Cold Spray Action Team (CSAT) Meeting

May 17, 2011
Worcester, MA

Everything fails… but that can't be predicted with FEA modeling alone

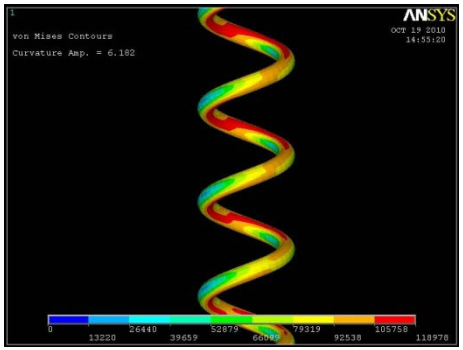
MSC Software
Simulating Reality, Delivering Certainty™

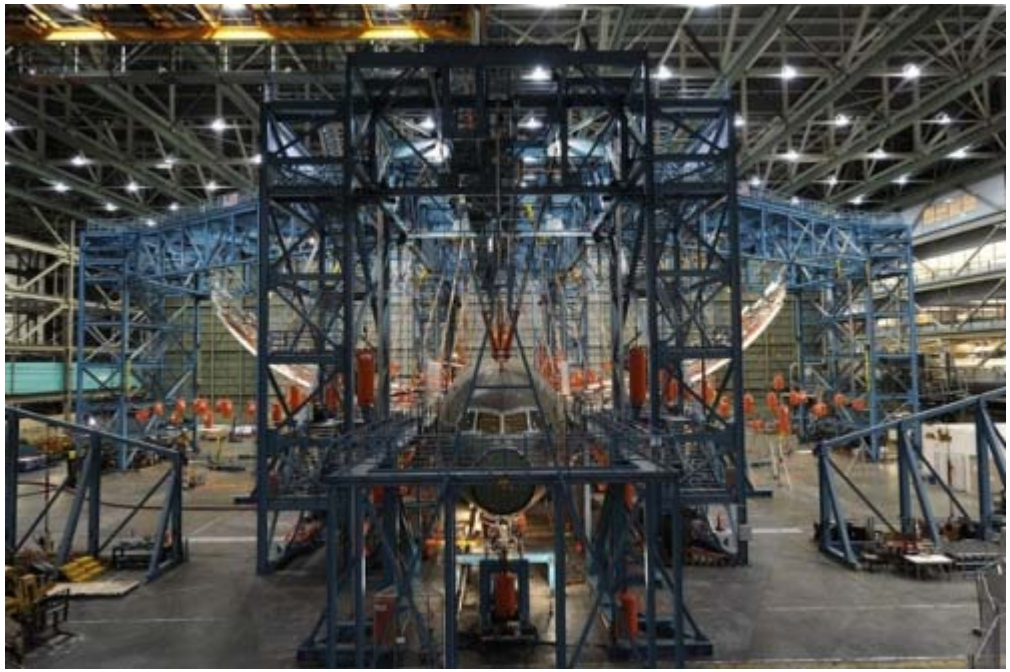
ANSYS®

SIMULIA

PTC®

Design & Stress





1 year and $14 million test data point

Physical Testing for Every Possible Operating Situation is Not Practical

- Although 10,000 -100,000 units produced, often less than 10 test data points
- Although each unit planned for 10,000 operating hours, testing often limited to 100 hrs
- Although unit use tested one way, actual in-service is something completely different
- Unit pre-production sales qualification one plant, while volume production another

