Durability of ACERT Engine Components

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2011 Vehicle Technologies Annual Merit Review
and Peer Evaluation Meeting
Arlington, VA, 11 May 2011

Project ID: PM033

Overview

Timeline

- **Start – Oct 2008**
- **End – Sept 2010**

Budget

- **Total project funding**
  - **DOE – $400K**
- **Funding received**
  - **FY2009: $200K**
  - **FY2010: $200K**

Barriers

- **Advanced Combustion Engine:**
  - ✓ Durability
  - ✓ Cost
- **Propulsion Materials**
  - ✓ Changing internal engine combustion regimes
  - ✓ Long lead time for commercialization
  - ✓ Need to reduce weight

Target

21CTP: Enable heavy duty diesel engine thermal efficiency of 55% by 2018
ACE: Improve commercial vehicle fuel economy at least 20%

Partners

- **Caterpillar Inc.**
- **Argonne National Lab**

Objectives

- Support ORNL-Caterpillar CRADA for materials-enabled high-efficiency diesel engine.
- Indentify the effect of heavy duty diesel (HDD) environment on the degradation processes of materials and components.
- Develop test methodology to characterize mechanical properties of complex-shaped HDD components with and without protective thermal coatings.
- Characterize thermal cycle durability of commercial and developmental protective thermal barrier coatings designed for HDD engine components.

Materials-Enabled Technologies for High Efficiency Diesel Engines: CRADA

This CRADA makes use of engine/combustion and materials expertise at Caterpillar and ORNL to provide new insight into the integration of these technologies through a materials-by-design approach to high temperature, high pressure engine operation.

- **Engine & tool**
- **Identification & prioritization of materials R&D needs**
- **Technical & hardware support**

CAT C15 ACERT Engine in ORNL Engine Cell

- **Engine performance studies**
- **Advanced diagnostics & combustion analysis**
- **Materials characterization & modeling**

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Materials & Engines approach provides a more complete understanding to better improve combustion, thermal management, emissions & cost reductions.

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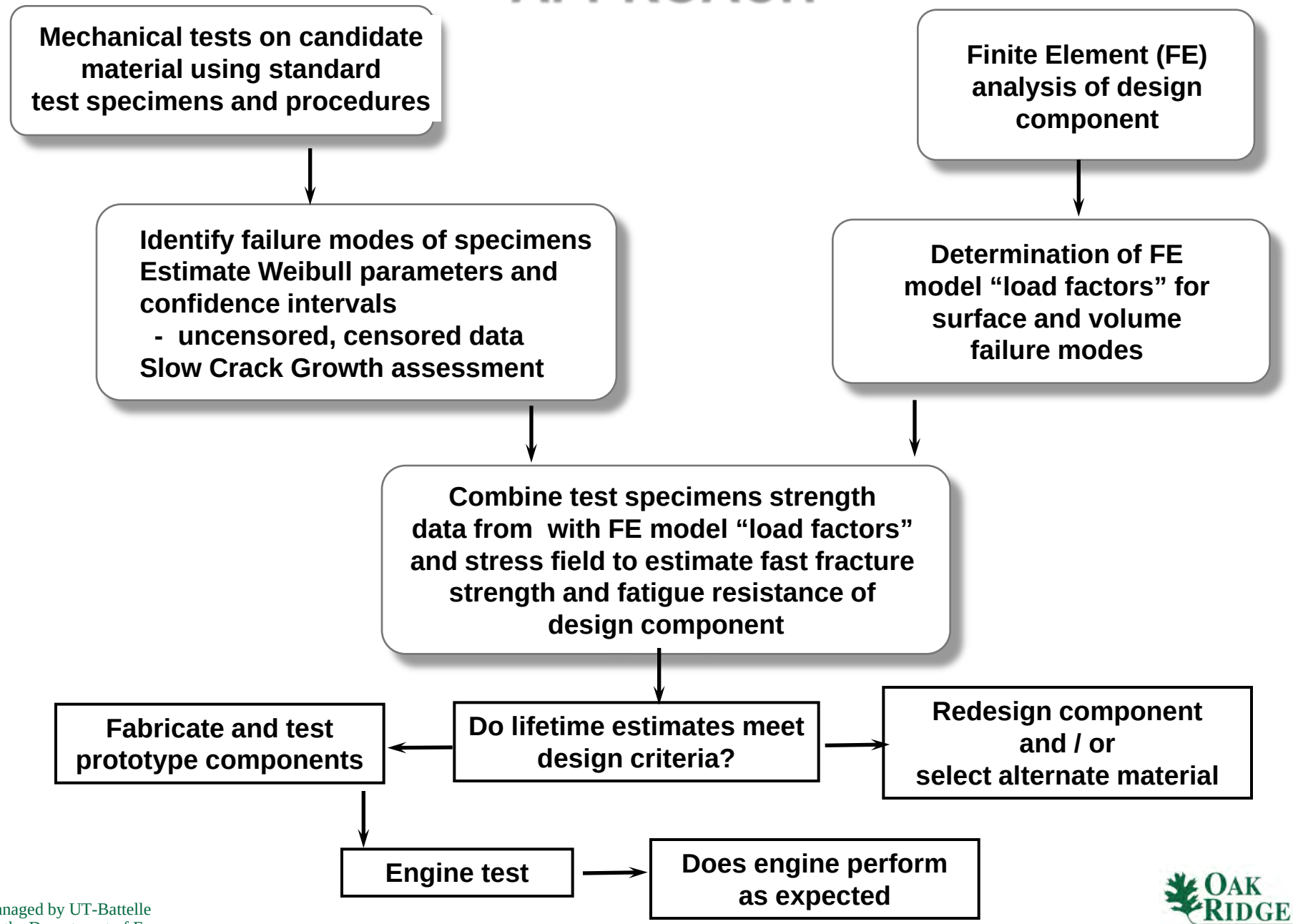
Milestones

Sept 2009 - Milestone: complete thermal cycle testing on coated coupons to understand the failure mechanisms (completed).

Sept 2010 – Milestone: testing and analysis of a prototype ACERT component with and without coating.

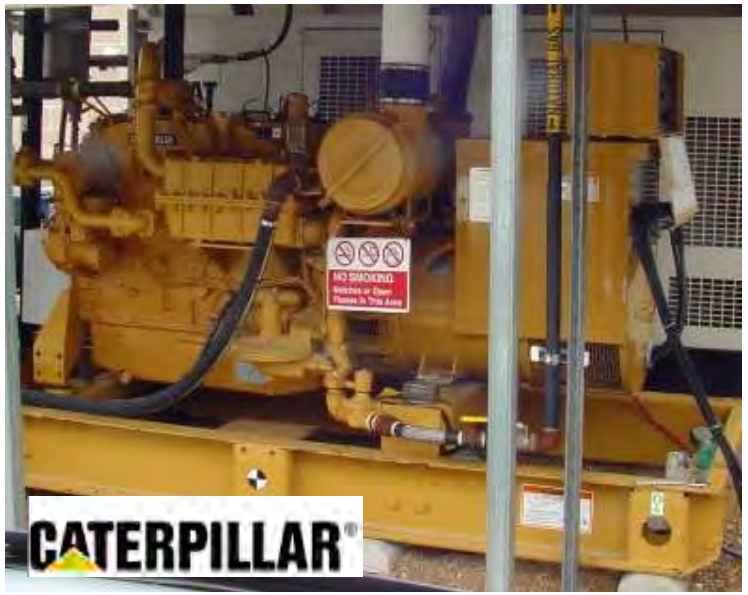
Sept 2011 – Present program summary and accomplishments at Annual Merit Review, April, 2011.

