Using ICME to Simulate Fatigue and Fracture of Additive Manufactured Components

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Acknowledgements

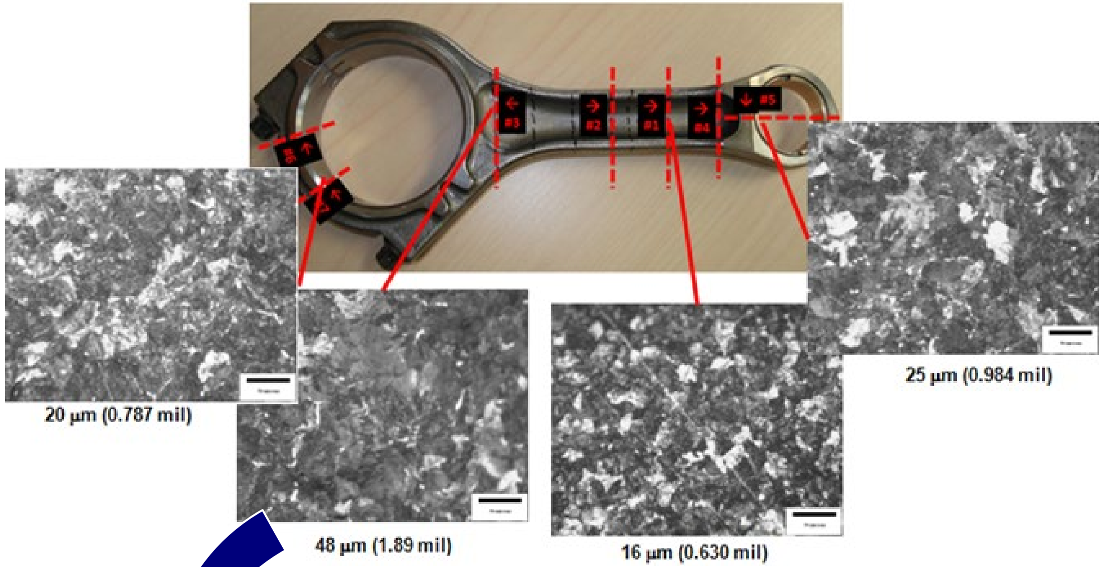
- Kishan Goel and Madan Kittur (NAVAIR)
- Pat Golden and Mike Gran (AFRL)

Objectives

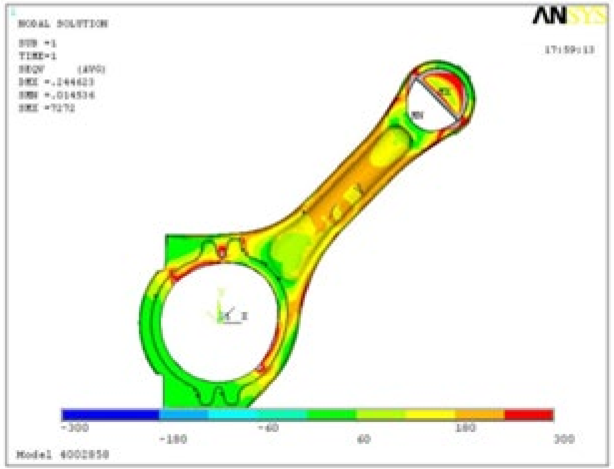
<u>Use Integrated Computational Materials Engineering (ICME) to aid in the lifing of AM products</u>

- **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**

Application of ICME



Map microstructure from part to FEA



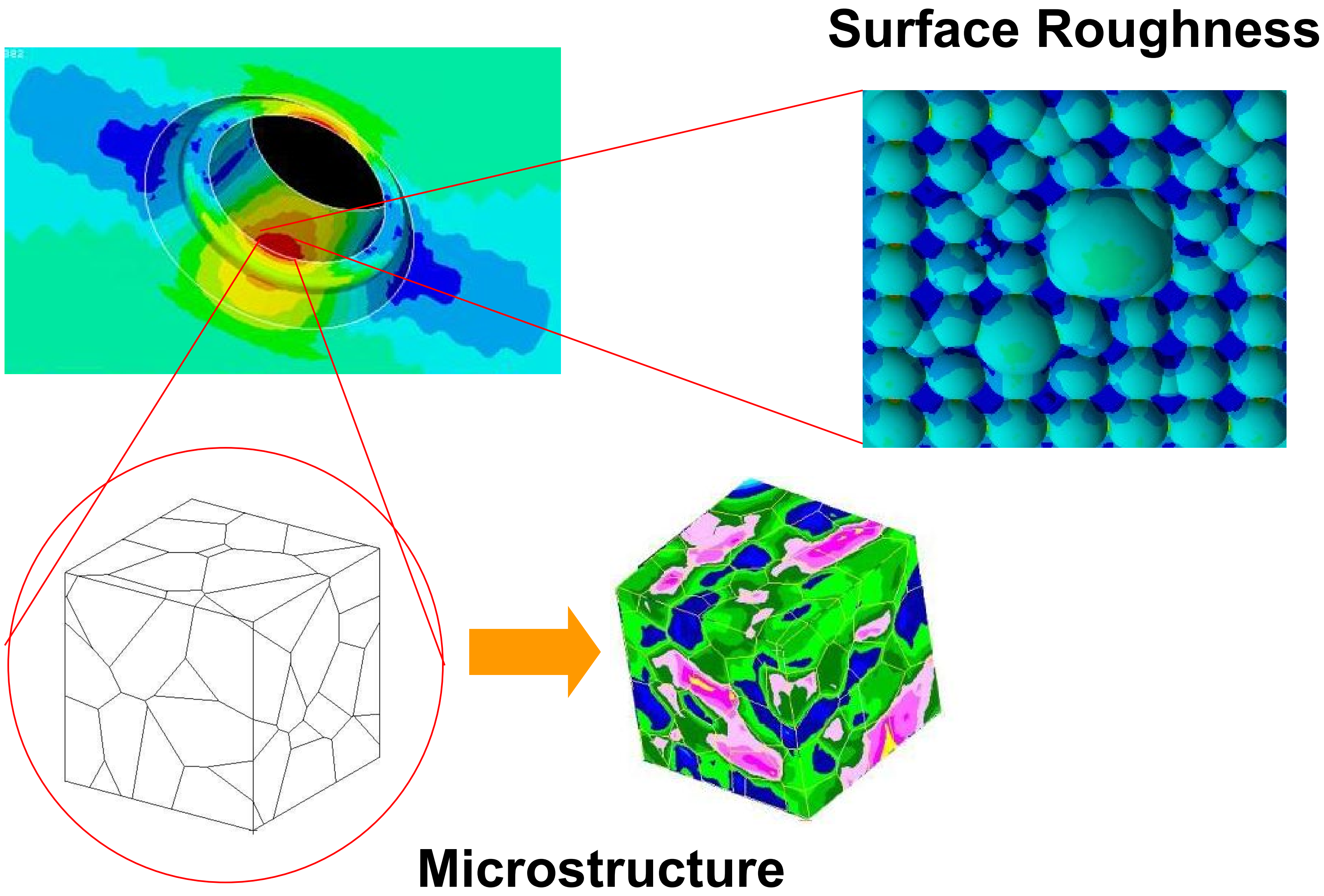
VPS-MICRO® – computational micro*structural* fatigue software

- 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

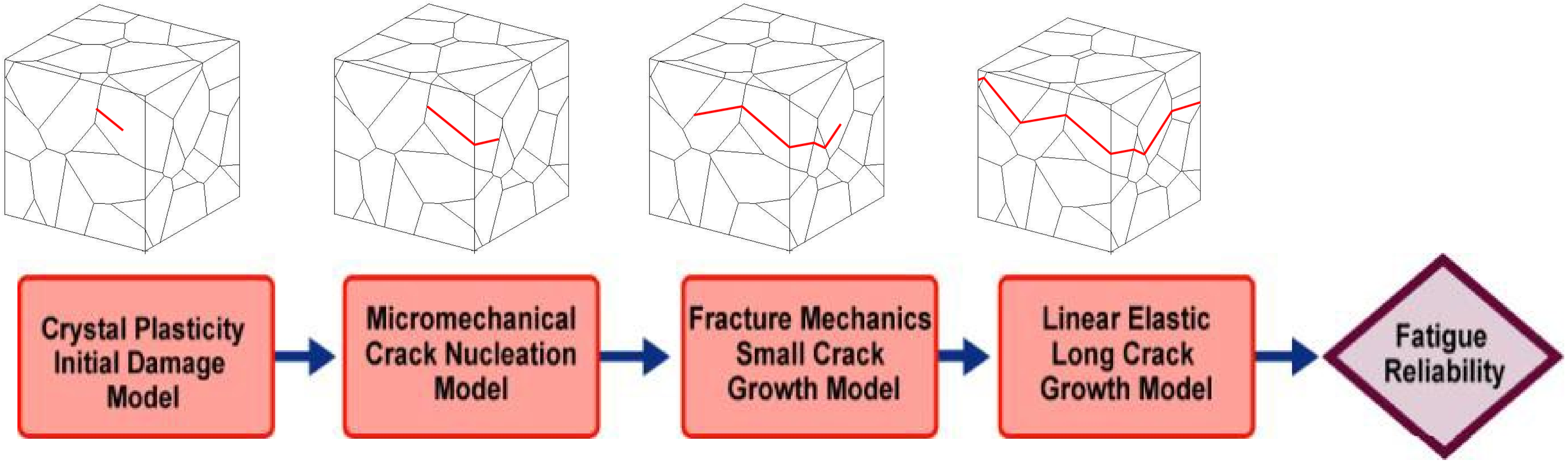
Durability Certification in Fatigue

- **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[1]**
  - **Explicitly modeled differences in microstructure, defects, and damage mechanisms**

Microscopic Structural Analysis



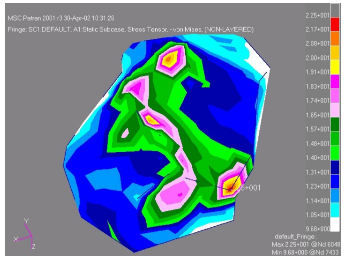
ICME Constitutive Equations for Damage Evolution



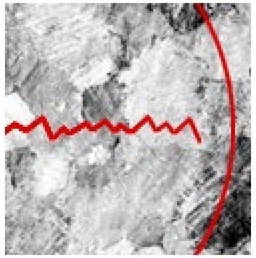
Software uses proven equations for each damage stage

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

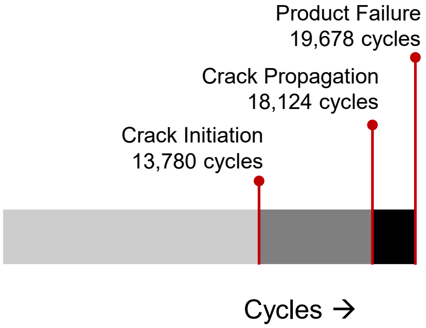
ICME Computational Process Flow



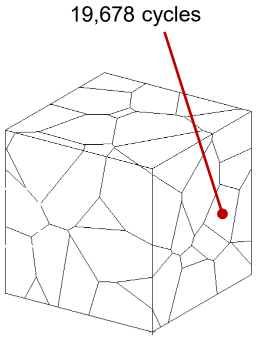
Begin Grain Damage Simulation



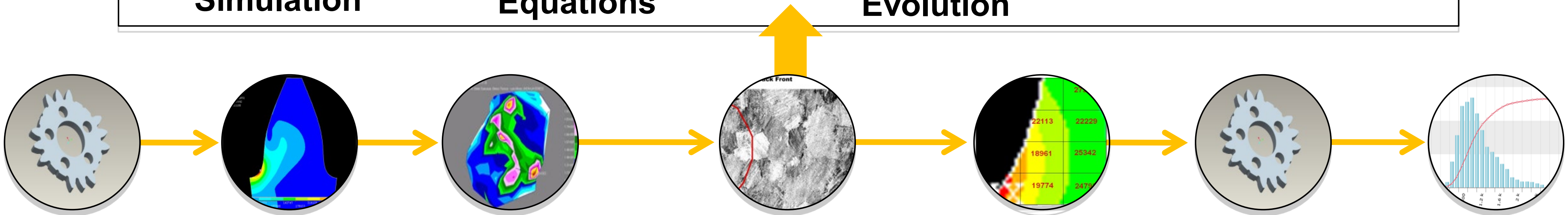
Apply Multiple Constitutive Equations



Grain Damage Evolution



Failure: 19,678 cycles
Cause: Grain Cracking

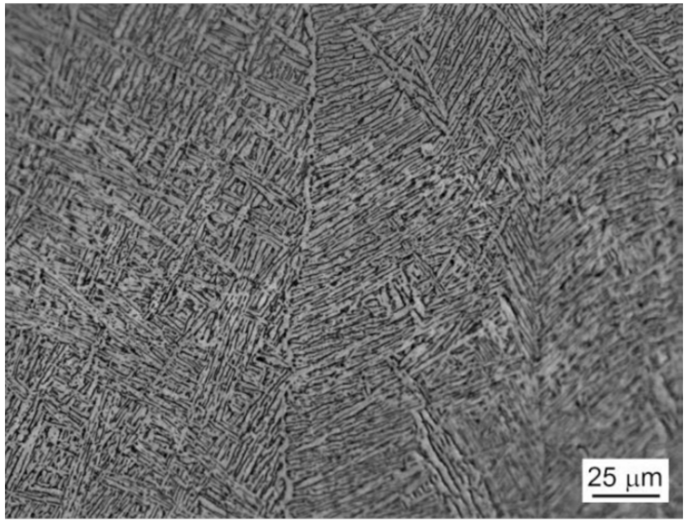


Component → Design → Material → **Computational Processing** → Mapping the Elements → Component Simulation → Fleet Simulation

