

Durability of ACERT™ Engine Components

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June 10, 2010, Washington, D.C.

**Project ID
#pm033**

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Overview

Timeline

- **Start – Oct 2008**
- **Finish – Sept 2011**
- **~ 50% Complete**

Budget

- **Total project funding**
 - DOE – \$600K
- **Funding received in FY09**
 - \$200K
- **Funding so far for FY10**
 - \$149K

Barriers

- **Advanced Combustion Engine:**
 - ✓ Increasing efficiency while reducing pollutant formation
 - ✓ Controls for lean-burn combustion engines
- **Propulsion Materials**
 - ✓ Materials issues impacting high efficiency engines using conventional & alt. fuels

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**
- **Jet-Hot**



Objectives

- **Support ORNL-Caterpillar CRADA for materials-enabled high-efficiency diesel engine.**
- **Identify 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



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

CAT® C15 ACERT™
Engine in ORNL
Engine Cell

CATERPILLAR

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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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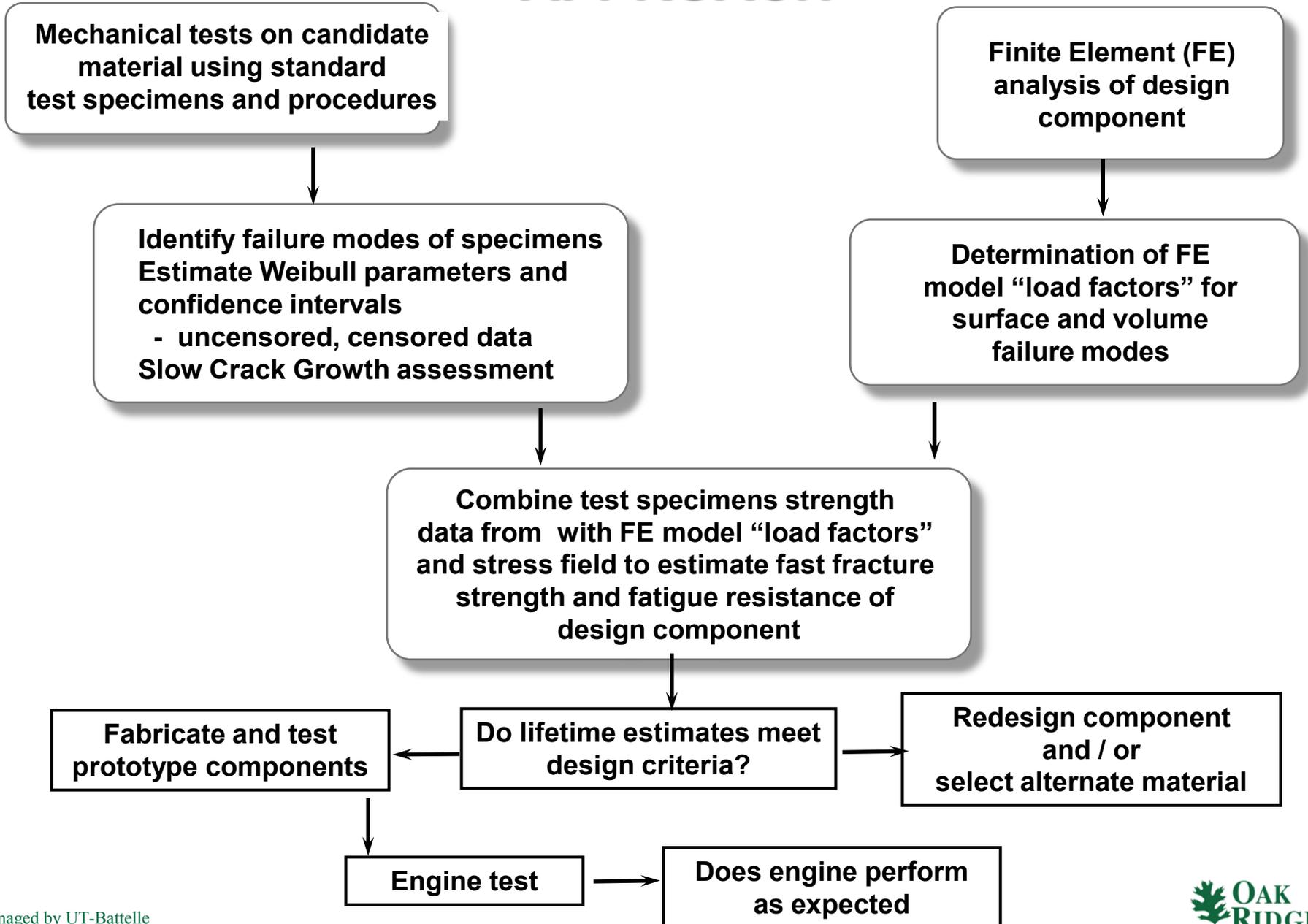
Milestones

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.

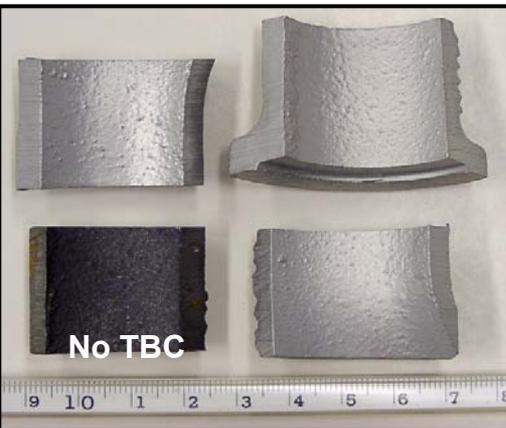
Sept 2011 – Milestone: testing and analysis of candidate Tier 4 ACERT™ components after field test.