APPROACH

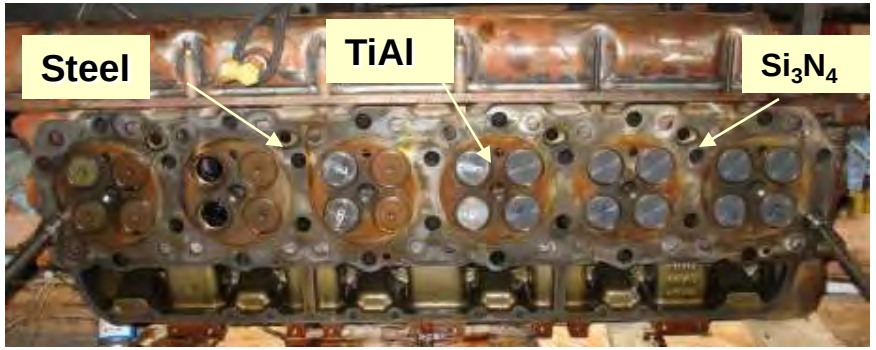


Accomplishments

Engine field test verified the component design and life prediction model for advanced light-weight valves



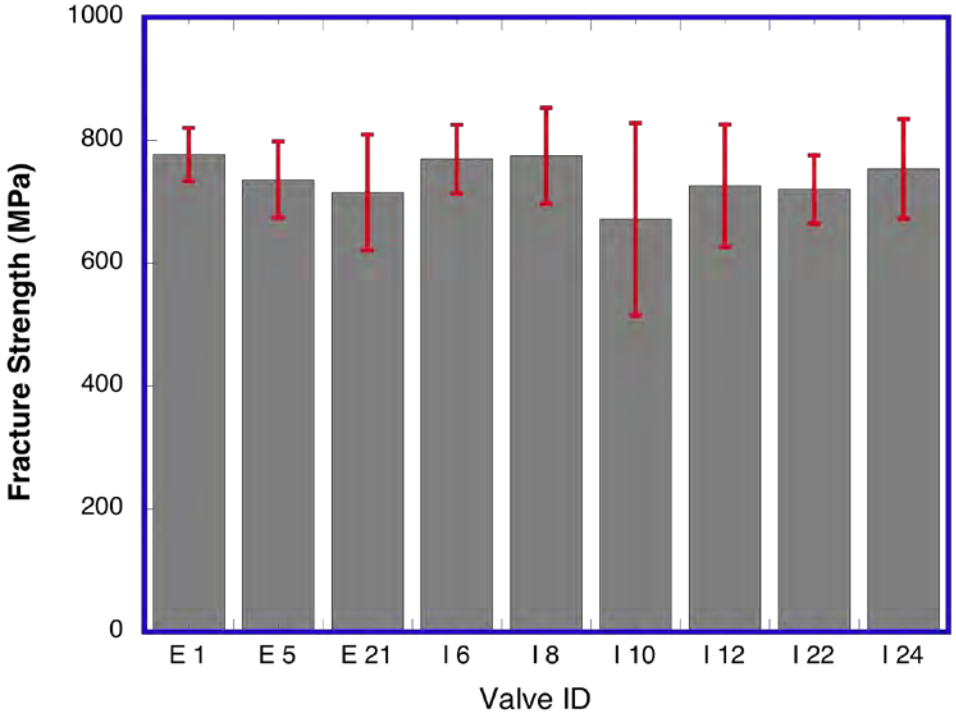
Valves tested:
Silicon nitride: Kyocera SN235P
TiAl: HOW45
Inconel: Nimonic 80A & 90
(current production materials)

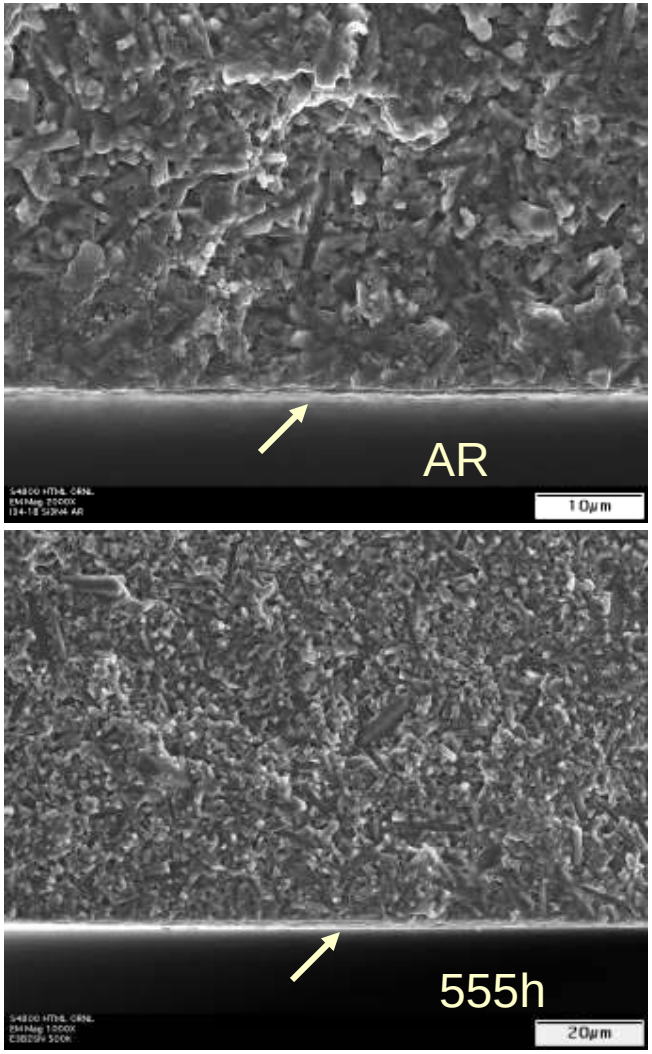


After 555h test at Cat G3406 natural gas engine the field test was discontinued

Accomplishments (continued)

Fracture strength data of tested valve stems provide insight into the environmental effect on the mechanical reliability of TiAl and Si_3N_4 engine-tested valves





Successfully verify ceramic valve design and life prediction

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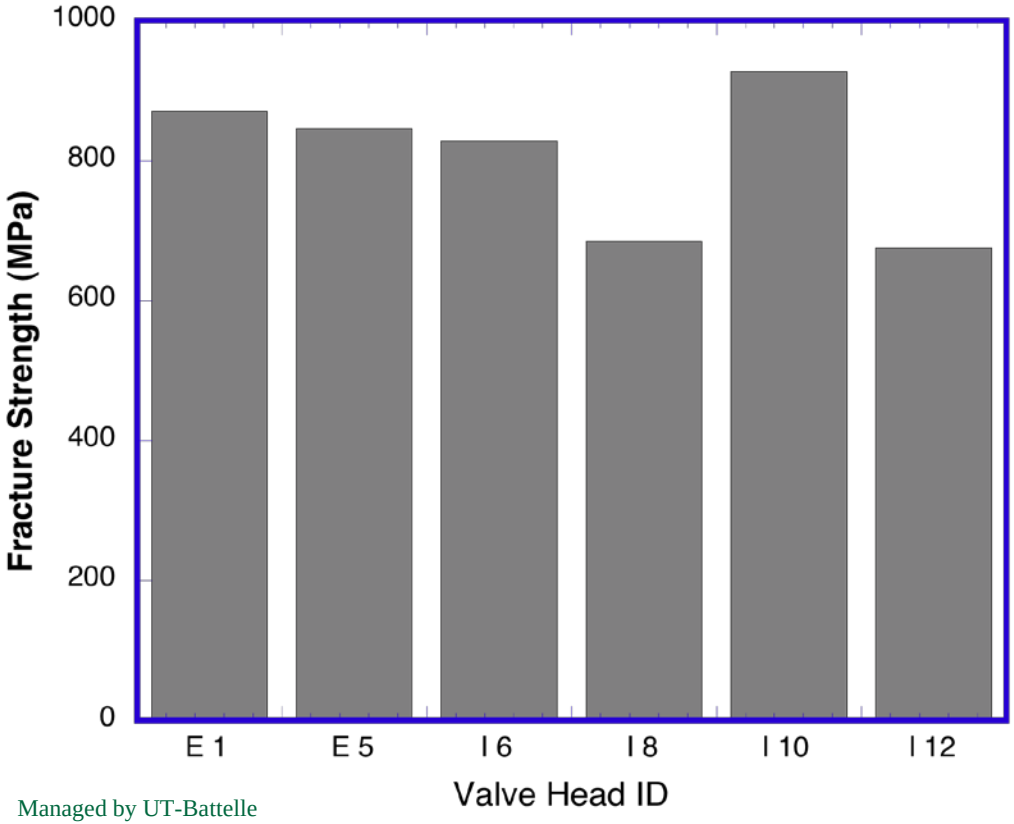
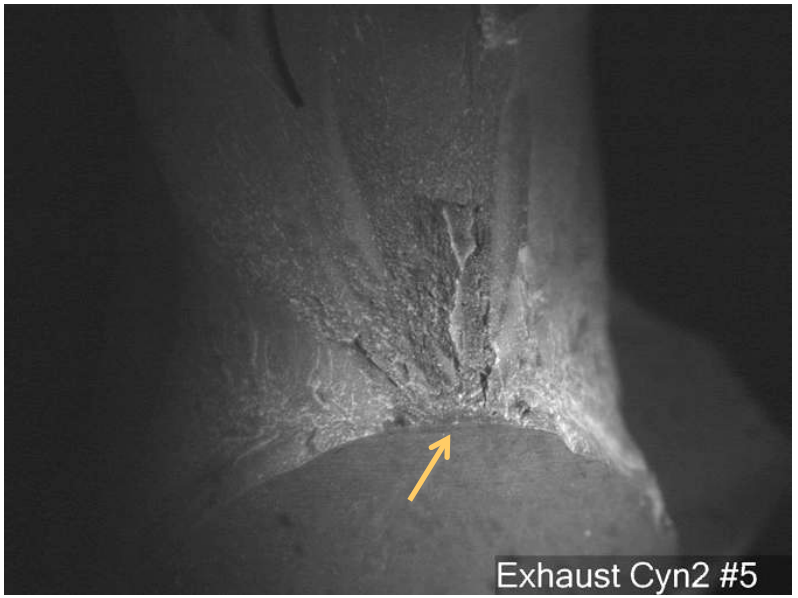
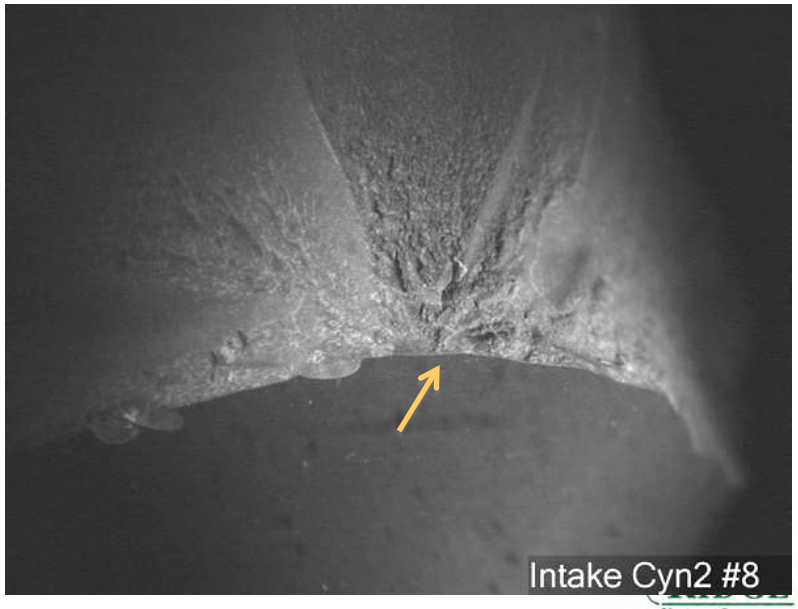
Accomplishments (continued)

