VEXTEC

Microstructural Small Flaw Fracture Mechanics for Improved Design Analysis

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Discussion Topics

- **Issues and Objectives**
- **Laboratory Testing**
- **Damage Mechanisms**
- **Computational Modelling**

Acknowledgements

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- Adam Pilchak, Air Force Research Laboratory, Materials and Manufacturing Directorate
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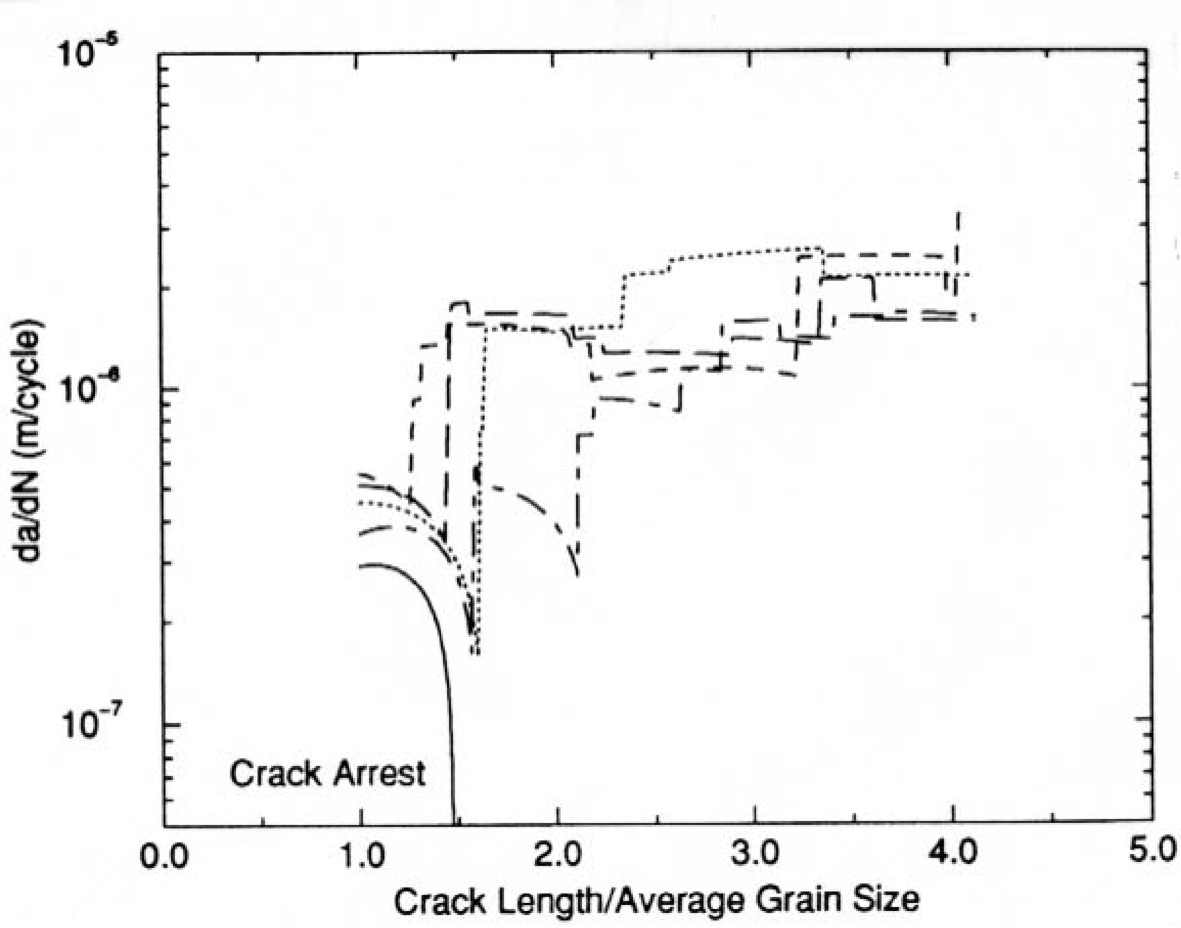
- Ji Eun Park, Lockheed Martin
- Peter Liaw, University of Tennessee

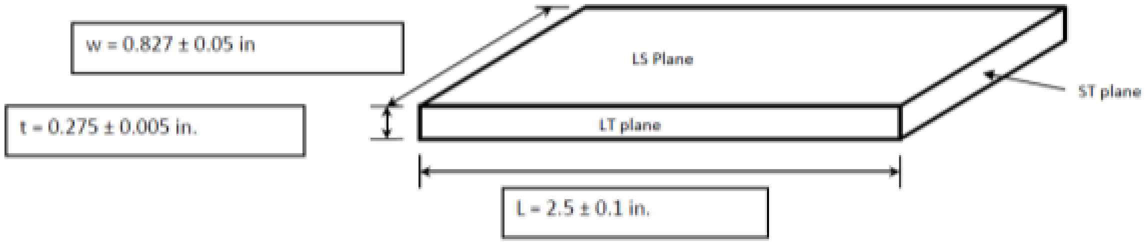
Issues and Objective

- Issue:
  - Linear elastic fracture mechanics (LEFM) methods are sometimes erroneously applied where the initial defect size is outside the range LEFM applicability.
  - Typically this occurs when starting flaw size assumptions are on the same order as the length scale of the microstructure.
- Objective:
  - Determine approaches that can be applied based on flaw size, orientation, material, and applied loading
  - Develop methods for accurate damage propagation prediction outside of the traditional LEFM regime (small crack growth)
  - Use a physically based treatment instead of purely empirical approaches

Large Scatter in Small Crack Growth Rate



Material Specimen Geometry



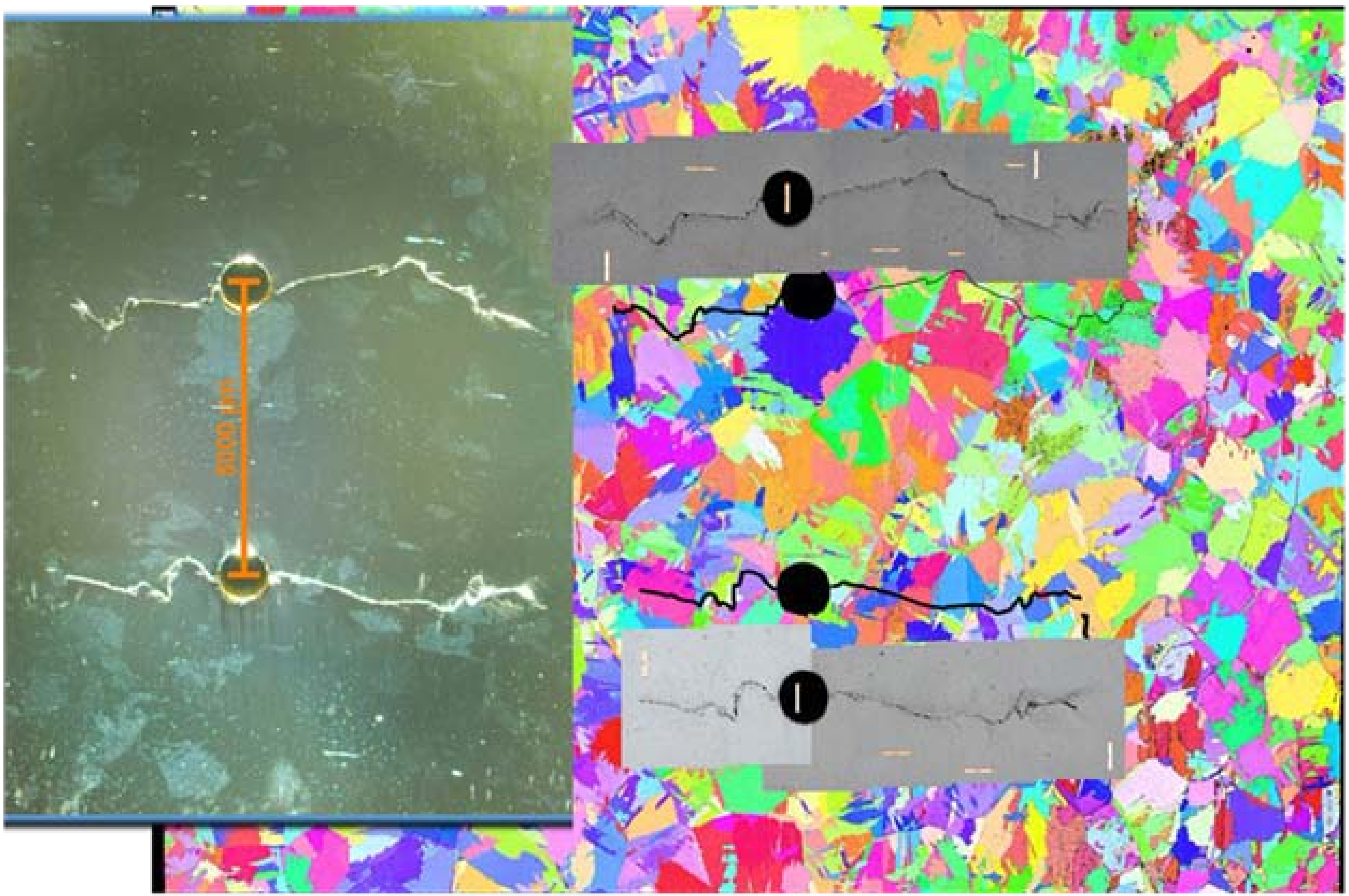
- Two holes are D = 1/32" and spaced 5 mm apart, centered on the center of the specimen

