VEXTEC

EATON

Gear Tooth Bending Fatigue Life Prediction Using Integrated Computational Material Engineering (ICME)

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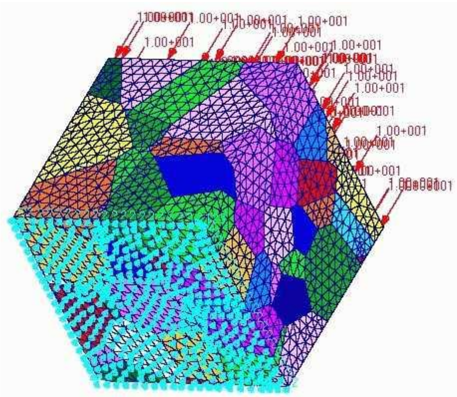
ASME
SETTING THE STANDARD

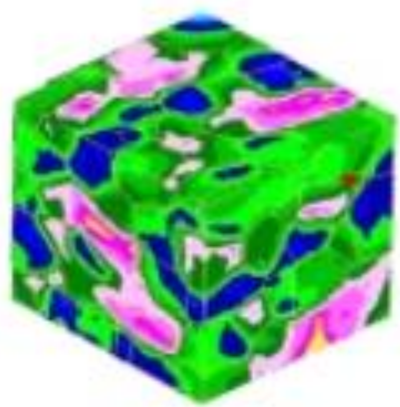
Outline

1. Integrated Computational Materials Engineering (ICME)
2. Project Objectives
3. VLM® Process – Develop VLM Gear Model
4. VLM Gear Model Calibration / Validation
5. Virtual DOE Results
6. Summary and Conclusions

Integrated Computational Materials Engineering (ICME)

Integrating computational methods with materials engineering - probabilistic approach to account for randomness and uncertainty in microstructure





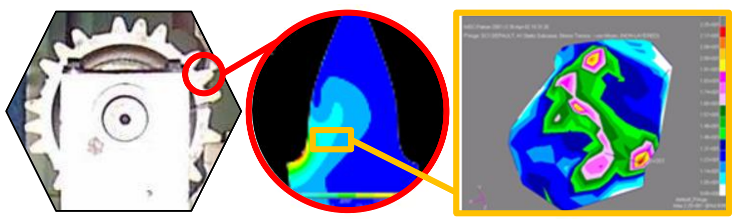
Grain-level reactions to global stresses, as depicted by a Statistical Volume Element (SVE)

- Material performance is governed by a microscopic size scale where commercially-available computational design tools are ineffective
- Engineering of new materials to suit needs of a design takes years by current processes
- Computational methods are not widely used in materials engineering, therefore a need for integrated material prediction tools exist
- VEXTEC has developed a virtual simulation ICME technology – Virtual Life Management® (VLM®)
  - Framework accounts for a material’s reaction to the stress imparted upon it, its variability and its damage mechanisms, its geometry, and usage conditions over time
  - Integration of computational structural models with probabilistic microstructural characterization

Virtual Life Management (VLM) and ICME

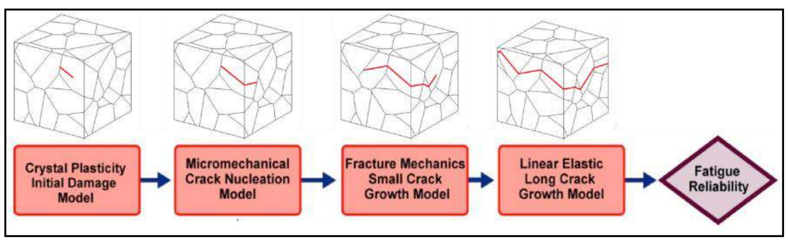
- Combining available structural analysis and material test data with VEXTEC probabilistic models of material, geometry and loading
- Models built with physics-based relationships of material, design, and application that directly affect the fatigue performance of components
- "What If" analyses enable designers and engineers with capability to accommodate material and/or design changes, and let risk managers define maintenance and warranty intervals

