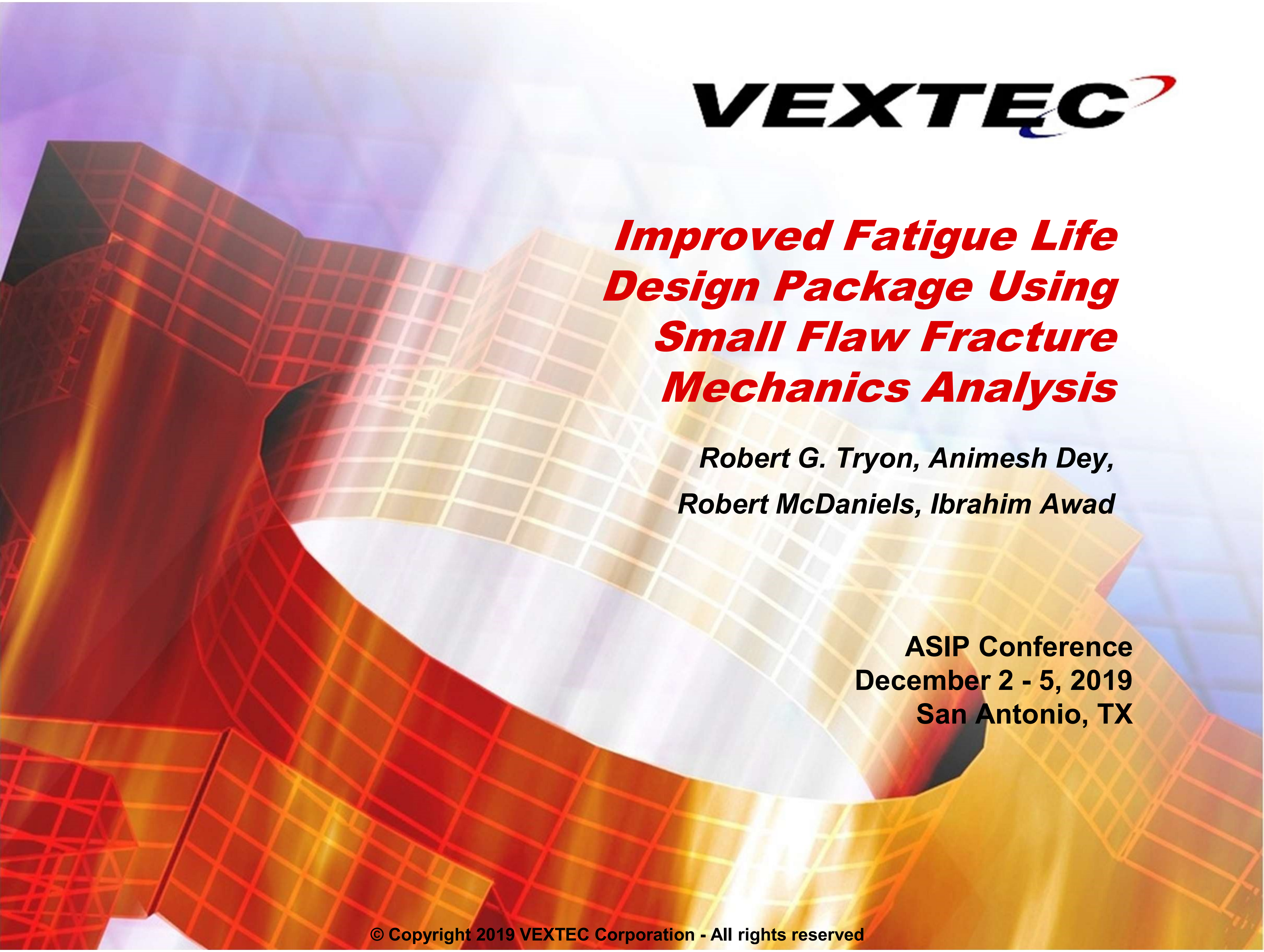

VEXTEC

Improved Fatigue Life Design Package Using Small Flaw Fracture Mechanics Analysis

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Robert McDaniels, Ibrahim Awad

ASIP Conference
December 2 - 5, 2019
San Antonio, TX

Acknowledgements

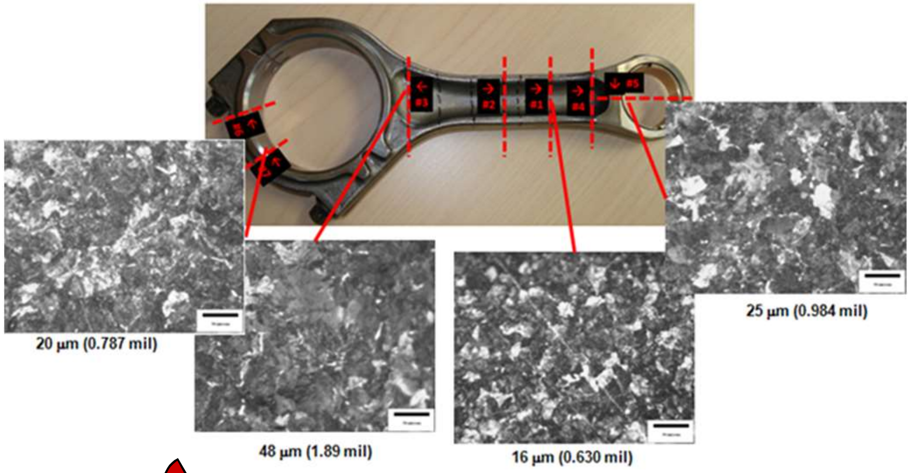
- Mike Gran (AFRL/RQ)

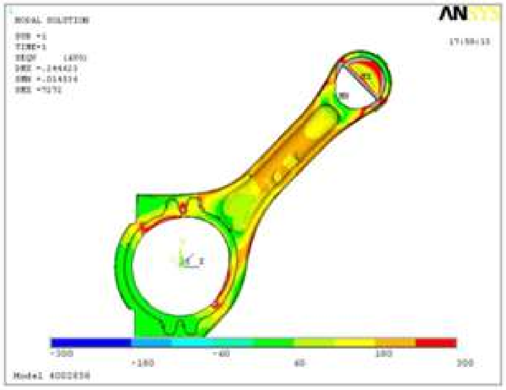
Objectives

Use Integrated Computational Materials Engineering (ICME) and Small Flaw Fracture Mechanics (SFFM) to aid in the lifing of products

- Link local properties to overall component DADT for β-annealed Ti-6Al-4V
- Quantify effects of microstructure variations on mechanical performance of parts
- Extend modeling of conventionally-processed materials to predict performance of AM-processed materials

Application of ICME





Map microstructure from part to FEA

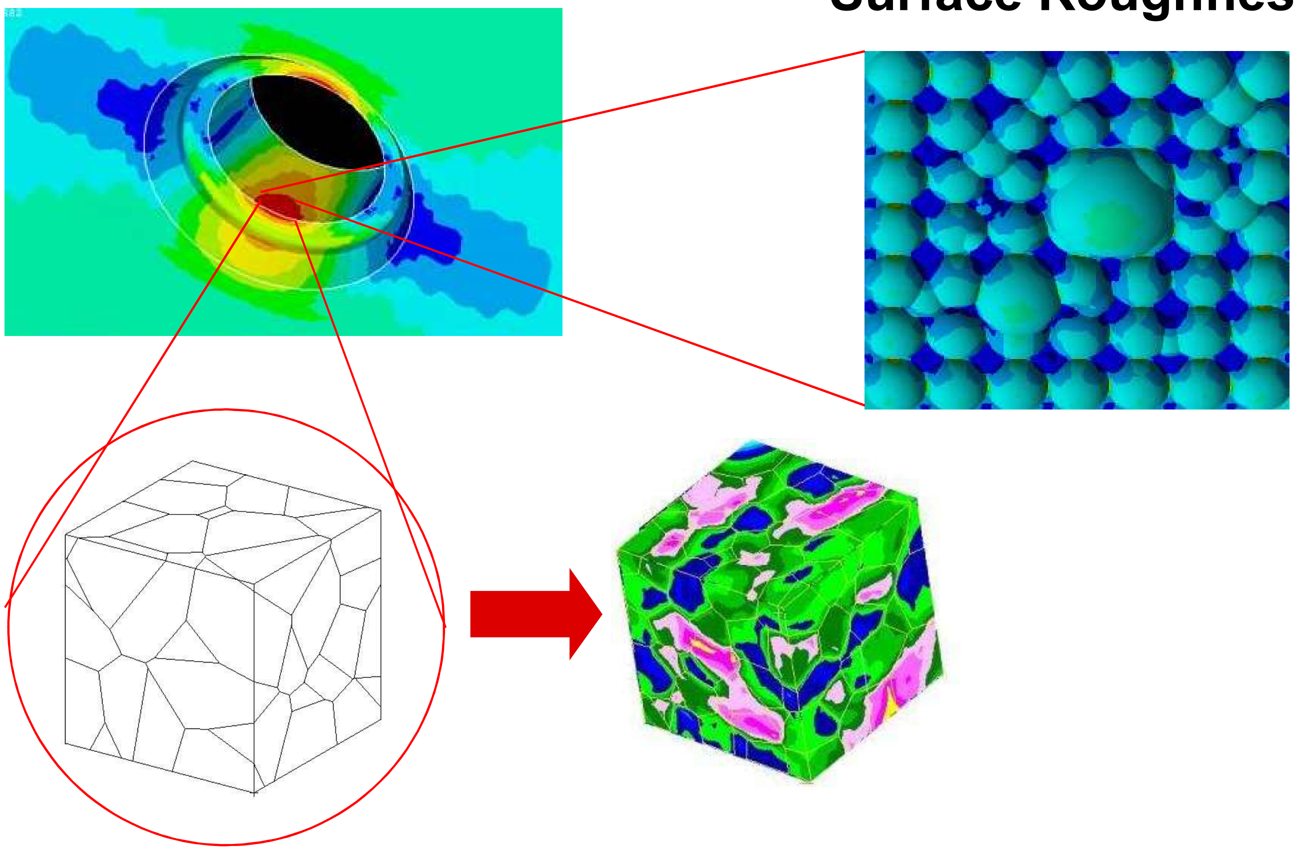
VPS-MICRO® – computational micro*structural* fatigue software

- 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)

