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TRX
WEBINAR SERIES

9/23/2020

ICME Methods for Fatigue Performance Prediction of Metal AM Components

Presented By: **VEXTEC**

Host:
Jason Thomas, America Makes

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TRX WEBINAR SERIES

Today's Webinar:

ICME Methods for Fatigue Performance Prediction of Metal AM Components

Today's Presenters:

Michael Oja

Animesh Dey

Bob Tryon

To efficiently use Metal Additive Manufacturing to produce structural components, it is essential to have a robust protocol and software tool to certify the parts, especially if they are fatigue critical. With the objective of accelerating the qualification and adoption processes for new additive manufactured materials, VEXTEC's webinar presents a method for augmenting the traditional verification process with a model-informed software tool called VPS-MICRO®.

VPS-MICRO is an Integrated Computational Materials Engineering (ICME) based tool that predicts the risk of cyclic fatigue failure of an additive manufactured metal part based on the location-specific microstructure, defects, residual stress, and surface roughness. Using the software eliminates unsuccessful design options early in the design processes. Also, the software greatly reduces the test cost and time needed to determine the statistical confidence in the certified lifetime, reducing the need to acquire a large population of fatigue tests needed to do the same.

Presentation Outline

- Introduction
- Role of ICME in AM – rapid certification
  - Issues
  - Work with USAF
- Computational fatigue model
  - VPS-MICRO models, features
- Live overview of the software
- Examples
  - AM fatigue certification / prediction
- Q&A

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

Why Our Clients Work with Us

We help our clients to ***save time and money*** by:

Reducing

physical testing burden for qualification of new materials/sources

Accelerating

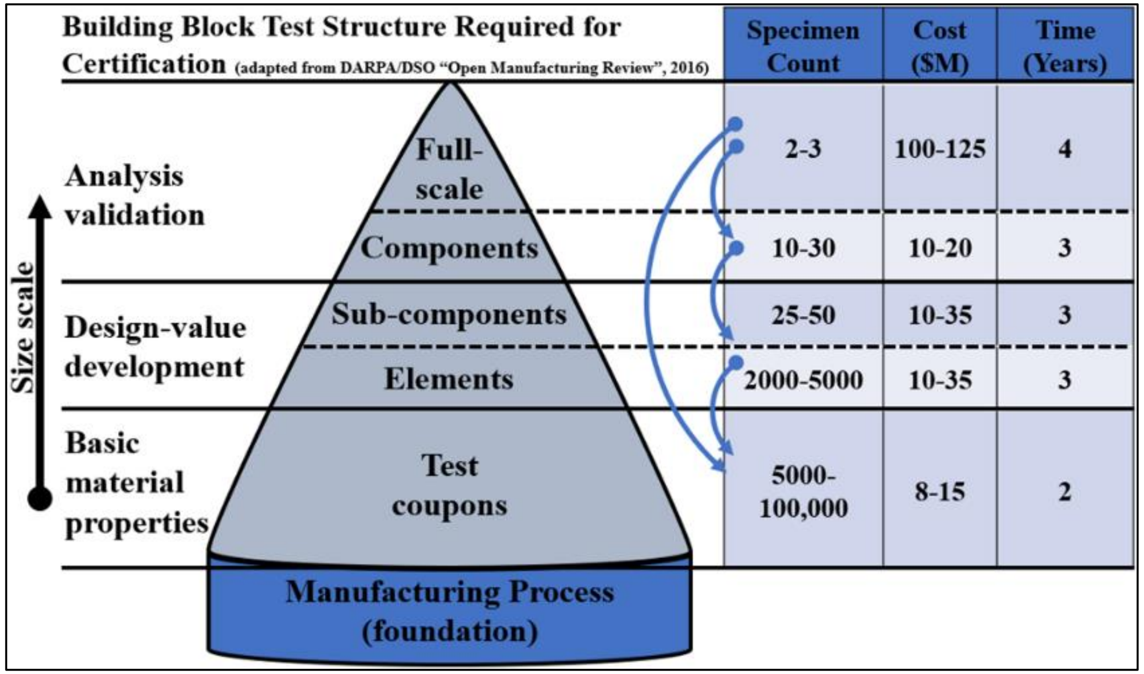
push of Additive Manufacturing into standard production

Identifying

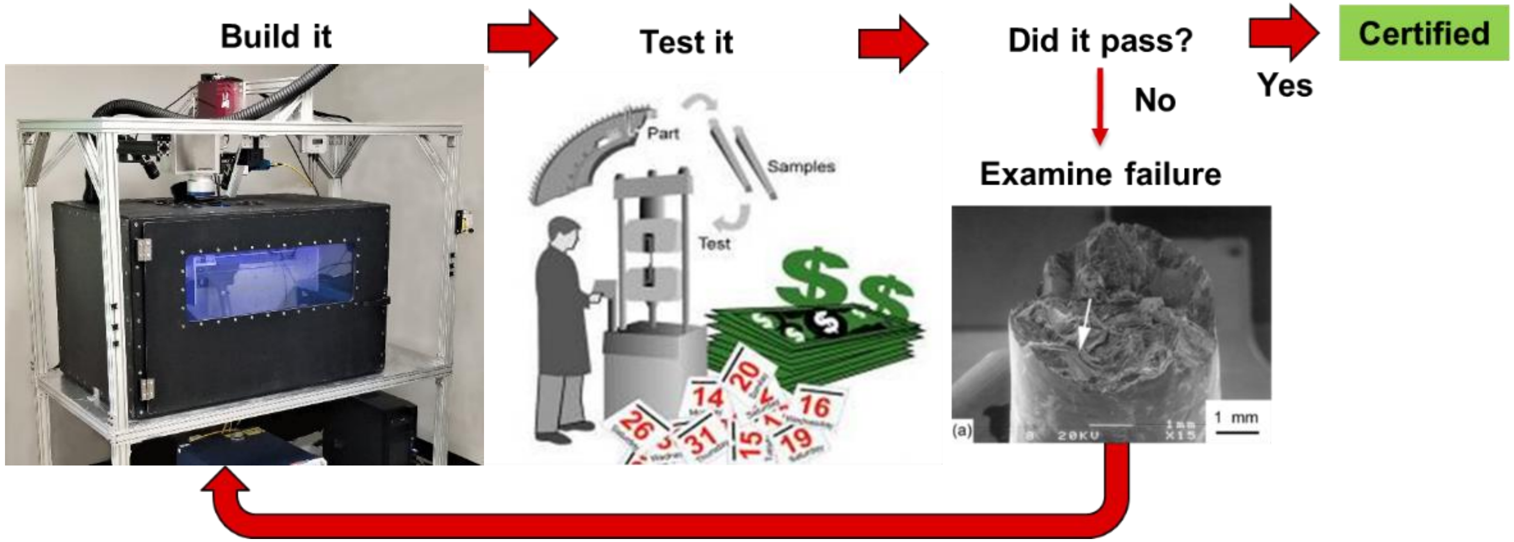
causes of component fatigue failure

Why ICME?

- **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

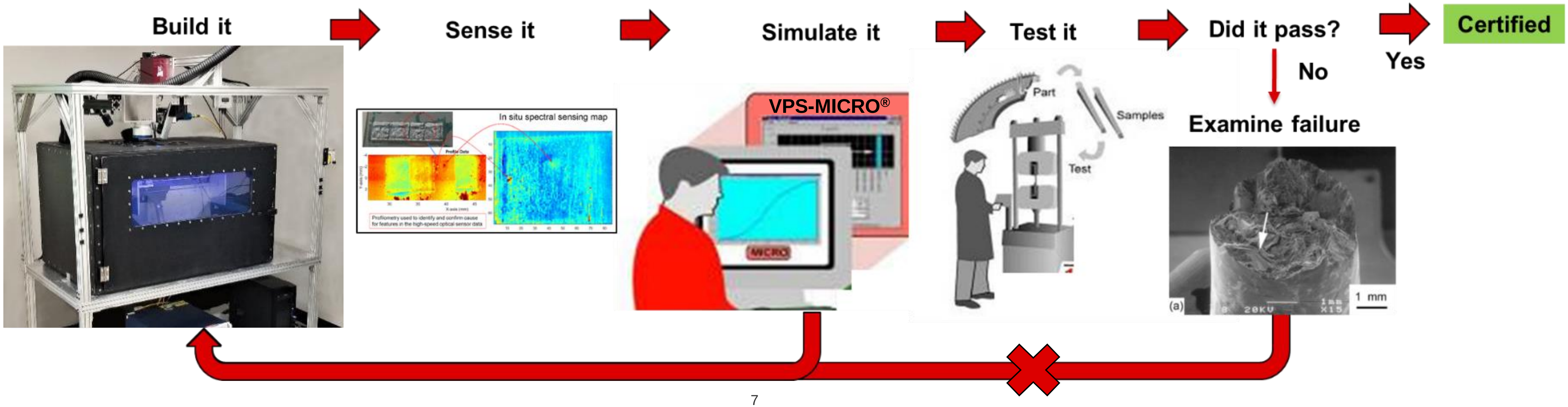


Integrated Computational Material Engineering (ICME) tools can provide up to **50% time/cost savings** for AM process development.