Evaluation of Fatigue and Fracture Mechanism

Horizontal Specimens

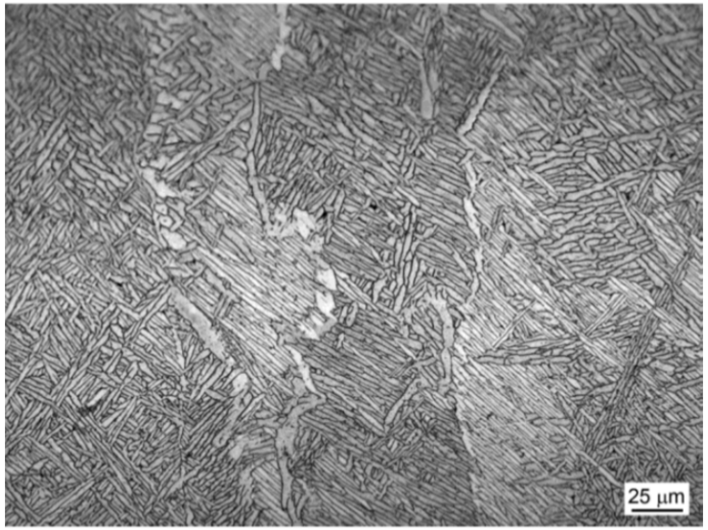
Load direction



Build direction

Vertical Specimens

Load direction



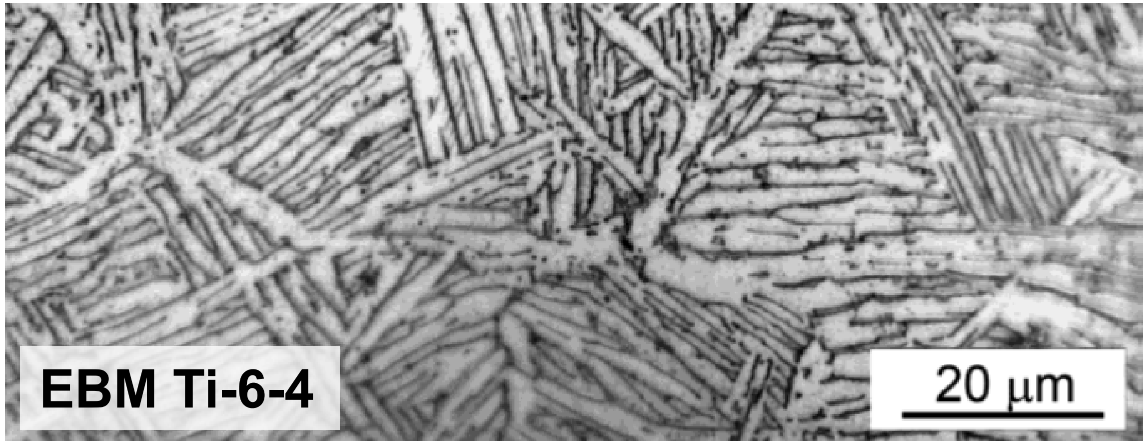
Build direction

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

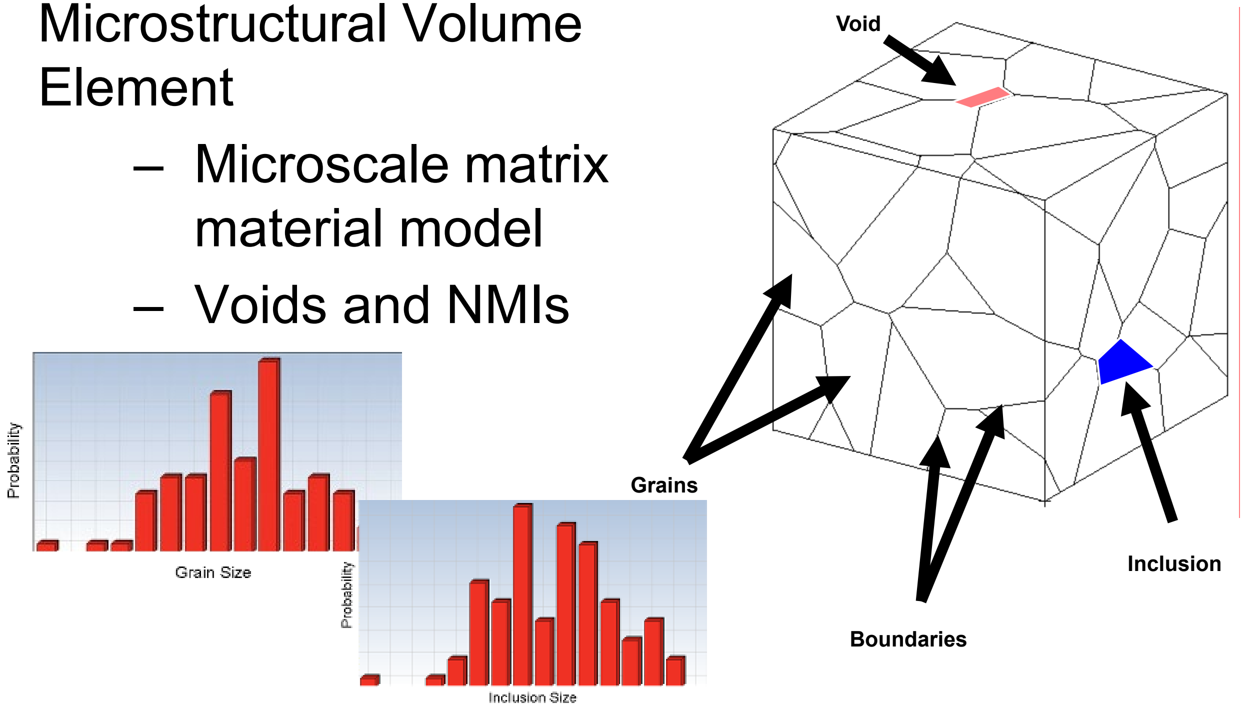
- **Slightly lower tensile strength due to build defects**
- **Rough fatigue fracture surface**

[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

Microstructural Comparison (Forged vs. EBM)



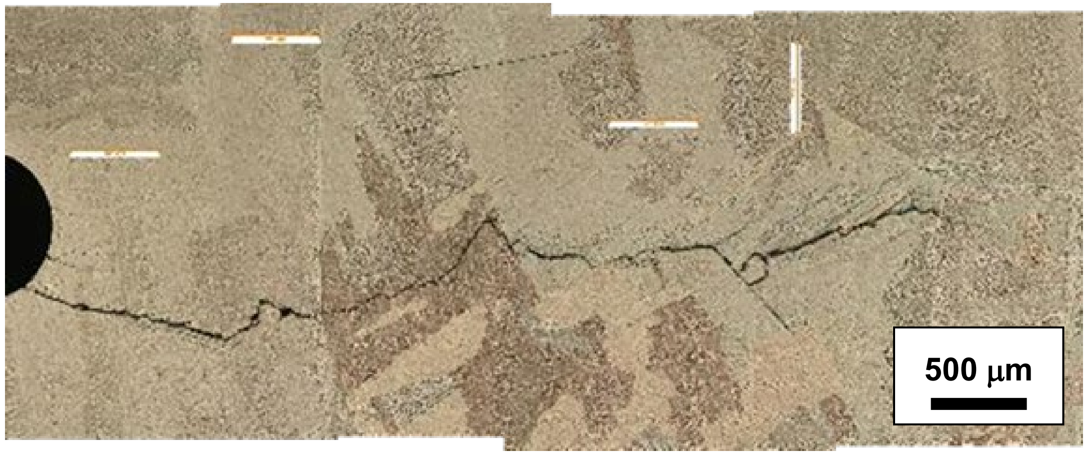
Microstructural Volume Element
- Microscale matrix material model
- Voids and NMIs

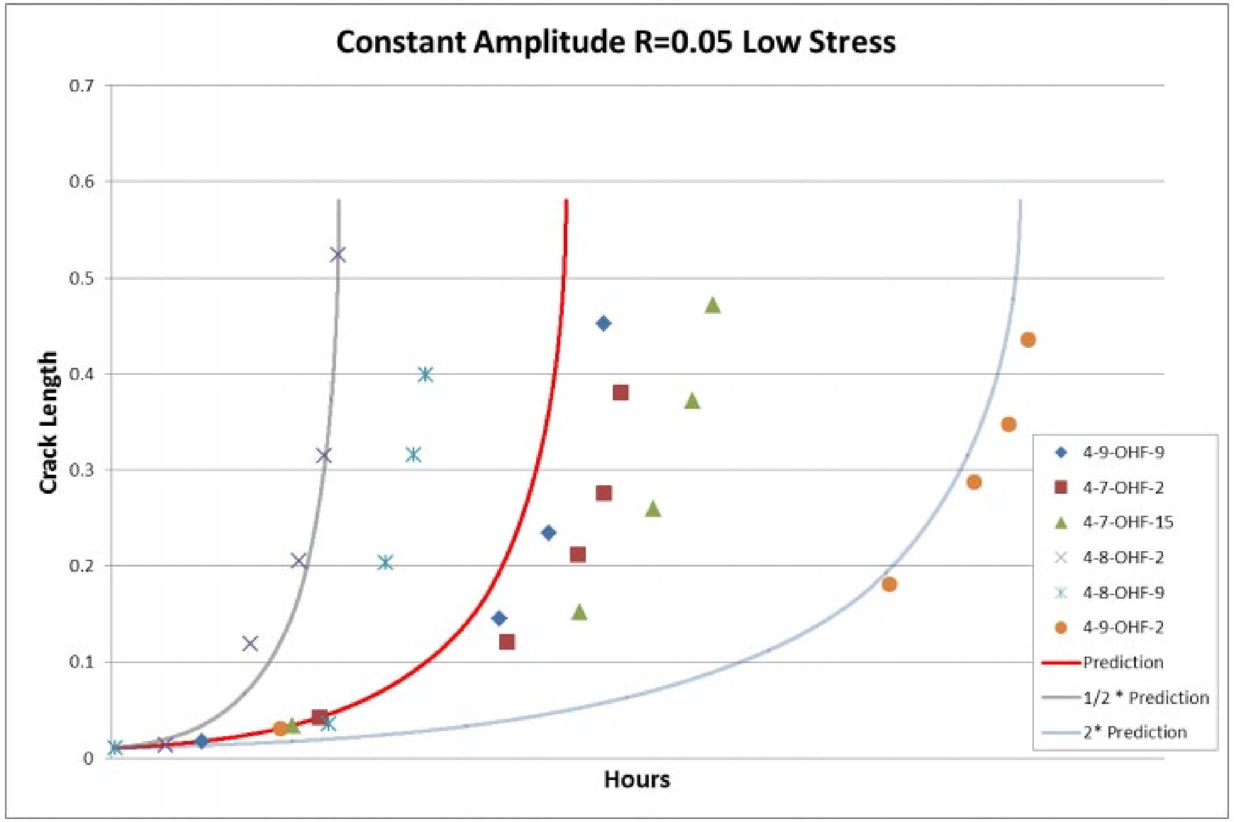


- EBM Ti-6-4 has similar morphology, but a smaller grain size
- Used model previously-calibrated to forged Ti-6-4, to predict EBM Ti-6-4

