Implementation of Integrated Computational Materials Engineering or ICME to Manage the Fatigue Life of Components / Assemblies

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Sanjeev Kulkarni, PhD
Robert Tryon, PhD

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Who is VEXTEC?

- Founded in 2000: Over $25 million from the United States Department of Defense Innovative Research programs for Technology Development
- Proprietary Software and Seven Patents: Virtual Life Management® (VLM®) generates VIRTUAL TWIN®
- Customers: Federal Government and Industries (Aerospace, Automotive, Electronics, Energy, MEDICAL DEVICES)
- Value Proposition: Help companies improve products and reduce cost
  - New products to market quickly
  - Improve reliability of existing products
  - Reduce physical and prototype testing requirements
  - Forecast product durability and manage product life cycle risk
- Business Model: Hybrid – Consulting Services, Software Licensing and Training

VEXTEC accepted into FDA’s Medical Device Development Tool (MDDT) pilot Program

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Introduction
Software-enabled provider of solutions which test, assess and predict product fatigue/corrosion life

- Patented materials science algorithms based software to analyze and predict failure timelines and rates – applicable from simple levers to complex machines
- Software is a sophisticated computer simulation with inputs that can easily be varied to replace extensive and expensive physical testing programs
- Enables VEXTEC’s clients to forecast product durability and manage product life cycle risk
- Knowing the life cycle of any given part or machine, the client can better manage utilization and replacement rates – a significant economic benefit

Applicable Across Multiple Industries
- Aerospace & Defense
- Automotive & Transportation
- Industrial Equipment
- Medical Implants

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Virtual Life Management® (VLM®)

The capability of providing VLM provides relevant and important data to clients with an end result of improved cost containment and operating efficiency

Value Proposition

Replace or supplement physical testing for increased confidence

Forecast product durability and manage product life cycle risk

Bring new products to market quickly

Assure product reliability and reduce cost

How It Works

- Generate predictive fatigue and corrosion durability models by combining client’s available data with VEXTEC probabilistic models of material, geometry and loading
- Durability models simulate physics-based relationships of material, design, and application directly affecting fleet performance
- Provide client quick “What If” analysis to enable material and/or design changes and define maintenance and warranty cost programs

Product Analysis Results

Predict Risk of Failure

Simulate Damage in the Material

- Predict Risk of Failure
- Simulate Damage in the Material

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Technology

Damage is a process – VLM predicts failure by simulating the damage accumulation process

- The physics that drives the damage process changes as the damage accumulates
- Mathematical models exist to describe the physics at each stage
- **VLM contains a library of damage models and stage transition rules that are applied as appropriate to the materials being simulated**
**Demonstrated Success**

*VEXTEC has engaged its solutions for a variety of government and commercial applications for multiple industries in more than 100 successful implementations*

<table>
<thead>
<tr>
<th>Industry</th>
<th>Client Type</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace</td>
<td>Airline (American)</td>
<td>- Simulated lubrication changes &amp; identified fix</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- FAA approved</td>
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<td></td>
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<td>- $4M/year saved on bearings</td>
</tr>
<tr>
<td>Automotive</td>
<td>Engine Maker (Cummins)</td>
<td>- Simulated 150 designs &amp; identified top 3</td>
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<tr>
<td></td>
<td></td>
<td>- $5M saved on engine block development program</td>
</tr>
<tr>
<td>Industrial Equipment</td>
<td>Specialty Manufacturer</td>
<td>- Forecast maintenance schedule based on current usage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- $3M saved in reducing manufacturing line downtime</td>
</tr>
<tr>
<td>Healthcare</td>
<td>Medical Devices (Boston Scientific)</td>
<td>- Evaluated material suppliers for different markets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Avoided expensive developmental test program</td>
</tr>
</tbody>
</table>
Software: VPS-MICRO®
Simulated Fatigue Tests

- 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

- Output
  - Simulated S-N Curve
  - Virtual fracture surface
  - Detailed statistical analysis

- Customizable Software Product
  - Interface with Standard FEA software
  - Predict risk of failure from complex in-service loading spectrums

Software Partners

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VEXTEC VLM Analysis Simulation Process

Build Design Input File → Predict Micro-Stress

Build Material Input File → Predict Material Behavior

Build Business Input File

VEXTEC VLM Software

Predict Product

VEXTEC Proprietary Information and Patents

Predict Fleet

VLM simulation. (Computational simulation rather than actual testing.)

