Tailored Materials for High Efficiency CIDI Engines (Caterpillar CRADA)

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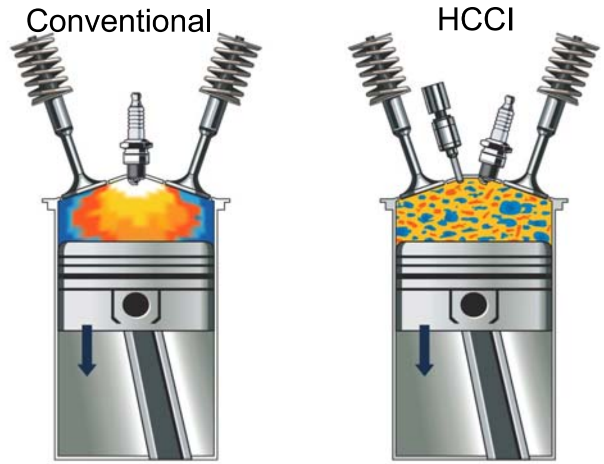
Purpose of Work

New combustion strategies (HCCI, lean burn, “High Speed” diesel) can increase engine efficiency

However,

- Peak loads can be much higher than conventional engines (potentially requiring higher cost materials)
- Conventional light weight engine materials (aluminum) are sensitive to high temperatures, potentially requiring high cost alternatives



New combustion strategies are putting greater demands on current engine materials. More robust engine materials (Ni alloys, Ti, CGI, Nodular Fe, micro-alloyed steels) can have steep cost penalties.

To enable the development of high efficiency engines, a lower cost alternative may be to modify or tailor only the surface of the lower cost, conventional material to achieve the higher properties required

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Overview

Timeline

- Start: FY2008 - CRADA signed Nov 2007
- Project end date: Dec. 2010
- Percent complete: 25%

Budget

- FY08: $375k (DOE)
  FY09:$340k (DOE)
- 50/50 Cost Share with Caterpillar through in-kind contribution

Barriers

- Fuel Efficiency
  - New combustion strategies necessary for increased engine efficiency are putting higher demands on traditional engine materials. Without better materials gains can't be realized
- Thermal Management
  - Keeping heat where it belongs increases thermodynamic efficiency. Better TBCs are needed
- Reduced manufacturing costs
  - Engineered surfaces on conventional materials could be lower cost option than some high performance materials.

Partners

- CRADA with Caterpillar, Inc.
  - Steering committee made up of members from Surface Engineering and High Temperature Materials groups within Caterpillar Tech Center
- Project lead: PNNL

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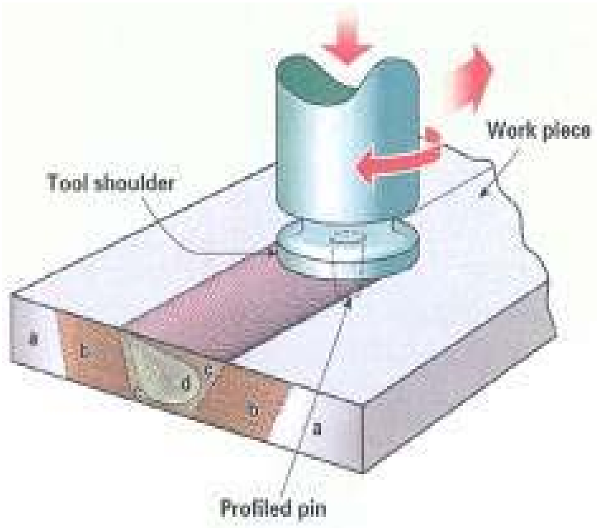
Project Objectives

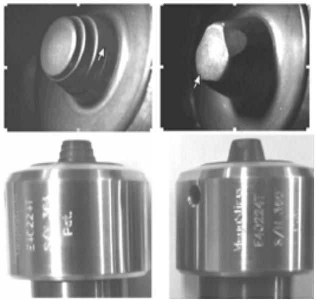
- To increase the thermal and mechanical efficiency and durability of engine materials through the development of a new surface engineering technology – Friction Stir Processing

