



***Virtual Testing to Supplement  
Rapid Certification of  
Reverse Engineered Parts***

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# *Acknowledgements*

Dean Hutchins of DLA

Eric Tuegel of AFRL

## *Issues*

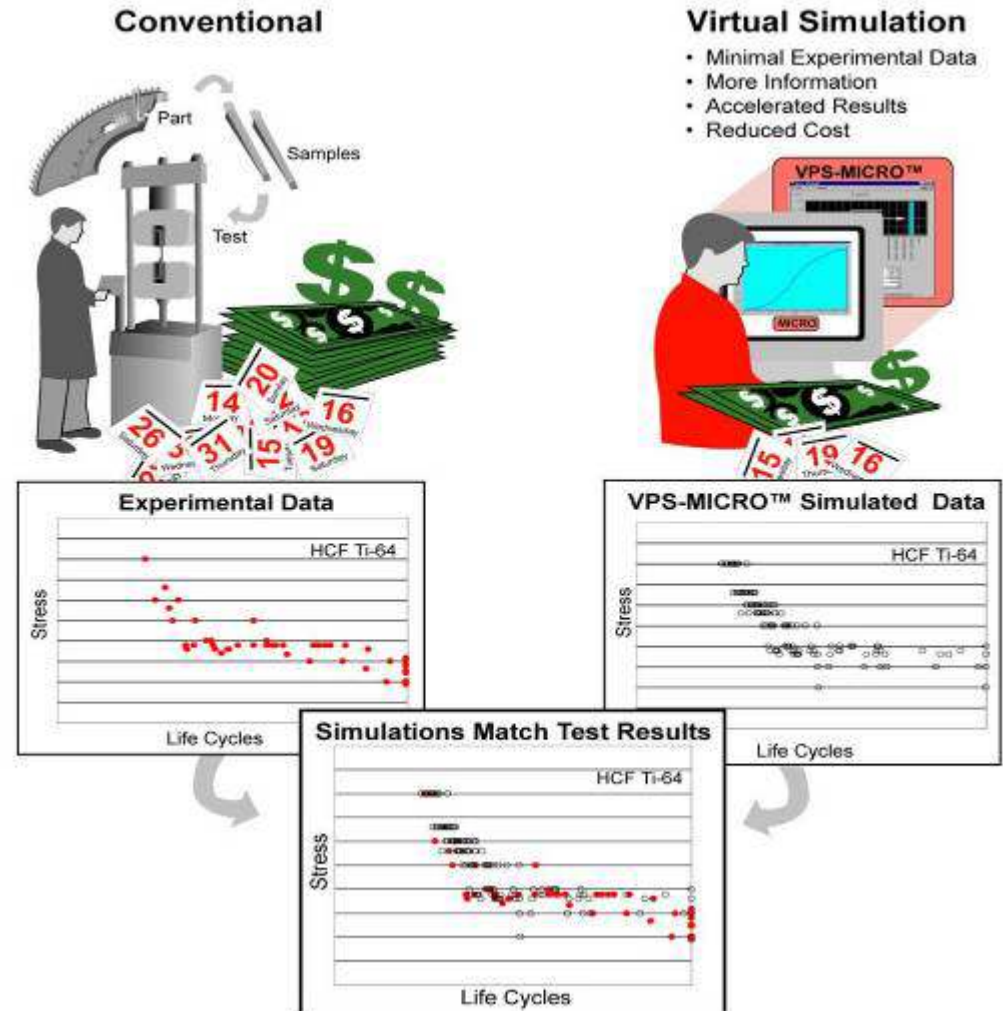
- A major issue confronting the DoD is obtaining structural components which are difficult to find or stock and have exorbitant cost or lead times
  - OEMs and vendors may have stopped production or are out of business or are unwilling to produce limited quantities
  - Any replacement part must be certified 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

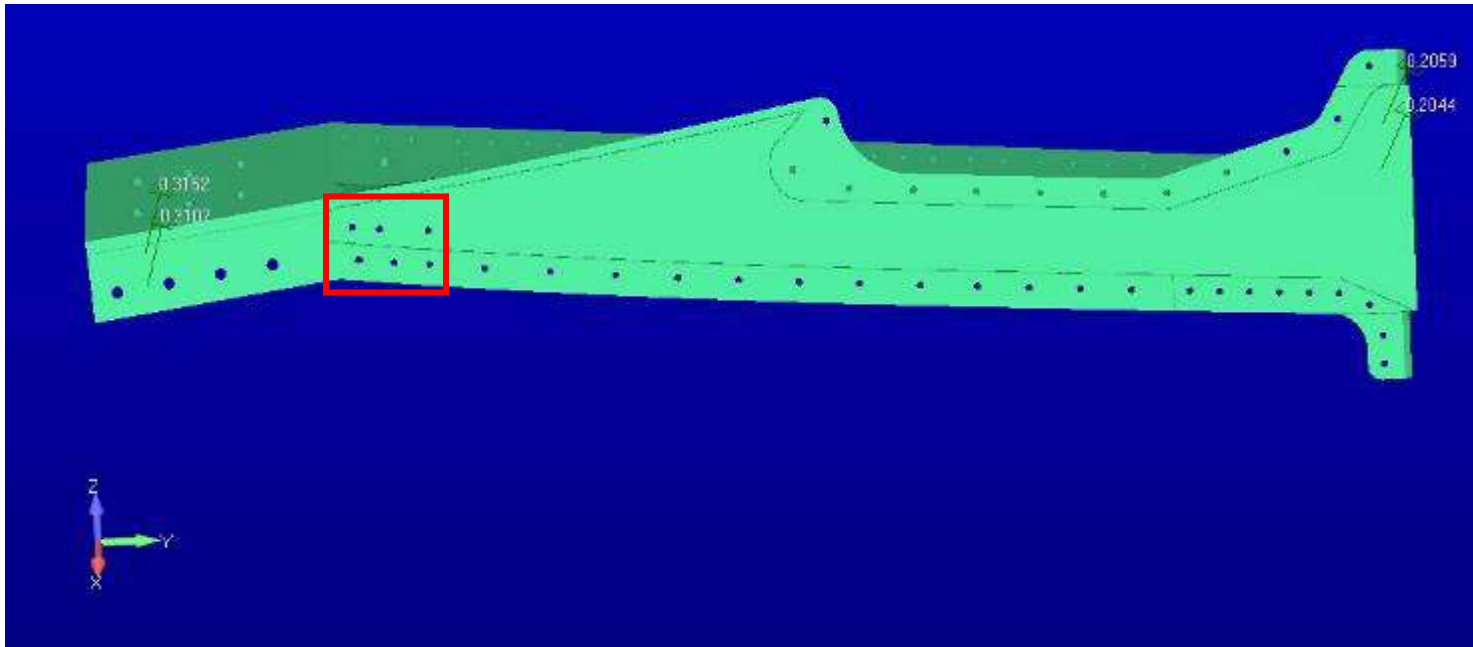
- Use Structural FEA with calibrated material models to simulate the testing of:
  - Many original parts
  - Many replacement parts
- Compare the simulated test result to assess the viability of the replacement part



## Virtual Simulation

- Minimal Experimental Data
- More Information
- Accelerated Results
- Reduced Cost

## Forged Component Geometry

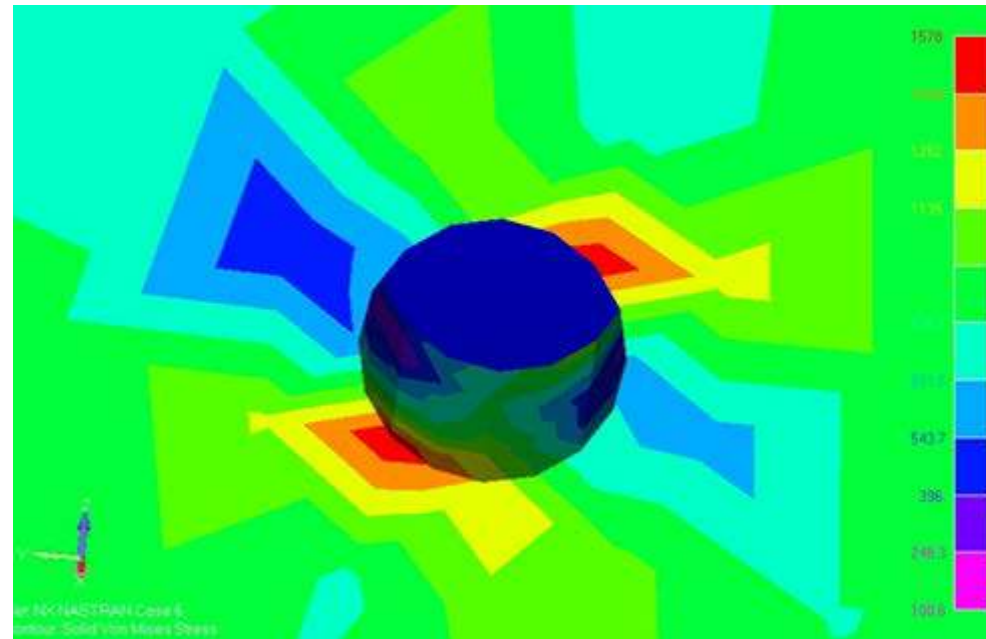


- CAD model of example part showing location of holes that crack and require the part to be replaced.