Post-Processing

VLM reduces the amount of testing needed by computational simulation
Traditional vs. Computational Fatigue Analysis
Traditional Fatigue Analysis

Empirical Methods

Fatigue Life

\[ N_f = A \sigma_a^b \]
Fatigue Modifying Factors

“Fatigue Strength” is not a material property

\[ S_e = k_a k_b k_c k_d k_e k_f k_g k_h k_i k_j k_k S'_e \]

\[ S_e = \text{fatigue strength of component} \]

\[ S'_e = \text{fatigue strength of test coupon} \]

\[ k_a = \text{surface factor} \]
\[ k_b = \text{size factor} \]
\[ k_c = \text{mean stress factor} \]
\[ k_d = \text{reliability factor} \]
\[ k_e = \text{temperature factor} \]
\[ k_f = \text{notch factor} \]
\[ k_g = \text{residual stress factor} \]
\[ k_h = \text{texture factor} \]
\[ k_i = \text{corrosion factor} \]
\[ k_j = \text{plating factor} \]
\[ k_k = \text{multi-axial stress factor} \]

Advice from Prof. Shigley

“It is a relatively simple matter to design against a static failure because our knowledge is quite complete. But fatigue is a much more complicated phenomenon, only partially understood, and the engineer seeking to rise to the top of the profession must acquire as much knowledge of the subject as possible. Anyone can double or triple factors of safety, because of a lack of knowledge of fatigue, and get a design the will not fail. But such designs will not compete in today’s market, and neither will the engineers who produce them.” J. E. Shigley, Mechanical Engineering Design, McGraw-Hill, 1977, pp. 178
Fatigue Analysis

Why are there so many modifying factors?

Fatigue response is much more complex than

\[ N_f = A\sigma^b \]

Fatigue is a process, not an event

A lot is going on from the first cycle to the last
Intense slip bands of plastic deformation

Prof. Christ and co-workers, 2013
Intense slip bands crack

Prof. Suresh and co-workers, 1991
Fatigue Damage
Micro crack dominated fatigue

• Some materials (high strength aluminum) crack during the manufacturing process.
Micro crack dominated fatigue

- Fatigue is dominated by the growth and coalesce of very small cracks.
- Fatigue is always governed by very localized damage.
Complex Behavior: Infinite Strength
JIS Steel Data

- S-N curve from typical $10^7$ cycles laboratory tests of fatigue specimens
  - Test results indicate infinite (fatigue) strength of 52 ksi
  - Multiple tests suspensions at $10^7$ cycles
• Testing beyond $10^7$ cycles shows infinite strength well below 52 ksi
• Testing provided false assurance
• Test must be supplemented with modeling to reduce risk
Dual Mechanism Long Life SN Curve

• Testing to determine risk is prohibitively expensive
  – Testing to full life is very expensive
  – Testing production hardware is very expensive
  – Testing many samples is very expensive
• Computational models allow simulation of required test protocols for risk assessment
• Mechanics understanding of fatigue allows computational prediction.
Complex Behavior: Notch effect

JIS Steel Data

- S-N curve for notched specimen (Kt = 3) plotted with local notch root stress
  - Fatigue notch factors (Neuber and Glinka) are available but they require experimentally determine notch sensitive factors.
Notch Fatigue Predictions

Kt = 3

Kt = 2.5
Size Effect

- IN 100 laboratory test data
- Smooth round bars cut from the same block with the same microstructure
Empirical Fatigue Models

- Simple empirical models relating the number of cycles to “crack initiation” vs. applied load
- Do not account for the local process of crack formation
- Do not account for multiple phases of fatigue
- Cannot accurately represent damage processes that are not explicitly a part of the database test program
- How to handle extrinsic uncertainties within the fleet?
  - Random stress among components
  - Random geometry among components
  - Random stress amplitude for a single component
Computational Fatigue Models

- Crystal Plasticity Initial Damage Model
- Micromechanical Crack Nucleation Model
- Fracture Mechanics Small Crack Growth Model
- Linear Elastic Long Crack Growth Model

Material Libraries

Variability
- Grain Size
- Grain Orientation
- Micro-Applied Stress
- Micro-Yield Strength

Fatigue Reliability
Computational Material Model

• Model the material at a fundamental level.
• Loading and environment become extrinsic factors to the material model.
• This allows simple test coupon data to be used directly in fatigue analysis of complex components.
VLM Predicts How, When, Where, and Why Damage Occurs

Standard Industry Analysis

VLM Analysis

Design & Stress

Life & Where & Why
Computational Structural Models

Example: Finite element analysis

Hooke’s Law + Plasticity + Plate Theory = Displacement
Strain
Stress
Mode Shapes
Computational Material Models

Example: VPS™ MICRO fatigue analysis

\[
\text{Dislocation Theory} + \text{Crystal Plasticity} = \text{Fracture Mechanics}
\]

\[
\text{Crack Nucleation}
\]

\[
\text{Small Crack Growth}
\]

\[
\text{Long Crack Growth}
\]
Uncertainty Management

VLM approach predicts failures

Conventional view of component

Fatigue strength is traditionally determined by testing

VEXTEC’s view of component, grains & damage
VLM: Grain – FEA – Component – Fleet

Component Design Configuration Material Configuration VLM Computational Processing Mapping the Elements Component Simulation Fleet Simulation