- To develop and deploy this technology on traditional (low cost) engine materials and subsystems; cast iron, alloy steels, and aluminum alloy parts



FY 2009 Focus

- Experimentally develop FSP in aluminum materials that are compositional analogs to the typical piston and head alloys seen in small to mid-sized CIDI engines.
- Quantify performance advantages at the coupon scale
- Develop Friction Stir tools and parameters that allow surface modification of steels



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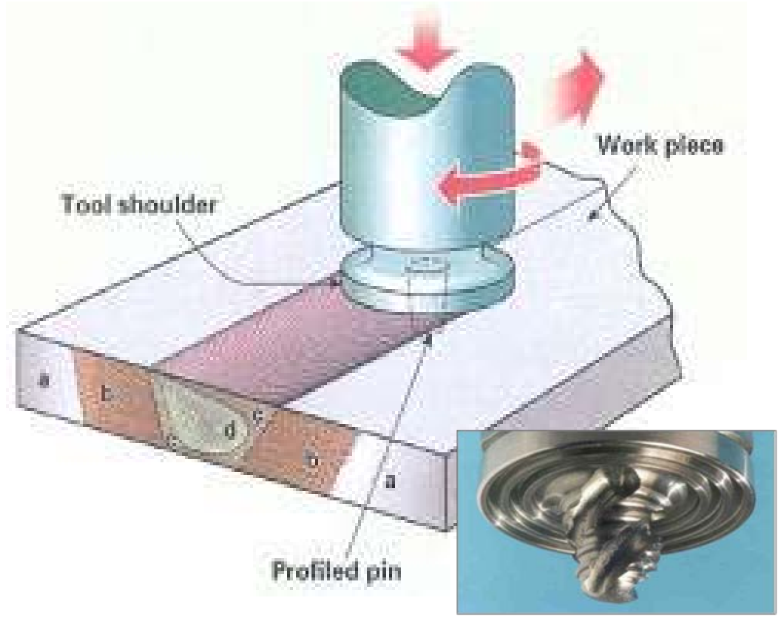
Technical Background - Friction Stir Processing

Solid-state process to create an engineered surface
(not a coating process)

- Spinning, non-consumable tool is plunged into the surface of a material.
- Friction and plastic work energy heats the material sufficiently to lower the flow stress.
- When material softens, the tool is then translated along the surface causing material in front of the pin to be deformed around to the back



Process Advantages

- FSP creates refined microstructure
  - Turns cast to wrought
  - Refines second phase particle size
- FSP can close porosity in castings
  - FSP eliminates surface and subsurface voids
- FSP can be used to form surface composites
  - Can "stir" insoluble ceramic or other components into surface in a solid state

FSP can selectively modify an area of a part to produce better properties

- Strength improvement by 50%
- Ductility improvement by factor of 5
- Fatigue improvement by factor of 2
- FSP surface composites can increase wear resistance and potentially modify thermal conductivity

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Project Milestones

FY08/09 Tasks

- FSP work on aluminum engine alloys
  - Performance metric:
    - 2x improvement in thermal fatigue life
    - 10% change in surface thermal conductivity
    - Significant reduction in thermal fatigue crack initiation
    - > 20% ceramic particulate incorporation into surface
- Tool screening studies for steel FSP
  - Performance Metric
    - Are there tool materials capable of FSP in cast iron and engine steels without tool failure or extreme wear

Primary Milestone Table	Anticipated Completion (in months from project start)	Progress
Identify highest value material system and at least two specific targeted components for study during the program. Identify metrics by which success will be gauged. (PNNL, CAT)	4	100%
Demonstrate that FSP is possible in an aluminum alloy and describe the resulting thermal and mechanical properties (PNNL)	15	50%
Demonstrate that FSP is possible in a steel alloy and describe the resulting thermal and mechanical properties (PNNL)	24	20%
Demonstrate FSP on a prototype aluminum engine component and initiate testing and evaluation program (PNNL, CAT)	22	0%
Demonstrate FSP on a prototype steel engine component and initiate testing and evaluation program (PNNL, CAT)	30	0%
Completion of Final Report (PNNL, CAT)	36	0%