Test Apparatus at University of Tennessee

- Load 2400 lb (max concentrated stress ~ 132 ksi)
- R ratio (min stress / max stress) = 0.1
- Frequency 5 Hz
- Triangle wave
- Room Temperature
- Laboratory Air

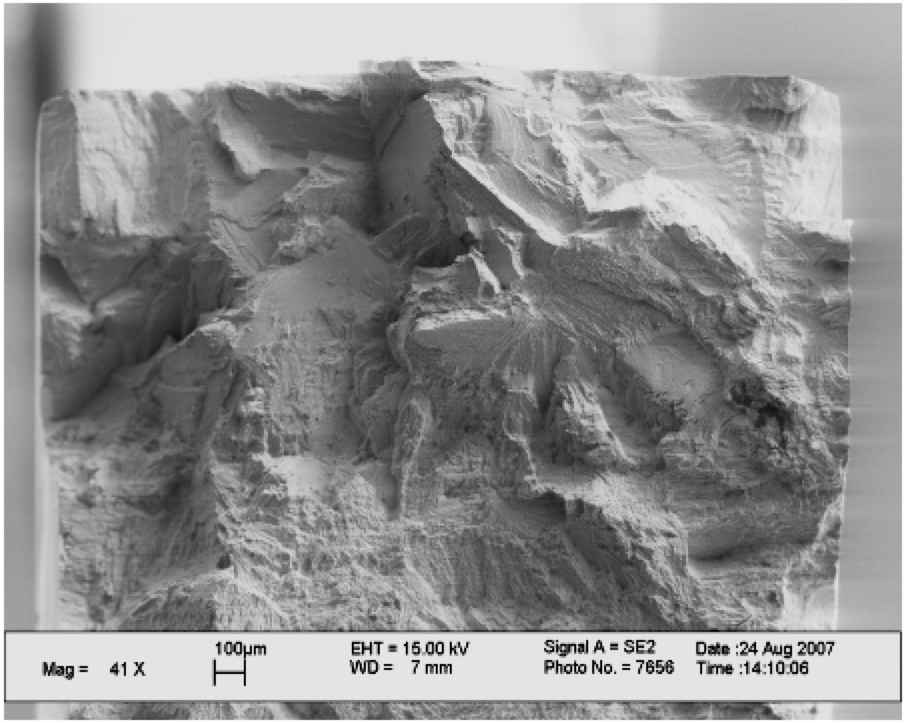
Cracked Fatigue Specimen

Another Cracked Fatigue Specimen

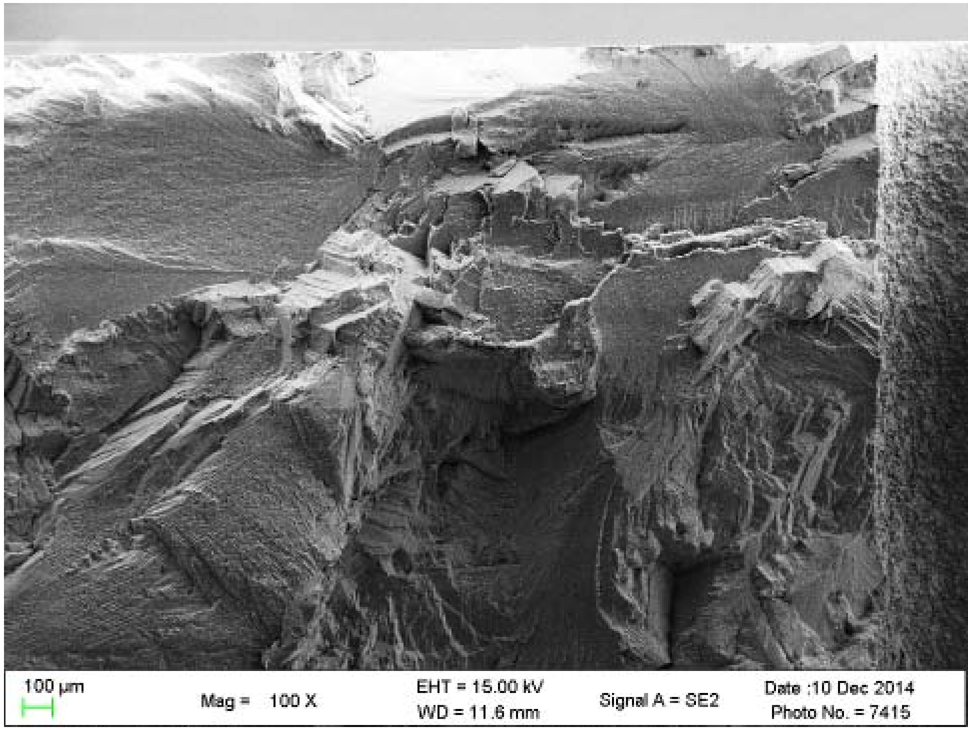


Fracture Surface

Typical Ti64 from VEXTEC Library

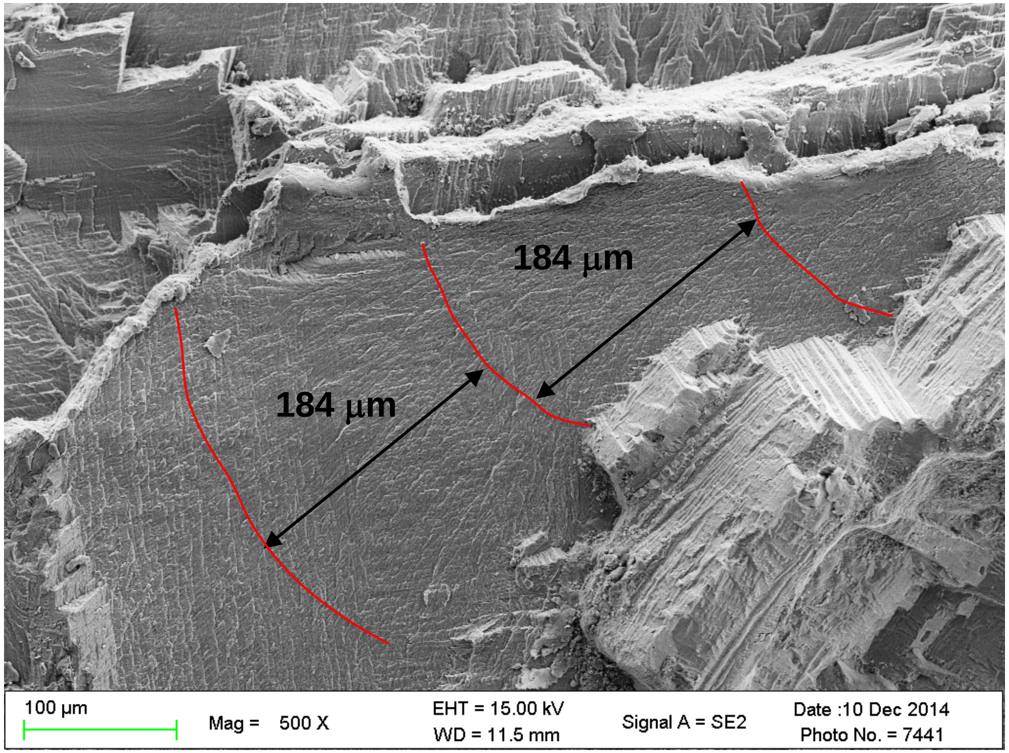


VEXTEC Test Specimen 1



Crystallographic crack growth rate

- Planes do not brittle cleave
  - For figure at right, crack growth rate of 0.07 μm/cycle.
  - Compared, the average crack growth rate across specimen of 0.2 μm/cycle.
- Therefore a significant amount of the crack growth life is spent in crystallographic crack growth.

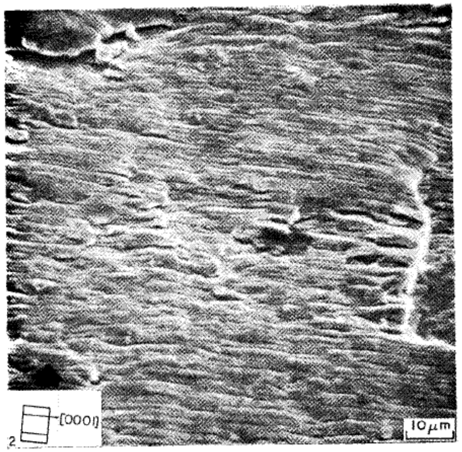


Marker bands (highlighted in red) on Specimen 1 showing the crack growth distance (da) in 2500 cycle increments (dN).