Durability Certification in Fatigue

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

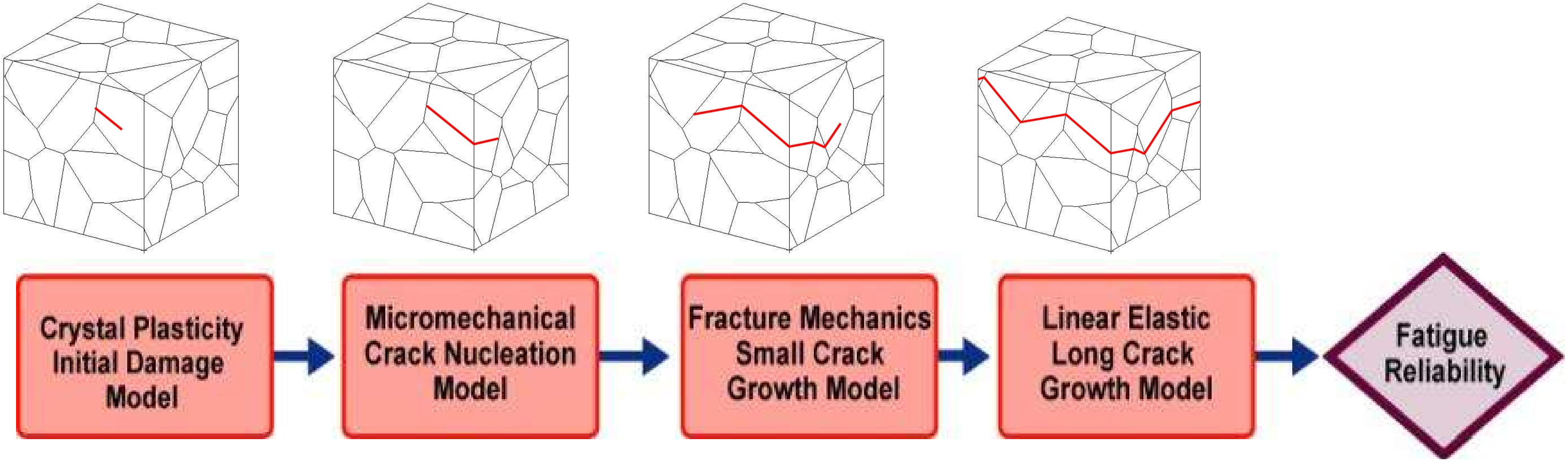
Microscopic Structural Analysis



Surface Roughness

Microstructure

ICME Constitutive Equations for Damage Evolution



Crystal Plasticity Initial Damage Model

Micromechanical Crack Nucleation Model

Fracture Mechanics Small Crack Growth Model

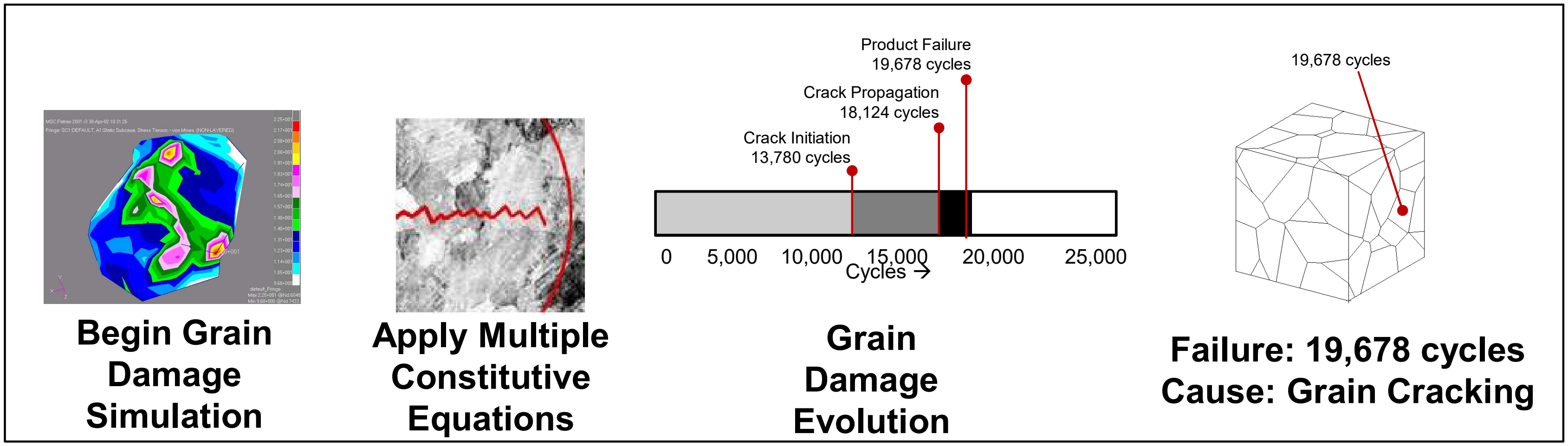
Linear Elastic Long Crack Growth Model

Fatigue Reliability

Software uses proven equations for each damage stage

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

ICME Computational Process Flow

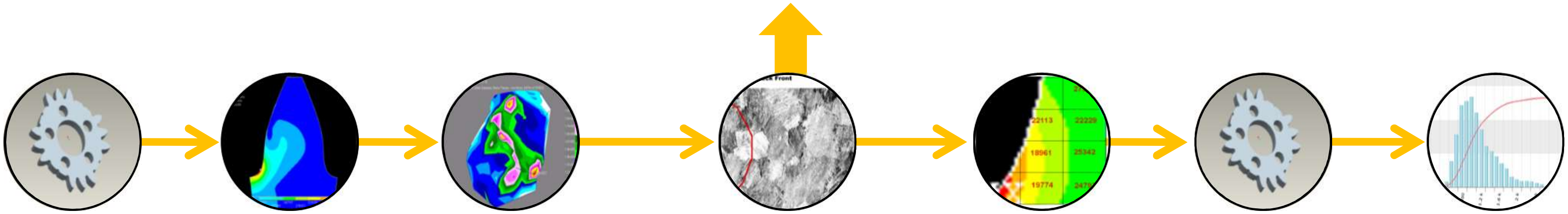


Begin Grain Damage Simulation

Apply Multiple Constitutive Equations

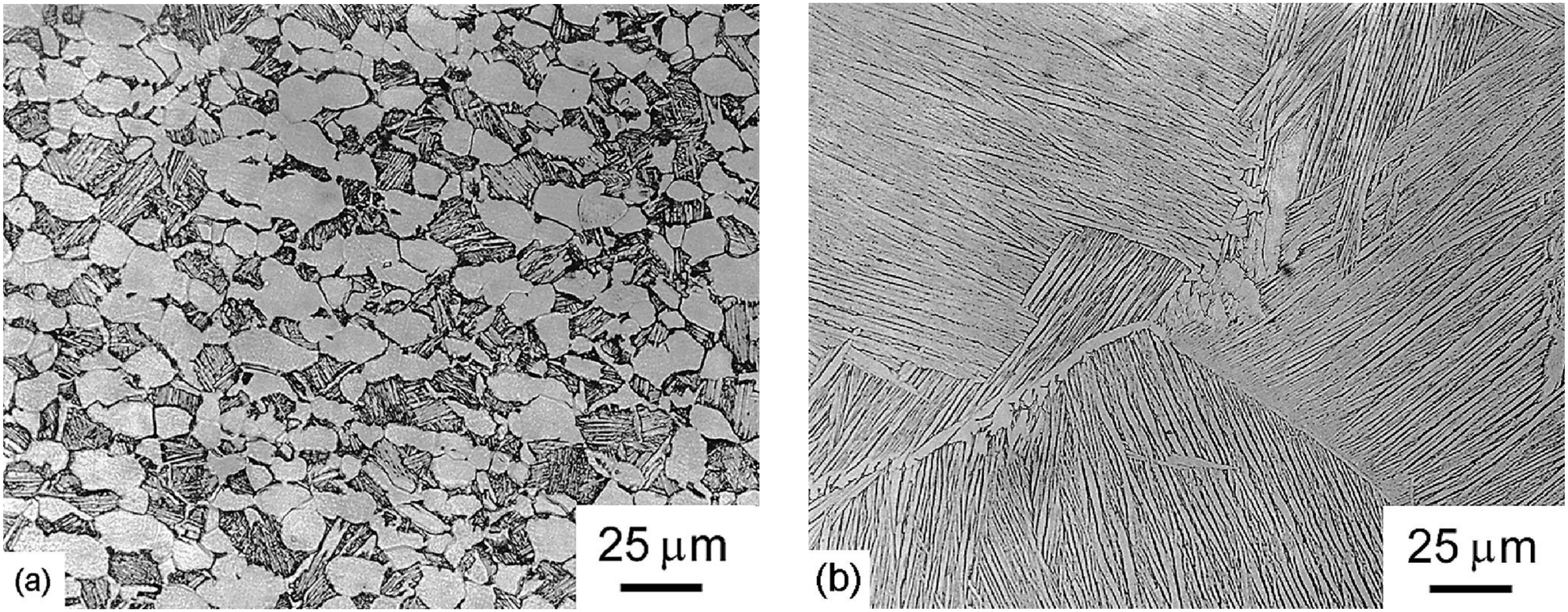
Grain Damage Evolution

Failure: 19,678 cycles
Cause: Grain Cracking



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

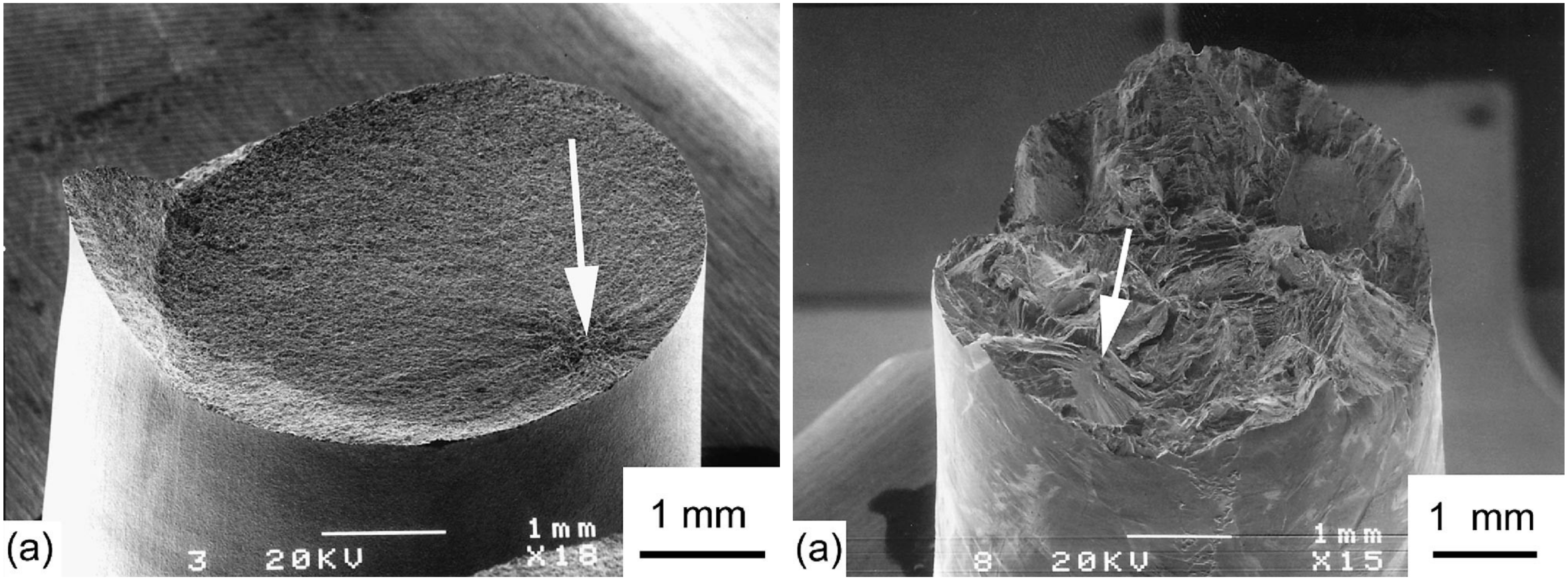
Issue of Titanium: Microstructure