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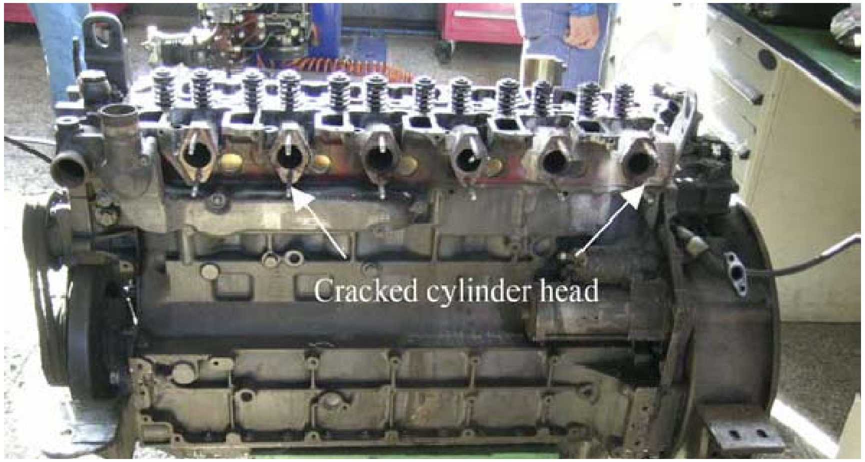
Potential uses for FSP technology in heavy-duty engine environments

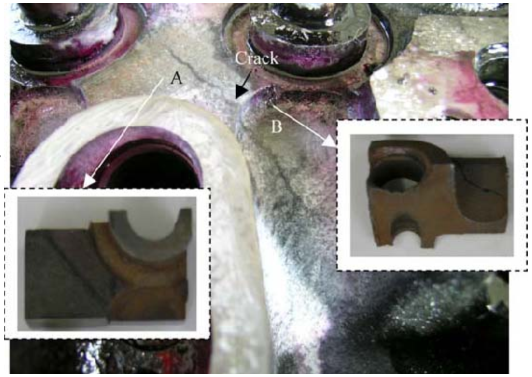
Aluminum Materials

- Pistons
  - Thermal Fatigue of bowl rim areas
  - Aluminum material temperature limits – need for thermal barrier layer
  - High temp strength and fatigue resistance of Pin strap area
  - Costly cast-in insert for top ring
- Heads
  - Top deck fatigue
  - Bottom deck thermal fatigue



Steel / Cast Iron Materials

- Pistons
  - Ring groove wear
  - Thermal fatigue of bowl rim
  - Costly forged steels (better to use cast with selective property enhancement
  - Thermal barrier layer
- Valves
  - Valve seat wear
- Crankshafts
  - Fillet fatigue enhancement
  - Oil hole fatigue enhancement
- Liners
  - Prevention of cavitation
  - Thermal resistance to allow cast iron use on higher temperature
- Head
  - Thermal fatigue enhancement on cross cut
  - Top deck fatigue
  - Thermal resistance