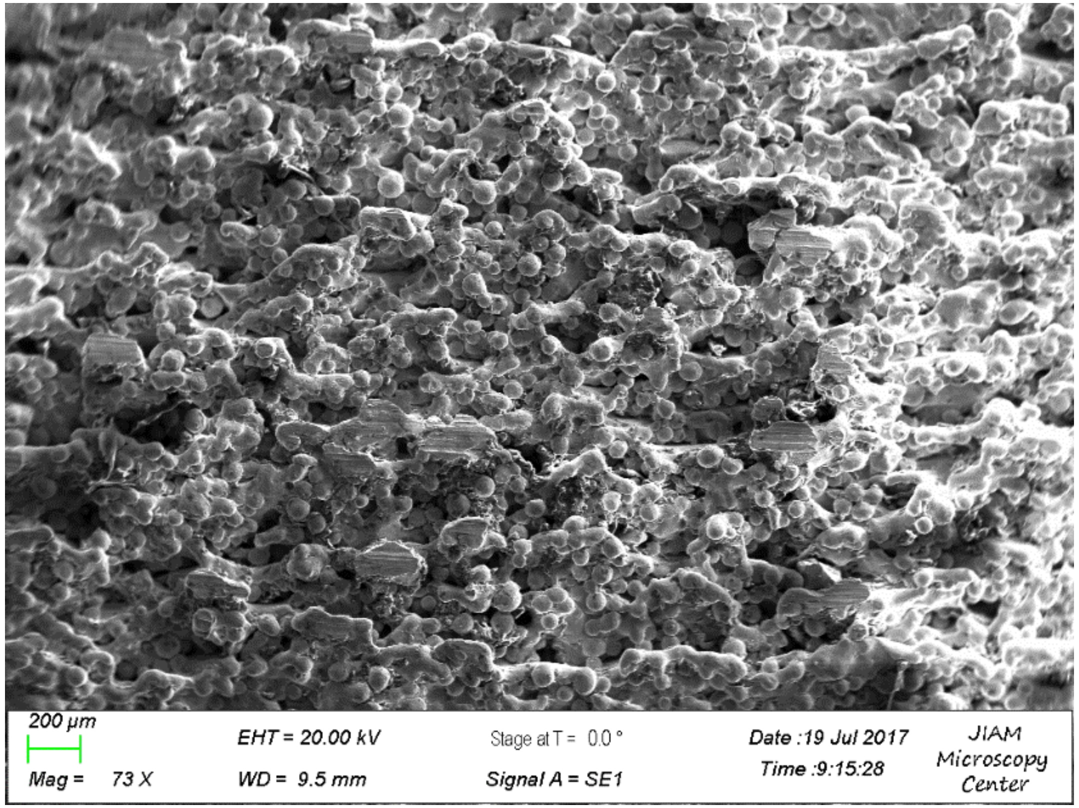


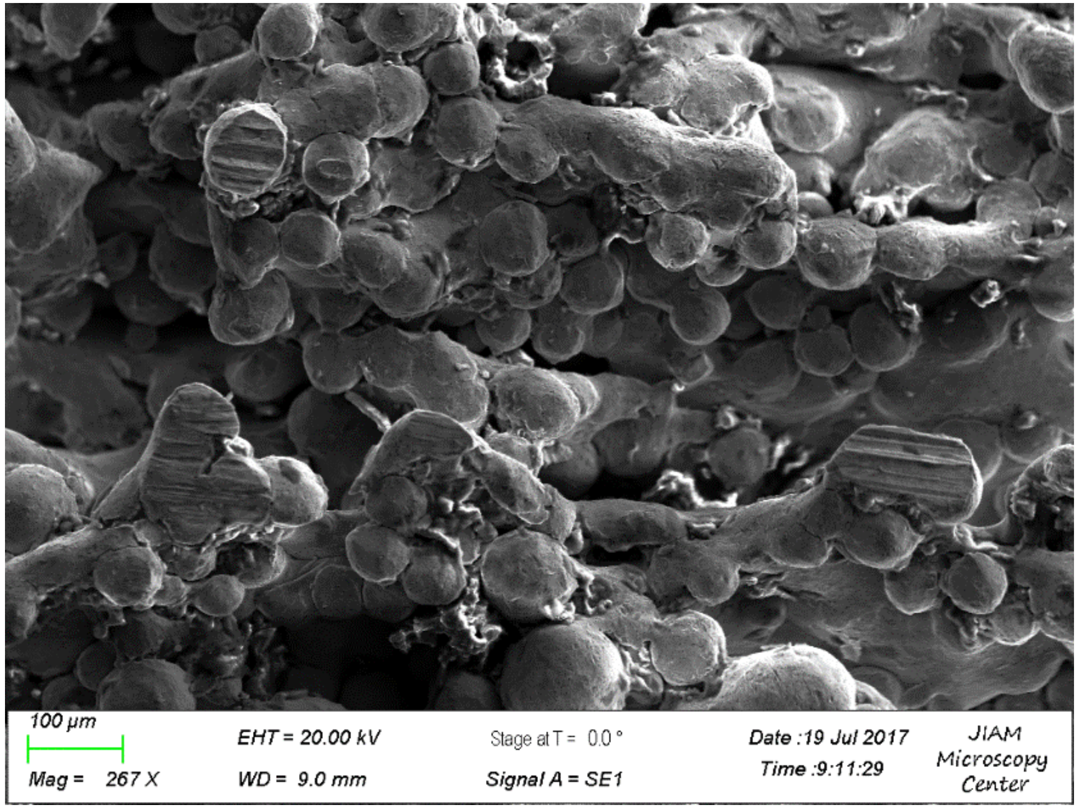
What Do We Mean by ICME-Based Certification?

- We are not changing the required elements 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.