Optical micrographs of the microstructures of Ti-6Al-4V: (*a*) bimodal (solution treated and overaged, STOA) and (*b*) lamellar (β annealed).

R. K. Nalla et al. (2002) Met Trans A 33A 899 - 918

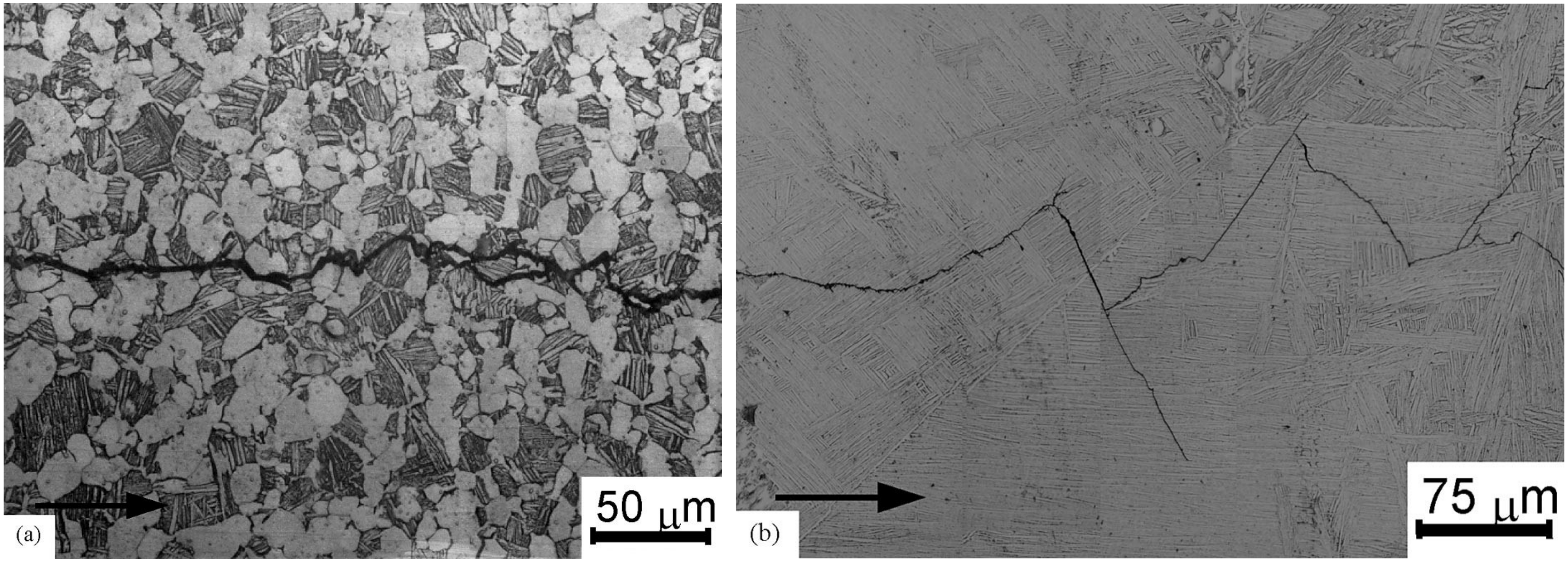
Issue of Titanium: Damage



Fracture surface and initiation site for Ti-6Al-4V: (*a*) bimodal and (*b*) lamellar

R. K. Nalla et al. (2002) Met Trans A 33A 899 - 918

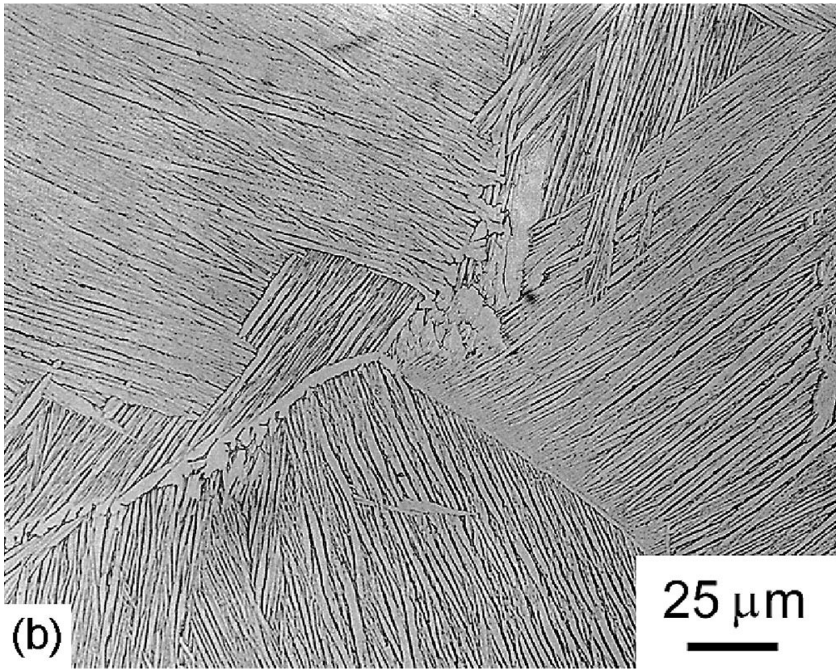
Issue of Titanium: Damage



A typical near-threshold crack profile observed for the (*a*) bimodal and (*b*) lamellar microstructure (R = 0.1, and da/dN ~ 10E-10 m/cycle)

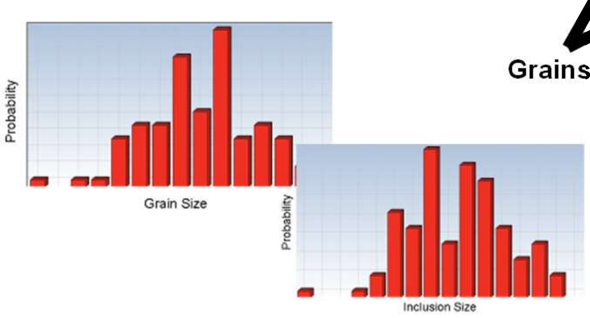
R. K. Nalla et al. (2002) Met Trans A 33A 899 - 918

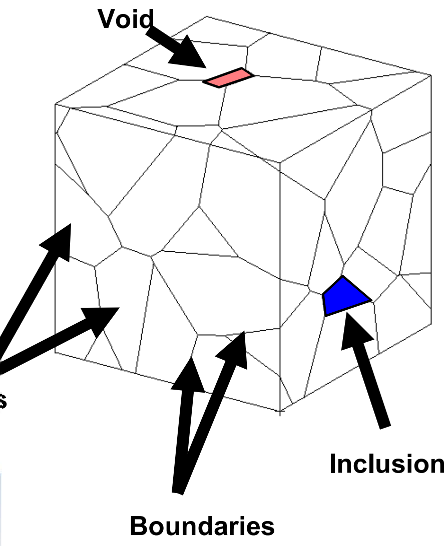
Microstructural Model



Microstructural Volume Element

- Microscale matrix material model
- Voids and NMIs

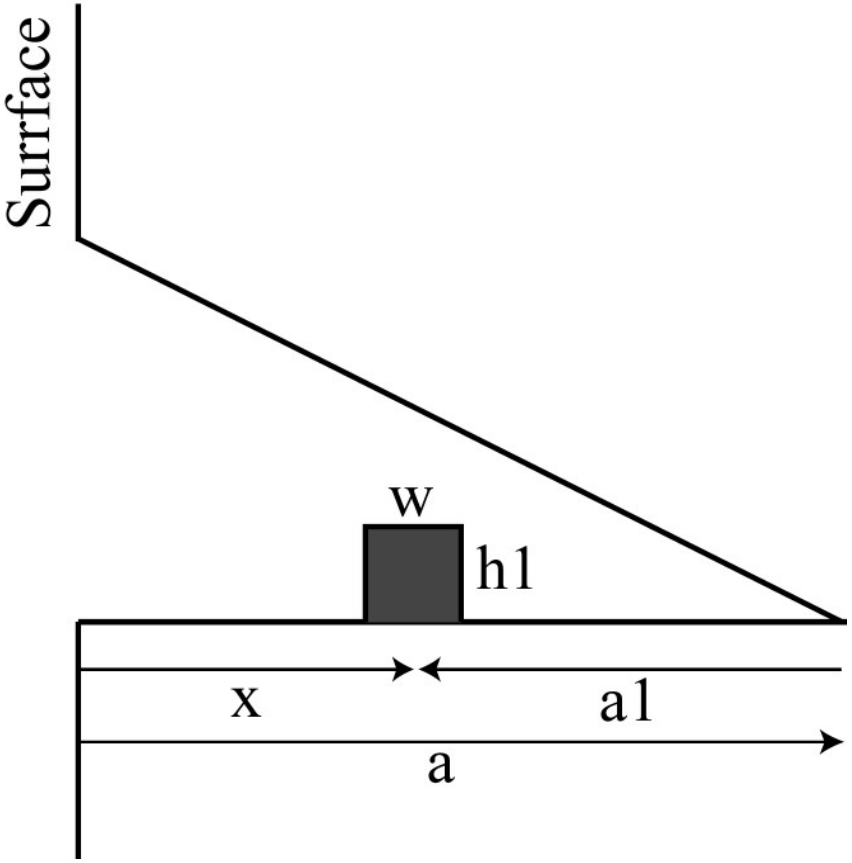




Grain size, orientation, shape along with voids and inclusions are model as district structural elements

