ICME to Quantify the Effect of Uncertainty in Microstructure on the Fatigue Performance of Additively Manufactured Parts

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Acknowledgements

- **Additional authors:**
  - **Robert Tryon, Robert McDaniels, Animesh Dey (VEXTEC)**
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- **Visit VEXTEC's exhibit booth in the Poster Hallway and pick up a Nashville-original GooGoo Cluster!**

Objectives

Use Integrated Computational Materials Engineering (ICME) to:

- Link processing-to-microstructure, and microstructure-to-performance

- Link local properties to overall component durability

- Quantify effects of AM process variations on mechanical performance of AM-built parts

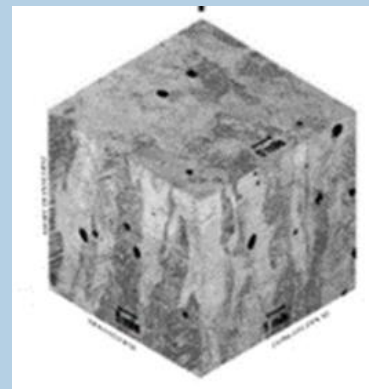- Extend modeling of conventionally-processed materials to predict performance of AM-processed materials

AM Presents New Opportunities

- **Conventional design based on a static materials library**

  – **Design is separated from material development**

- **<u>AM requires integration of product design and material properties</u>**

Class 3 Testing
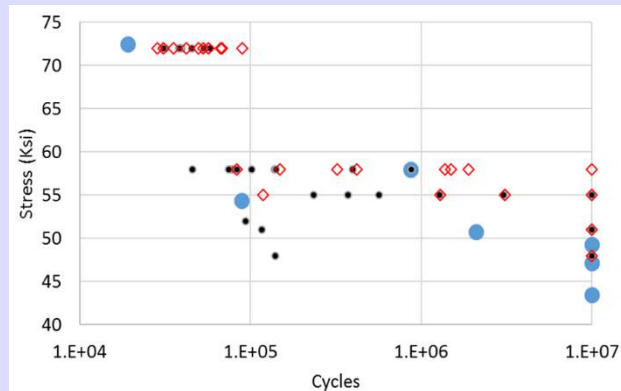
Class 1 Testing

Required Durability → **Allowable Microstructure** → **Range of Processing Parameters**

AM: An Ideal Application for ICME

20 μm (0.787 mil)

48 μm (1.89 mil)

16 μm (0.630 mil)

25 μm (0.984 mil)