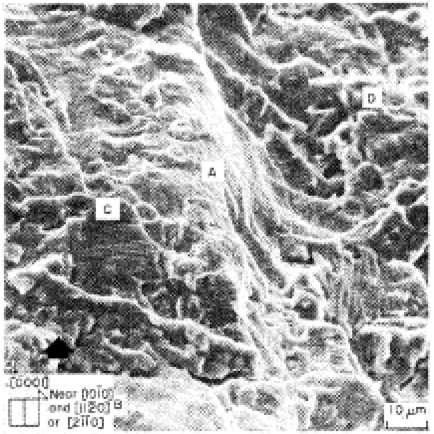
Grain level damage

Bowen, Acta Metall., Vol 23, 1975

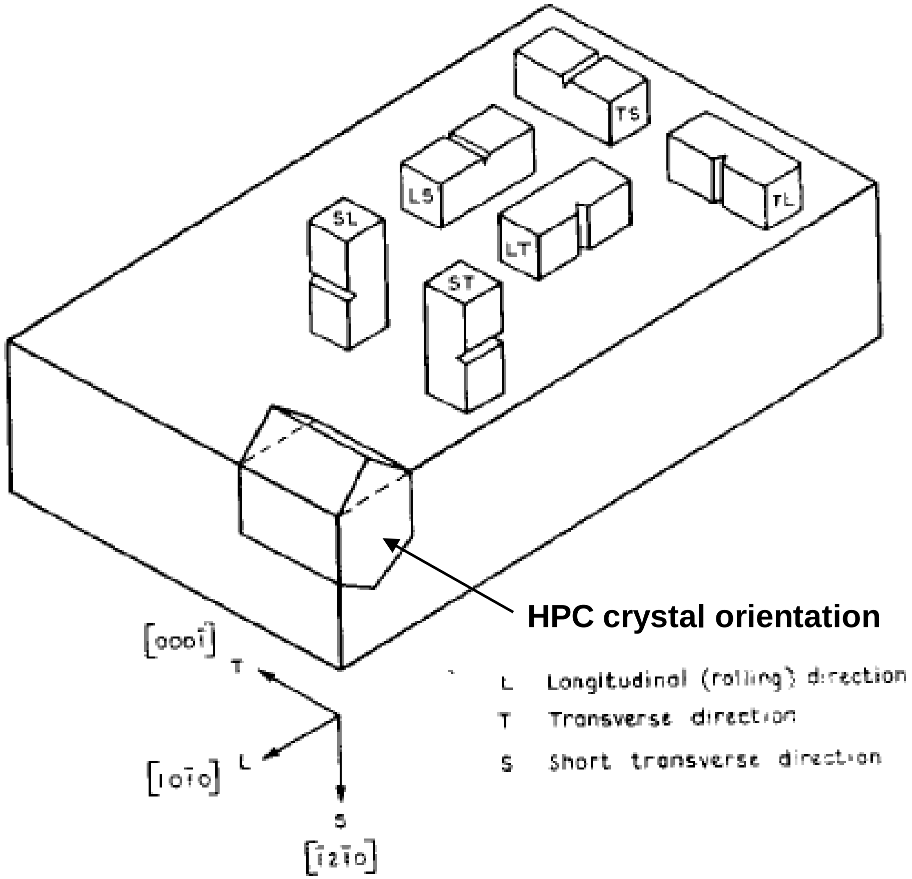
- Bowen cycled specimens cut for crack growth on different crystal orientations
- Observed fracture surfaces.



LS, SL and TS, fracture surface covered with striations parallel to crack growth



LT, ST and TL, fracture surface with few striations not parallel to crack growth



Design Analysis Package Framework

Standard Industry Analysis

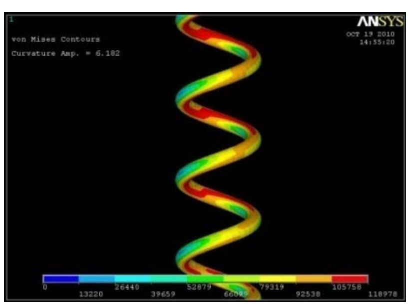
MSC Software — Simulating Reality, Delivering Certainty