Component Life Usage

Element Life: 17,561 cycles
Failure Cause: Defect cracking

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VLM: Grain – FEA – Component – Fleet

Tooth Life: 15,932 cycles
Failure Cause: Defects

Component Life: 14,334 cycles

Integrate VLM Results with FEA
VLM Integration for Entire Component
Repeat Sequence for Each Tooth
1st Virtual Twin Gear Simulated

VT₁, VT₂, VT₃ … VT₁₀₀₀

Run 1,000 Simulations
1. Determine nodal stress
2. Determine nodal area.
3. Perform microstructural fatigue analysis at each node.
4. Set component life to minimum life of all nodes.
VLM Notch Effects $R = 0.1$

VLM predicted the notch effect from a single smooth bar data point.
Spectrum Loading Fatigue

Same material model used for various geometry/loads
Vibration Mode Dependent Fatigue

VEXTEC predictions validated with test

Mode 1 Predictions
Mode 2 Predictions
Mode 1 Expt. Data
Mode 2 Expt. Data

1st Bending Mode (Mode 1)

1st Torsion Mode Mode 2
Cardiac Leads: Summary and Outcomes

Summary

- Simulated fatigue buckling test under 2 load conditions
- Virtual DOE consisted of 9600 individual coil simulations

Outcomes / Next Steps

- Sensitivity study around particle size, density and residual stress
- Determined residual stress to be a calibrated value - new knowledge
- Developed Insights - Design alternatives, Material substitution, Vendor management
- Potential - Sensitivity analysis, Design trade studies, Supplier controls, Design optimization
- Add Realism – Coiling Simulation for Residual Stresses

VDOE Results for Residual Stress
VLM Implementation
Software: VPS-MICRO®

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Software Partners

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VEXTEC - VPS-MICRO® FEA Example

Bracket

Step: Load1, Pressure
Increment: 1, Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U, Deformation Scale Factor: 1.000e-09
Bracket – Local Stress

Bracket – Probability of Failure
For a simple specimen (smooth round bar), provide surface areas.
Loading Inputs

For a simple specimen enter max and min stress.
Select the appropriate material in the library and click "Add"
# Current VLM Material Library

<table>
<thead>
<tr>
<th><strong>Steels</strong></th>
<th><strong>Aluminum Alloys</strong></th>
<th><strong>Electronic Materials</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1010</td>
<td>AA 2024</td>
<td>SnPb (eutectic) solder</td>
</tr>
<tr>
<td>AISI 304 Stainless</td>
<td>AA 7075-T651</td>
<td>SnAgCu (lead-free) solder</td>
</tr>
<tr>
<td>AISI 4340</td>
<td>AA 7050-T3</td>
<td>OFHC-Oxygen free high conductivity copper</td>
</tr>
<tr>
<td>AISI 9310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM 355 Stainless</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pryowear 53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pryowear 675</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-4PH 1025 Martensitic Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-4PH 1150 Martensitic Steel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Nickel Super Alloys</strong></th>
<th><strong>Titanium Alloys</strong></th>
<th><strong>Medical Materials</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimodal Waspaloy at 1000F</td>
<td>Cast Ti64</td>
<td>MP-35N</td>
</tr>
<tr>
<td>Bimodal Waspaloy at Room temperature</td>
<td>Cold Rolled Bimodal Ti64</td>
<td>MP-35LT</td>
</tr>
<tr>
<td>Coarse grain Waspaloy at 1000F</td>
<td>Cold Rolled Equiaxed Ti64</td>
<td>Nitinol</td>
</tr>
<tr>
<td>IN 100</td>
<td>Fine Bimodal Ti64</td>
<td></td>
</tr>
<tr>
<td>IN 713 - Directionally Solidified</td>
<td>Forged Bimodal Ti64</td>
<td></td>
</tr>
<tr>
<td>IN 713 – Equiaxed</td>
<td>Forged Equiaxed Ti64</td>
<td></td>
</tr>
<tr>
<td>IN 713 - Radially Solidified</td>
<td>Forged Ti64</td>
<td></td>
</tr>
<tr>
<td>IN 713 - Single Crystal</td>
<td>HCF Ti64</td>
<td></td>
</tr>
<tr>
<td>Medium Grain Waspaloy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rene 88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Iron Super Alloys</strong></th>
<th><strong>Cast Iron</strong></th>
<th><strong>Intermetallics</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ductile (Nodular)</td>
<td>Gamma – TiAl</td>
</tr>
<tr>
<td></td>
<td>Grey (Graphite Flake)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cold Spray Coatings</strong></td>
<td><strong>Cobalt Super Alloys</strong></td>
<td><strong>Magnesium</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZE-41A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rene 88</td>
<td></td>
</tr>
</tbody>
</table>

VEXTEC is continuously expanding the library of standard materials. In the future users will be able to add their own material models.
In General, the “Microstructural Phases” & “Crack Growth Property” inputs are “locked” and the user cannot change them. Super-users can modifying these input parameters.
If appropriate, input defect (or inclusion) size & defect density parameters as statistical variables.
Damage Mechanisms

Fatigue is a multi-stage process. Select the stages of crack growth to be simulated.