Modeling Rough Fatigue Fracture Surface

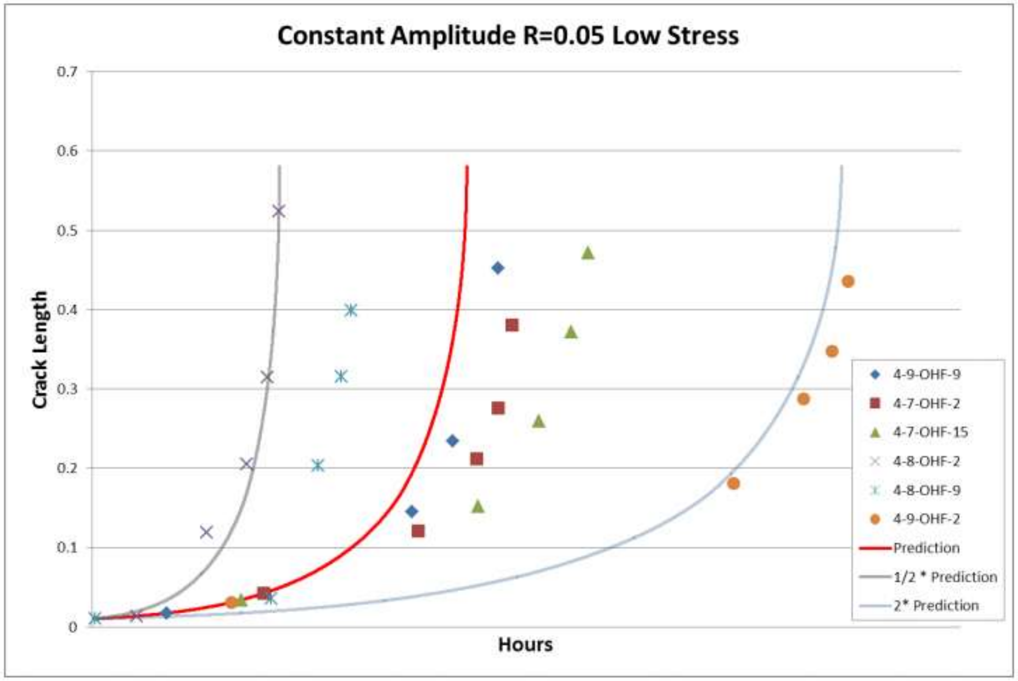
- Difference between physically small crack and long cracks
  - Plastic deformation of the wake
  - Wake roughness caused by crystallographic crack growth
  - Shielding caused by crack branching
  - Wake roughness caused by oxidation products
- Wake roughness caused by crystallographic crack growth is the driver in β annealed Ti



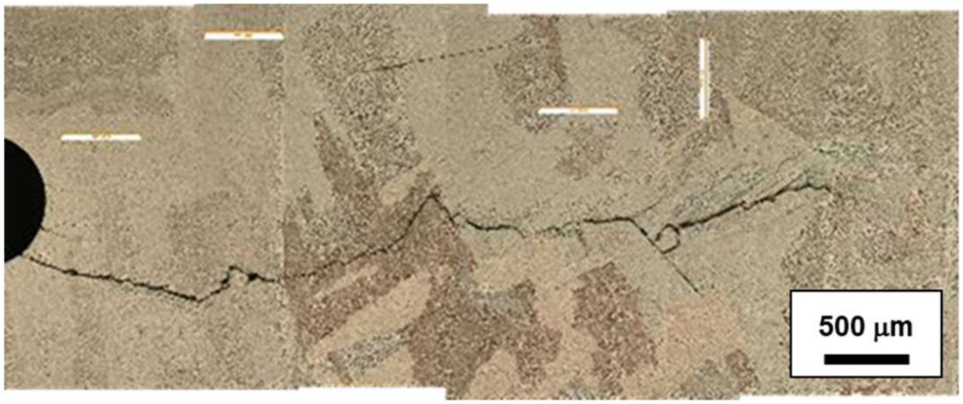
Crack with asperity of height h1 and width w.

Fatigue Behavior of β-Annealed Ti-6-4

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



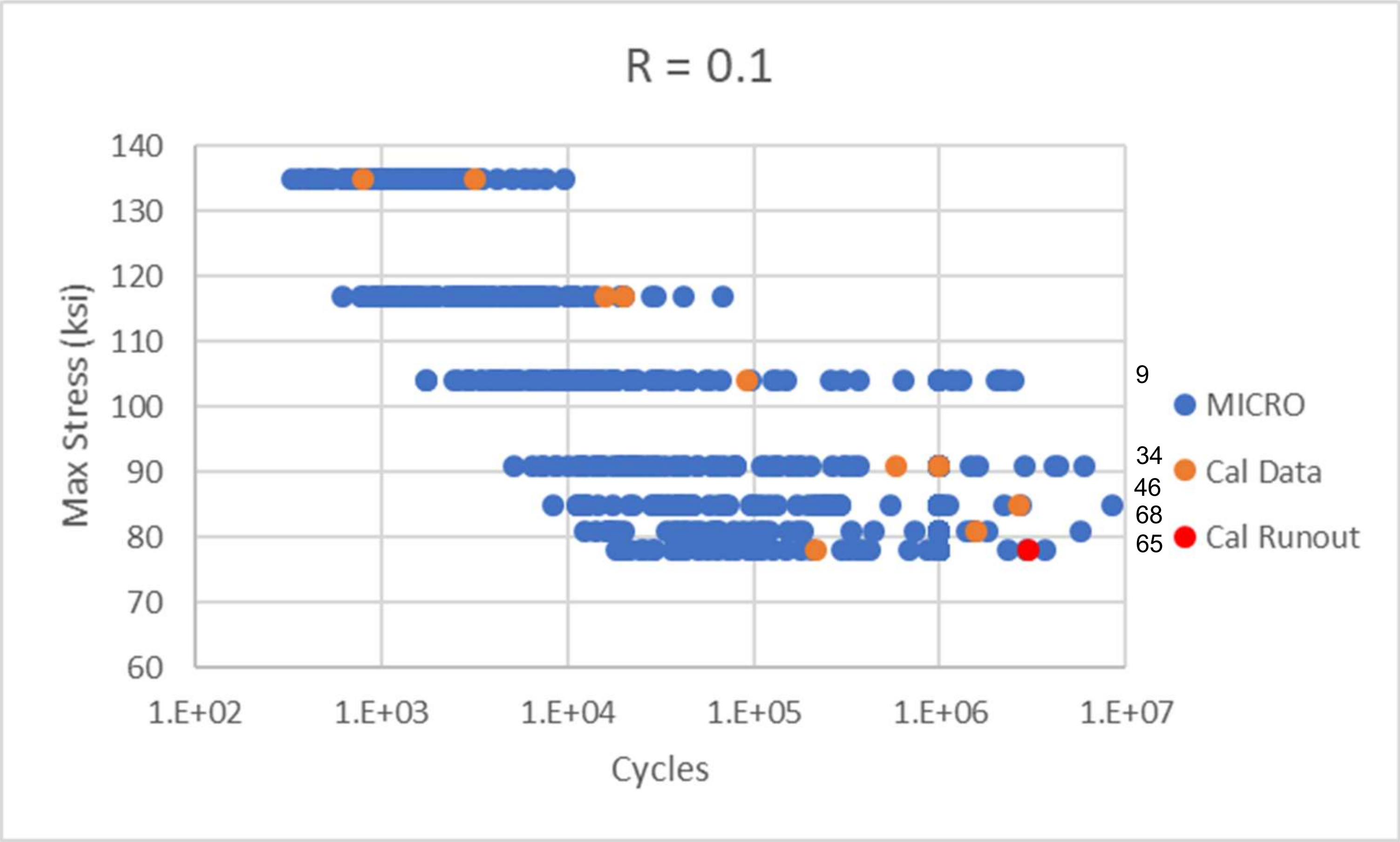
Park, Ji, et al. "Titanium 6Al-4V Durability Method Development and Test Verification Results" (2014). Presented at the Aircraft Structural Integrity Program (ASIP) annual conference.



