Virtual Testing to Supplement Rapid Certification of Reverse Engineered Parts

Robert Tryon,

Animesh Dey, Mike Oja

December 5, 2018

Acknowledgements

Dean Hutchins of DLA

Eric Tuegel of AFRL

Issues

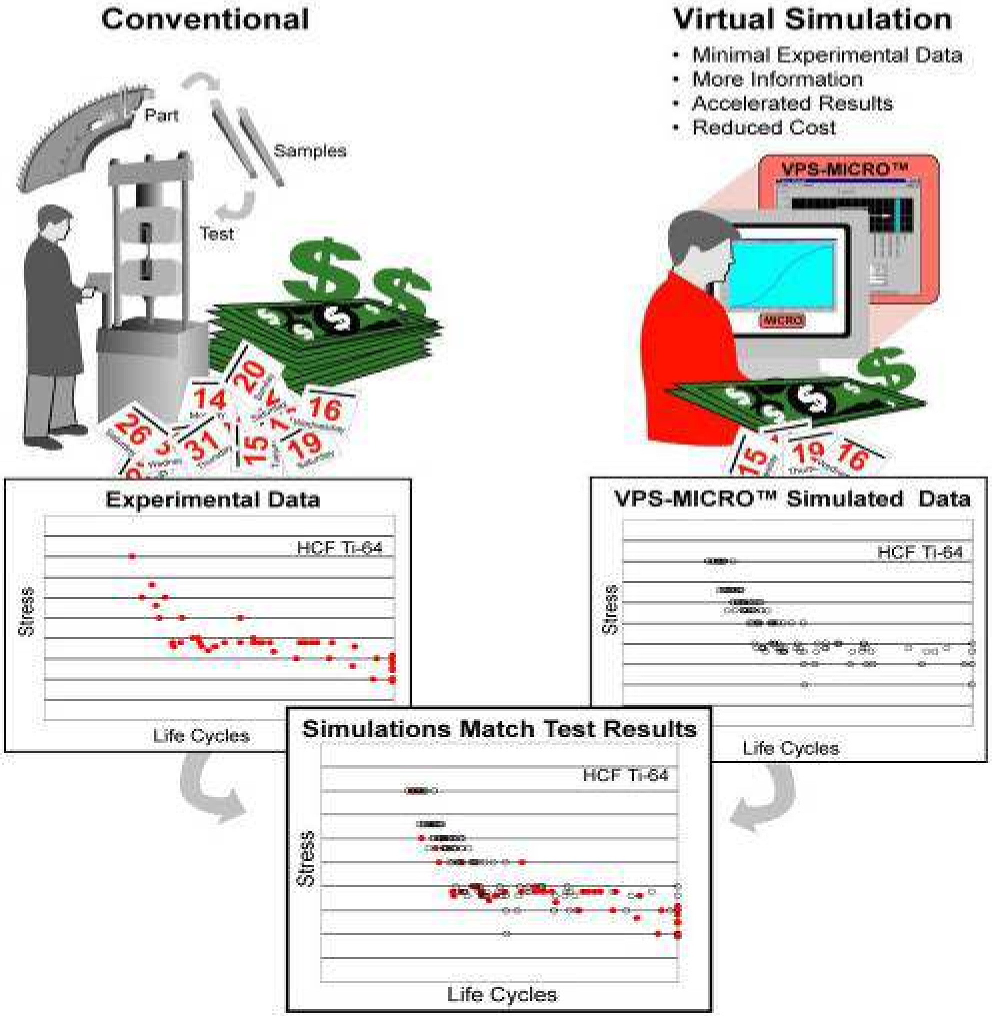
- A major issue confronting the DoD is obtaining structural components which are difficult to find or stock and have exorbitant cost or lead times
  – OEMs and vendors may have stopped production or are out of business or are unwilling to produce limited quantities
  – Any replacement part must be certified for use
- Certifying replacement for fatigue critical parts is expensive
- Much of the high cost can be attributed to certification testing of the part; especially when a limited number of parts are acquired
- Computational testing is an advanced technology that holds promise in drastically lower the certification costs

Objectives

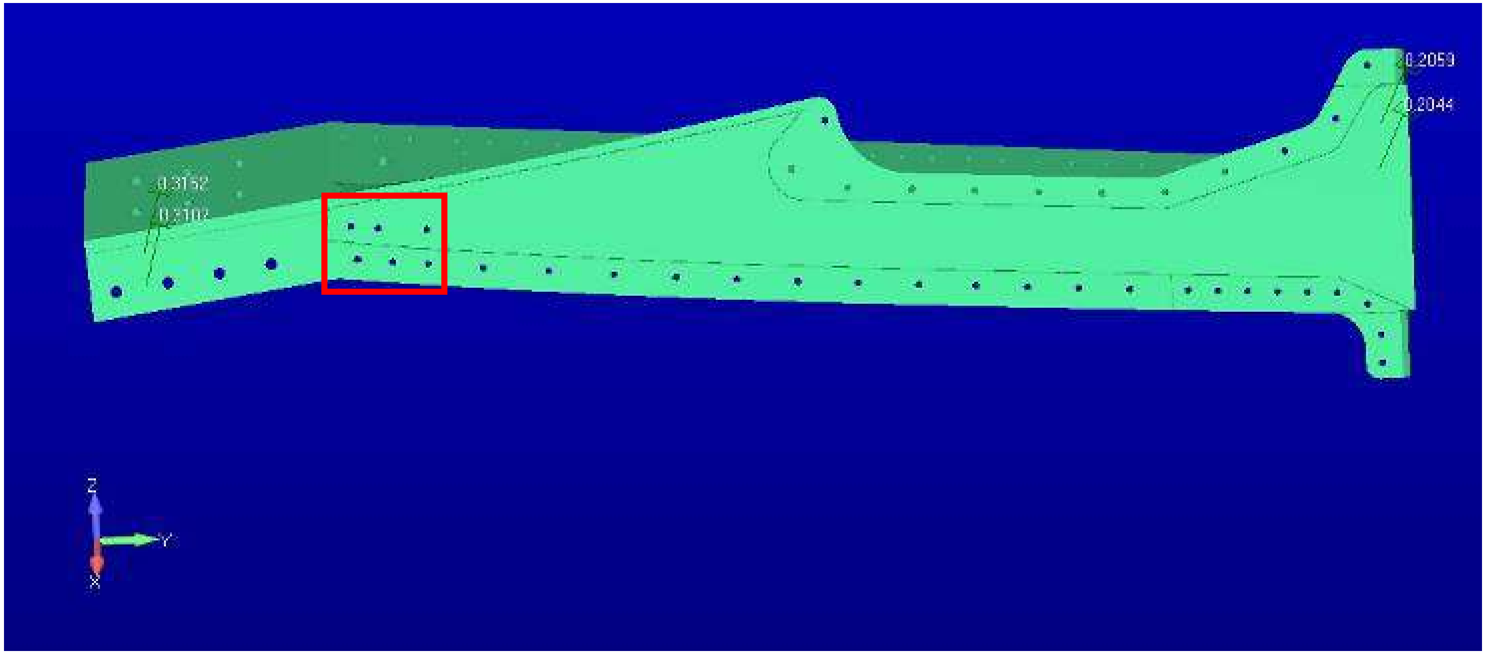
- Develop a computational software to:
  - Predict fatigue life of a original forged part
    - Given:
    - Part geometry
    - In-service loading
    - 3-D microstructure map
  - Predict fatigue life of a replacement part machined from stock material
    - Given:
    - Part geometry (same as original forged part)
    - In-service loading (same as original forged part)
    - 3-D microstructure map (for stock material)
  - Compare fatigue durability of original versus replacement part

Use Computational Models to Simulate Replacement Part Certification Testing

- Use Structural FEA with calibrated material models to simulate the testing of:
  - Many original parts
  - Many replacement parts
- Compare the simulated test result to assess the viability of the replacement part



Forged Component Geometry

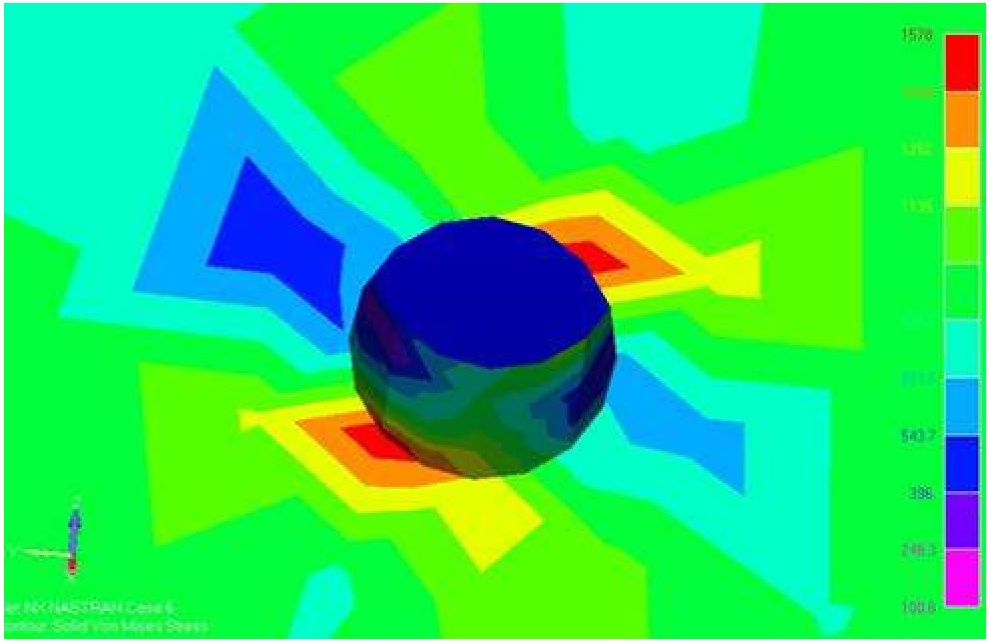


- CAD model of example part showing location of holes that crack and require the part to be replaced.