APPROACH



Accomplishments

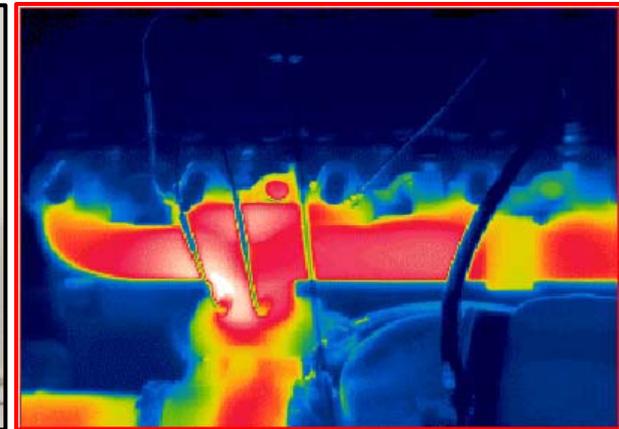
- Application of durable thermal barrier coatings (TBCs) could significantly reduce heat rejection (thermal stress) and prevent the oxidation/corrosion induced degradation of HDD components
- Avoid the use of high-cost stainless steel materials for exhaust ports and manifolds component (\$5M saving per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



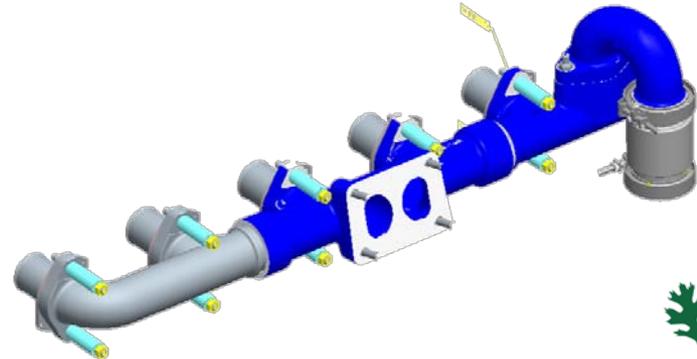
(1" x 1" coupons)



(2" x 2" coupons)



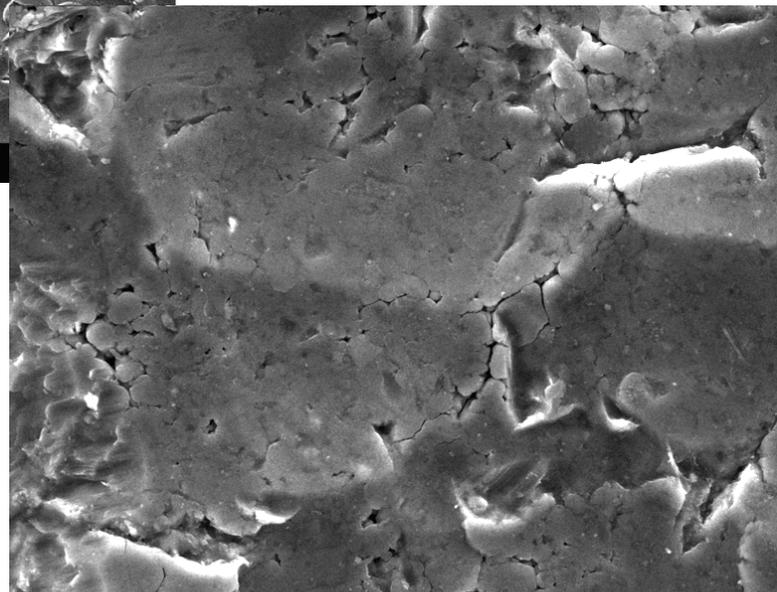
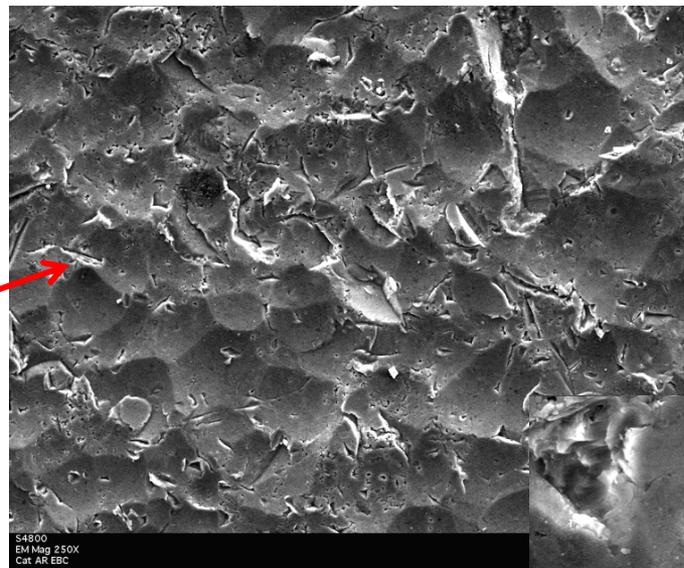
As-received ductile ferritic Fe-Si alloy coupons (similar to SAE J2582) with commercial oxide-based coating



Accomplishments (continued)