Product



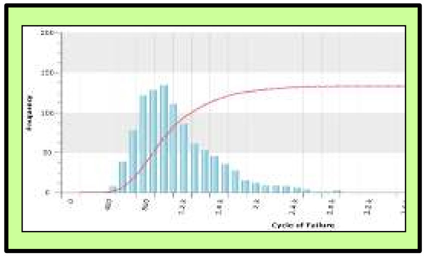
Model the Material's Inhomogeneity

Analysis



Simulate the Damage in the Material

Results



Predict the Fleet-Wide Risk of Failure

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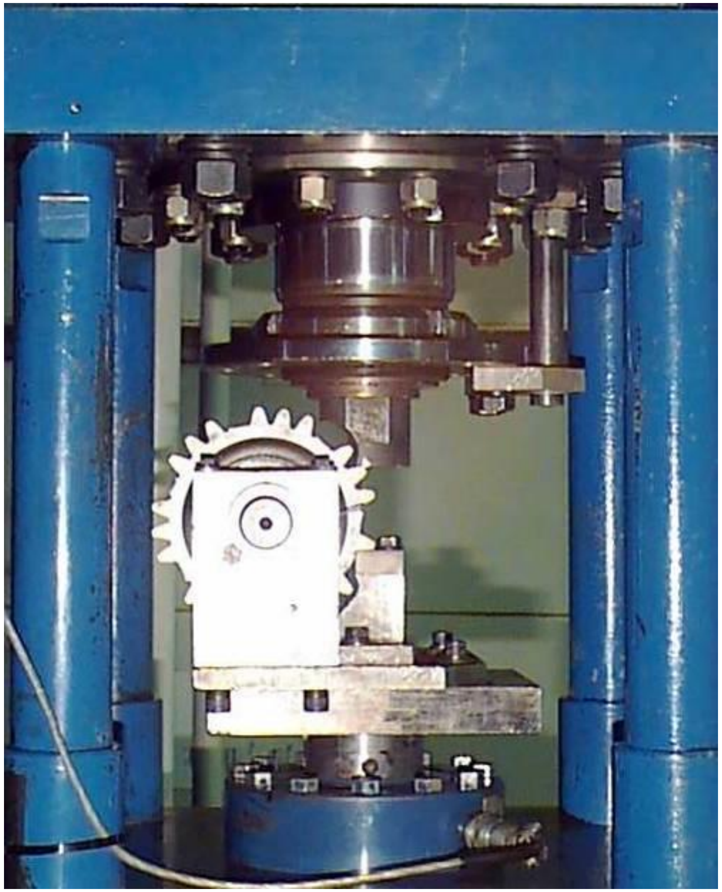
Project Objectives

- Use VLM and VPS-MICRO® software to replicate physical testing and the fatigue performance of gears subjected to *Single Tooth Bending Fatigue Test (STBF)*
- Determine bending fatigue curves of gears made from two different steels (Eaton P/N ‘X’ and P/N ‘Y’)
- Perform Virtual Design of Experiments (VDOE) and predict STBF lives by varying a heat treatment parameter (degree of intergranular oxidation)



Gear subjected to single tooth bending fatigue

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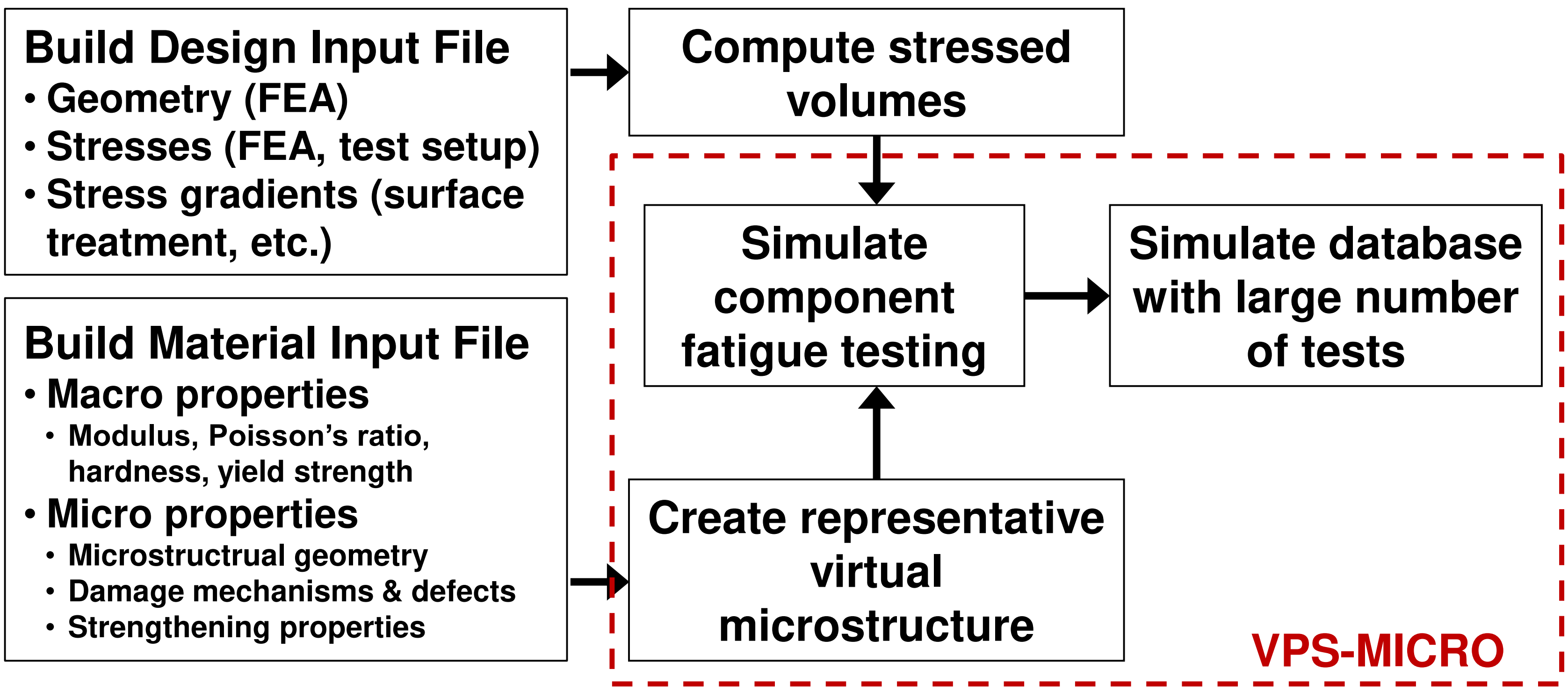
VLM Process Flow for Component Simulation



VPS-MICRO software is the computational engine of the VLM process. Structural analysis results (such as FEA) and limited material testing data provide the software inputs.