Our Technology Extends FEA To Simulate Testing & Predict Durability Virtually

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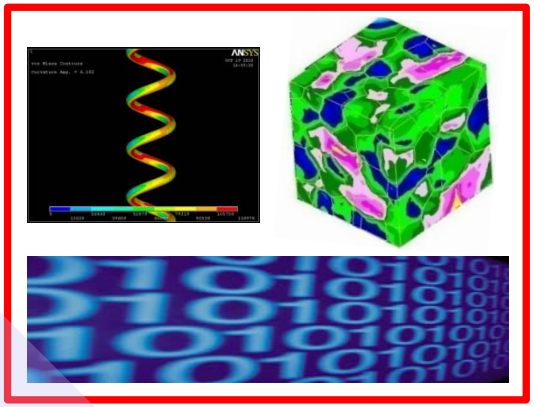
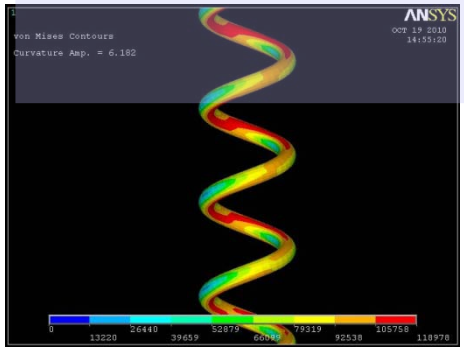
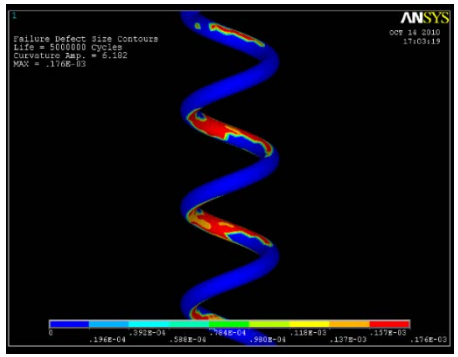