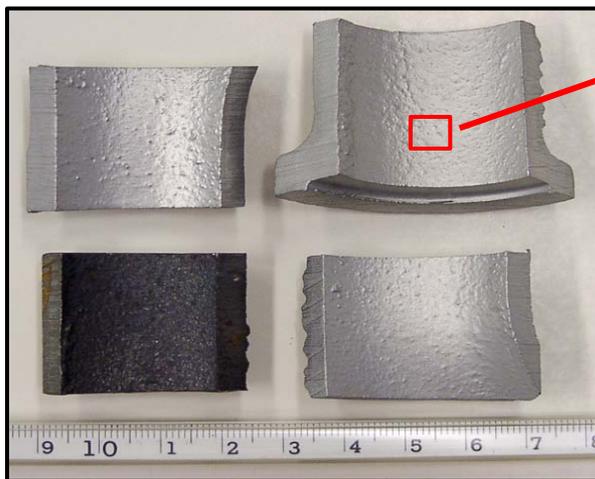
- Conversion Coating (by a commercial supplier) - corrosion resistant surface treatment (CRST) is a dip coating process can readily access manifold center section, which is highest wear/oxidation state

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



20µm

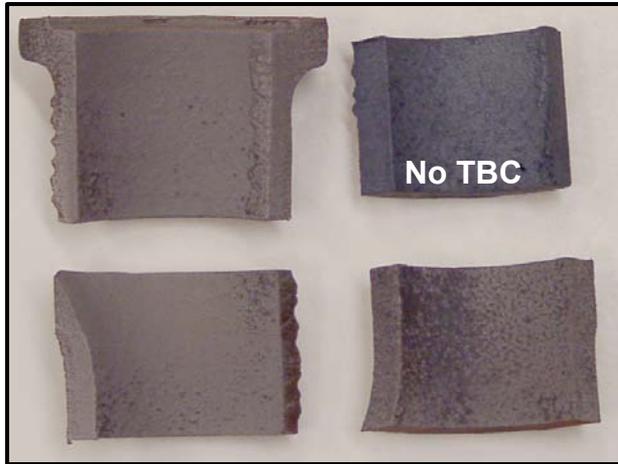
Nominal compositions
(as-coated state):
89Al-1Mg-3P-7O (by wt%)



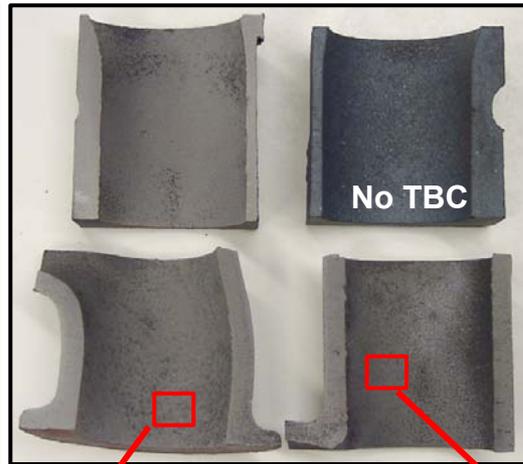
(1" x 1" coupons)

Accomplishments (continued)

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



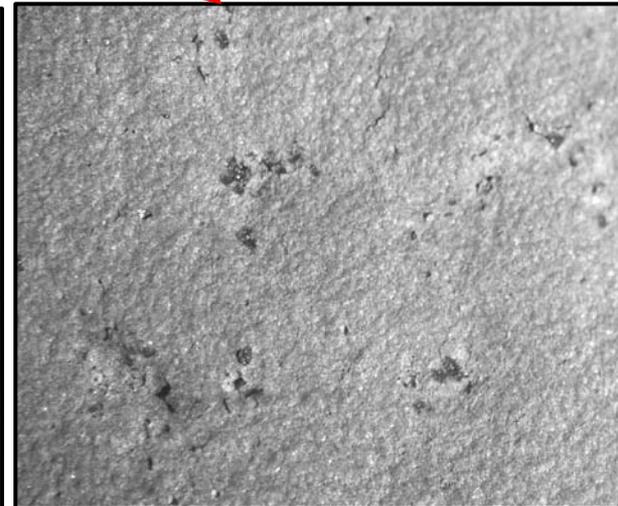
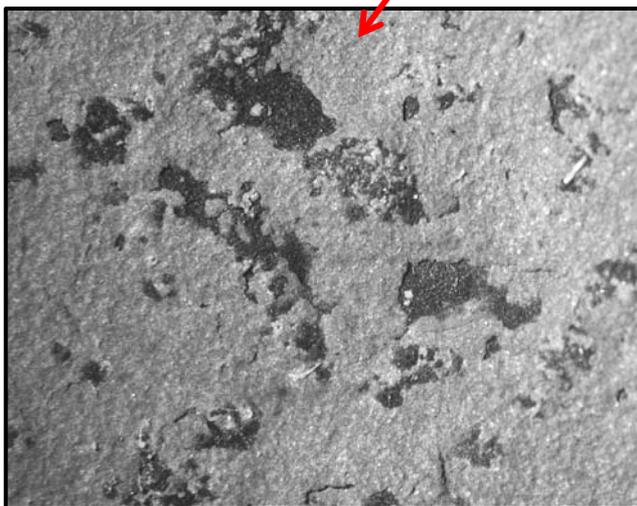
(1" x 1" coupons)