# Structural Analysis

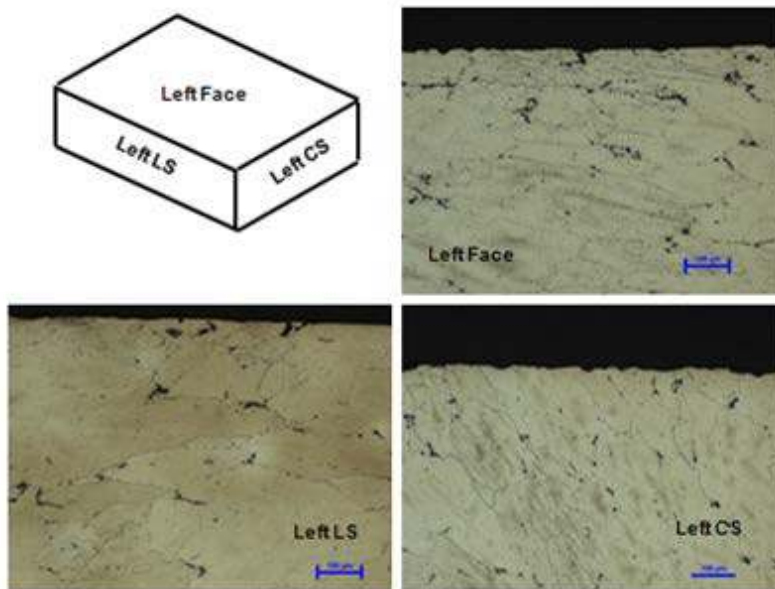
- Relative Stress
  - Close examination of local stress distribution show that most of the stress is bending with a small amount to axial and torsion.
  - For all maneuvers, most of the load is bending
  - Relative stress can be scaled to approximate in-service loads.
- Relative durability
  - Assessed 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)

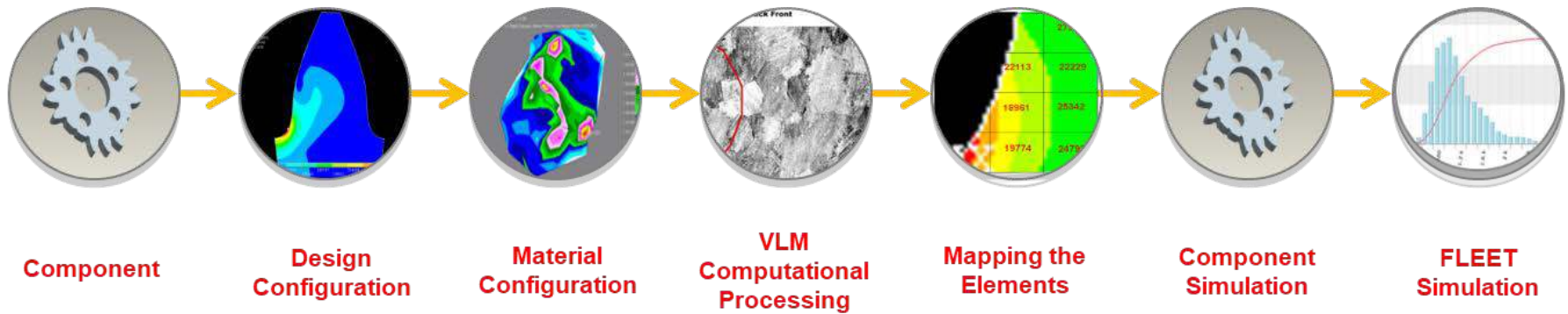
## Stock Plate



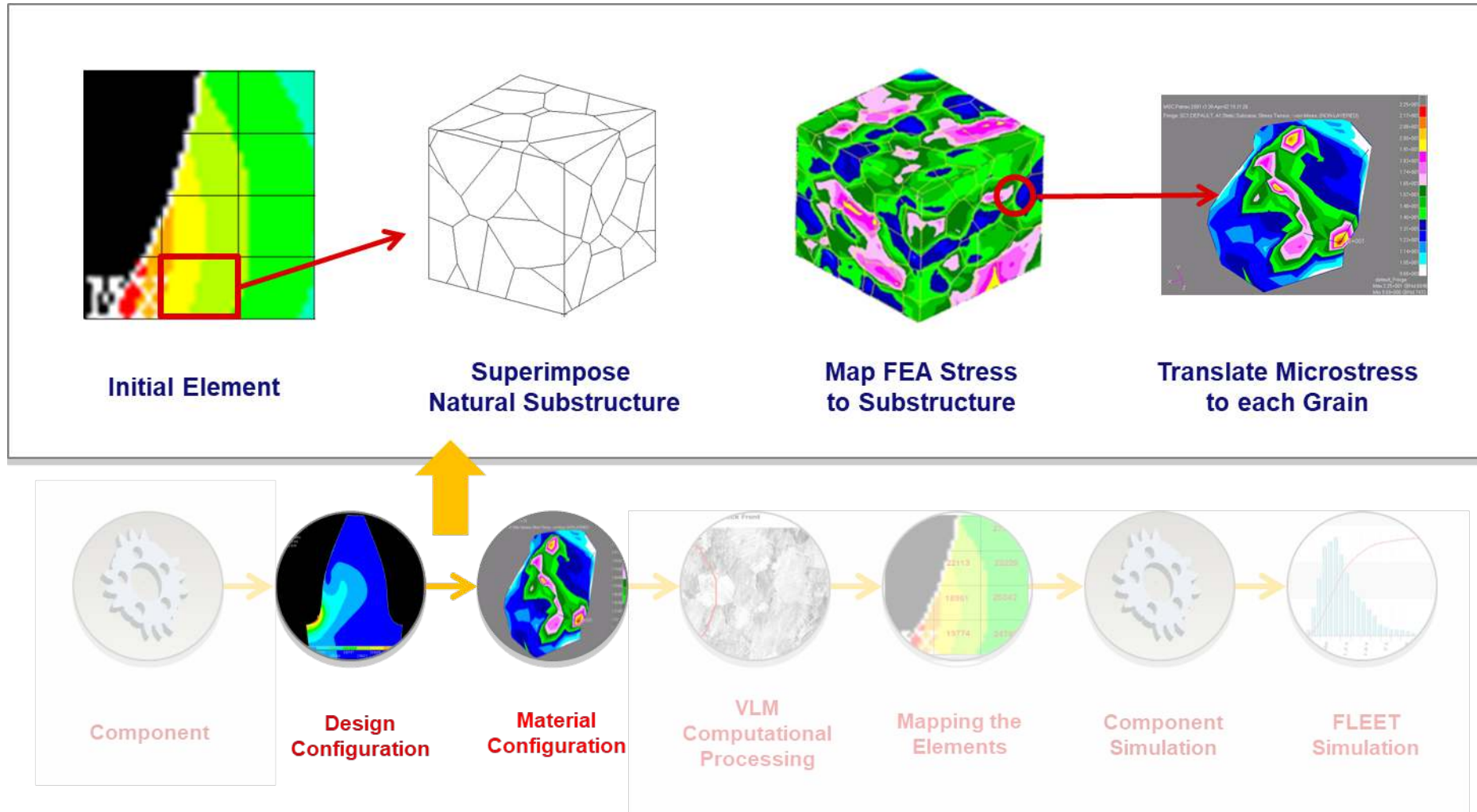
- Grain size = .003 in (COV = 0.33)
- Particle size = .000176 in (COV = 0.58)
- Particle population density = 522,760/sq in (COV = 0.3)