Fracture mostly initiated at the original machining flaw (groove) region. There is little or no environmental effect on the mechanical performance of Si_3N_4 valves after 555h engine test.

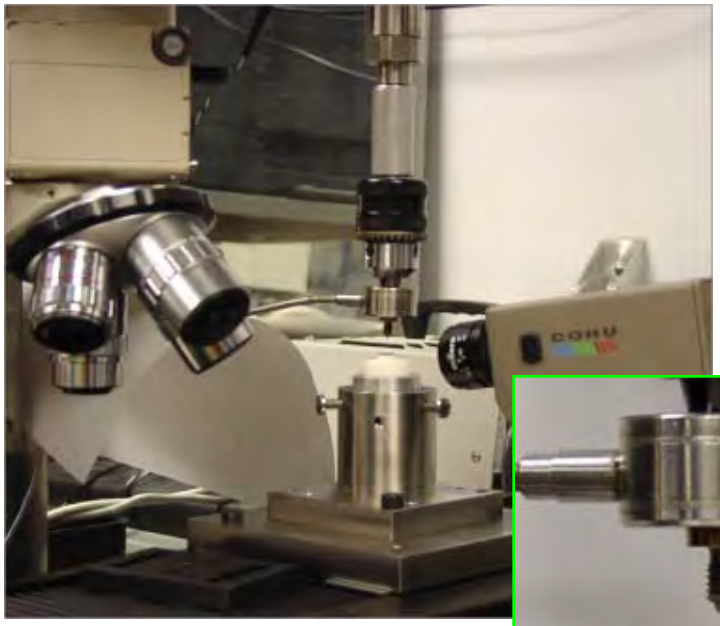


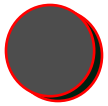




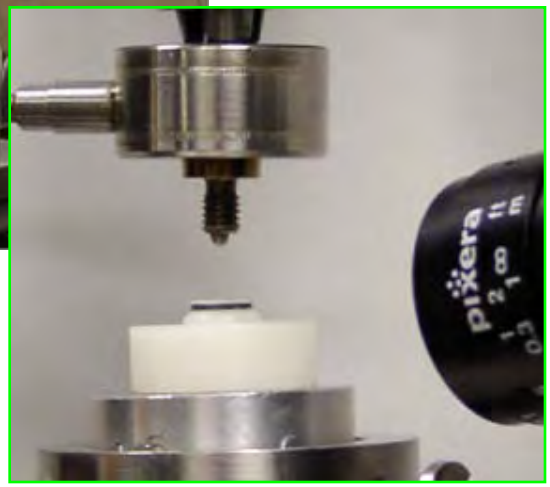
Accomplishments (continued)

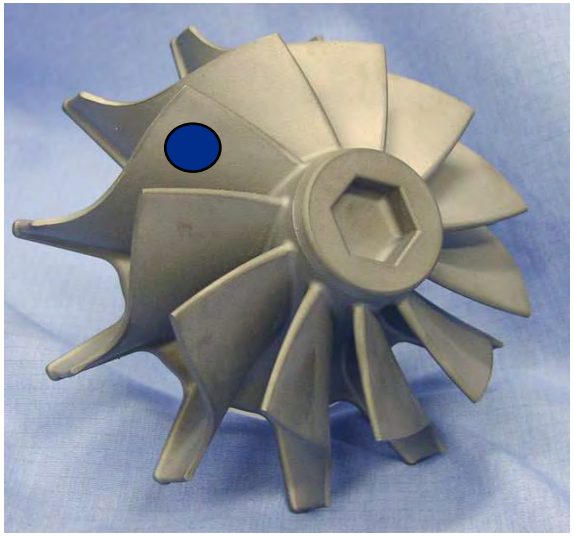
- Determine the mechanical properties of airfoils from TiAl turbo wheel.
- Provide “real” component database for verification of design and life prediction.