(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).**

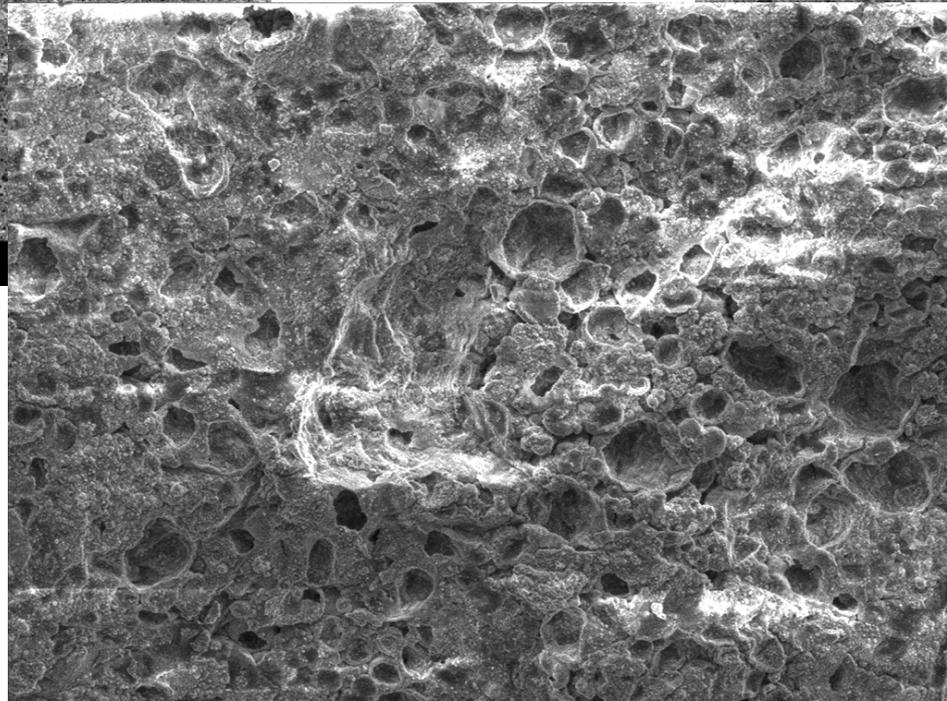
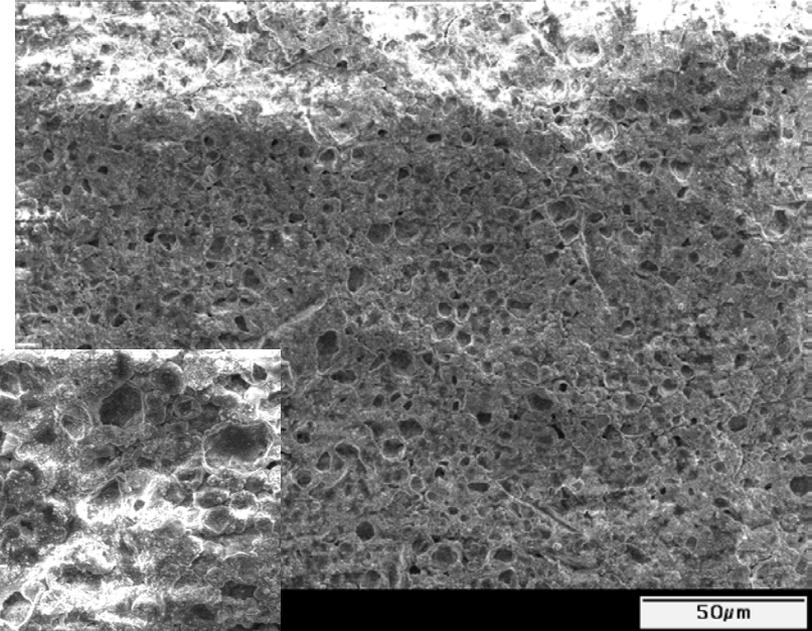
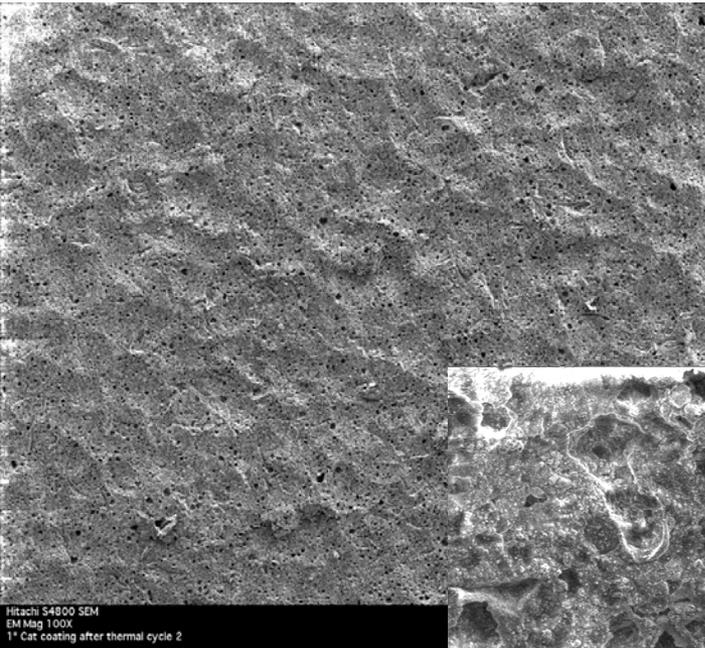
**Coating
spallation
occurred in
localized
regions**



**Optical surface
features of
coated
coupons after
500h thermal
cycles**

Accomplishments (continued)