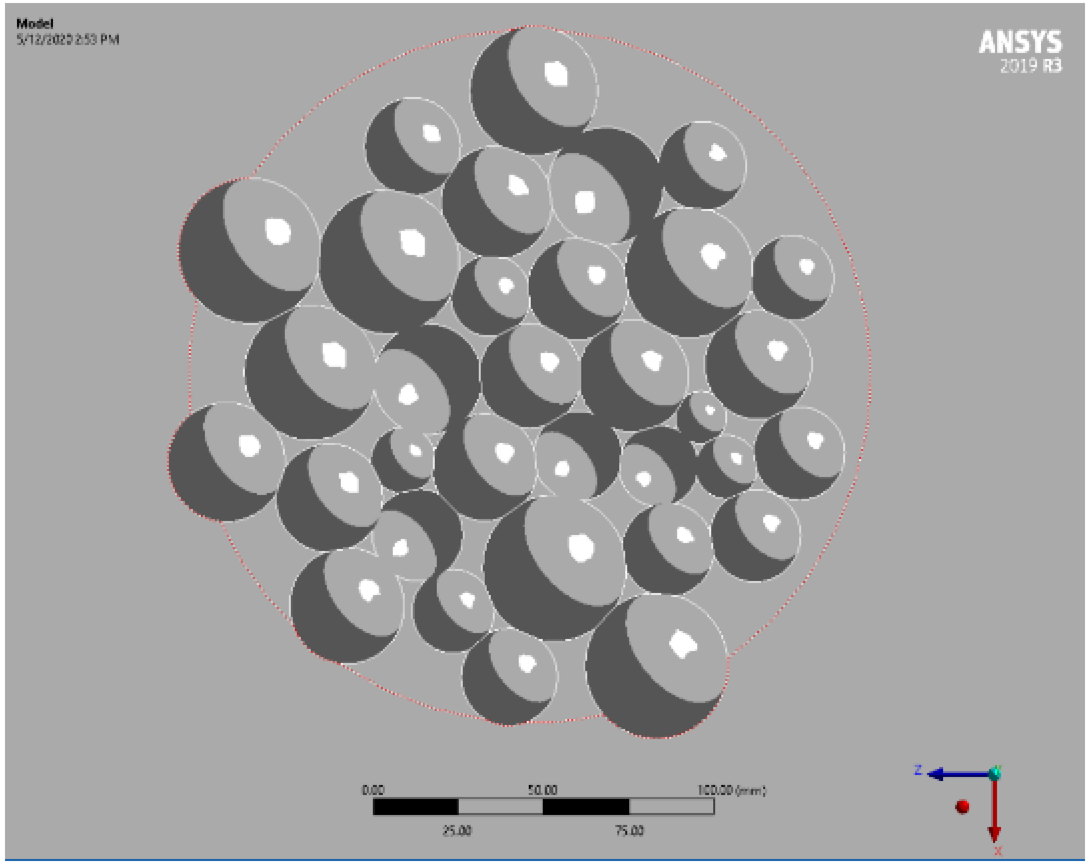


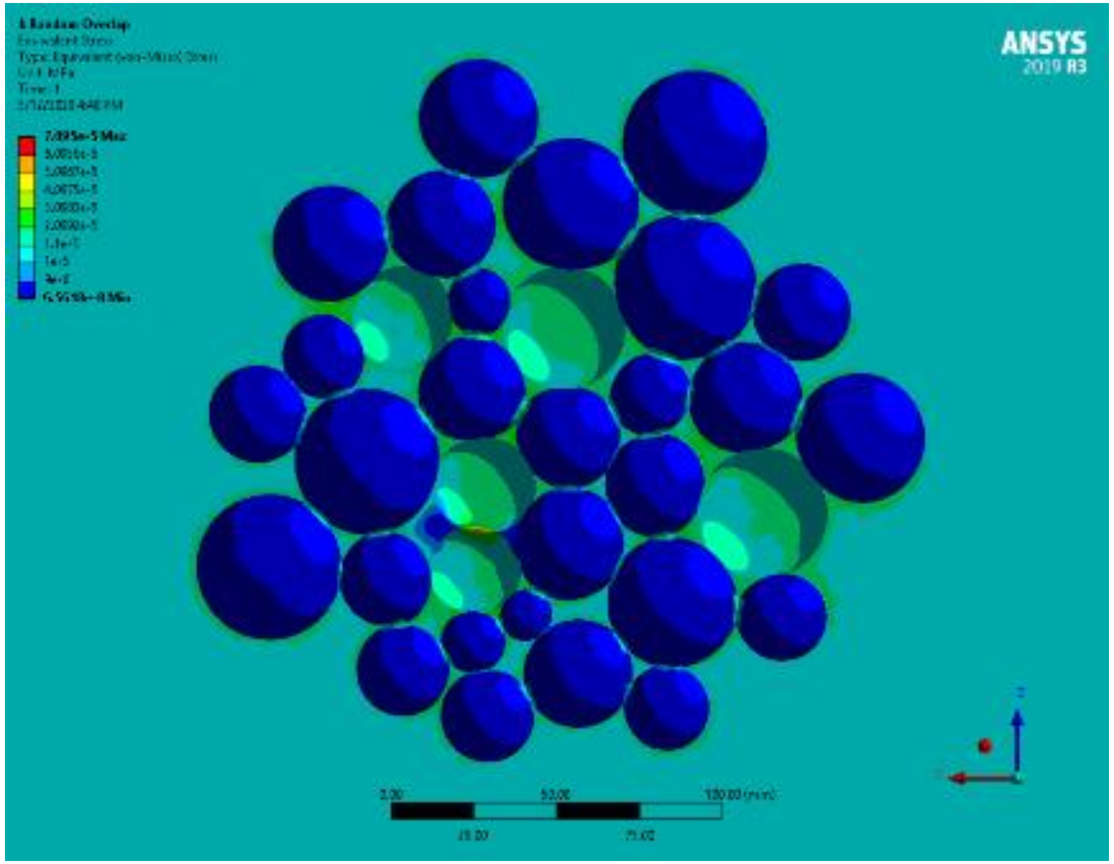
Metal AM Issues: As-Built Surface Morphology





FEA Model of Surface Features

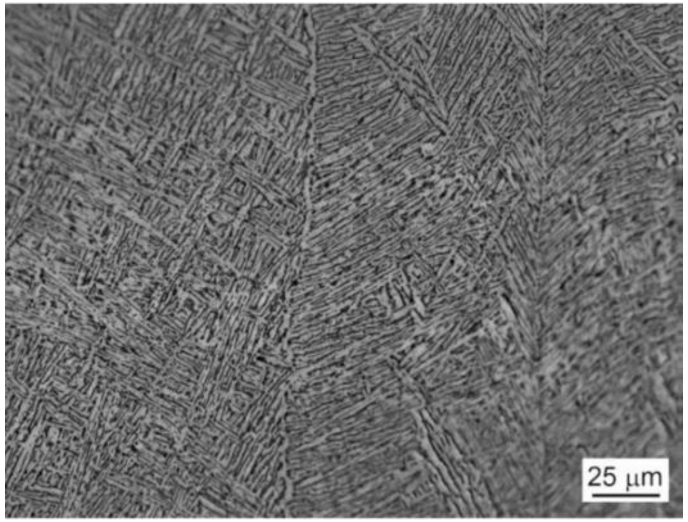




Build Orientation vs. Damage Mechanism

Horizontal Specimens

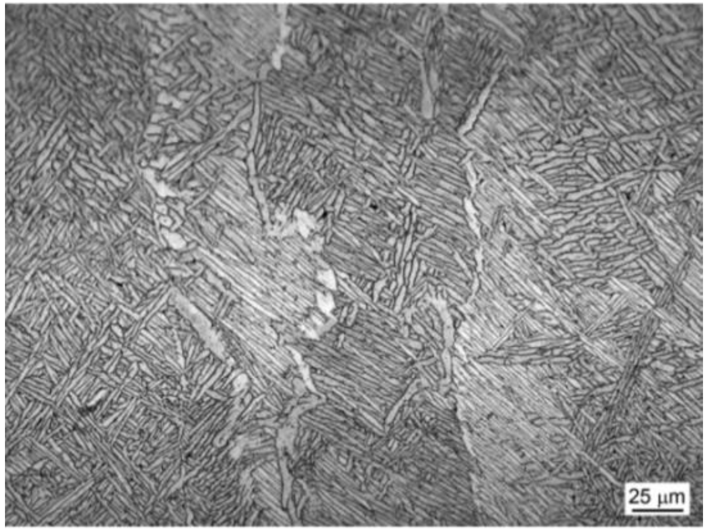
← Load direction



↑ 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)

