Ultra-Fast Chemical Conversion Surfaces

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March 11, 2011

Project ID # PM027

Overview

Timeline

- Start: 10/01/2009
- Finish: 9/30/2014
- % Complete: 30%

Budget

- Total project funding:
  - DOE Share: $1M
  - Contractor Share: $250K
- Funding Received in FY10
  - $200K
- Funding received in FY11
  - $200K

Barriers

- Ultra fast chemical conversion of ferrous and light-weight material (such as Ti) surfaces into very hard and thick boride layers in a very short processing time without distortion and cracks.
- Applications to intricate (odd-shaped) engine parts with excellent uniformity.

Targets

- Drastically increase wear durability and reduce friction of various engine parts and components.
- Develop and scale up the process and demonstrate superior performance and efficiency under severe operating conditions.
- Verify cost competitiveness and transfer demonstrated technology to industry for use in automotive and heavy vehicle propulsion systems.

Partners

- Bodycote Thermal Processing, Inc. and several engine part manufacturers
- Lead: Argonne National Laboratory

Objectives

- Develop and optimize an ultra-fast chemical conversion (electrochemical boriding) process for achieving much higher wear durability and performance in sliding, rolling, and rotating engine components, including, gears, bearings, piston pins and rings, fuel injector components, and tappets that require higher wear resistance and lower friction, especially under severe operating conditions of modern engines.
- Compare results with carburized and nitrided surfaces and elucidate friction and wear mechanisms.
- Demonstrate technical feasibility and superior property, performance, and durability characteristics of treated parts.
- Demonstrate scalability, cost-competitiveness, commercial viability.

Milestones or Go/No-Go Decisions

- **FY10:**
  - **Milestone:** Demonstrate ultra-fast electrochemical boriding of large numbers of test samples made out of the same steels as those used in the manufacturing of engine components.
  - **Milestone:** Complete testing and comparison of the mechanical and tribological properties of ultra-fast borided surfaces with those of the carburized and nitrided surfaces.
- **FY11:**
  - **Milestone:** Further optimize and scale up the boriding technique so that larger number of test samples and/or parts can be processed effectively and reliably.
  - **Milestone:** Demonstrate reproducibility/reliability of the ultra-fast boriding process one batch after another.
  - **Milestone:** Validate applicability on large numbers of engine components. Initiate component-level testing and characterize their surface mechanical and tribological properties using bench-top and component-level test systems.

Approach

- Optimize process variables and develop reliable boriding protocols that can consistently result in ultra-hard and uniformly thick boride layers on test materials and actual engine parts.
- Perform comprehensive lab-scale studies to confirm superior performance and durability of borided surfaces compared to nitrided and carburized surfaces.
- Determine effects of boride layer thickness, hardness, and chemical state on friction, wear, and scuffing performance.
- Employ optimized boriding protocols to appropriate engine parts, like piston pins, rings, tappets, etc., and confirm their superior mechanical and tribological properties.
- Demonstrate scalability and cost-competitiveness, and transfer optimized technology to industry.

Technical Accomplishments/Progress/Results

(Process Optimization and Scale-up: Pilot Scale Production)

Small, bench-scale boriding unit

- **5.3 in. ID reactor**
- **5 kg melt capacity**
- **15 A (total boriding current)**
- **Suitable for small test pieces for tribological testing**

- The pilot scale system
  - Increases our ability to boride some of the larger components.
  - Gives us flexibility during boriding of several actual parts.
  - Enables us to confirm process efficiency and reliability.