ANSYS

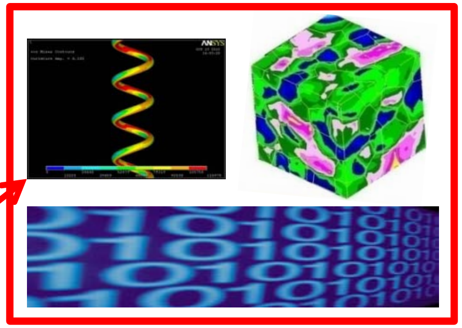
SIMULIA

PTC

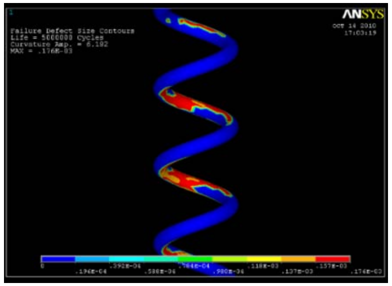
Design & Stress



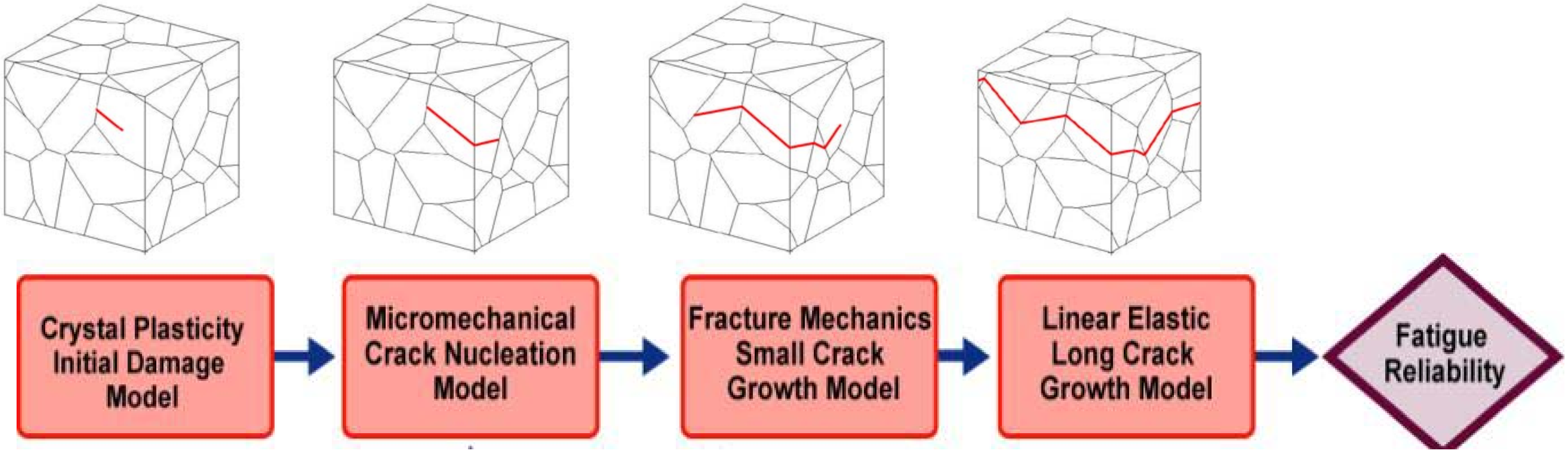
SFFM Analysis



Life & Where & Why



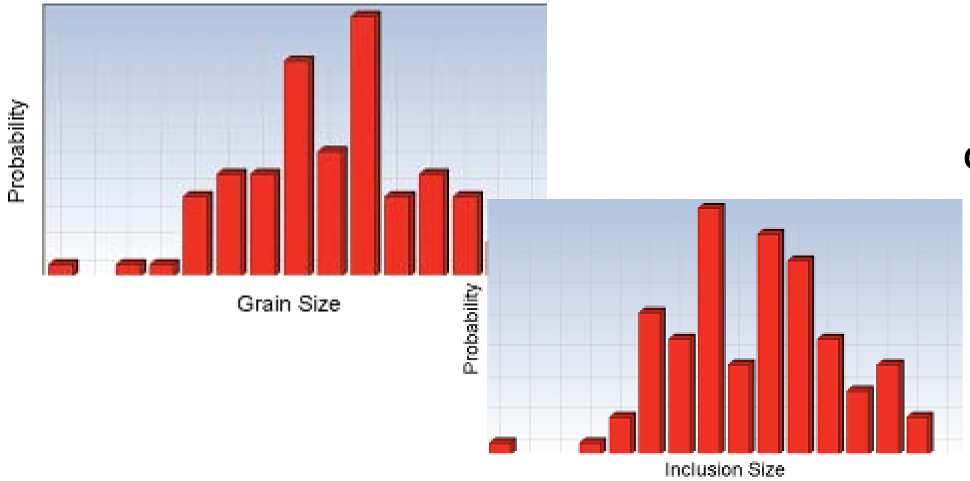
Design Analysis Package Framework

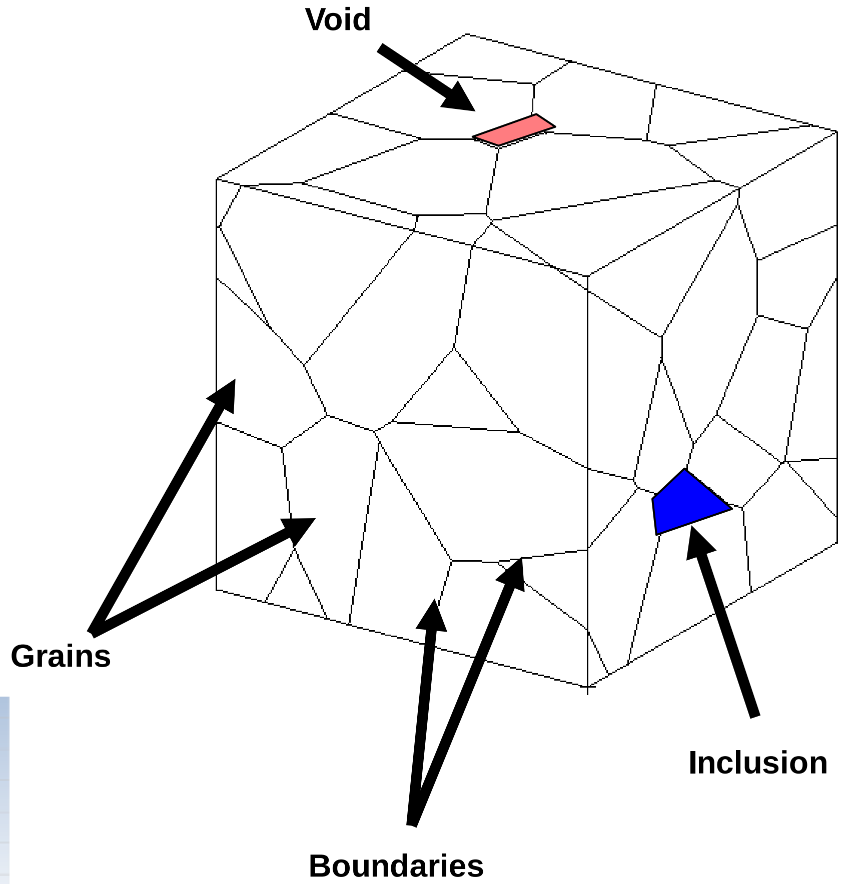


- VEXTEC uses proven Equations for each damage stage
  - Use testing to gather damage mechanisms
  - Use testing to gather parameter values
  - Establish transition rules from experimental observations

Statistical Modeling of Materials

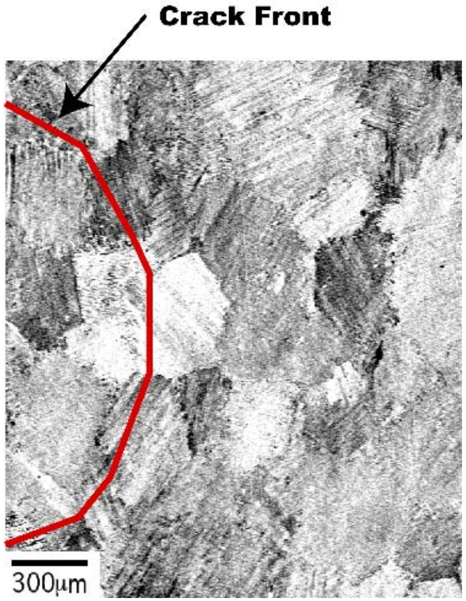
- Damage mechanisms used to determine potential crack nucleation sites
  - Grains, Inclusions, Voids
  - Grain Boundaries, Triple Points
- Damage element available for each mechanism
- SVE populated with damage elements



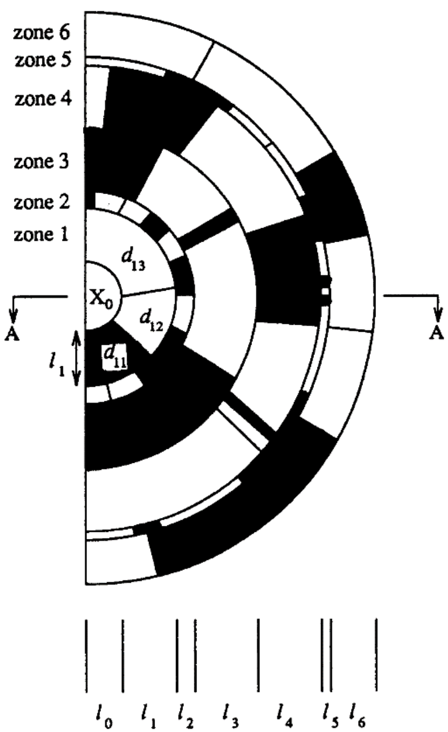


Example: Microstructurally Short Crack

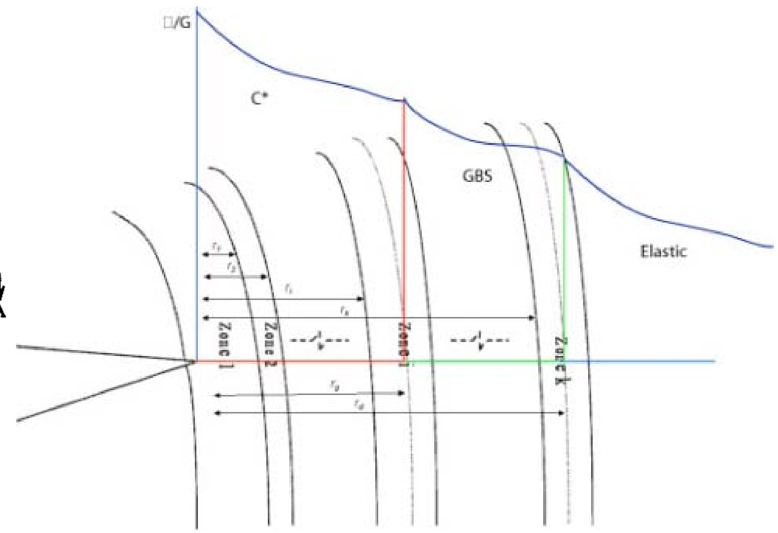
Top view of real crack



Top view of idealized crack



Side view of idealized crack



Damage Equations in the Package

- Fatigue crack growth

$$\frac{da}{dN} = C'\Delta\phi_t$$

- Microstructurally small crack

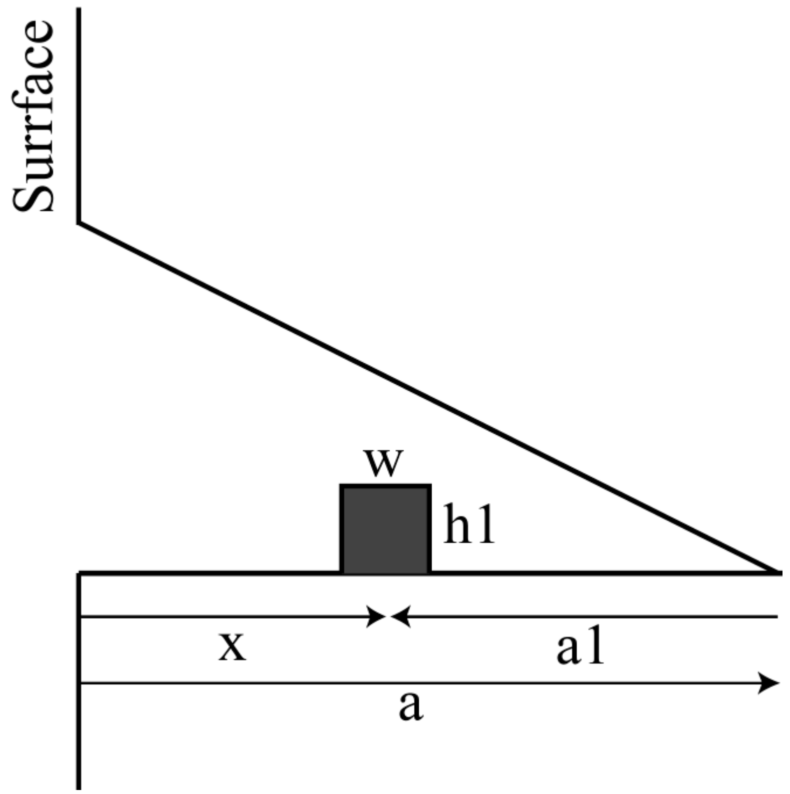
$$\phi_t = \frac{2k_j a}{\pi^2 A}\ln\frac{c}{a} + \sum_{i=j+1}^{n}\frac{\left(\tau_{i-1} - k_{i-1}\right) - \left(\tau_i - k_i\right)}{\pi^2 A} g\left(a; c, L_{i-1}\right)$$