Current USAF Initiatives

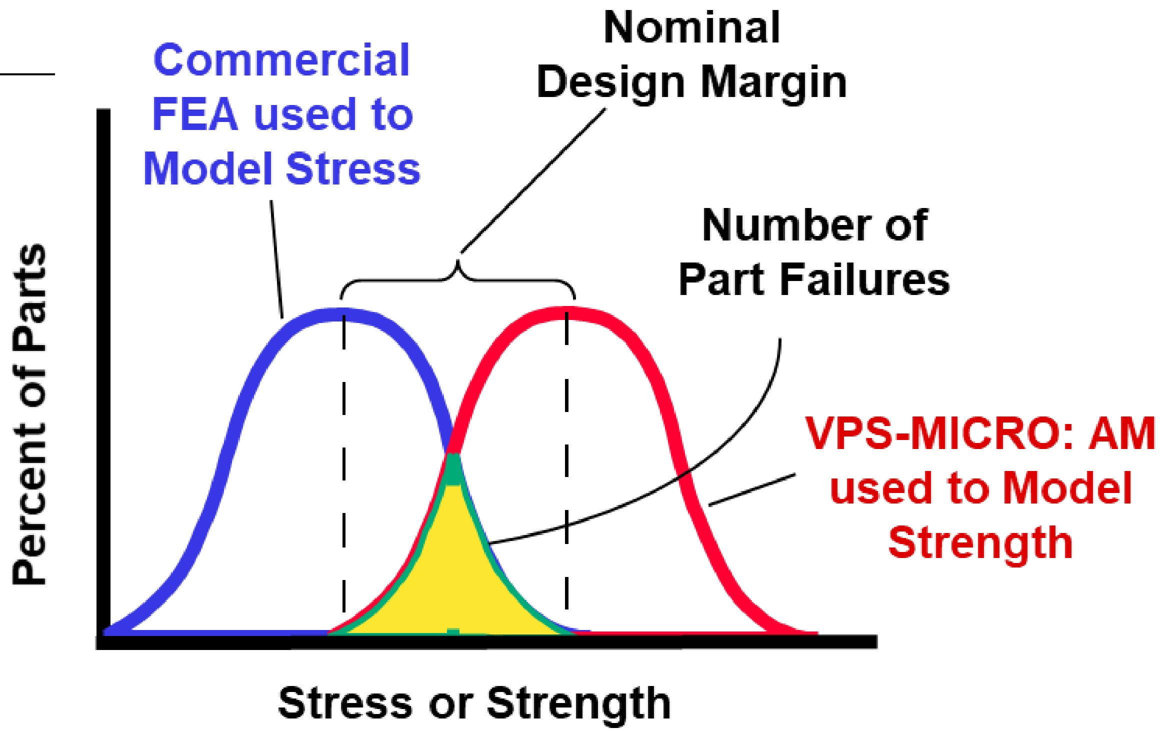
- **AFLCMC/RO Rapid Sustainment Office**
  - Rapid Qualification for Metal Additive Manufactured Parts
  - TPOC: Howard Sizek, howard.sizek@us.af.mil

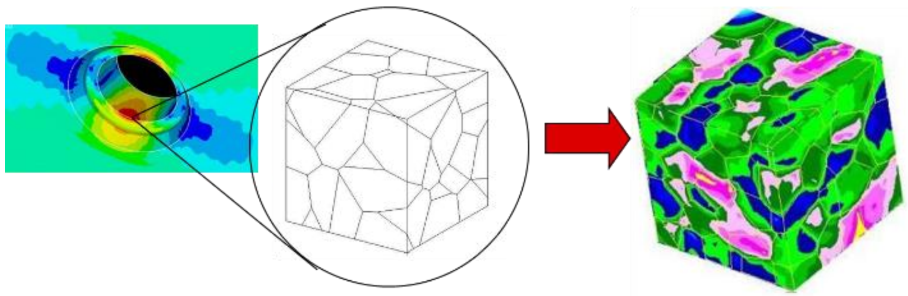
- **AFRL/RX**
  - Computational Simulation Software for Improved Fatigue Prediction of Additive Manufactured Components
  - TPOC: Pat Golden, patrick.golden@us.af.mil

VPS-MICRO Description

- 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.
  - VPS-MICRO addresses fatigue strength.
  - VPS-MICRO creates digital models of the material microstructure.
  - VPS-MICRO simulates effect of surface roughness.

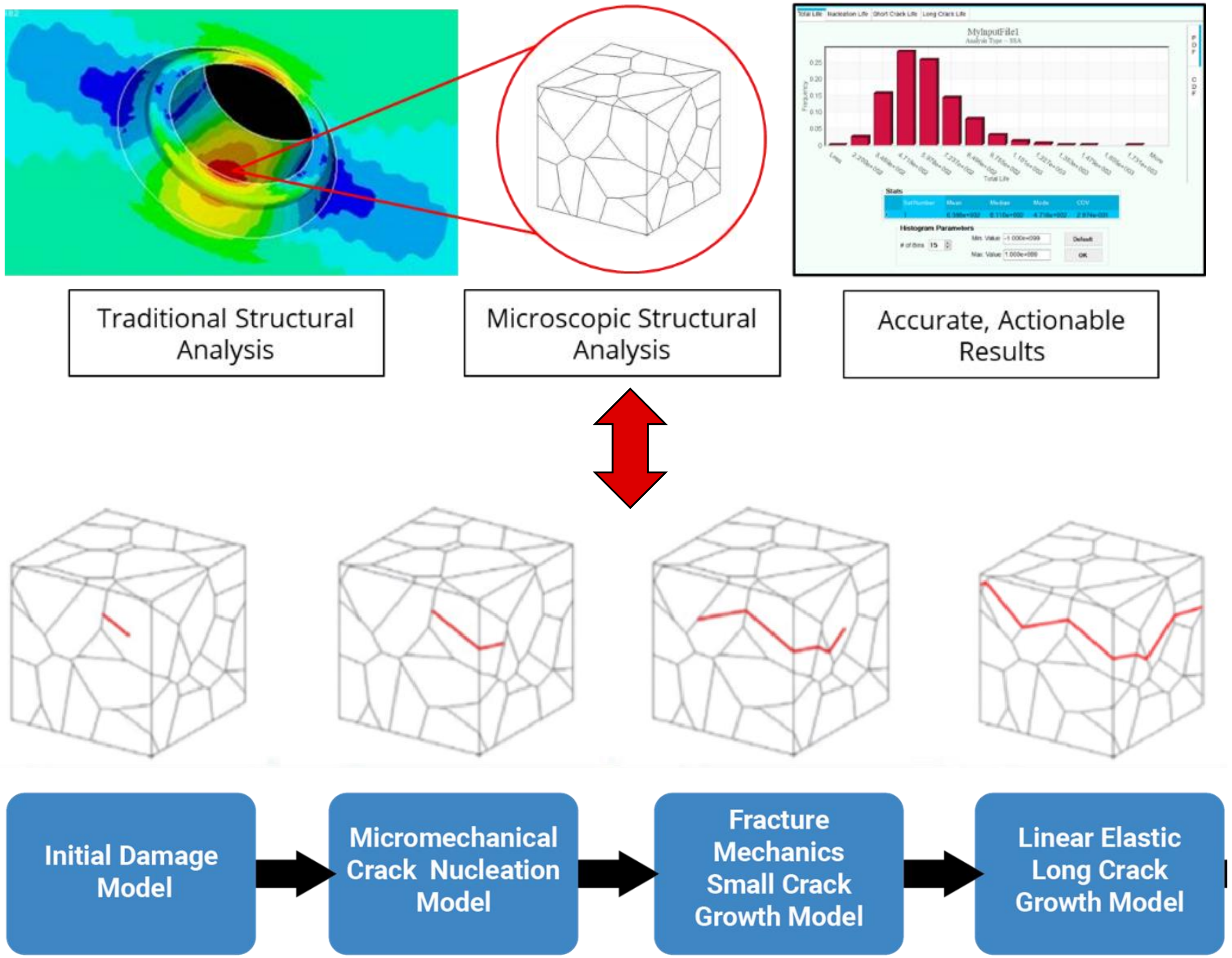
With AM, the need for analysis software is even more urgent because of the difficult-to-test-for internal surface roughness of complex geometries.





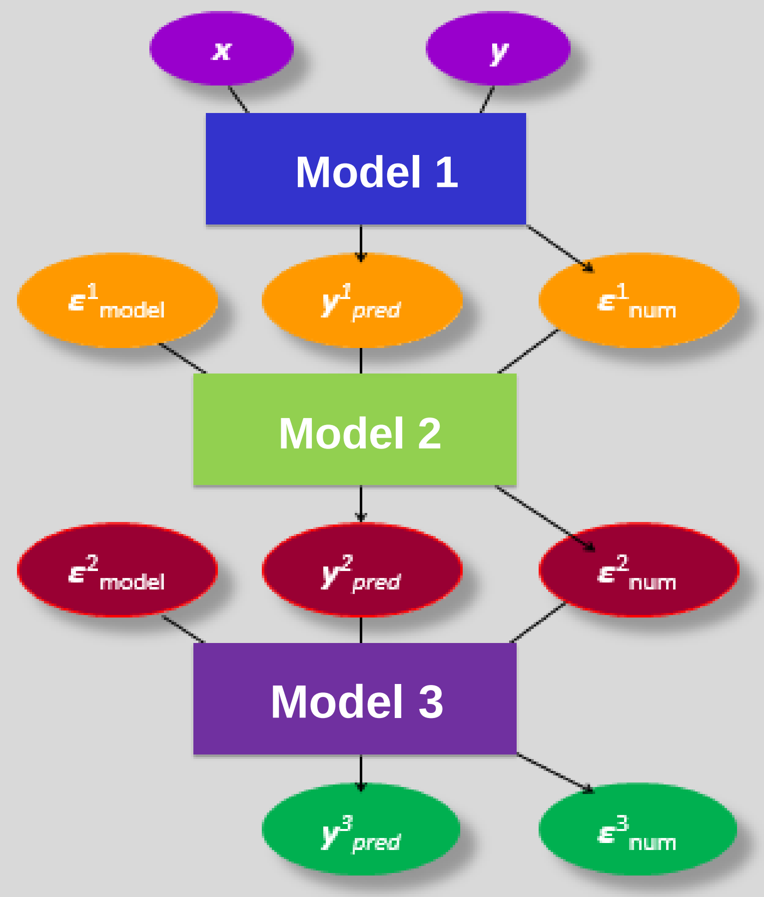
Non-Defense Commercial Solution: VPS-MICRO

