Coatings for Centrifugal Compression*

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Coatings for Centrifugal Compression

Argonne NATIONAL LABORATORY

Annual Merit Review & Peer Evaluation Meeting

2011 U. S. Department of Energy Hydrogen and fuel Cells Program and Vehicle Technologies Program

PD050 Fenske

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Introduction

Overview

Timeline

- Start: Oct 2006
- Completion: Sept 2012
- Completion (%): 50 %

Budget

Total project funding DOE share ($725K)

Funding FY10 received ($100K)
Funding FY11 received ($150K - subject to Continuing Resolution)
Project continuation and direction determined annually by DOE

Barriers

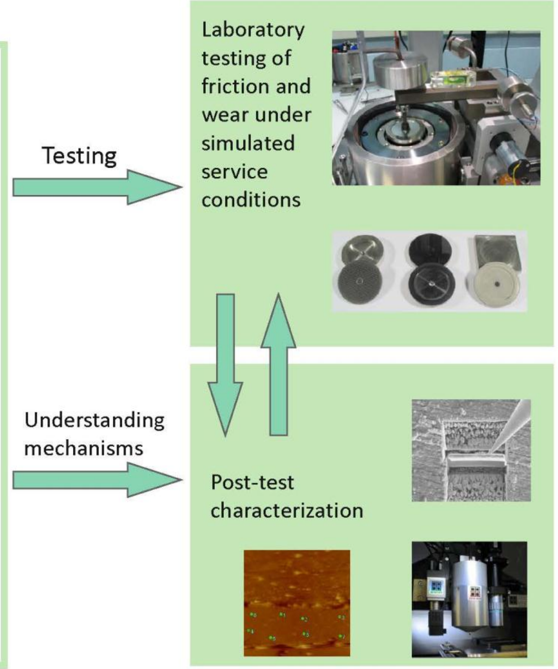
- Barriers addressed
  - Delivery Barrier B – "Reliability and Costs of Hydrogen Compression"
- Targets – Hydrogen Delivery Targets related to Hydrogen Delivery of large compressors for FY2012 are:
  - Reliability --> improved
  - Efficiency - 98%
  - Capital investment - $12M/compressor
  - Maintenance – 7% of TCI

Partners

- MITI – Mohawk Innovative Technologies Incorporated - oil-free, high-speed centrifugal compressor (bearings)
- CSM – test machine development
- John Crane - seals

Technical Approach

- Identify critical dynamically loaded compressor components, materials/alloys/surfaces, and operating environments.
- Evaluate tribological performance of commercial or lab materials under well-defined tribological conditions:
  - Temperature, H_2 pressure
  - Speed, load/stress
  - Air/H_2/impurities
- Characterize/identify critical phenomena/mechanisms that control tribological performance.
- Target: durable friction coefficient <0.1 and extremely high durability.
- Engineer and validate solution(s) into compressor design.



Relevance

- Overall objective:
  - develop enabling technology to attain *the cost and reliability* targets for oil-free centrifugal and forecourt compressors by reducing/eliminating downtime or repair costs
- Means to objective:
  - identify, and develop as required, advanced materials and coatings that can achieve the *tribological performance* necessary for durable operation of dry-sliding seals and bearings
- Two-prong technical approach:
  - using commercial or lab materials and coatings (compound, composite, intermetallic, carbon based), test and identify those materials that produce the lowest friction and wear in a hydrogen environment
  - "focus on understanding" the tribological mechanisms by which the best materials produce low friction and wear the properties
- Objectives FY11:
  - Perform acceptance test of new elevated-temperature hydrogen test machine (tribometer)
  - Perform high temperature tests of candidate materials to eliminate poor performers
  - Conduct longer-term sliding tests on materials used in forecourt compressors