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

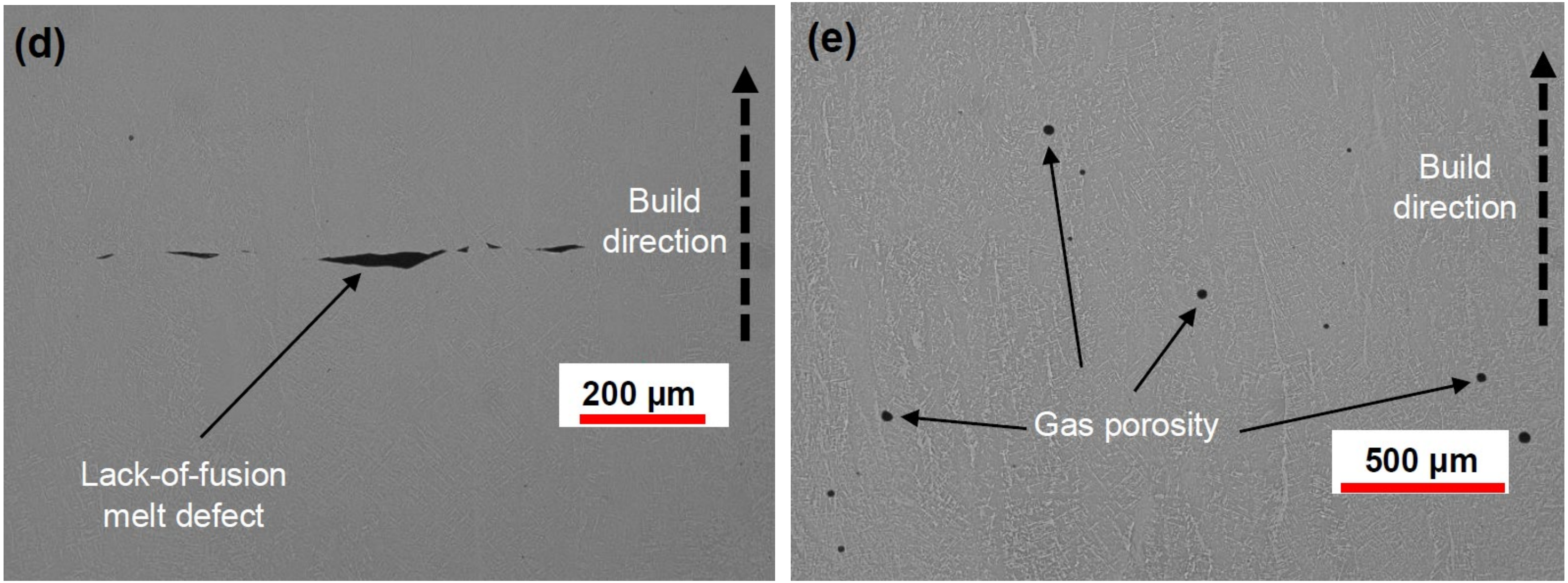
- **Majority of life spent in crack growth when damage initiates at a large defect**
- **Large variation in crack growth**
  - **Limited slip systems in basket-weave titanium alloys**
  - **Coarse microstructure**





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.

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

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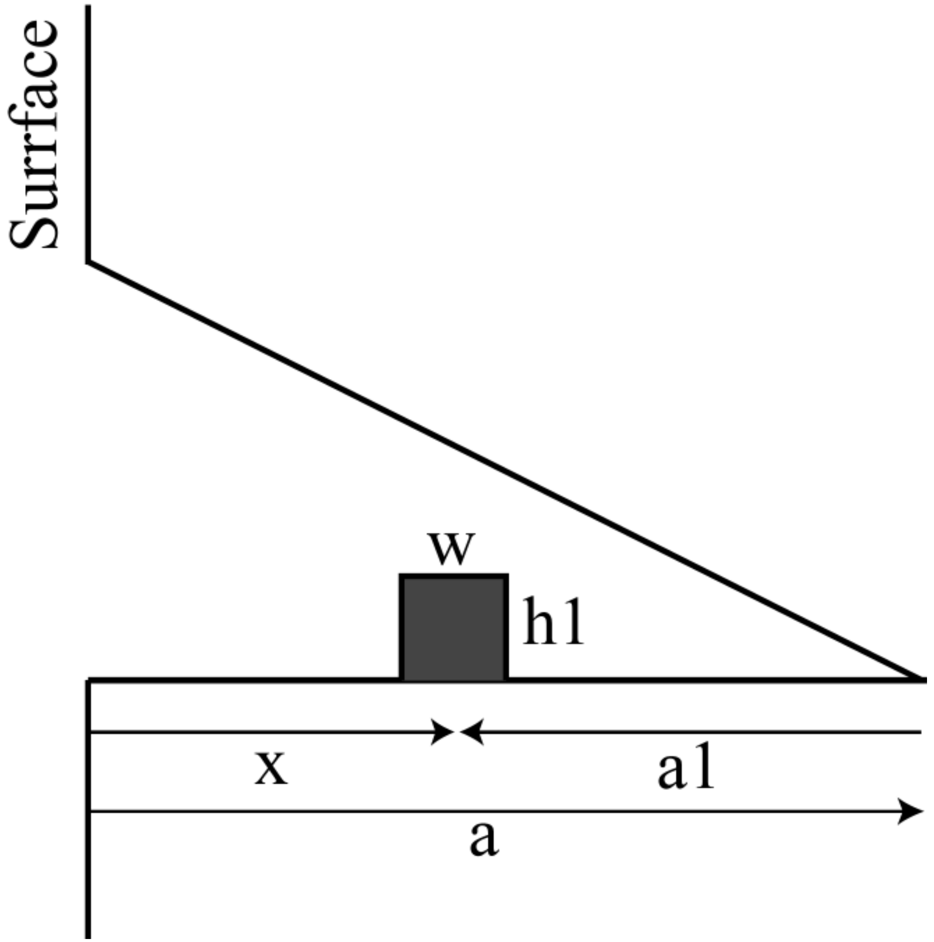
Modeling Rough Fatigue Fracture Surface

- **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.

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Material Property Inputs

		Conventional		AM (Horizontal)	
Description	Distribution	Mean Value	COV	Mean Value	COV
CTOD Law Coefficient	Deterministic	0.1	N/A	0.1	N/A
Slip length	Lognormal	0.025 in.	0.3	0.0034 in	.3
Bulk shear modulus	Deterministic	3610 ksi	N/A	3610 ksi	N/A
Frictional strength	Weibull	113 ksi	0.3	83 ksi	0.3
Grain boundary SIF	Deterministic	2.5 ksi√in.	N/A	3.0 ksi√in.	N/A
Paris Law Coefficient	Lognormal	6.58E-11	0.45	6.58E-11	0.45
Paris law exponent	Deterministic	3.96	N/A	3.96	N/A
Specific fracture energy	Deterministic	7500lbs/in	N/A	7700lbs/in	N/A
Micro-stress	Normal	Applied stress	0.15	Applied stress	0.15
Poisson's ratio	Deterministic	0.3	N/A	0.3	N/A
Defect size	Lognormal	None	N/A	None	N/A
Asperity	Lognormal	0.01, .1, 1, 1	N/A	None	N/A

VEXTEC

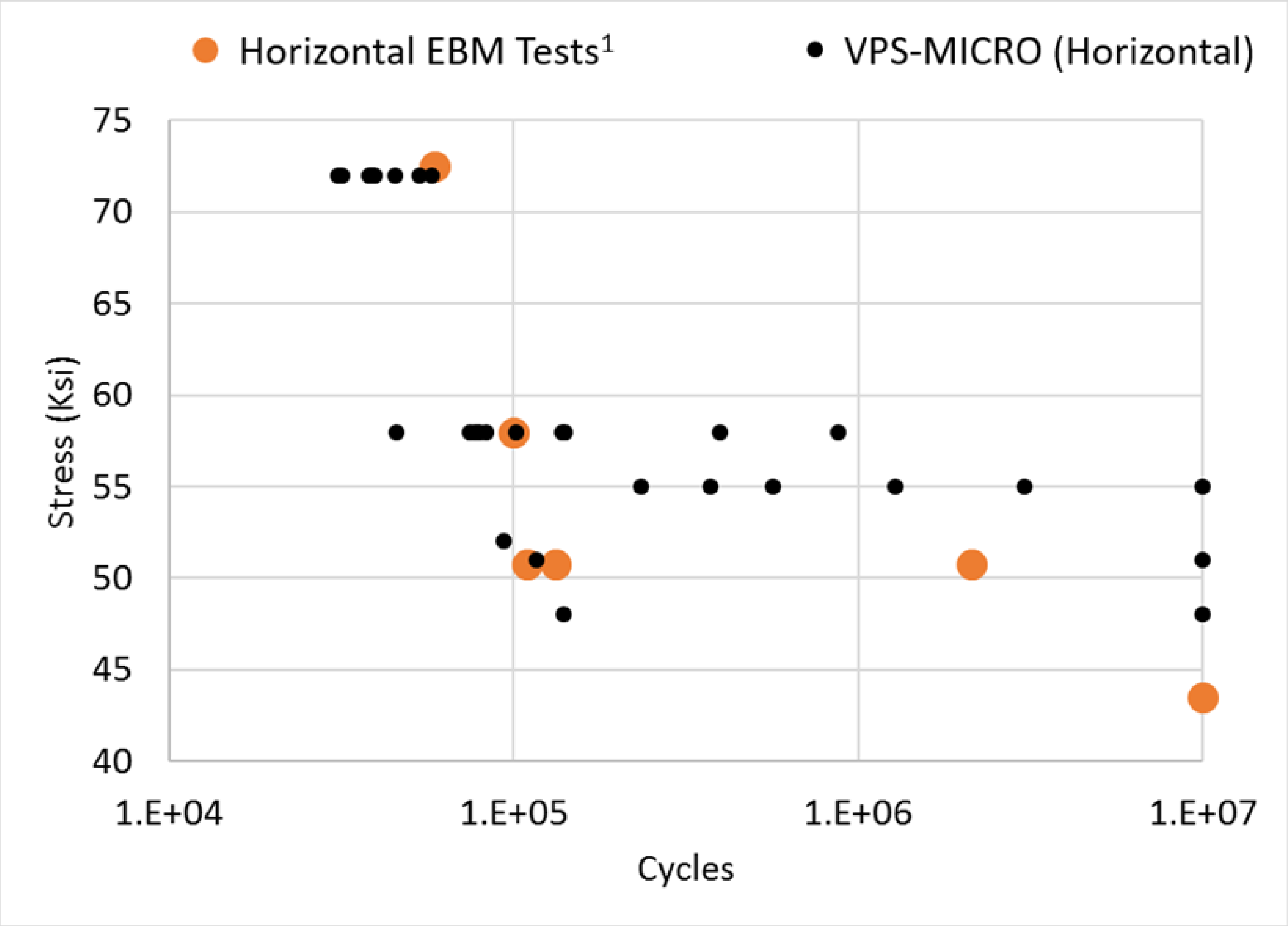
Material Property Inputs

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).