Map microstructure from part to FEA

**VPS-MICRO® – computational microstructural 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)**
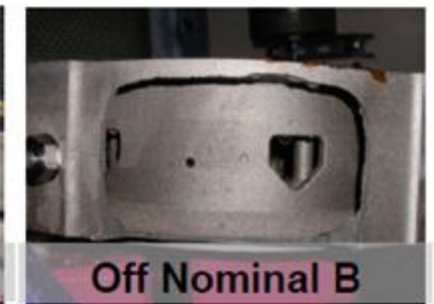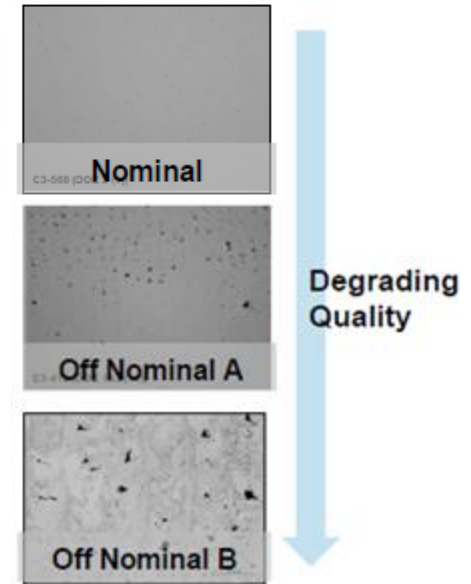- **Now being validated on AM parts**
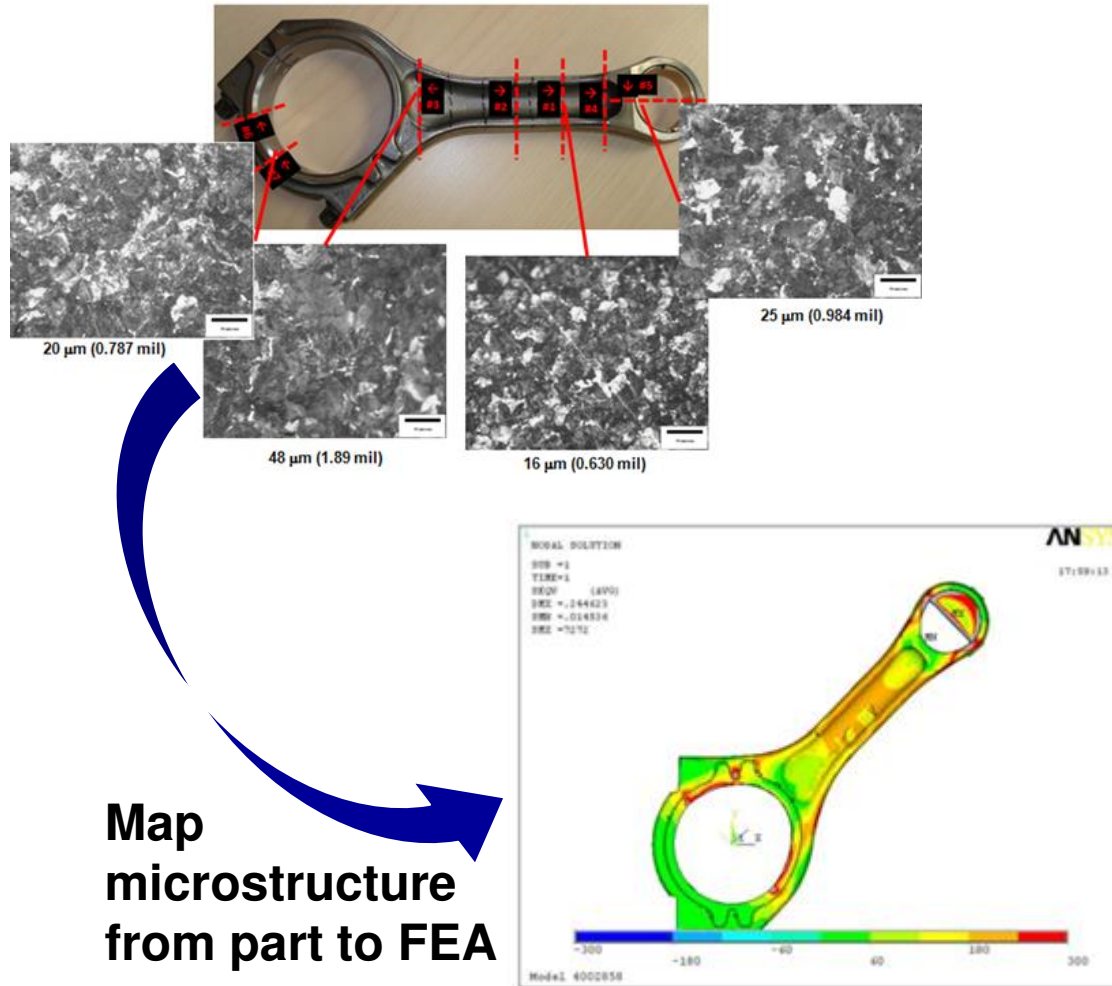
Burst Test Prediction of AM Nickel Nozzles

Nickel Superalloy Nozzle

- SLM Mondaloy
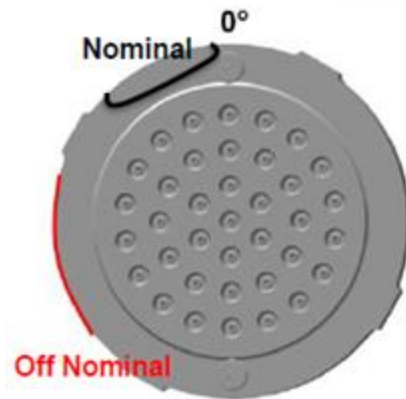
Unit	Identifier	Operating Pressure	Proof Pressure	Vextec Calculated Burst	Actual Burst
Nominal	C3-11/28/16	6.5 KSI	7.8 KSI	>13 KSI	15.022KSI
Off-Nominal A	C3-11/14/16	6.5 KSI	7.8 KSI	11-13 KSI	12.218 KSI
Off-Nominal B2	C3-120816	6.5 KSI	7.8 KSI	11-12 KSI	In Process
Off-Nominal B3	C3-011217	6.5 KSI	7.8 KSI	11-12 KSI	10.555 KSI

Nominal

Off Nominal A

Degrading Quality

Off Nominal B

Nominal 0°

Off Nominal

Nominal

Off Nominal A

Off Nominal B

VPS-MICRO accurately predicted burst test location & pressure for different AM process settings

Durability Certification in Fatigue

<u>NAVAIR-funded program to develop ICME-based certification of electron beam melted (EBM) Ti-6Al-4V alloy [STTR N16A-T004]</u>

- **Certification for cyclic load resistance is expensive**

  – **Long duration of each test**

  – **Large scatter in results requires many tests to achieve confidence**

- **VEXTEC used knowledge about forged / β-annealed Ti-6-4 to develop a certification model for AM Ti-6-4, and compared to physical test data[1]**

  – <u>**Explicitly modeled differences in microstructure, defects, and damage mechanisms**</u>

[1]Gong, Haijun, "Generation and detection of defects in metallic parts fabricated by selective laser melting and electron beam melting and their effects on mechanical properties." (2013). Electronic Theses and Dissertations. Paper 515.