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



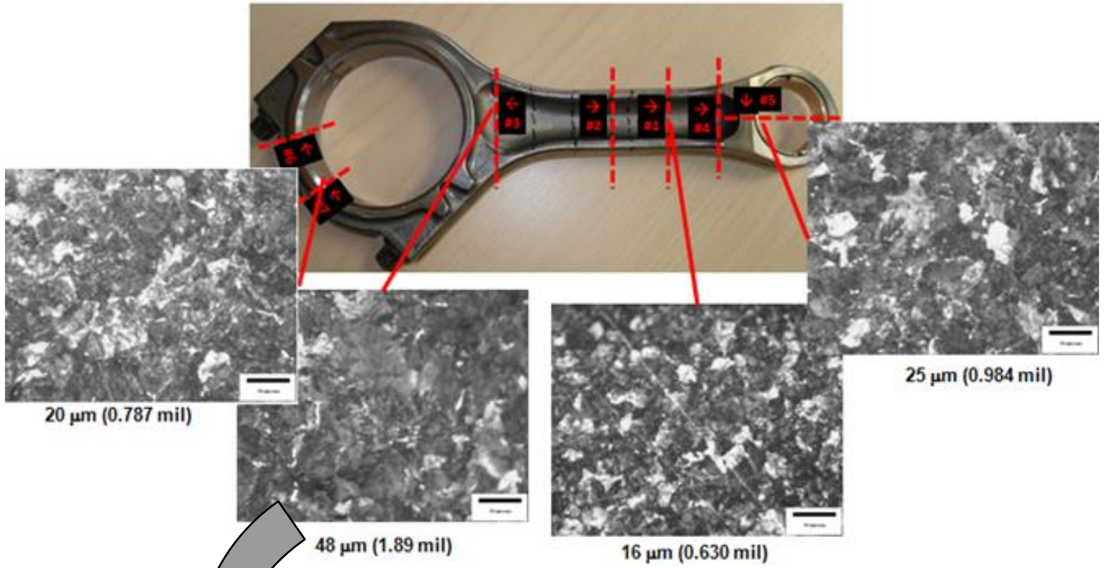
Uncertainty Propagation

- 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.

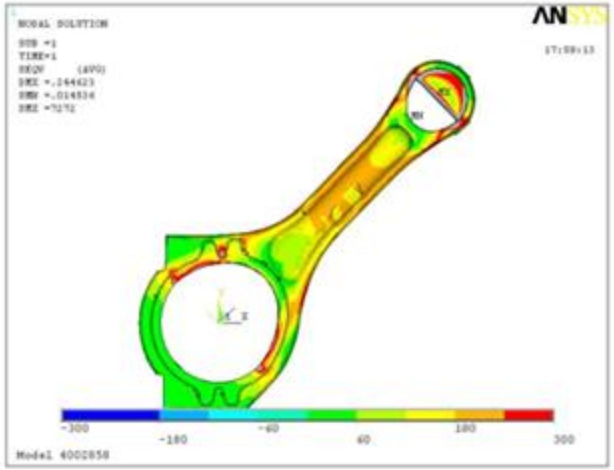


Uncertainty propagation across multiple levels in the Virtual Twin®

Application of ICME



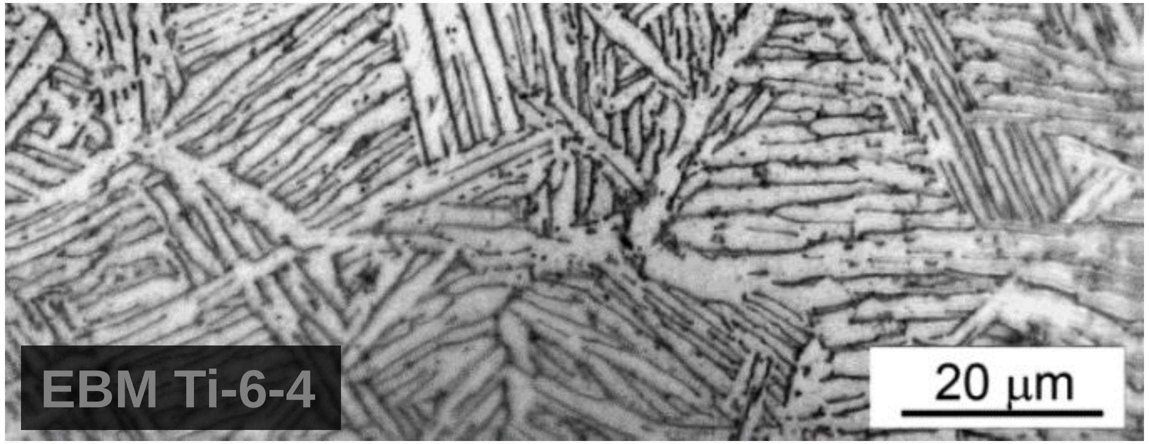
Map microstructure from part to FEA



VPS-MICRO – computational micro*structural* fatigue software.

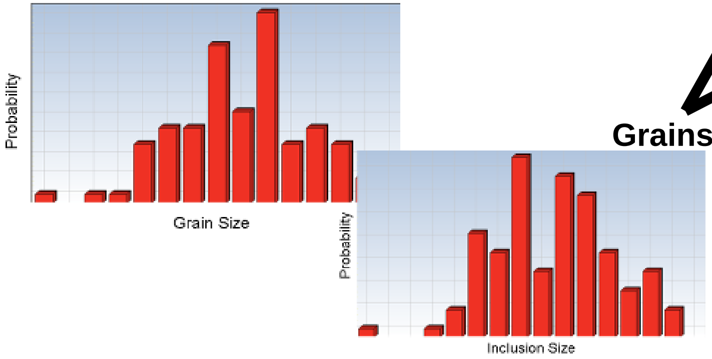
- Each element in a FE model can have a different distribution of microstructural properties.
- Virtual fatigue analysis simulation grain → element → component.
  - System reliability
- Proven technology on forgings, castings, weldments (2 decades).
- Now being validated on AM parts.