Design & Stress

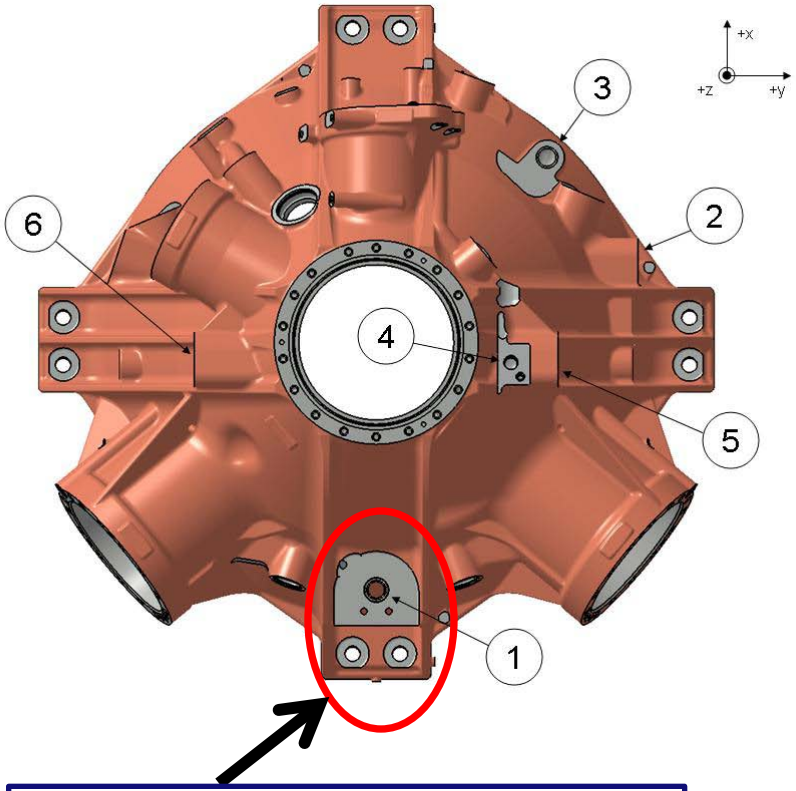


Probability of Failure & Why



Embedded demo shows how our VLM technology works

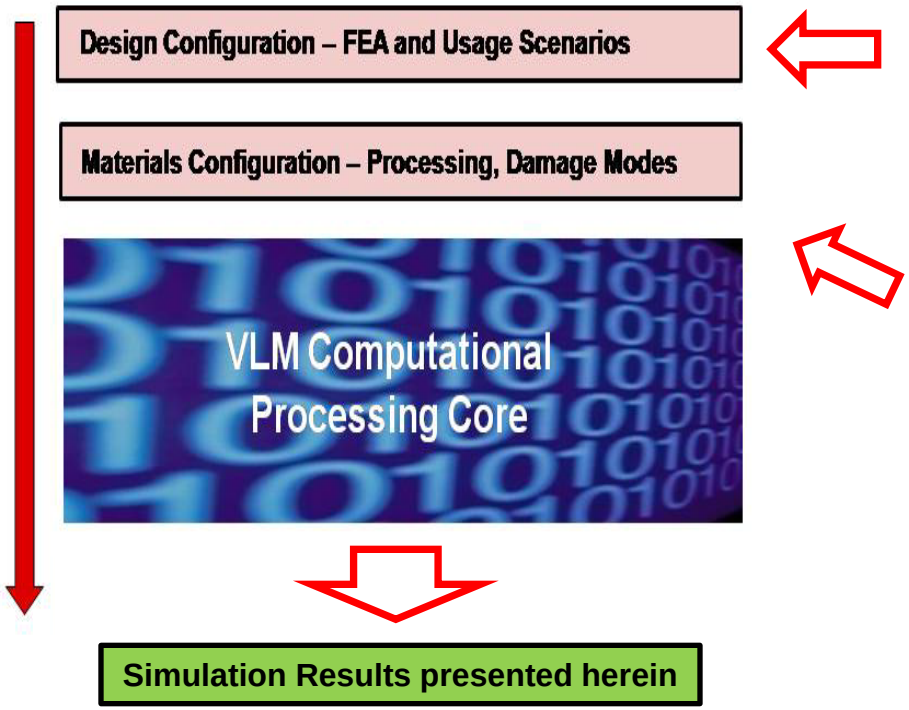
Flight Control Pad



UH-60 Flight Control Pad

- Durability simulation of UH60 Control Pad
- Part cast w/ Ze41A (Magnesium) material
- VEXTEC to simulate application of 6061(He) spray repair
- VEXTEC to compare with simulation results for uncoated part
- Rig test performed on uncoated part but not coated part as of yet