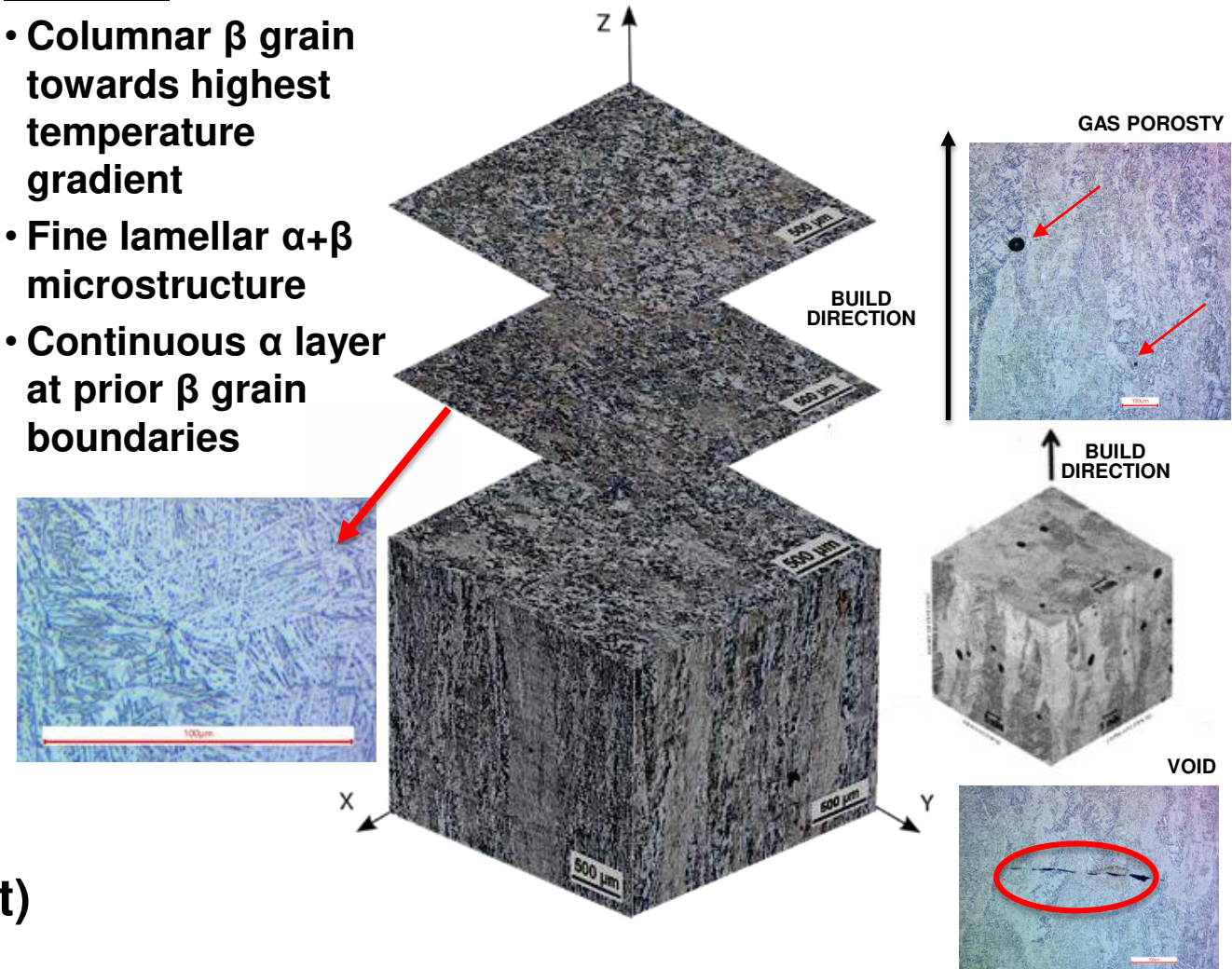# Influence of EBM Processing on Microstructure

	Relative Porosity	α Lath Size	Prior β Grain Size	Surface Roughness
Speed Function Index / Scan Speed	+	-	-	0*
Line Offset (mm)	+	-*	-*	-*
Max Beam Current (mA)	-	+	+*	0*
Focus Offset (mA)	-/+	+*	+*	-

*Trend not seen in literature

**Assume increasing the process parameter value only (all other variables remain constant)**

Features

- **Columnar β grain towards highest temperature gradient**
- **Fine lamellar α+β microstructure**
- **Continuous α layer at prior β grain boundaries**

GAS POROSTY

BUILD DIRECTION

BUILD DIRECTION

VOID

Fatigue Behavior of Forged / β-Annealed Ti-6-4

- **Majority of life spent in crack growth when damage initiates at a large defect**