VLM Process Flow for Component Simulation

Build Design Input File
- Geometry (FEA)
- Stresses (FEA, test setup)
- Stress gradients (surface treatment, etc.)

Compute stressed volumes

Build Material Input File
- Macro properties
  - Modulus, Poisson's ratio, hardness, yield strength
- Micro properties
  - Microstructrual geometry
  - Damage mechanisms & defects
  - Strengthening properties

Simulate component fatigue testing

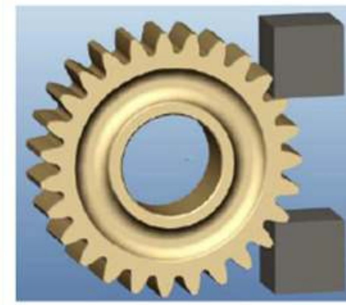
Simulate database with large number of tests

Create representative virtual microstructure

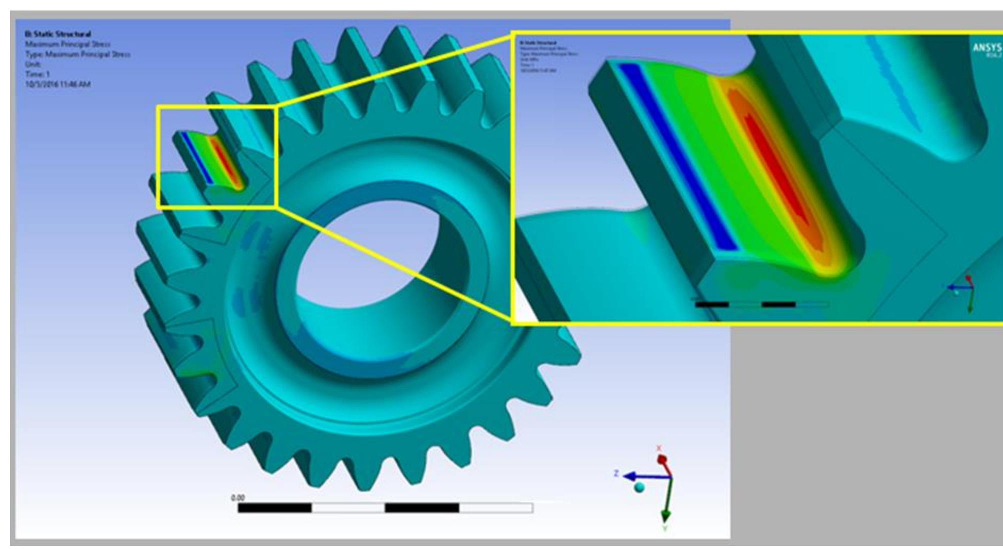
VPS-MICRO

VLM Gear Model Design Inputs

The objective is to capture the volume of material under stress, how the stress changes with depth, and the cyclic amplitude