Dia. ~ 10 mm
t = 0.5 mm





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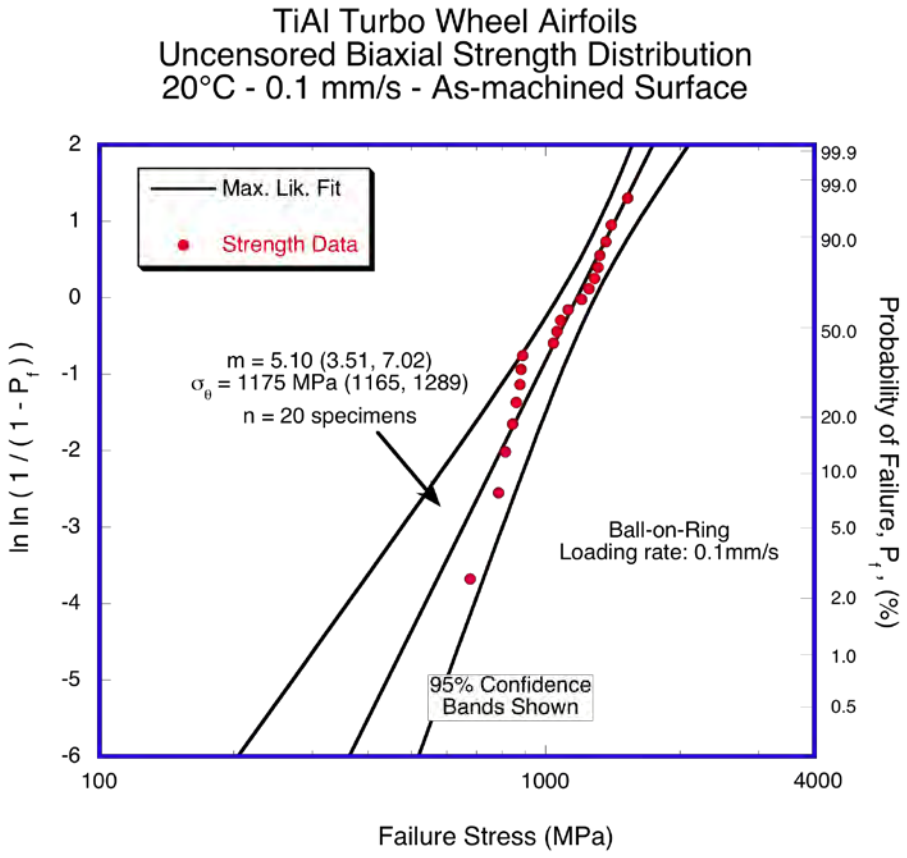
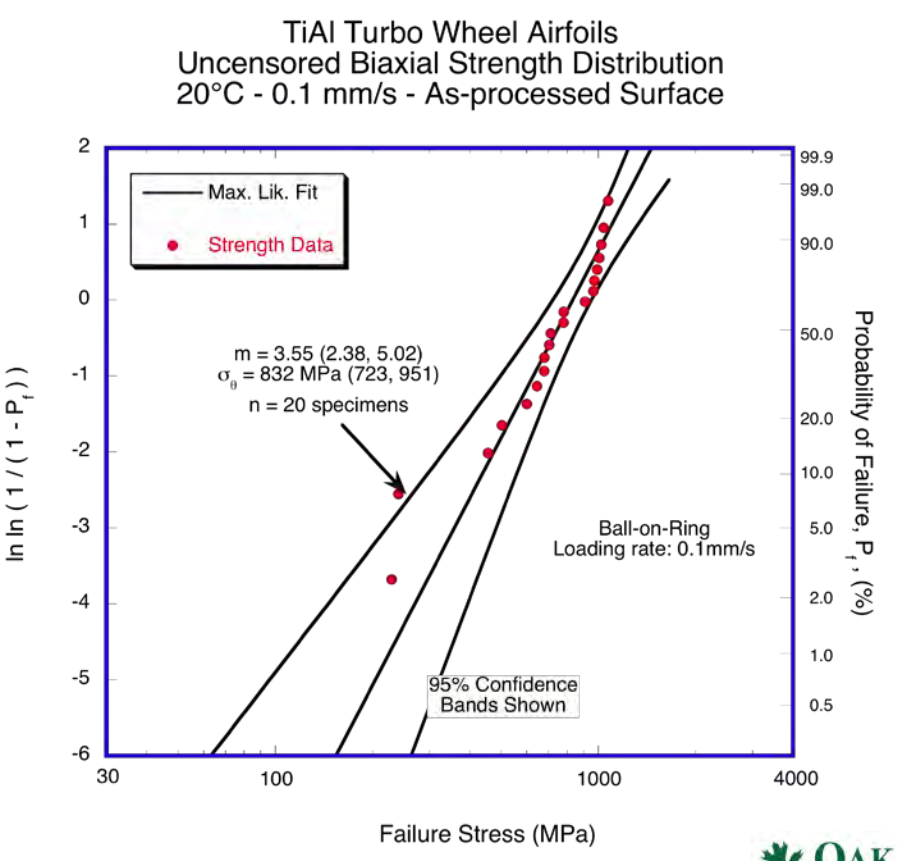
Controlled by personal computer with LabView program

Accomplishments (continued)

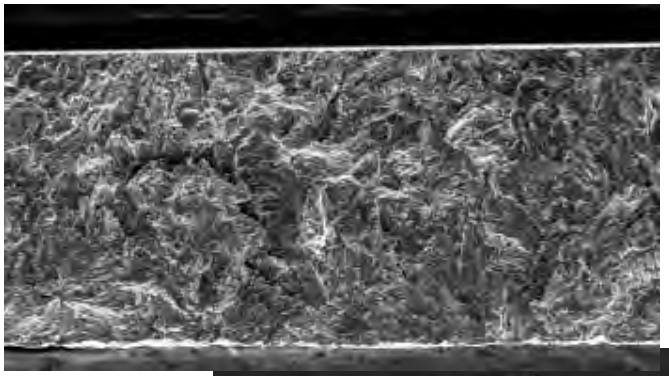
- **Fractography has been conducted on tested specimens.**
- **The strength of specimens with as-processed surface is ~ 30% lower than those with as-machined surface.**

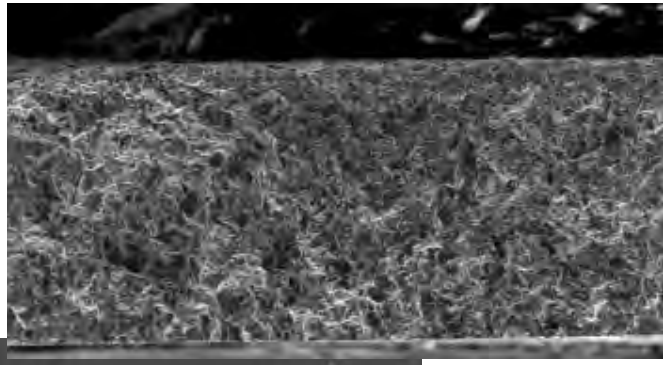


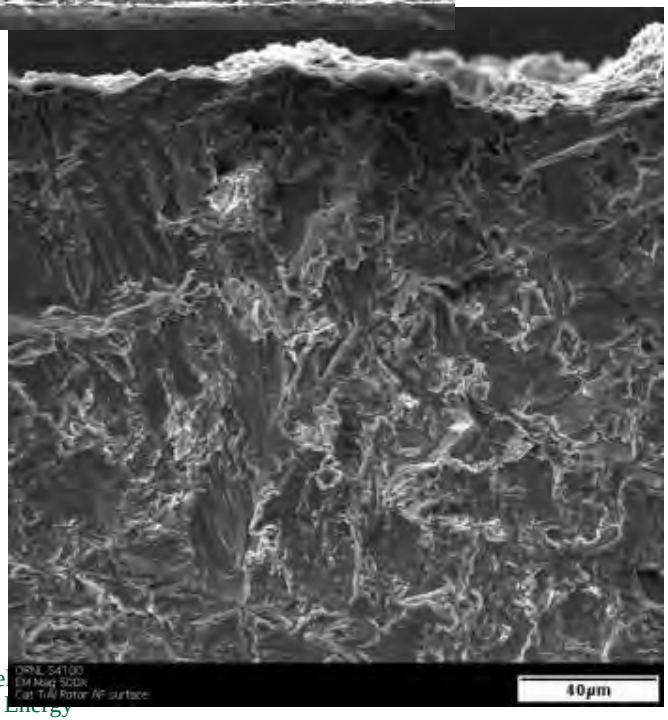


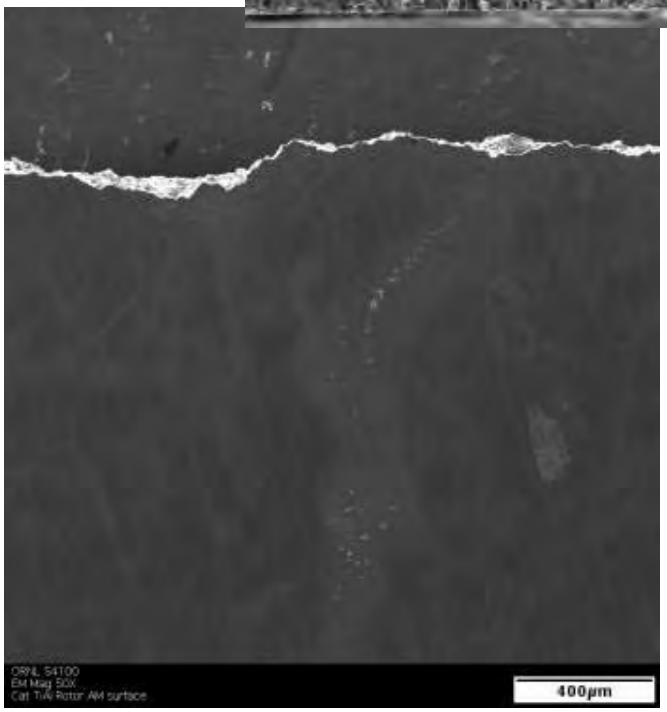
Accomplishment (continued)

- **The surface roughness feature contributed to the lower fracture strength measured for samples with as-received surface**