- **Large variation in crack growth**
  - **Limited slip systems in basket-weave titanium alloys**
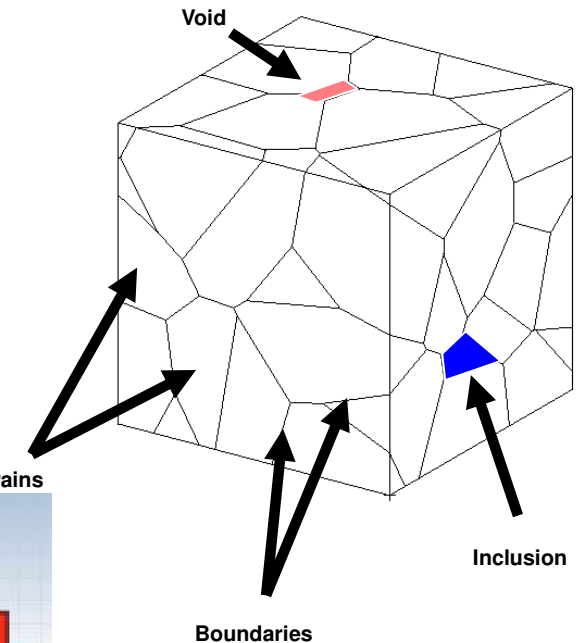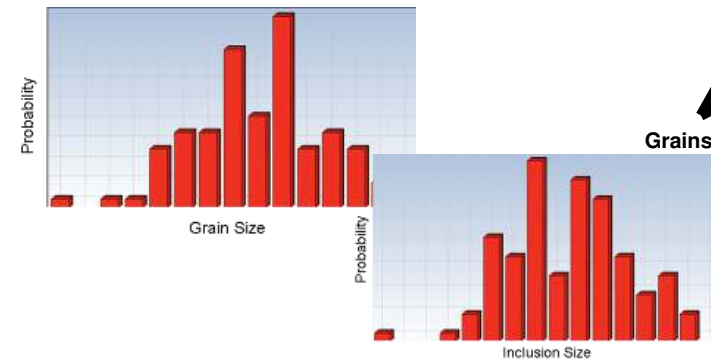 - **Coarse microstructure**

500 μm
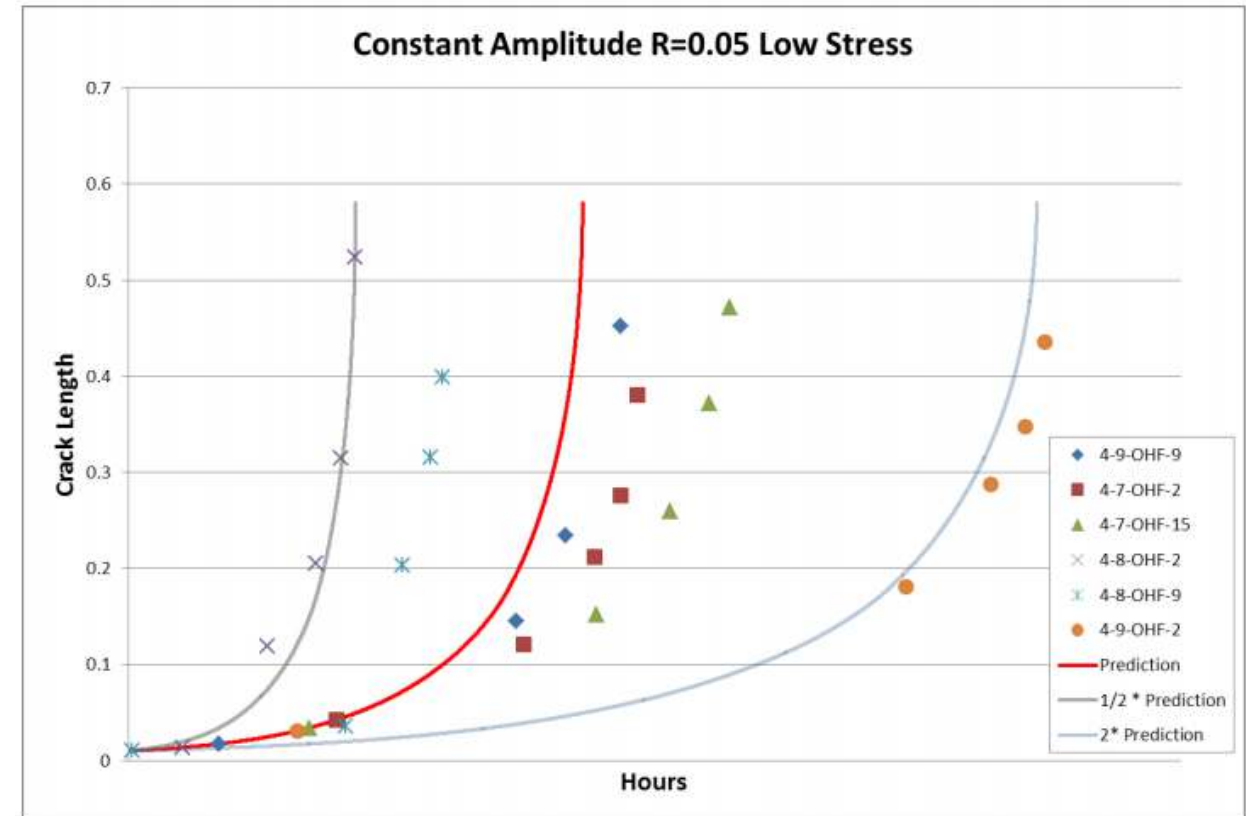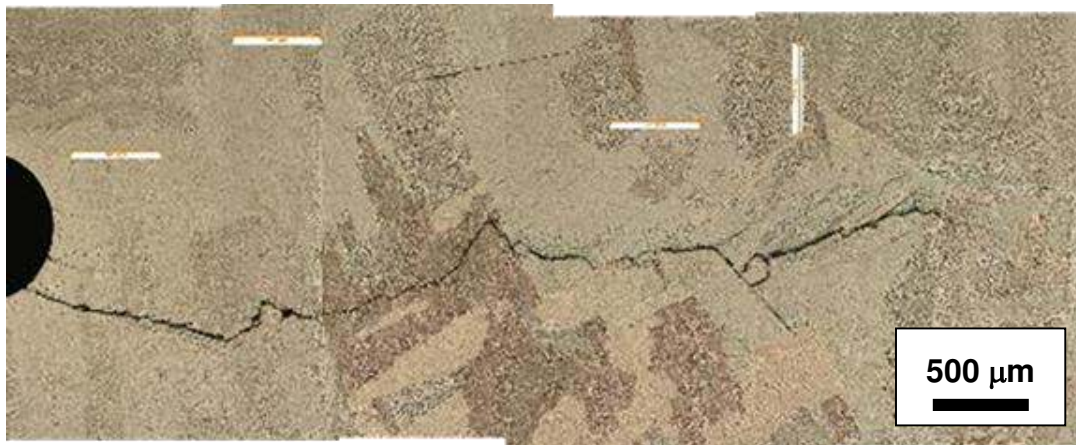
Park, Ji, et al. "Titanium 6Al-4V Durability Method Development and Test Verification Results" (2014). Presented at the Aircraft Structural Integrity Program (ASIP) annual conference.