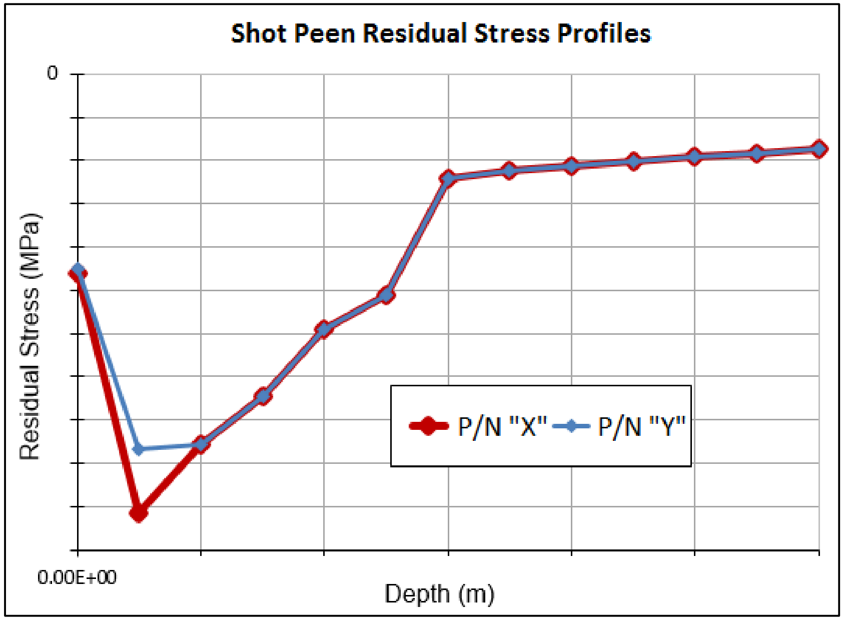


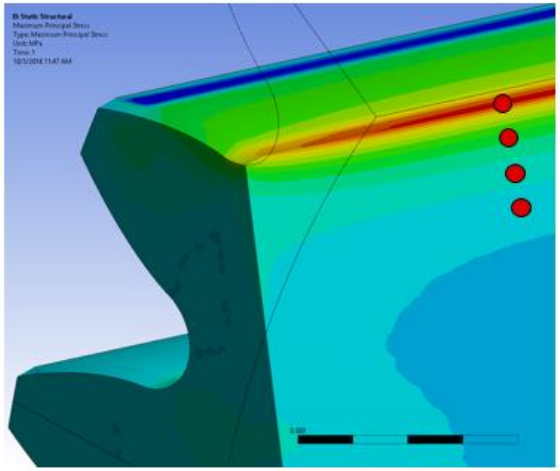
- Structural geometry
- Stress analysis
- VEXTEC-developed translator interrogates FEA results and collects nodal areas/volumes and stresses

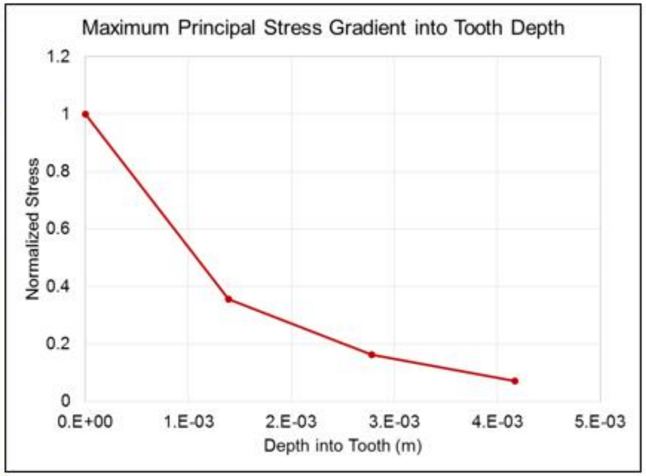


VLM Gear Model Design Inputs

- Stress gradients determined from FEA
- Shot peening residual stress profiles (measured by X-ray diffraction)







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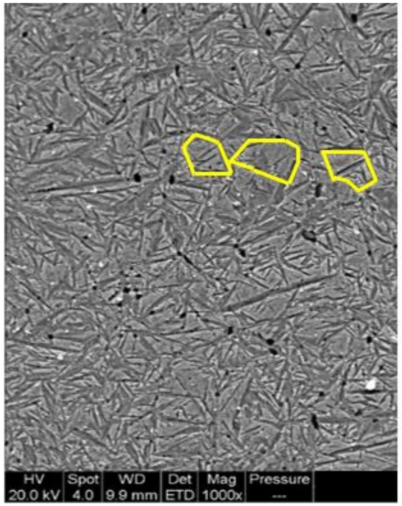
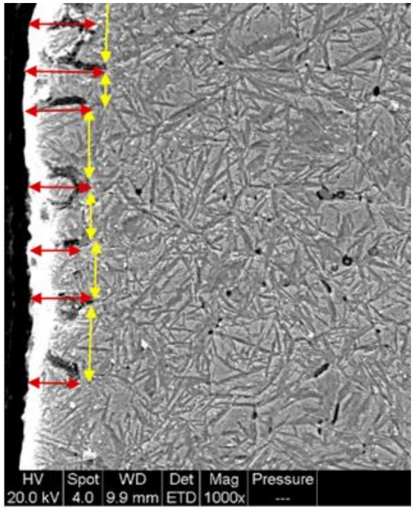
VPS-MICRO

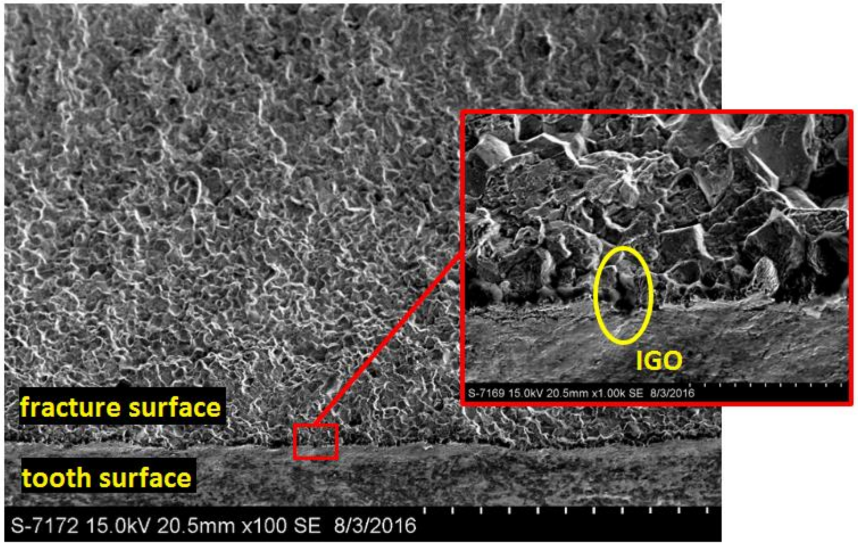
VLM Gear Model Material Inputs

The objective is to capture the microstructural geometry that plays a role in the active damage mechanism(s), and the uncertainties in that geometry