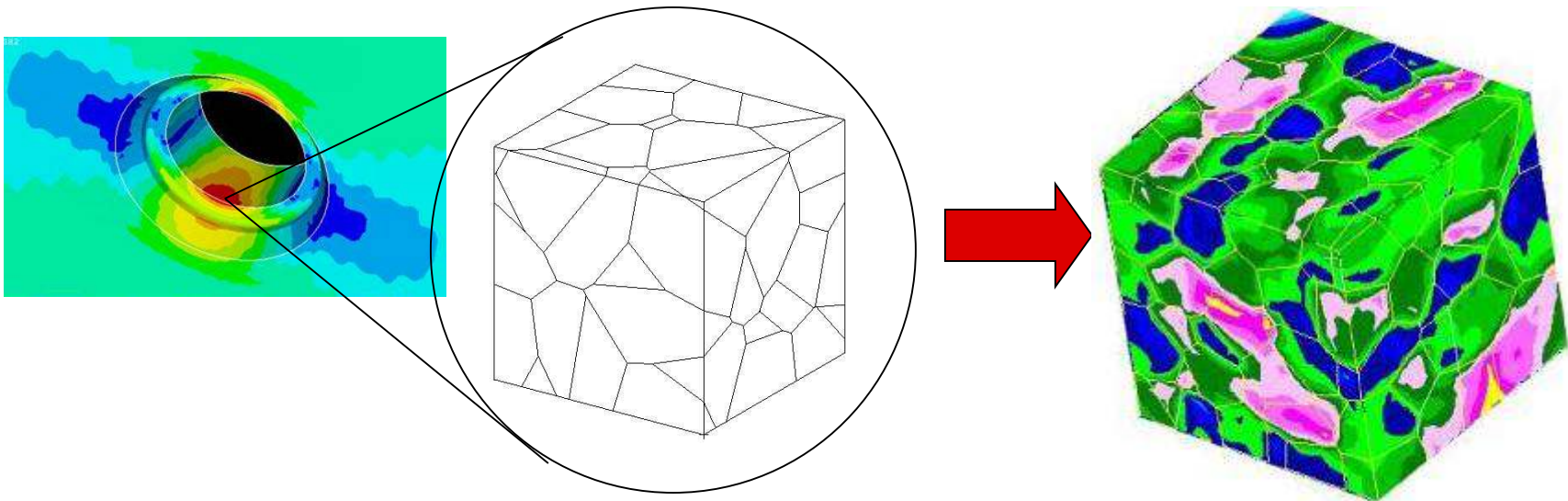
# Computational Process Flow



# Material Configuration

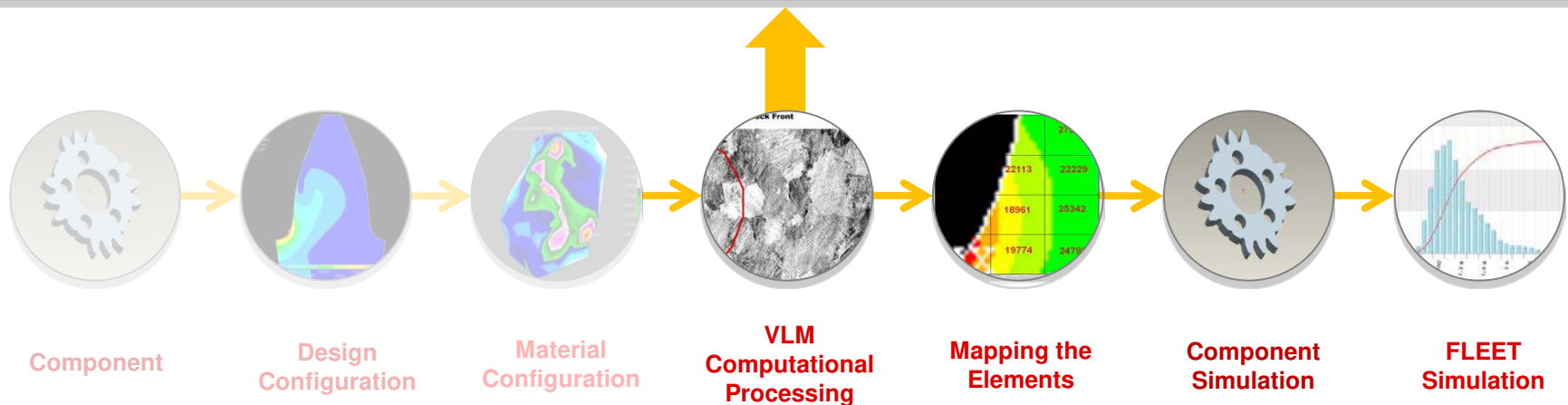
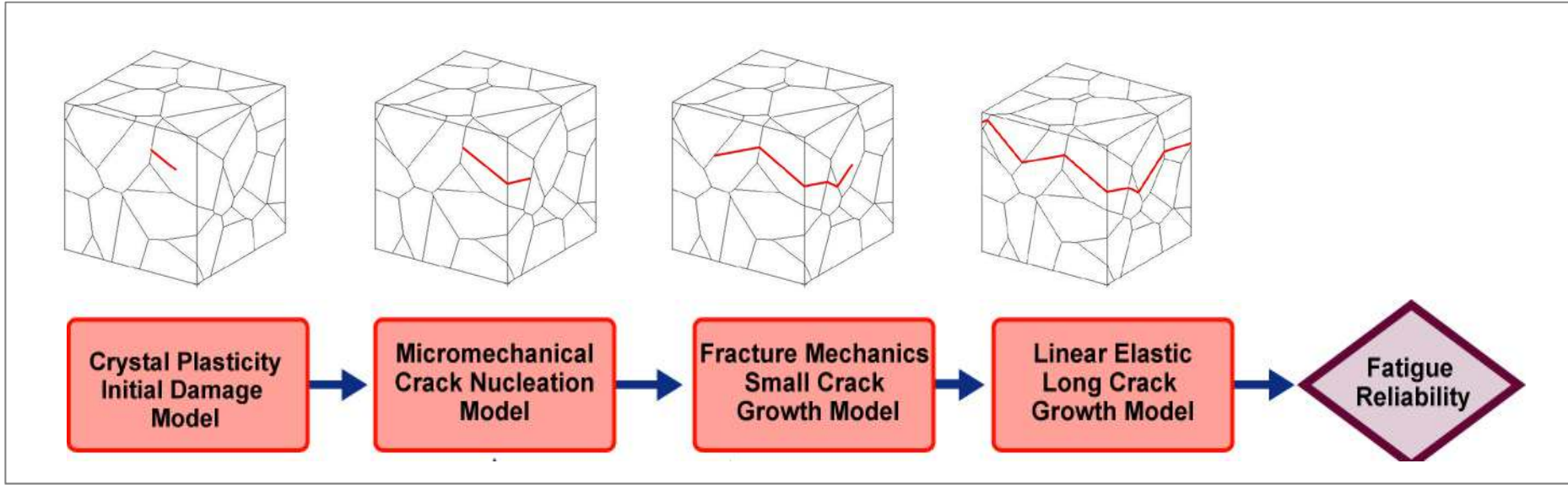


# *Computational Stress Model*



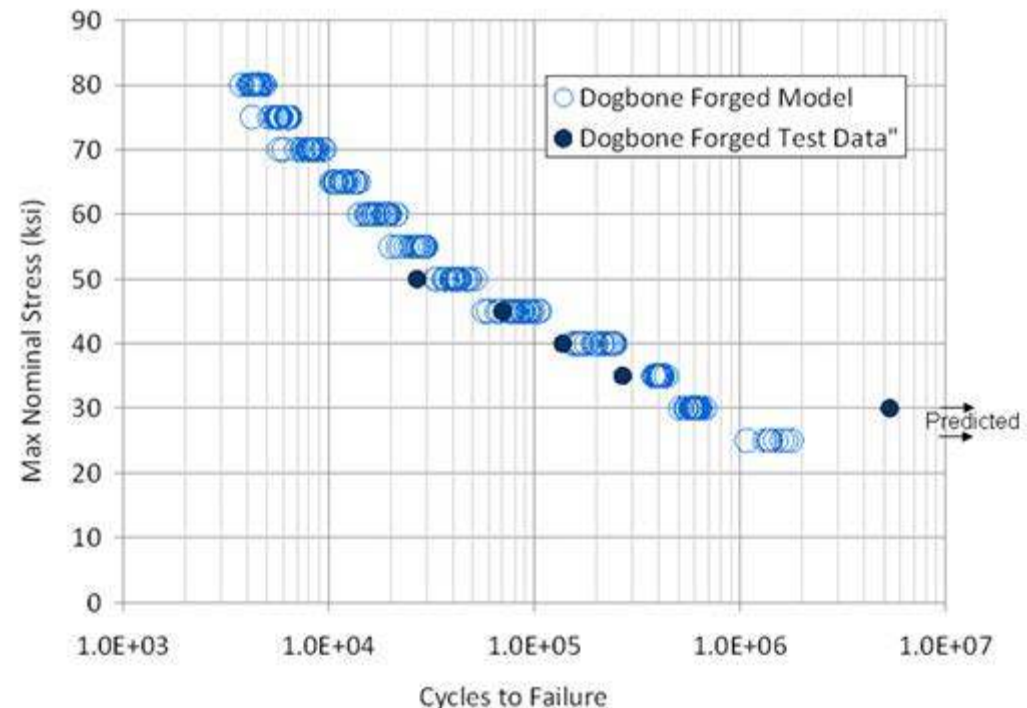
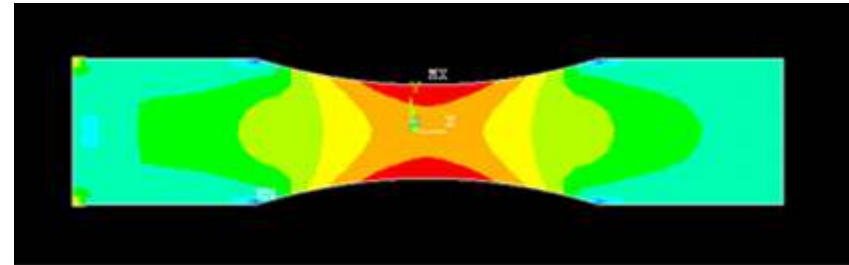
- Perform global FEA
- Create microstructure geometry model (SVE)
- Perform microstructural FEA on SVE