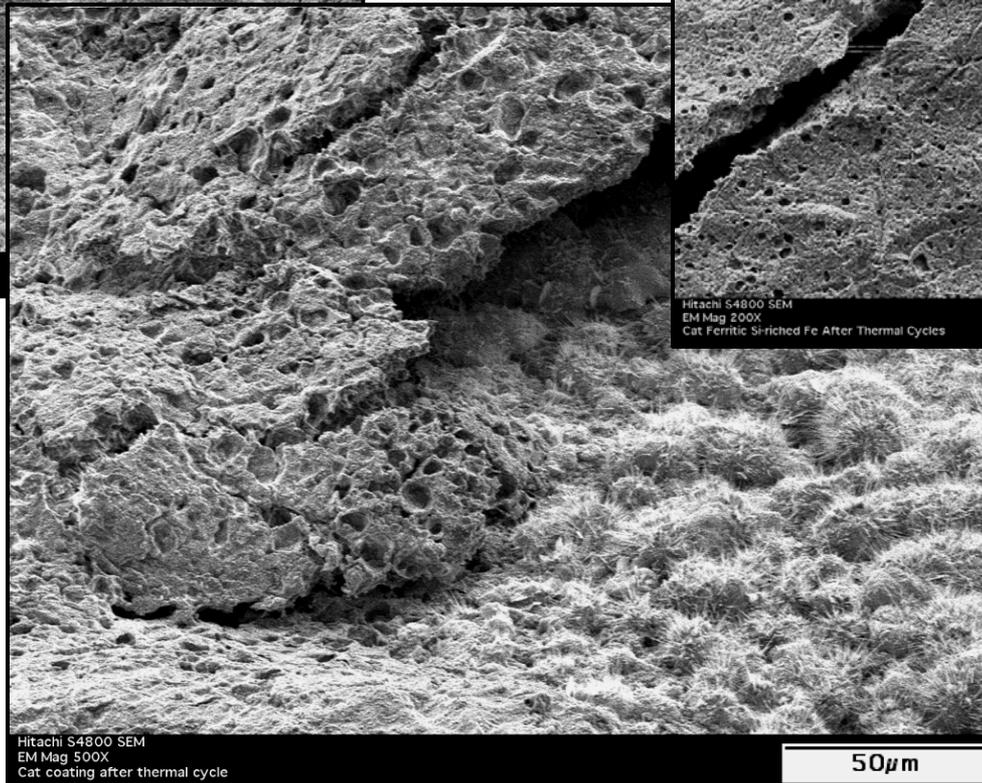
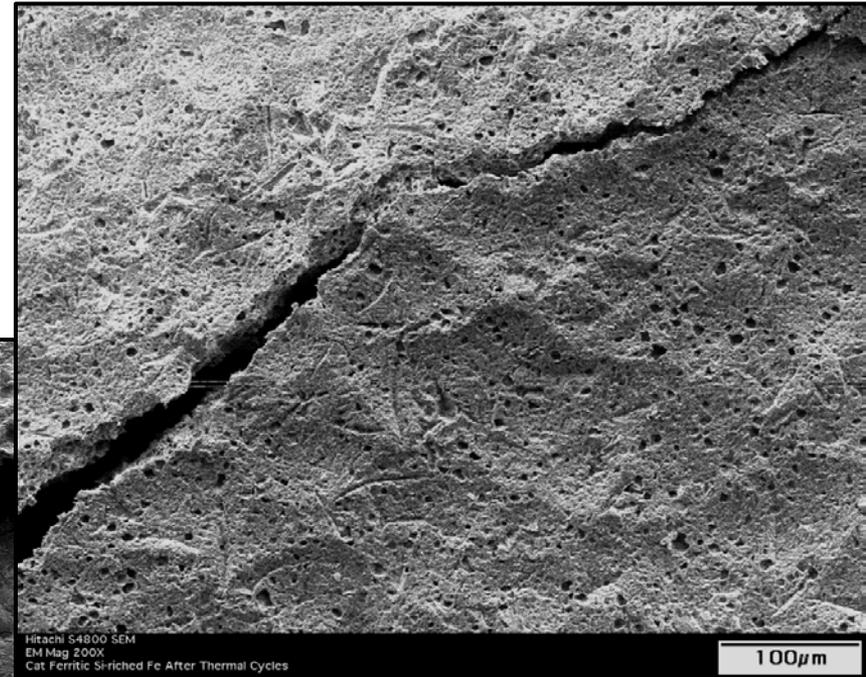
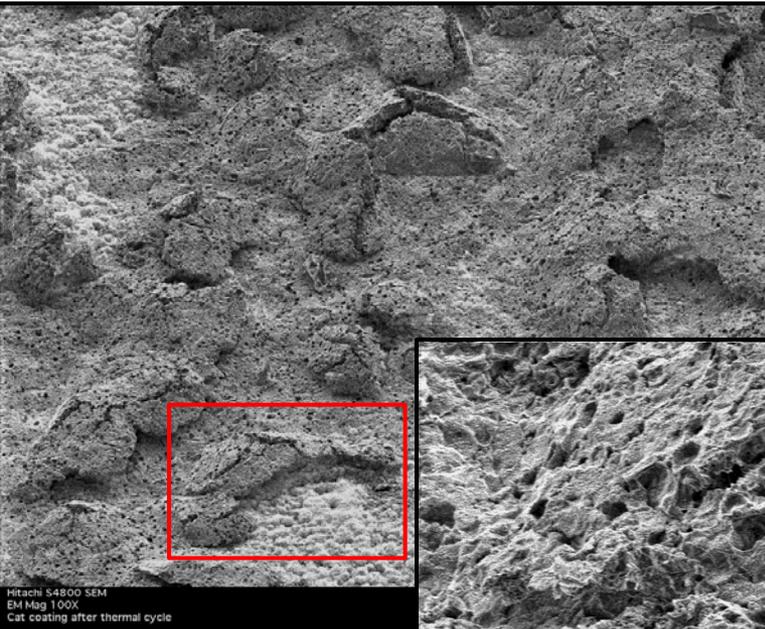
- Porous microstructure observed in intact region after 500 thermal cycles between 300 and 760°C in air



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

Accomplishments (continued)