- Physically small crack

$$\Delta K_{Eff} = \beta(\sigma_{\max} - \sigma_{\mathrm{clos}})\sqrt{\pi a}$$

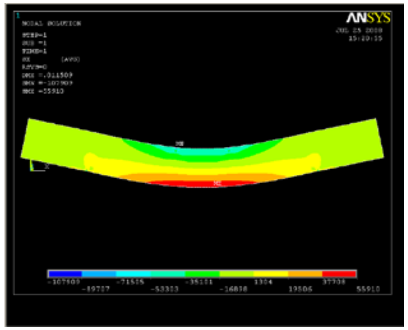
Modeling Closure

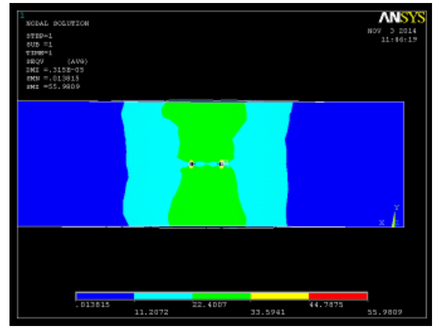
- Difference between physically small crack and long cracks
  - Plastic deformation of the wake
  - Wake roughness caused by crystallographic crack growth
  - Shielding caused by crack branching
  - Wake roughness caused by oxidation products
- Wake roughness caused by crystallographic crack growth is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

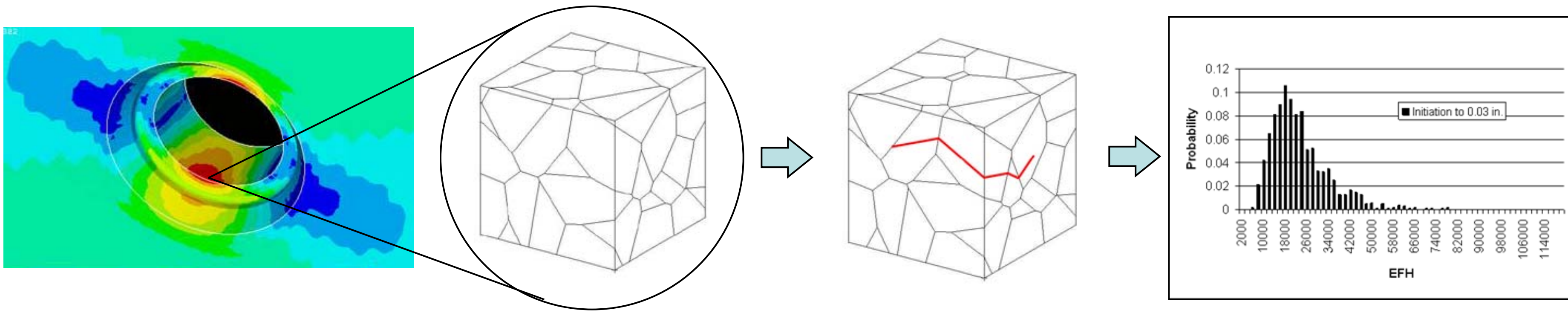


Crack with asperity of height h1 and width w.

Link SFFM to FEA







VEXTEC inserts microstructure into FEA element using Microstructural Volume Element approach to predict statistical distribution of hours to a LEFM initial flaw size.

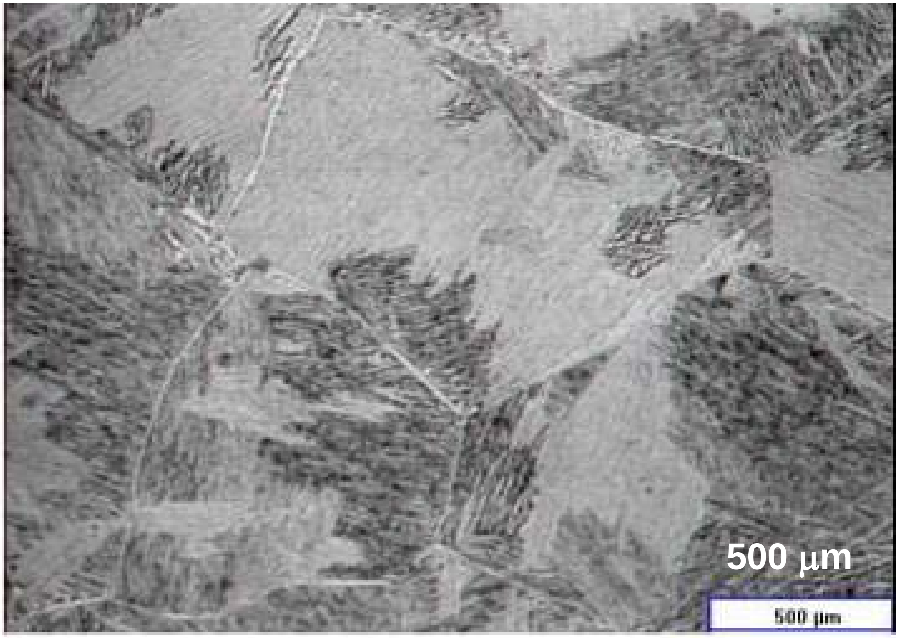
US Patent 7,016,825: Method and Apparatus for Predicting the Failure of a Component

Develop Demonstration Software

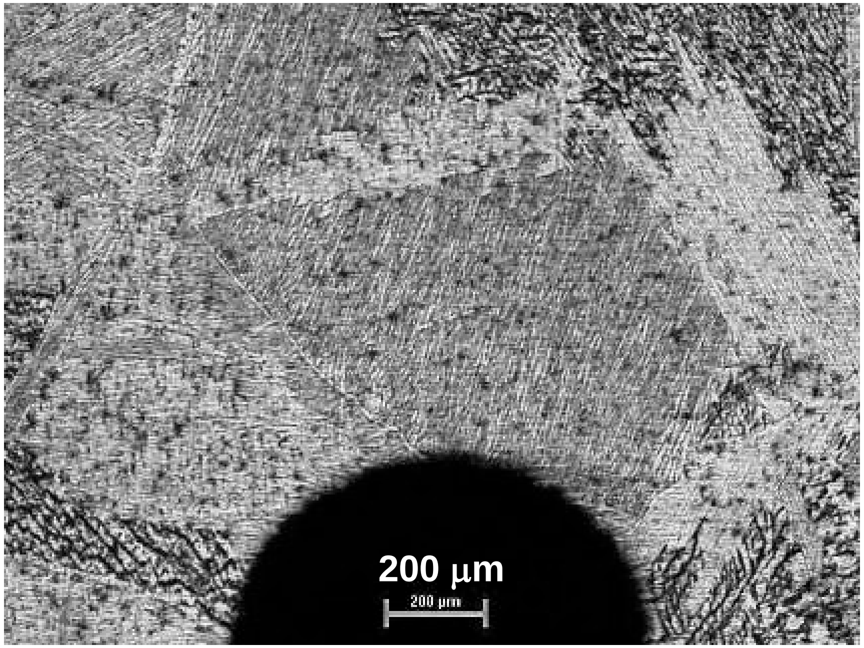
- Combine models into a demonstration tool that predicts fatigue life of *β* annealed titanium specimens
- Inputs includes
  - Load
  - Specimen geometry
  - Material microstructure:
    - Grain size
    - Texture
    - Mechanisms
- Output: statistical distribution of damage size vs. cycles