# Computational Damage Model



# Original Forged Material Model Calibration

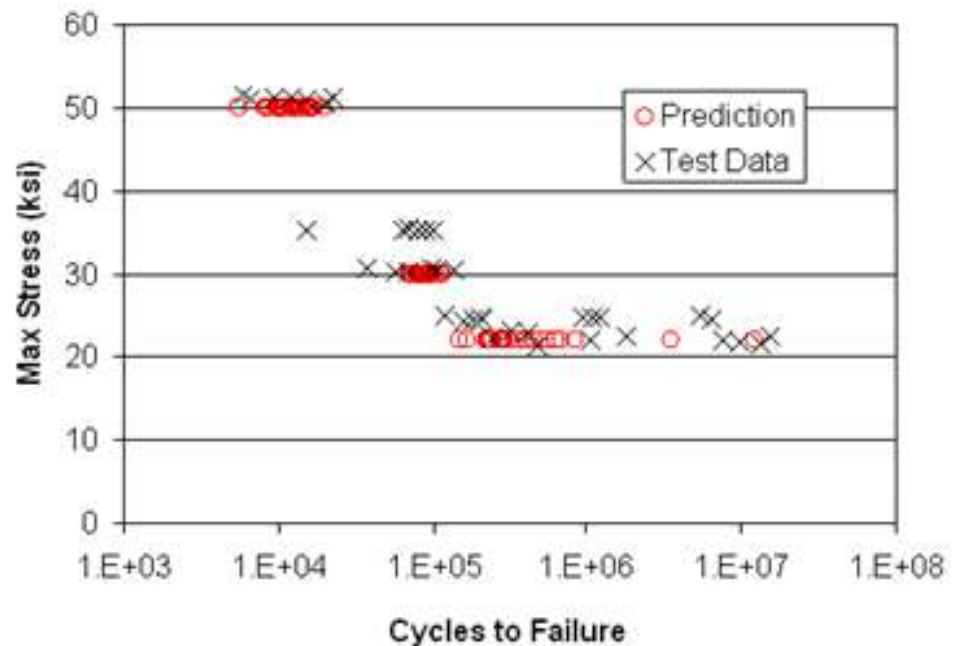
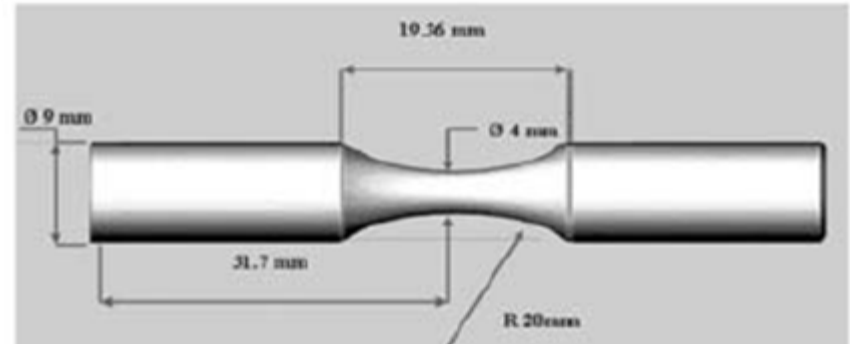
- Material characterization from previous Air Force and Navy programs
  - Laboratory fatigue tests data on flat plate dog bone specimens (solid circle symbols)
  - Predicted fatigue tests data on flat plate dog bone specimens. 50 specimens simulated for each stress level (open circle symbols)



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

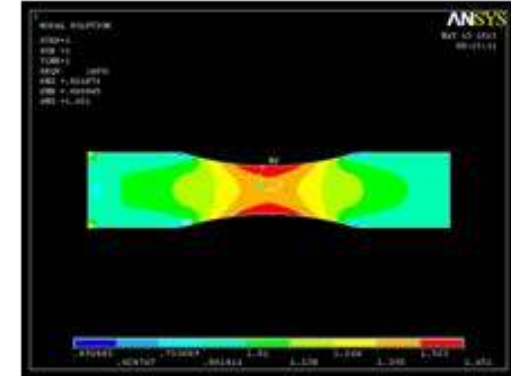
- Comparison of material parameter from calibrated models indicate difference in:
  - Grain size (measured)
  - Particle sized and density (measured)
  - CTOD short crack parameter (calibrated)
  - Grain boundary strength (SIF) calibrated

INPUT PARAMETER	Original AA 7075-T 7351 Forged	Replacement AA 7075-T 7351 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