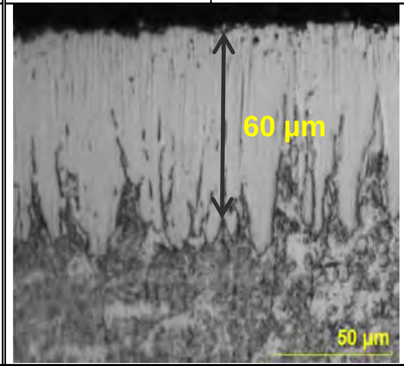
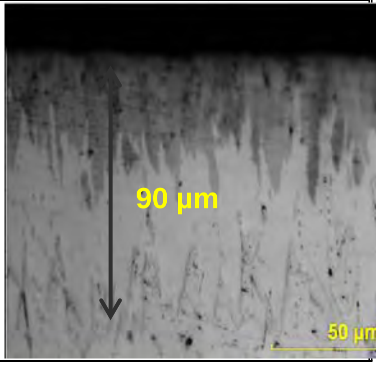
Pilot-scale boriding unit

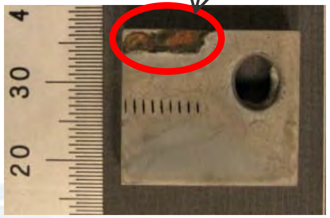
- **22 in. ID reactor**
- **130 kg melt capacity**
- **200 A (total current)**
- **Ideal for treatment of engine components**

Technical Accomplishments/Progress/Results
(Product Optimization)

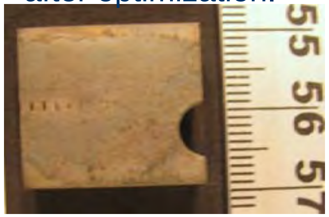
- Using borax and a variety of other boron-based salts, electrolyte composition has been further optimized.
- As a result, significant improvements in process efficiency and end-product quality have been achieved.
  - Much faster boriding resulting in significantly thicker layers
  - Reduction of boriding temperature
  - Uniform thickness across all odd shapes, denser structure (no cracks or delamination)
  - Higher hardness and superior wear resistance
  - Improved surface finish with no oxidation of treated parts and no damage to crucible and anode-cathode materials.

Comparison of boride layer thickness before and after electrolyte optimization.

15 min boriding followed by 45 min holding	Before electrolyte optimization		After electrolyte optimization	
	Total Borided Layer Thickness (µm)	FeB Layer Thickness (µm)	Total Borided Layer Thickness (µm)	FeB Layer Thickness (µm)
Maximum	84	0	118.78	53.30
Minimum	23	0	42.64	0.26
Average	59.34	0	89.98	21.82
Cross sectioned optical microscopy pictures				



Before optimization some corrosive attacks were seen.

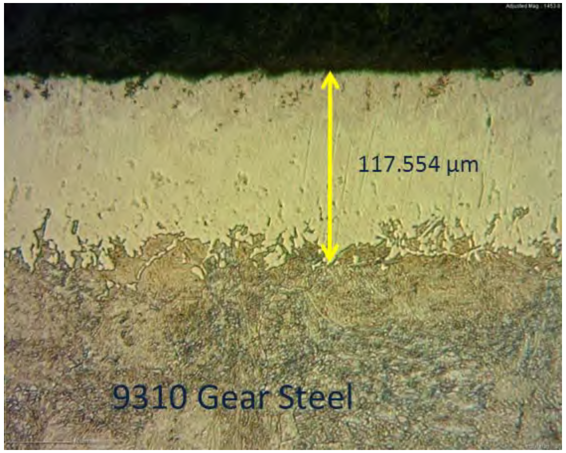


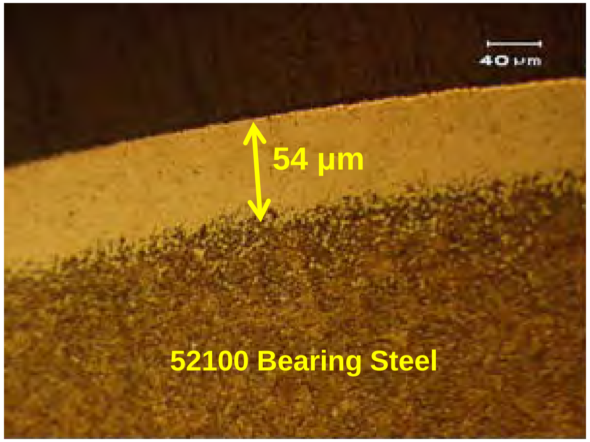
No corrosive attacks after optimization.

