Coatings for Centrifugal Compression

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Argonne National Laboratory
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Overview

Timeline
- Start: Oct 2006
- Completion: Sept 2012
- Percent Completed: 40%

Budget
- Total project funding
  - DOE share: ($725K)
  - Funding for FY09: ($100K)
  - Funding for FY10: ($100K)

Barriers
- Delivery Barrier B – Reliability and costs of hydrogen compression
- Hydrogen delivery targets related to hydrogen delivery of large compressors for FY2012:
  - Reliability – > improved
  - Efficiency - 98%
  - Capital investment - $12M/compressor
  - Maintenance – 7% of TCI

Partners
- MITI (Mohawk Innovative Technologies Inc.) - Oil-free, high-speed centrifugal compressor (bearings)
- CSM – test machine development
- John Crane - seals
Relevance

- **Overall objective:**
  - Develop the 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 and optimize the properties

- **Objectives FY10:**
  - Install and bring to operation new elevated-temperature hydrogen test machine (tribometer)
  - Focus on *understanding the mechanisms* by starting nanoindentation and FIBS (focused ion beam spectroscopy) work
  - Conduct longer-term sliding tests on materials used in forecourt compressors
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, $\text{H}_2$ pressure
  - Speed, load/stress
  - Air/$\text{H}_2$/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

Testing

Laboratory testing of friction and wear under simulated service conditions

Understanding mechanisms

Post-test characterization
## Milestones

<table>
<thead>
<tr>
<th>Milestones</th>
<th>Progress Notes</th>
<th>Comments</th>
<th>% Comp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continue room temperature tests of commercial and lab materials/coatings.</td>
<td>Performed tests of following new materials: amorphous carbon Diamonex and Argonne NFC7 amorphous hydrogenated carbon. First tests of nanoindenter/nanoprobe with hydrogen worn specimens.</td>
<td>The new Argonne NFC7 carbon performs better than current leader NFC6. Later tests are harsher: 2-hr duration at 6,000 rpm, 50% duty cycle, up to 15 N.</td>
<td>60%</td>
</tr>
<tr>
<td>Acceptance test demonstrating 2000 rpm operation for 1 hour in 0.9 bar H₂ gas at 800°C nominal temperature with continuous measurement of friction, wear, temperature, and sliding distance.</td>
<td>Attained 2000 rpm operation for 1 hr in 0.9 bar N₂ gas at 800°C with continuous measurement of friction, wear, and temperature, but not in tests scheduled with H₂ gas.</td>
<td>Hydrogen environment test awaiting installation of thermal insulation.</td>
<td>80%</td>
</tr>
<tr>
<td>Complete ball-on-disk tests on the test materials from inventory (N3FC, NFC6, MoS₂/graphite, X-750, boride, carbon composite) at temperatures up to 400°C for durations up to 12 hours or until materials fail.</td>
<td>Tests done on inventory specimens at room temperature but not 400°C using new machine due to shakedown problems.</td>
<td>Damaging effects of hydrogen on uncoated nickel alloys were dramatized when new test machine jammed and galled during maintenance.</td>
<td>0%</td>
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</tbody>
</table>
Technical Accomplishments 2010

- Successful receipt and installation of elevated-temperature hydrogen tribometer
- Shakedown tests (2000 rpm at 800°C) were performed in N₂ but not in H₂
- Reducing nature of H₂ on uncoated nickel alloys was dramatized when new machine jammed and galled during maintenance – necessitating factory repair
- Special high-performance thermal insulation has been designed
Technical Accomplishments 2010

- First tests of mechanical properties of specimens were performed with nanoindenter/nanoprobe using Berkovich indenter that had been tested in hydrogen.
- Force/displacement curves of N3FC (either new or worn) are not typical and are extremely elastic (lower graphs) in comparison to transfer film or metal substrate. Tests are ongoing to understand this unusual behavior.