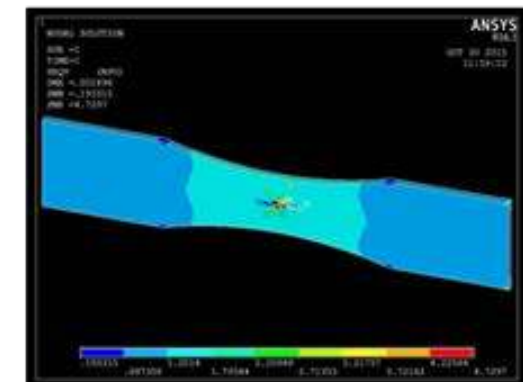
# Durability Simulation Analysis

- 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

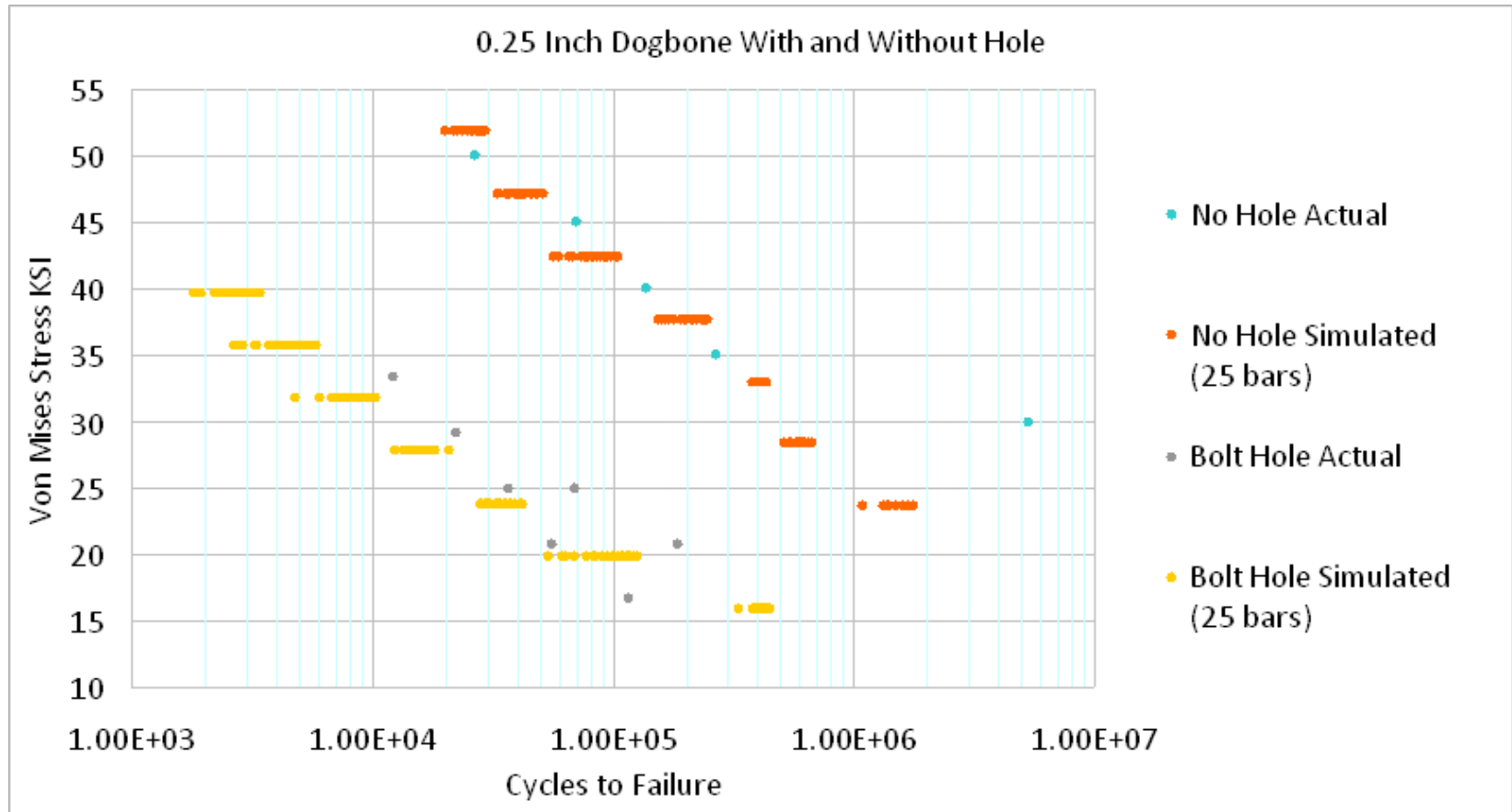


Bolt Hole





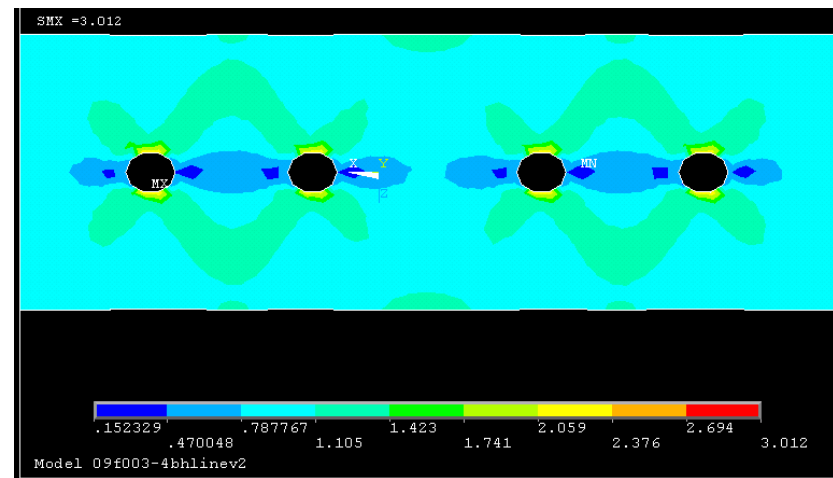
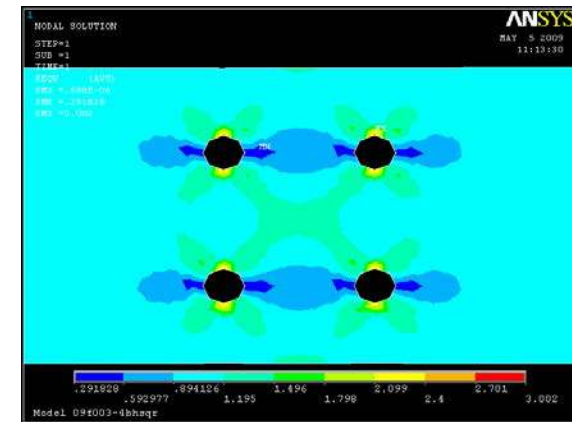
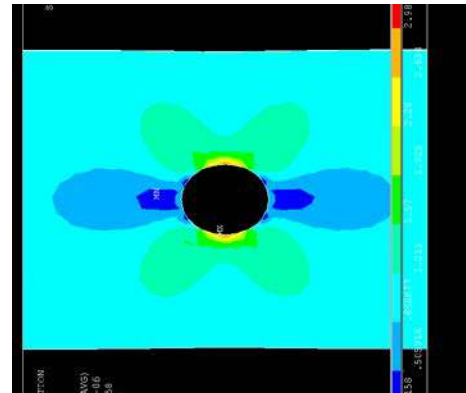
# Simulated Results Compare to Test Data



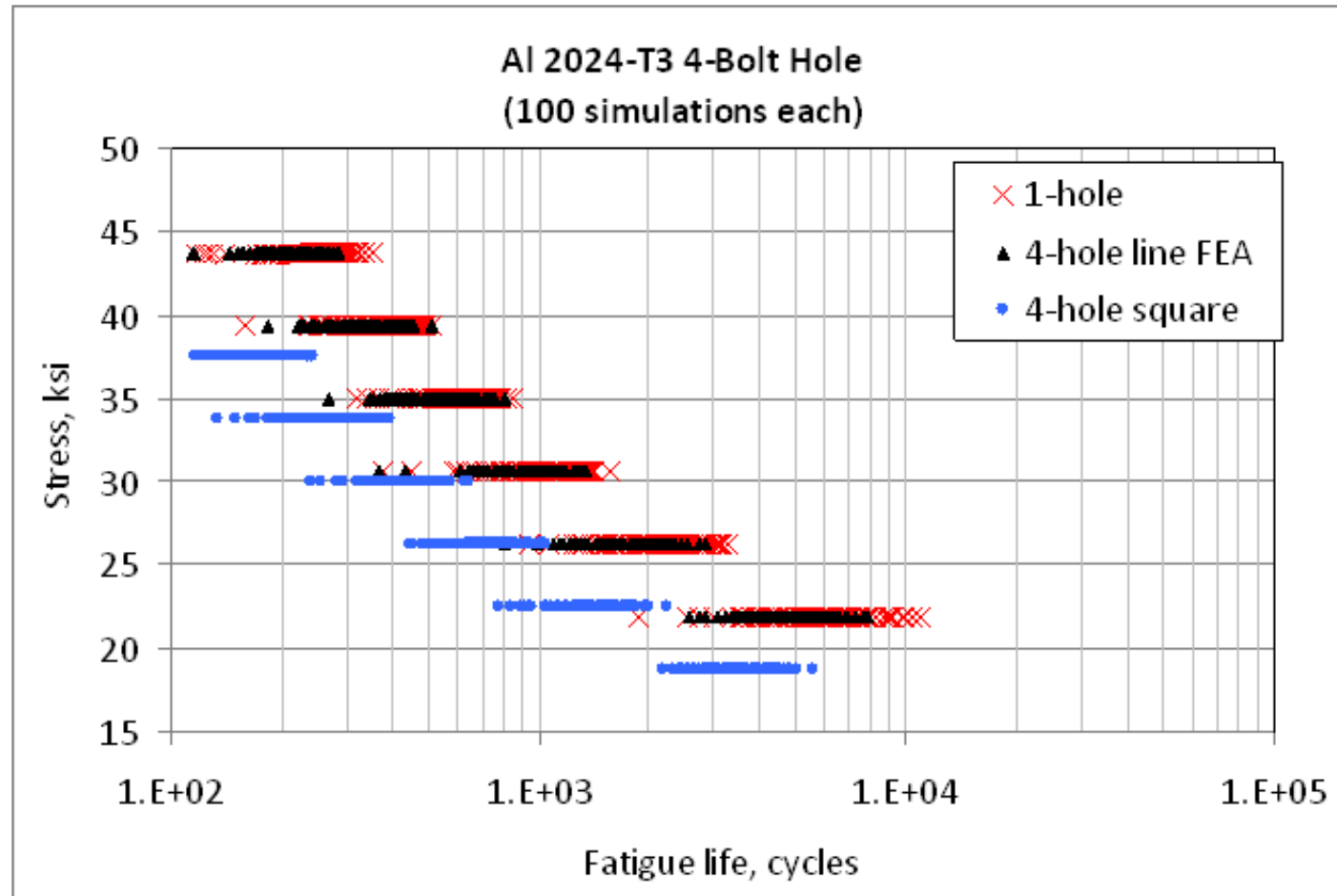
**Results shows excellent comparison of simulation with actual data**