Structural Analysis

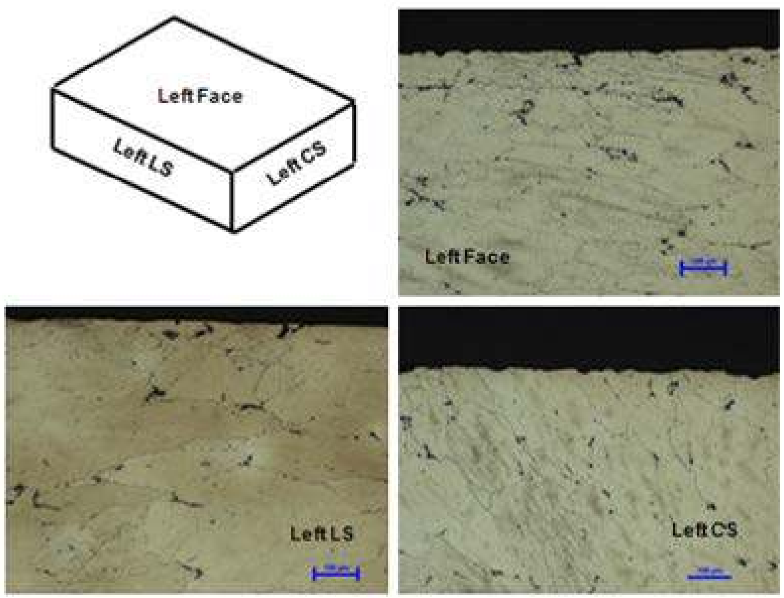
- Relative Stress
  - Close examination of local stress distribution show that most of the stress is bending with a small amount to axial and torsion.
  - For all maneuvers, most of the load is bending
  - Relative stress can be scaled to approximate in-service loads.
- Relative durability
  - Assessed by simulating testing the CSL with boundary conditions that simulate the relative stress.
- SN curve
  - Created by simulating the test for a several different absolute stress levels

Relative stress



Material Microstructure Analysis

Part Forging



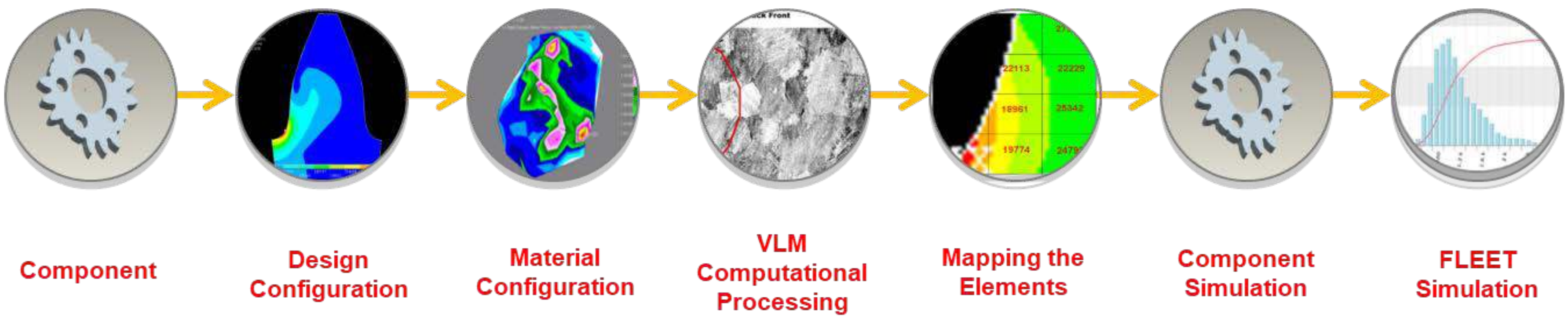
- Grain size = .003 in (COV = 0.33)
- Particle size = .00066 in (COV = 0.3)
- Particle population density = 14000/sq in (COV = 0.3)

Stock Plate

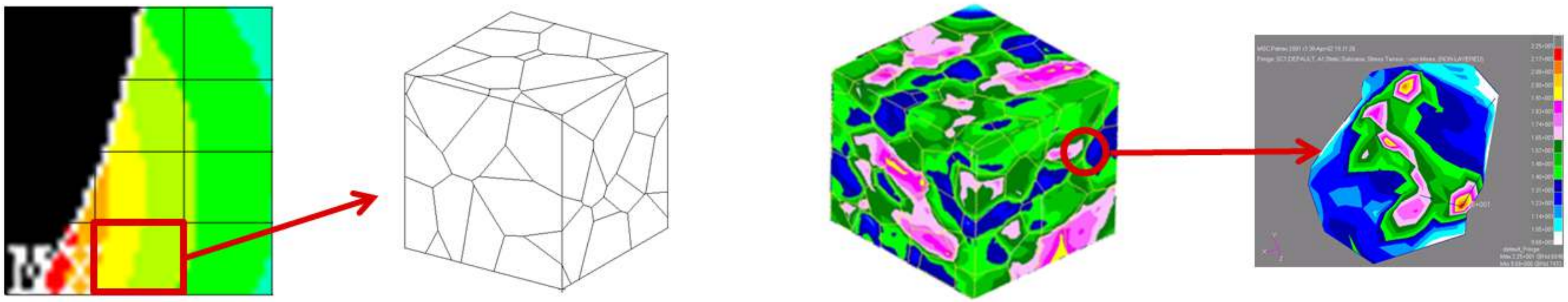
- Grain size = .003 in (COV = 0.33)
- Particle size = .000176 in (COV = 0.58)
- Particle population density = 522,760/sq in (COV = 0.3)