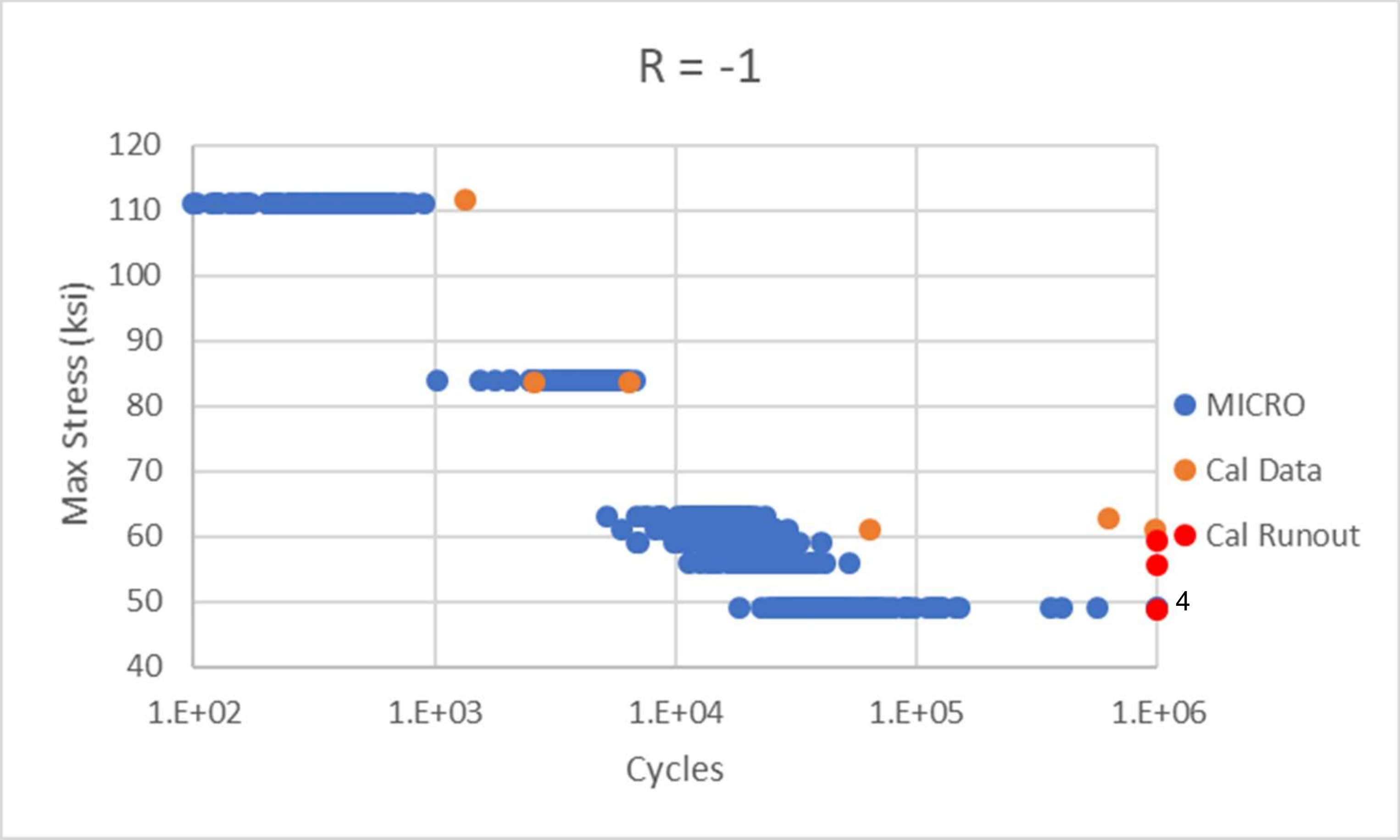
Material Property Inputs

Parameter	Nature and Description of Parameter	Typical Source of Data
Grain Boundary Strength	Deterministic; the minimum strength a nucleated crack must have to propagate.	Threshold crack growth per ASTM E647 (slow rate; high R-ratio).
Small Crack Coefficient	Deterministic; the multiplicative coefficient to small crack growth.	Used in this process as a calibration parameter.
Specific Fracture Energy	Deterministic; the energy barrier for crack nucleation.	Proportional to the area under the stress/strain curve per ASTM E8.
Grain Size	Probabilistic; the size of the microstructure participating in damage.	Metallography (preparation per ASTM E3); measure per ASTM E1382 (or equivalent).
Frictional Strength	Probabilistic; the micro-yield strength of a grain to resist dislocation motion.	Proportional to monotonic yield strength per ASTM E8; cyclic yield strength per ASTM E606 (for parameter refinement).
Long Crack Growth Parameters	Exponent ‘n’ (deterministic) and coefficient ‘C’ (probabilistic) of Paris Equation: $da/dN = C\Delta K^n$.	Long crack growth regime per ASTM E647.
Defect Size / Population	Probabilistic; size and area density of the defects participating in the damage.	Metallography (preparation per ASTM E3); measure per ASTM E1245 (or equivalent).

Smooth Round Bar R = 0.1

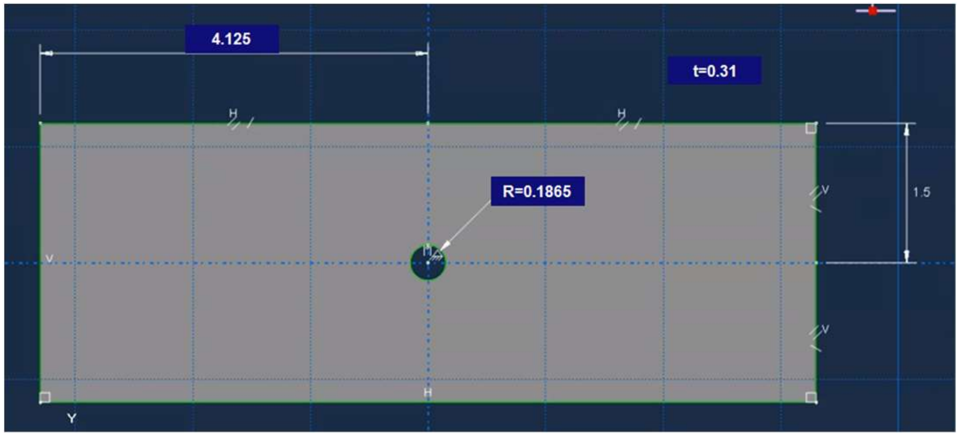


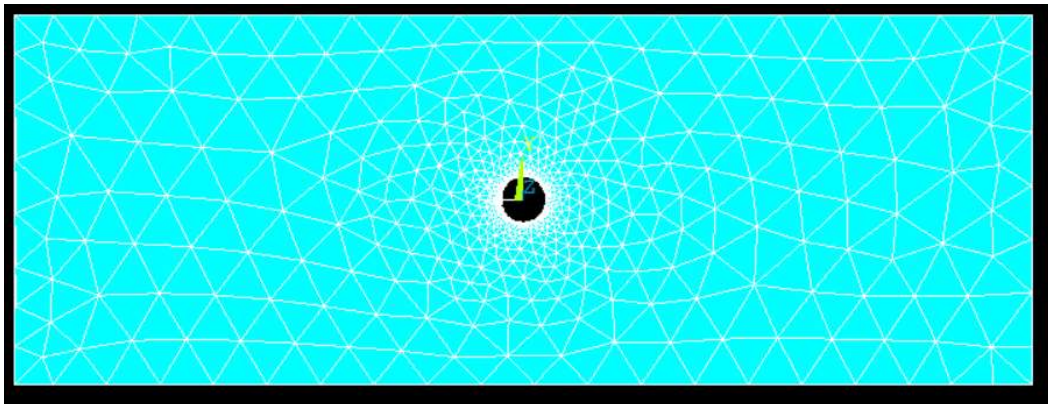
Smooth Round Bar R = -1



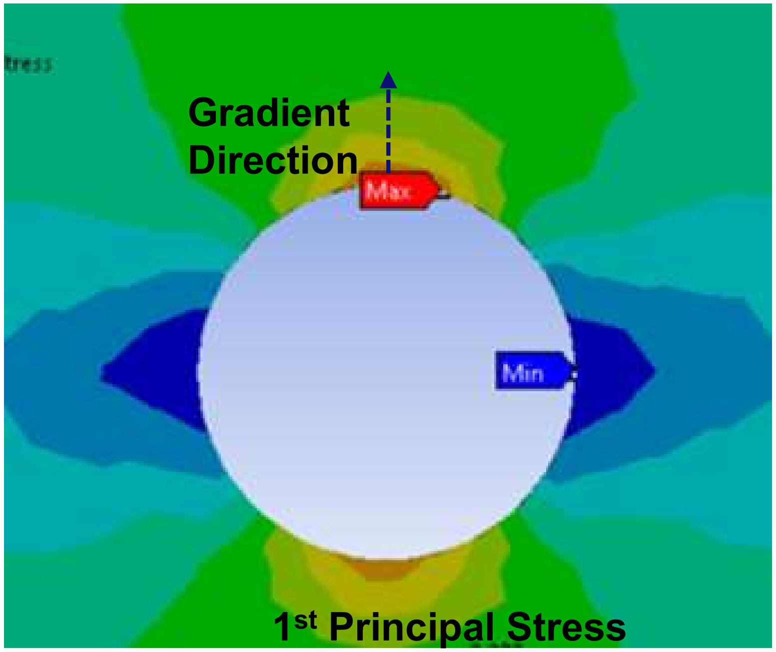
Open Hole Specimen

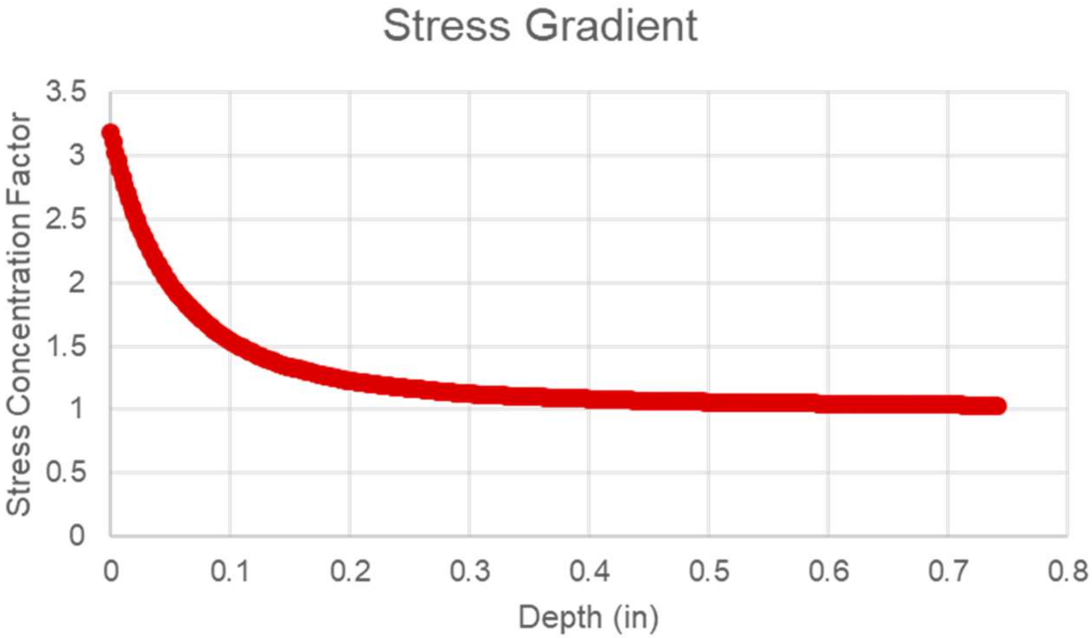
- Poisson’s ratio = 0.3
- E = 16155 ksi
- Elastic material model for stress concentration gradient evaluation.
- Elastic-plastic material model for residual stress gradient evaluation