# 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.



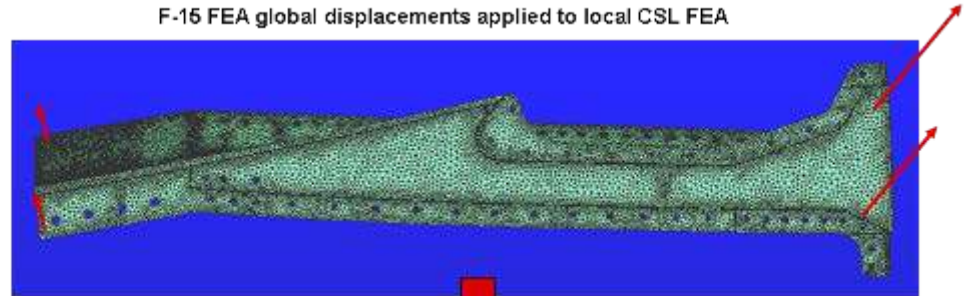
# Simulated Durability



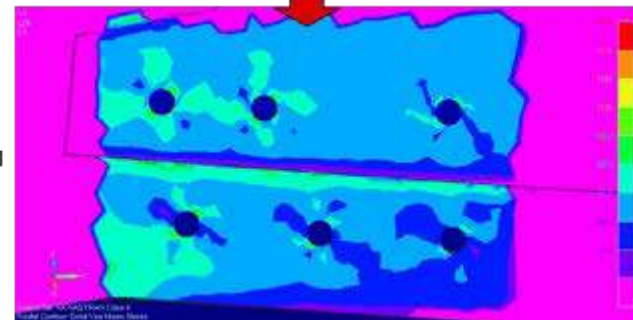
# Simulate In-Service Loads Levels

- 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

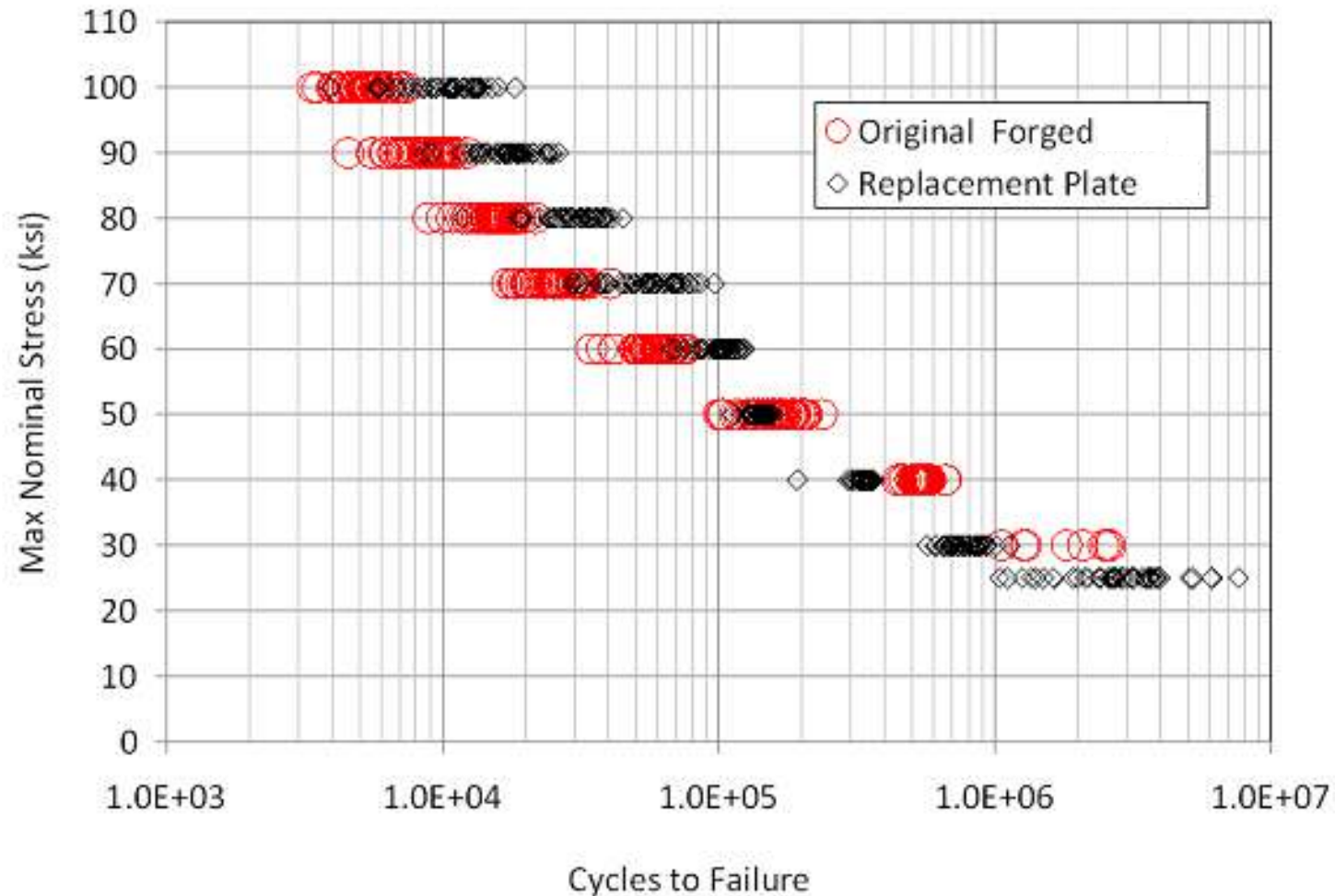
F-16 FEA global displacements applied to local CSL FEA



CSL FEA Solved for local stresses



# Simulated S-N Curve for Original and Replacement Part



# Importing FEA Files

The screenshot displays the VEXTEC VPS-MICRO software interface. The main window is titled "Model Type" and contains the following elements:

- Material Explorer (CR-Bimodal-Ti-...):** A tree view on the left showing material categories: MP35N, STEEL, and TITANIUM. Under TITANIUM, there is a sub-category "Ti-6Al-4V" with several options, including "CR-Bimodal-Ti-64" which is highlighted.
- Model Type:** A central area with the text "Select between simple component with uniform stress or a complex finite element model." Below this, there are two radio buttons: "Simple Model" (unselected) and "FEA Model" (selected).
- Area Factor:** A text input field containing the value "1".
- Selected FEV File:** An empty text input field next to a "Select FEV File" button.

An "Open" file dialog is overlaid on the software interface, showing the following table of files:

Name	Date modified	Type
90kN_MPA_M.fev	10/24/2018 2:41 PM	FEV File
90kN_MPA_M_2.fev	10/24/2018 2:41 PM	FEV File
dummy.fev	10/24/2018 2:47 PM	FEV File
ErrorT651.fev	10/24/2018 2:47 PM	FEV File

The "File name" field in the dialog contains "90kN\_MPA\_M.fev" and the file type filter is set to "FEV files (\*.fev)".

**VEXTEC S/W allows FEA files to be imported**

# Material Selection

Material Selection

Select a material within the VPS-MICRO® material database or create a new material.

Unit System: English

**Properties**

**Global Properties**

Selected Material	CR-Bimodal-Ti-6-4
Shear Modulus(ksi)	5970
Poissons Ratio	0.34

**Local Properties**

Grain Boundry Strength(ksi/in)	1.65
COV on Micro Stress	0.15

**Select the appropriate material in the library and click "Add"**

Next

Model Type: SSA Current Material: CR-Bimodal-Ti-6-4

# Number of Simulations

The screenshot shows the VEXTEC VPS-MICRO software interface. The window title is "VEXTEC VPS-MICRO® - MyInputFile2". The menu bar includes "File", "Materials", "Options", "Analysis", and "Help".

The interface is divided into several panes:

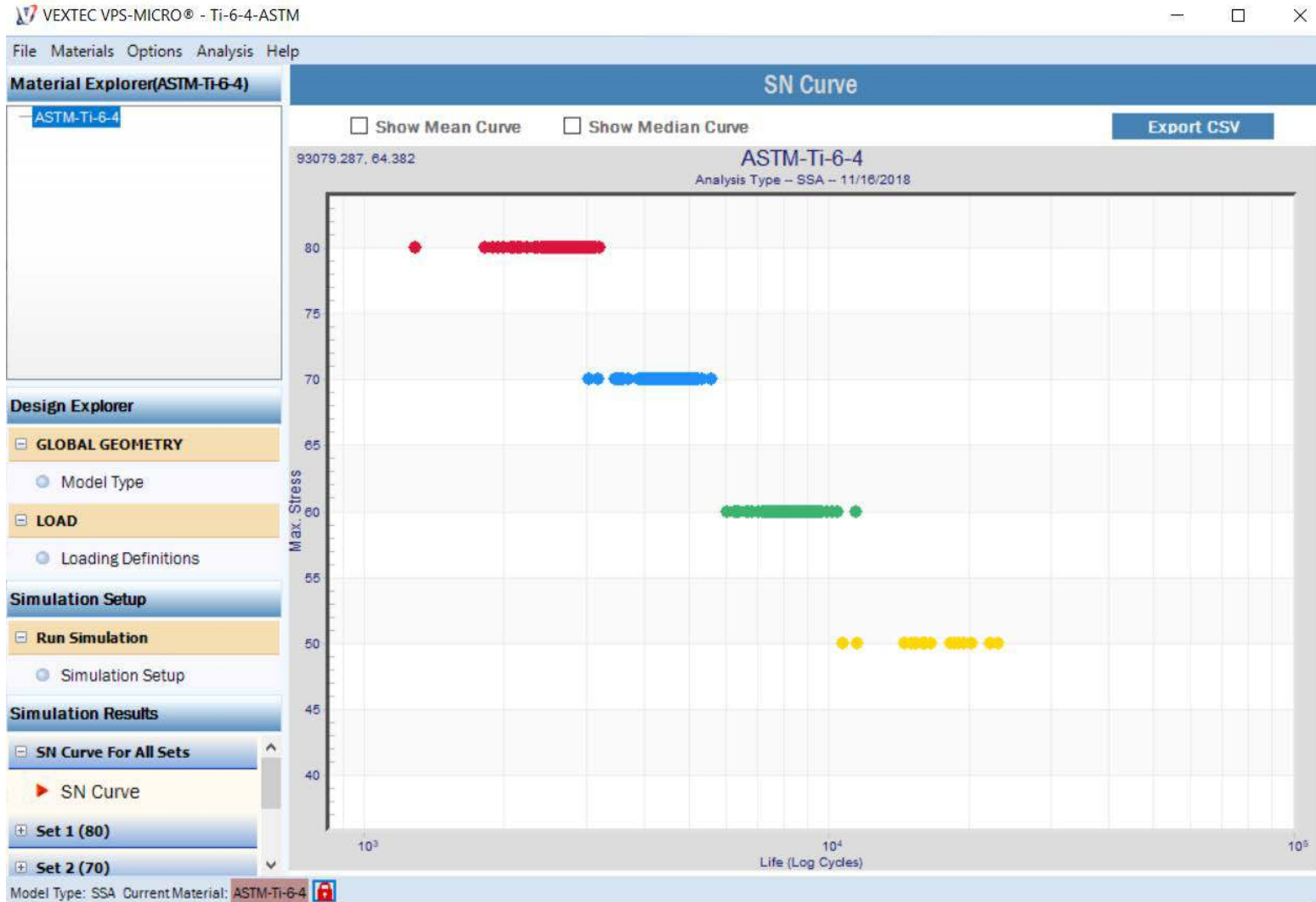
- Material Explorer (CR-Bimodal-Ti-...)**: A tree view showing material categories:
  - MP35N
  - STEEL
  - TITANIUM
    - Ti-6Al-4V (expanded)
      - CR-Bimodal-Ti-6-4 (selected)
      - CR-Equiaxed-Ti-6-4
      - Fine-Bimodal-Ti-6-4
      - Forged-Bimodal-Ti-6-4
      - Forged-Equiaxed-Ti-6-4
      - HCFTI-6-4
    - Ti-Al

- Design Explorer**: Contains "GLOBAL GEOMETRY" and "LOAD" sections. Under "LOAD", there is a "Loading Definitions" option.
- Simulation Setup**: The active pane, titled "Simulation Setup". It contains the text: "Having built the model, run or restart the desired number of simulations." Below this text is a "New Simulation Run" dialog box.
- New Simulation Run**: A dialog box with a text input field labeled "Number of Simulations per Set" containing the value "100". Below the input field is a "Run Simulations" button.
- Simulation Results**: A section at the bottom of the left pane.