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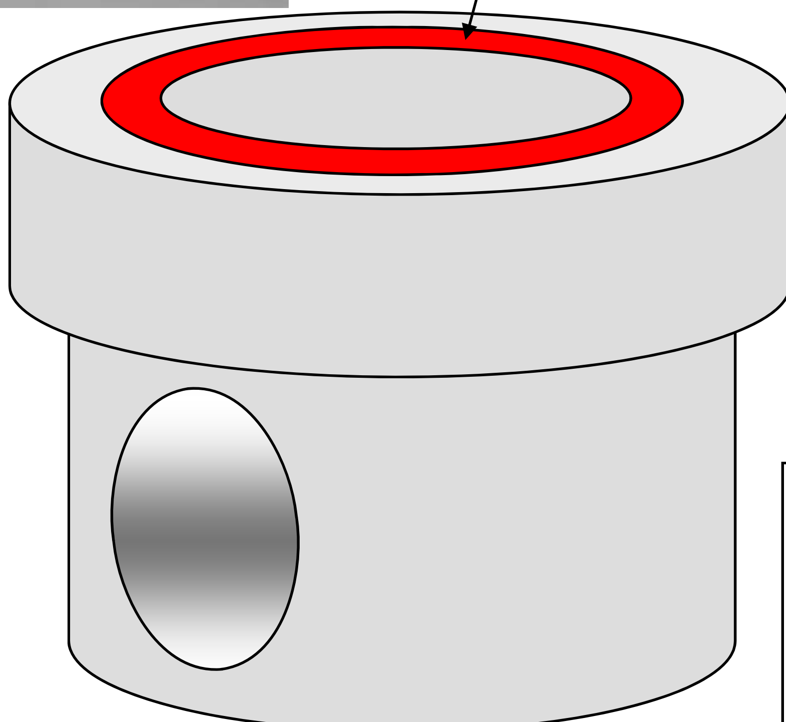
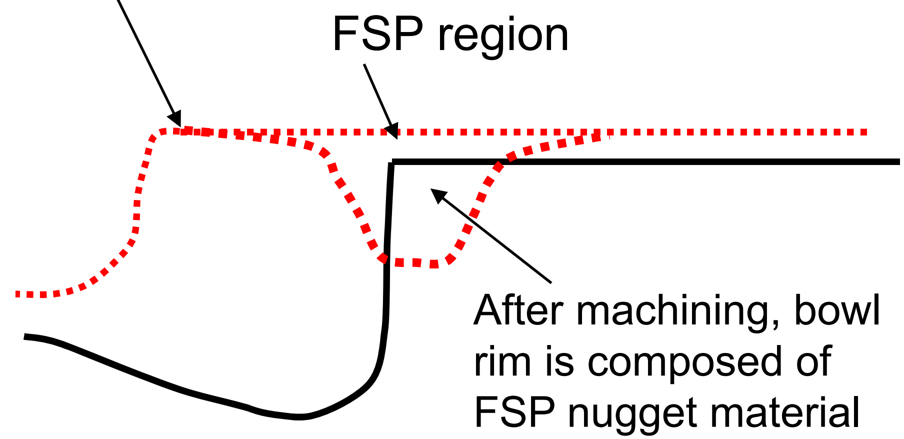
Approach 1 - Increased thermal fatigue strength of piston bowl rim

FSP region



Forged or cast blank prior to final machining



Goal for processed region:
- Increased thermal fatigue resistance
- Decreased fatigue crack growth rate
- Lower CTE (by addition of other components)
- Higher conductivity (by addition of other components)

Approach 2 – Increased strength and durability of top ring land and increased wear resistance of skirt

Start with high temp alloy with better fatigue properties (hypo-eutectic?) and selectively engineer regions that need high wear resistance and strength

FSP region
Top ring land prior to final machining

Stir in ceramic component and achieve high loading of Al_2O_3 or SiC

FSP region
Piston skirt

Goal for processed region:
- Increased wear resistance
- Increased hot hardness

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Technical Accomplishments / Results

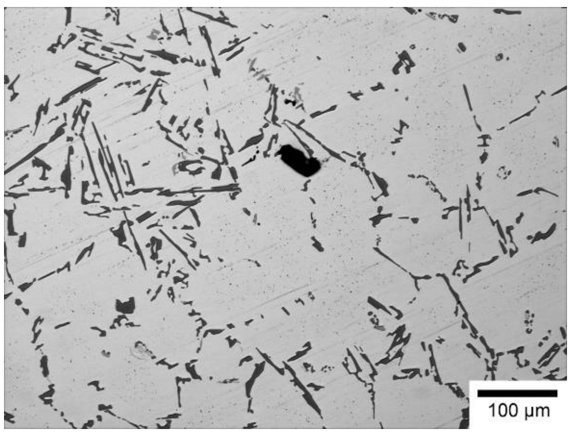
- During 2008 the project focused on FSP in aluminum materials that are compositional analogs to the typical piston and head alloys seen in small to mid-sized CIDI engines. At this point all our work is on flat coupons.
- Investigations were primarily of two types:
  - FSP of cast hypo-eutectic aluminum with <u>no introduction of any new component materials</u>
  - FSP of eutectic Cu-Ni aluminum alloys by <u>physically "stirring in" various quantities of carbon nanotubes and nanofibers</u>.