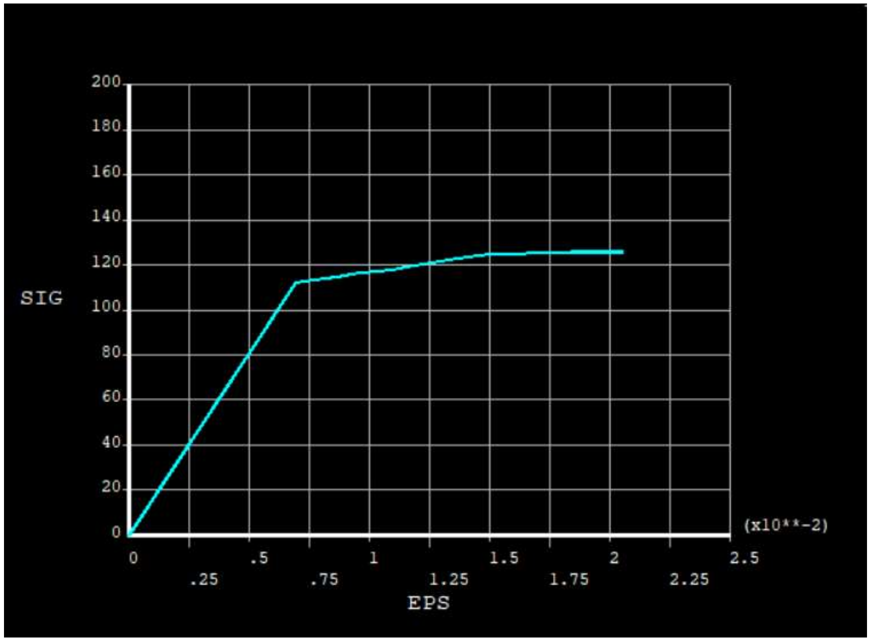
Stress Gradient

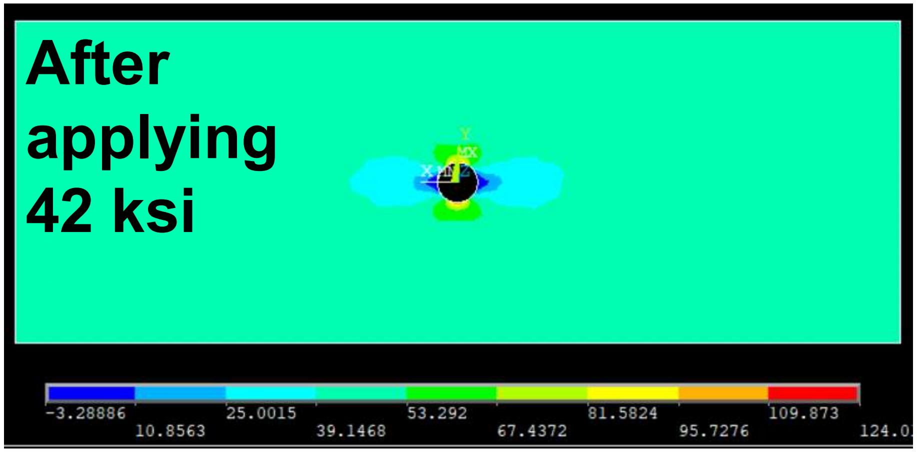




Residual Stress

- Elastic-plastic material model is used.
- Stress-strain curve is obtained from experimental evaluations.
- 42 ksi is applied, then load is removed.
- The residual stress gradient is determined.

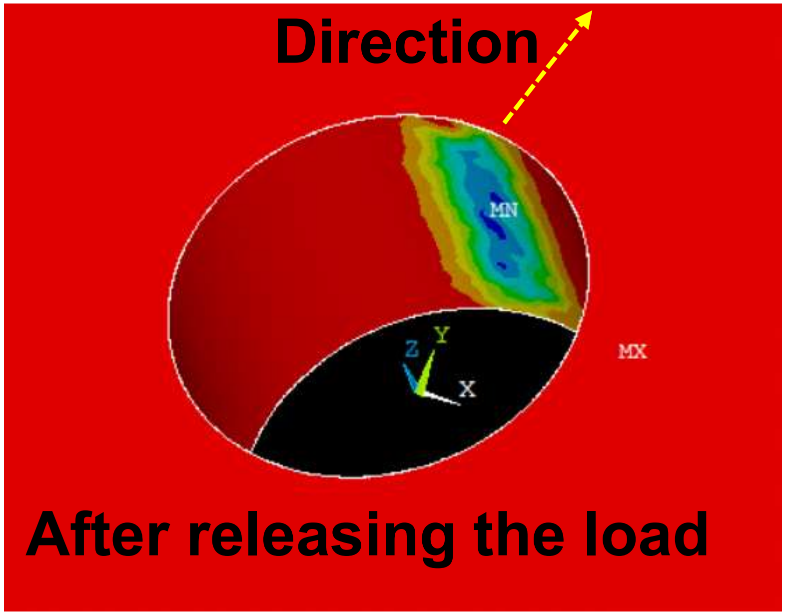




Residual Stress

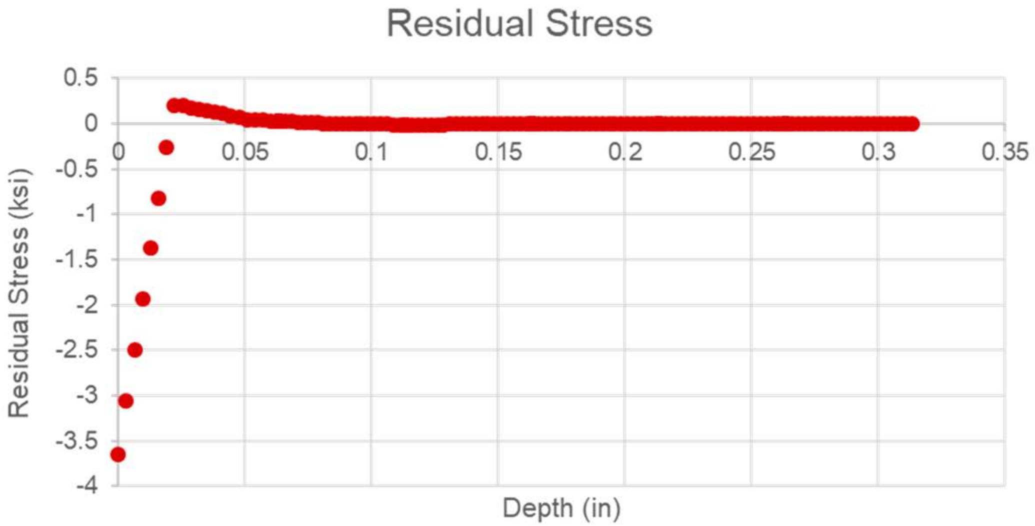
- After the load is released, the residual stresses are evaluated.