At the bottom of the window, a status bar displays: "Model Type: SSA Current Material: CR-Bimodal-Ti-6-4". A "Back" button is located in the bottom right corner of the main window area.



# Output - SN Curve for Part

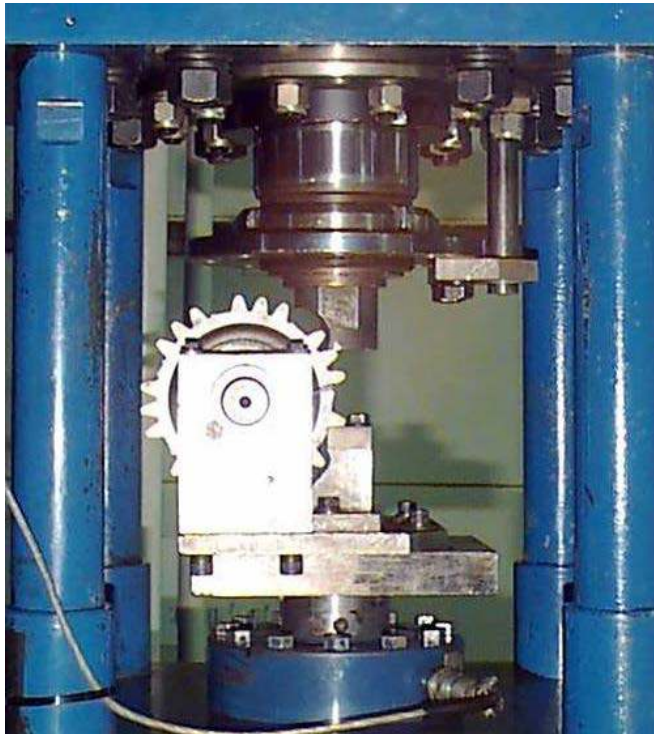


# Vehicle Gears

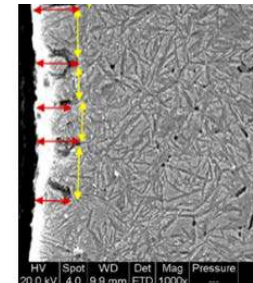
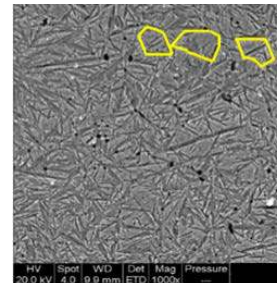
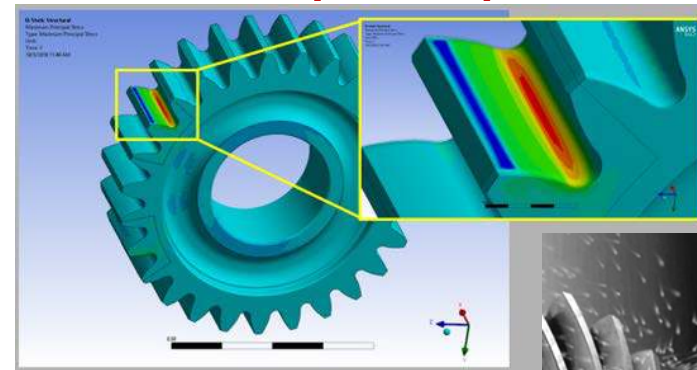
Extracted from work presented Aug. 2017 at  
2017 ASME International Power  
Transmission and Gearing Conference

## Virtual Gear Tooth Fatigue Testing for Trade Studies

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

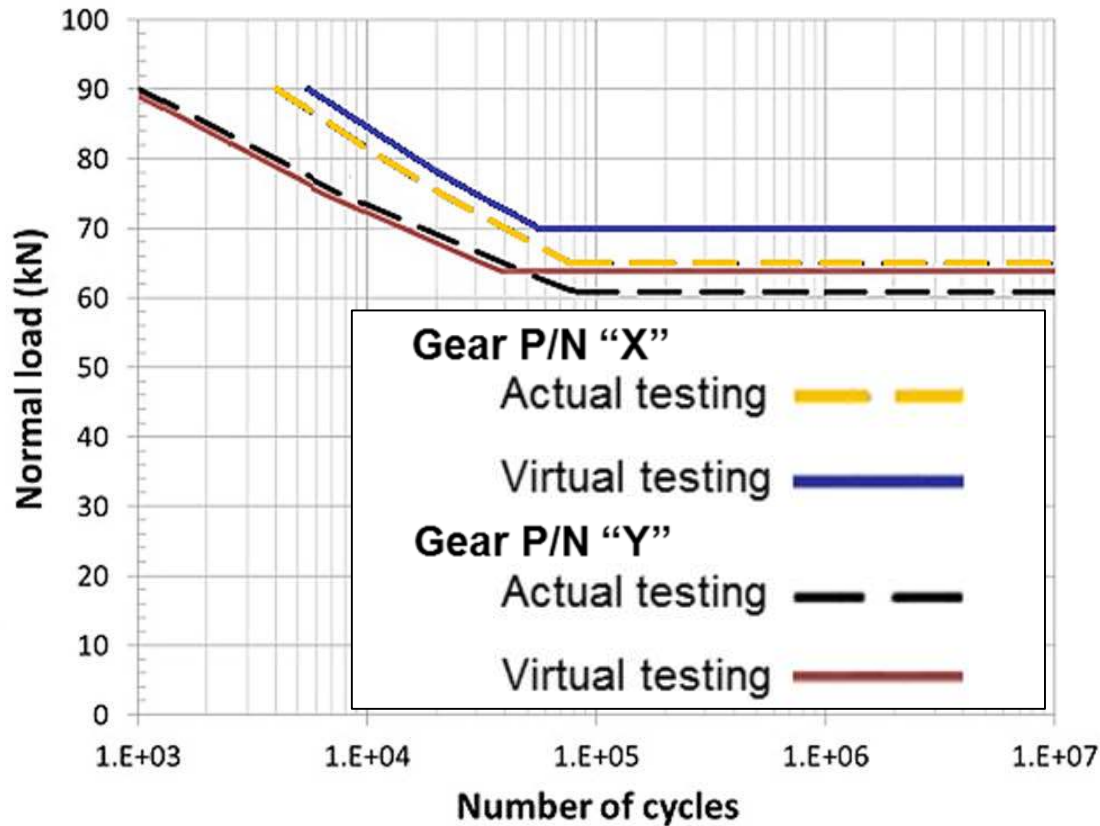


## VPS-MICRO Design & Material (ICME) Modeling



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

## 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

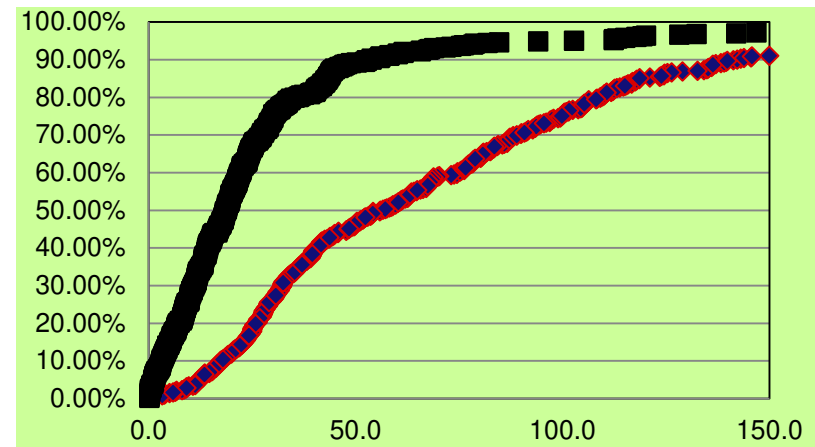
Premature failure costing \$4M/year

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

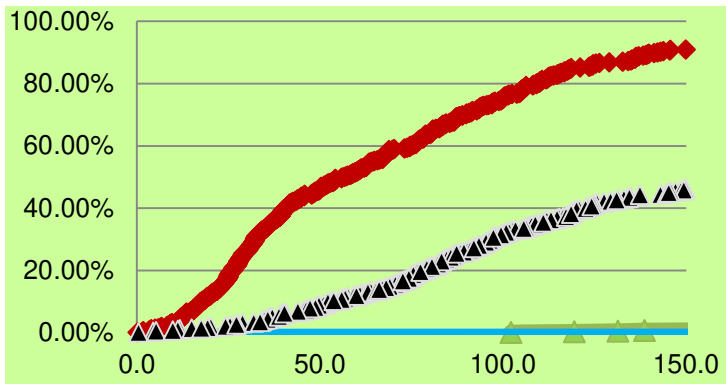
Airline provided broken parts, historical data, and general operating conditions