VLM™ Configuration & Checkout



Designs

- **H60 Control Pad**
- **RR Moore Specimen**

Materials

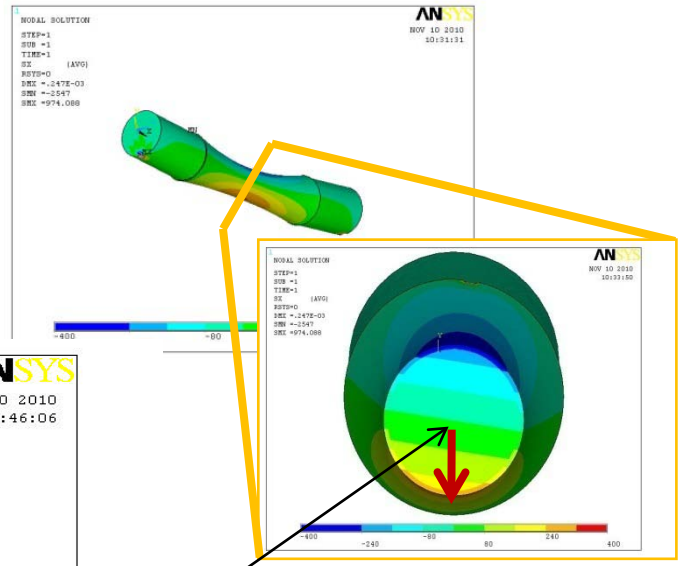
- **6061-He**
- **Mg (no coating)**

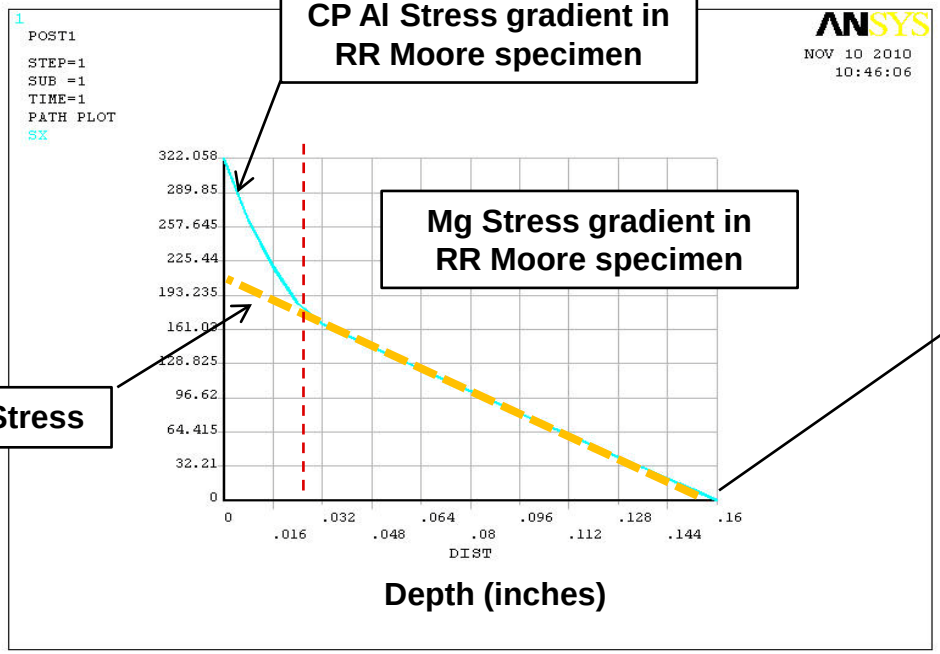
VLM integrates 3-D material representation within each element of FEA. When cycled virtually, VLM predicts part durability

Design Configuration

Specimen FEA

- RR Moore specimens
- Unit load applied
- Modeled as parent material with coating
- Crack starts in Al and grows into Mg





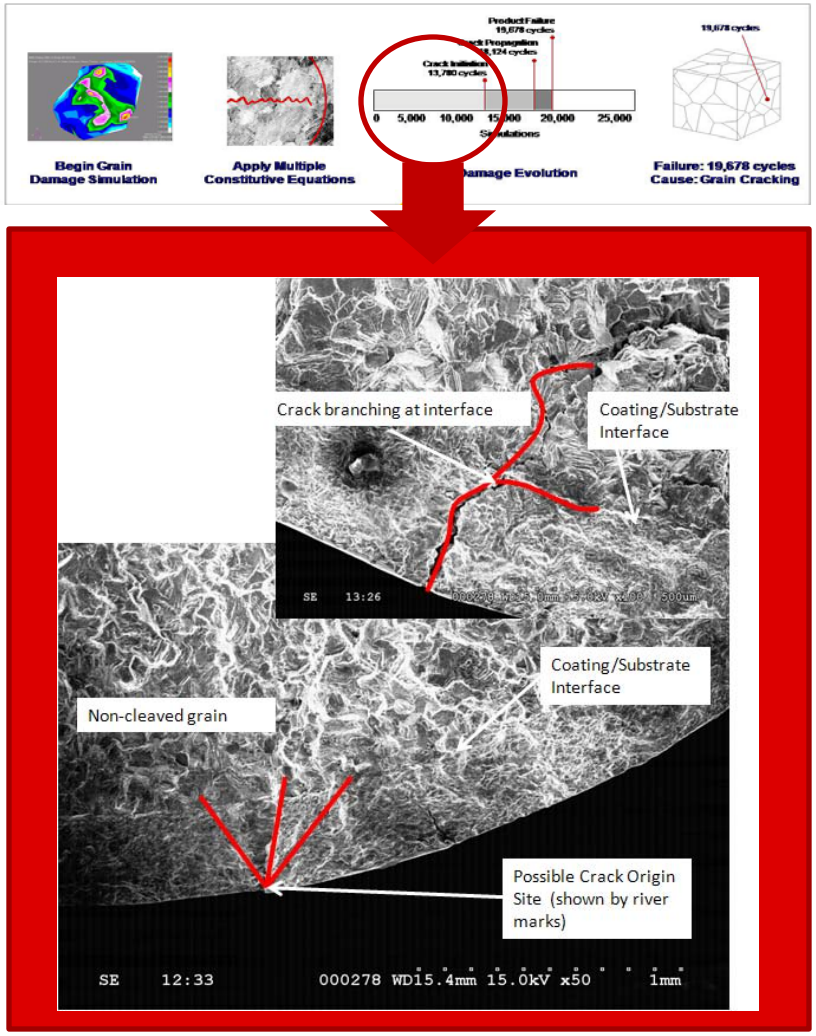
CP Al Stress gradient in RR Moore specimen