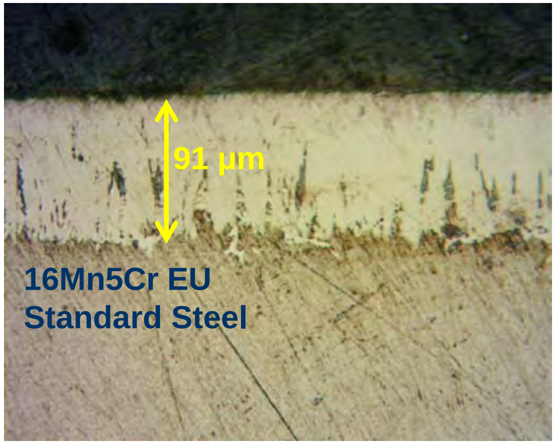
Technical Accomplishments/Progress/Results

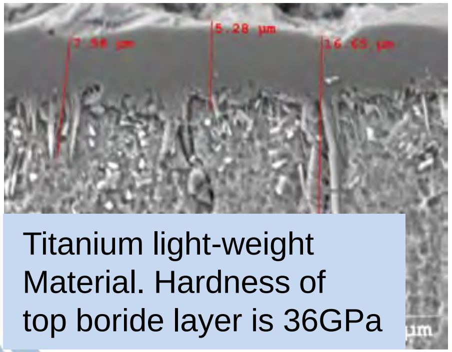
(Process Efficiency and Applicability)

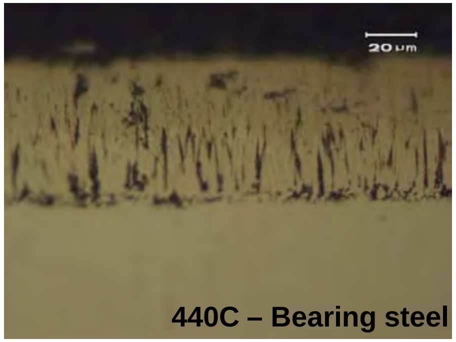
- Successfully treated a large number of gear, bearing, and piston pin and ring materials that are used in the making of actual engine components.
  - Demonstrated very fast, thick, and hard nature of boride layers formed on a variety of relevant substrates as shown below.