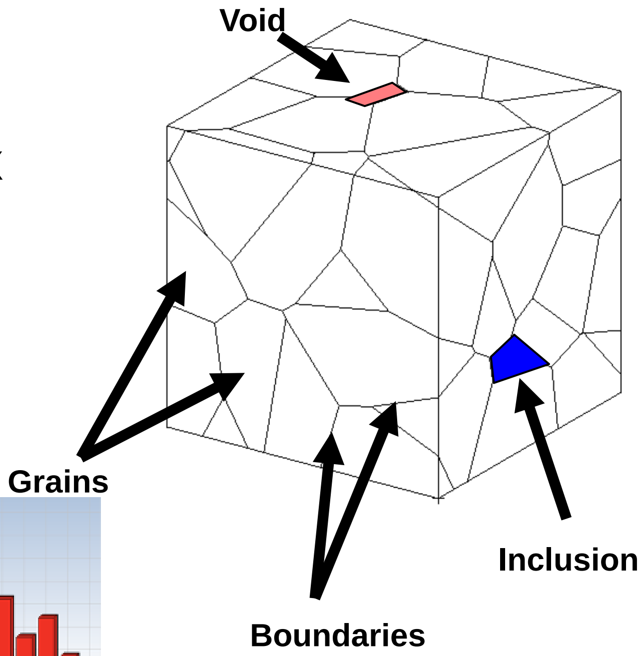
Microstructural Definition



Microstructural Volume Element

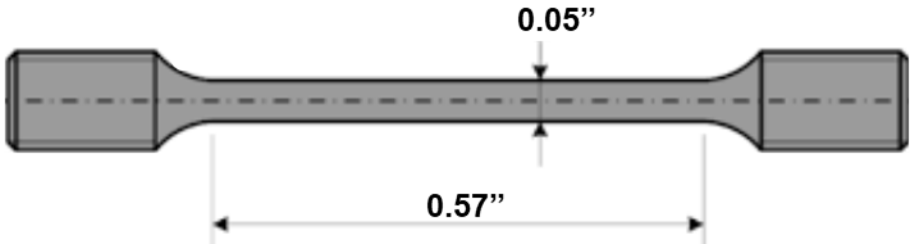
- Microscale matrix material model
- Voids and NMIs





Use VPS-MICRO to Simulate Fatigue Test

- Specimen will be a machined smooth round bar.
  - Gage diameter = 0.05 in
  - Gage length = 0.57 in
  - **Gage surface area = π * 0.05 in * 0.57 in = 0.09 in^2**
- Material is Ti-6Al-4V.
  - Forged/β-annealed vs. EBM
- First: simulate constant amplitude experiments on forged/β-annealed specimens at six different stress levels.
  - Ranging from 78-117 ksi; cyclic stress ratio R= 0.1
- In this example, 100 different bars are being simulated at each load level.

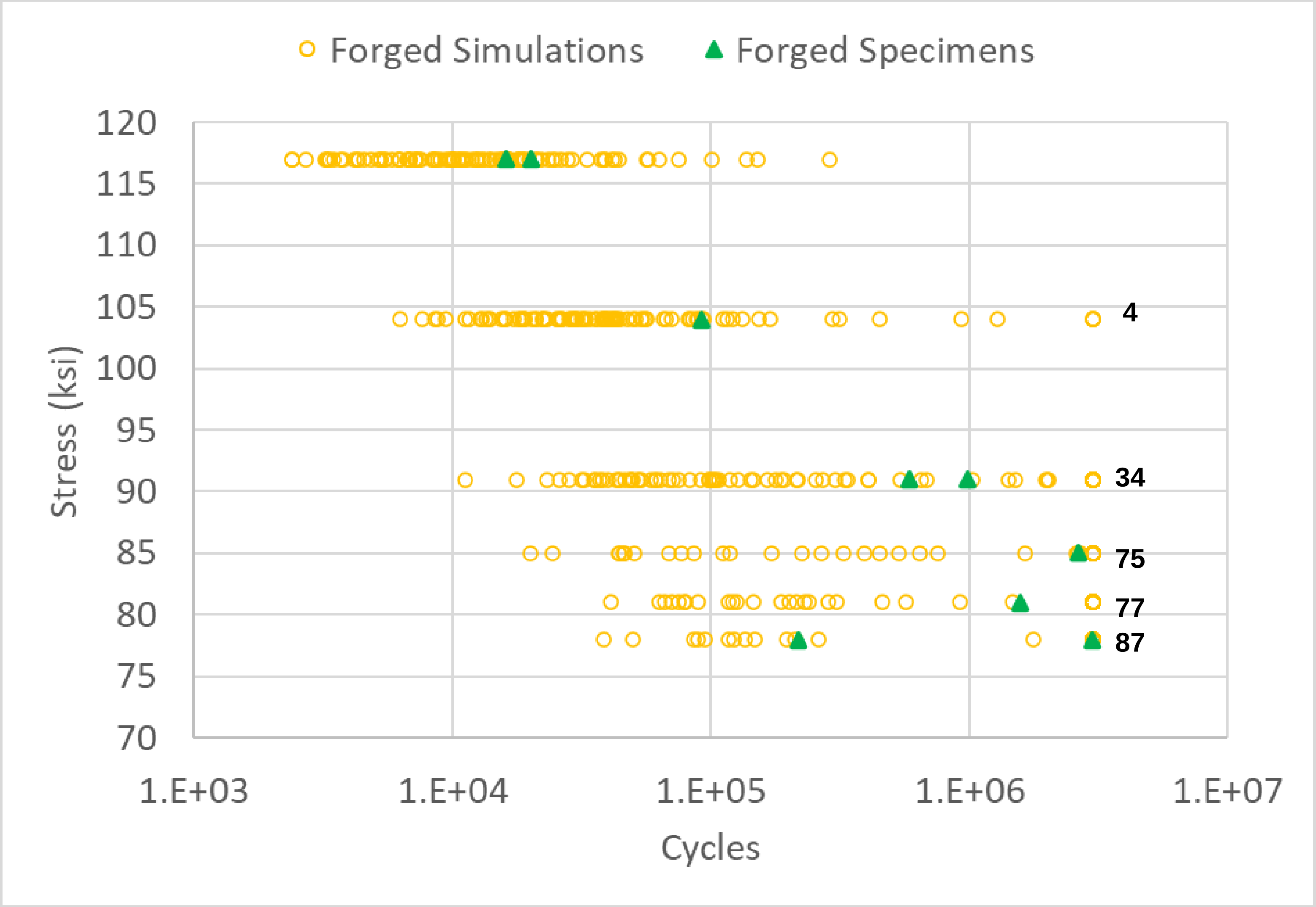


Forged Ti-6Al-4V Fatigue Specimens – Machined

EBM Ti-6Al-4V Fatigue Specimens – Unmachined

VPS-MICRO Results Compared to Test Data

- Forged specimens
- 100 specimens simulated per loading level



Material Property Comparison (Forged vs. EBM)

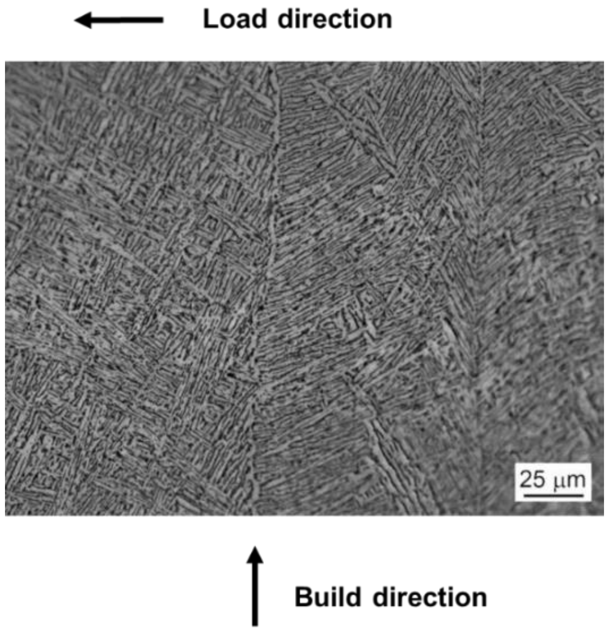
†Additional model parameters (not listed) were unchanged between forged & EBM conditions