Microstructural Comparison (Forged vs. EBM)

Forged β Ti-6-4 from VEXTEC Material Library

100 μm

EBM Ti-6-4

20 μm

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

Void

Grains

Inclusion

Boundaries

Probability — Grain Size

Probability — Inclusion Size

- **EBM Ti-6-4 has similar morphology, but a smaller grain size**
- **Used model previously-calibrated to forged Ti-6-4, to predict EBM Ti-6-4**
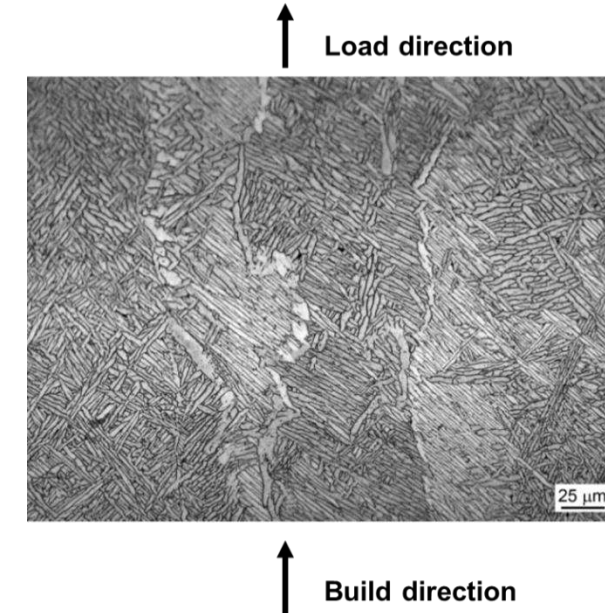
Microstructural Comparison (EBM Directionality)