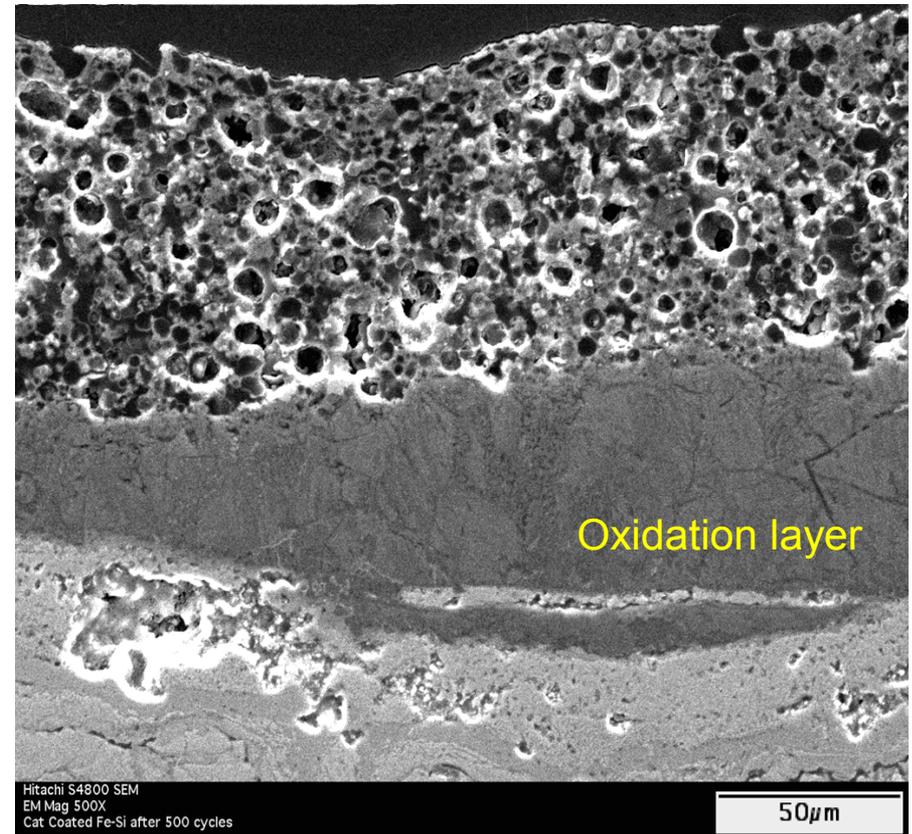
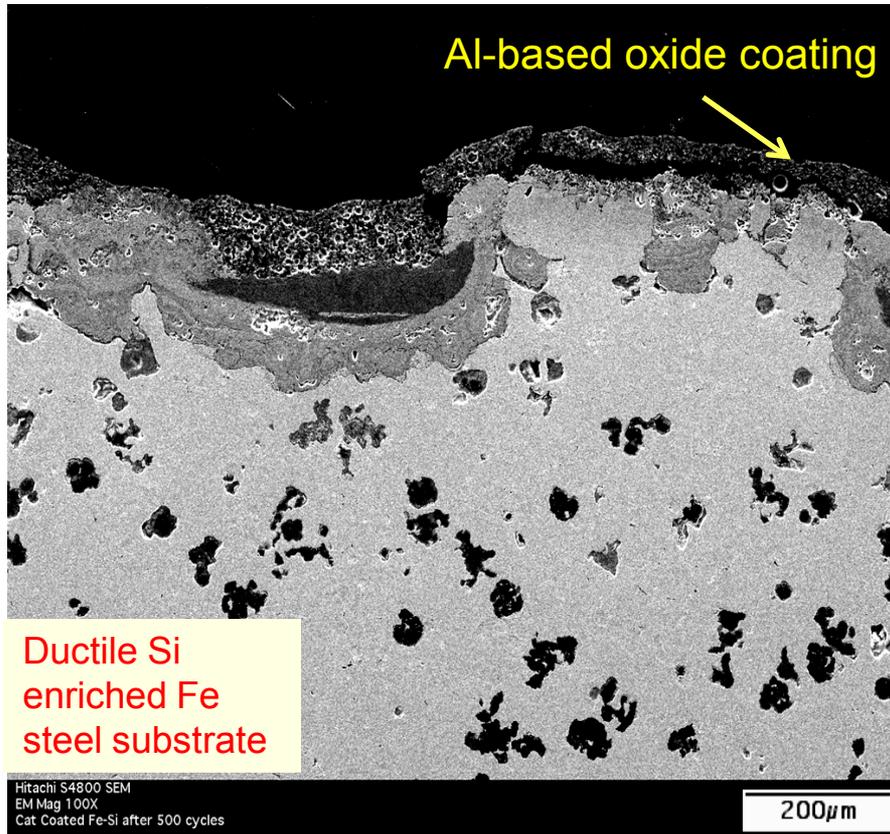
- Extensive cracking, delamination, and spallation features observed after 500 thermal cycles between 300 and 760°C