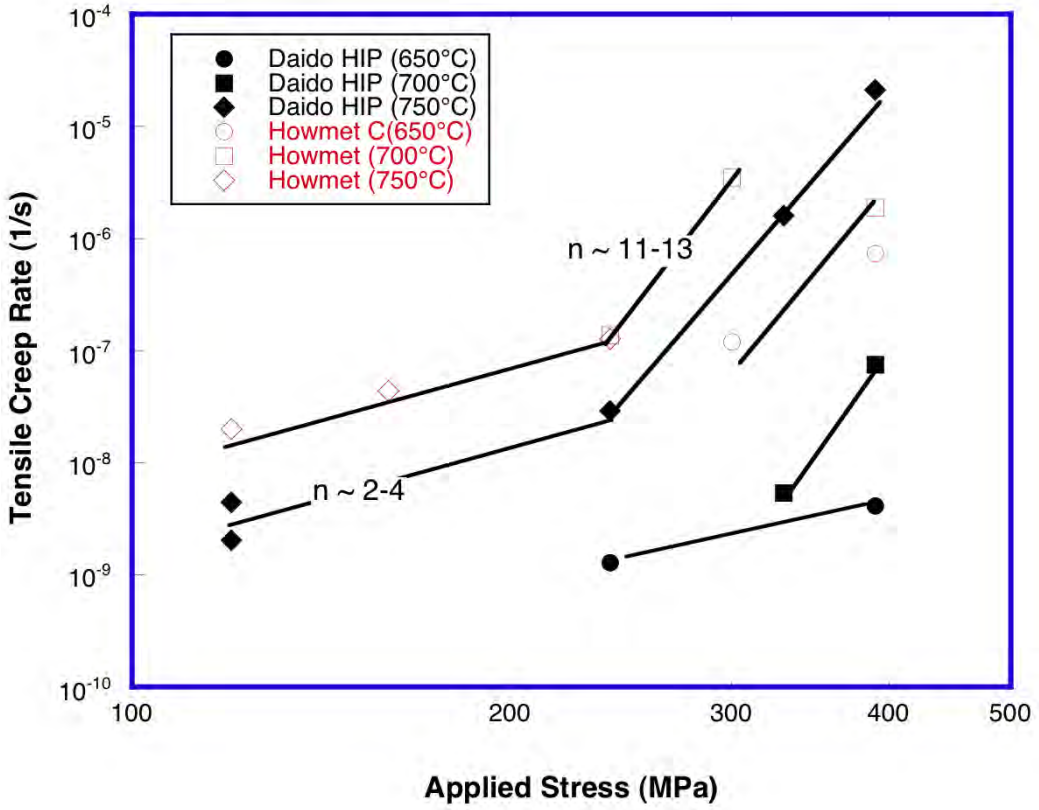


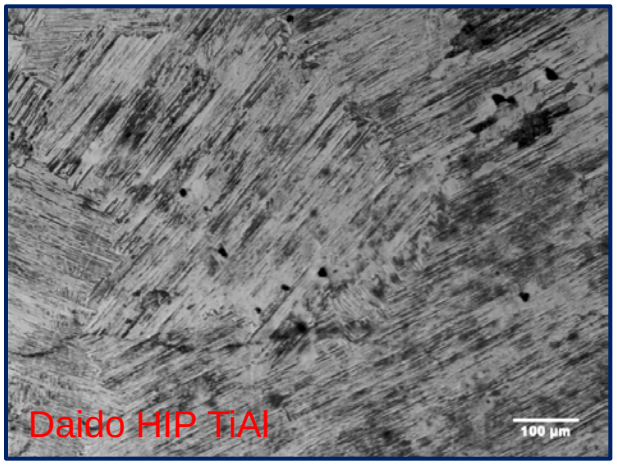
Ra= 0.33 µm

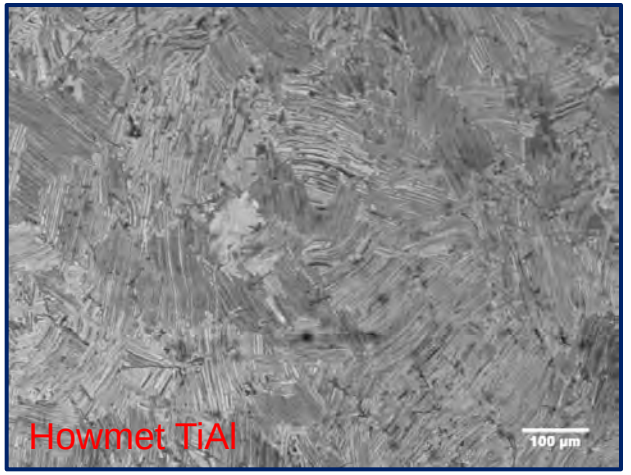
Ra= 3.28 µm

Accomplishments (continued)

- **Tensile creep database of commercial TiAl alloys was generated for probabilistic turbo rotor component design and life prediction**



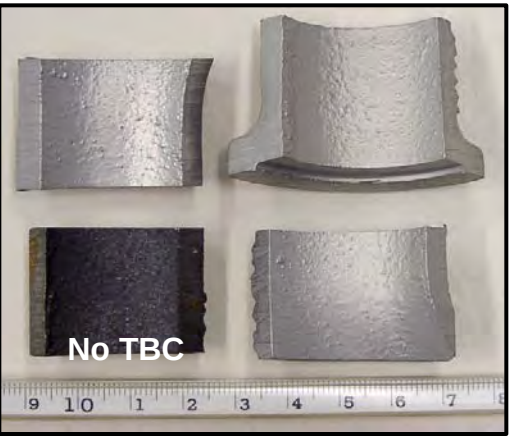




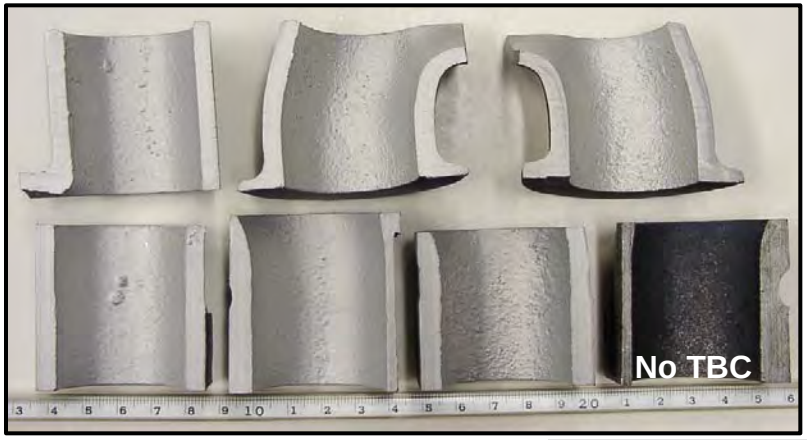
Differences in creep rates between two commercial alloys might result from the size of lamellar spacing, grain size, and composition

Accomplishments

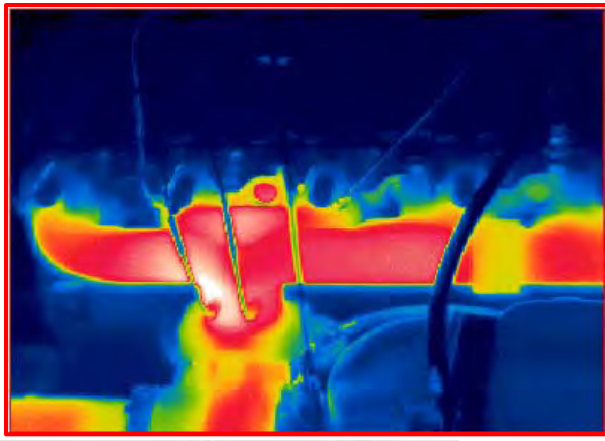
- **Application of durable thermal barrier coatings (TBCs) could significantly reduce heat rejection (thermal stress) and prevent the oxidation/corrosion induced degradation of HDD components**
- **Avoid the use of high-cost stainless steel materials for exhaust ports and manifolds component ($5M saving per year)**