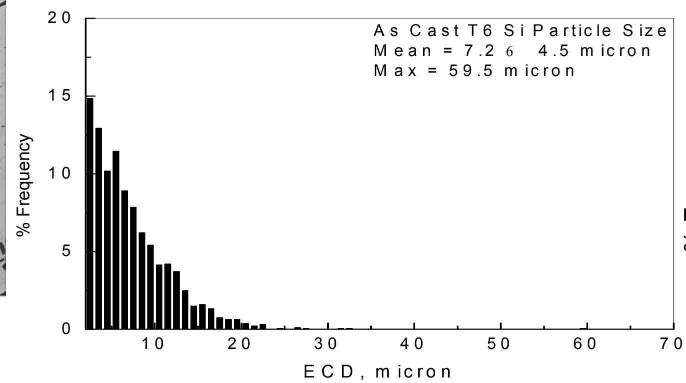
Technical Accomplishments / Results

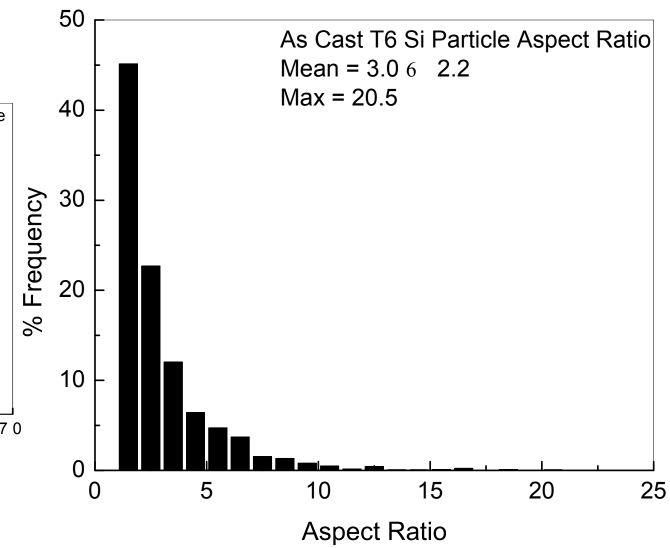
Aluminum Cylinder Head Alloys Improvement of Microstructure with FSP

The primary reasons for poor thermal fatigue performance of conventional cast aluminum when exposed to higher temperatures and loads include:

- **Porosity**
- **Si Particle Size and Shape**







- Avg. Si particle size = 7.2 µm, Avg. aspect ratio = 3.0
- 30-40% particles have size and aspect ratio more than the mean values.

(Jana, Suamyadeep, 2008)