Milestones 2011

Milestones	Progress Notes and Comments	% Comp
(for 11/10) Acceptance test demonstrating 2000 rpm operation for 4 h in 0.9-bar H_2 gas at 500°C with continuous measurement of friction, wear, temperature, and sliding distance.	Acceptance test verified for 2000 rpm operation for 1 hr in 0.9-bar H_2 gas at 500°C with continuous measurement of friction, wear, temperature, and sliding distance.	100%
(for 03/11): Complete durability testing of a NFC7 compressor foil bearing material and demonstrate a coefficient of friction that meets the desired compressor design requirements of < 0.1 under 14 kPa load, over a temperature range of 100 – 500°C, and in 99.999% H_2.	Room temperature, 100°C, 200°C, 300°C tests, on compressor foil-bearing material producing coefficients of friction <0.1, at 5.6 kPa load, in 99.999% hydrogen. Friction and wear are excessive at 400°C.	90%
(for 4/11) Complete ball-on-disk tests on the test materials from inventory (N3FC, NFC6, MoS_2/graphite, X-750, boride, carbon composite) at temperatures up to 400°C for durations up to 12 hours or to point where materials fail.	Preliminary testing has been completed using room temperature test rig in early part of FY 2011.	10%
(for 6/11) Obtain and examine failed forecourt compressor parts from reciprocating compressor partner to identify failure mechanisms and possible remedies.	Some pump manufacturers and a compressed H_2 deliver station operator were contacted, but no parts were obtained.	0%

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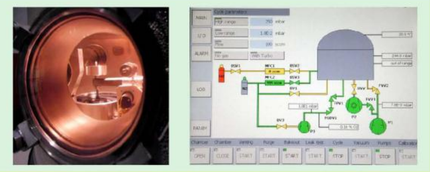
U.S. DEPARTMENT OF ENERGY

Technical Accomplishments 2011

Technical Accomplishments 2011

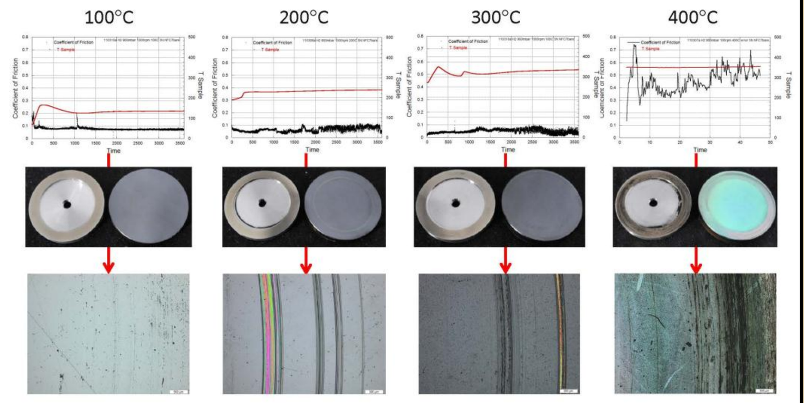
Successful acceptance test verified 2000 rpm operation for 1 hr in 0.9-bar H_2 at 500°C with continuous measurement of friction, wear, and temperature.

Problem with H_2 pressure regulation limits operation in certain hydrogen pressure regimes – repair in progress.



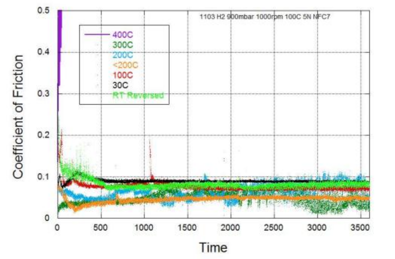
Technical Accomplishments 2011

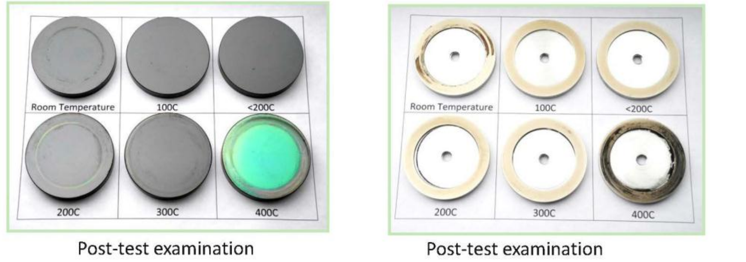
- Milestone RT, 100°C, 200°C, 300°C, 400°C tests, on candidate material
- Friction and wear are excessive at 400°C..