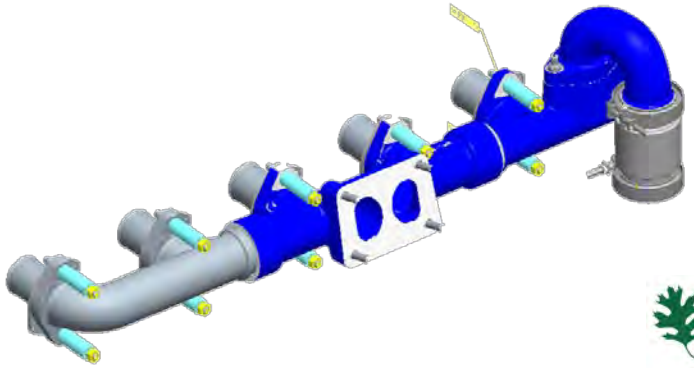
(1” x 1” coupons)



(2” x 2” coupons)

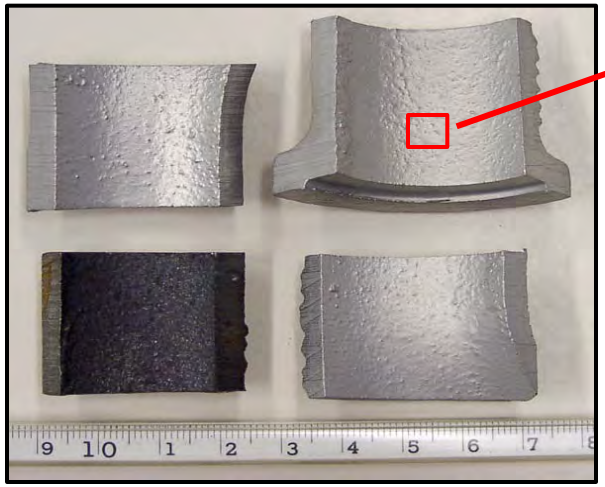


As-received ductile ferritic Fe-Si alloy coupons (similar to SAE J2582) with commercial oxide-based coating

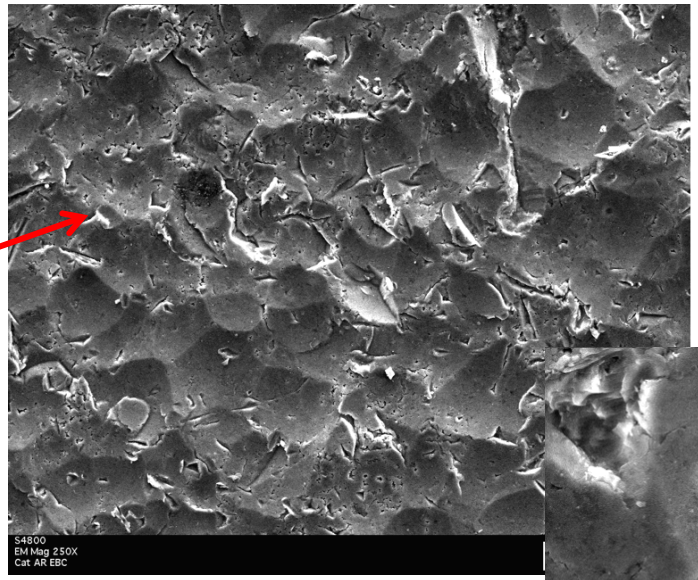


Accomplishments (continued)

- **Conversion Coating (by a commercial supplier) - corrosion resistant surface treatment (CRST) is a dip coating process can readily access manifold center section, which is the highest wear/oxidation state**

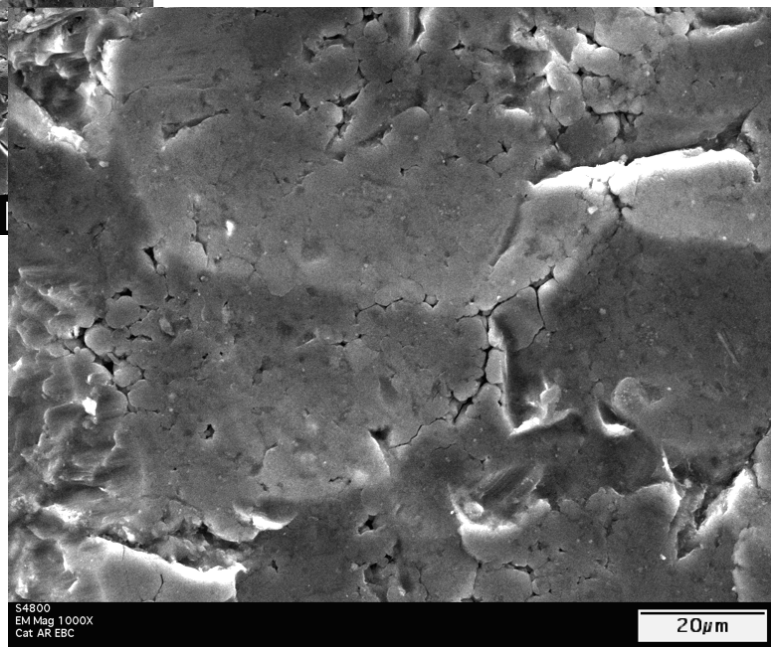


(1” x 1” coupons)



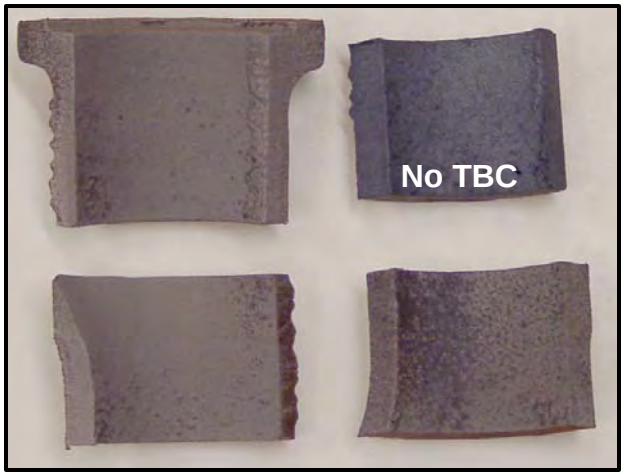
The as-deposited Al-oxide based coating exhibited concave feature with distinct granular microstructure

Nominal compositions (as-coated state): 89Al-1Mg-3P-7O (by wt%)

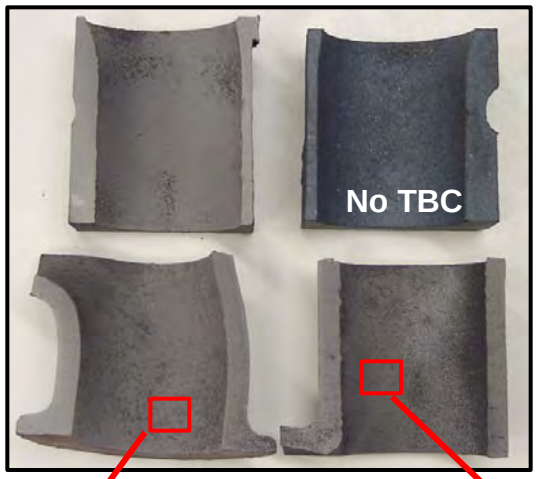


Accomplishments (continued)

- **Thermal durability test provides the baseline database and critical insight into the durability and integrity of TBCs**



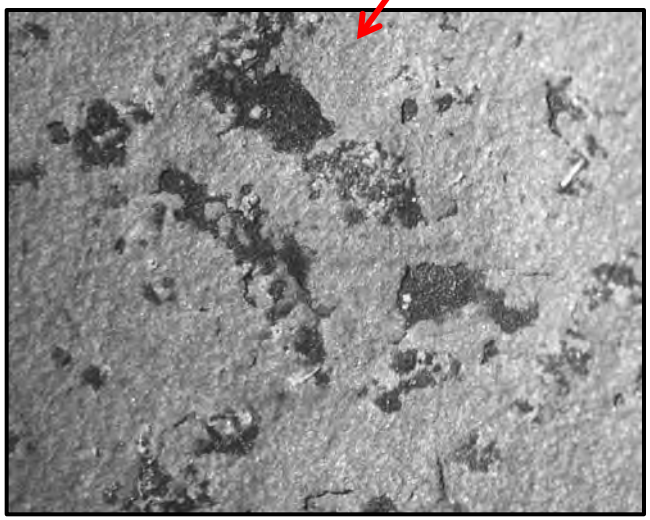
(1” x 1” coupons)

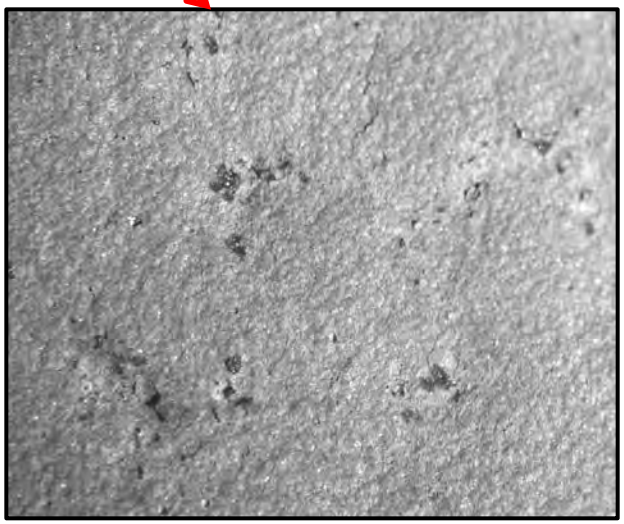


(2” x 2” coupons)

Thermal durability test: 500 thermal cycles between 300°C and 760°C in ambient air (simulated thermal cycles of HDD operation condition).