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)

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

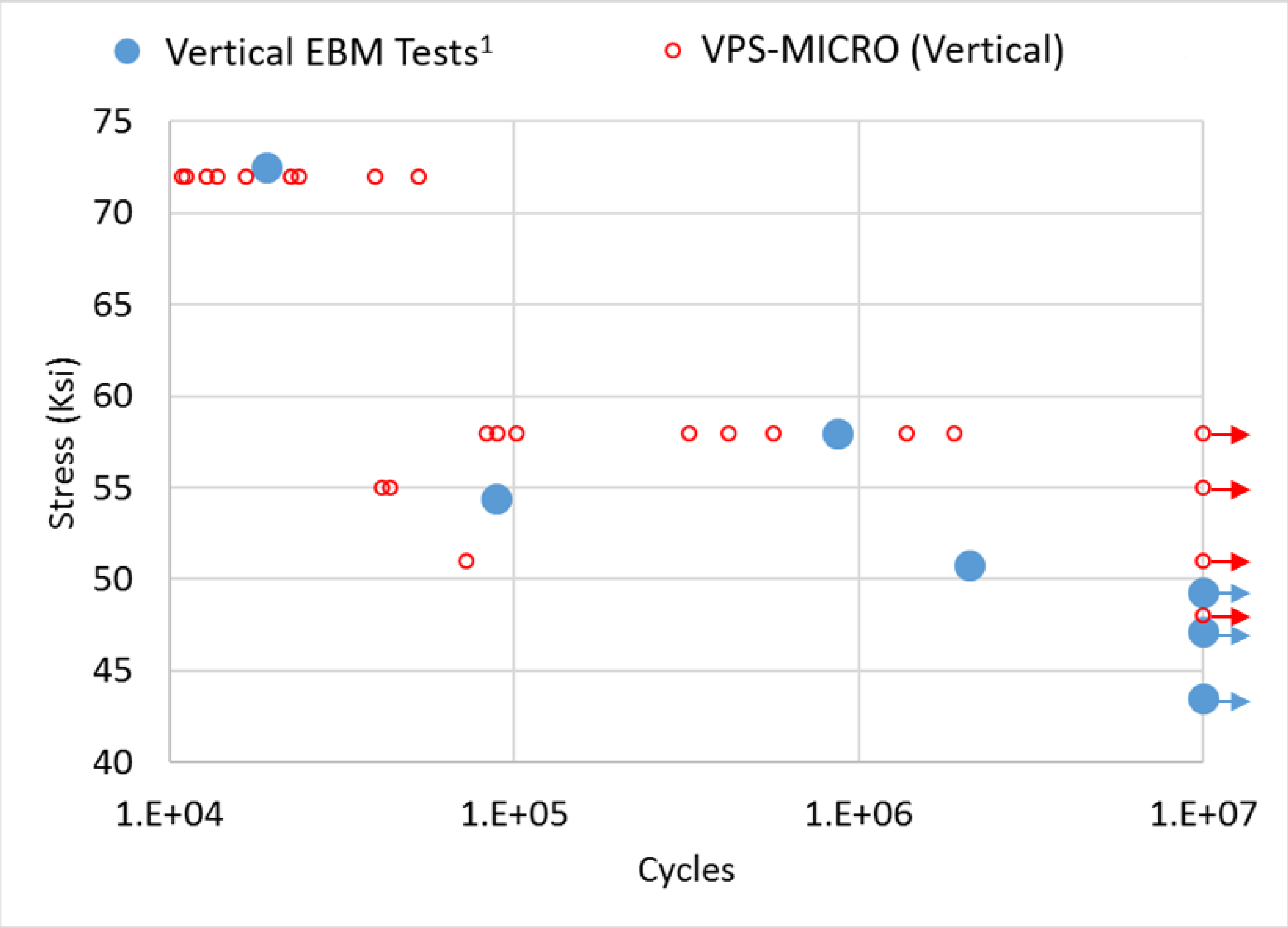
	Material Properties Influenced by Manufacturing Technique†		Ti-6Al-4V Forged + β-Annealed		Ti-6Al-4V EBM (Horizontal)		Ti-6Al-4V EBM (Vertical)	
	Description	Distribution	Mean Value	COV	Mean Value	COV	Mean Value	COV
Probabilistic	Grain size††	Lognormal	0.025 in	0.3	0.0034 in	0.3	0.0034 in	0.3
Probabilistic	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 Specimens w/ both Defects and Asperities i.e., Vertical Specimens

Experimentally observed mechanistic differences between Horizontal and Vertical specimens

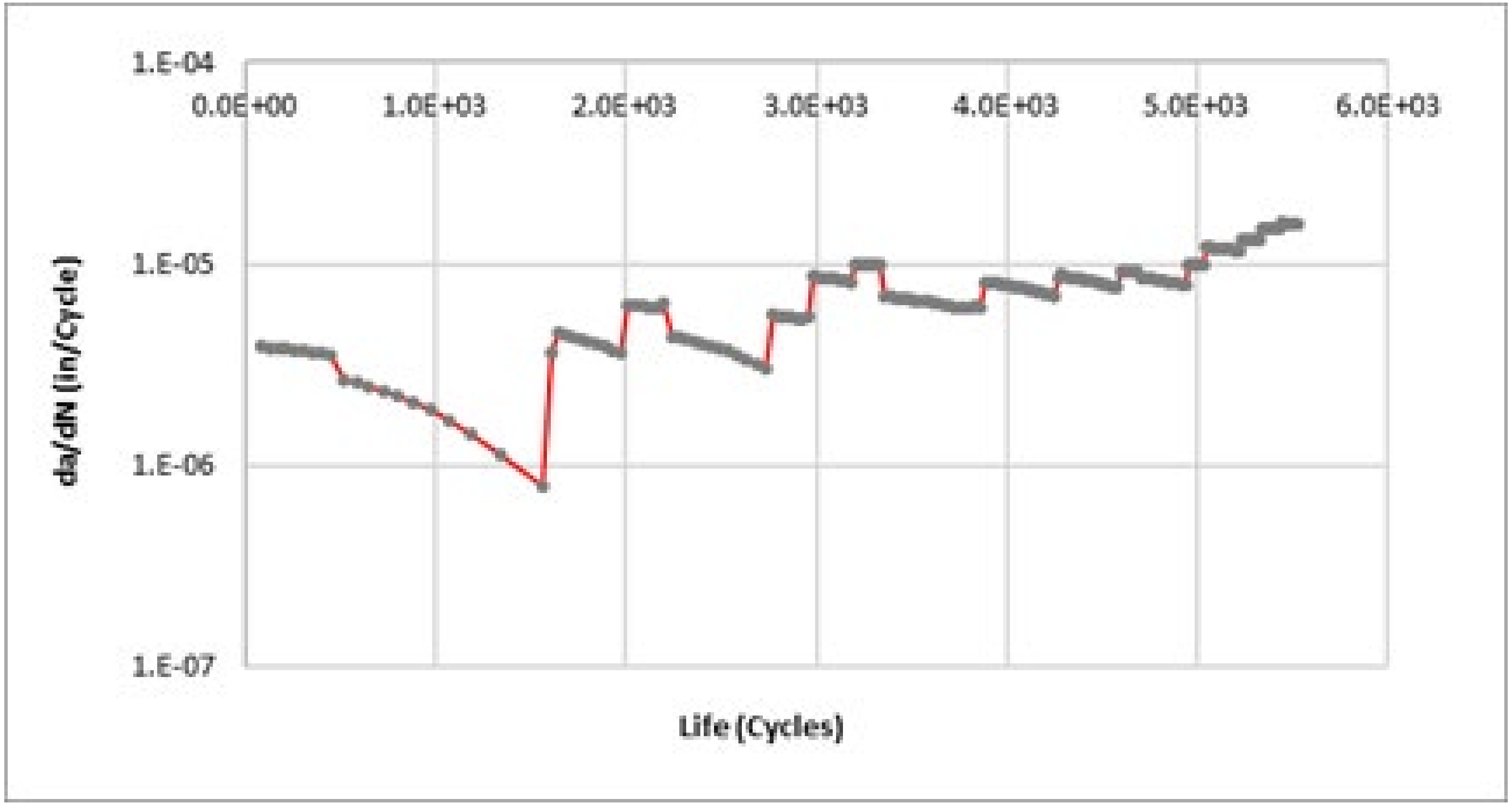
- **Defects are active damage sources in Vertical specimens**
- **Tortuous fracture surfaces of Vertical specimens (asperities)**

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

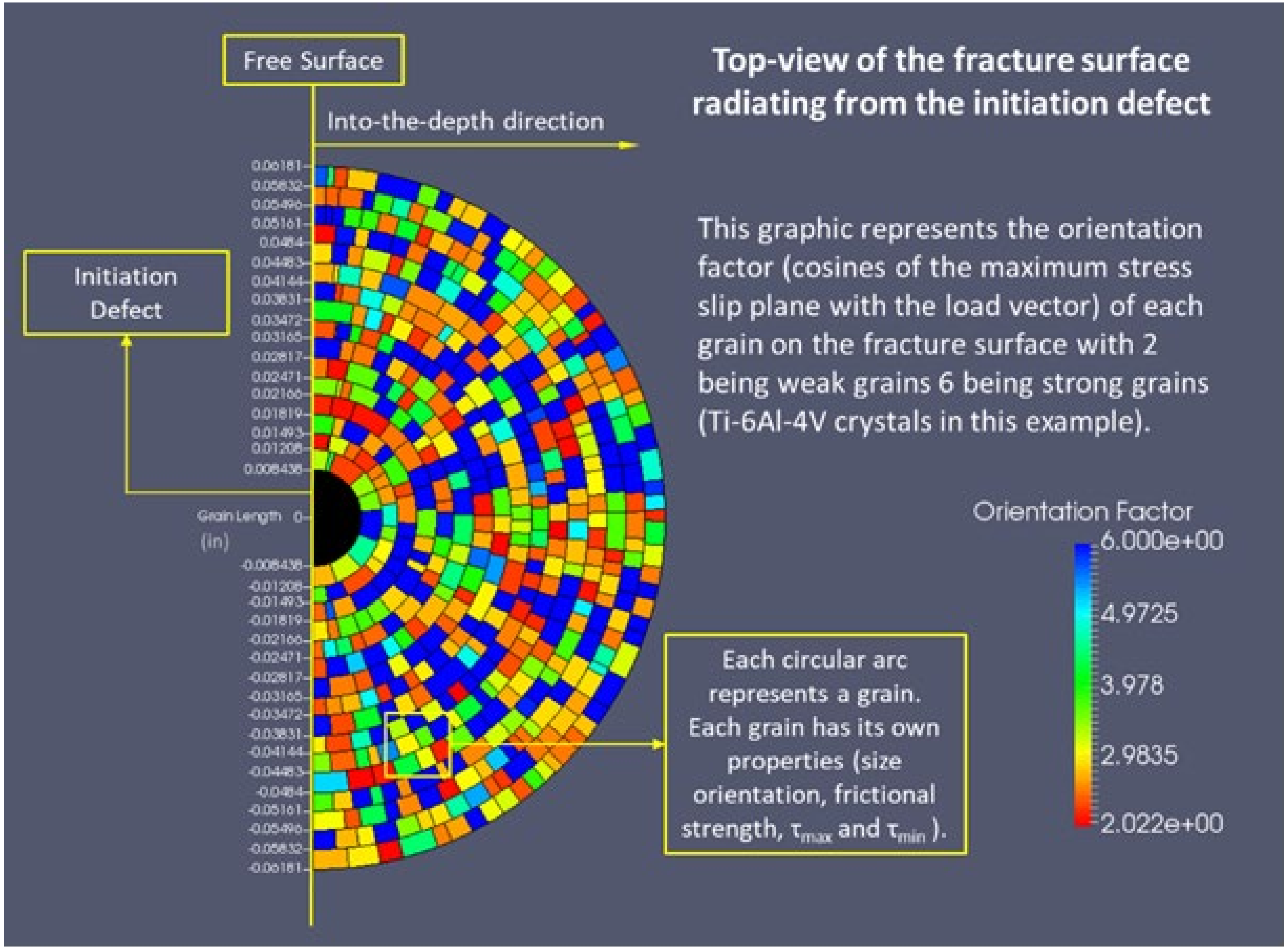


Gong (2013)