- Martensitic lath packets within the steel's prior austenite grains
- Material characteristics and effects of carburization (hardness, intergranular oxidation - IGO)
- 6 probabilistic parameters
- 6 deterministic parameters







VLM Gear Model Material Inputs (Macro)

Parameter	Nature and Description of Parameter	Typical Source of Data
Shear Modulus (G)	Deterministic; ratio of the material's shear stress to the shear strain. Related to Elastic Modulus (E) through Poisson's Ratio (ν): $G = E / [2(1+\nu)]$	Material data sheets for alloy system and heat treatment.
Poisson's Ratio (ν)	Deterministic; ratio of the material's transverse strain to axial strain.	Material data sheets for alloy system and heat treatment.
COV on Micro Stress	Probabilistic; Coefficient Of Variation (COV) describes the level of anisotropy in the material crystal system.	Based on the material system's anisotropy (Zener ratio); available in literature.
Orientation	Probabilistic; describes the orientation of the crystallographic slip systems in the material.	Based on the material's crystal system; available in literature.

- Macro properties refer to the bulk properties of the material, and generally describe the material's resistance to stress

VLM Gear Model Material Inputs (Micro-1)

Parameter	Nature and Description of Parameter	Typical Source of Data
Grain Boundary Strength	Deterministic; the minimum strength a nucleated crack must have to propagate beyond initiation.	Threshold K per ASTM E647 (at a slow rate and high R-ratio, to remove effects caused by fatigue crack closure).
Small Crack Coefficient	Deterministic; the multiplicative coefficient to the small crack regime growth rate.	Testing for this parameter is costly. It is 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.

- Micro properties describe the probabilistic nature of localized material response to stress (microstructure, strength and energy)

VLM Gear Model Material Inputs (Micro-2)

Parameter	Nature and Description of Parameter	Typical Source of Data
Grain Size (martensitic lath packets)	Probabilistic; the size of the microstructural features participating in the damage mechanism(s).	Metallography (preparation per ASTM E3); ASTM E1382 (or an approximate manual method to this procedure) for measurements.
Frictional Strength	Probabilistic; the micro-yield strength of a grain to resist dislocation pile-up.	80% of monotonic yield strength (used as preliminary approximation); cyclic yield strength per ASTM E606 (opportunity for model refinement).
Long Crack Parameters	Exponent ‘C’ (deterministic) and coefficient ‘n’ (probabilistic) of Paris Equation: $da/dN = C\Delta K^n$.	Region II crack growth regime per ASTM E647.
Defect Size / Population	Probabilistic; size and area density of the defects participating in the damage mechanism(s).	Metallography (preparation per ASTM E3); ASTM E45 for measurements.

- Micro properties describe the probabilistic nature of localized material response to stress (microstructure, strength and energy)

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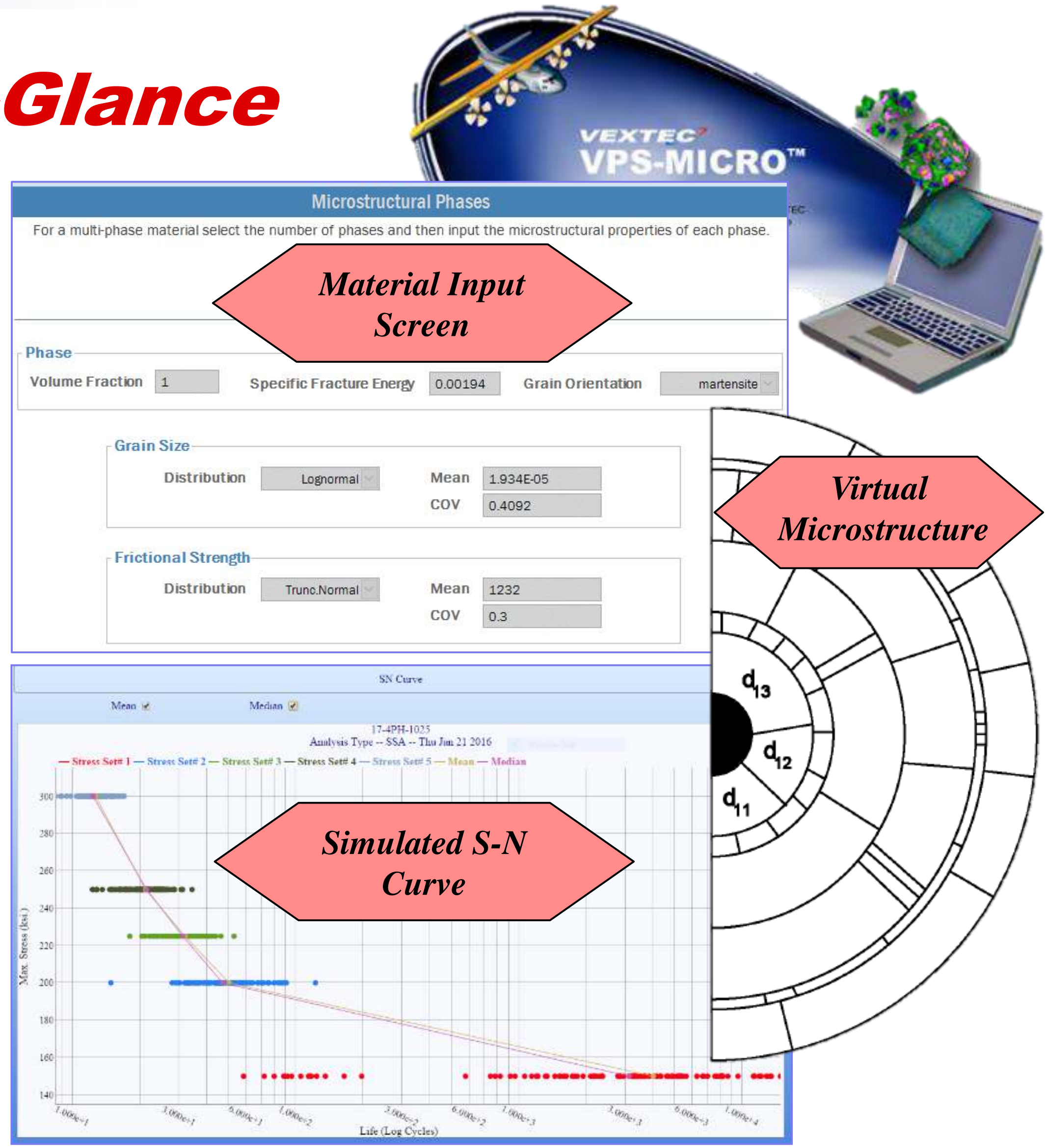
VPS-MICRO