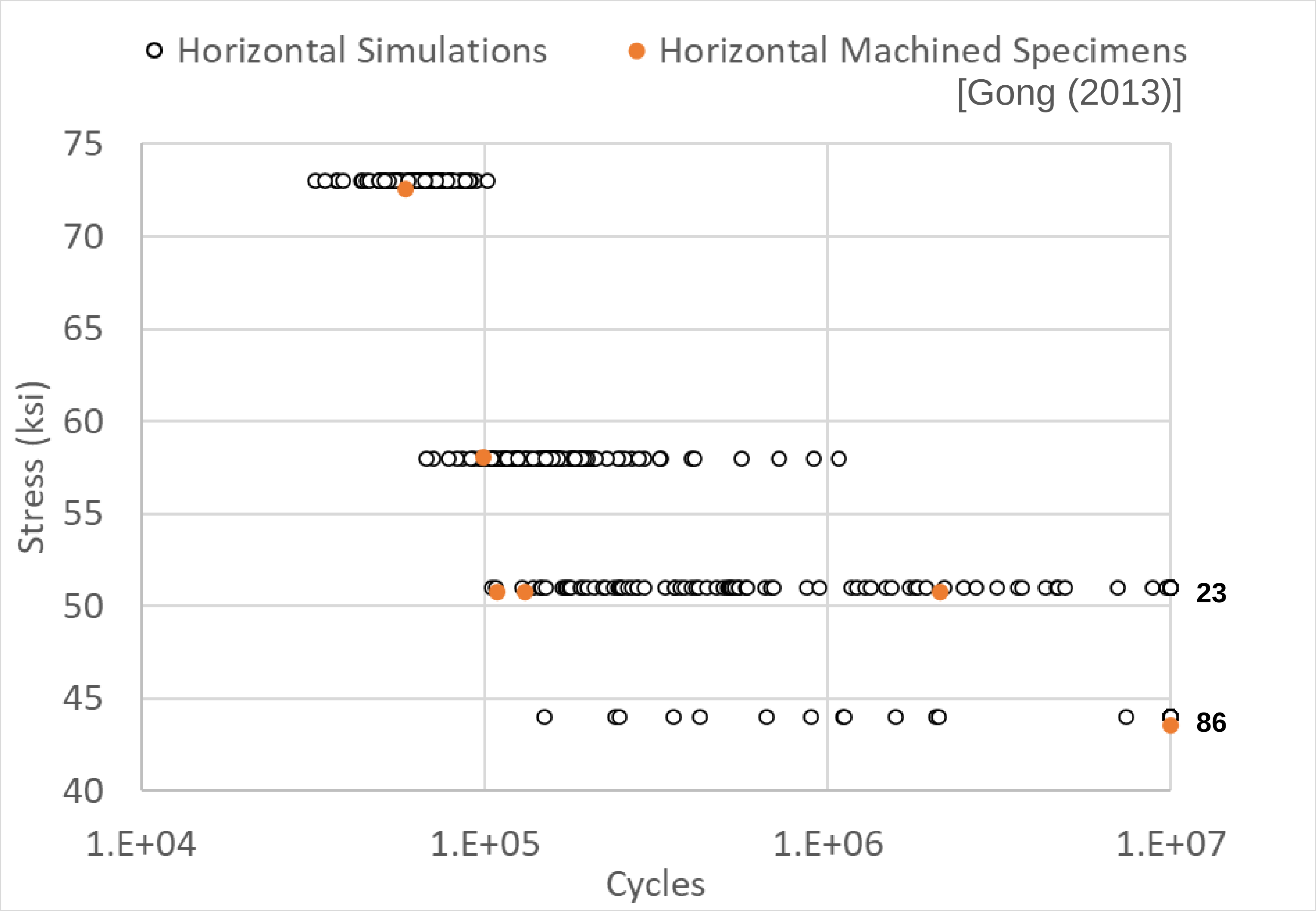
††"Grain size" is the size of the α-lamellar colonies within prior β grains