VEXTEC

Computational Process Flow



Material Configuration

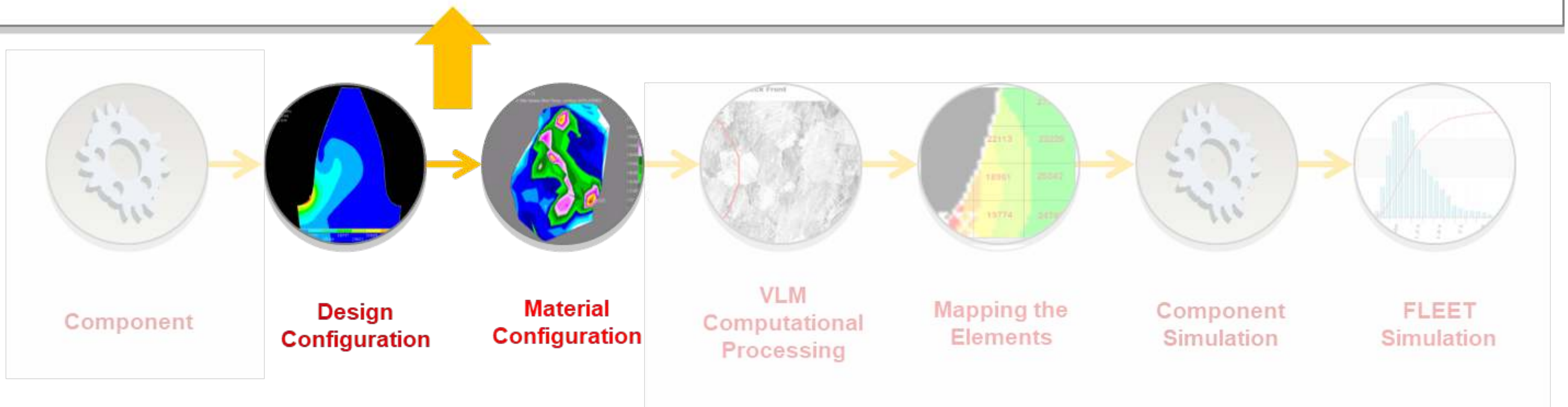


Initial Element

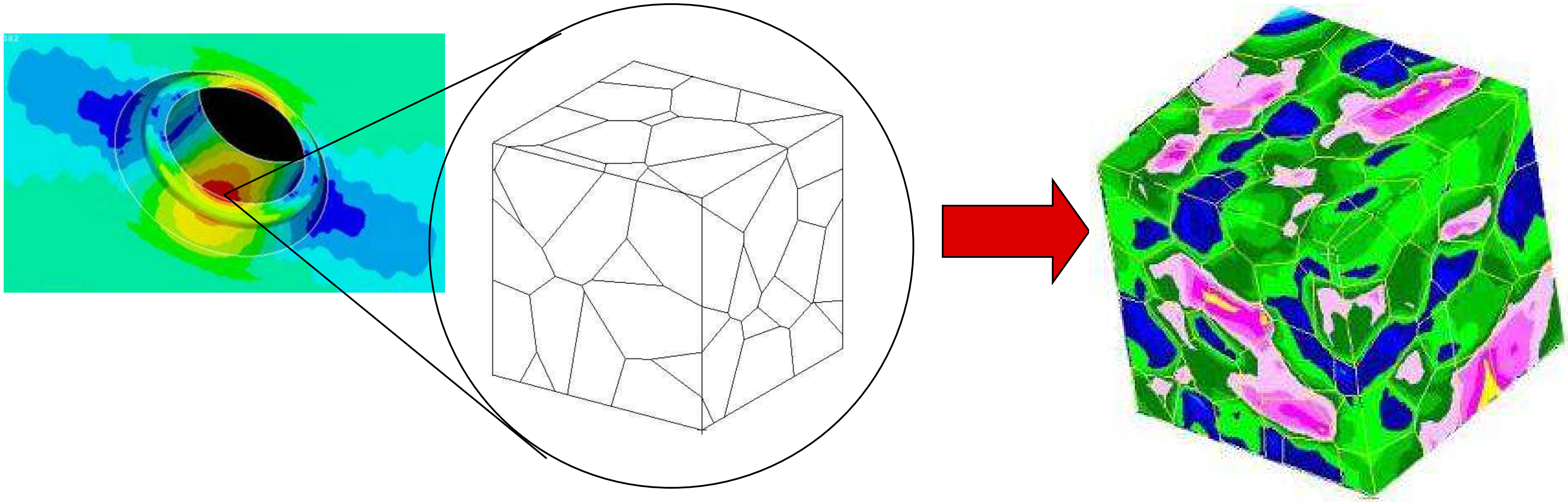
Superimpose Natural Substructure

Map FEA Stress to Substructure

Translate Microstress to each Grain

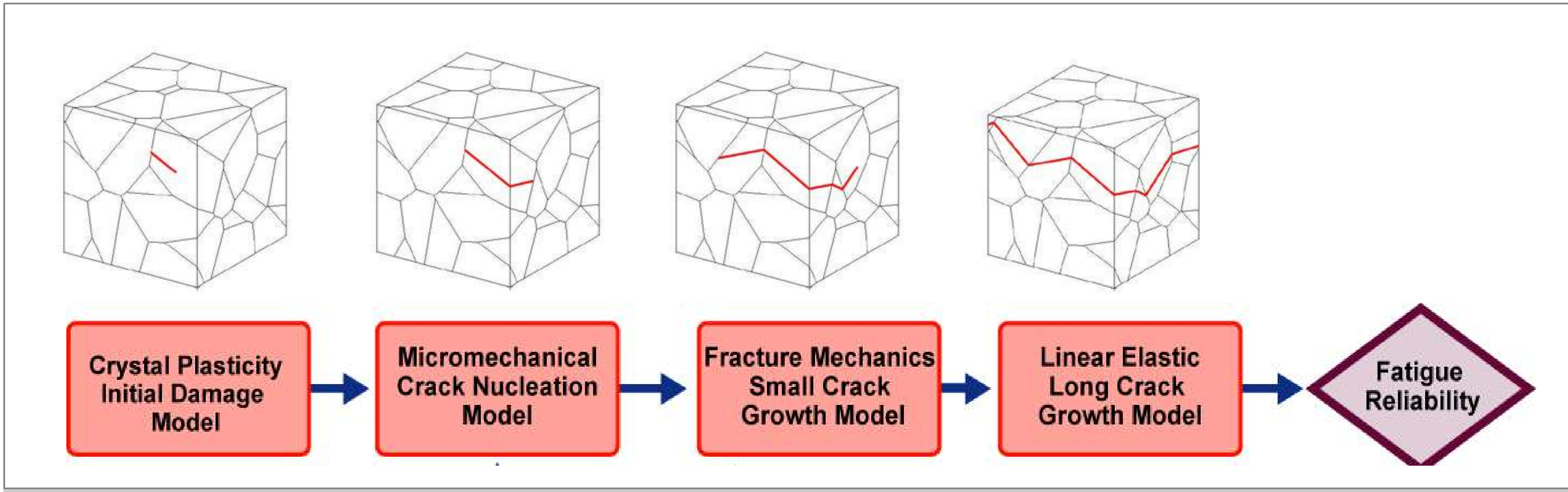


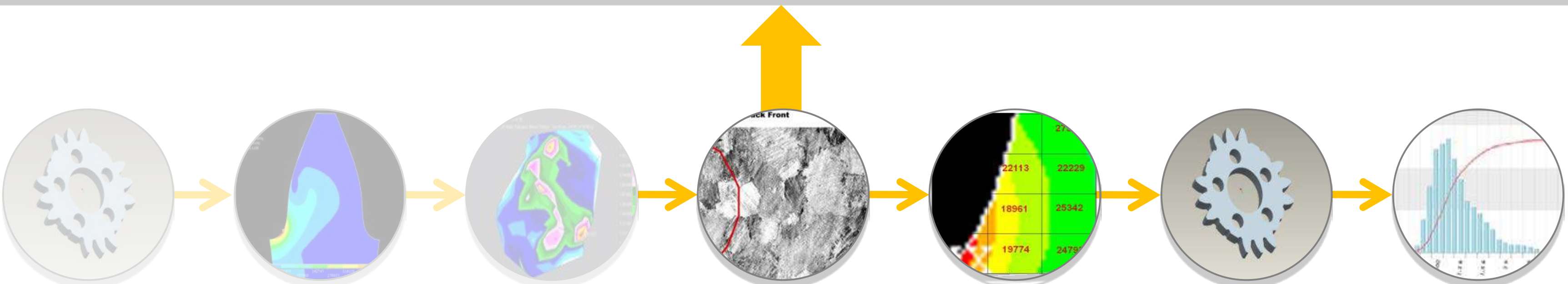
Computational Stress Model



- Perform global FEA
- Create microstructure geometry model (SVE)
- Perform microstructural FEA on SVE

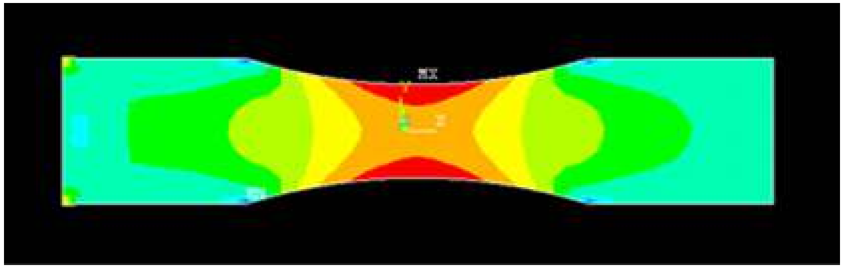
Computational Damage Model

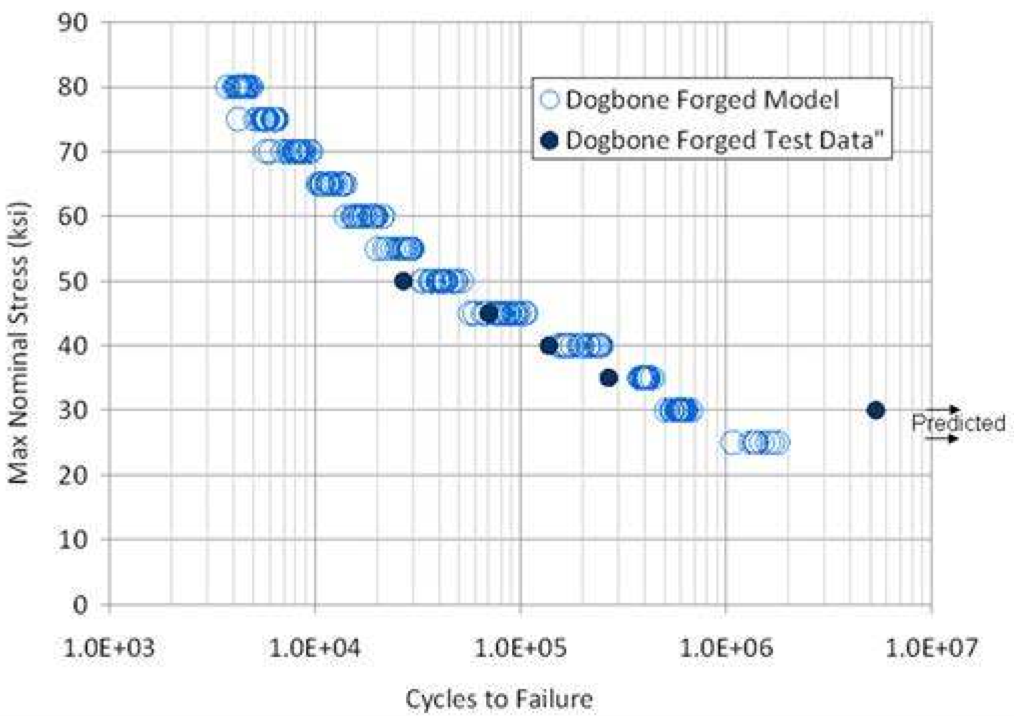




Original Forged Material Model Calibration

- Material characterization from previous Air Force and Navy programs
  - Laboratory fatigue tests data on flat plate dog bone specimens (solid circle symbols)
  - Predicted fatigue tests data on flat plate dog bone specimens. 50 specimens simulated for each stress level (open circle symbols)

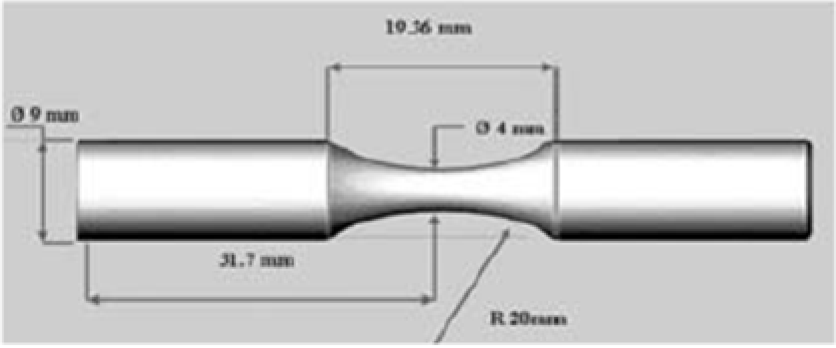


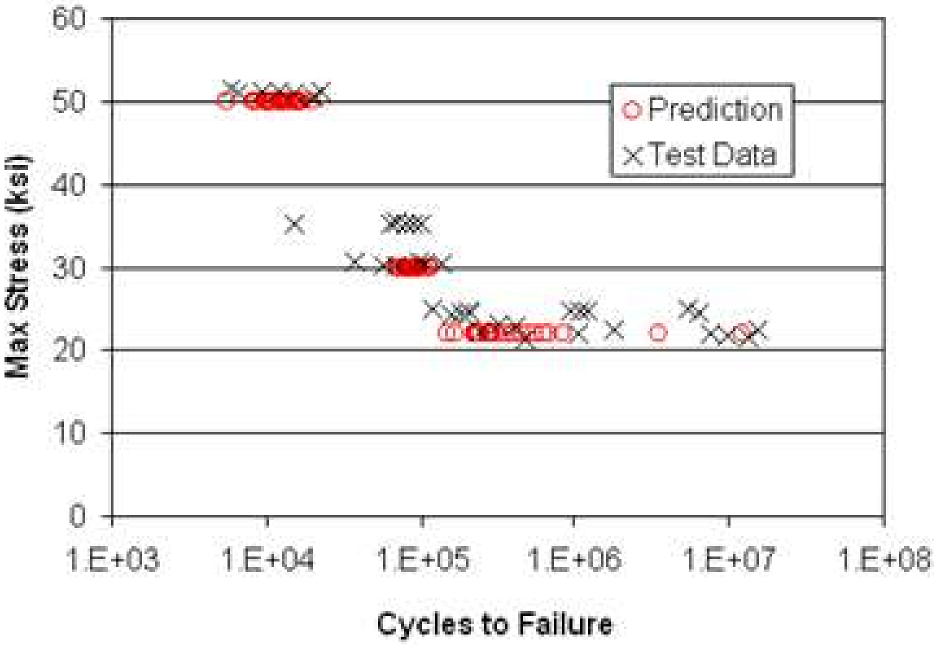


Ford, S., C., "Exploratory Development of Design Data on Joints," AFML-TR-76-52, Feb, 1976.

Replacement Plate Material Model Calibration

- Material characterization from open literature
  - Laboratory fatigue tests data on rotating bending specimens (open circle symbols)
  - Predicted fatigue tests data on rotating bending specimens. 50 specimens simulated for each stress level (X symbols)





Monsalve, et al., "S-N-P curves in 7075 T7351 and 2024 T3 aluminum alloys subjected to surface treatments," Fatigue Fract Engng Mater Struct 30, 748–758. (2007).