Technical Accomplishments 2011

- Milestone of hydrogen tests at different temperatures accomplished
- Friction and wear characterized
- COF < 0.1 in all tests except 400C
- Total loss of material at 400°C and above

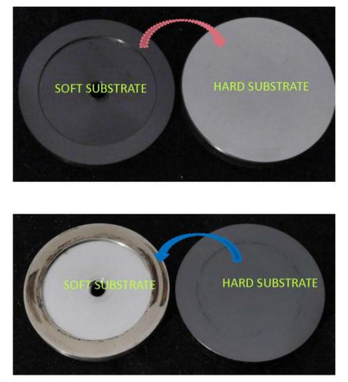




Post-test examination Post-test examination

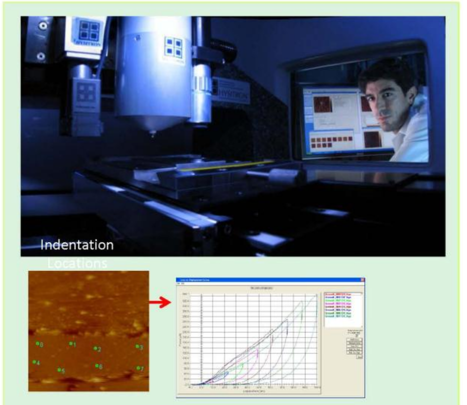
Technical Accomplishments 2011

- Examination of sliding surfaces from room temperature tests revealed that transfer film occurs from hard coating to soft counterface, but not from hard coating to hard counterface after 60,000 cycles in H_2. Friction does not seem to be significantly affected.



Technical Accomplishments 2011

- First tests of mechanical properties of specimens that had been tested in hydrogen were performed with nanoindenter .
- Force/displacement curves of carbon films (either new or worn) are extremely elastic (lower graphs) in comparison to transfer film or metal substrate. Tests are ongoing to understand this unusual behavior.



Sample and region of probing	Hardness (GPa)	Elastic Modulus (GPa)
Plain 4118 steel	13.8±1.3	234±20
Transfer film of H_2 tested N3FC DLC	1.7±0.42 1.7±0.5	60±14 30±5
N3FC tested in H_2	5.3±2.5	35±15
N3FC DLC	6.4±2.6	44±22
N3FC12	9	66
NFC7 (area 1) NFC7 (area 2)	17.3±0.5 16.6±0.5	122±1 111±3
NFC6	7.8±0.8	69±4
NewDLC	18.4	142

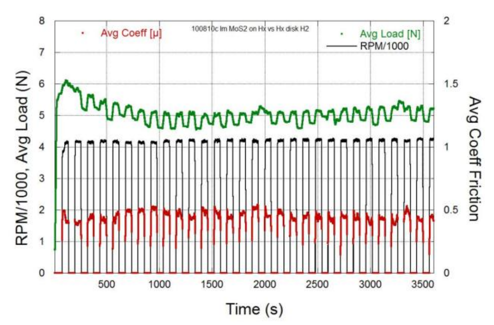
Technical Accomplishments 2011

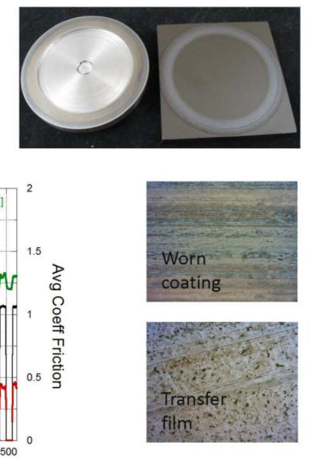
Summary of ball on disk tests run for coatings deposited on hard 4118 or H13 substrates

Coating Material on hard 4118 substrate	Test Environment	Ball Wear Rate (µm³/N/m)	Disk Wear Rate (µm³/mm/N/lap)	Coefficient of Friction
NewDLC	Air	1.7	0.06	0.2→0.4
NewDLC	Hydrogen	21	0.523	0.05
NewDLC	Vacuum	703	11.9	0.3
NewDLC	Nitrogen	403	2.2	low-> 0.4
NewDLC	Oil	3.7	0.00006	0.1 boundary
N3FC6	Air	0.45	0.12	0.25
N3FC6	Hydrogen	0.19	0.04	0.03
N3FC6	Vacuum	42.4	7.5	0.06
N3FC6	Nitrogen	0.135	0.03	0.03
NFC7	Air	-1.68	0.37	0.3
NFC7	Hydrogen	1.27	0.61	0.04
NFC7	Vacuum	432	18	Low to 0.4
NFC7	Nitrogen	-466	23	Low to 0.1

Technical Accomplishments 2011

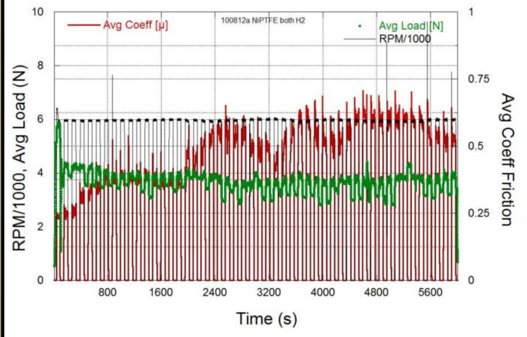
- New MoS_2-based coating exhibits improved durability compared to other MoS_2 materials.
- 18 km sliding distance.