Compare with other microstructure in VEXTEC library

Typical Ti64 from VEXTEC Library



AF Ti64

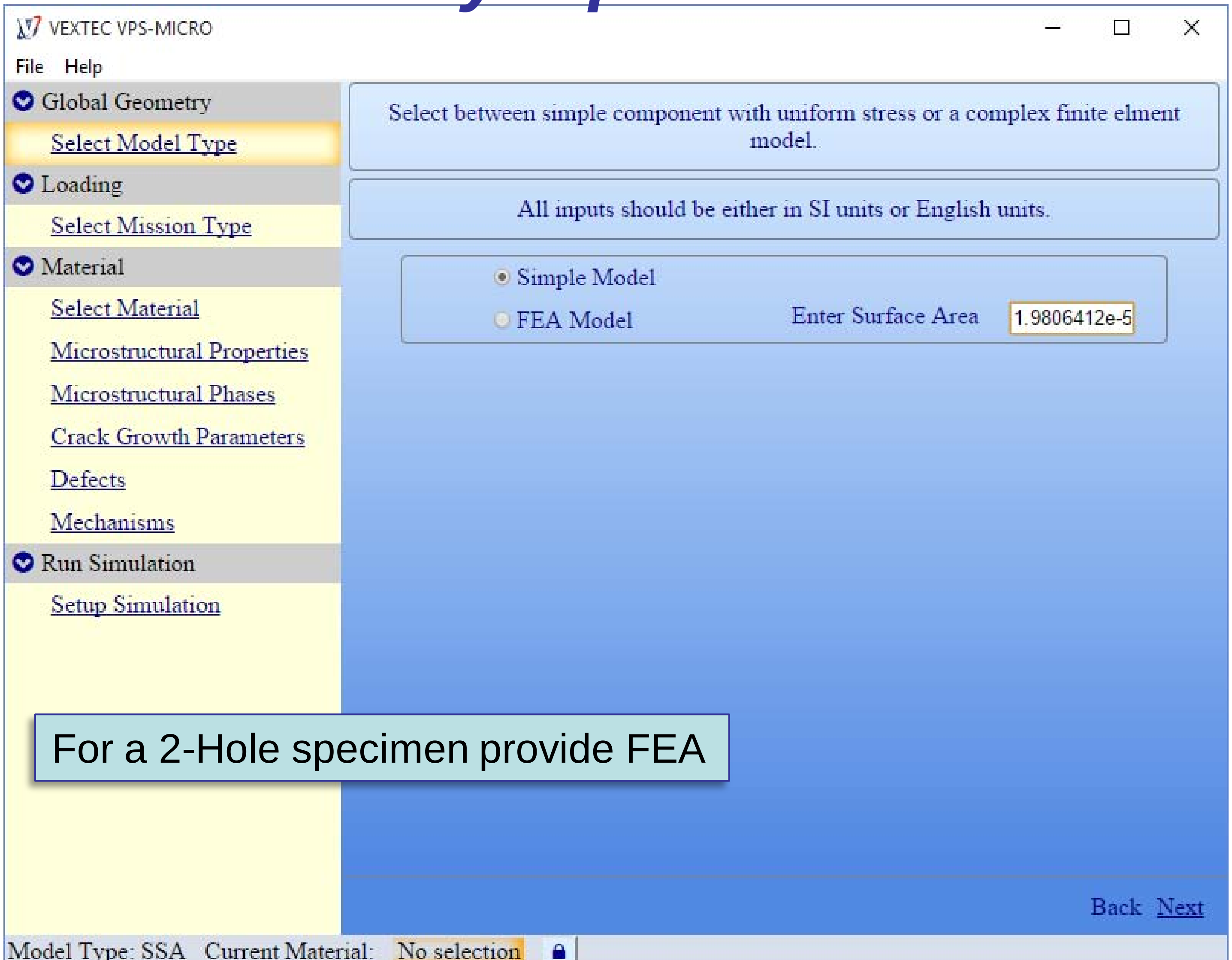


AF Ti64 is smaller grain size with similar morphology

Model update

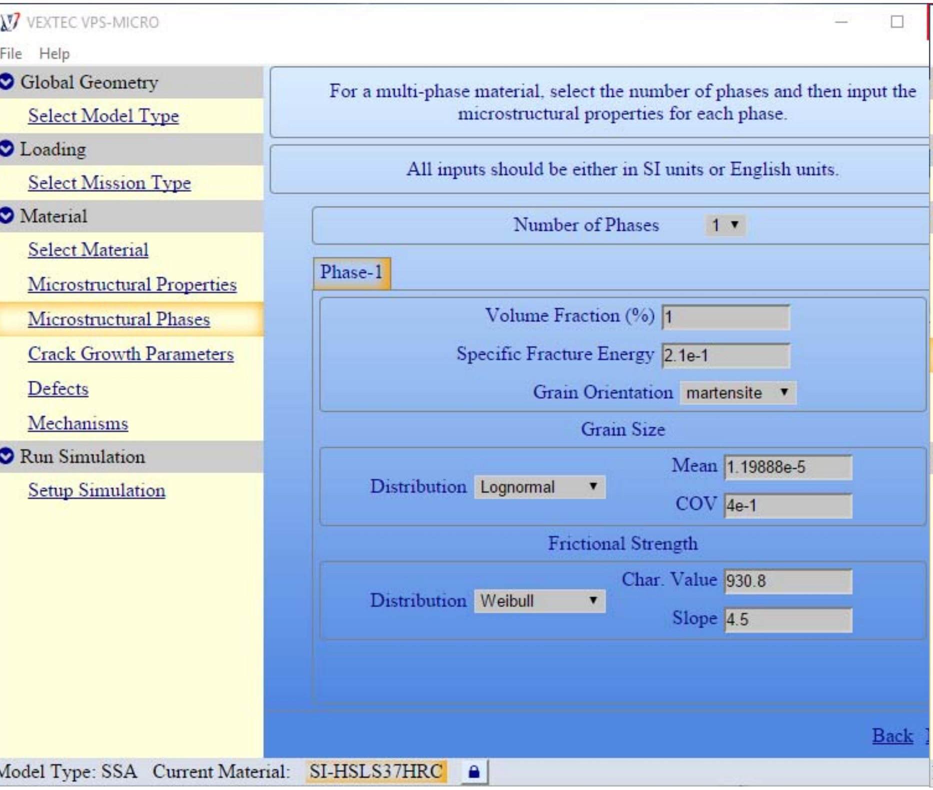
#	Parameter	Explanation
1	Grain size	Mean=640 μ; CoV=0.417
2	Grain Boundary SIF	2.5ksi√in
3	Frictional Strength	Weibull; Char. Val.= 113 ksi; Slope=4.5
4	Small Crack Coeff.	0.01
5	Paris Law Exponent	3.9
6	Paris Law Coeff.	Normal; Mean=5.0E-12; CoV=0.3
7	Shear Modulus (G)	6.31E+3 ksi
8	Poisson's Ratio (v)	0.3
9	Orientation	Beta (see previous report)
10	Asperity (% of grain size)	Height=1% ; Width=10%; Distance=100%; Modulus=100%