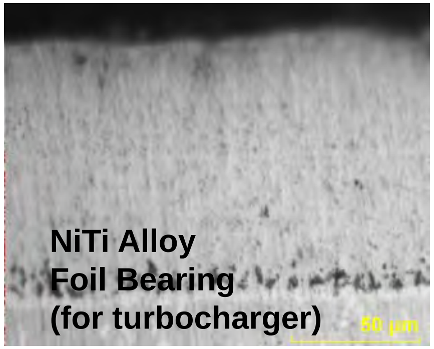


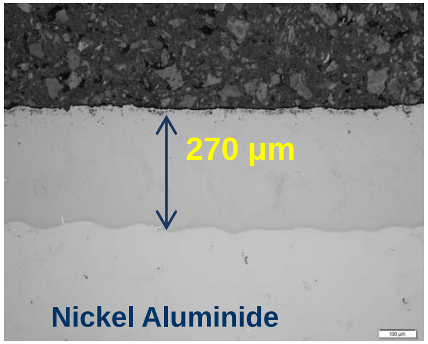






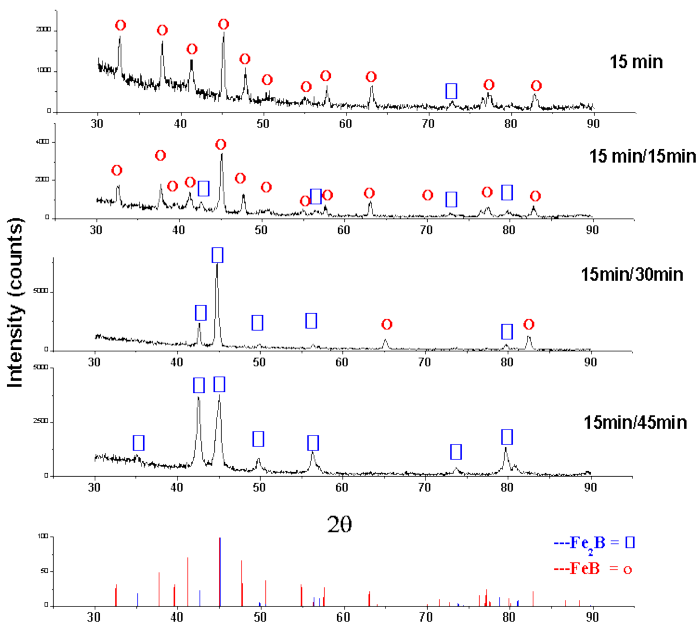




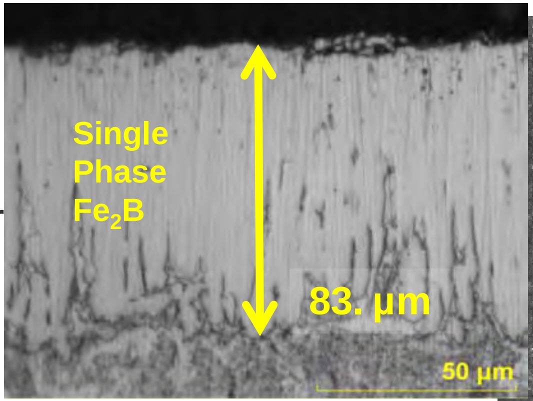


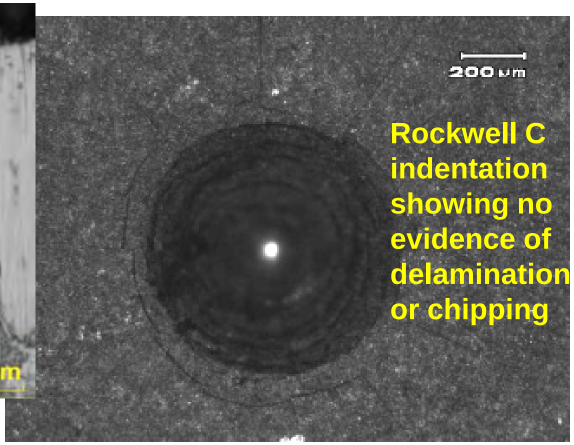
Technical Accomplishments/Progress/Results
(Structural and Mechanical Characterization)

- Accomplished single (most desirable) Fe_2B phase that showed excellent fracture toughness, hardness, and wear resistance even under dry sliding conditions.

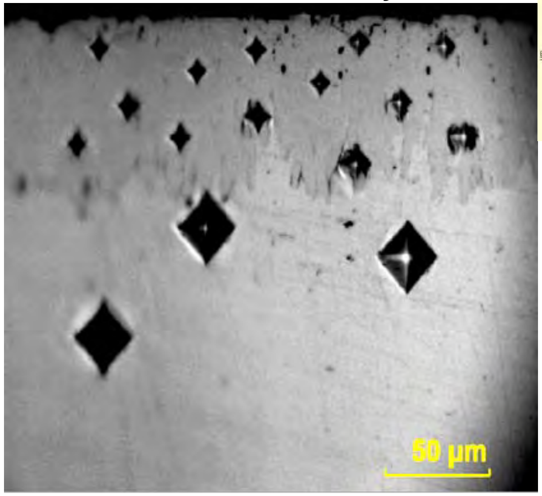


These XRD results show that a 15 min boriding followed by 45 min soaking/holding is the optimum protocol for single-phase Fe_2B phase.

