Probabilistic Computational Fatigue and Fracture Modeling of Additive Manufactured Components

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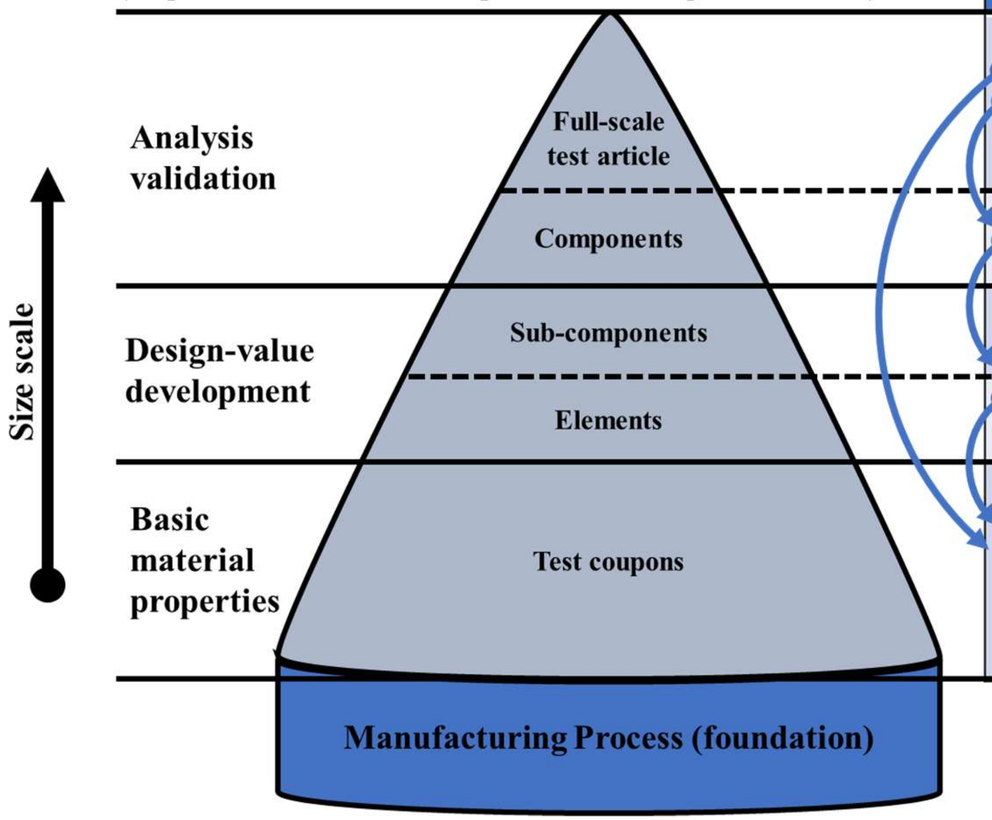
Objectives

Use Integrated Computational Materials Engineering (ICME) to aid in the certification of AM products

- **Link processing-to-microstructure, and microstructure-to-performance**
- **Link local properties to overall component durability**
- **Quantify effects of microstructure variations on mechanical performance of AM-built parts**
- **Extend modeling of conventionally-processed materials to predict performance of AM-processed materials**

Product Certification Costs

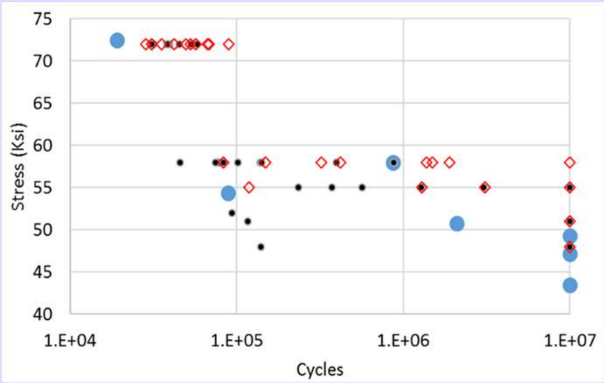
Building Block Test Structure Required for Certification
(adapted from DARPA/DSO "Open Manufacturing Review", 2016)



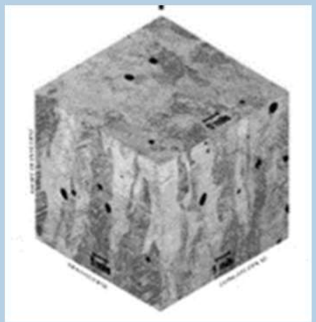
Specimen Count	Cost ($M)	Time (Years)
2-3	100-125	4
10-30	10-20	3
25-50	10-35	3
2000-5000	10-35	3
5000-100,000	8-15	2

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>**



Required Durability →



Allowable Microstructure →

Range of Processing Parameters

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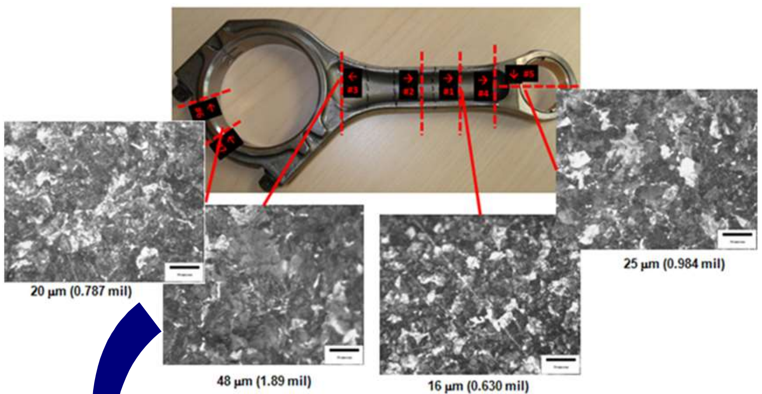
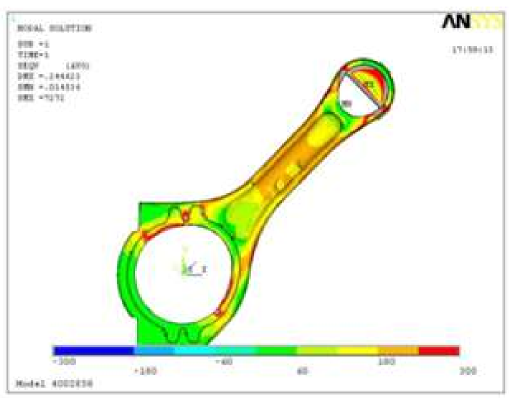
AM: An Ideal Application for ICME