Typical Geometry Input

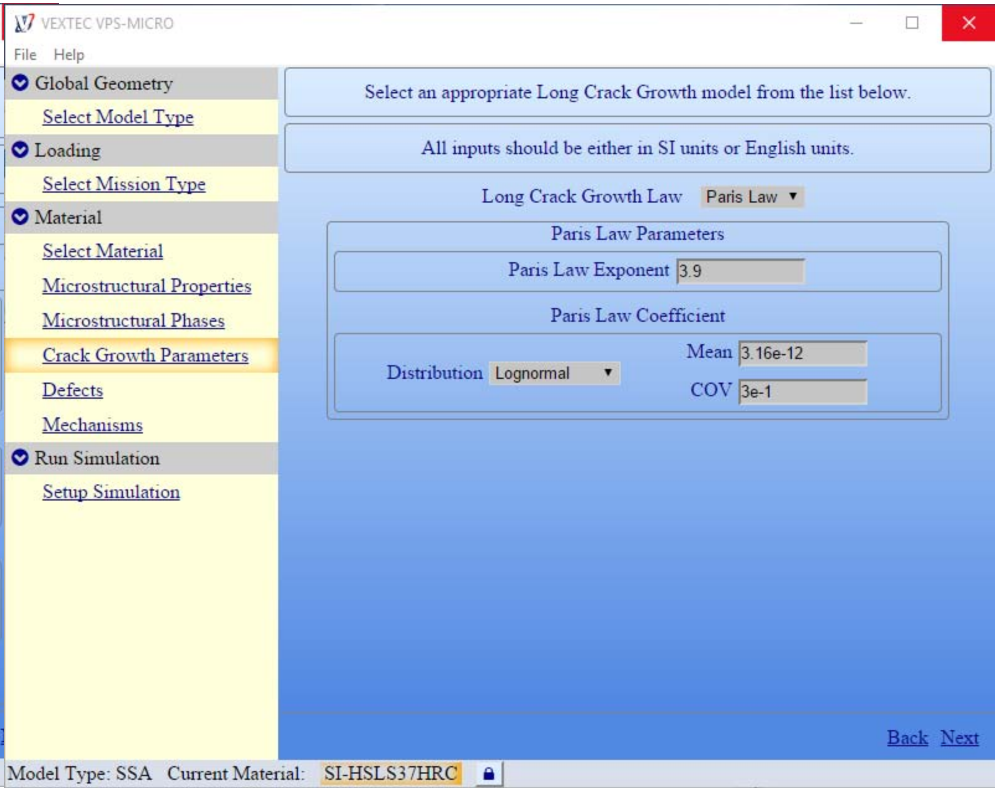


For a 2-Hole specimen provide FEA

Microstructural Phases

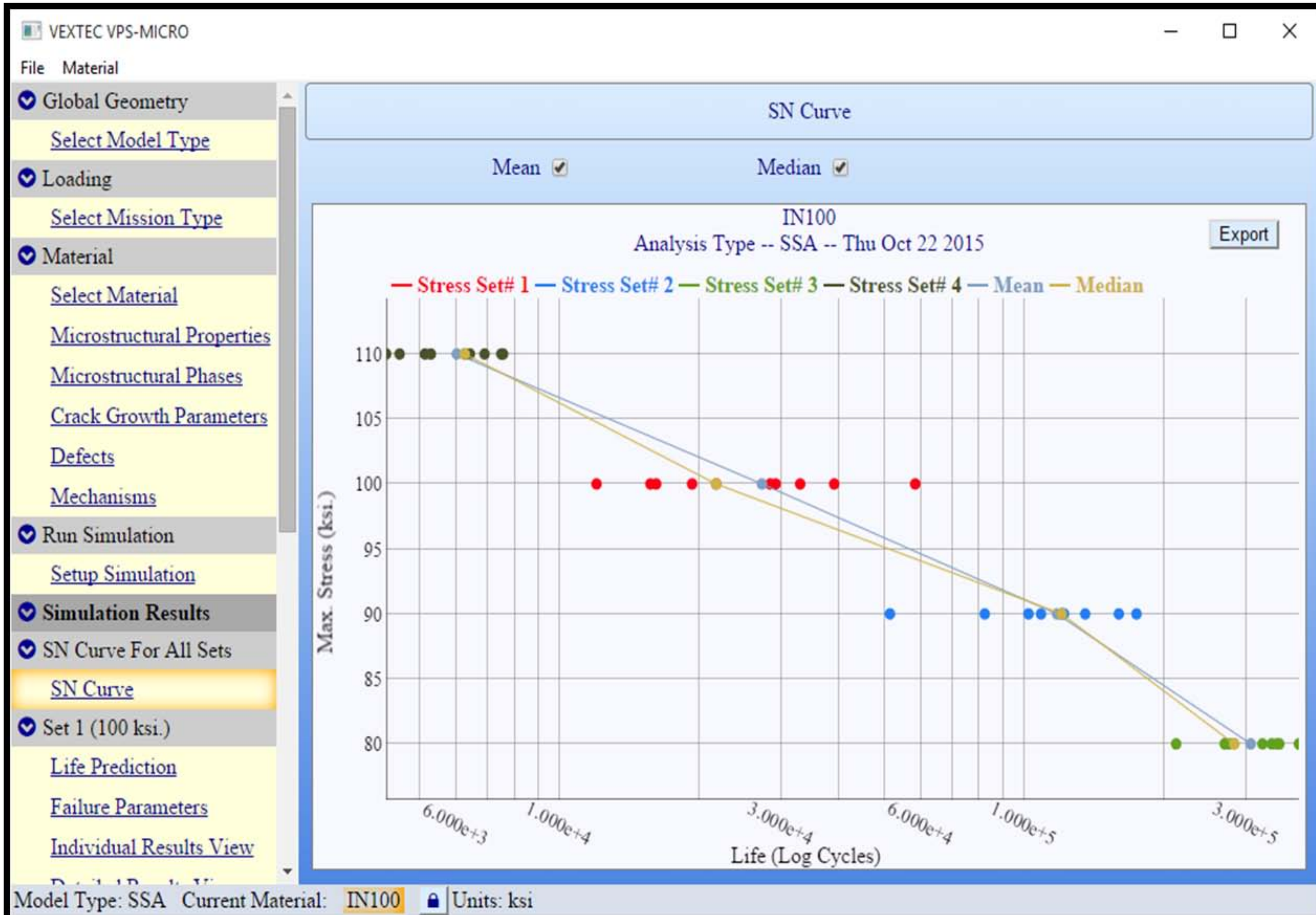


Crack Growth Properties

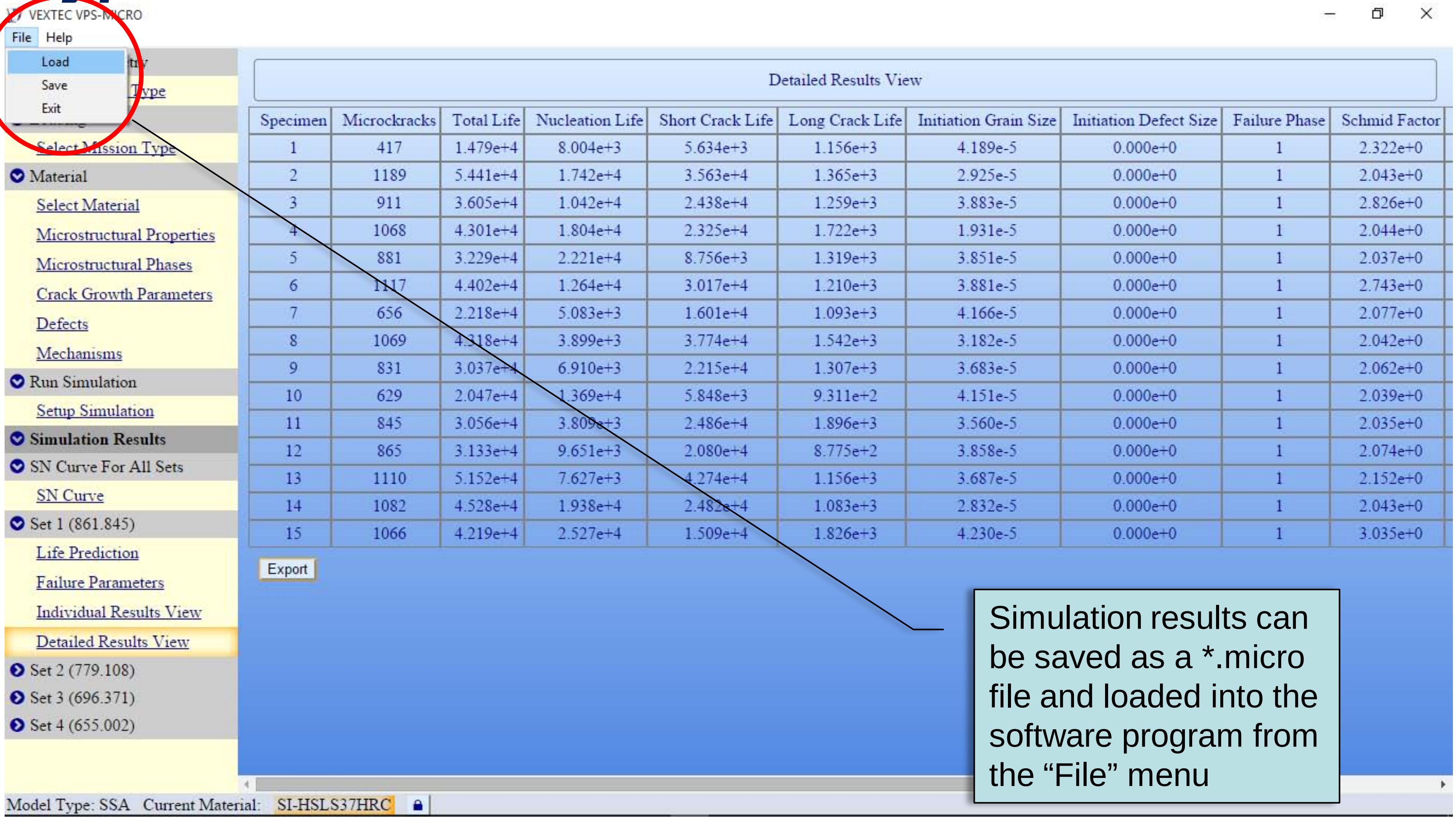


In General, the "Microstructural Phases" & "Crack Growth Property" inputs are "locked" and the user cannot change them. Super-users can modifying these input parameters.