Gradient Direction



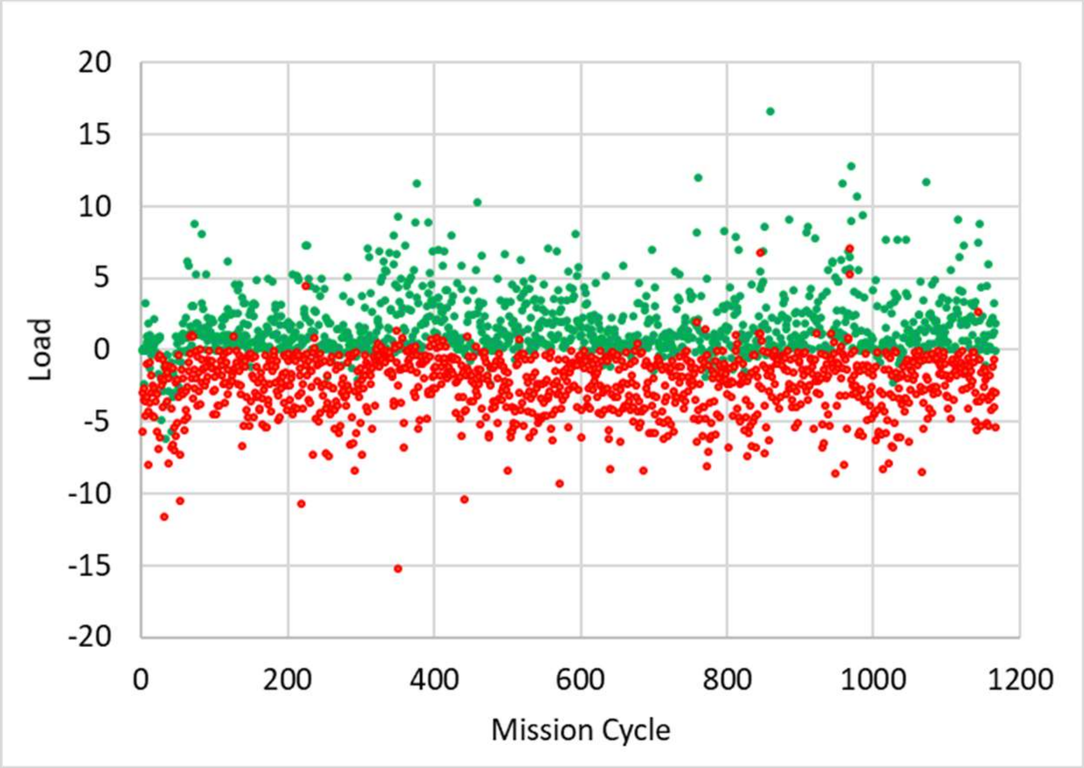
After releasing the load

Principal Stress



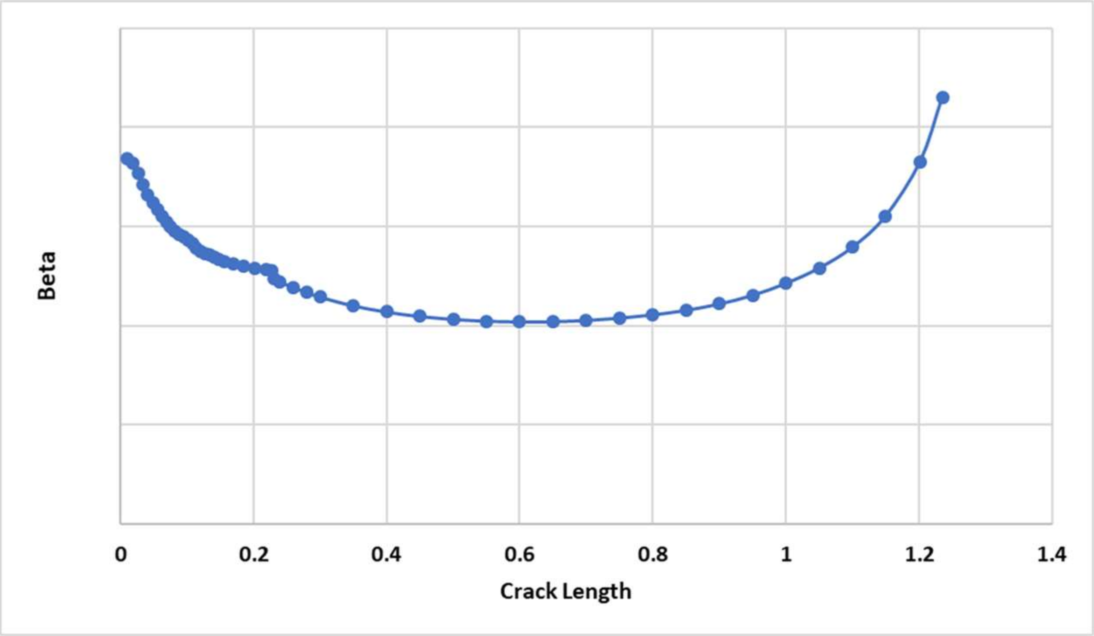
Spectral Loading

Loading input as a file of max and min pairs

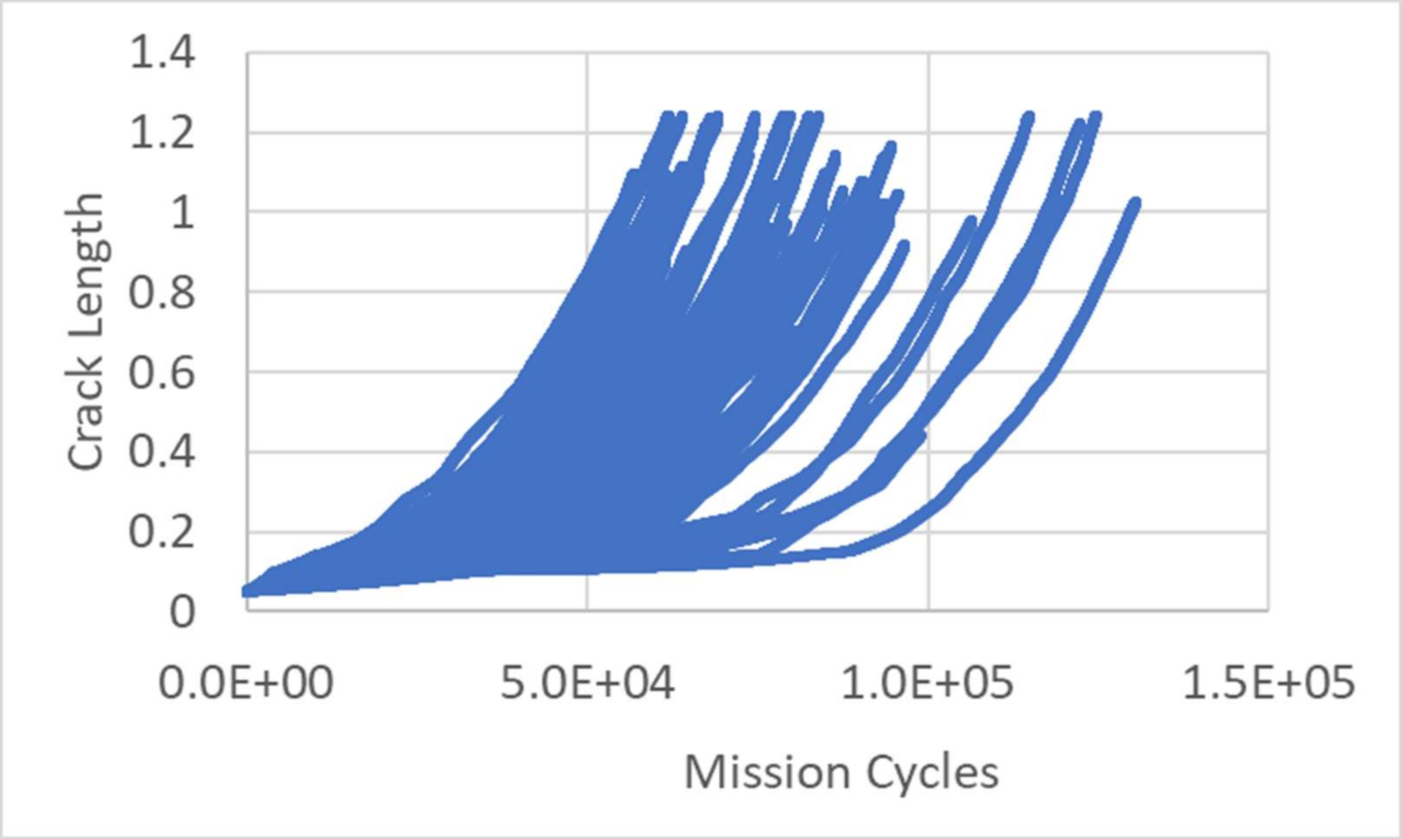


LCG Model Inputs c vs β

Linear elastic crack tip stress intensity solution (K) is input in tabular format as a function of crack length

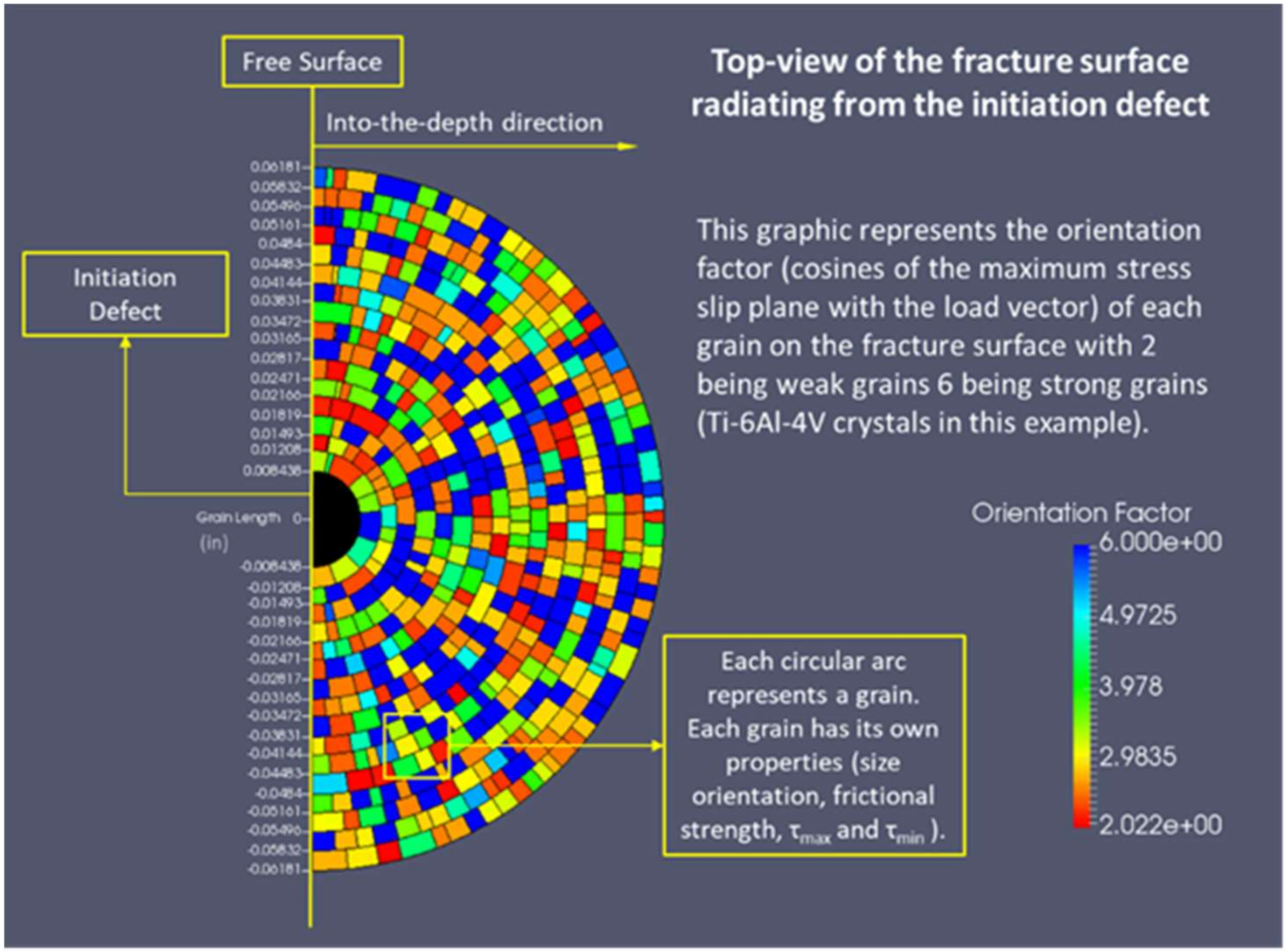


Results – Crack Length vs. Cycles



100 simulated open hole specimens

Simulated Fracture Surface



Top-view of the fracture surface radiating from the initiation defect

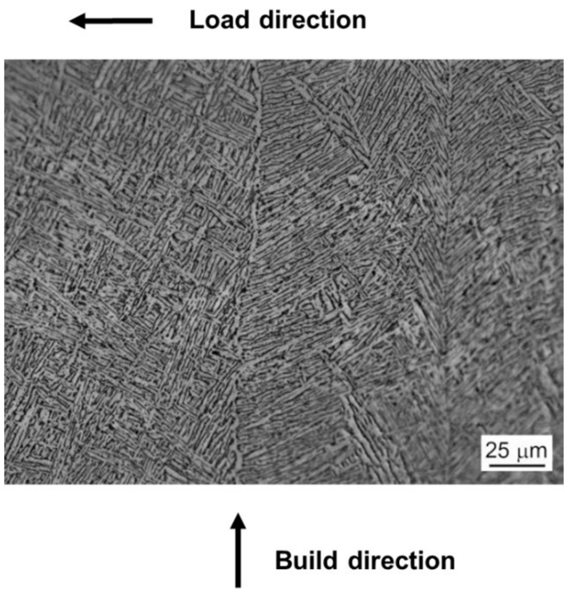
This graphic represents the orientation factor (cosines of the maximum stress slip plane with the load vector) of each grain on the fracture surface with 2 being weak grains 6 being strong grains (Ti-6Al-4V crystals in this example).

Each circular arc represents a grain. Each grain has its own properties (size orientation, frictional strength, τ_{max} and τ_{min}).