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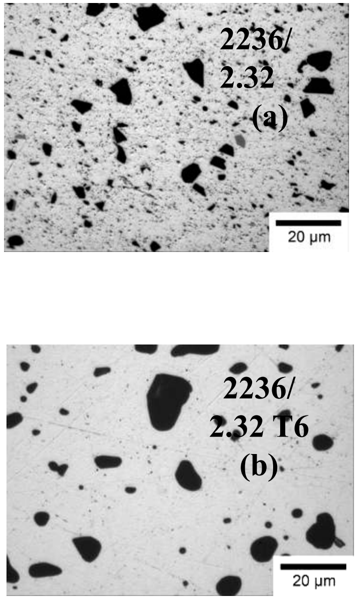
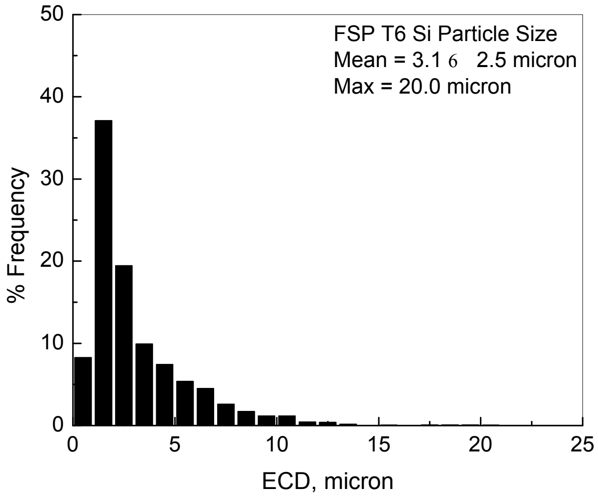
Technical Accomplishments / Results

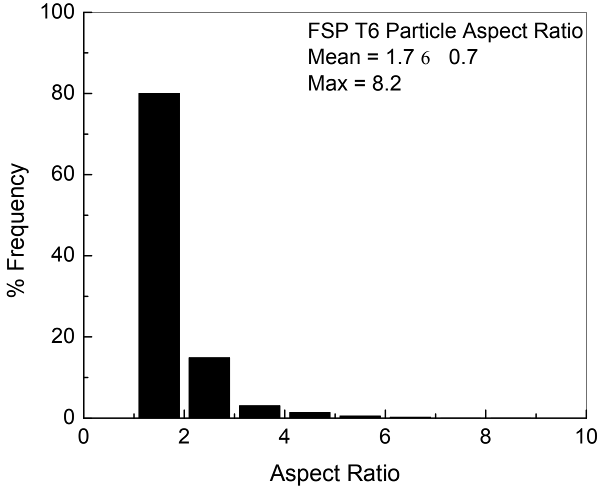
Aluminum Cylinder Head Alloys Improvement of Microstructure with FSP

Friction Stir Processing reduces particle size, aspect ratio and gets rid of “big” particles

- Mean particle size = 3.1 µm (reduced from 7.2 µm)
- Mean particle aspect ratio = 1.7 (reduced from 3.0)
- FSP was able to refine the Si particles by more than 50 %.
- Compared to as-cast condition, 20-25 % of total particles were above mean value after FSP. (reduced from 30% to 40%)
- FSP was also instrumental in eliminating comparatively bigger particles from the matrix.







(Jana, Suamyadeep, 2008)