Map microstructure from part to FEA



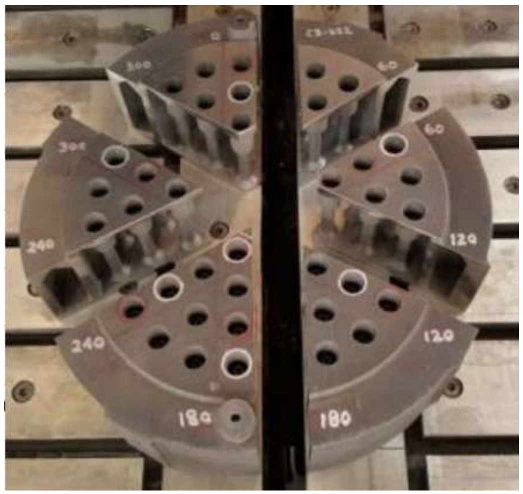
VPS-MICRO® – computational microstructural fatigue software

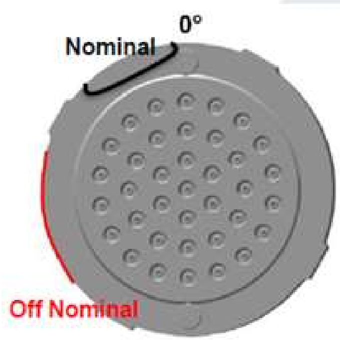
- Each element in a FE model can have a different distribution of microstructural properties
- Virtual fatigue analysis simulation grain → element → component
  - System reliability
- Proven technology on forgings, castings, weldments (2 decades)
- Now being validated on AM parts

Burst Test Prediction of AM Nickel Nozzles

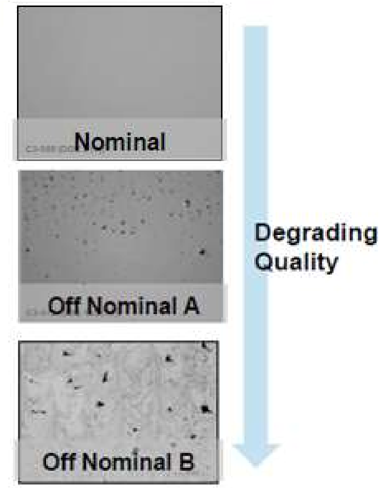
Nickel Superalloy Nozzle

- 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



Software accurately predicted burst test location & pressure for different AM process settings

Durability Certification in Fatigue

NAVAIR-funded program to develop ICME-based certification of electron beam melted (EBM) Ti-6Al-4V alloy

- **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]**
  - **Explicitly modeled differences in microstructure, defects, and damage mechanisms**

[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

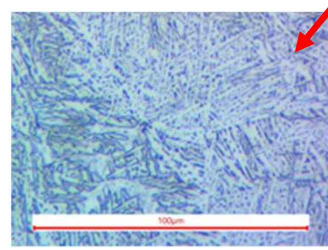
	Relative Porosity	α Lath Size	Prior β Grain Size	Surface Roughness
Speed Function Index / Scan Speed	+	-	-	0*
Line Offset (mm)	+	-*	-*	-*
Max Beam Current (mA)	-	+	+*	0*
Focus Offset (mA)	-/+	+*	+*	-