Mg Stress gradient in RR Moore specimen

If no Al Stress

Material Considerations

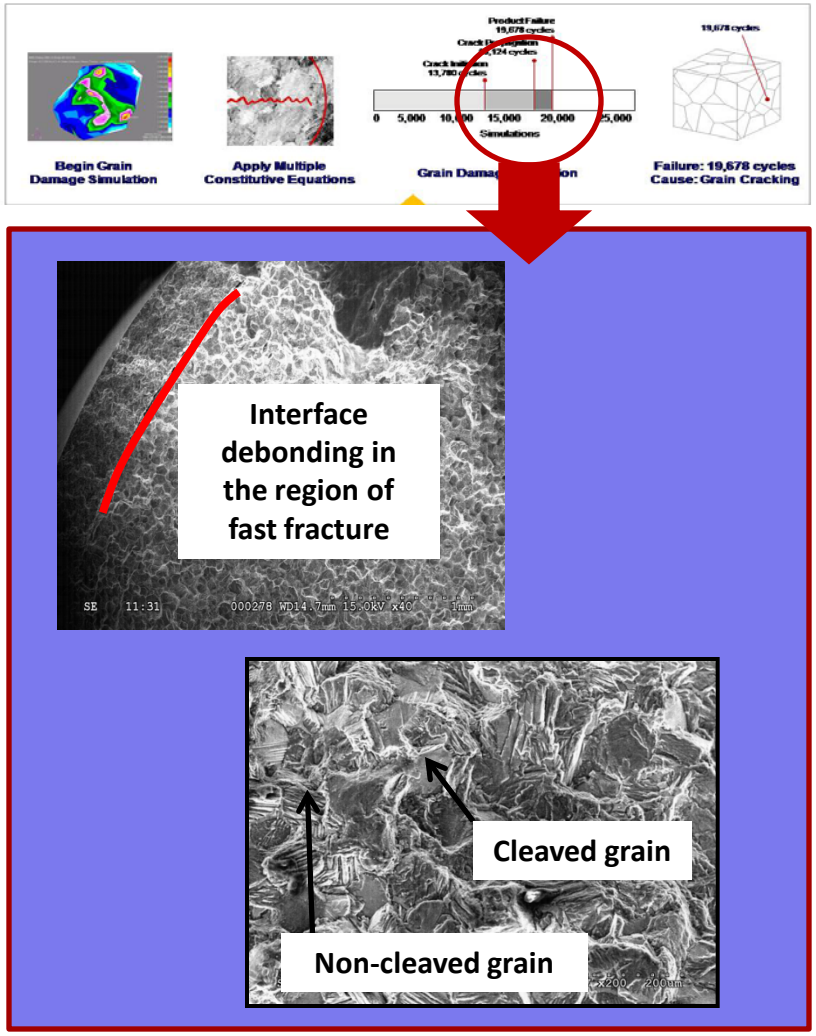
6061-He Material: Simulation of Damage Initiation



Damage Mechanisms:

- **Multiple crack origin site (intergranular initiation).**
- **Short crack growth is also intergranular.**
- **Crack branching observed in multiple cracks at the coating- substrate interface.**
- **Primary crack continues to grow into substrate.**

6061-He Material: Simulation of Damage Growth



Damage Mechanisms :

- **Modeled based on fracture surface observations**
- **Long crack growth in magnesium (hexagonal close packing) crystal structure is via cleavage on the basal plane – cleaved grains show distinct grain facets**