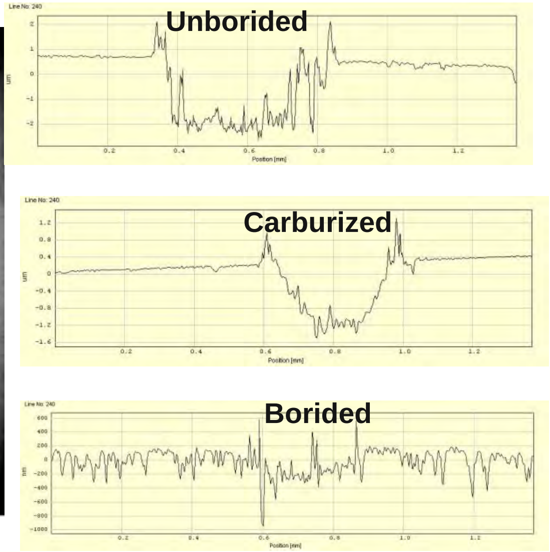




Optical micrograph indicates single-phase Fe_2B; Rockwell C indentation shows no chipping or delamination and hard nature of boride layer.



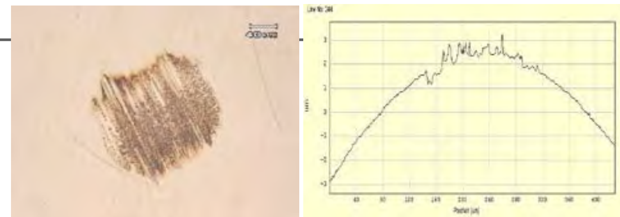
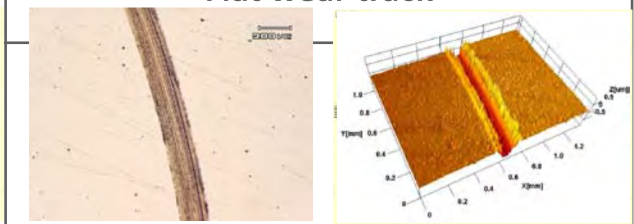
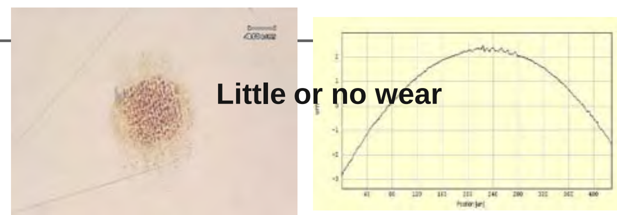
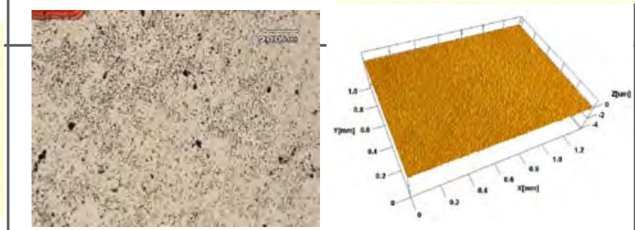
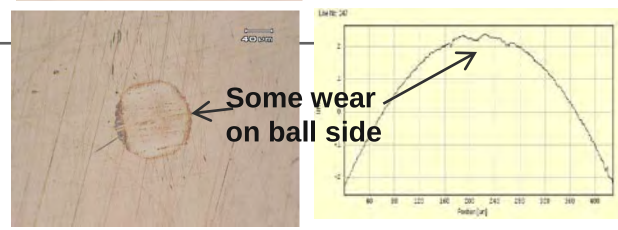
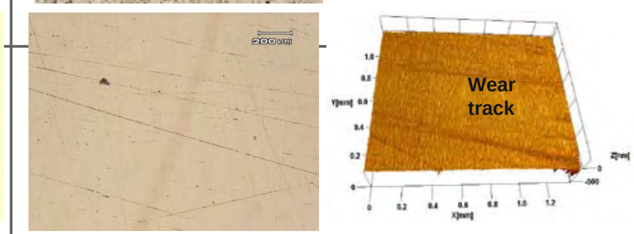
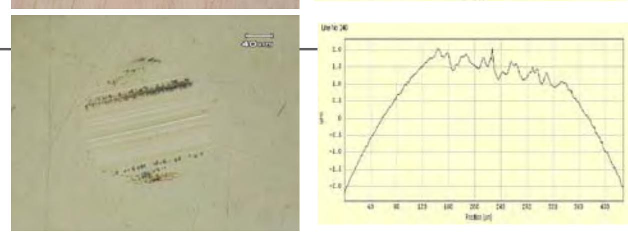
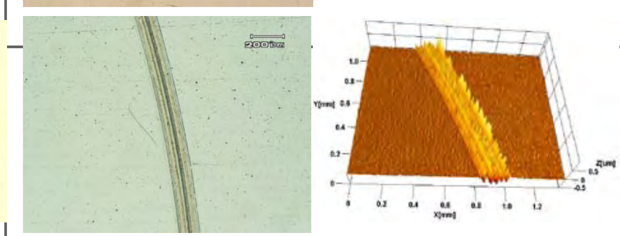
Comparison of wear performance under dry sliding condition.