Horizontal Specimens
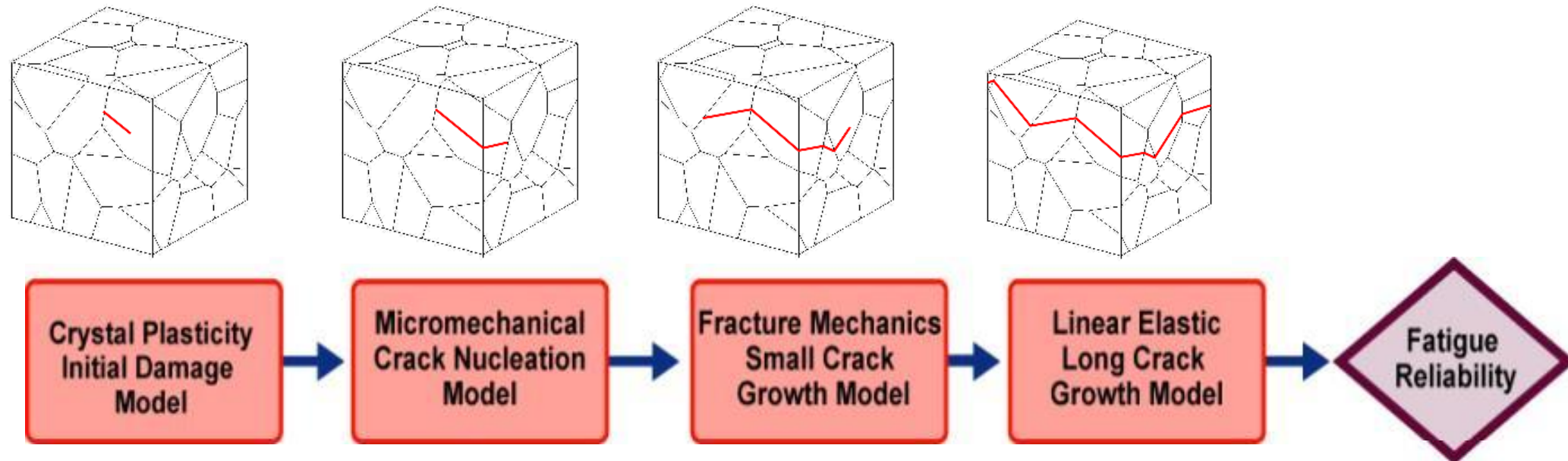

Vertical Specimens
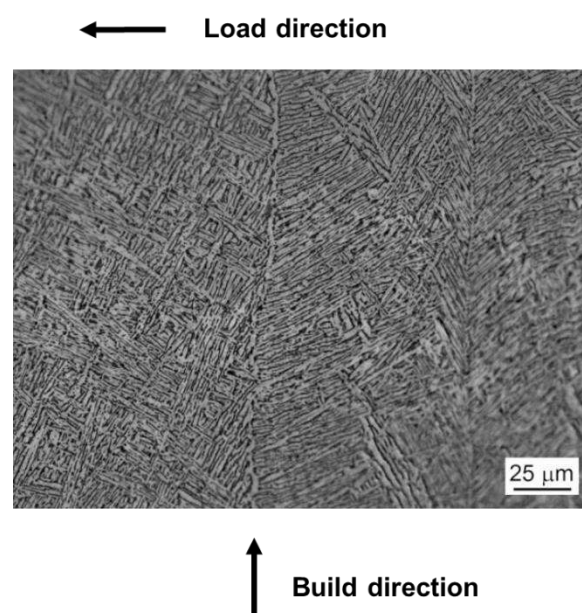
- **Slightly higher tensile strength due to absence of build defects**
- **Smooth fatigue fracture surface**