Material Parameters

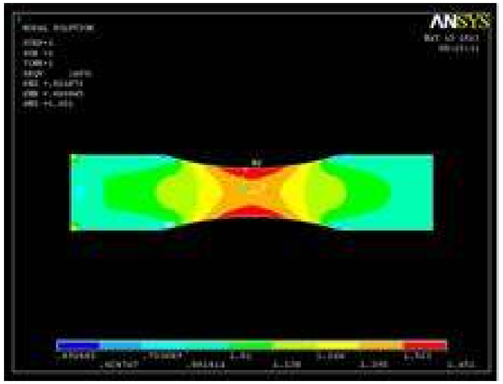
- Comparison of material parameter from calibrated models indicate difference in:
  - Grain size (measured)
  - Particle sized and density (measured)
  - CTOD short crack parameter (calibrated)
  - Grain boundary strength (SIF) calibrated

INPUT PARAMETER	Original AA 7075-T7351 Forged	Replacement AA 7075-T7351 Plate
Shear Modulus	3800	3800
Poisson's ratio	0.33	0.33
Mean Grain size (in.)	0.0033	0.0033
Grain size (COV)	0.32	0.32
Particle Size	6.60E-04	1.76E-04
Particle Size COV	0.3	0.58
Particle Density	14000	522,760
Particle Density COV	0.3	0.3
CTOD Law Coefficient	0.001	0.01
Frictional strength	50 (7.5)	50 (7.5)
Grain boundary SIF	0.8	0.48
Paris Law Coefficient	1.82E-11	1.82E-11
Paris law exponent	4.73	4.73
Specific fracture energy	1	1
Orientation	FCC	FCC
Micro-stress variation	0.15	0.15

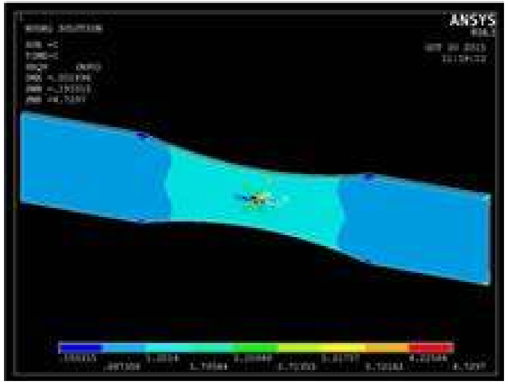
Durability Simulation Analysis

- FEA of bolt hole specimen created in ANSYS
- Stress and surface area of each node input to durability analysis
- Perform durability analysis for several different applied load levels
- Perform analysis for 25 bars at each load level. Each bar with a unique (statistical) microstructure
- Compare simulation with laboratory tests

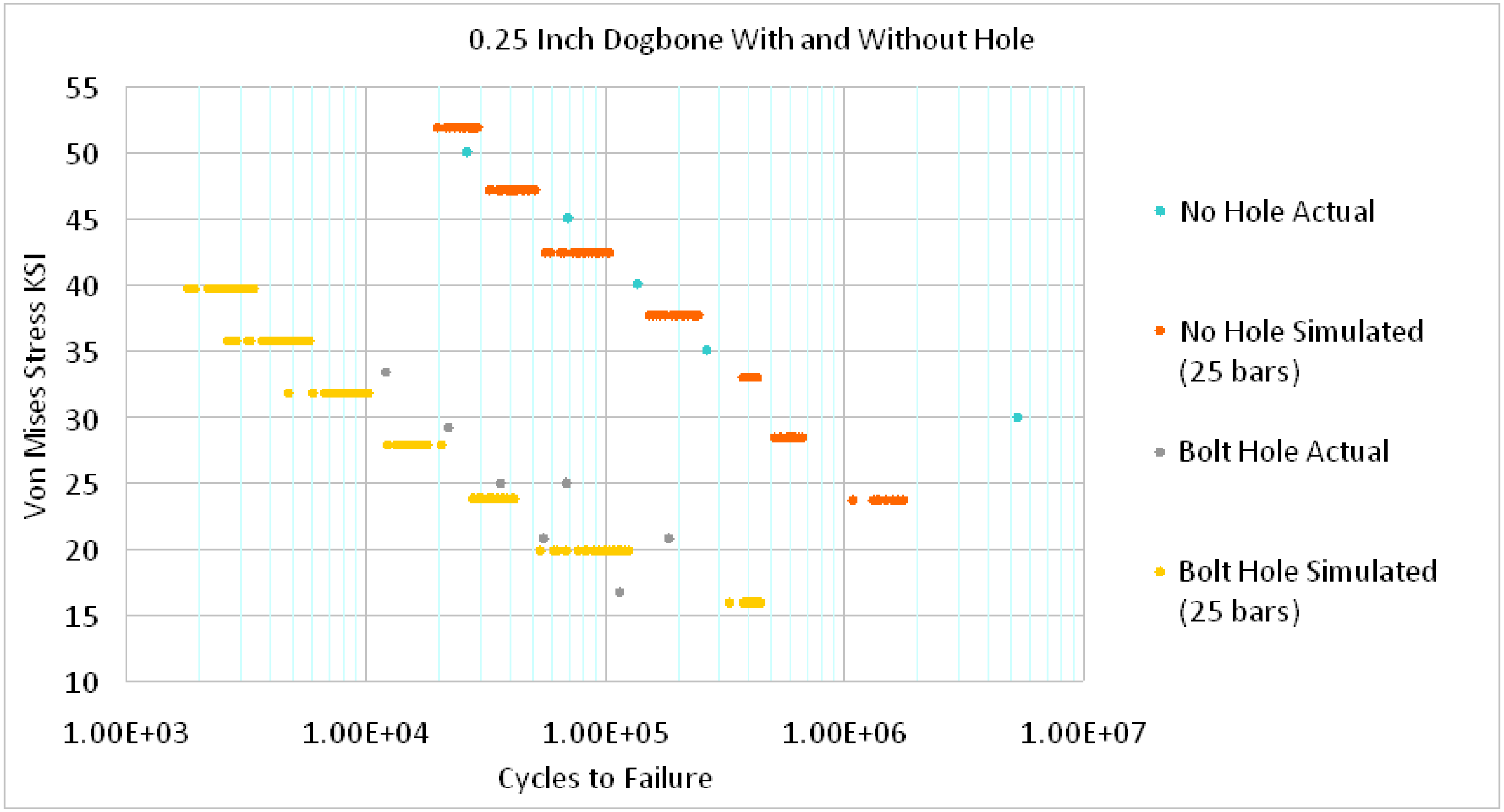
Smooth Bar



Bolt Hole



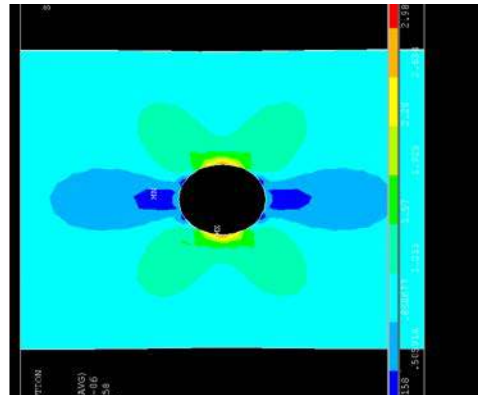
Simulated Results Compare to Test Data

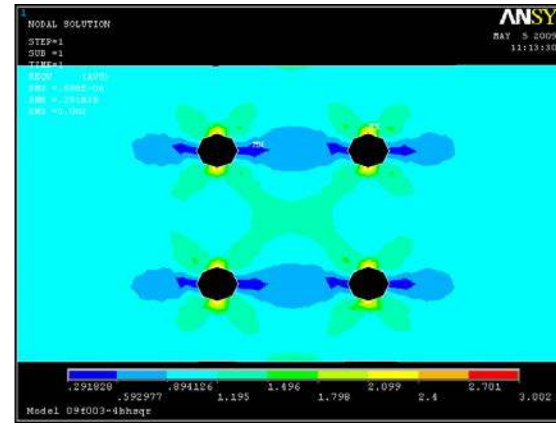


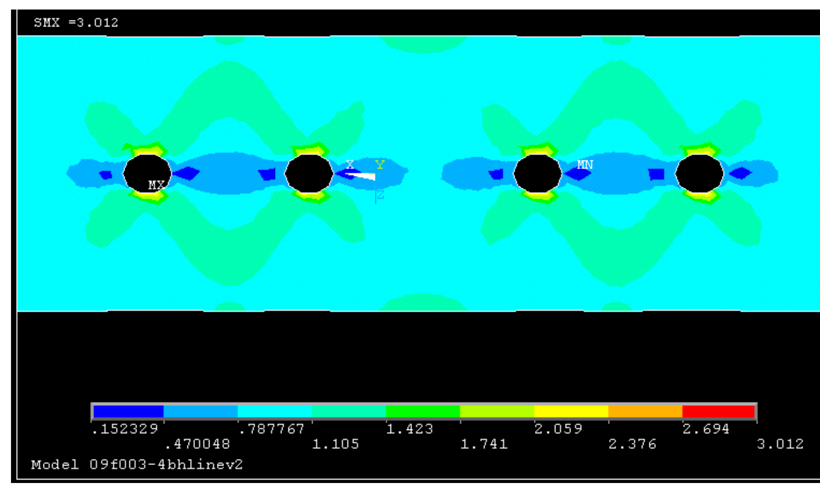
Results shows excellent comparison of simulation with actual data

Example of Different Geometries

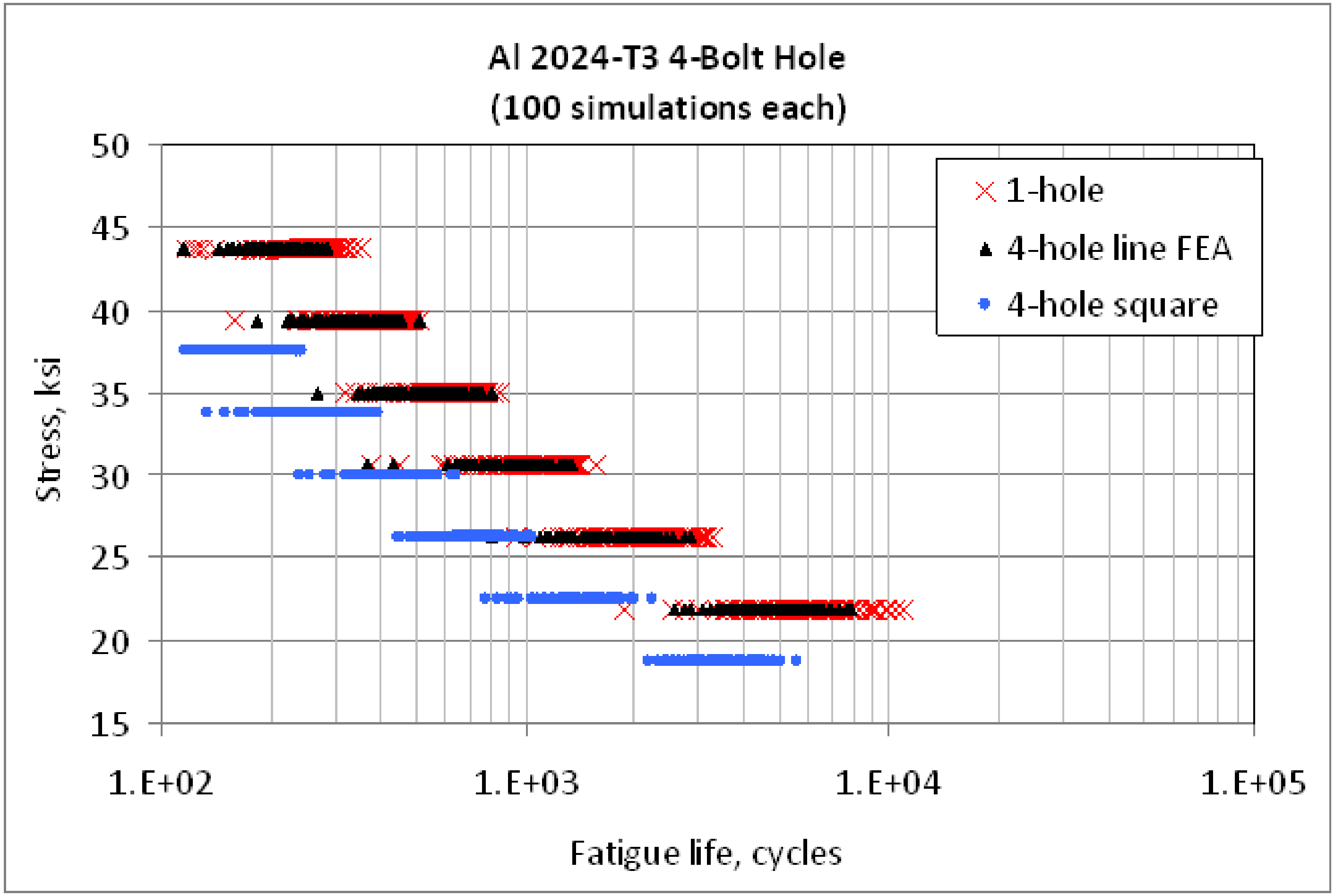
- FEA model of three different geometries with the same stress.
- Traditional fatigue analysis would predict that each model would have the same fatigue life.
- Probabilistic microstructural fatigue analysis takes into account stressed volume and stress gradient to predict different fatigue life.