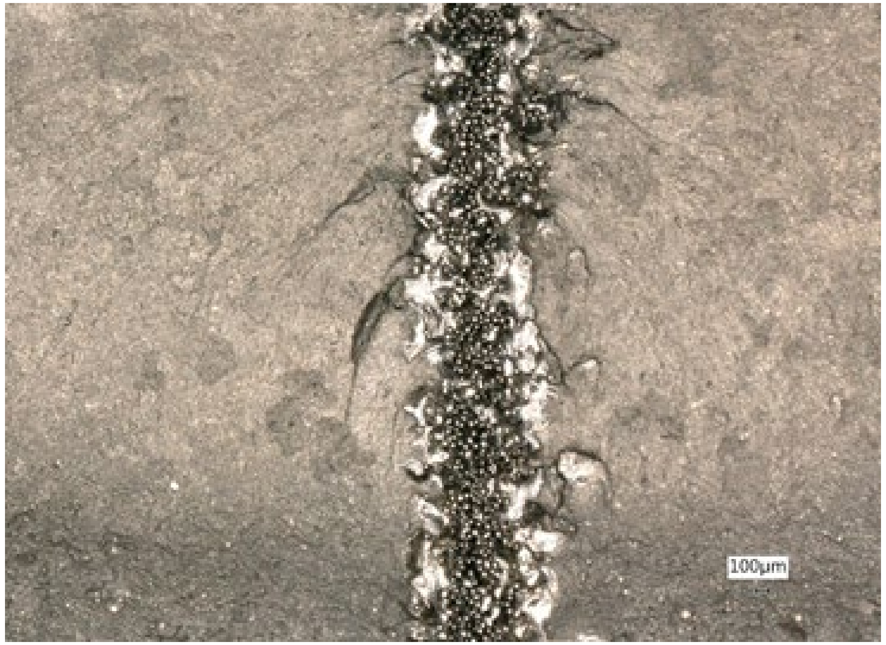
Simulated Crack Growth Rate

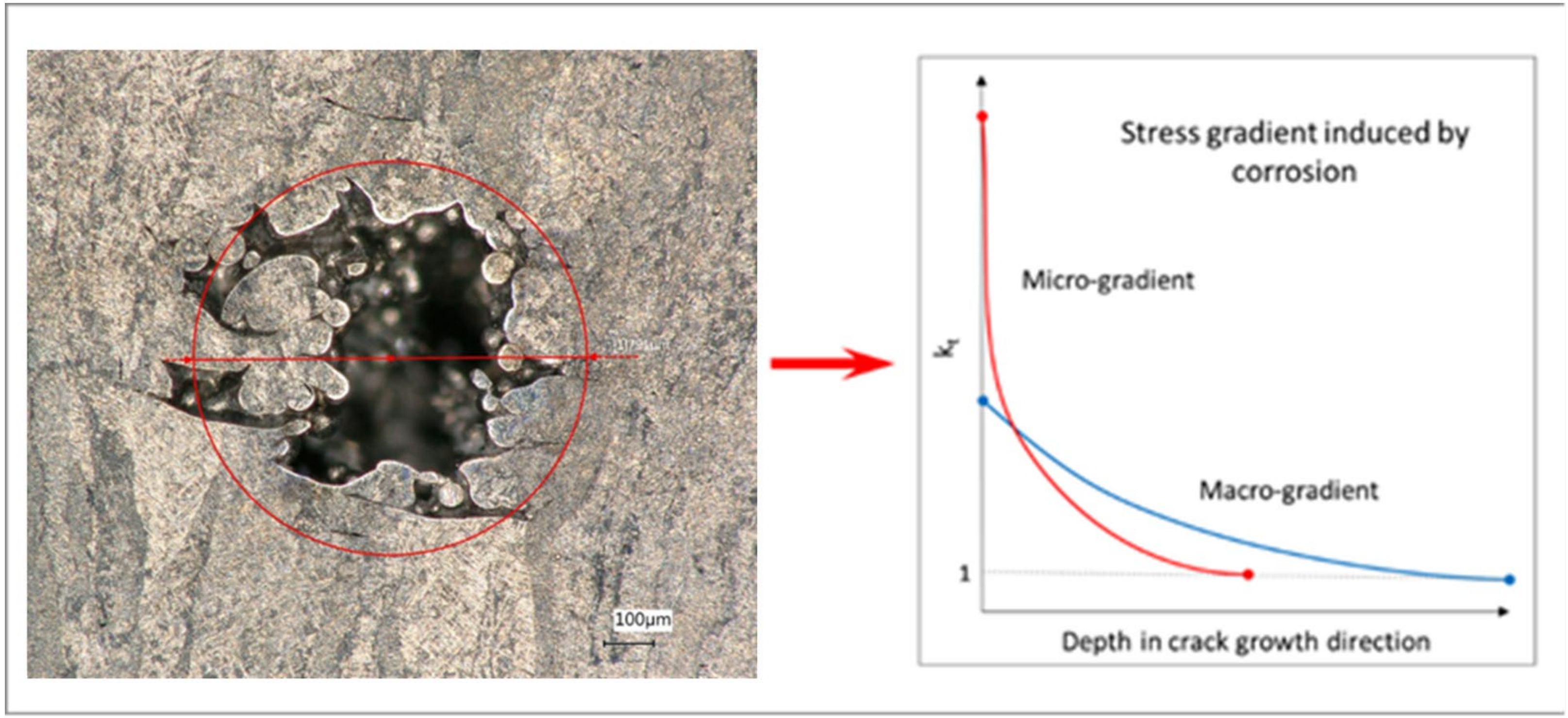


Simulated Fracture Surface

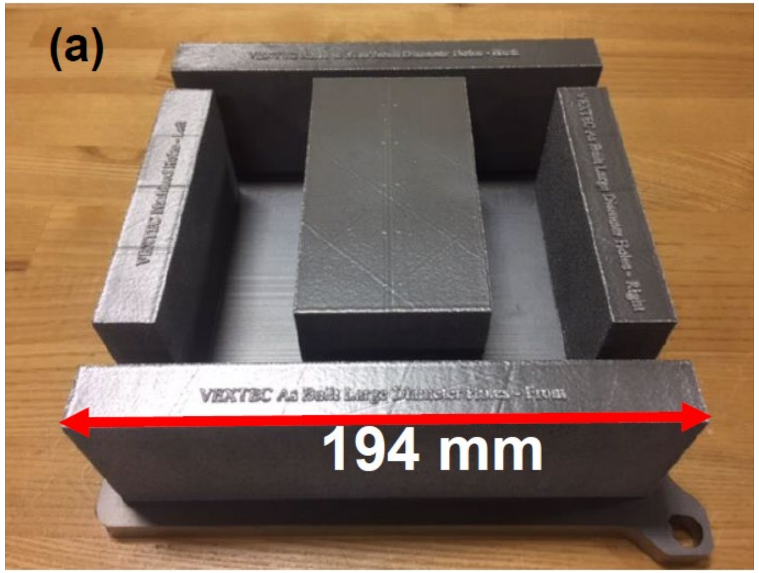


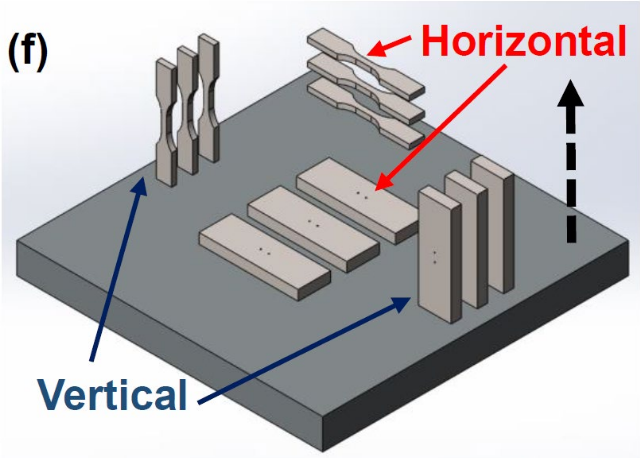
Next Steps: Model Surface Roughness effect on Fatigue