Coating spallation occurred in localized regions

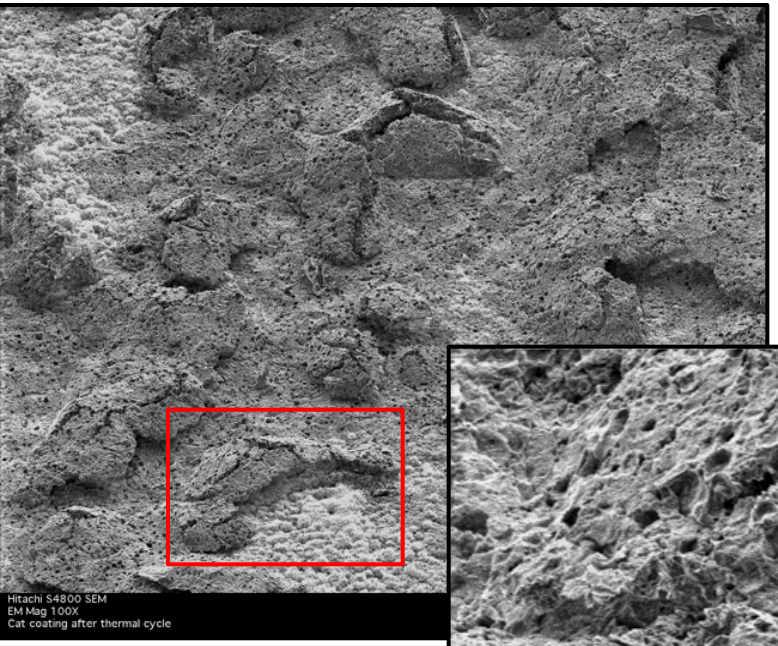


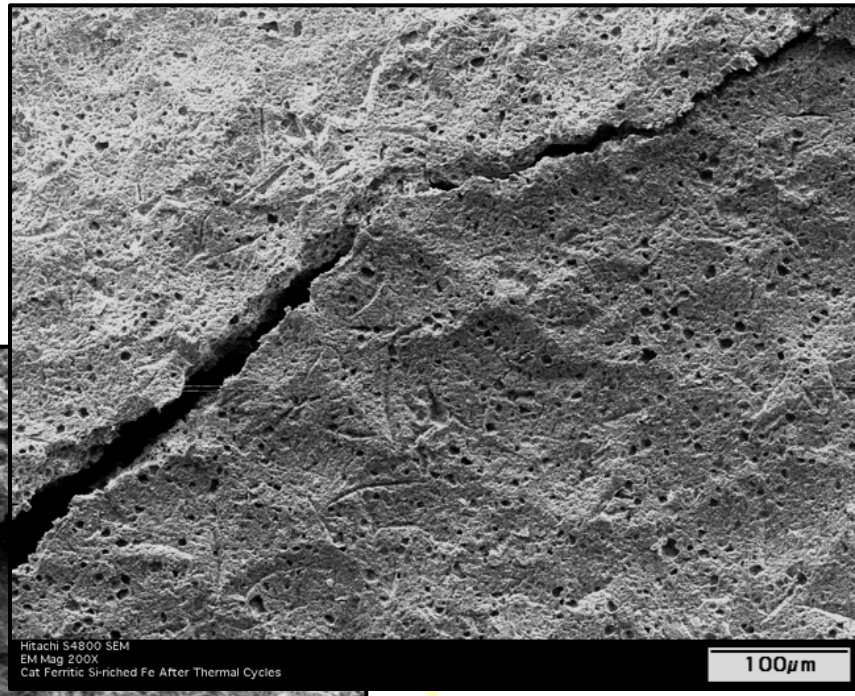


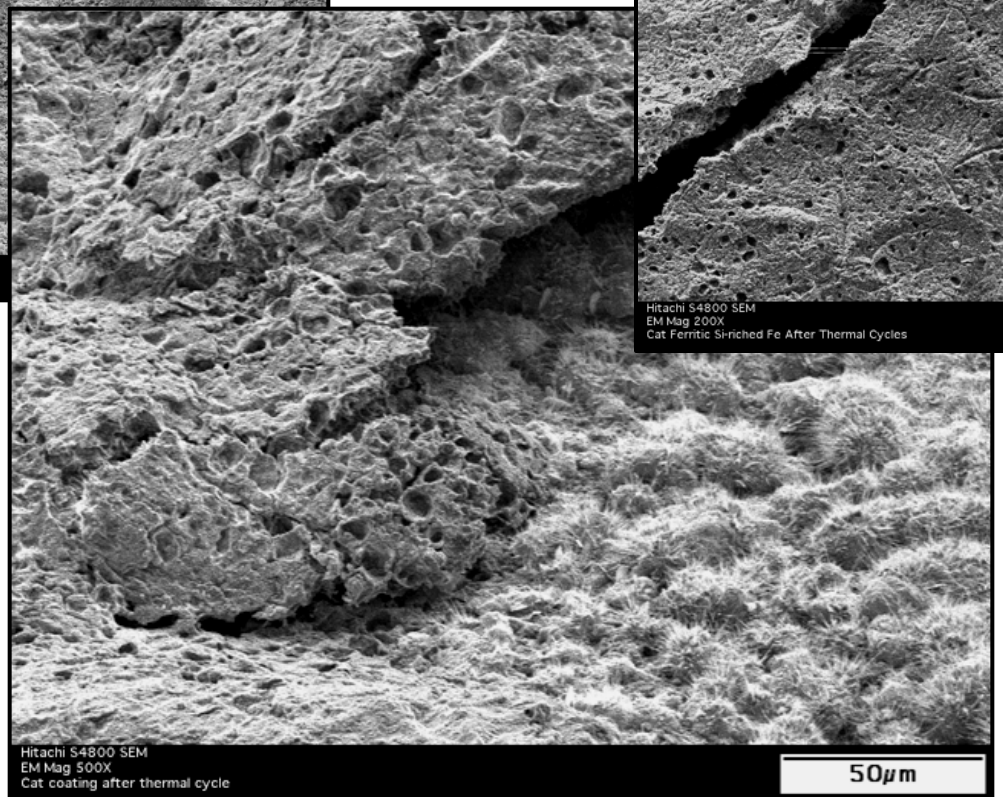
Optical surface features of coated coupons after 500h thermal cycles

Accomplishments (continued)

- **Extensive cracking, delamination, and spallation features observed after 500 thermal cycles between 300 and 760°C**





