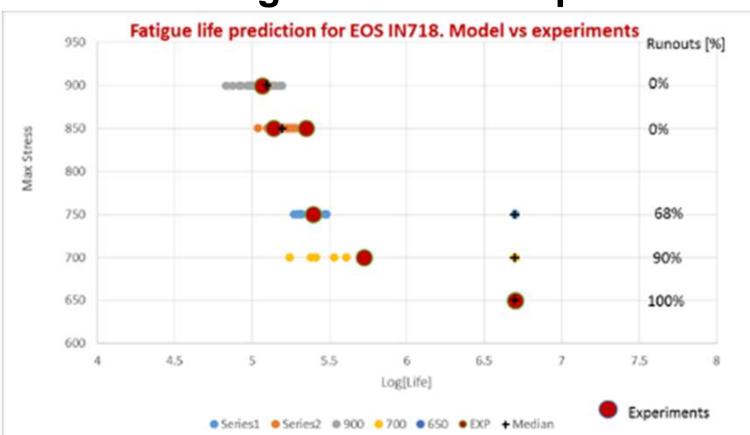
- Fatigue and tensile specimens built

Orientation Imaging Analysis

- Grain size and orientation in different directions within the specimens
- Used as inputs to VPS-MICRO model



Calibrated Fatigue Model w/Experiments



Conclusions

- Material and damage models in VPS-MICRO can predict fatigue response of SLM IN-718
- Evaluation of scatter in fatigue life for certifying AM components (difficult to do with limited physical tests) can be readily performed using this ICME method

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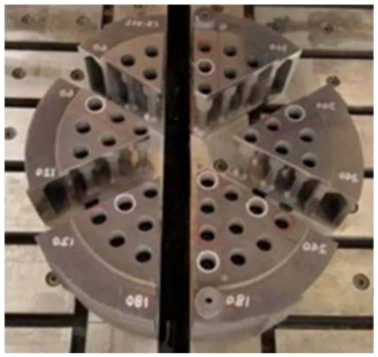
AEROJET ROCKETDYNE

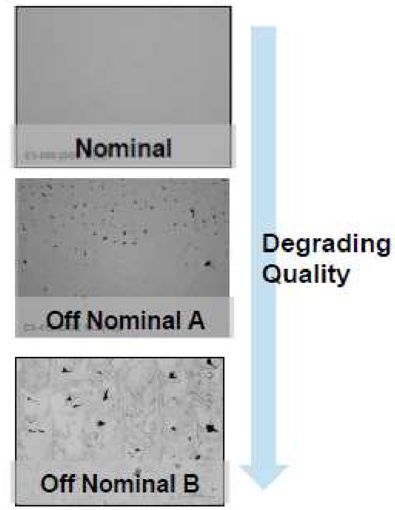
Burst Prediction of AM Nickel

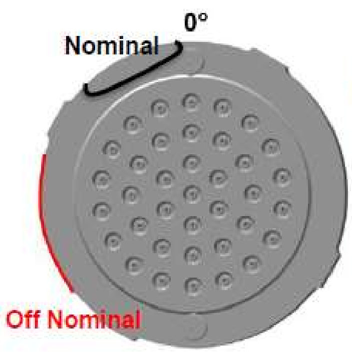
Superalloy Nozzle

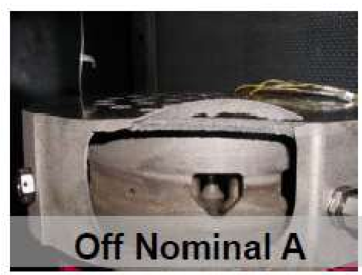
- SLM Mondaloy

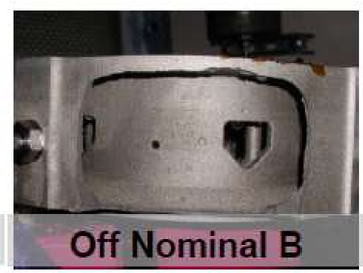


Unit	Operating Pressure	Proof Pressure	Vextec Calculated Burst	Actual Burst
Nominal	6.5 KSI	7.8 KSI	>13 KSI	15 KSI
Off-Nominal A	6.5 KSI	7.8 KSI	11-13 KSI	12.2KSI
Off-Nominal B3	6.5 KSI	7.8 KSI	11-12 KSI	10.5KSI
Off-Nominal B2	6.5 KSI	7.8 KSI	11-12 KSI	9.2 KSI









VEXTEC accurately predicted burst test failure location & pressure for different AM process settings.

VEXTEC

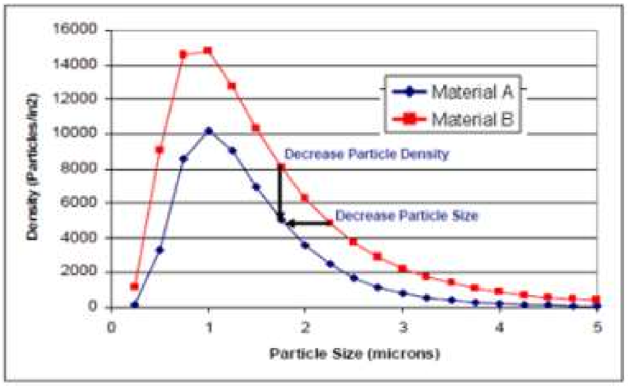
Boston Scientific

New Material Qualification

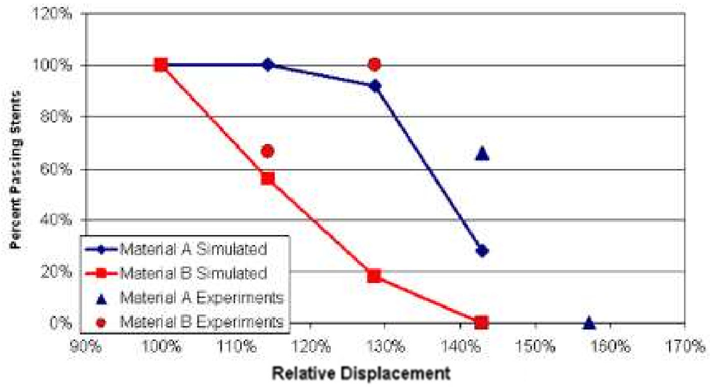
Alternative Material for Airway Stent

- **Sourcing a new material for entry into new markets**
- **Testing regimen to qualify a new material is a costly proposal**

Virtual Test of Material Cleanliness



Simulations vs. Physical Survival Tests



Conclusions

- **VPS-MICRO DOE simulations used by BSCI to develop response surface / design envelope**
- **Inclusion density was durability driver**
- **'Material B' was removed from new material candidate list (saved time and money by avoiding protocol testing)**

Re-cap

- Application of integrated computational materials engineering (ICME) software as part of a framework that uses:
  - AM process information
  - AM in-situ sensors
  - Stress analysis and damage tolerance simulations
- It allows the certification process to be re-structured into an affordable, rapid solution on a part-by-part basis:
  - Quantification of AM variation within and between parts
  - Reducing costs in operation and sustainment activities, while also increasing readiness
  - Proven workflow of the software's inputs/outputs allows for a reliable, repeatable computational process to assist decision making

This computational framework will provide the ability to optimize and scale AM processes virtually, reducing the subsequent physical test burden for qualification