*Material & Design Sensitivity*



*Lubrication & Operating Virtual DOE*

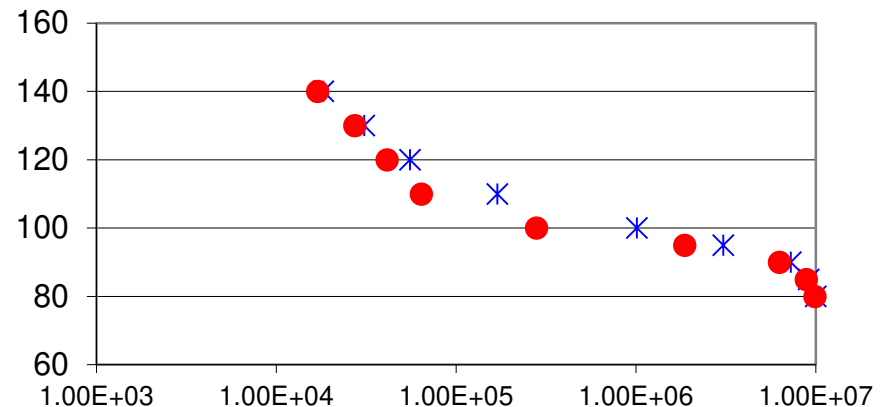


*Conclusions & Results*

- 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



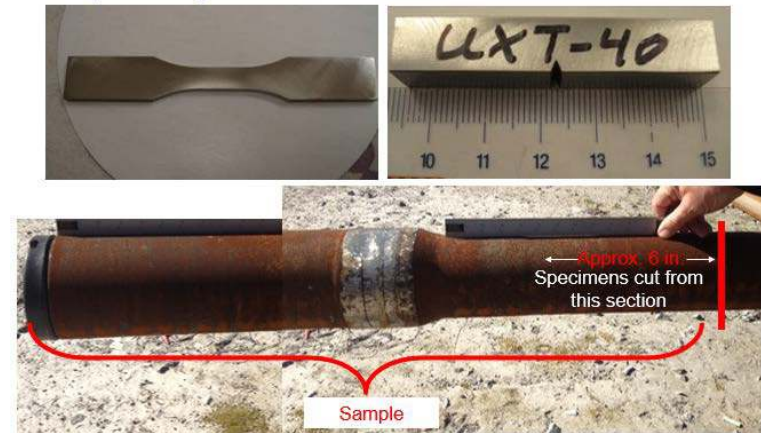
# Oil & Gas Pipe – Material Second Sourcing

## Benefits of Material Second Sourcing

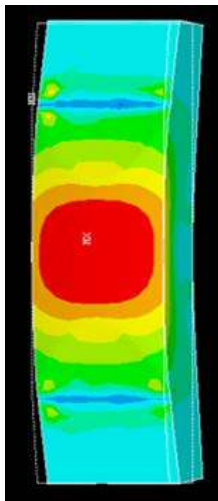
- Oil & Gas drilling eqpt renter is buying over 1 M feet at premium grade pipe at 12 – 14% higher cost over standard grade pipe for a drill pipe application.
- VEXTEC performed
  - Laboratory investigation for material strength of two materials for monotonic and cyclic loading
  - VPS-MICRO simulations 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

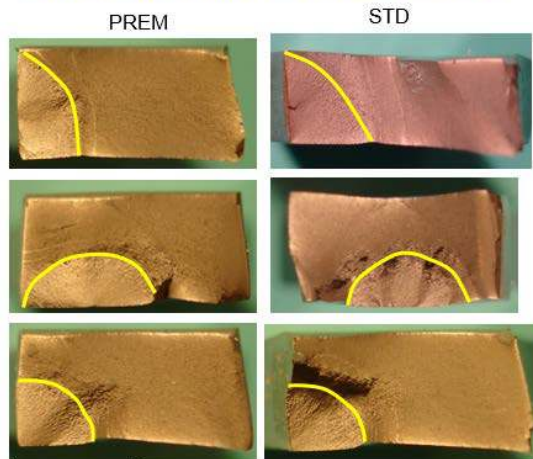
### Pipe Samples and Test Articles



## Pipe Stress and Fracture Surfaces



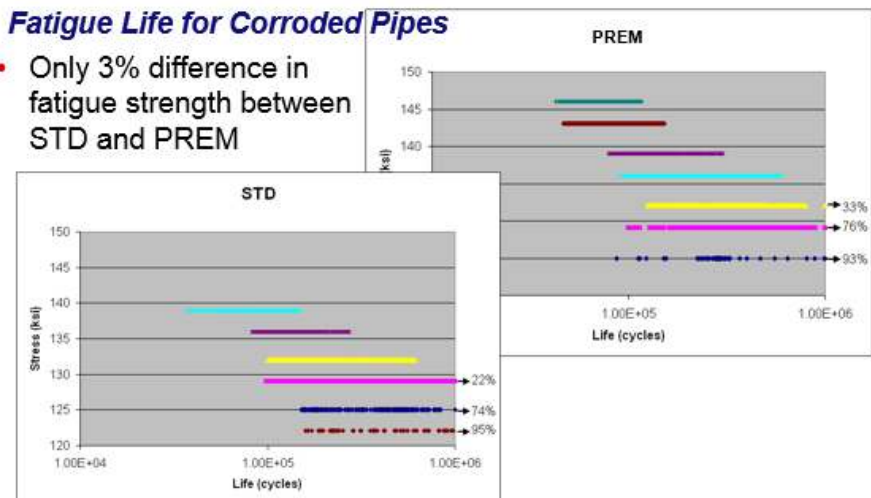
### Critical Crack Size for PREM vs. STD



## Premium Pipe vs. Standard Pipe

### Fatigue Life for Corroded Pipes

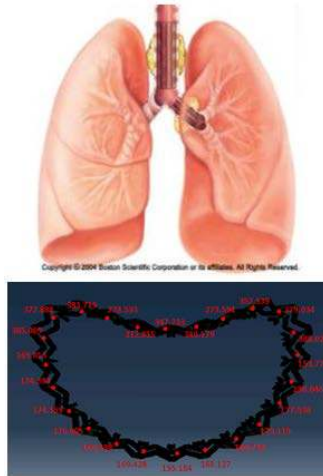
- Only 3% difference in fatigue strength between STD and PREM



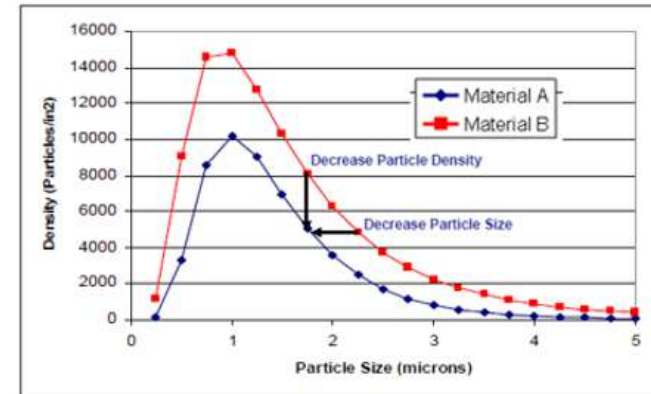
# Medical Device – Material Second Sourcing

## 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.

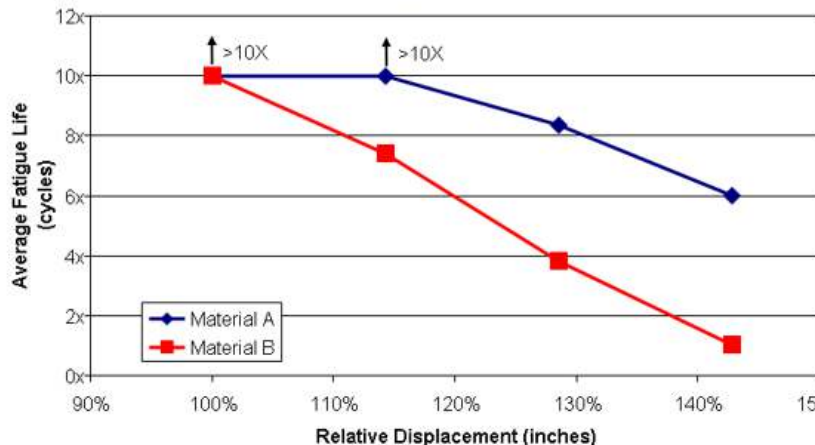


## Particle Density for Material B higher than for A Stent Durability is Improved by Changing Particle Size and Particle Density

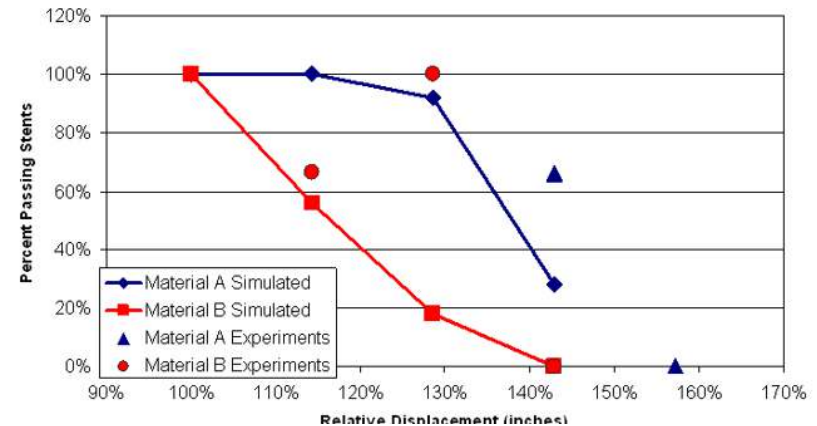


## Material A vs. Material B

### 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.





*Thank You*

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Demonstration***