Technical Accomplishments/Progress/Results

Tribological Performance

Friction and Wear Performance of Plain Carbon Steel after Different Treatments

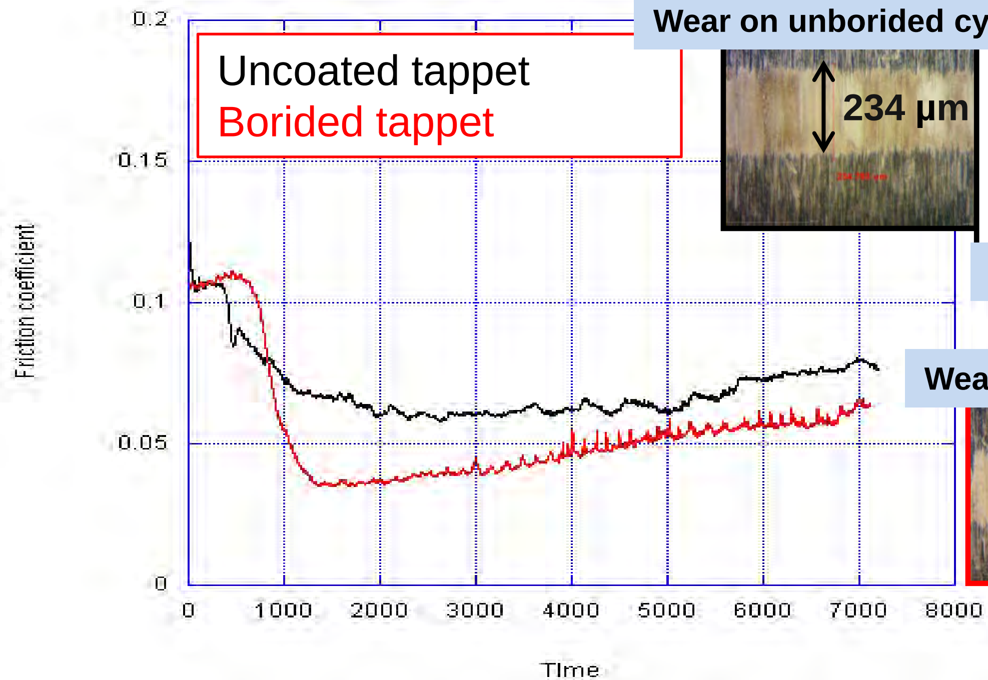
Treatment Type	Friction Coefficient	Ball wear scar	Flat wear track
Base Material (1018 Steel)	0.14		
Argonne Process	0.11		
Carburized	0.139		
Carbo-nitrided	0.12		

Ball-on-Disk Test Conditions: Lubricant, Fully Formulated 5W30 Oil; Contact Pressure, 830 MPa; Sliding Speed, 15 mm/s; Temperature, Ambient.