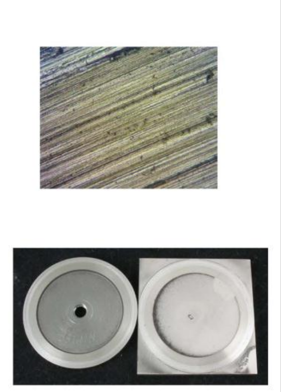




Technical Accomplishments 2011

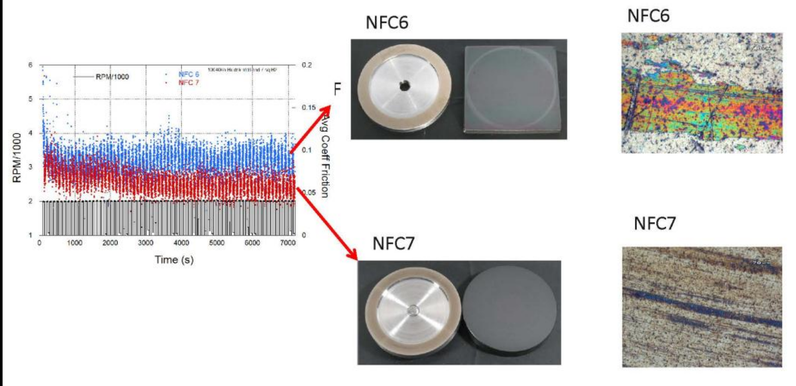
- New NiPTFE coating evaluated.
- Short lifespan and high friction found.





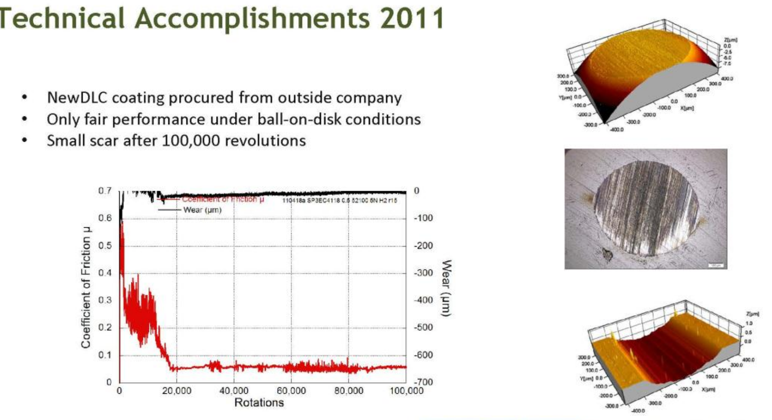
Technical Accomplishments 2011

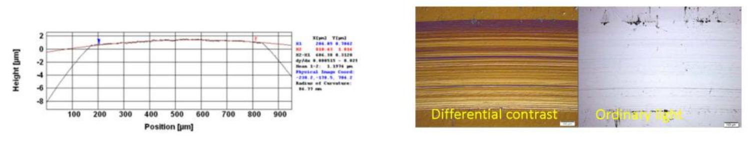
- New Argonne NFC7 carbon performs better than former leader NFC6. Tests are harsher with 2-hr duration at 6,000 rpm, 50% duty cycle, up to 15 N load.