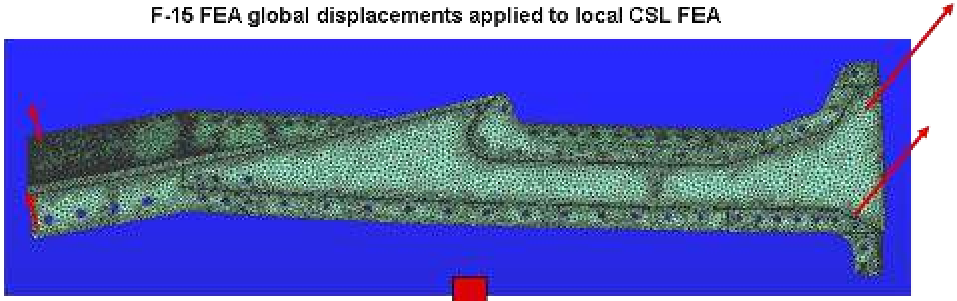
Simulated Durability



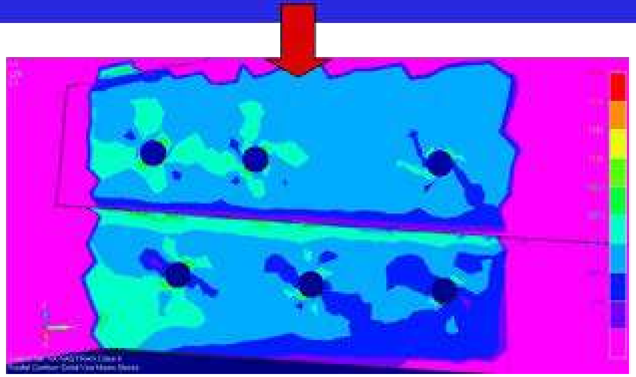
Simulate In-Service Loads Levels

- Simulate laboratory testing CSL
  - Test for different stress level to simulate SN curve
  - Scale relative loads to account for in-service axial, bending and torsional loads

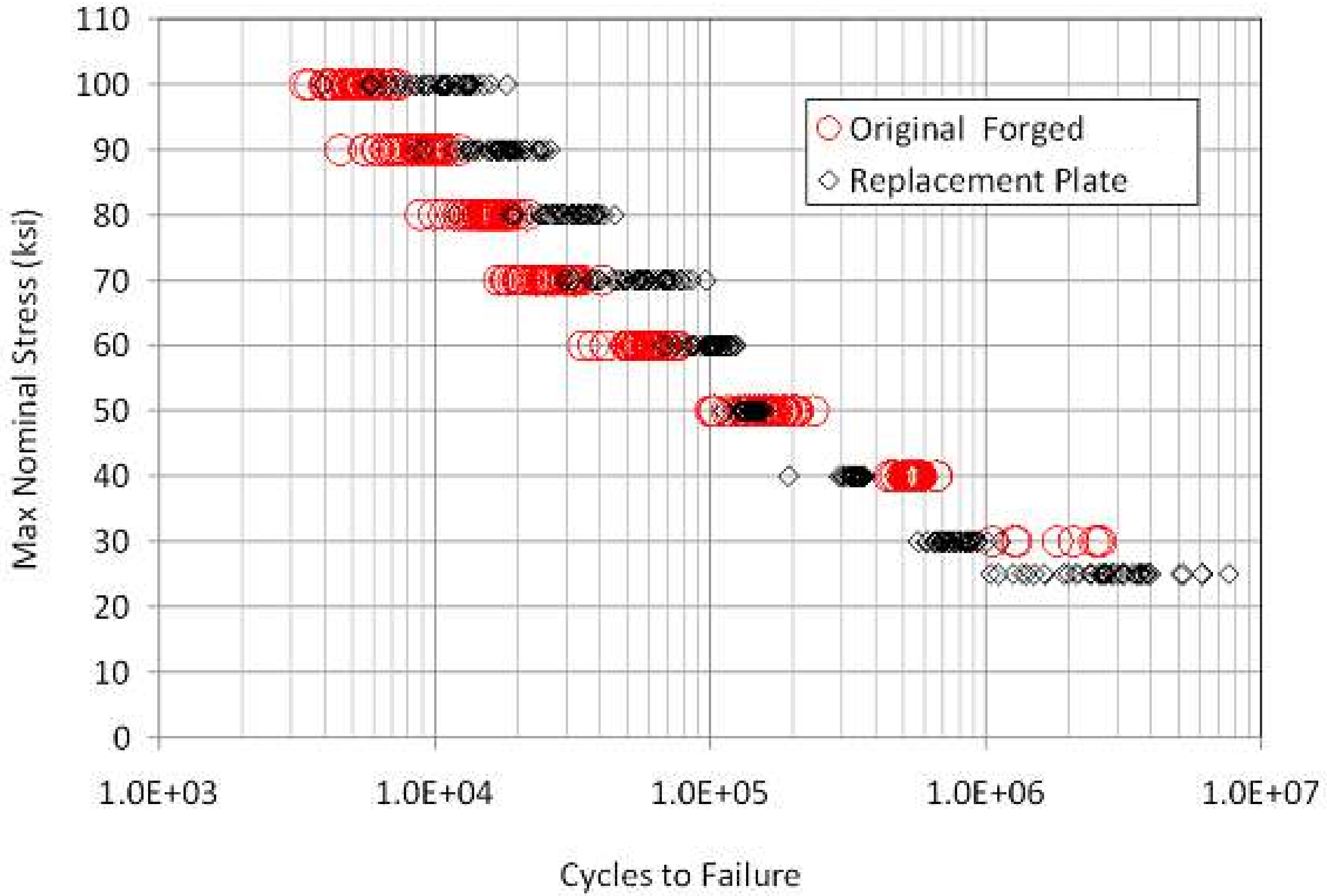
F-15 FEA global displacements applied to local CSL FEA