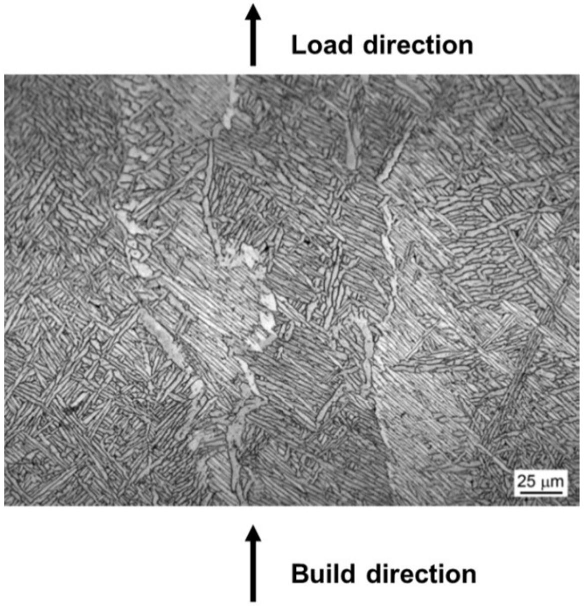
Applying ICME and SFFM to Additive Manufactured Materials

Evaluation of Fatigue and Fracture Mechanism

Horizontal Specimens



Vertical Specimens

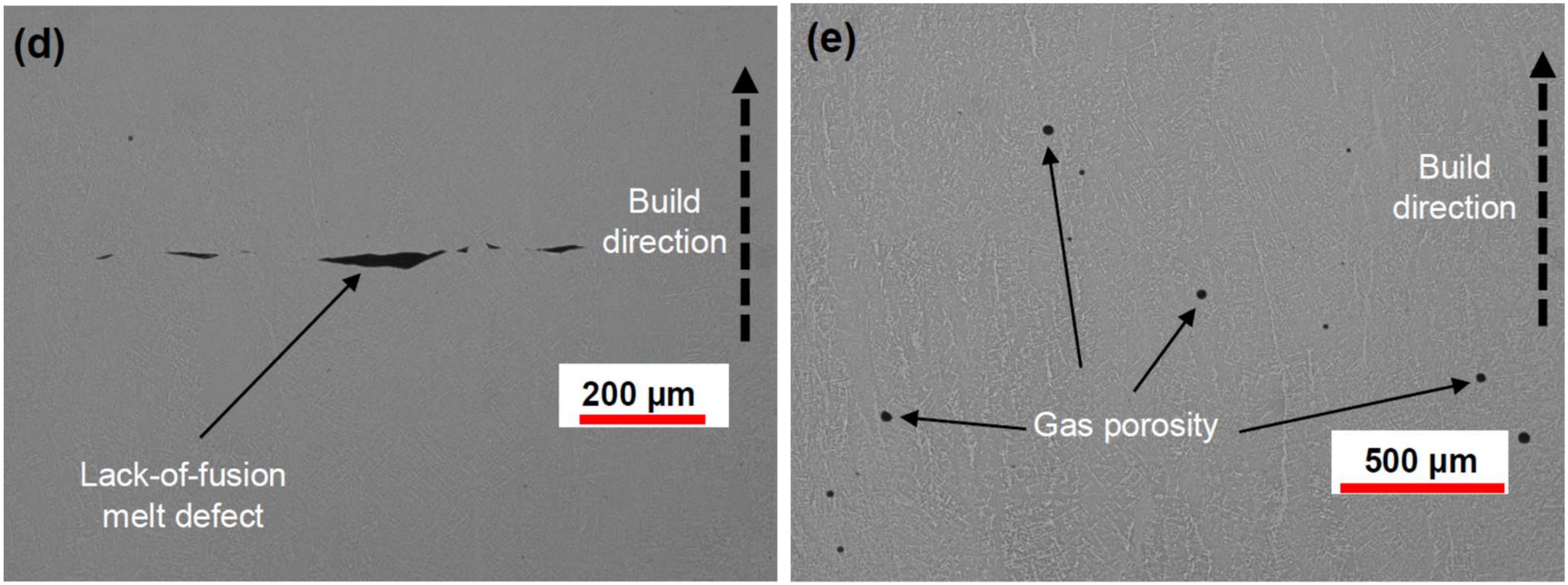


- Slightly higher tensile strength due to absence of build defects
- Smooth fatigue fracture surface

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

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

Build Defects: Geometric Features



Chern, Andrew (2018) “Build orientation, part size geometry, and scan path influence on the microstructure and fatigue life of Ti-6Al-4V fabricated by Electron Beam Melting,” MS Thesis, UTK

Material Property Comparison (Forged vs. EBM)

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

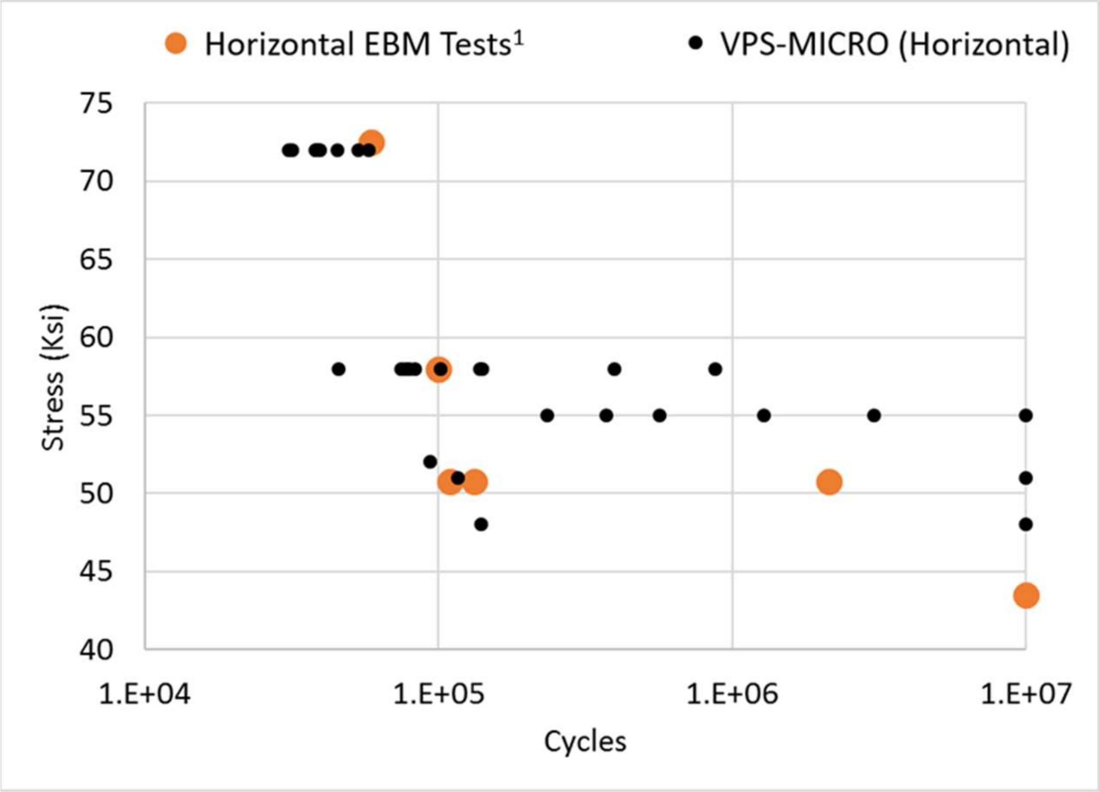
[††] "Grain size" refers to the microstructural feature of interest: the size of the α-lamellar colonies within prior β grains

	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

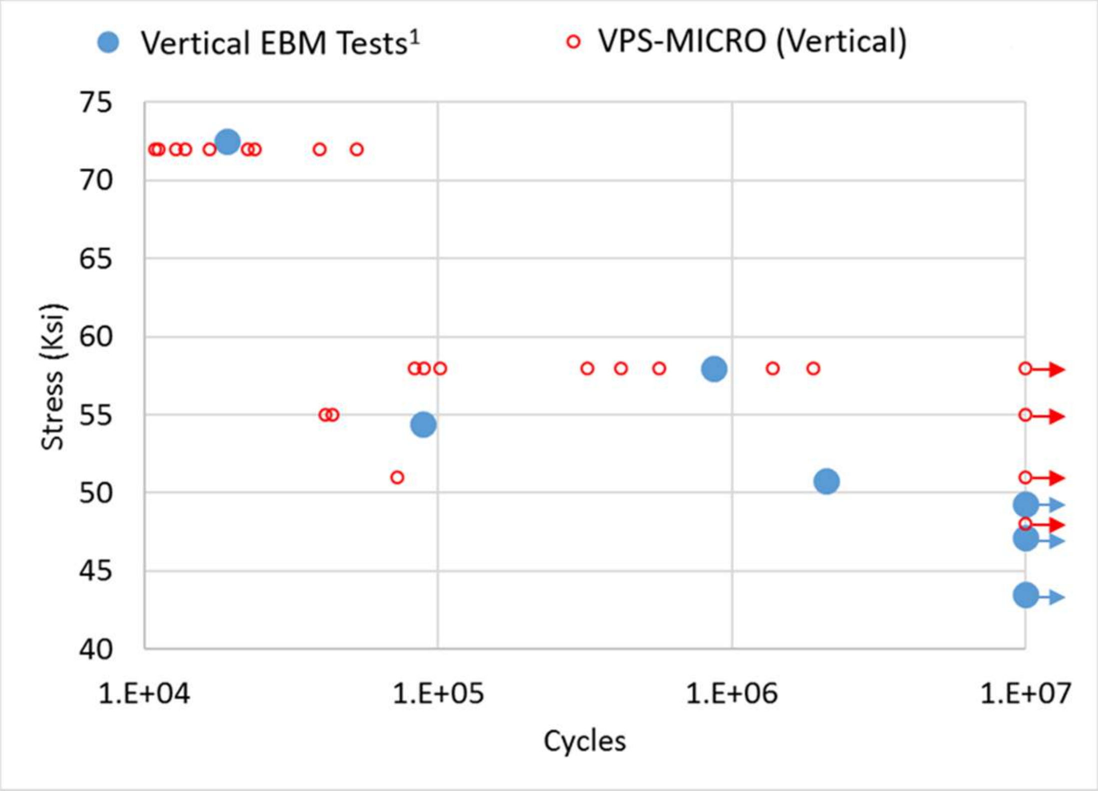
- 10 specimens simulated at each stress level (all complete < 1 hr.)
- Results show good comparison between actual and predicted fatigue lives



Gong (2013)

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



Gong (2013)

Conclusions

- ICME with SFFM is used to link microstructure-to-performance
- A probabilistic SFFM fatigue model previously calibrated to conventionally processed Ti-6Al-4V is 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

Thank You