VPS-MICRO At-A-Glance

- Windows desktop tool
- Wide range of applications
  - Stand-alone tool for simple specimen geometry models
  - Integrate FEA models for complex geometry of full-scale components
- Outputs
  - Simulated S-N Curve
  - Detailed statistical analysis
- Customizable Software Product
  - Interface with standard FEA software
  - Predict risk of failure from complex in-service loading spectrums



FEA Software Partners:

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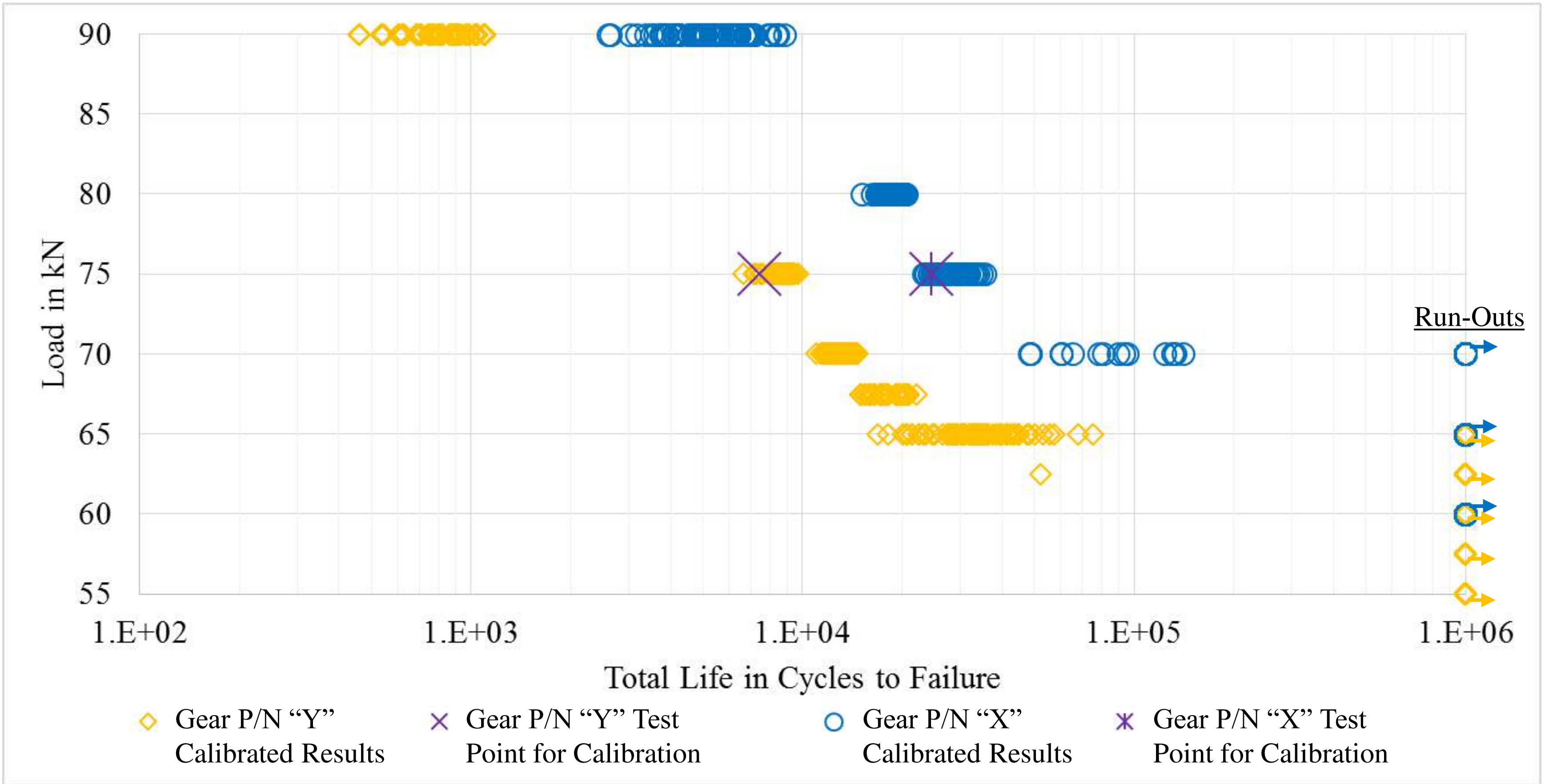
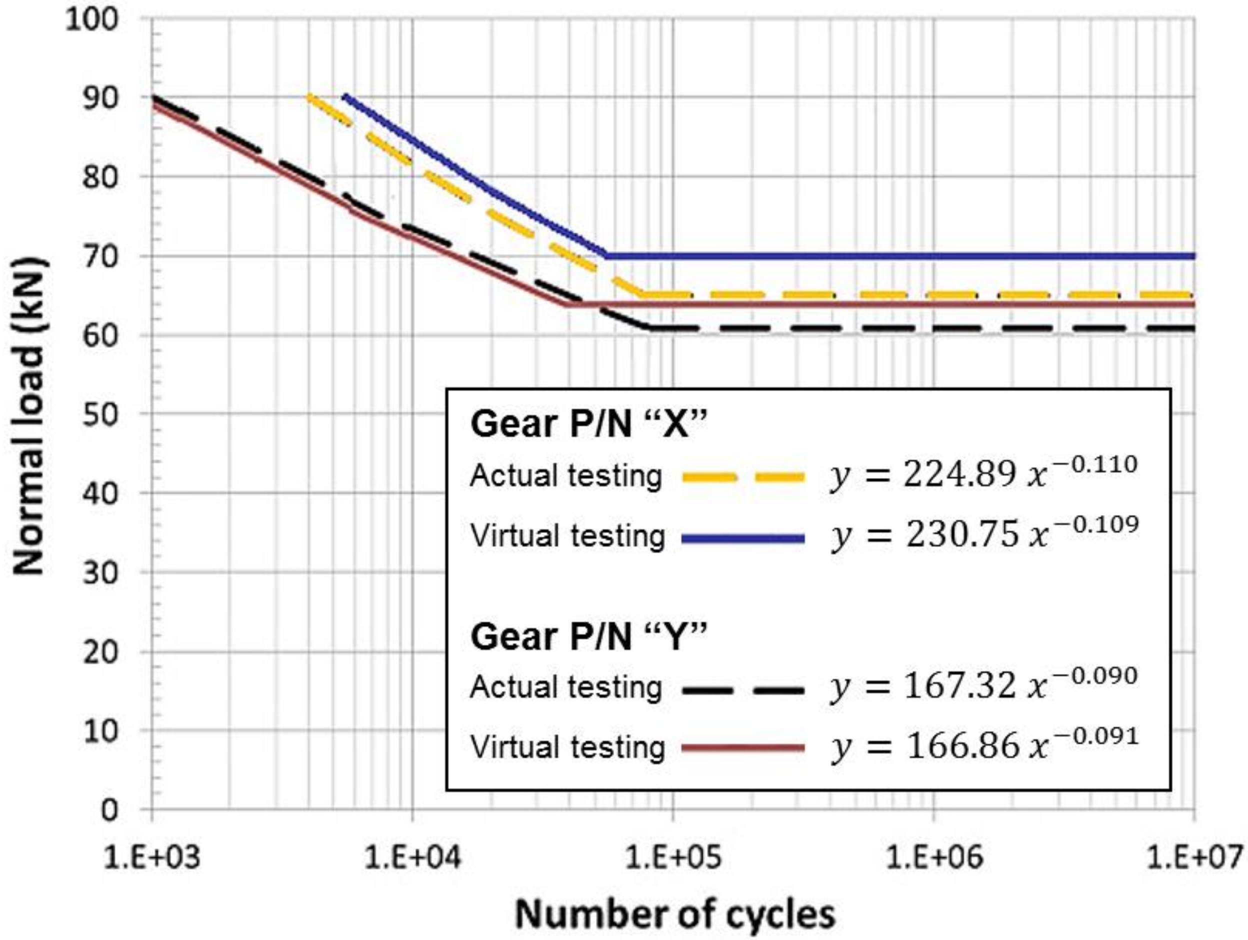
VLM Gear Model Calibration / Validation



Eaton provided one STBF test data point for each of the two gear materials. The models were calibrated to those two points, and other loading levels were predicted.