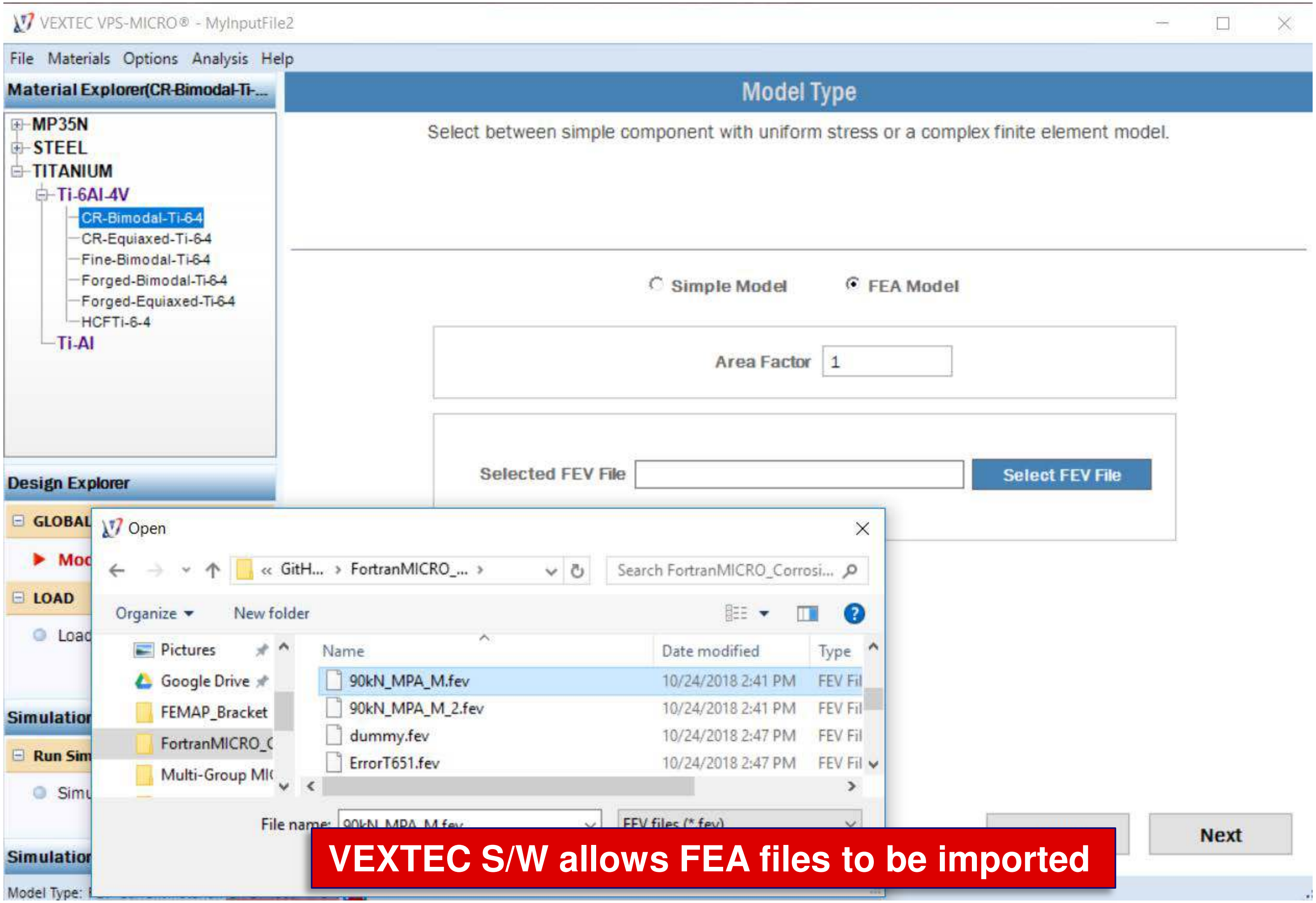
CSL FEA Solved for local stresses



Simulated S-N Curve for Original and Replacement Part

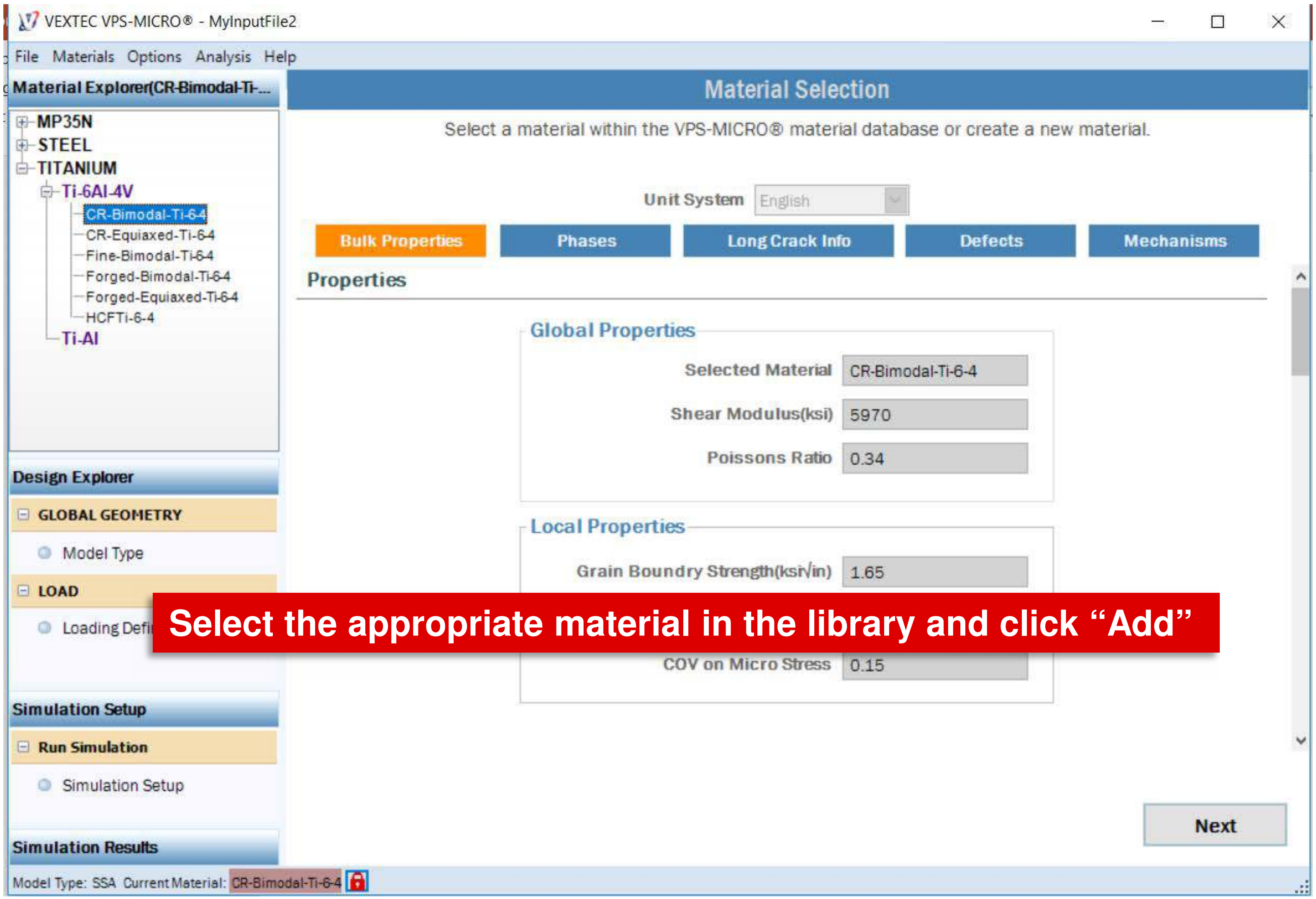


Importing FEA Files

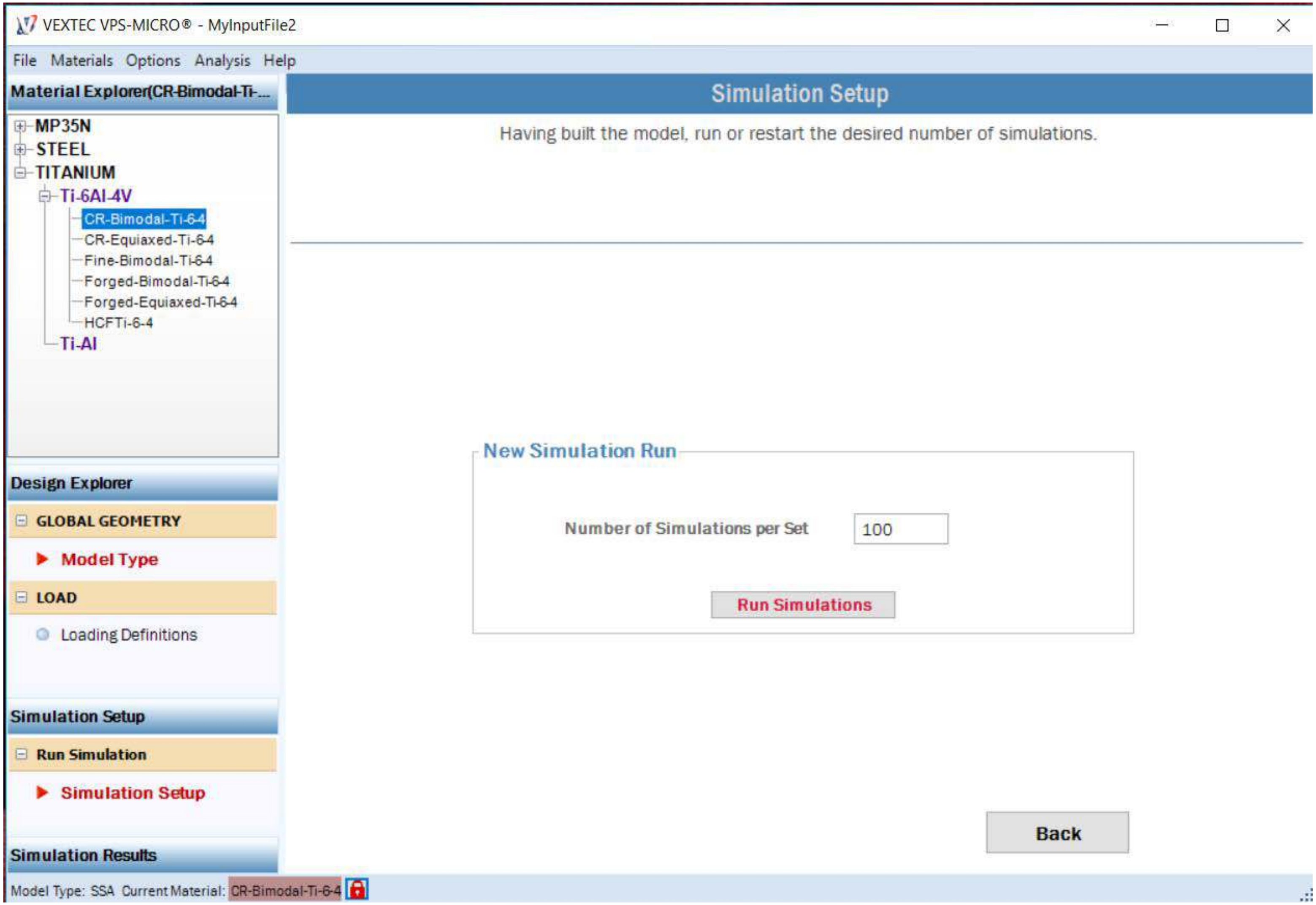


VEXTEC S/W allows FEA files to be imported

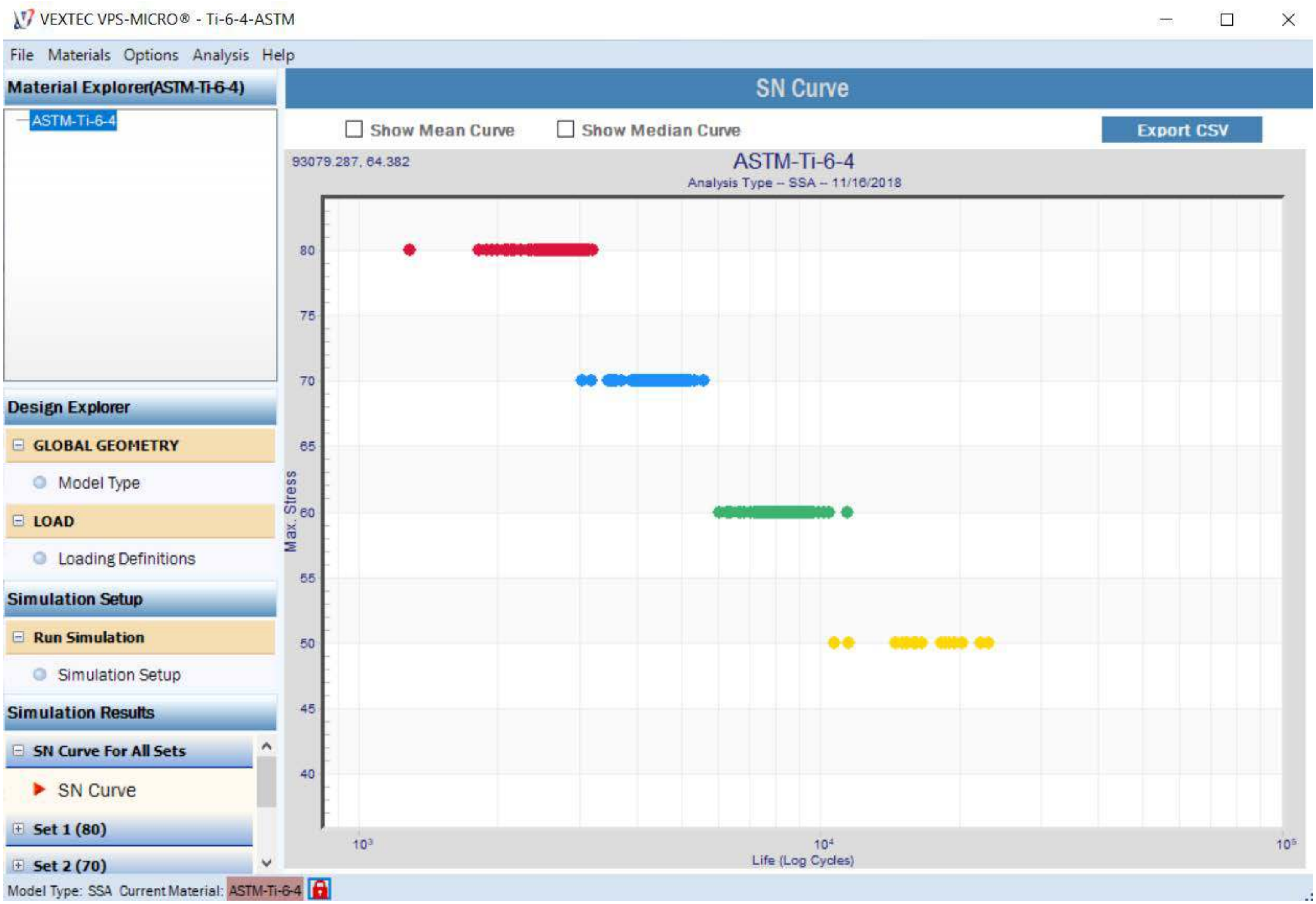
Material Selection



Number of Simulations



Output - SN Curve for Part



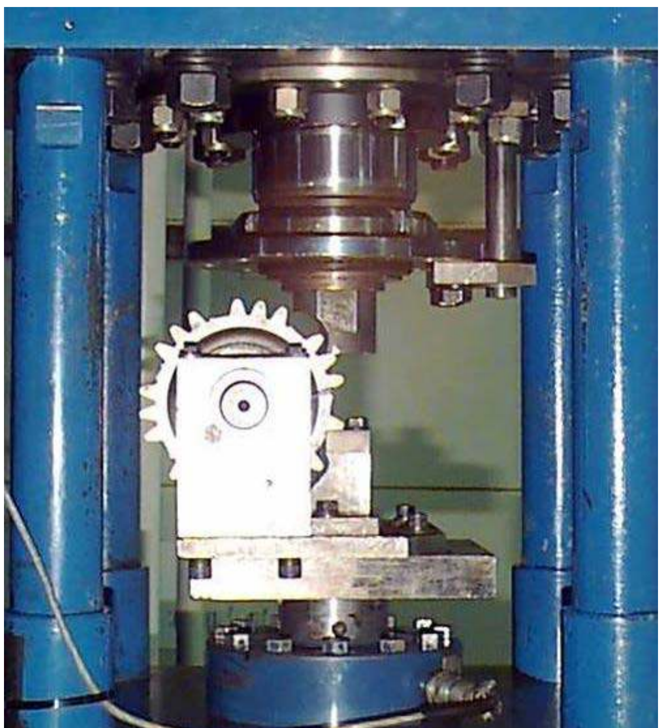
VEXTEC

Vehicle Gears EATON

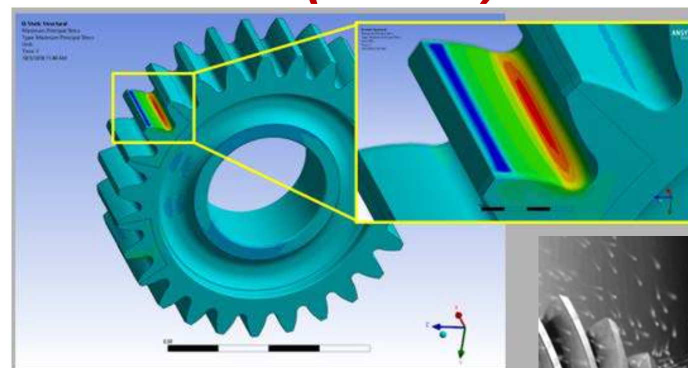
Extracted from work presented Aug. 2017 at
2017 ASME International Power Transmission and Gearing Conference

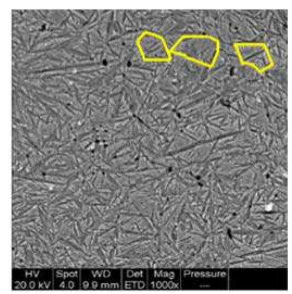
Virtual Gear Tooth Fatigue Testing for Trade Studies

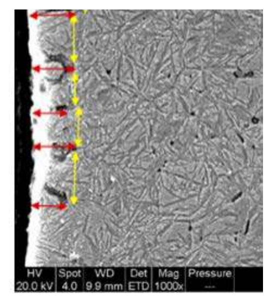
- **High time and cost commitment to comparatively evaluate gear materials / processing**



VPS-MICRO Design & Material (ICME) Modeling







- **Stresses from FEA and processing are incorporated**
- **Integrated Computational Materials Engineering (ICME) accounts for microstructural features & variability**

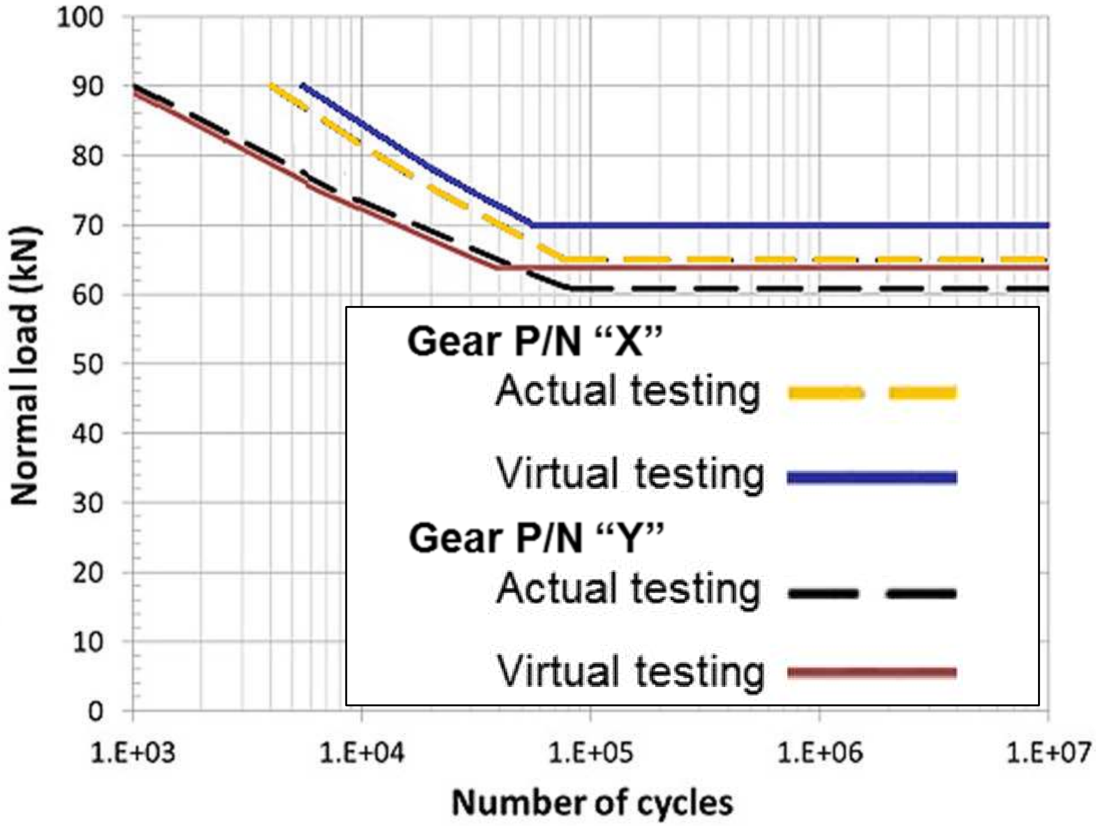
VEXTEC

Vehicle Gears

EATON

Extracted from work presented Aug. 2017 at
2017 ASME International Power Transmission and Gearing Conference