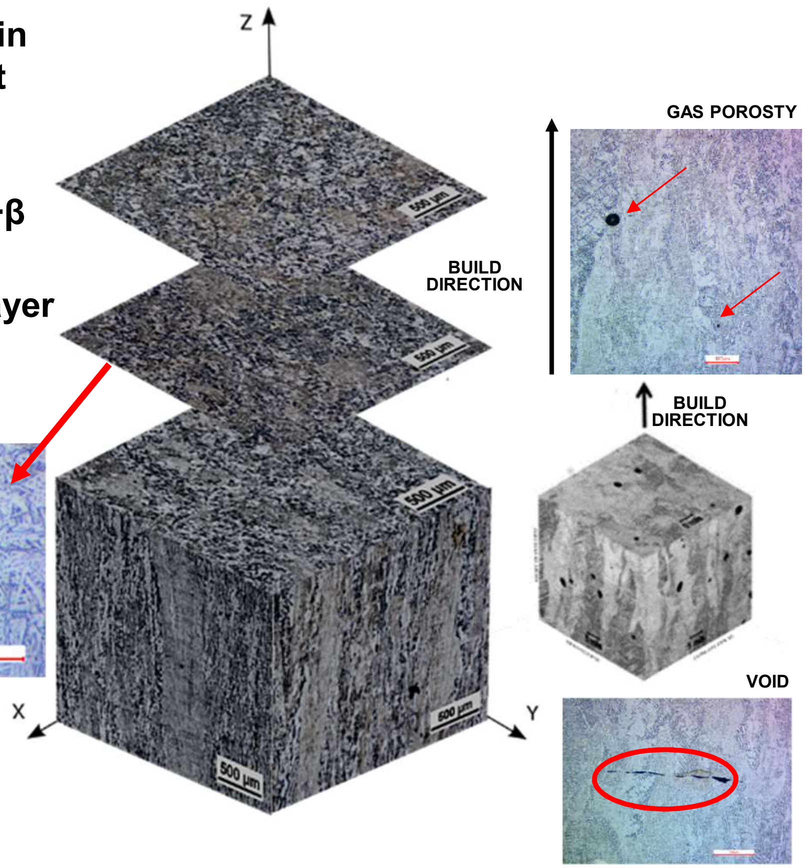
***Trend not seen in literature**

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

Features

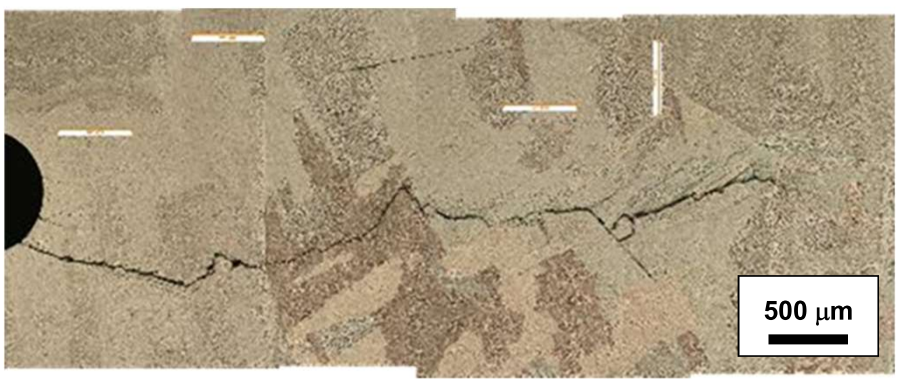
- **Columnar β grain towards highest temperature gradient**
- **Fine lamellar α+β microstructure**
- **Continuous α layer at prior β grain boundaries**

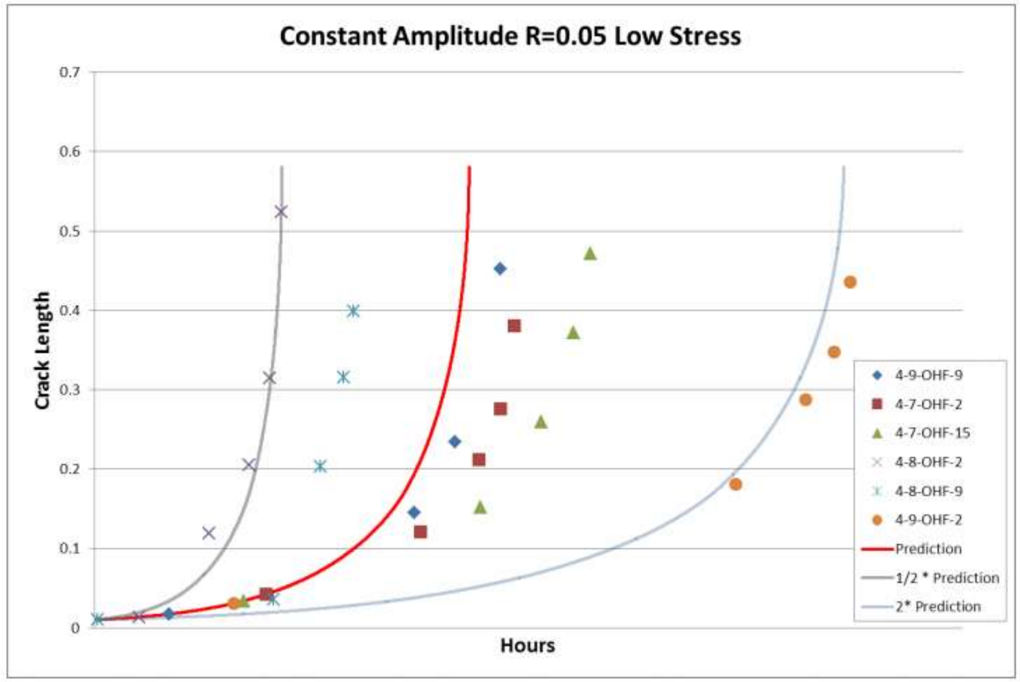




Fatigue Behavior of Forged / β-Annealed Ti-6-4

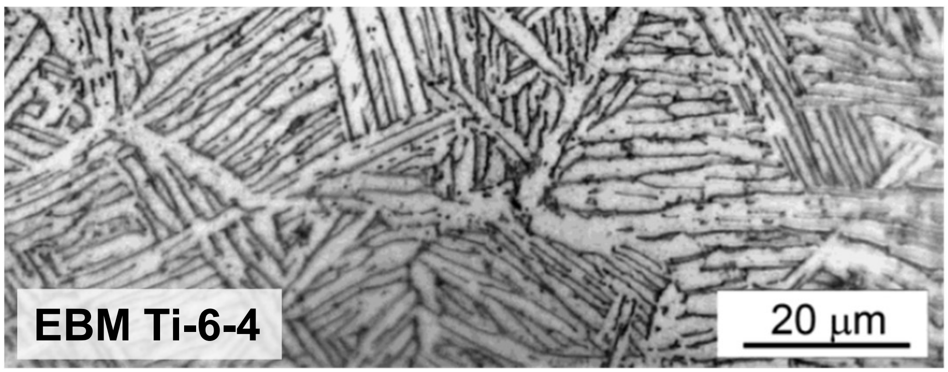
- Majority of life spent in crack growth when damage initiates at a large defect
- Large variation in crack growth
  - Limited slip systems in basket-weave titanium alloys
  - Coarse microstructure