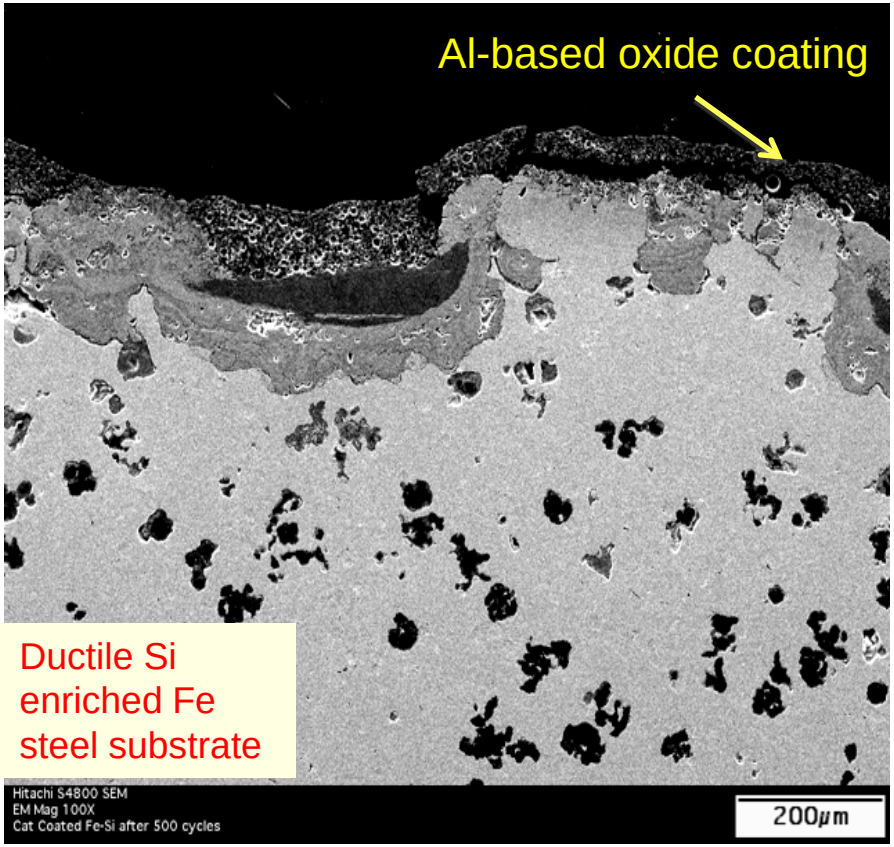


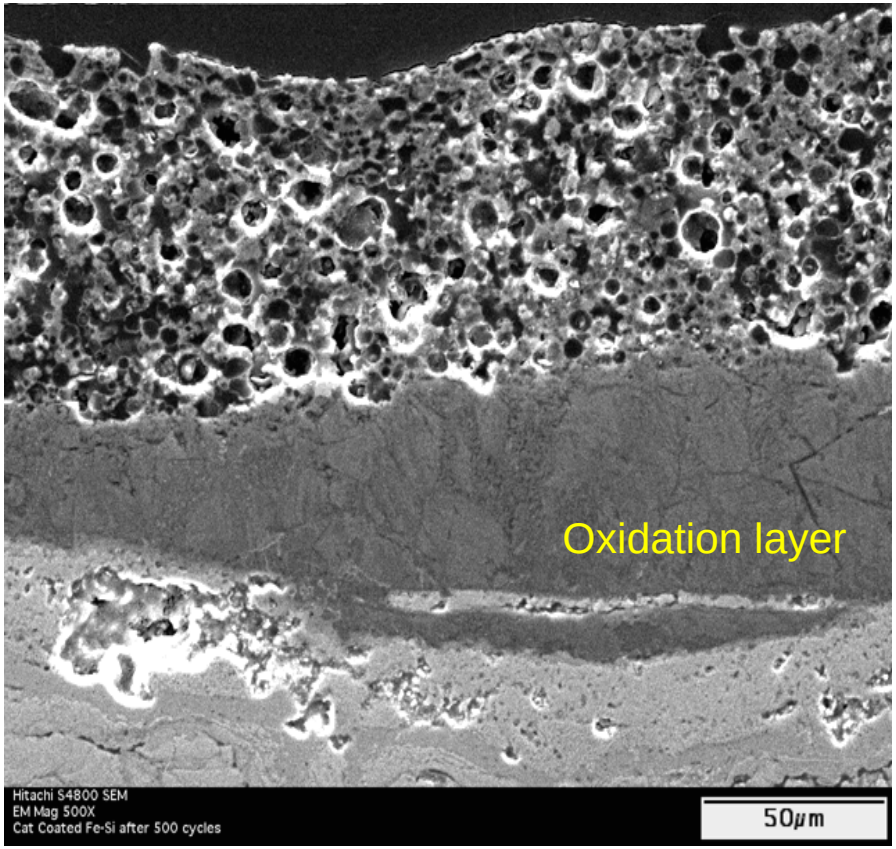
Presence of pores might result from the volatilization of unstable residual phase(s) during thermal cycles

Nominal compositions (after thermal cycle): 45Al-4Mg-6P-45O (by wt%)

Accomplishment (continued)

- **SEM of polished cross section show extensive cracking, delamination, and porous features**



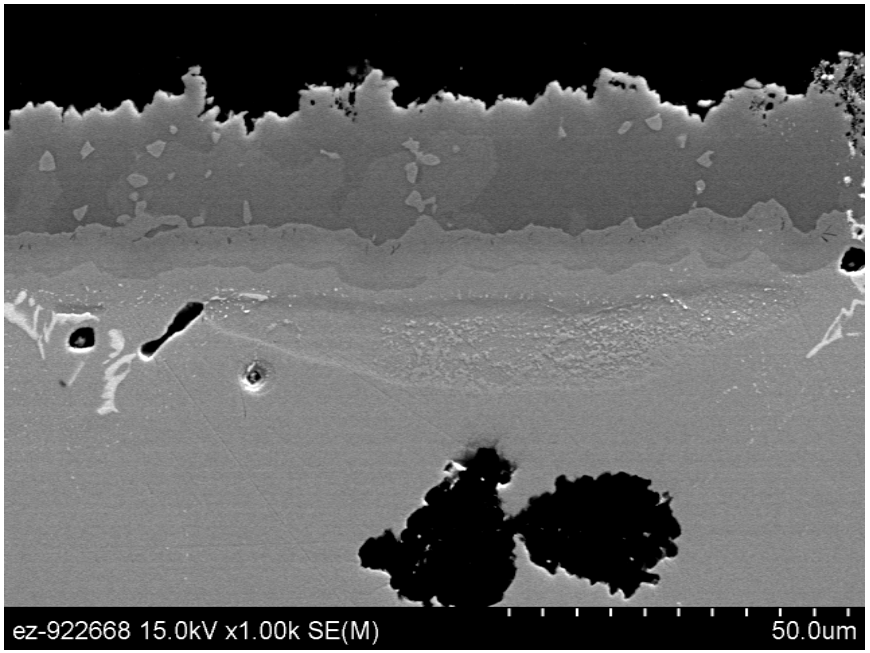


500 thermal cycles between 300° and 760°C in air

Presence of porous coating still provide some capability to slow down oxygen inward diffusion and thus oxidation reaction of ductile Fe steel substrate

Accomplishments (continued)

- Al-based coating deposited via ORNL colloidal process
- Colloidal process offers alternative low cost technology to deposit uniform coating on complex-shaped component
- Coating could be processed at lower temperature to reduce interaction between coating and Fe-based substrate



- Aluminum powder
- Polyacrylic acid (PAA) - dispersant
- PL001 – rheological modifier
- 750°C, 2 hrs in argon

Uniform, dense, and coherent Al-oxide based coating was successfully achieved via slurry process

Collaborations

Partners

• Argonne National Laboratory: collaborations on the NDE of advanced HDD engine components with and without protective thermal barrier coating.

• Caterpillar: A 3-years ORNL-Caterpillar CRADA on high-efficiency HD engine (ACERT) was officially established and carried out since Oct. 2008.

• Jet-hot: a commercial coating supplier.

Technology transfer

• Collaborations with Argonne National Laboratory allow one to identify the critical pre-existing flaws or flaws introduced after ACERS engine testing that could impact on the long-term component durability and performance.

• CRADA with Caterpillar would facilitate the identification of key components and materials technology to implement advanced materials to achieve 55% engine thermal efficiency by 2018.

• Collaboration with Jet-hot could lead to the optimization of coating processing and composition to improve the long-term durability.

Materials Evaluation Research Plan – Future Work

- Program was successfully completed in FY2010. The expected future work is product development and commercialization by our industry partner, Caterpillar.

Summary

- This poster provides a summary of research efforts accomplished between FY2009 and FY2010.
- Characterization of mechanical properties and microstructure of engine tested valves were completed. Mechanical and microstructure results confirmed probabilistic valve component design and life prediction.
- As-cast TiAl turbo wheel airfoil exhibited 30% lower strength than the machined surface.
- The commercial coating became porous in nature after thermal cycling. Also, features of extensive cracking, delamination, and spallation of coating were also observed.
- An Al-oxide based coating via a dip or slurry based approach was developed by ORNL. Test results showed the coating was dense and intact after the conversion process.
- This presentation is a final summary of the accomplishments for the program.