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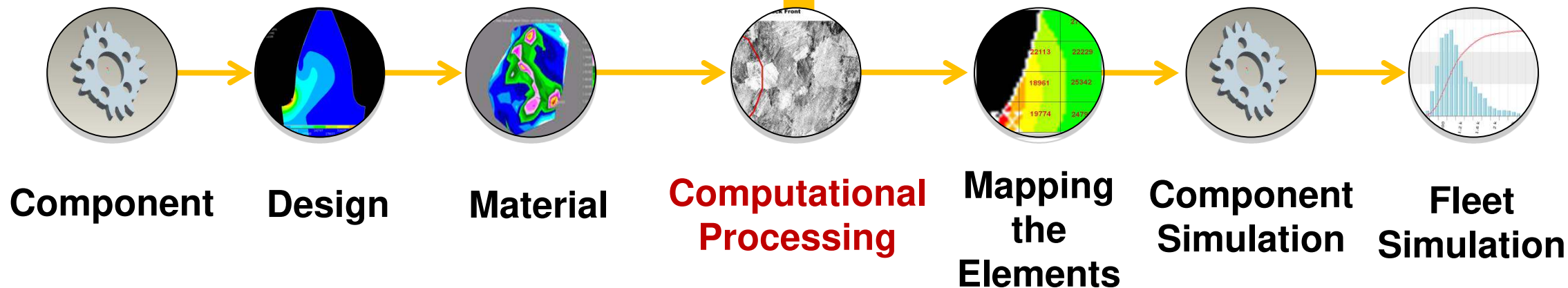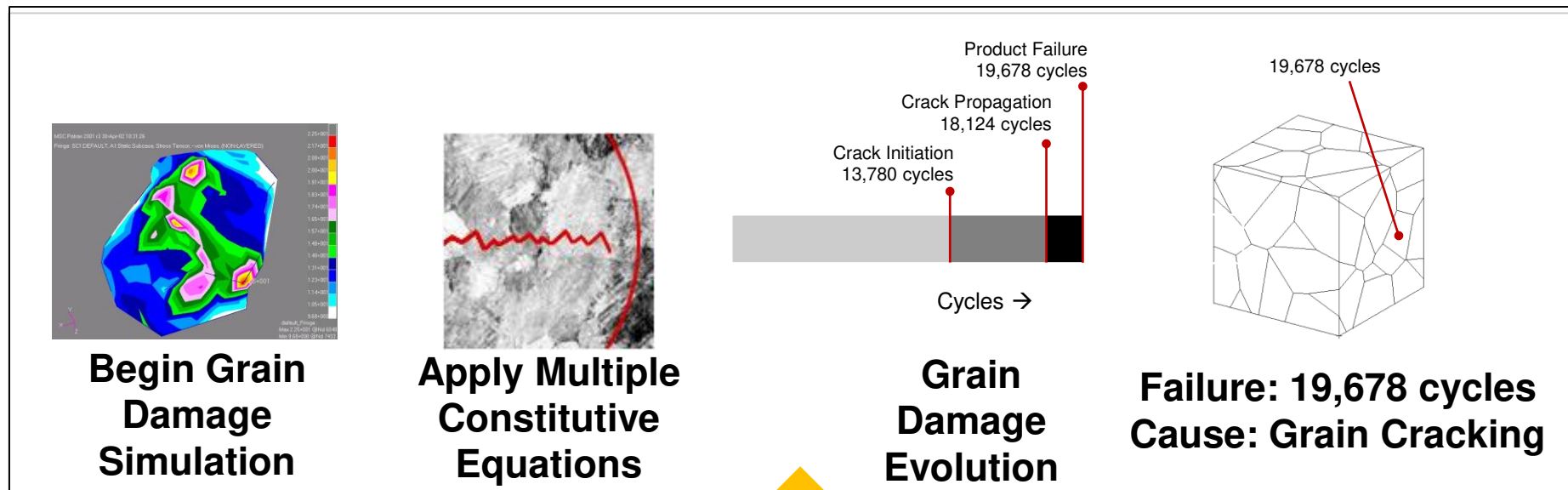- **Rough fatigue fracture surface**

ICME Constitutive Equations for Damage Evolution

VPS-MICRO software uses proven equations for each damage stage

- **Material property values and damage mechanisms from testing**
- **Stage transition rules from experimental observations**

ICME Computational Process Flow

Begin Grain Damage Simulation

Apply Multiple Constitutive Equations

Product Failure
19,678 cycles

Crack Propagation
18,124 cycles

Crack Initiation
13,780 cycles

Cycles →

Grain Damage Evolution

19,678 cycles

**Failure: 19,678 cycles
Cause: Grain Cracking**

Component → **Design** → **Material** → **Computational Processing** → **Mapping the Elements** → **Component Simulation** → **Fleet Simulation**

Material Property Comparison (Forged vs. EBM)

Material Properties Influenced by Manufacturing 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
	Grain boundary SIF	Deterministic	2.5 ksi√in	N/A	3.0 ksi√in	N/A	3.0 ksi√in	N/A
	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 (200/in²)	0.3
	Asperity	Deterministic	0.01,0.1,1,1	N/A	None	N/A	0.01,0.5,1,1	N/A