VPS-MICRO Test Results Agree with Physical Testing



- **Virtual testing captures the gears' physics of failure**
- **Cost-effective trade studies with interdependent design / material / processing variables**
- **Limited material testing yields a high-fidelity ICME model**
- **Supplement / reduce future physical testing needs**
- **Assist decision-making in product life cycle risk & durability**

→ REDUCE TIME TO MARKET

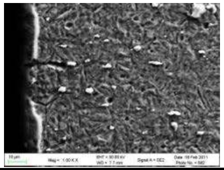
American Airlines 777 APU Bearing

Premature failure costing $4M/year

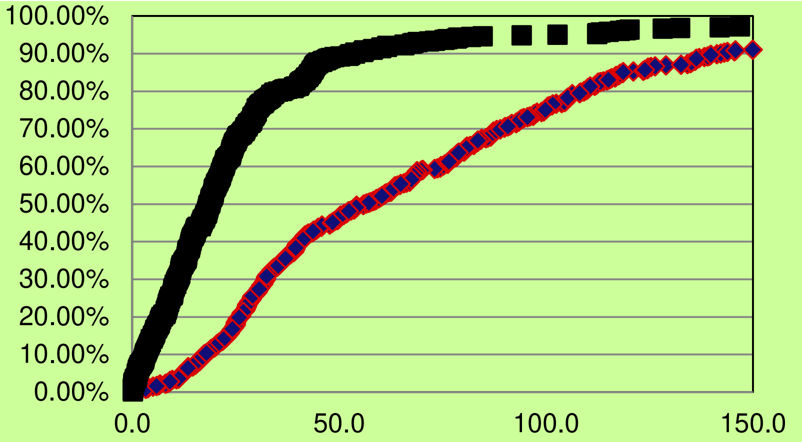
Possible causes were bearing material, bearing design, lubricant, or operating protocol

Airline provided broken parts, historical data, and general operating conditions

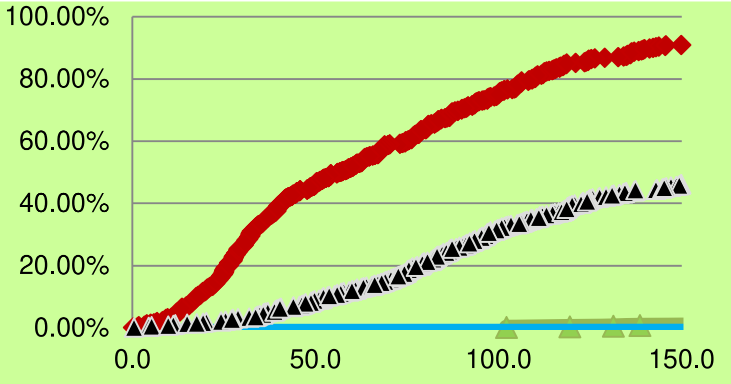




Material & Design Sensitivity



Lubrication & Operating Virtual DOE

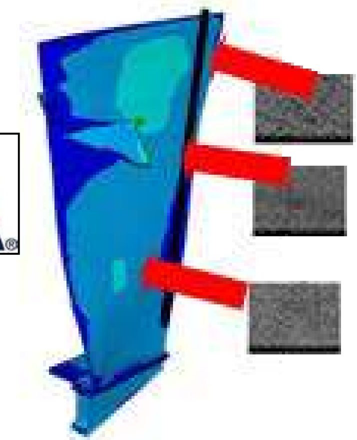


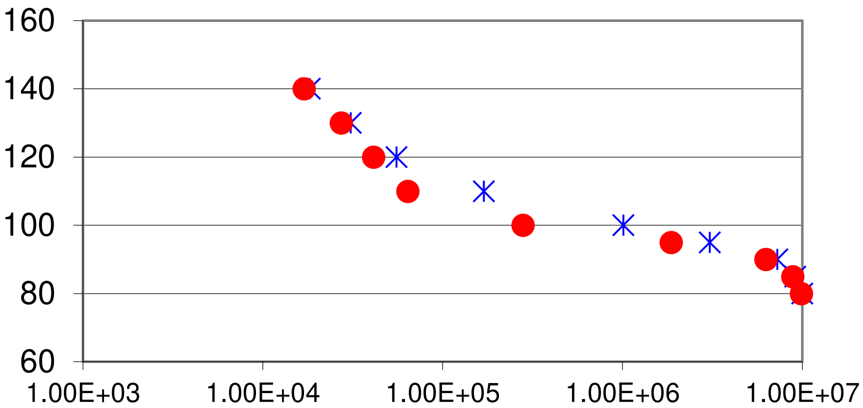
Conclusions & Results

- Material & design meet application need
- Change in Lubricant & Operating Protocol would resolve problem
- FAA approved change to Operating Protocol
- AA made VLM prescribed changes to 777 Fleet
- No failures since; 7+yrs & $4M annual savings