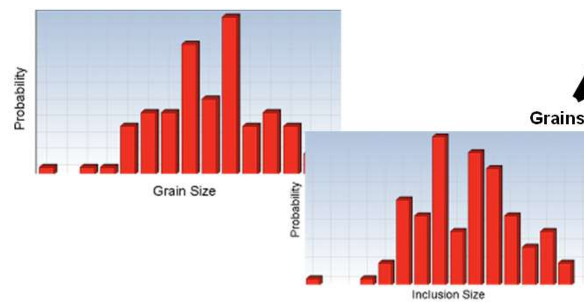


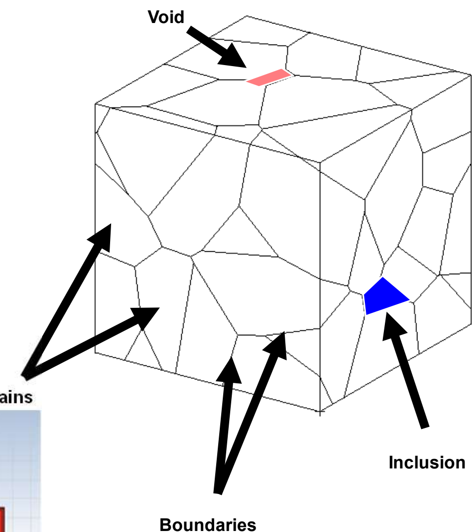
Park, Ji, et al. "Titanium 6Al-4V Durability Method Development and Test Verification Results" (2014). Presented at the Aircraft Structural Integrity Program (ASIP) annual conference.

Microstructural Comparison (Forged vs. EBM)



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

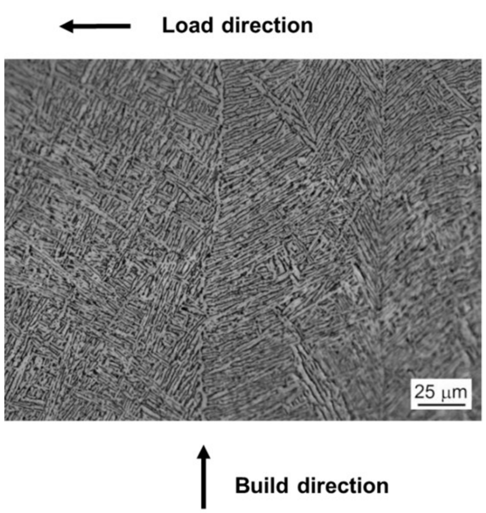




- **EBM Ti-6-4 has similar morphology, but a smaller grain size**
- **Used model previously-calibrated to forged Ti-6-4, to predict EBM Ti-6-4**

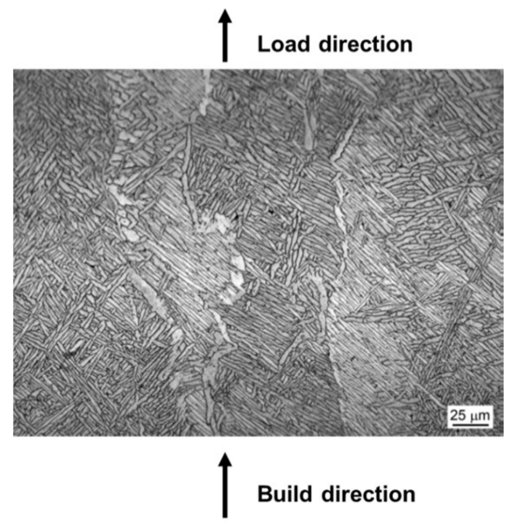
Microstructural Comparison (EBM Directionality)

Horizontal Specimens



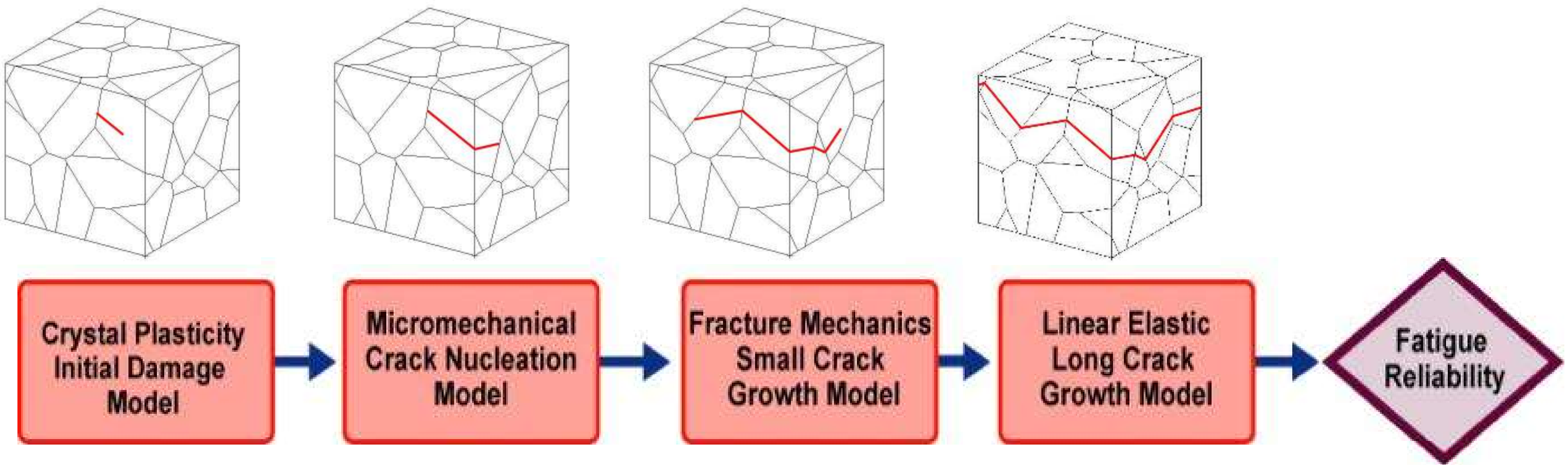
- Slightly higher tensile strength due to absence of build defects
- Smooth fatigue fracture surface