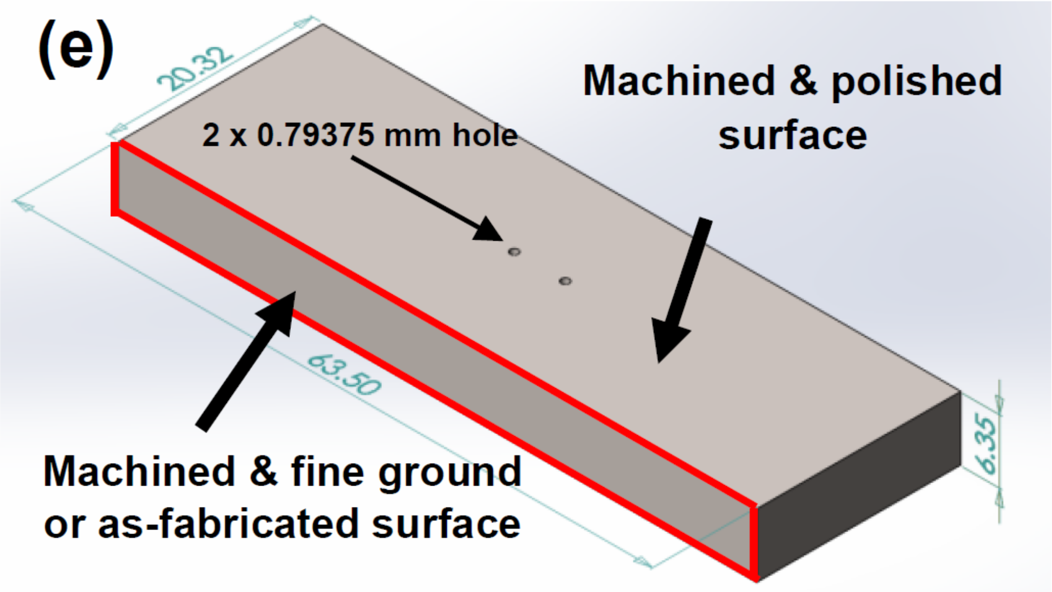




Built Blocks and Machined Specimens

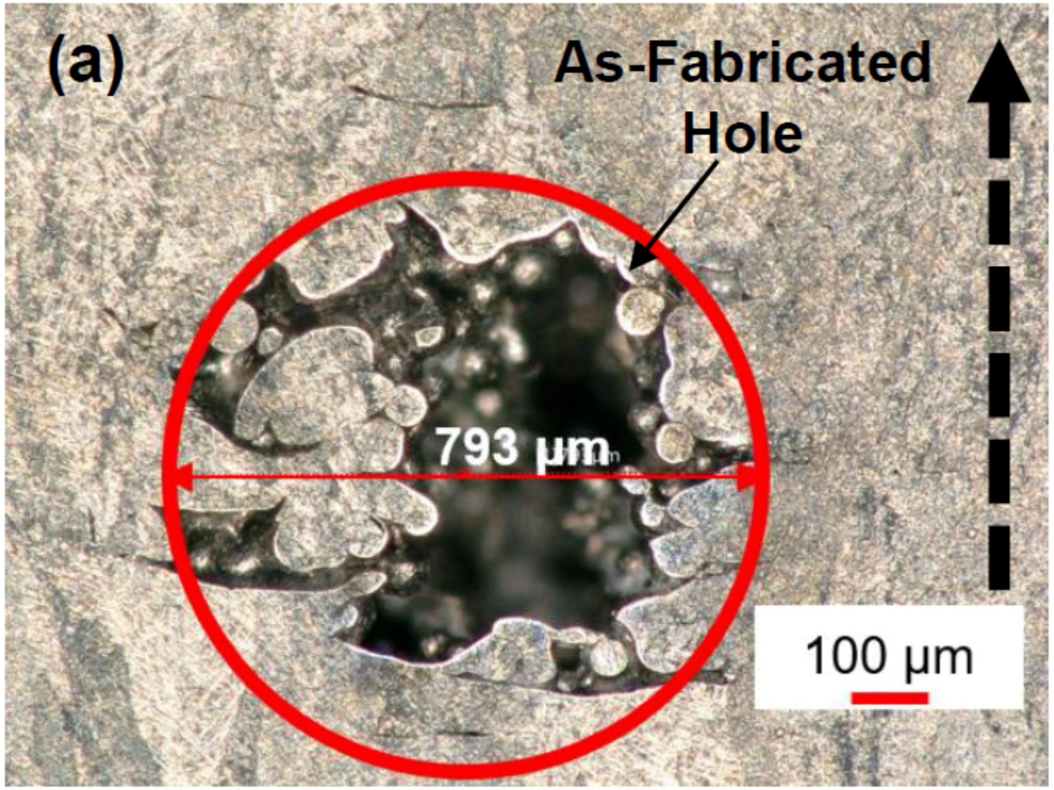


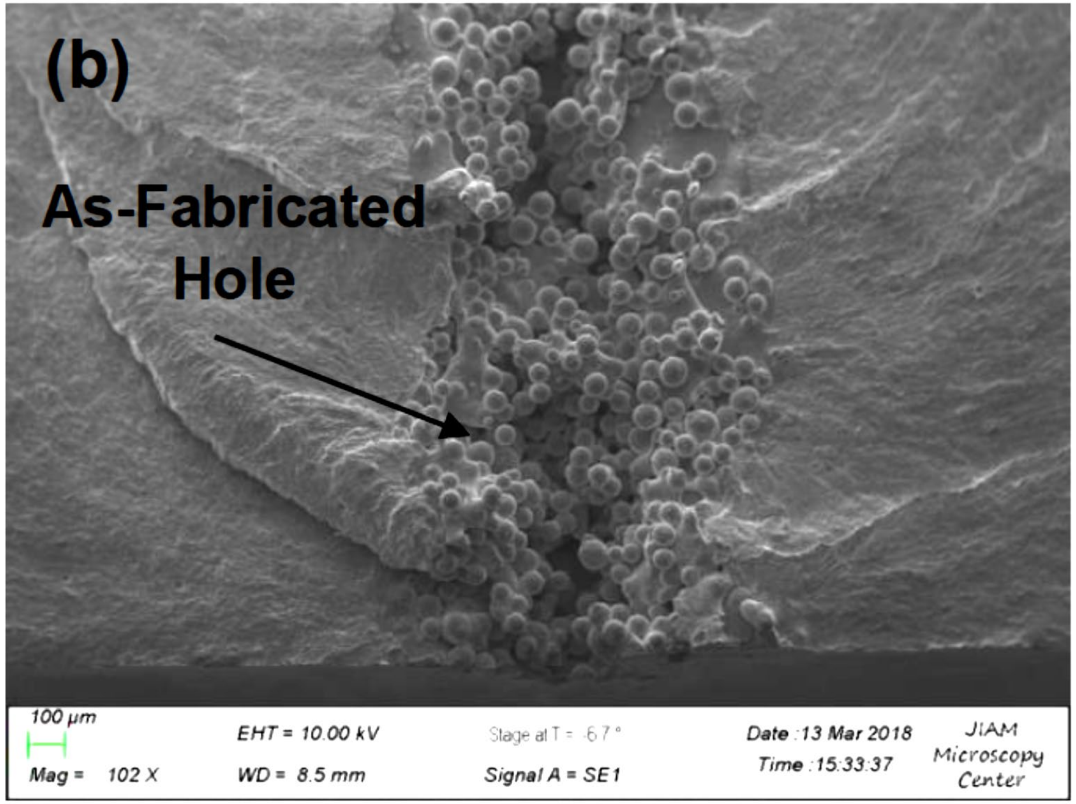




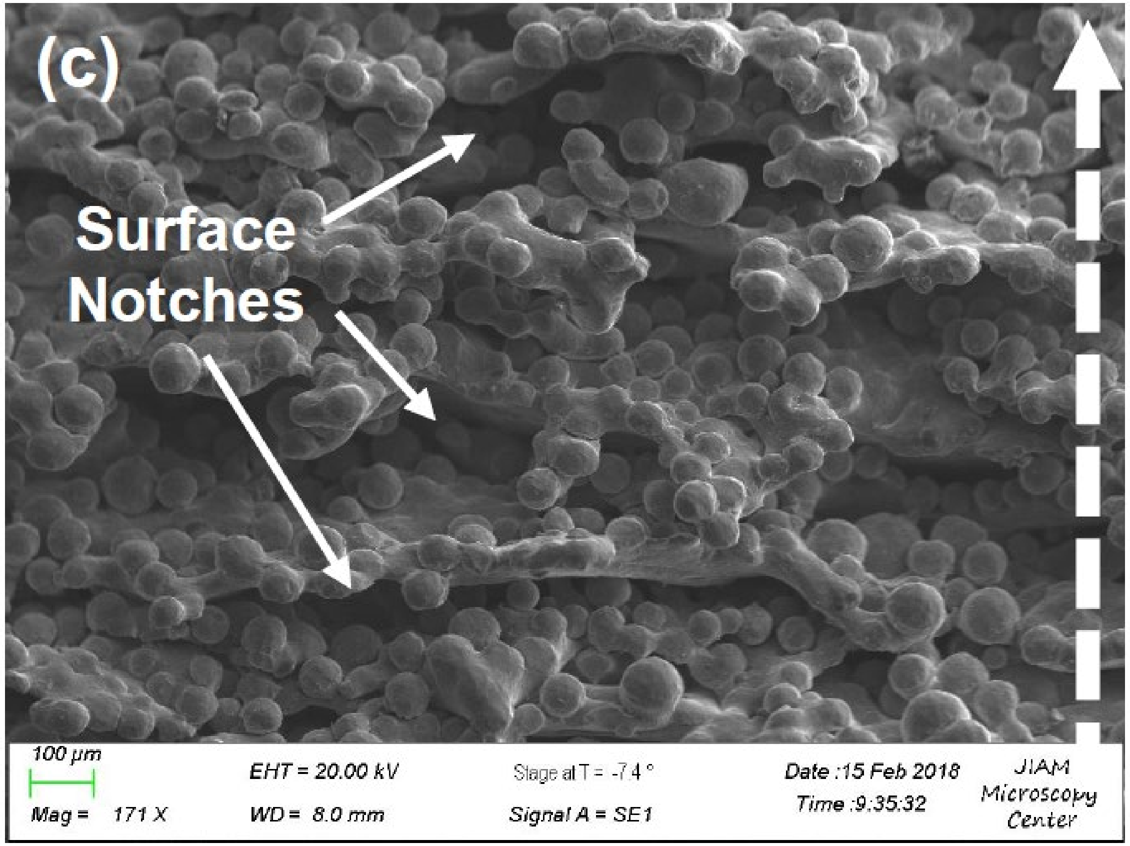
1. As-Built Surface/As-built holes (Vertical)
2. As-Built Surface/Machined holes (Vertical)
3. Machined Surface/Machined hole (Vertical)
4. Machined Surface/Reamed hole (Horizontal)
5. Machined Surface/Machined hole (Horizontal, Small B)
6. Machined Surface/Machined hole (Horizontal, Large B)
7. Wrought

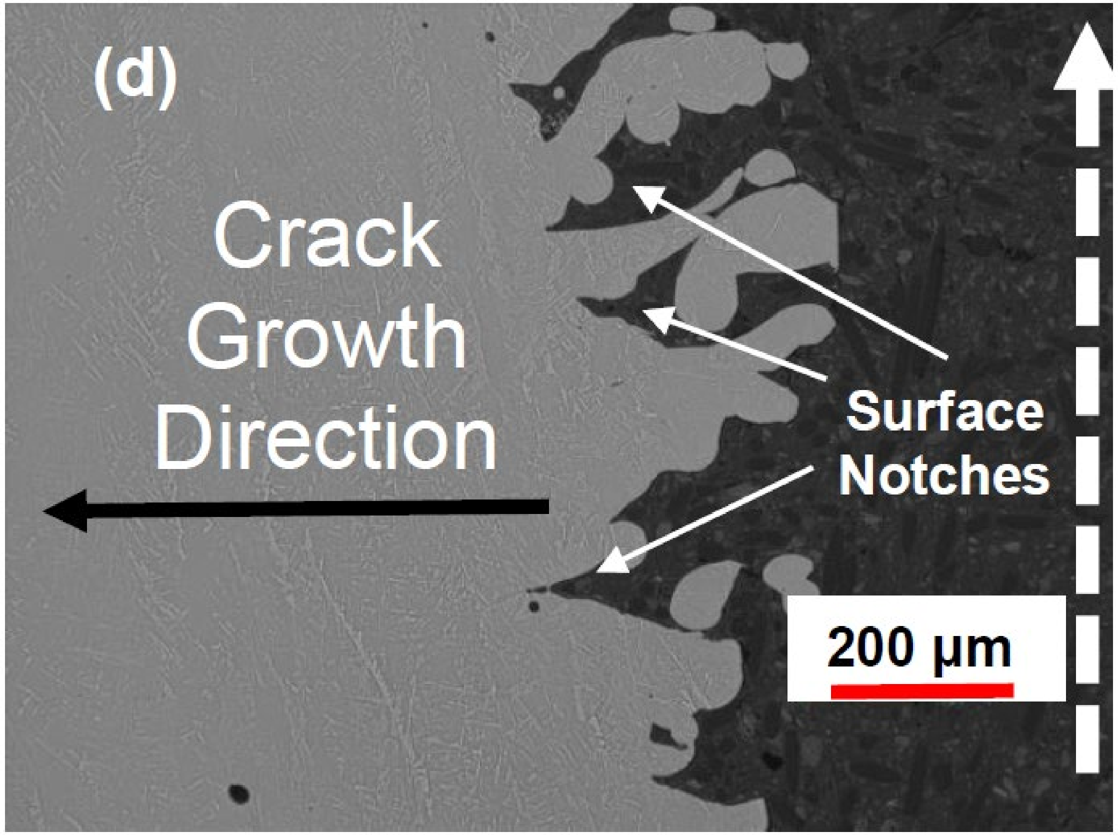
Surface: As-Built Hole





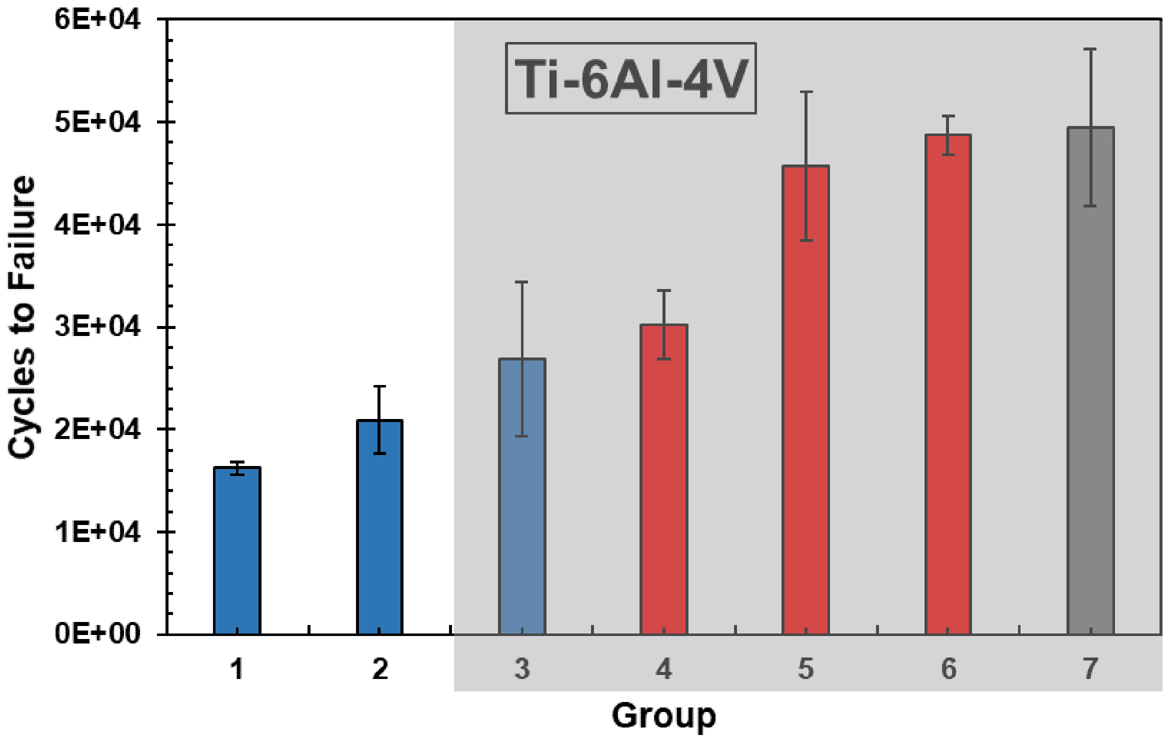
Surface: As-Built Side Face

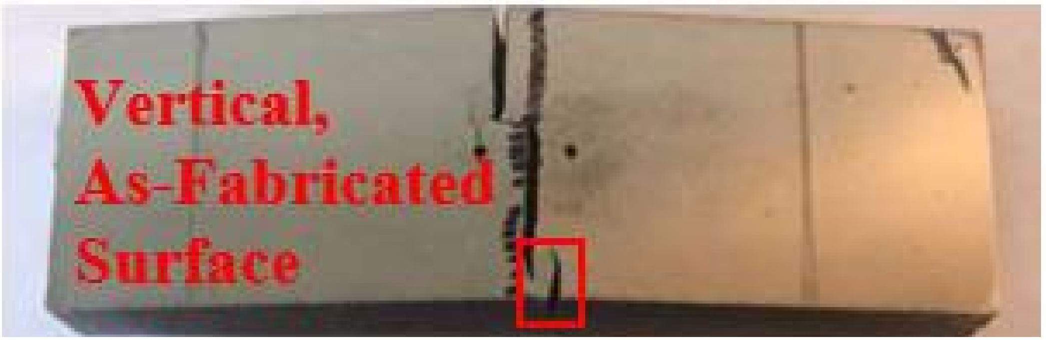




Fatigue Life DOE

1. As-Built Surface/As-built holes (Vertical)
   - Avg: 16200, SD: 700 cycles
2. As-Built Surface/Machined holes (Vertical)
   - Avg: 20,900, SD: 3200 cycles