New / Refurbished Component Certification

- EB Airfoils' Challenge
  - Qualify a Fan Blade LE repair for minimal cost and time?
- VEXTEC's Solution
  - Modeled repaired blade including fusion zone material variation for a specific mission
  - Determined repair blade life would meet operational requirement without changes to inspection/maintenance schedules





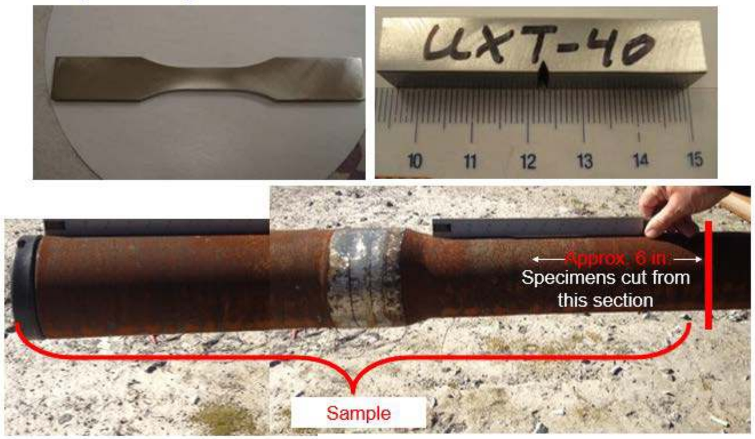
Oil & Gas Pipe – Material Second Sourcing

Benefits of Material Second Sourcing

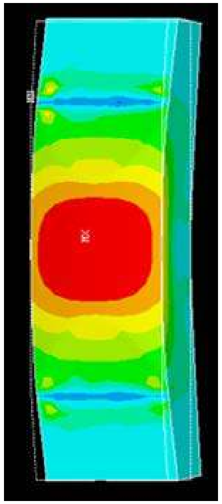
- **Oil & Gas drilling eqpt renter is buying over 1 M feet at premium grade pipe at 12 – 14% higher cost over standard grade pipe for a drill pipe application.**
- **VEXTEC performed**
  - **Laboratory investigation for material strength of two materials for monotonic and cyclic loading**
  - **VPS-MICRO simulations to assess the relative durability differences are between the two pipes**
- **Finding – Strength in monotonic and cyclic loading as well as pipe durability was a within 3 – 4% for the two materials**
- **Outcome resulted in >$10M in savings per year for the Equipment provider**

Piping Configuration

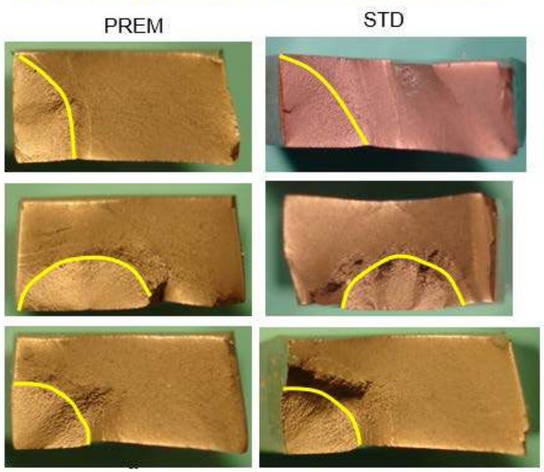
Pipe Samples and Test Articles



Pipe Stress and Fracture Surfaces

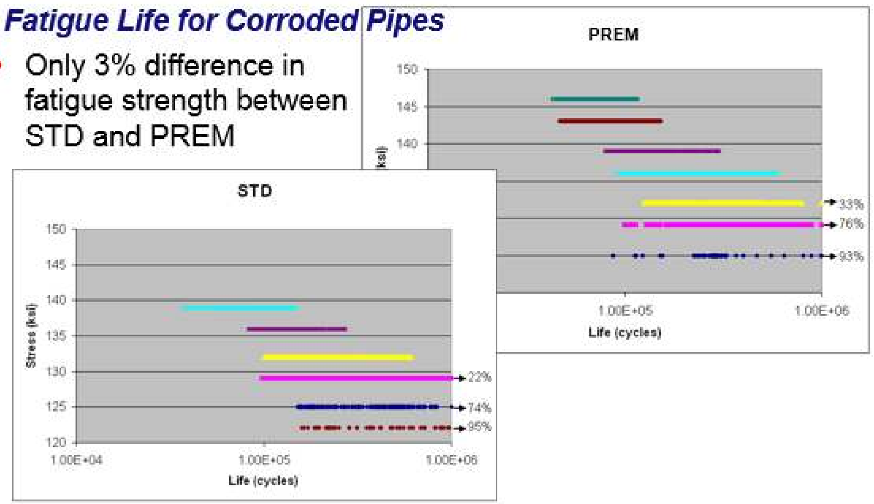


Critical Crack Size for PREM vs. STD



Premium Pipe vs. Standard Pipe

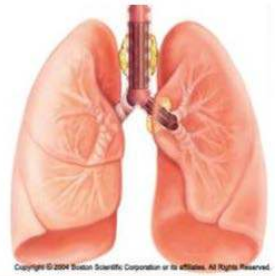
Fatigue Life for Corroded Pipes

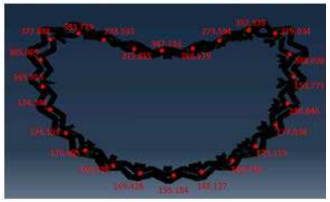


Medical Device – Material Second Sourcing

Alternate Materials for Stent

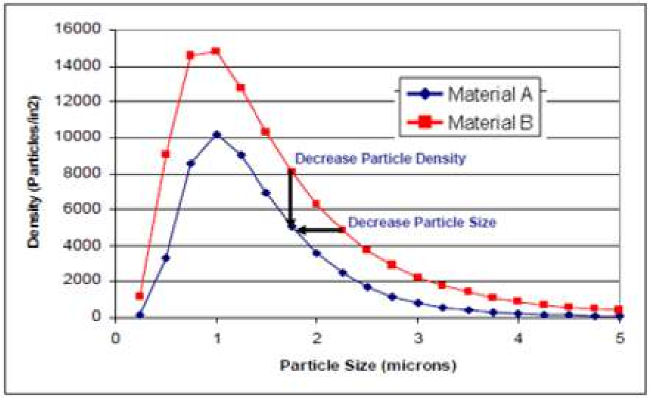
- **Boston Scientific Endoscopy evaluated effect metal cleanliness on the fatigue life of airway stents.**
- **Fatigue life evaluated by running a stent for a fatigue cycles to failure at a displacement to simulate coughing.**
- **The test is intended to provide insight into product design and material performance.**
- **Two materials with different inclusion sizes and population densities were evaluated using VLM.**





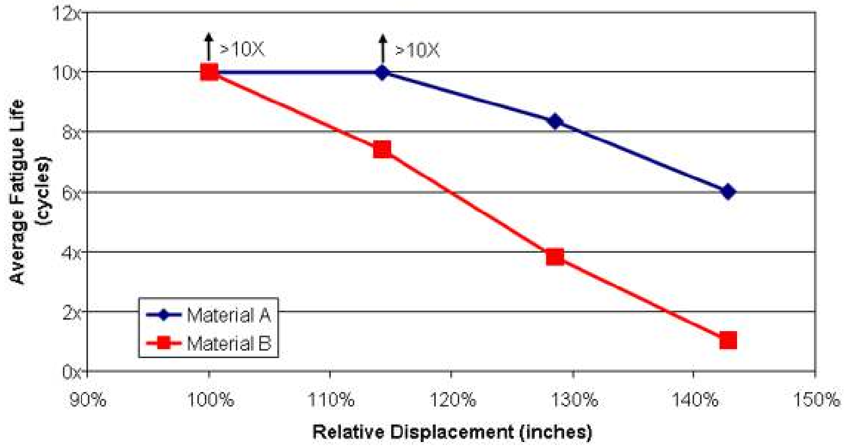
Particle Density for Material B higher than for A

Stent Durability is Improved by Changing Particle Size and Particle Density



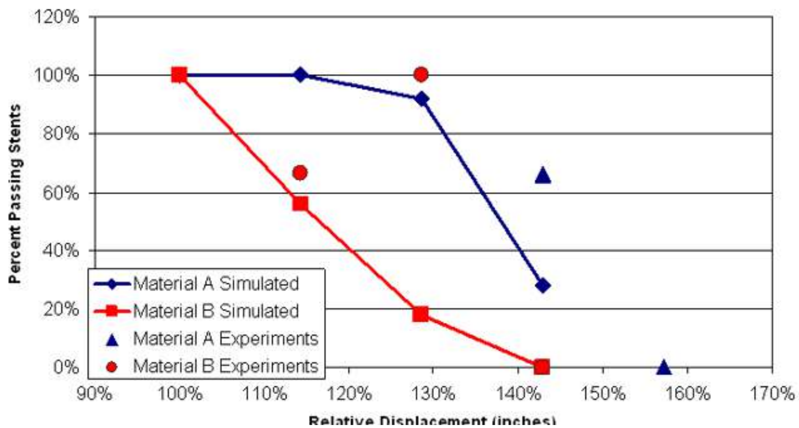
Material A vs. Material B

Simulated Mean Cycles to Stent Failure



Material A vs. Material B

Probability of Stent Survival



Conclusions

- A method and software that allows depot engineers to assess the acceptability of replacing forged parts with parts machined from stock material.
- Method is general and can be used for
  - Castings
  - Additive Manufacturing
  - Welds
- Method will
  - Use of all available knowledge
  - Use physics-based models
  - Explicitly model uncertainty
  - Update the model when new knowledge is available.
- The depot engineer will have the valuable addition of “simulated data” from an exhaustive “simulated” test program to help make informed decisions on the acceptability of replacement parts.

VEXTEC

Thank You

Visit us in Booth 151 for a Software Demonstration