	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

VPS-MICRO Results Compared to Test Data

- Horizontal built specimens
- 100 specimens simulated per loading level

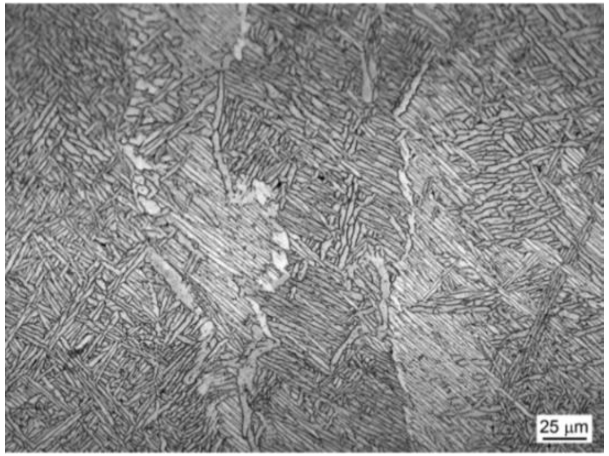




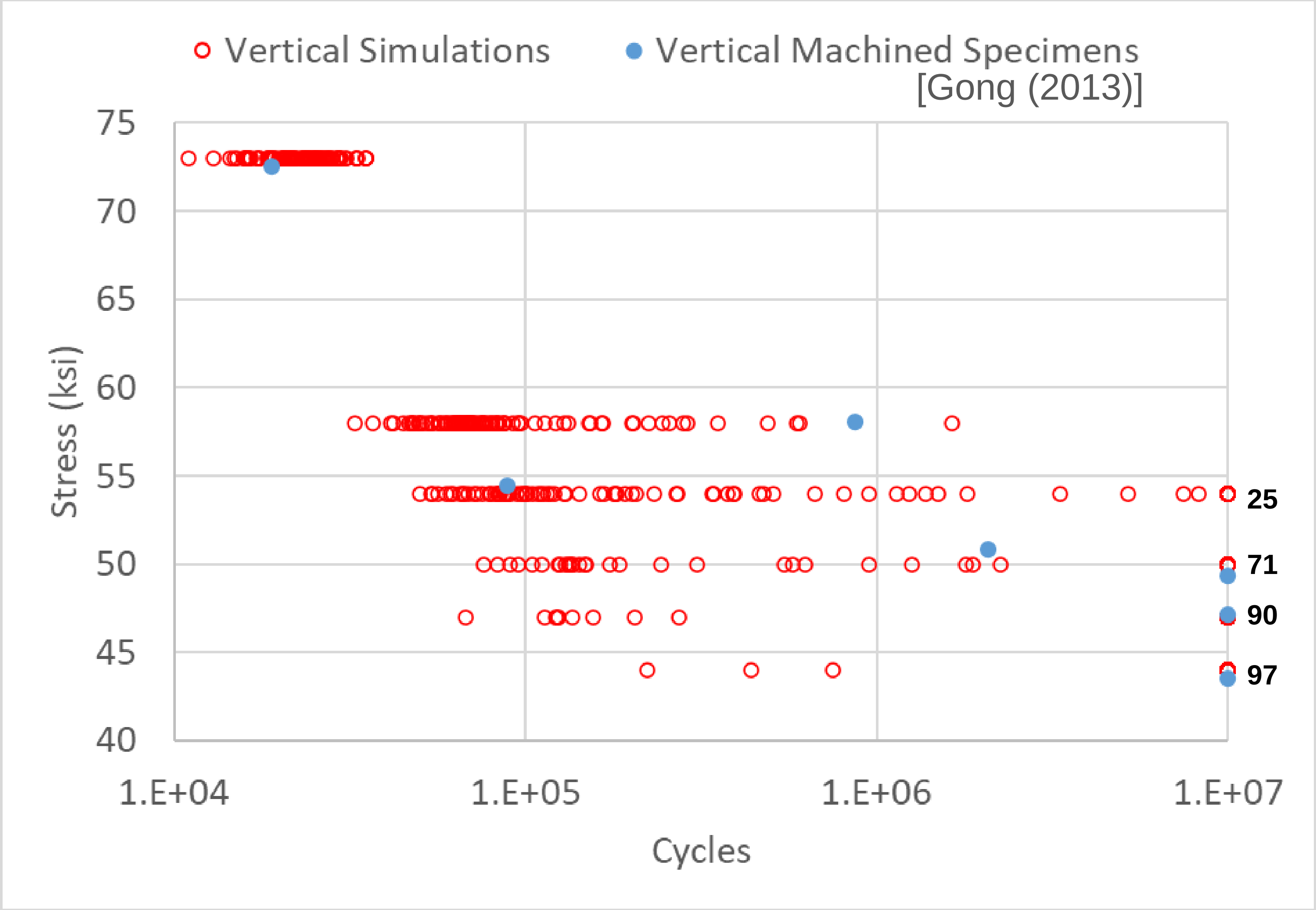
VPS-MICRO Results Compared to Test Data

- Vertical built specimens
- 100 specimens simulated per loading level

Load direction

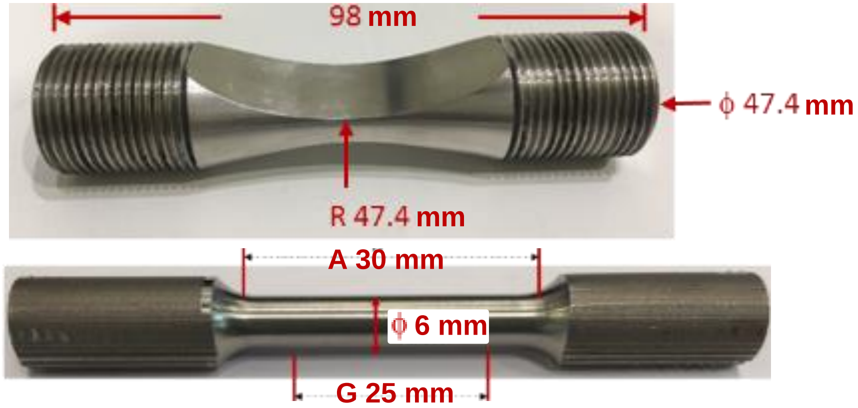


Build direction



Additive Manufacturing of IN-718

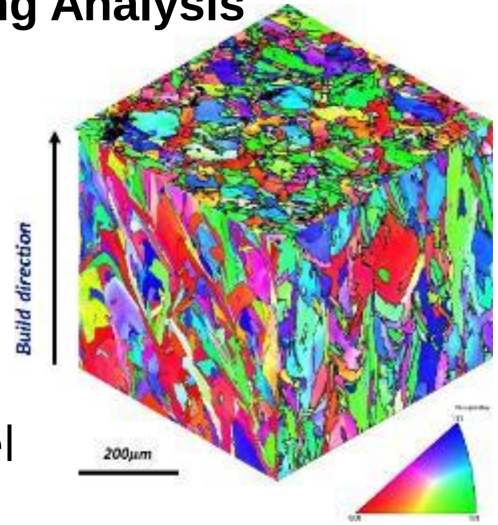
SLM → Heat Treated & Hardened IN-718



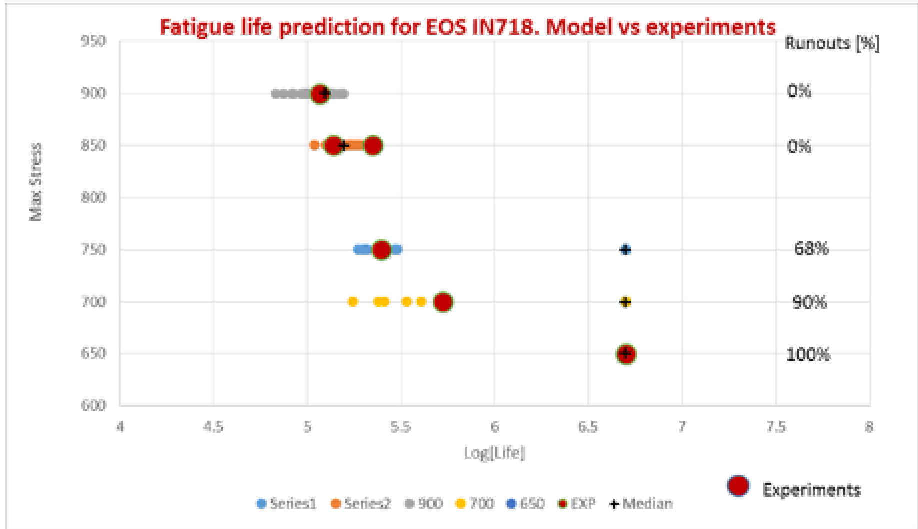
- Fatigue and tensile specimens built

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



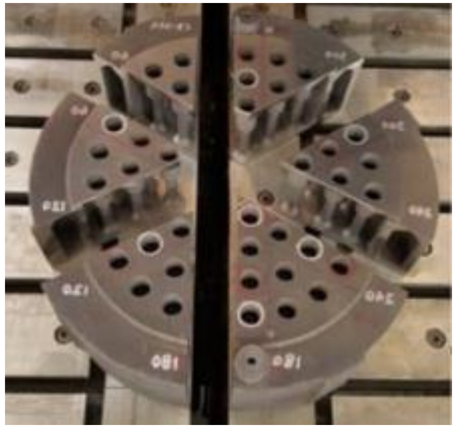
Conclusions

- 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

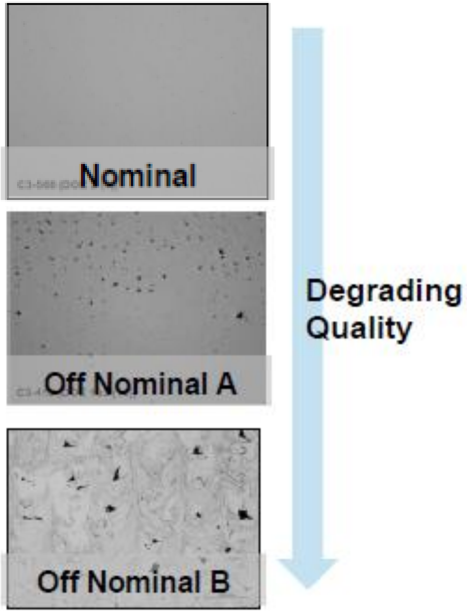
Burst Prediction of AM Nickel

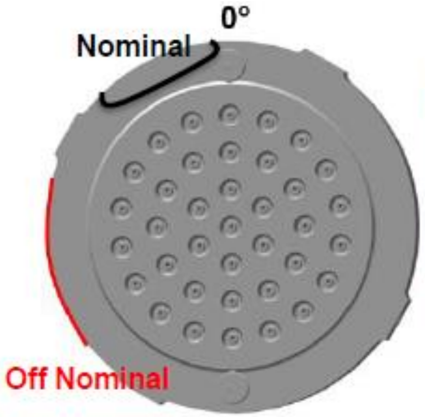
Superalloy Nozzle

- 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





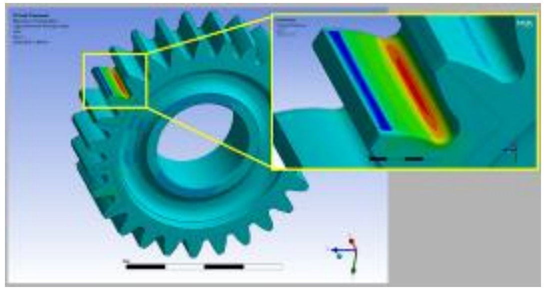
VEXTEC accurately predicted burst test failure location & pressure for different AM process settings.

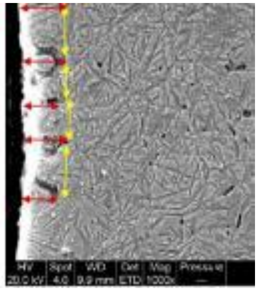
Gear Tooth Fatigue Testing

Single Tooth Bend Fatigue

- Standard test used to evaluate gear materials and processing
- Large time and cost commitments

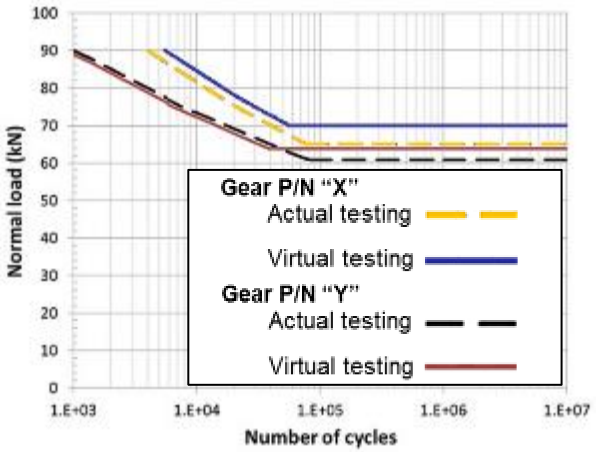
VPS-MICRO Computational Models





- FEA and residual stresses (peening)
- Modeling accounts for microstructural features & variability (carburization)

Virtual Results vs. Physical Testing



- Virtual testing captured S-N behavior, damage mechanisms & physics of failure

Conclusions

- Limited material testing → high-fidelity ICME fatigue model that accurately predicted performance
- Virtual trade studies with interdependent design / material / processing variables
- Reduced risk in evaluating new materials and processing schemes

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Partnerships with our clients are formed on convenient terms:

Software subscription packages (licensing and support)

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QUESTIONS?

Please type your questions into the Q&A section of the WebEx screen and we will do our best to answer them all.

If you have additional questions that require a more in-depth conversation, please contact Michael Oja directly via moja@vextec.com.