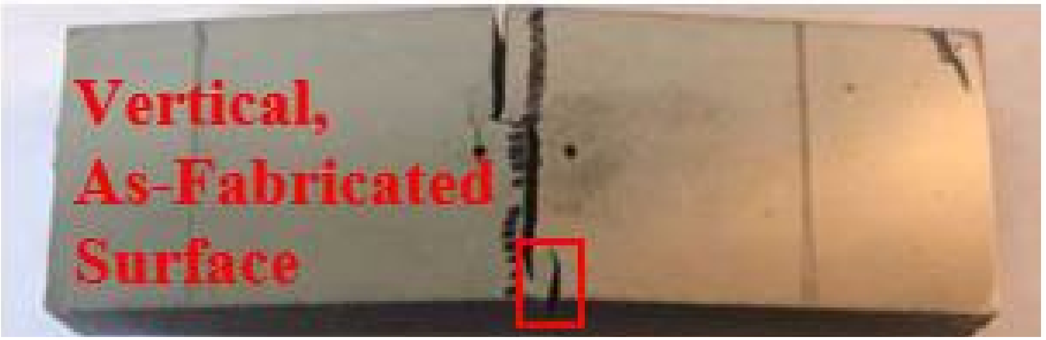


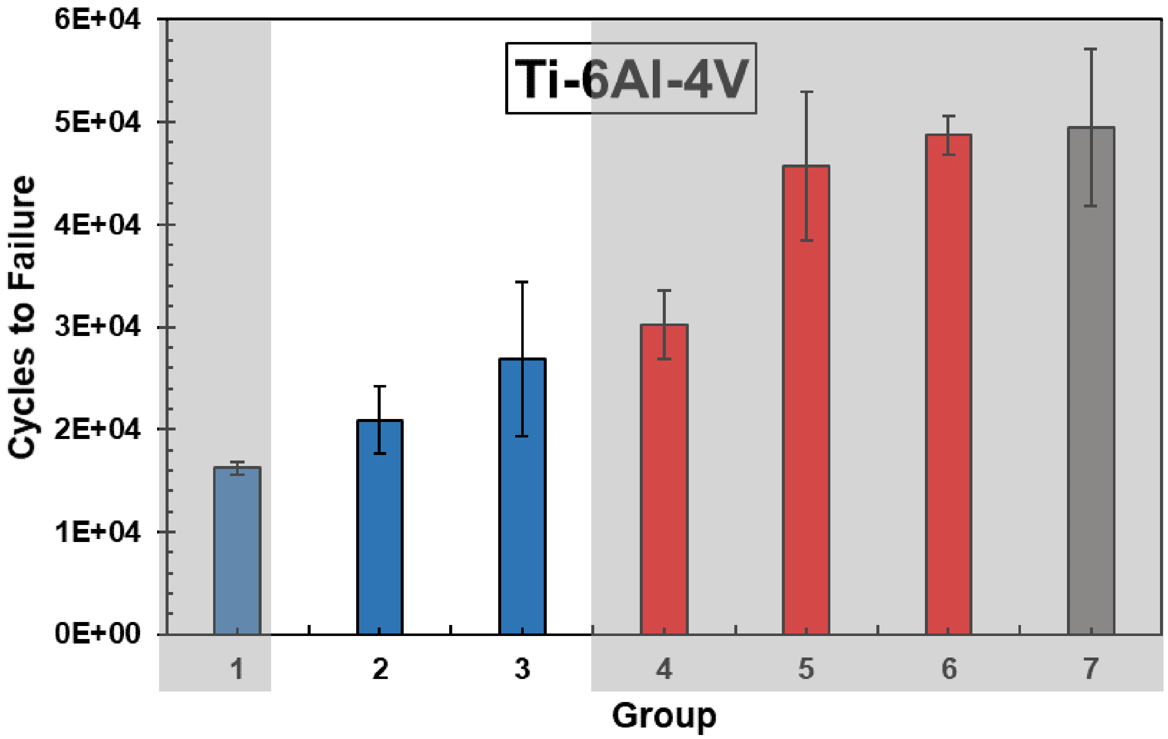


Chern (2018)

Fatigue Life DOE

2. As-Built Surface/Machined holes (Vertical)
   - Avg: 20,900, SD: 3200 cycles
3. Machined Surface/Machined hole (Vertical)
   - Avg: 26,900, SD: 7500 cycles





Chern (2018)

Fatigue Life DOE

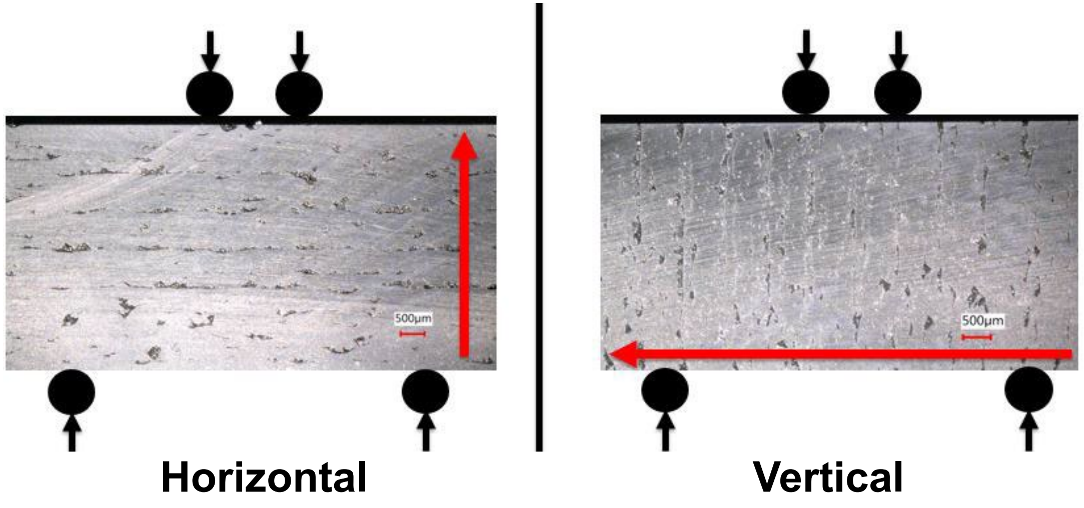
Vertical vs. Horizontal

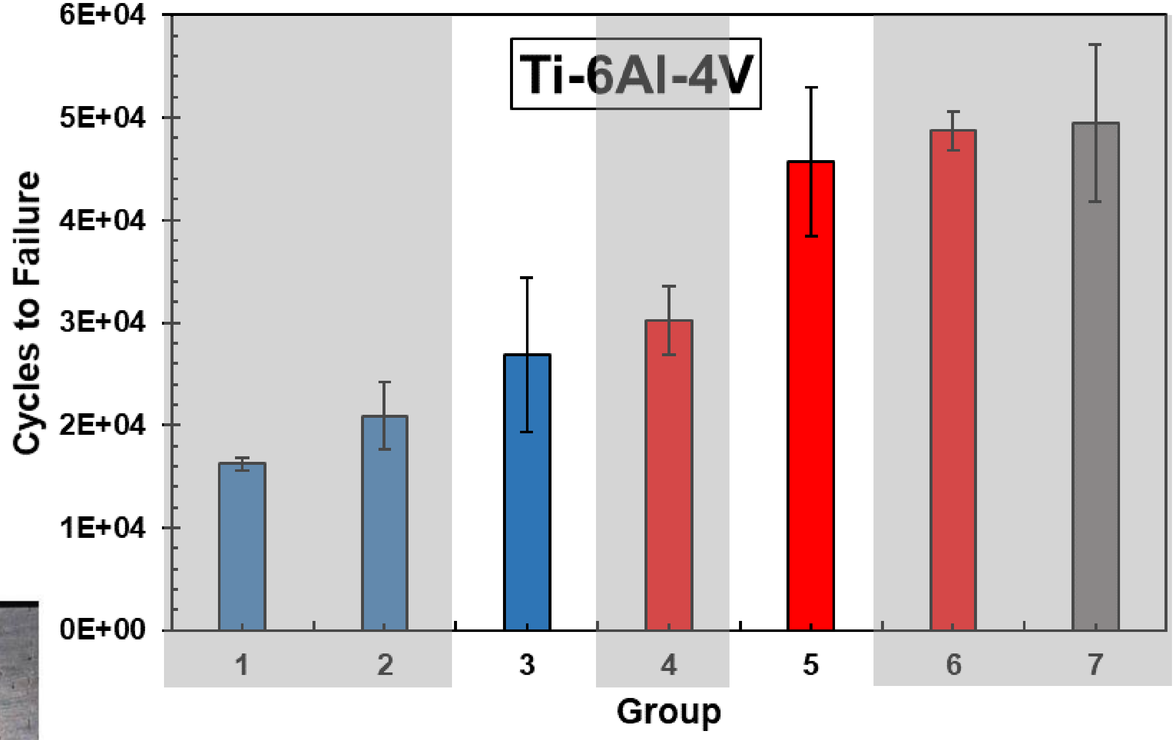
3. Machined Surface/Machined hole (Vertical)

- **Avg: 26,900, SD: 7500 cycles**

5. Machined Surface/Machined hole (Horizontal)

- **Avg: 45,800, SD: 7300 cycles**





Chern (2018)

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Fatigue Life DOE

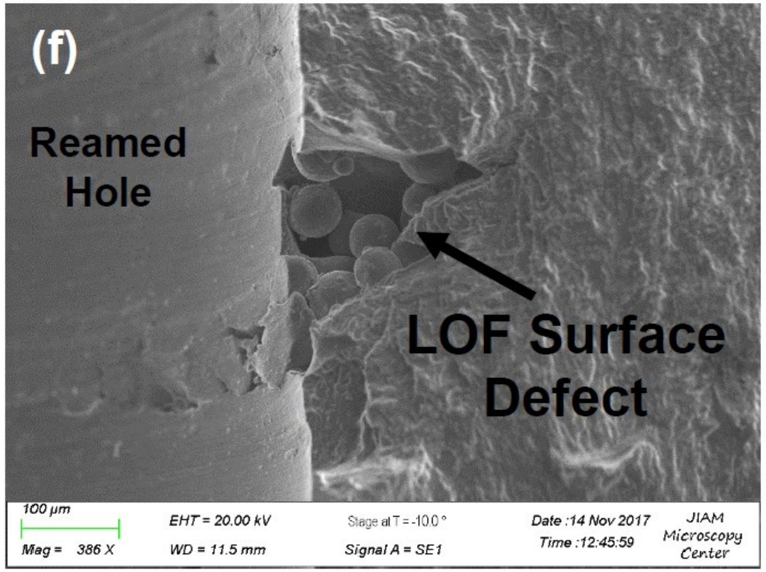
Reamed Hole vs. Machined Hole

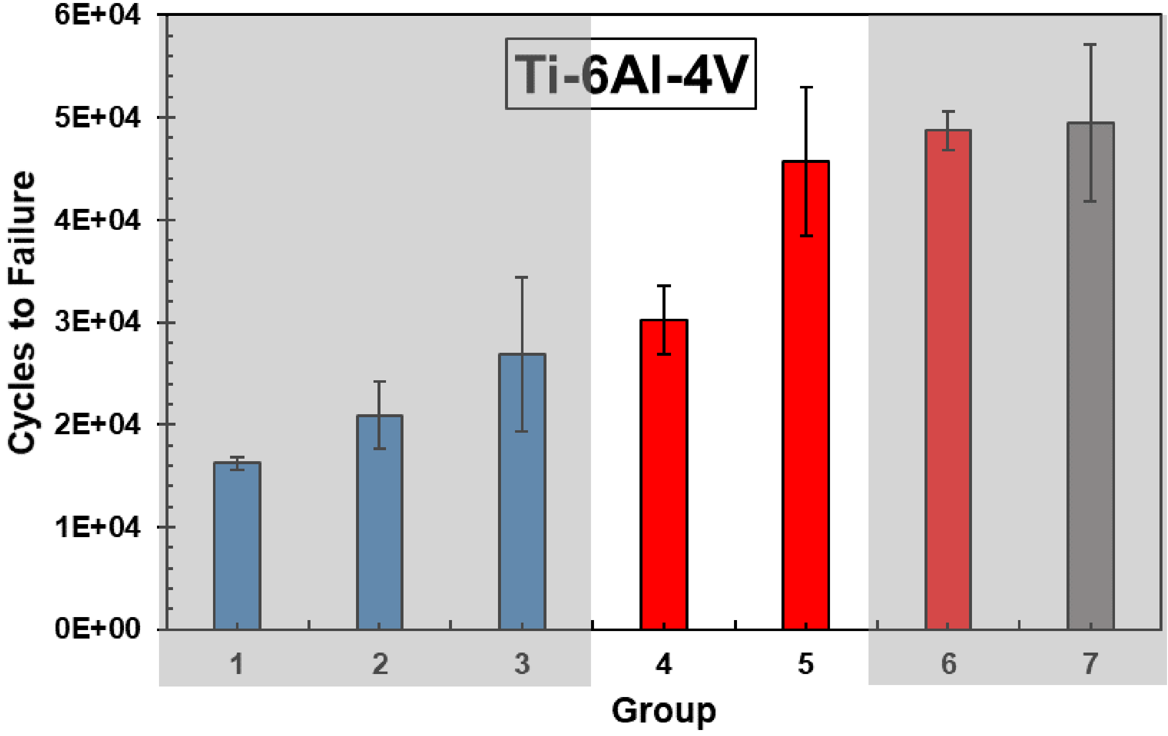
4. Machined Surface/Reamed hole (Horizontal)