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

††"Grain size" refers to the microstructural feature of interest: the size of the α-lamellar colonies within prior β grains
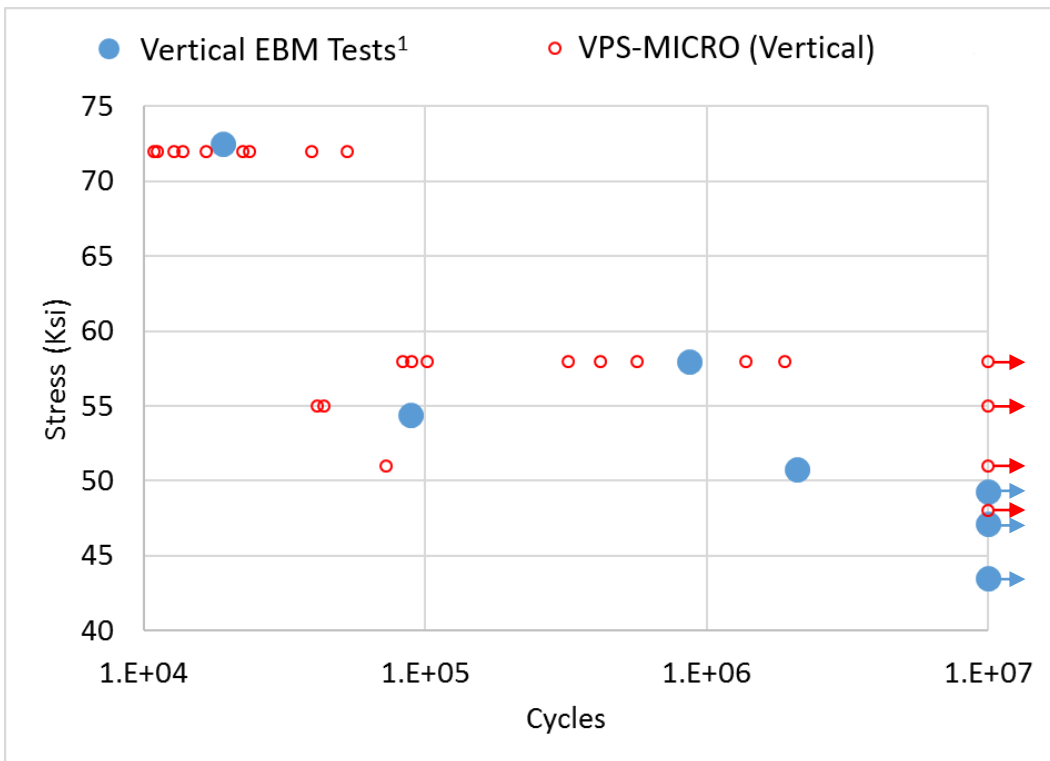
Model Predictions for Horizontal Specimens
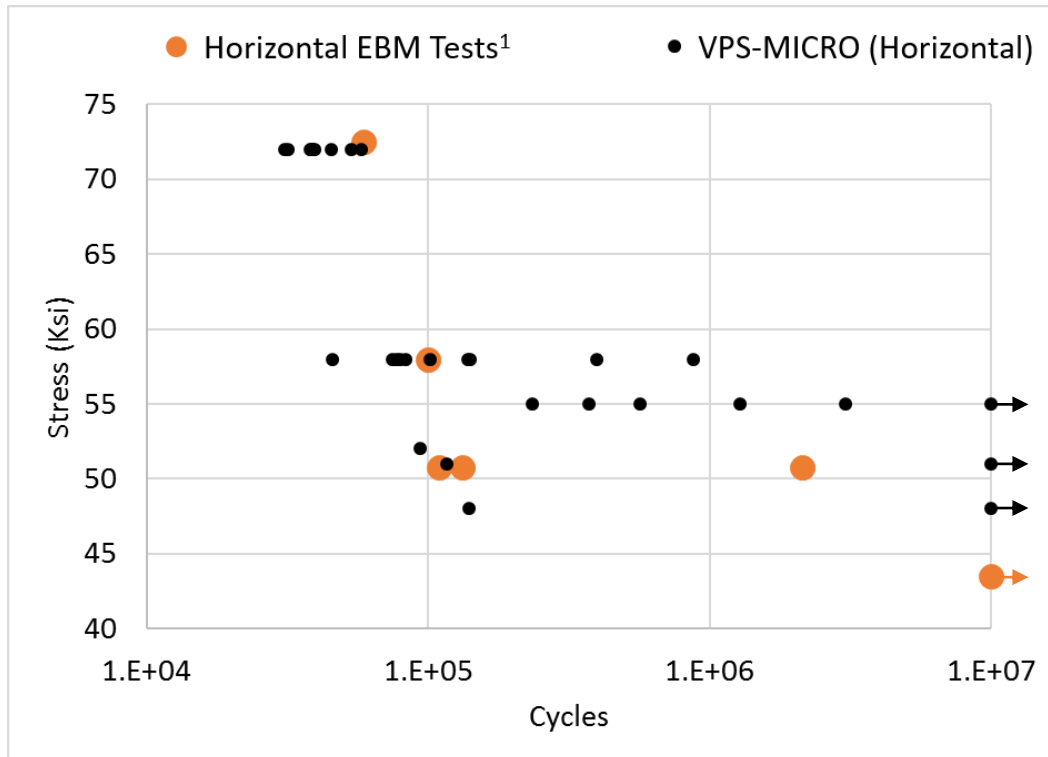
Used VPS-MICRO software with model for conventional Ti-6-4 updated with measured material properties from experimental tests

- 10 specimens simulated at each stress level (all complete < 1 hr.)
- Results show good comparison between actual and predicted fatigue lives

Model Predictions for Vertical Specimens

Experimentally observed mechanistic differences between Horizontal and Vertical specimens

- **Defects are active damage sources in Vertical specimens**
- **Tortuous fracture surfaces of Vertical specimens (asperities)**

- **10 specimens simulated at each stress level (all complete < 1 hr.)**
- **Good comparison between actual and predicted fatigue lives**

Conclusions

- **ICME was used to link processing-to-microstructure, and microstructure-to-performance**

- **Microstructural effects due to changes in AM processing characteristics were identified**

- **A probabilistic ICME fatigue model previously calibrated to conventionally processed Ti-6Al-4V was extended to predict fatigue of AM/EBM Ti-6Al-4V**

- **ICME software can decrease the time and resources needed to certify metal AM structural components exposed to fatigue (Benchmark 3)**