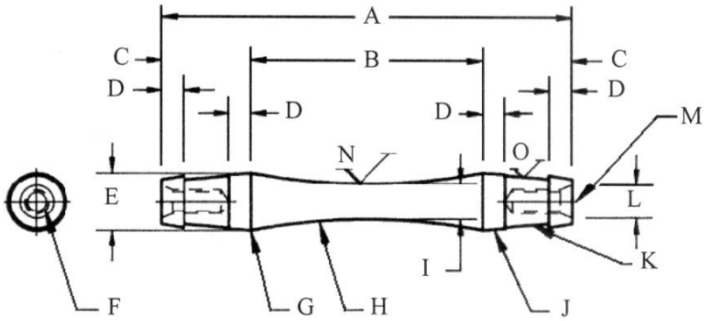
Simulation Material Configurations

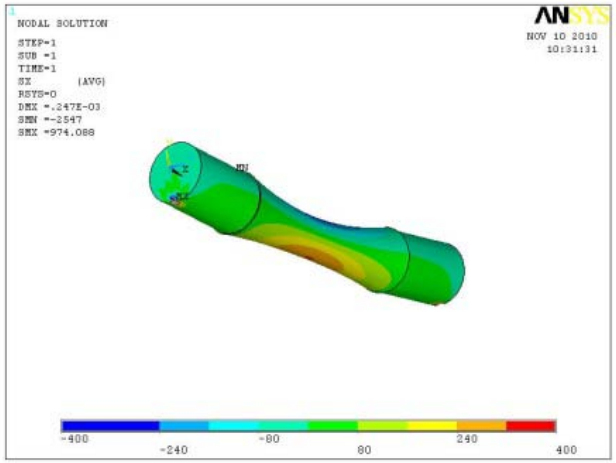
Simulation Modeling Parameter	6061-He		Baseline Mg (no coating)	
	Nominal Value	Coefficient of Variation	Nominal Value	Coefficient of Variation
Shear Modulus	3770 ksi		2461 ksi	
Poisson's Ratio	0.32		0.31	
Fracture Toughness (K_{IC})	21 ksi √in		14 ksi √in	
Defect Size	6.3 µ	COV=26% (Log-	N/A	N/A
Defect Density	31100/sq. in	COV=19% (Log-	N/A	N/A
Small crack coefficient 'c'	0.002		0.01	
Long crack coefficient 'C'	2.54E-08	COV=54% (Normal)	2.54E-08	COV=54% (Normal)
Long crack exponent 'n'	3.9		3.9	
Nucleation mechanism	Intergranular in coating		Transgranular	
Grain size (coating)	14.0 µ	COV=19% (Normal)	72.0 µ	COV=33% (Normal)
Sp. Fracture Energy	420 lb-in/in^2		290 lb-in/in^2	
Short Crack growth	Intergranular in coating		Transgranular	
Grain Boundary Strength	0.44 ksi √in		0.55 ksi √in	
Frictional Strength	22 ksi	COV=16% (Weibull)	19 ksi	COV=14% (Weibull)