VLM Gear Model Calibration / Validation



Fit lines to experimental test data population showed good agreement with fit lines to simulated data, particularly in the life-limited fatigue range.

At the endurance limits, over-predictions by the models could be addressed by refinement of long crack growth material input parameters.

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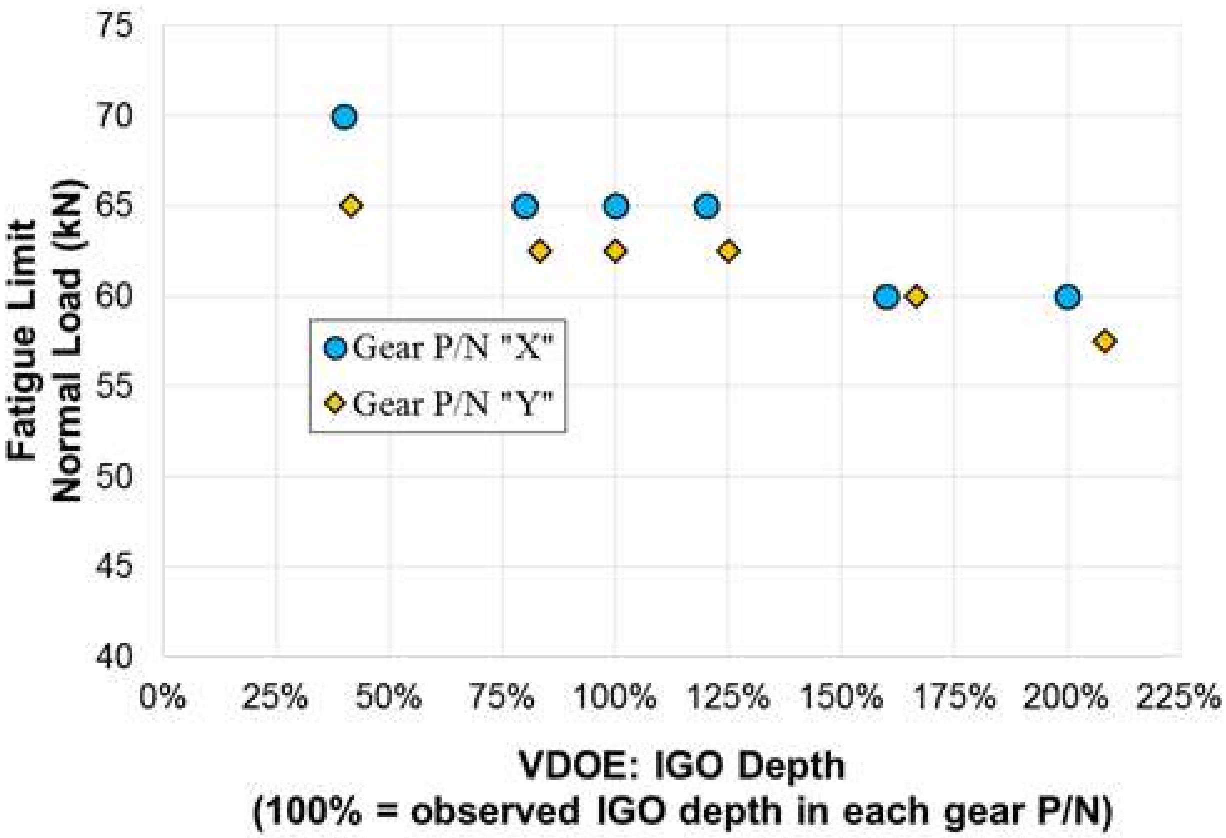
Virtual DOE Results



Virtual Design of Experiment (VDOE) studies, like this one for evaluating depth of intergranular oxidation (IGO), can be efficient ways for designers and engineers to efficiently perform "What-If" analyses of manufacturing process variations (i.e. atmosphere carburizing furnace conditions).

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Summary and Conclusions

- VEXTEC and Eaton collaborated to use VPS-MICRO to virtually replicate tooth bend fatigue testing of gears.
- Combined Eaton’s bend test FEA of gears with typical material microstructure derived from limited testing and characterization, to generate a high-fidelity ICME model.
- Simulated bend fatigue tests virtually with VPS-MICRO for two different carburizing gear steels, and matched simulation results with experimental data. Results demonstrate reducing, supplementing or (possibly) replacing physical testing with the implementation of VPS-MICRO.
- Performed Virtual Design of Experiments (VDOE) to predict broader gear bend response due to processing variability (furnace conditions affecting depth of intergranular oxidation).

Summary and Conclusions (continued)

- This effort was a demonstration of a strategic and technical collaboration between Eaton and VEXTEC.
- VEXTEC's VPS-MICRO provides a powerful and validated framework to get new and safer products in the market faster by:
  - replacing/supplementing physical testing;
  - implementing virtual DOEs such as material & process trade studies and geometrical design studies;
  - managing life cycle risk; and
  - defining and assuring product durability.
- Eaton's Vehicle Group can expand use of VPS-MICRO to other divisions, and at the corporate level.

Thank You for Your Attendance!

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