Technical Accomplishments 2011

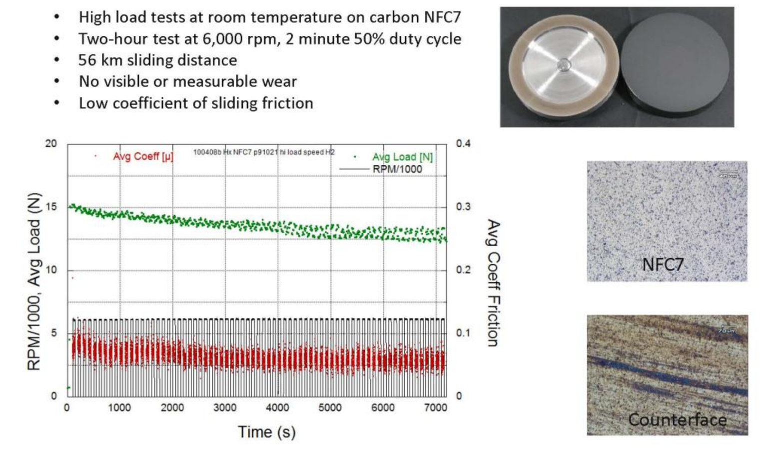
- NewDLC coating procured from outside company
- Only fair performance under ball-on-disk conditions
- Small scar after 100,000 revolutions





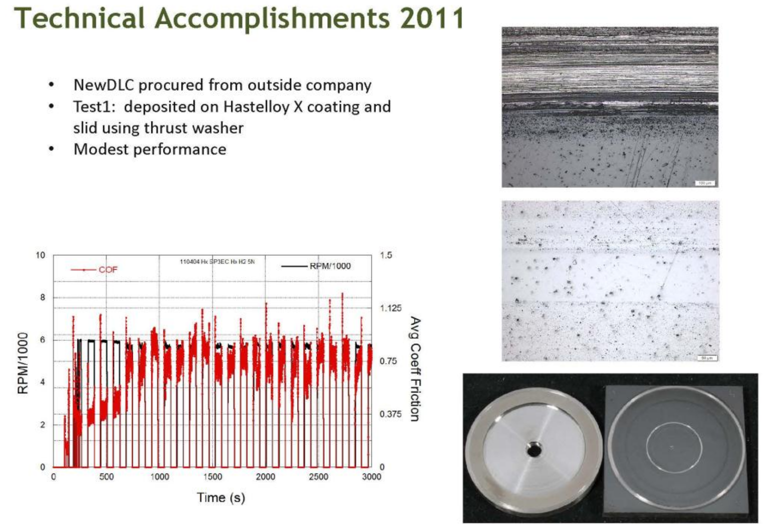
Technical Accomplishments 2011

- High load tests at room temperature on carbon NFC7
- Two-hour test at 6,000 rpm, 2 minute 50% duty cycle
- 56 km sliding distance
- No visible or measurable wear
- Low coefficient of sliding friction



Technical Accomplishments 2011

- NewDLC procured from outside company
- Test1: deposited on Hastelloy X coating and slid using thrust washer
- Modest performance



Notes

Summary

- Project initiated to address concern over potential impact of hydrogen on friction, wear, and embrittlement of dynamically loaded components (bearings and seals)
  - Despite limited funding, longer-duration room-temperature testing was performed of existing (NFC6) and new (amorphous carbon and Argonne NFC7) materials at start of FY2011.
  - Our new elevated temperature tribometer was accepted, and tests to 500°C have been performed, but some pressure regulation issues are ongoing.
  - A sequence of tests from room temperature to 400°C in hydrogen was performed with NFC7.
  - First tests of mechanical properties of tested specimens obtained using nanoindenter show very soft carbon films and transfer films, but much harder NFC7.
  - Development and testing of amorphous carbon coatings containing hydrogen (the Argonne NFCX series) showed excellent friction and wear behavior.

Collaborations

- **MITI – Mohawk Innovative Technologies Incorporated**
  - **Oil-free, high-speed centrifugal compressor (bearings)**
- **CSM**
  - **Advanced instruments for tribological testing in pure hydrogen gas**
- **John Crane**
  - **Oil-free, high-speed gas lubricated seals**
- **Discussions underway with manufacturers of positive displacement compressors (forecourt compressors 10-12 kpsi)**

Proposed Future Work

- Finish up required milestones at elevated temperatures.
- Obtain and examine failed forecourt compressor parts from reciprocating compressor partner to identify failure mechanisms and possible remedies
- Conduct longer-term sliding tests on materials used in forecourt compressors for "bone dry" use [e.g., polyether ether ketone (PEEK) and carbon tetrafluoroethylene (TFE) instead of nickel alloys, as has been done so far].
- Continue nanoprobe/nanoindentation studies to elucidate possible relationship of surface mechanical properties to tribology friction and wear.
- Conduct electron microscopy for wear mechanism studies (maybe).
- Use focused-ion-beam method to understand how H_2 can impact near-surface and subsurface failure.
- Study embrittlement and crack behavior.