All inputs should be either in SI units or English units.

Fatigue Type: Fatigue

Fatigue Stages
- Crack Nucleation
- Small Crack Growth
- Long Crack Growth

Crack Initiation Mechanism
- Transgranular
- Intergranular

At present none of the settings in this screen can be modified
Number of Simulations

Having built the model, run the desired number of simulations.

All inputs should be either in SI units or English units.

Simulations count: 15

Run Simulations

Model Type: SSA  Current Material: SI-HSLS37HRC
VEXTEC’s VPS-MICRO Software

Output - SN Curve

SL-HSLS37HRC
Analysis Type -- SSA -- Mon Oct 26 2015

Stress Set# 1 — Stress Set# 2 — Stress Set# 3 — Stress Set# 4
VEXTEC’s VPS-MICRO Software

Output - PDF (Histogram) of Total Life

SI-HSLS37HRC
Analysis Type -- SSA -- Mon Oct 26 2015

Set Number | Mean   | Median  | Mode   | COV
---------- | ------ | ------- | ------ | -----
1          | 3.611e+4 | 3.229e+4 | 3.003e+4 | 3.182e-1

Histogram Parameters

- # of Bins: 15
- Min. Value: 1e+99
- Max. Value: 1e+99
## Individual Simulation Results

### Individual Results View

**Component Number**: 1

**Fatigue Life**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Life</td>
<td>1.479e+4</td>
</tr>
<tr>
<td>Nucleation Life</td>
<td>8.004e+3</td>
</tr>
<tr>
<td>Short Crack Life</td>
<td>5.634e+3</td>
</tr>
<tr>
<td>Long Crack Life</td>
<td>1.156e+3</td>
</tr>
</tbody>
</table>

**Critical Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation Site</td>
<td>Grain</td>
</tr>
<tr>
<td>Initiation Grain Size</td>
<td>4.189e-6</td>
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<tr>
<td>Initiation Phase</td>
<td>1</td>
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<tr>
<td>Frictional Strength</td>
<td>5.559e+2</td>
</tr>
<tr>
<td>Micro Stress</td>
<td>1.857e+3</td>
</tr>
<tr>
<td>Schmid Factor</td>
<td>2.322e+0</td>
</tr>
<tr>
<td>Non Failing Cracks</td>
<td>417</td>
</tr>
</tbody>
</table>
**VEXTEC VLM – Test To Success**

**Reference**
- FDA Guidance Document for Stents and Delivery Systems – April 2010
- DOE Paradigm – Four Corners (can add plus Center Point)
- 90% Reliability / 90% Confidence

**Traditional Testing**
- 90 / 90 Test to Success translates into 22 tests per data point and for 5 points gives 110 tests
- Estimated Cost for 400M cycles at 50 Hz and Time based on assumptions made by VEXTEC
  - Cost ~$1M
  - Time Depends on # of Test Machines – 9 months to X years
  - Company should add own numbers

**VEXTEC VLM**
- Confirmatory Testing – Level1 (Test Sample) and Level 2 (Device / Component)
- Material Model Development
- Software License Cost
- Labor Cost
- Estimated Cost and Time
  - $80K
  - 4 months (Level 2 testing)
  - Expands to full matrix for 25% more

**Summary**
- Cost Advantage – 12.5 to 1
- Time Advantage – 2 to 1 and up
- Can Easily Scale for 95/95 or 99/99
**Reference**

- **Automotive Customer** – Gears, Bearings, Springs, ….
- Test to Failure to generate a S-N curve for Metal component subject to cyclic loading
- Test Matrix - Includes 5 Sizes from smallest to the largest and subject to 5 different Displacement amplitudes from smallest to largest – 10 samples at each

**Traditional Testing**

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- Estimated Cost for 400M cycles at 50 Hz and Time based on assumptions made by VEXTEC
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- Confirmatory Testing – Level 1 (Test Sample) and Level 2 (Device / Component)
- Material Model Development
- Software License Cost
- Labor Cost
- Estimated Cost and Time
  - $80K
  - 4 months (Level 2 testing)
  - Expands to full matrix for 25% more

**Summary**

- Cost Advantage – 12.5 to 1
- Time Advantage – 2 to 1 and up
- Can Easily Scale for 95/95 or 99/99
Thank You

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Spectrum Loading Fatigue

Same material model used for various geometry/loads