Vertical Specimens



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

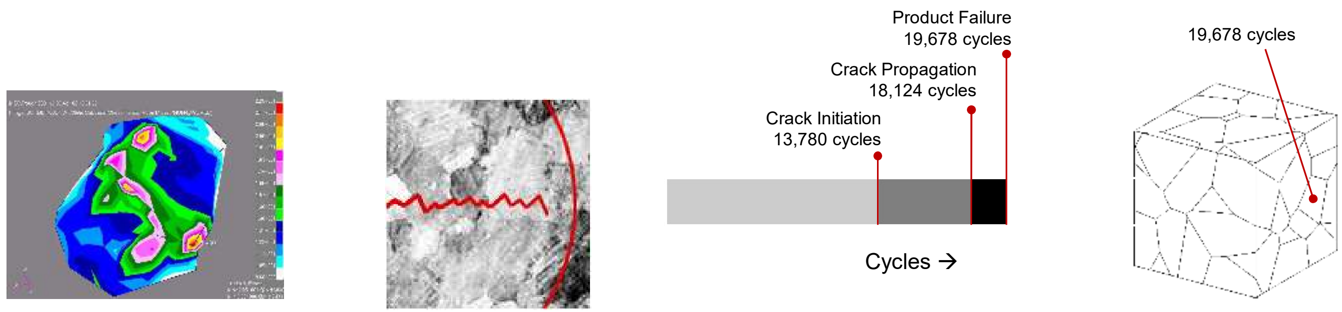
ICME Constitutive Equations for Damage Evolution



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

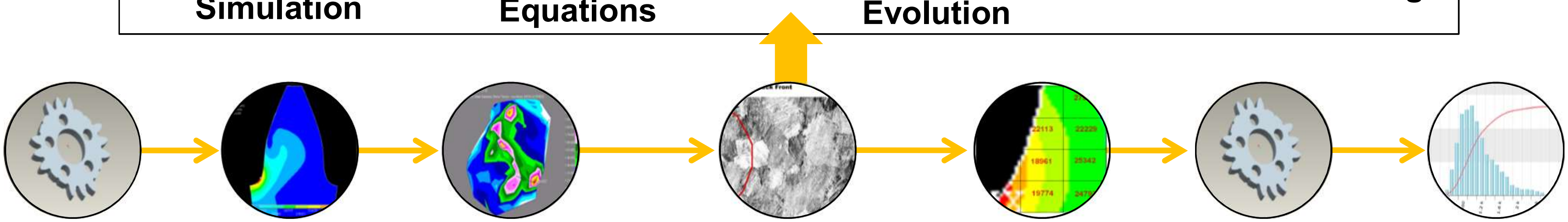


Begin Grain Damage Simulation

Apply Multiple Constitutive Equations

Grain Damage Evolution

Failure: 19,678 cycles
Cause: Grain Cracking



Component

Design

Material

Computational Processing

Mapping the Elements

Component Simulation

Fleet Simulation

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Material Property Comparison (Forged vs. EBM)

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

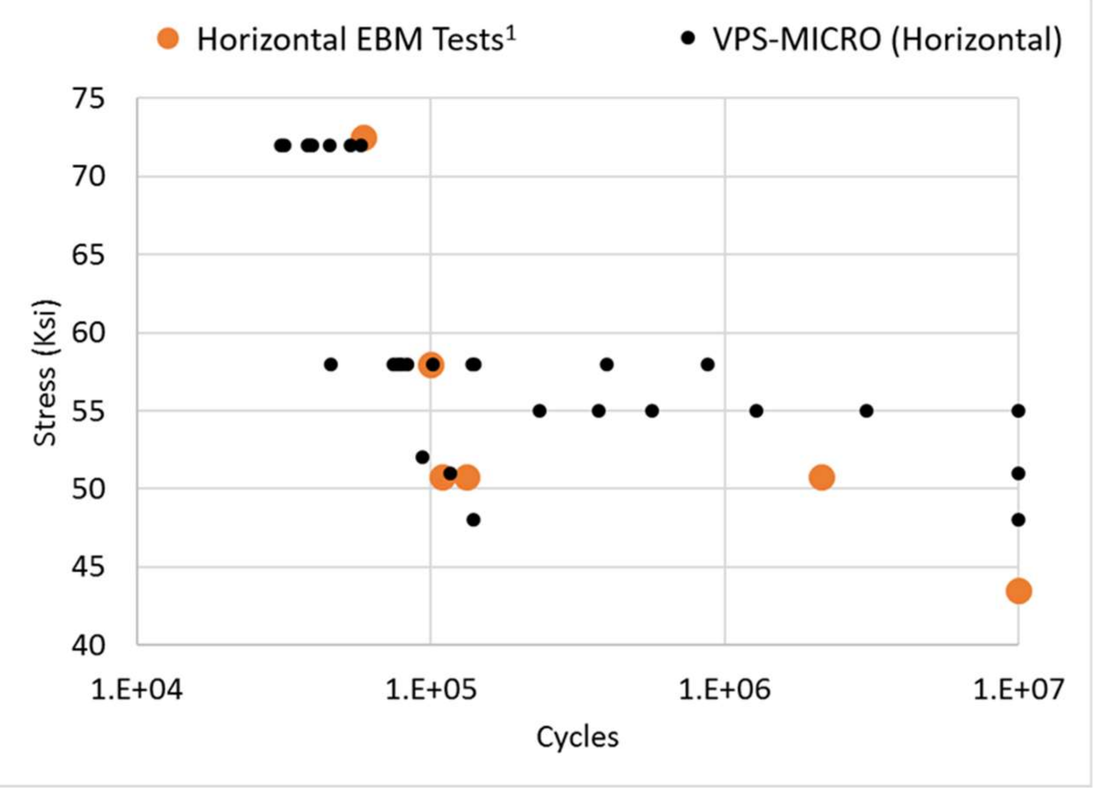
††"Grain size" refers to the microstructural feature of interest: the size of the α-lamellar colonies within prior β grains

	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/in^2)	0.3
	Asperity	Deterministic	0.01,0.1,1,1	N/A	None	N/A	0.01,0.5,1,1	N/A