- Avg: 30,200, SD: 3400 cycles

5. Machined Surface/Machined hole (Horizontal)

- Avg: 45,800, SD: 7300 cycles





Chern (2018)

Fatigue Life DOE

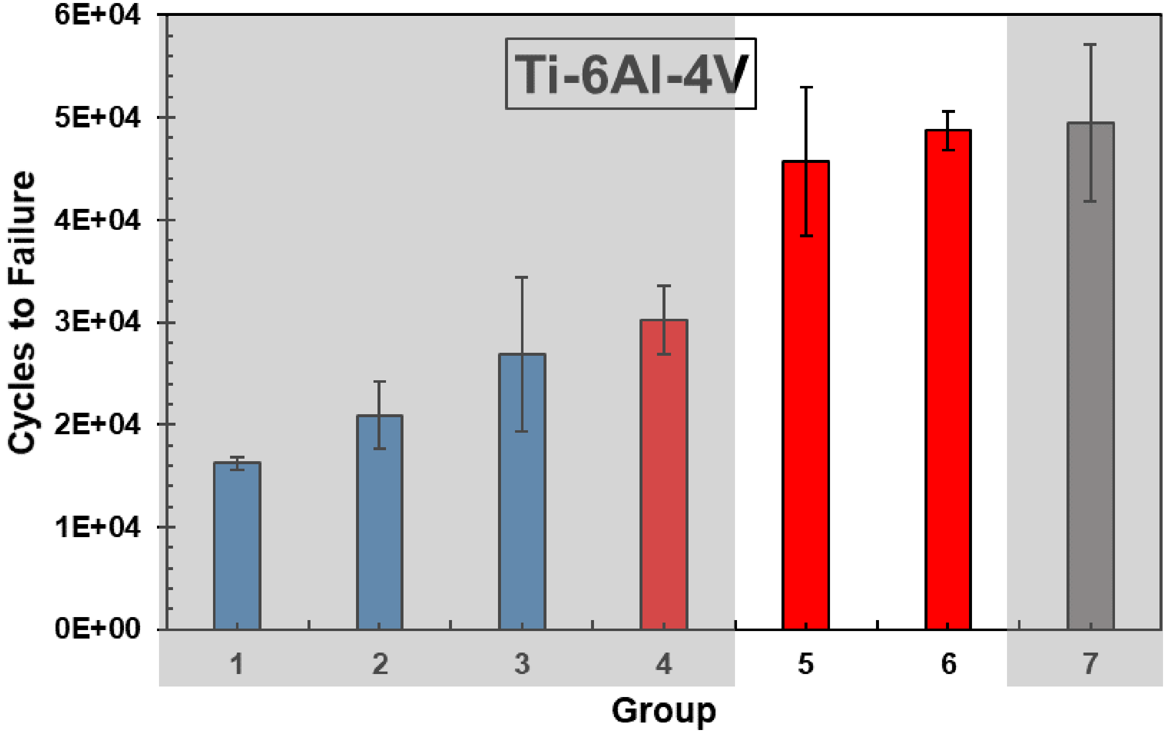
Block Size

5. Machined Surface/Machined hole (Horizontal, Small Block)

- **Avg: 45,800, SD: 7300 cycles**

6. Machined Surface/Machined hole (Horizontal, Large Block)

- **Avg: 48,700, SD: 1900 cycles**



Chern (2018)

Fatigue Life DOE

AM vs. Forged

3. Machined Surface/Machined hole (Vertical)

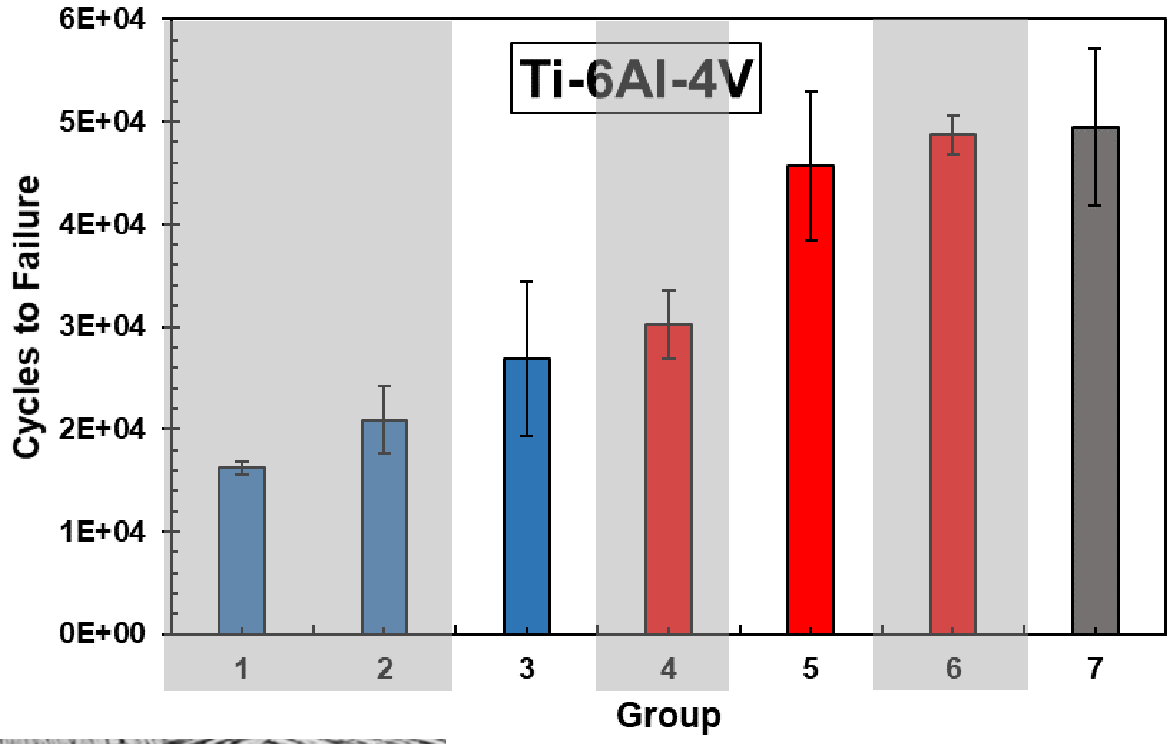
- **Avg: 26,900, SD: 7500 cycles**

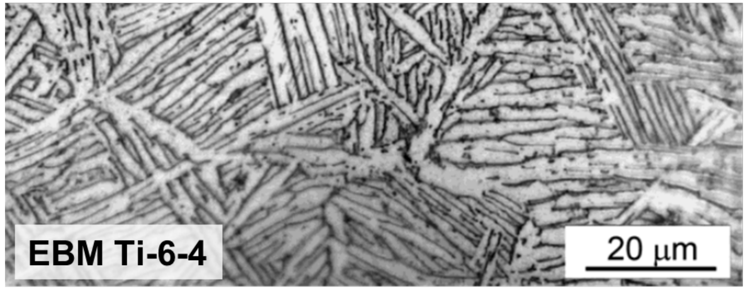
5. Machined Surface/Machined hole (Horizontal)

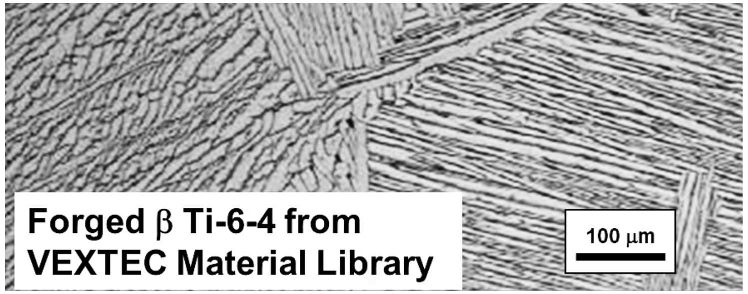
- **Avg: 45,800, SD: 7300 cycles**

7. Machined Surface/Machined hole (Wrought)

- **Avg: 49,500, SD: 7700 cycles**







Chern (2018)

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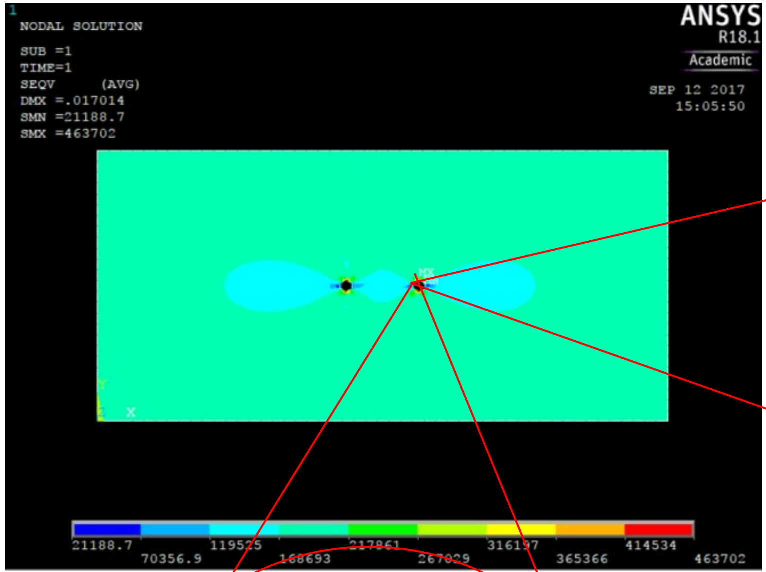
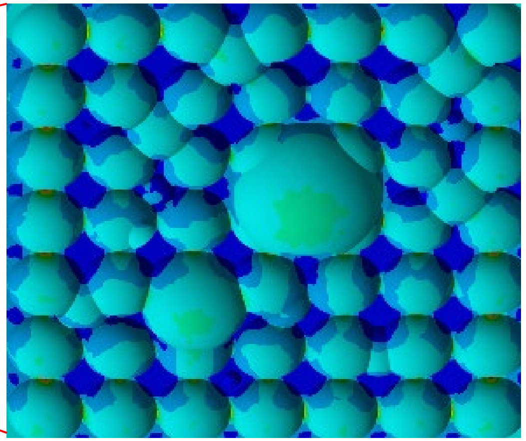
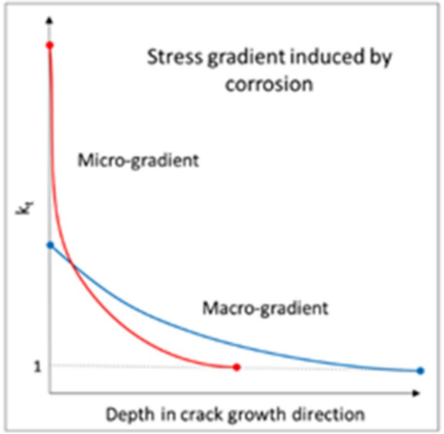
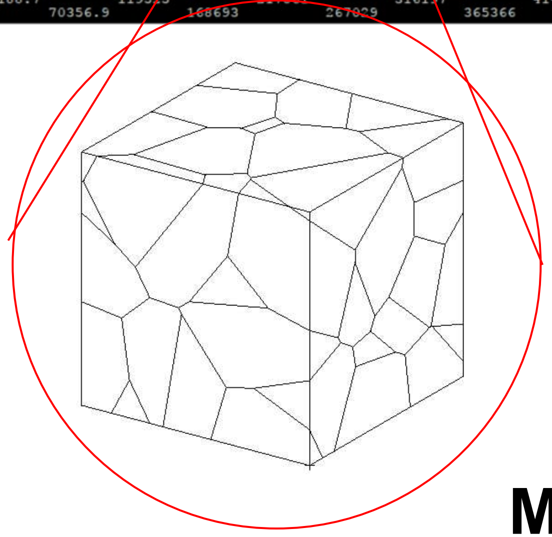
Next Steps

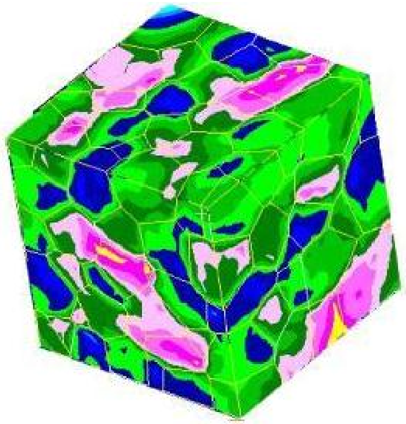


Surface Roughness









Microstructure

Conclusions

- ICME is used to link microstructure-to-performance
- A probabilistic ICME 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