<table>
<thead>
<tr>
<th>Sample and region of probing</th>
<th>Hardness (GPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4118 steel with no coating or transfer film</td>
<td>13.8±1.3</td>
<td>234±20</td>
</tr>
<tr>
<td>Transfer film of H₂ tested N3FC DLC</td>
<td>1.7±0.42</td>
<td>60±14</td>
</tr>
<tr>
<td>Transfer film of H₂ tested N3FC DLC</td>
<td>1.7±0.5</td>
<td>30±5</td>
</tr>
<tr>
<td>N3FC tested in H₂</td>
<td>5.3±2.5</td>
<td>35±15</td>
</tr>
<tr>
<td>As-deposited N3FC DLC</td>
<td>6.4±2.6</td>
<td>44±22</td>
</tr>
</tbody>
</table>
Technical Accomplishments 2010

- Started focused ion beam examination of near-surface region (O. Ajayi and C. Lorenzo-Martin)
  - FIB is means to perform detailed probing into the near-surface region
    - Large specimens – University of Illinois – Champaign-Urbana
    - Small specimens – Argonne

Mill first trench

Mill second trench to make wall

Remove thin sample for examination
Technical Accomplishments 2010

- 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 2010

<table>
<thead>
<tr>
<th>Rotating face</th>
<th>Stationary counterface</th>
<th>Environment</th>
<th>Friction</th>
<th>Wear face</th>
<th>Wear counterface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molykote MoS$_2$</td>
<td>X750</td>
<td>Hydrogen</td>
<td>Medium 0.4</td>
<td>High abrasion</td>
<td>Low</td>
</tr>
<tr>
<td>Fe/Mo/Boride</td>
<td>316ss</td>
<td>Hydrogen</td>
<td>Med high 0.6</td>
<td>Low abrasion</td>
<td>Low</td>
</tr>
<tr>
<td>CF composite</td>
<td>X750</td>
<td>Hydrogen</td>
<td>Medium 0.4</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>N3FC</strong></td>
<td><strong>4118 steel</strong></td>
<td><strong>Hydrogen</strong></td>
<td><strong>Low 0.15</strong></td>
<td><strong>Low</strong></td>
<td><strong>Immeasurable</strong></td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>Hastelloy X</td>
<td>Hydrogen</td>
<td>Very high &gt;1</td>
<td>High galling</td>
<td>High galling</td>
</tr>
<tr>
<td>X-750</td>
<td>X-750</td>
<td>Hydrogen</td>
<td>High 0.6-0.9</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>NFC6</td>
<td>Hastelloy X</td>
<td>Hydrogen</td>
<td>Low 0.1</td>
<td>None</td>
<td>Very low</td>
</tr>
<tr>
<td>316ss</td>
<td>316ss</td>
<td>Hydrogen</td>
<td>High 0.6-0.9</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>Diamonex</td>
<td>Hydrogen</td>
<td>Medium 0.4</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>NFC7</strong></td>
<td>Hastelloy X</td>
<td><strong>Hydrogen</strong></td>
<td><strong>Low 0.06</strong></td>
<td><strong>None</strong></td>
<td><strong>Immeasurable</strong></td>
</tr>
</tbody>
</table>
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)**
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 on existing (NFC6) and new (Diamonex amorphous carbon and Argonne NFC7) materials
  - Installation of new elevated temperature tribometer is 80% complete, with shakedown tests performed in N₂ but not in H₂. The reducing nature of H₂ on uncoated nickel alloys was dramatized when the new machine jammed and galled during maintenance – necessitating factory repair
  - Preliminary studies (room temperature) identified several promising candidate materials (e.g., non-metallic solid-lubricant composites and amorphous carbon films)
  - First tests of mechanical properties of tested specimens obtained using nanoindenter/nanoprobe show very soft carbon films and transfer films
  - Development and testing of amorphous carbon coatings containing hydrogen (the Argonne NFCX series) showed excellent friction and wear behavior
Proposed Future Work

- Complete installation of elevated temperature tribometer and finish up testing of promising materials at typical in-service temperatures
- Conduct longer-term sliding tests on materials used in forecourt compressors for “bone dry” use (e.g., PEEK and carbon-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
- Perform electron microscopy for wear mechanism studies (maybe)
- Apply focused-ion-beam method to understand how H₂ can impact near-surface and subsurface failure
- Study embrittlement and crack behavior