Model Predictions for Horizontal Specimens

Used 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**

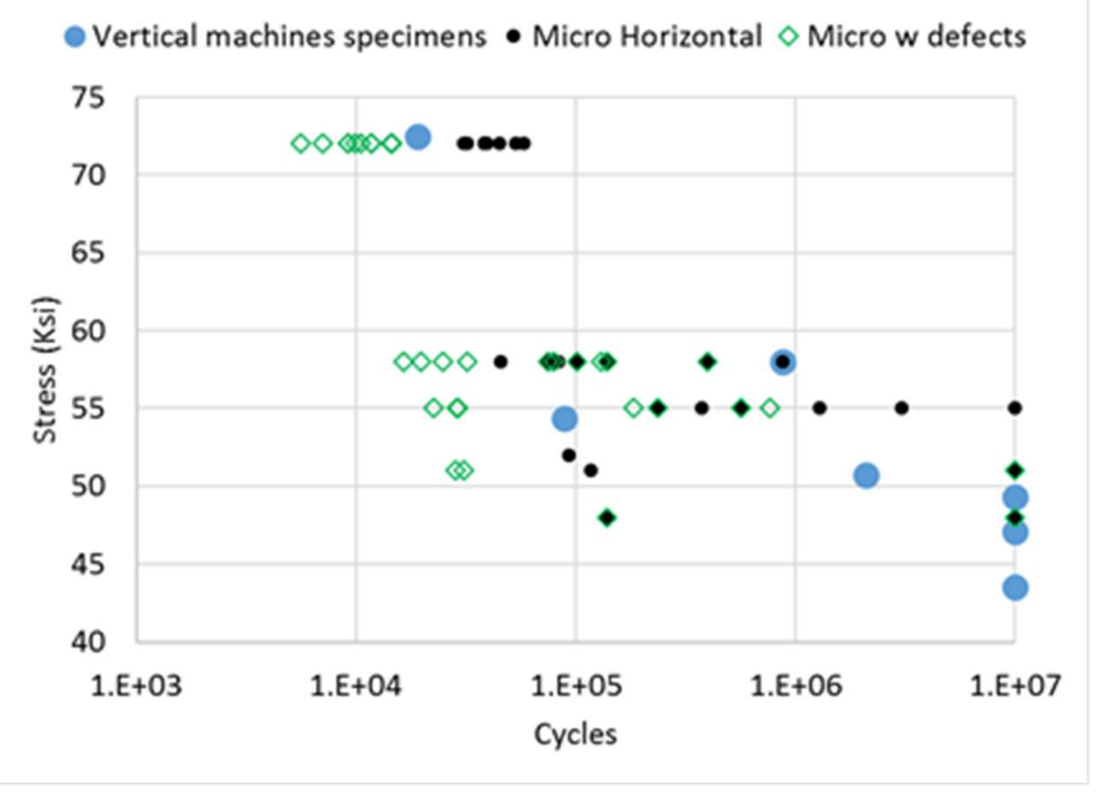


[1]Gong, 2013.

Model Predictions for Specimens w/ only Defects

Used software with model for Horizontal specimens updated with *only* the defects measured from Vertical specimen fracture surfaces

- **Defects are active damage sources in Vertical specimens**
- **10 specimens simulated at each stress level (all complete < 1 hr.)**
- **Summation under predicts the Vertical specimen lifetimes**

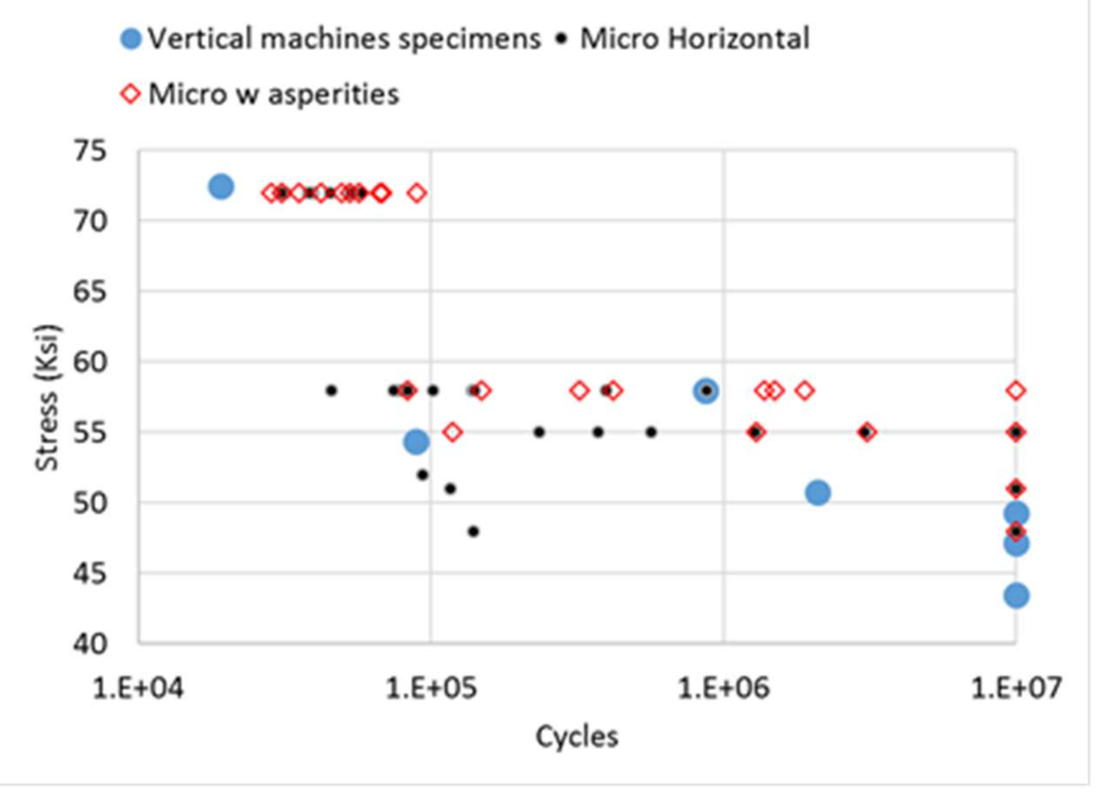


[1]Gong, 2013.