Simulator Calibration & Checkout

Simulator Calibration based on RR Moore Specimen Testing

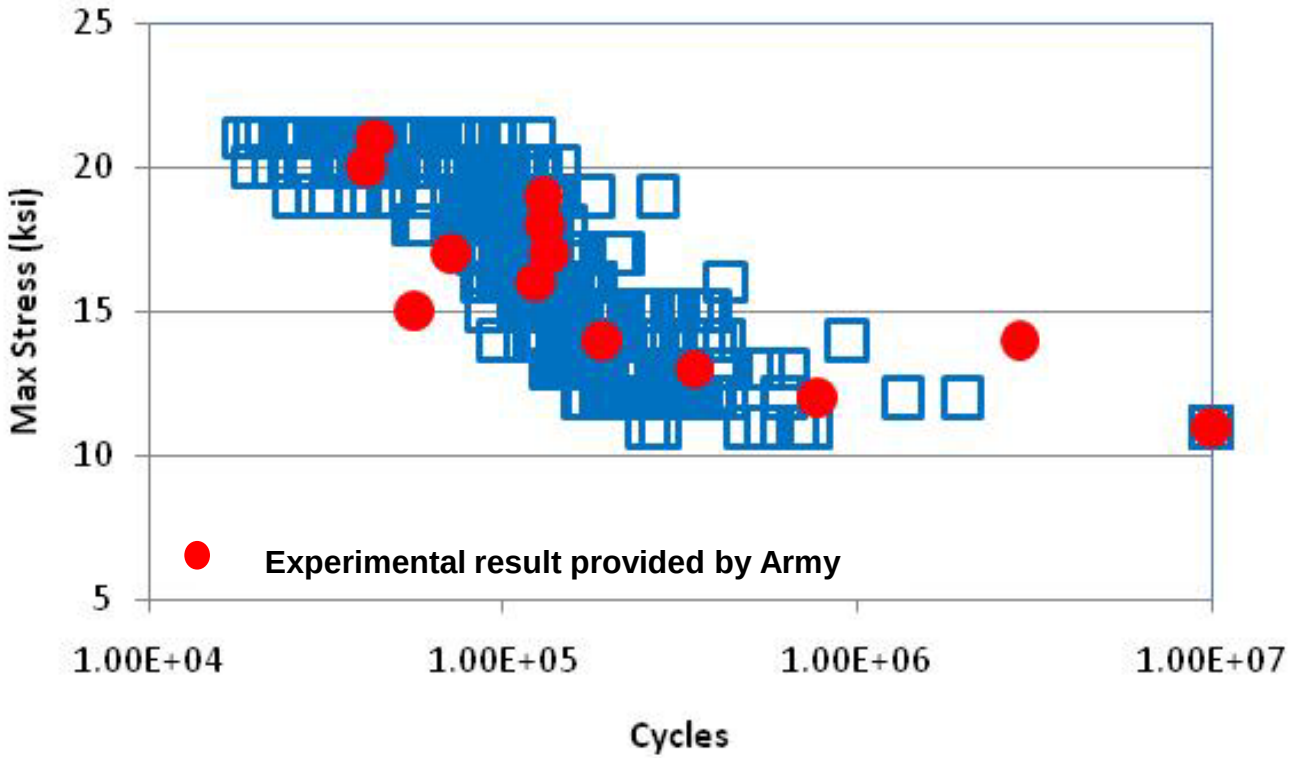
- **Operational speed 10,000 RPM**
- **Rotating bend R ratio = -1**
- **Ambient temperature**
- **Data acquired at several stress levels**





Virtual Simulation of Uncoated Specimen Tests

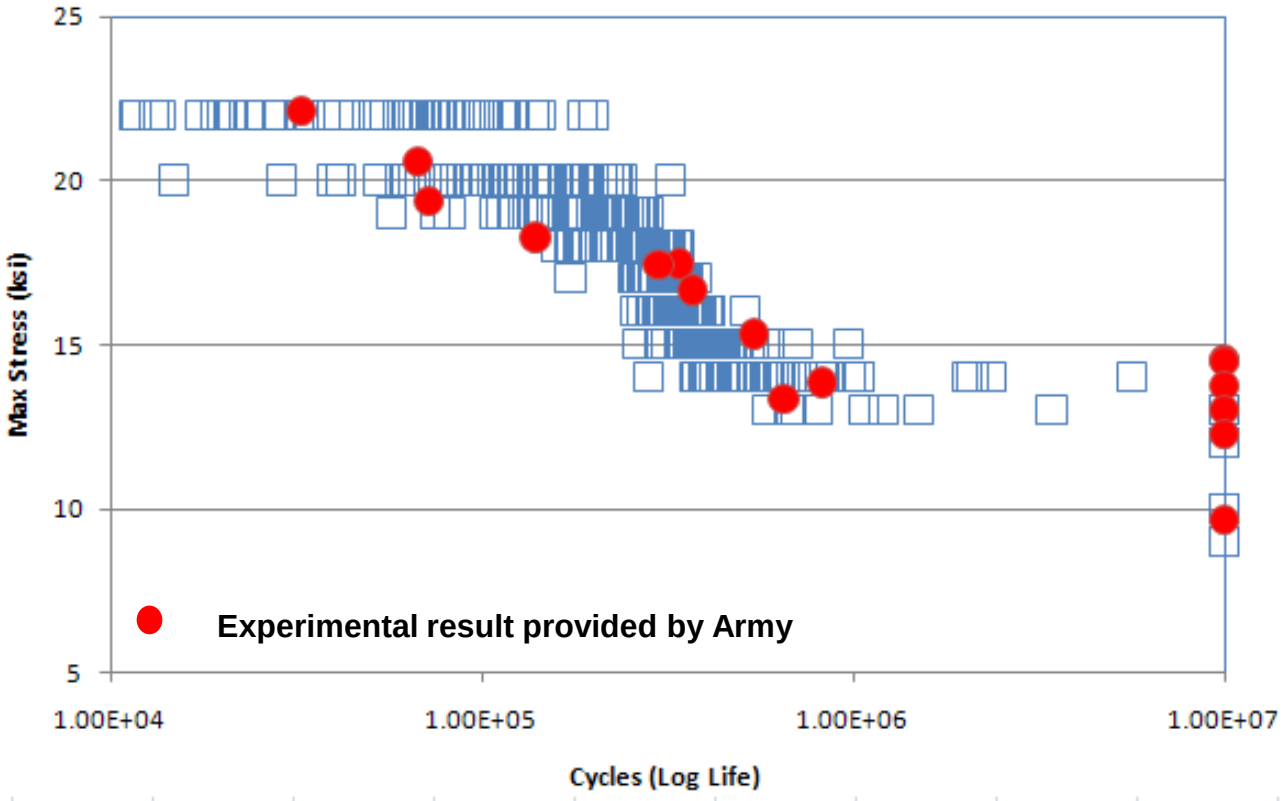
Simulated 600 RR Moore Specimens (12 Stress Levels, 50 Simulations Per Stress Level)