**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

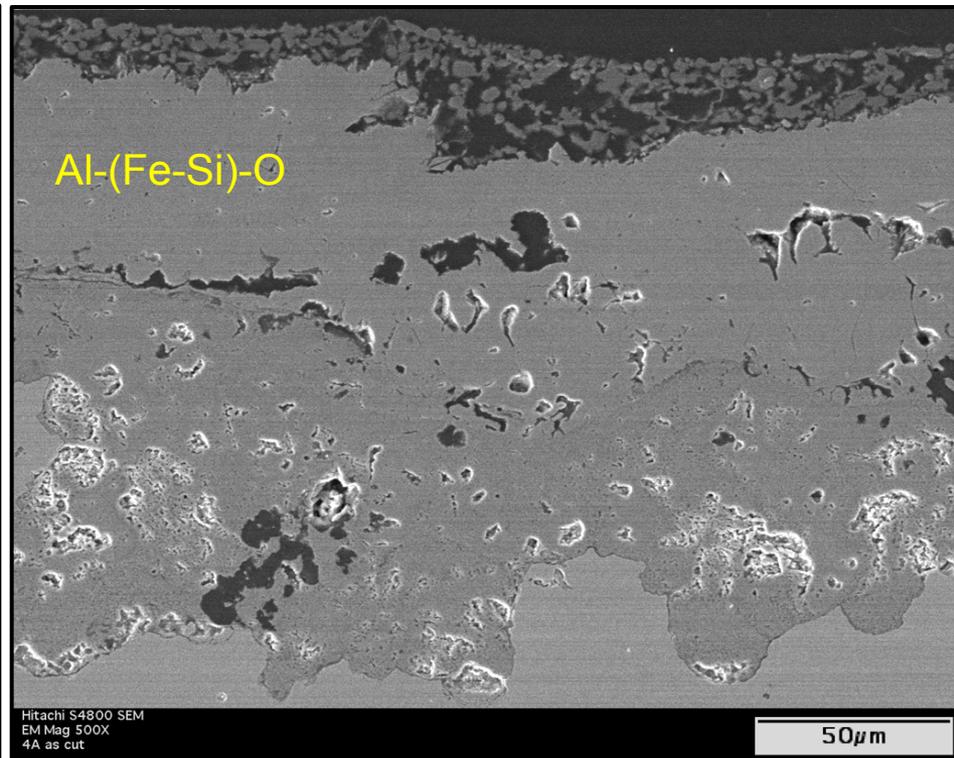
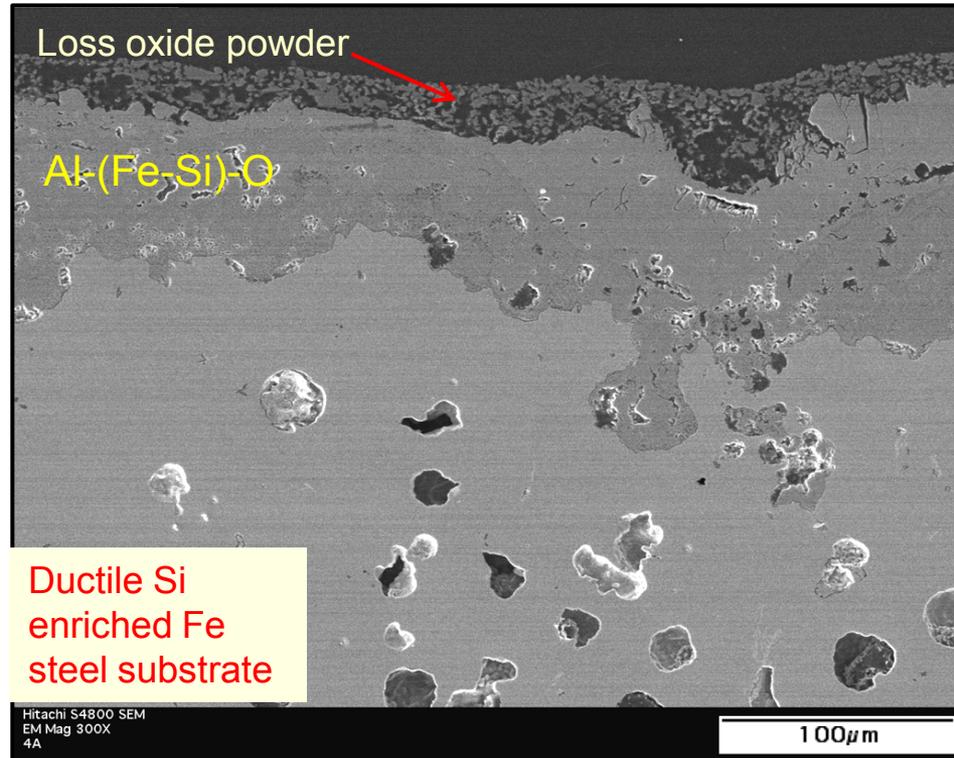
Presence of porous coating still provide some capability to slow down oxygen inward diffusion and thus oxidation reaction of ductile Fe steel substrate

Accomplishment (continued)

- Colloidal processing offers a low cost alternative approach for producing uniform coatings on complex-shaped components via a simple dip coating process (ORNL slurry process).
- Oxide-based coating could be processed at lower temperature and shorter times, thus preventing the interaction (chemical reaction) between the coating and ductile Fe-based substrate.
- Polyacrylic acid anionic polyelectrolyte) was used as the dispersant and PL001 as the rheological modifier for the Al system
- Aluminum metal powder ($\sim 13.19 \mu\text{m}$) was used in this study.
- The Al-oxide based coating was employed via a dip or slurry based process.
- A post heat treatment at 850°C in air was carried out to convert the slurry coating into the oxide based coating.