Typical VPS-MICRO Output



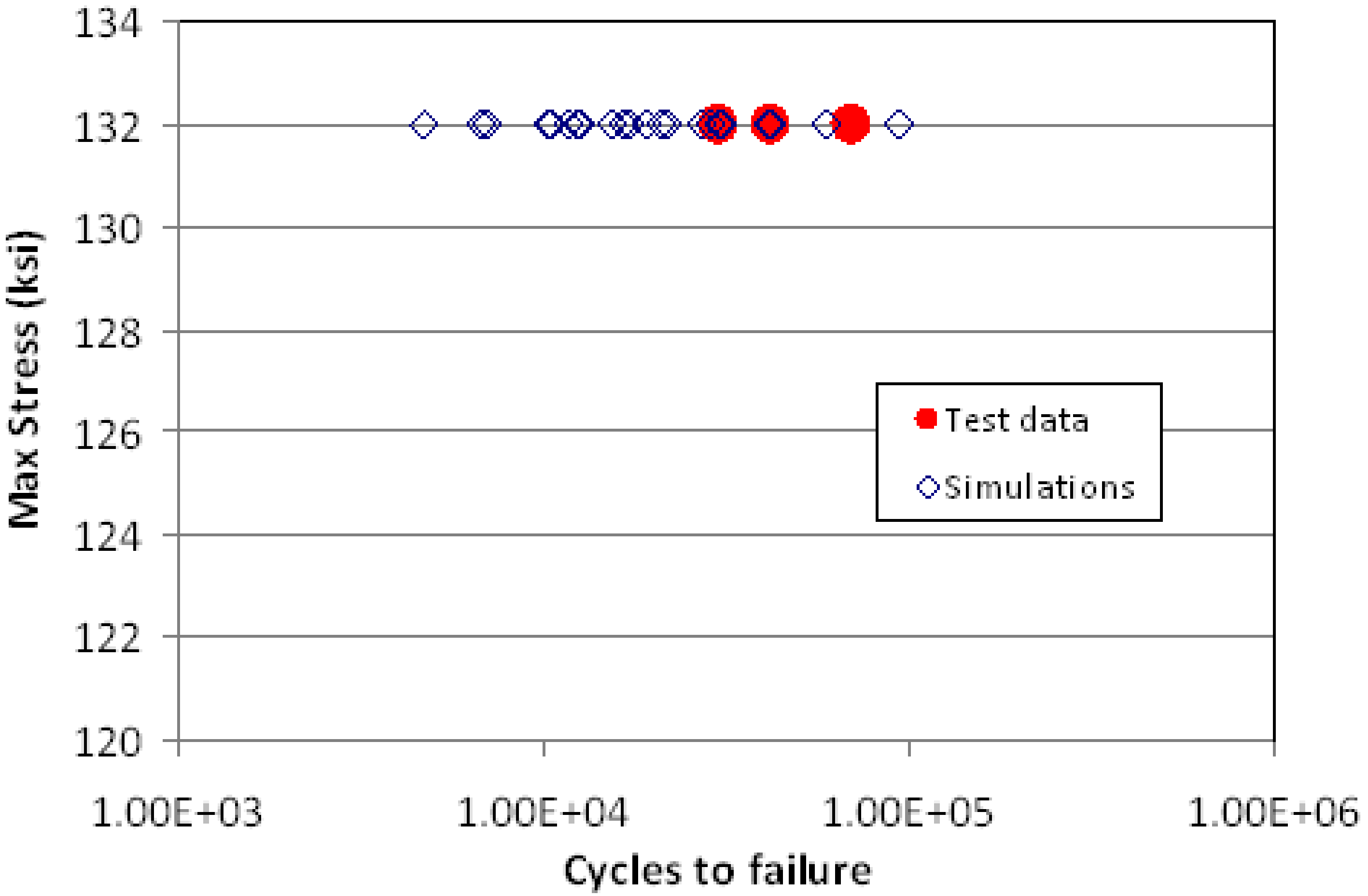
Typical Load and Save Simulation Results



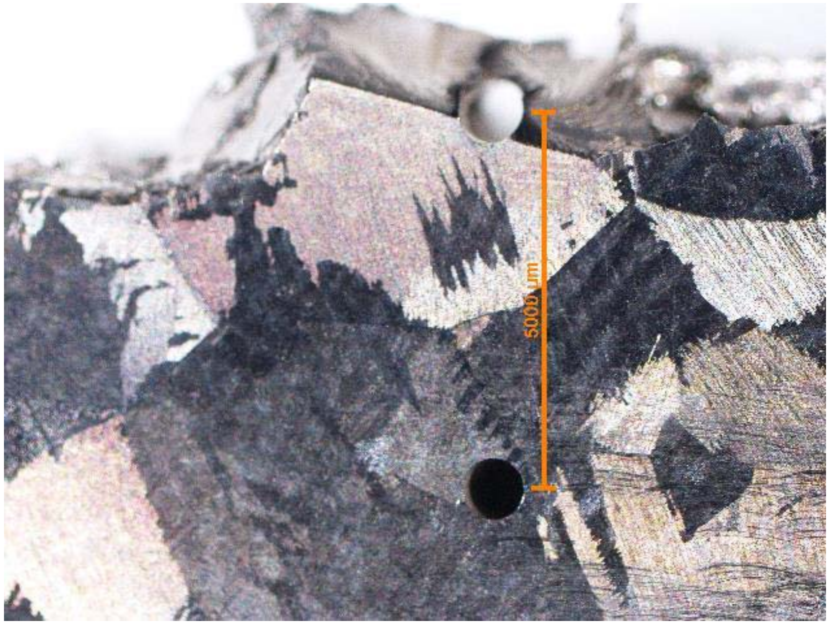
Specimen	Microcracks	Total Life	Nucleation Life	Short Crack Life	Long Crack Life	Initiation Grain Size	Initiation Defect Size	Failure Phase	Schmid Factor
1	417	1.479e+4	8.004e+3	5.634e+3	1.156e+3	4.189e-5	0.000e+0	1	2.322e+0
2	1189	5.441e+4	1.742e+4	3.563e+4	1.365e+3	2.925e-5	0.000e+0	1	2.043e+0
3	911	3.605e+4	1.042e+4	2.438e+4	1.259e+3	3.883e-5	0.000e+0	1	2.826e+0
4	1068	4.301e+4	1.804e+4	2.325e+4	1.722e+3	1.931e-5	0.000e+0	1	2.044e+0
5	881	3.229e+4	2.221e+4	8.756e+3	1.319e+3	3.851e-5	0.000e+0	1	2.037e+0
6	1117	4.402e+4	1.264e+4	3.017e+4	1.210e+3	3.881e-5	0.000e+0	1	2.743e+0
7	656	2.218e+4	5.083e+3	1.601e+4	1.093e+3	4.166e-5	0.000e+0	1	2.077e+0
8	1069	4.318e+4	3.899e+3	3.774e+4	1.542e+3	3.182e-5	0.000e+0	1	2.042e+0
9	831	3.037e+4	6.910e+3	2.215e+4	1.307e+3	3.683e-5	0.000e+0	1	2.062e+0
10	629	2.047e+4	1.369e+4	5.848e+3	9.311e+2	4.151e-5	0.000e+0	1	2.039e+0
11	845	3.056e+4	3.809e+3	2.486e+4	1.896e+3	3.560e-5	0.000e+0	1	2.035e+0
12	865	3.133e+4	9.651e+3	2.080e+4	8.775e+2	3.858e-5	0.000e+0	1	2.074e+0
13	1110	5.152e+4	7.627e+3	4.274e+4	1.156e+3	3.687e-5	0.000e+0	1	2.152e+0
14	1082	4.528e+4	1.938e+4	2.482e+4	1.083e+3	2.832e-5	0.000e+0	1	2.043e+0
15	1066	4.219e+4	2.527e+4	1.509e+4	1.826e+3	4.230e-5	0.000e+0	1	3.035e+0

Simulation results can be saved as a *.micro file and loaded into the software program from the “File” menu

Model Results



Next Steps



- Model
  - Additional investigation of mechanism for beta annealed Ti
  - Extend damage accumulation simulation
- Software
  - Damage models and interface to external damage models
  - Interface to FEA and inspection software
- Tests
  - Perform test to extend the mechanist models
  - Develop tests standards to gather data to populate model
- Commercialization
  - AFRL vehicle directorate and Lockheed Martin
  - FEA customer base

VEXTEC U.S. Federal Programs

VEXTEC Clients	Successes Achieved With VEXTEC Technology
USAF	• Partner in the Airframe "*Digital Twin" Initiative* • Use UQ/UM to calibrate and predict test results • Predict the confidence bounds on damage risk
FDA	• Only 1 of 2 companies in the *Medical Device Development Tool* program for computational modes • Use VLM to simulate and certify bench testing of cardiac leads
USN	• Use VLM +UQ/UM to forecast fleet maintenance • Predict Fatigue + Corrosion Damage risk

Aircraft Parts Automotive Industrial Equip Medical Implants

Over 100 VEXTEC Commercial Successes

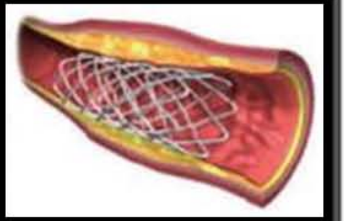
VEXTEC Clients	Successes Achieved With VLM
American Airlines	$4 M/yr saved on bearings
Cummins Engine	$5 M saved from $150K investment
Boston Scientific	Working with FDA towards methods approval
Oil & Gas Co.	$12 M /yr saved in equipment leasing
Fortune 500 Co.	$3 M saved in manufacturing line maintenance
Fortune 100 Co.	$250 K/month on machining efficiencies
Chrysler	Early Adopter using VEXTEC software since 2001

CHRYSLER American Airlines Cummins Boston Scientific


Aircraft Parts

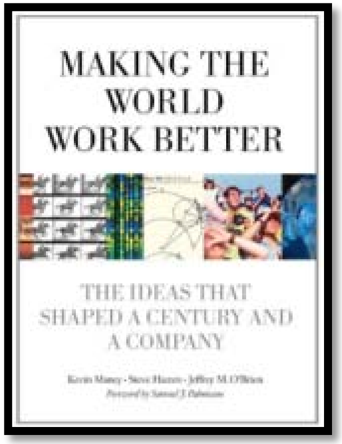

Automotive


Industrial Equip


Medical Implants

Thank You!

- ***Founded in 2000 in Nashville***
- ***Software backed by 7 Patents:*** *Virtual Life Management® (VLM®) & VPS-MICRO®*
- ***Value Proposition**: Help companies assure product reliability and reduce cost*
  - *New products to market quickly*
  - *Leverage physical testing for increased confidence*
  - *Forecast product durability and manage product life cycle risk*
- ***Business Model**: Hybrid – consulting services, software licensing and training*



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