VLM results match Army testing without any further setup adjustments

Virtual Simulation of Coated (6061-He) Specimen Tests

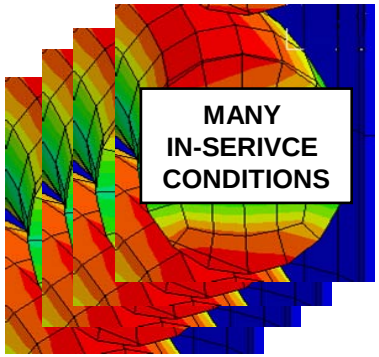
Simulated 600 RR Moore Specimens (12 Stress Levels, 50 Simulations Per Stress Level)



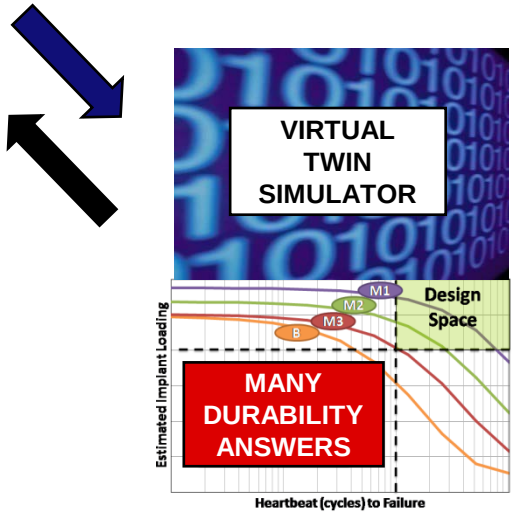
VLM results match Army testing without any further setup adjustments

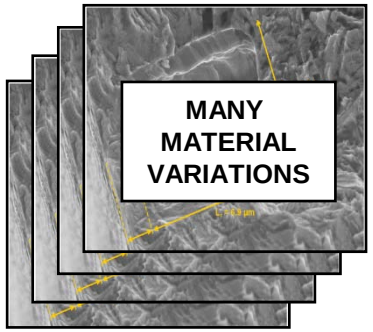
In the Time & Cost to Build & Test One Design Change, a Virtual Twin™ Evaluates Many

With time & budget constraints, how many product alternatives or usage conditions can the Product Manager evaluate?



Can we reduce design margin to reduce weight?





Change manufacturing processing to reduce cost?

Next Steps –

- Given that Simulator is now operational, VEXTEC can exercise it to benefit Army & Sikorsky program needs
- Simulation of uncoated vs coated control pad
- Potential simulation trade-studies
  - Spray velocity variation
  - Spray angle variation
  - Repair depth variation
  - Spray particle variation
  - Loading or mission scenarios
  - Etc.