Accomplishments (continued)

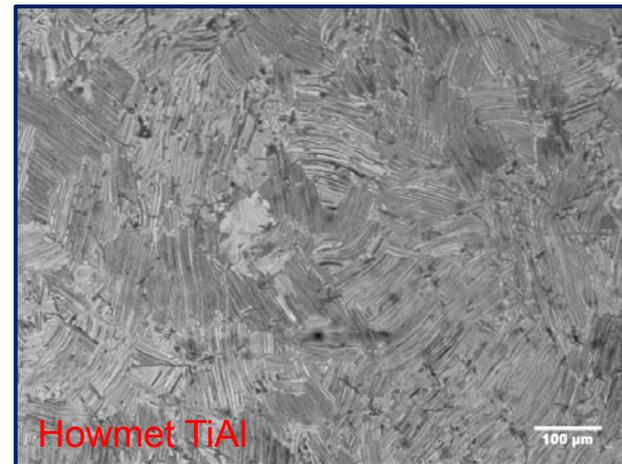
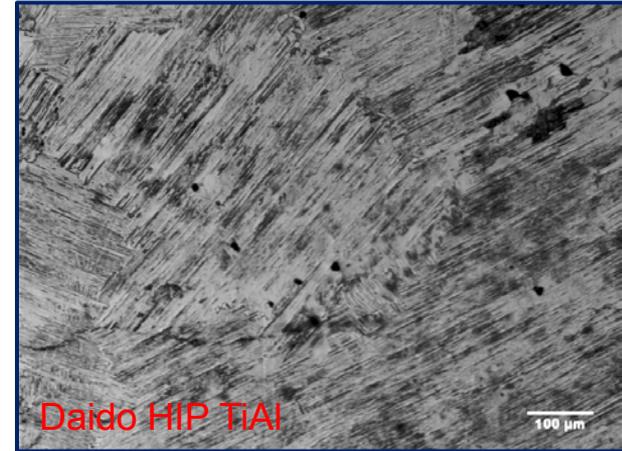
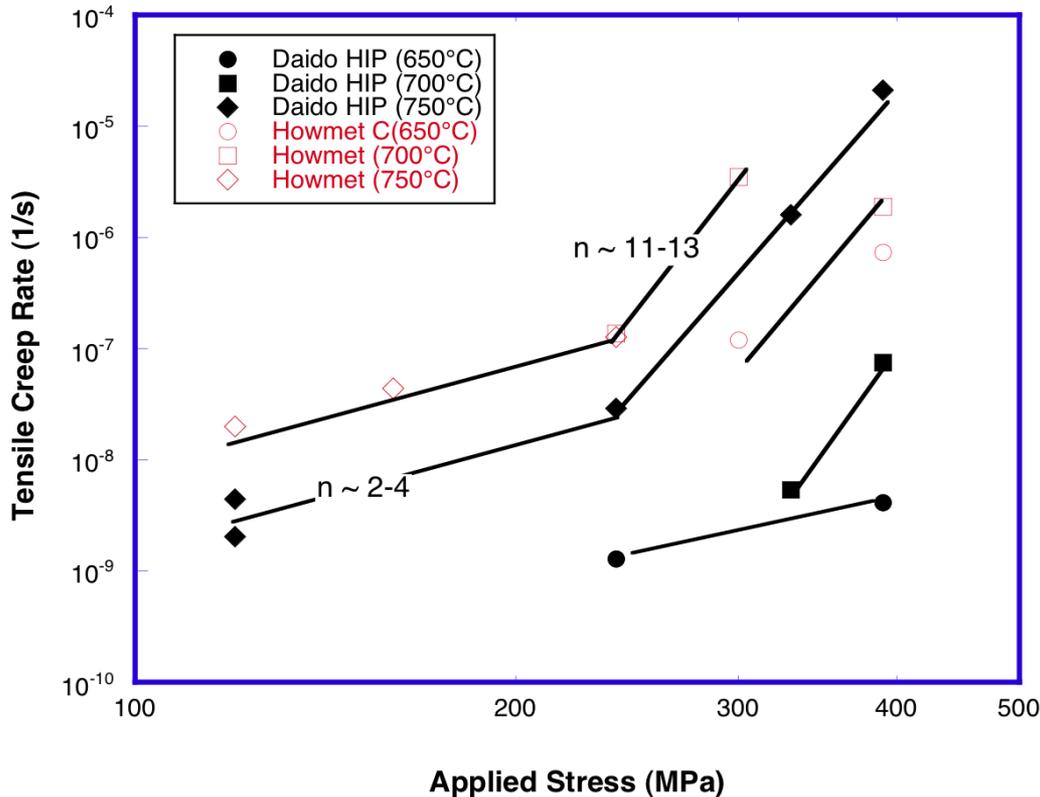
- SEM of polished cross section shows dense and intact Al-oxide based coating after the conversion process



Conversion process needs to be modified to reduce the oxidation reaction layer underneath the Al-oxide based coating

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

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 ACERT™ 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 Works

- **Develop and optimize oxide-based coatings that have the potential to:**
 - Reduce thermal losses
 - Reduce manufacturing cost
 - Improve durability and protection capability
- **Analyze components with and without protective coating for structural integrity after simulated thermal cycle test**
 - NDE
 - Microstructural analyses
 - Characterize alternative fuel effects on the corrosion and oxidation of hot section components with and without protective thermal barrier coating
- **Expand research plans to additional components & materials specifically aiming for Tier 4 version of C15 ACERT™ engine that is equipped with EGR and advanced emission control system**
 - NDE
 - Mechanical reliability database
 - Microstructural analyses

Summary

- Application of protective thermal barrier coating onto HDD components provides an enabling material technology to significantly reduce heat rejection and improve thermal efficiency.
- Evaluation of coating durability on the production ductile ferritic Fe substrates via thermal cycle was completed. Thermal barrier coating was employed by a commercial material supplier via dipping and conversion process.
- 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. Preliminary results showed the coating was dense and intact after the conversion process.
- Tensile creep database of two commercial TiAl alloy was generated for turbo wheel probabilistic life prediction and verification.
- Results obtained from thermal cycle tests and ORNL preliminary coating development provide an excellent guideline for further optimization of the coating system in FY2011.