Model Predictions for Specimens w/ only Asperities

Used software with model for Horizontal specimens updated with *only* the asperities observes on Vertical specimen fracture surfaces

- **Tortuous fracture surfaces of Vertical specimens (asperities)**
- **10 specimens simulated at each stress level (all complete < 1 hr.)**
- **Summation over predicts the Vertical specimen lifetimes**



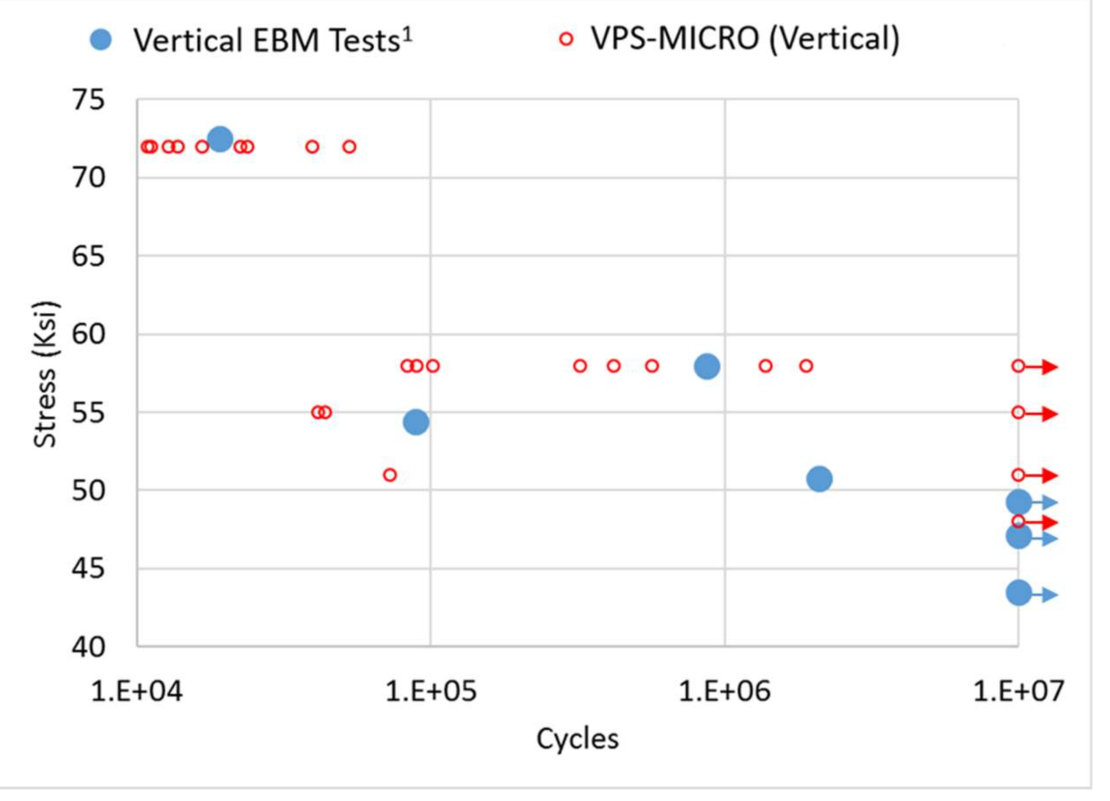
[1]Gong, 2013.

Model Predictions for Specimens w/ both Defects and Asperities i.e., Vertical Specimens

Experimentally observed mechanistic differences between Horizontal and Vertical specimens

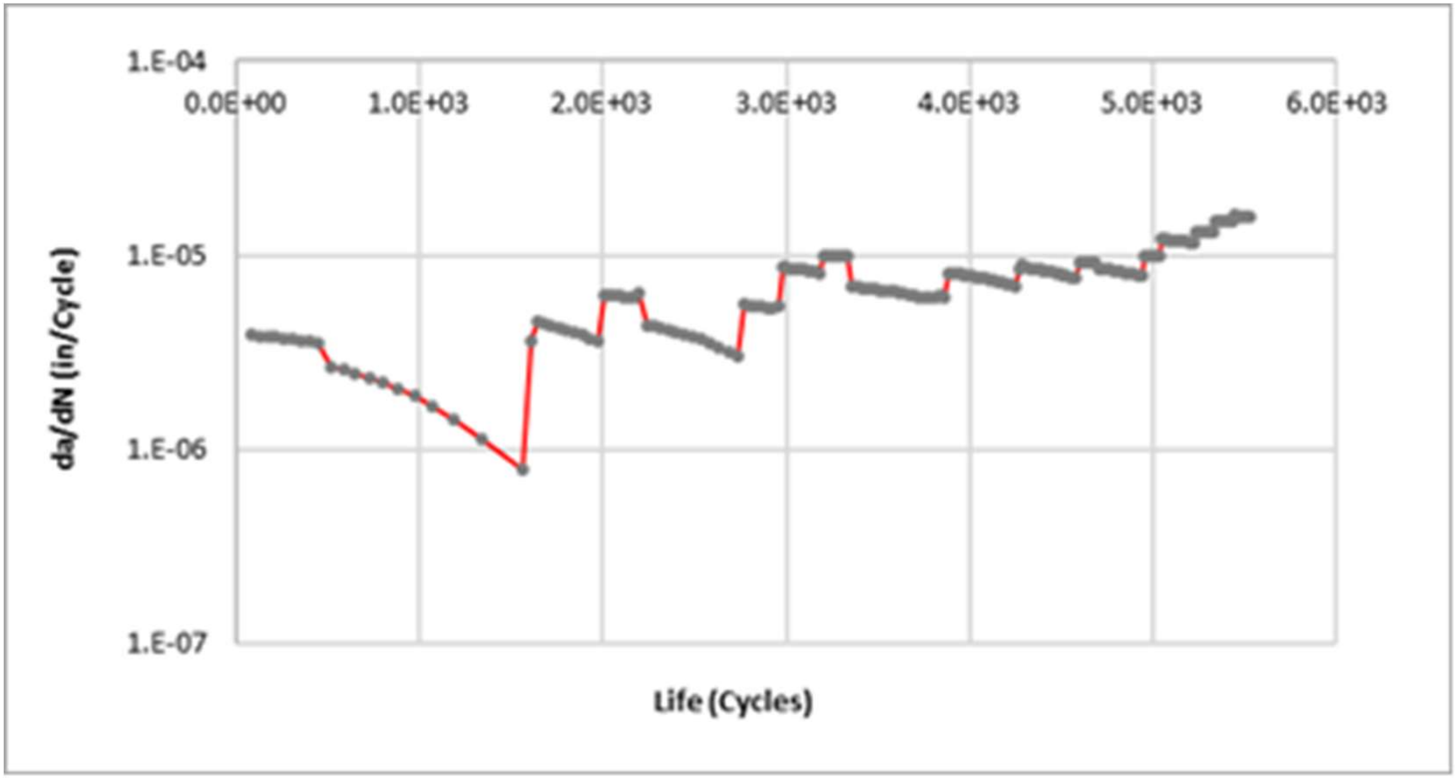
- **Defects are active damage sources in Vertical specimens**
- **Tortuous fracture surfaces of Vertical specimens (asperities)**