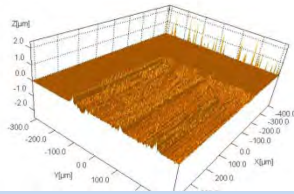
Technical Accomplishments/Progress/Results

Component Testing

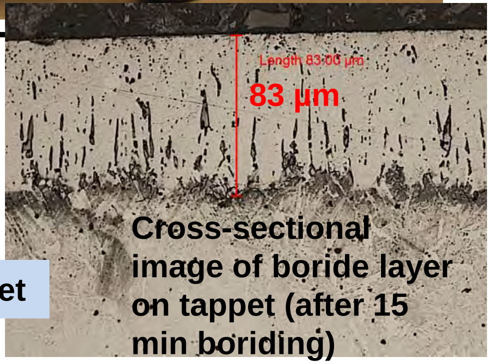
- Friction and wear experiments with actual engine components - Tappets
  - Cylinder on flat bench-top reciprocating test results. (Test conditions include maximum Hertzian contact pressure: 1GPa; lubricant: fully formulated 10W30 oil; time : 2 hours; speed: 300 rpm; temperature: 100ºC; stroke length: 6 mm.)



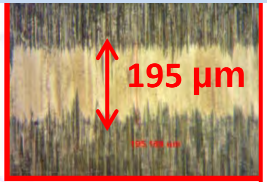
Wear on unborided cylinder

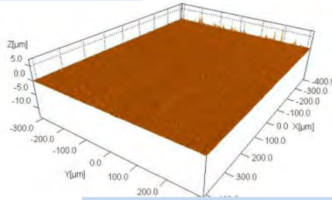


Wear on unborided tappet



Wear on unborided cylinder





Wear on borided tappet (no detectable wear)

Hurdle: Slight warping was observed on tappet surface after 15 min boriding. We are trying lower temperature and shorter (5 min) boriding time to eliminate this problem.

Proposed Future Work

- **For the Remainder of FY11:**
  – Concentrate on the boriding of actual engine components.
  – Further optimize/customize boriding process.
  – Develop reliable/repeatable protocols; further verify process efficiency and product quality.
  – Complete structural, mechanical, and tribological characterization studies.
  – Complete comparative studies with carburized, nitrided, and coated surfaces.
  – Initiate boriding of large batches of engine components.
- **FY2012:**
  – Explore viability of further scaling-up of the boriding process to handle larger numbers of engine parts. Select and concentrate on one kind (like tappet or piston pins) that is of great interest.
  – Demonstrate reproducibility/reliability of the ultra-fast boriding process one batch after another and develop repeatable/reliable process conditions and quality control protocols for large-scale manufacturing.
  – Initiate component-level testing of representative engine parts and components.
  – Prepare actual engine parts for fired engine tests and field evaluation.
  – Continue licensing talks with industrial partners.

Summary

- **Relevance:**
  - Ultra-fast production of very thick, hard, and slick boride layers on engine parts and components is expected to have a positive impact on the durability, efficiency, and performance of future engine systems and provide significant competitive edge for US heat-treating and auto industries.
    - In particular, severe operating conditions (high contact stresses, temperatures, exhaust gas recirculation, alternative fuels/lubricants, etc.) require hard and low-friction surfaces for durability/efficiency.
- **Technical Approach and Accomplishments:**
  - So far, we have made great strides in meeting our stated goals/milestones:
    - Designed and constructed pilot-scale boriding unit.
    - Achieved single-phase, very thick, hard, and low-friction boride layers on numerous steels and other materials relevant to engine applications.
    - Confirmed their superior mechanical and tribological properties.
    - Initiated work on actual engine parts. Results from tappets look very promising (near elimination of wear and 30-40% reduction in friction under severe boundary conditions).
- **Collaborations:**
  - Bodycote Thermal Processing, Inc. (USA) is our primary partner. Several automotive companies and part suppliers are also involved in our work.
- **Future Directions:**
  - Concentrate more on actual engine parts; validate superior performance in actual engines and test fleets; accelerate technology maturation and transfer.