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

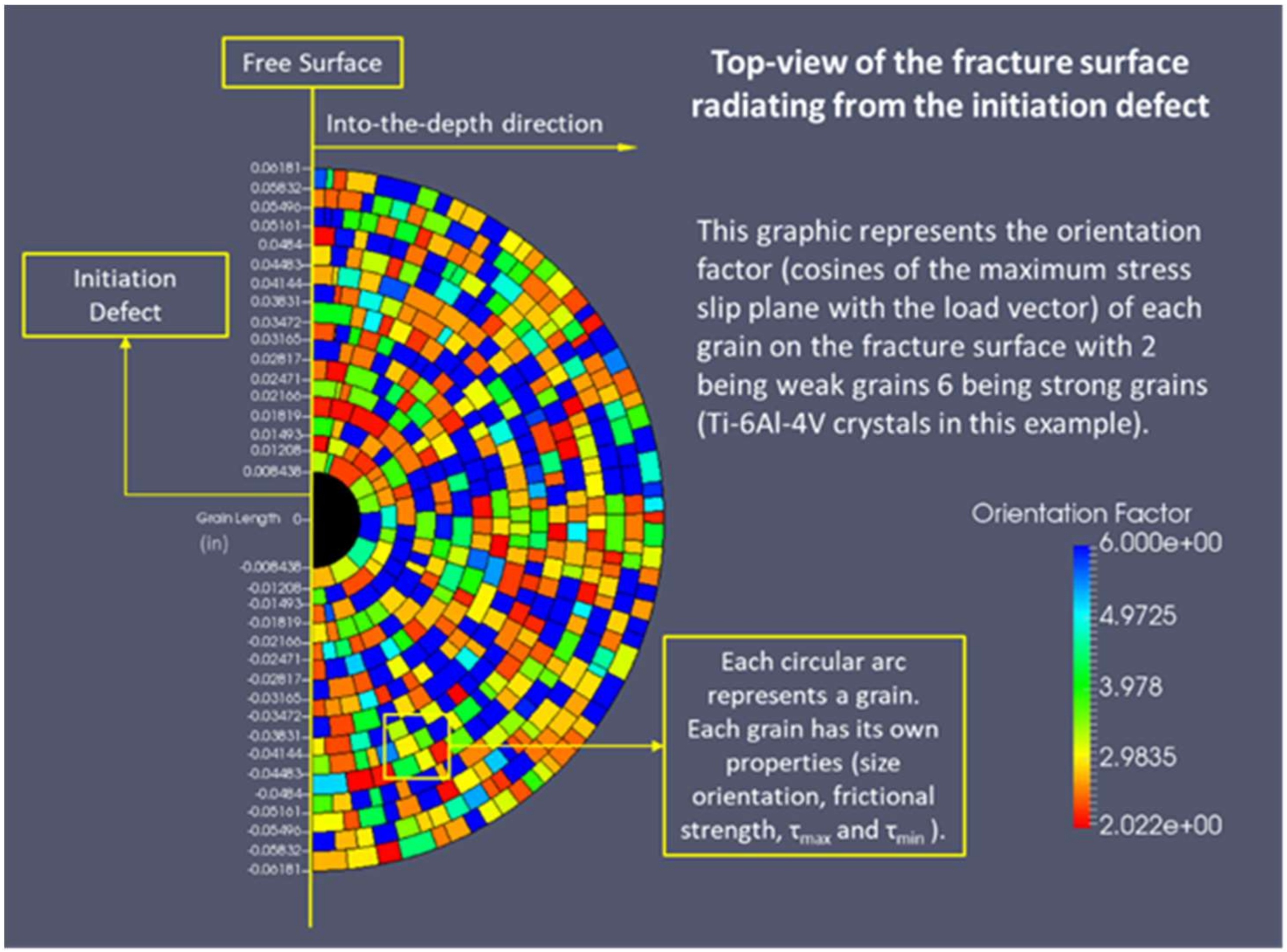


[1]Gong, 2013.

Simulated Crack Growth Rate



Simulated Fracture Surface



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.**

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THANK YOU