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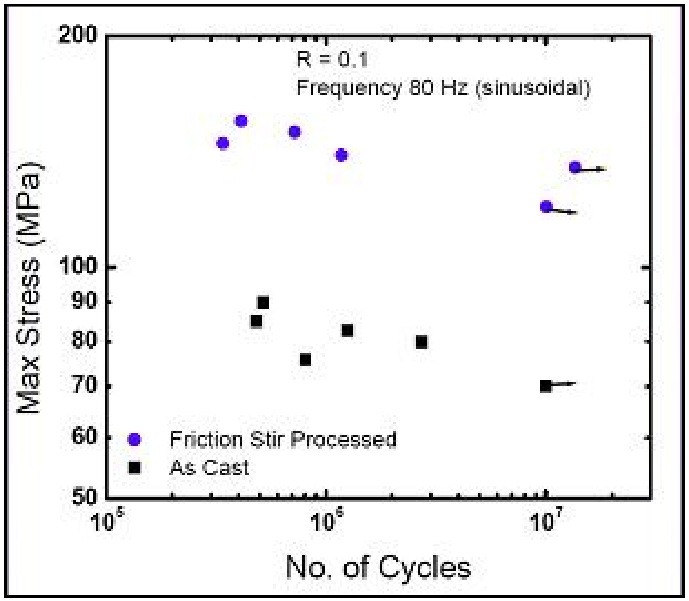
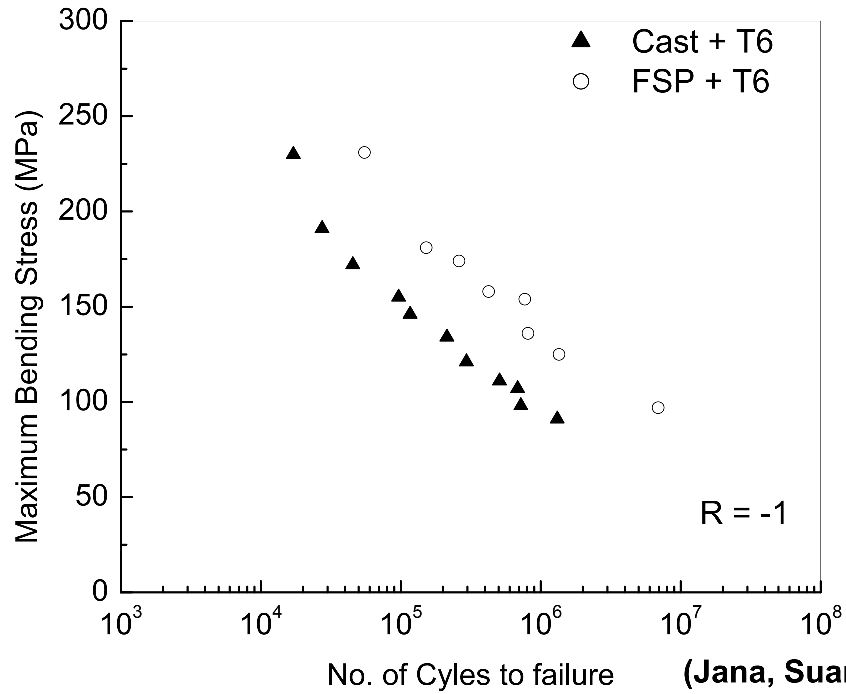
Technical Accomplishments / Results

The microstructural changes induced by FSP lead to significant improvement in fatigue performance in the processed region





(Jana, Suamyadeep, 2008)

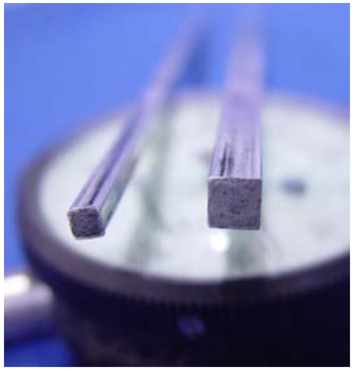
- The current solution to poor fatigue performance (including thermal fatigue) is to go to expensive casting techniques to reduce porosity, or make alloy changes to higher strength alloys.
- FSP (selectively applied to the problem areas) may allow lower cost alloys to be used at higher stress levels for the same durability level

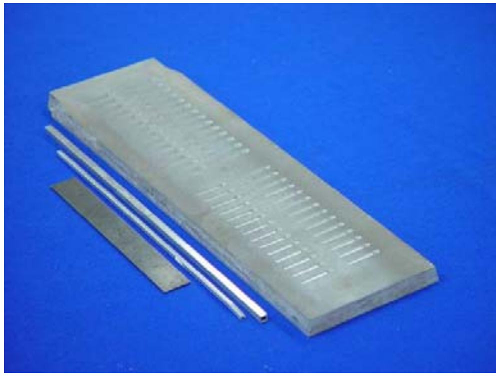
Technical Accomplishments / Results

Using FSP to “stir in” new components into piston alloys for improved bowl rim thermal fatigue

Material	Modulus	CTE	Conductivity
Aluminum	80 GPa	25 μm/m°C	180 W/m-K
SiC	410 GPa	4.4 μm/m°C	150 W/m-K
Al_2O_3	370 GPa	8.5 μm/m°C	13 W/m-K
Carbon Nanotubes	>600 GPa	Very low to 0	> 1000 W/m-K

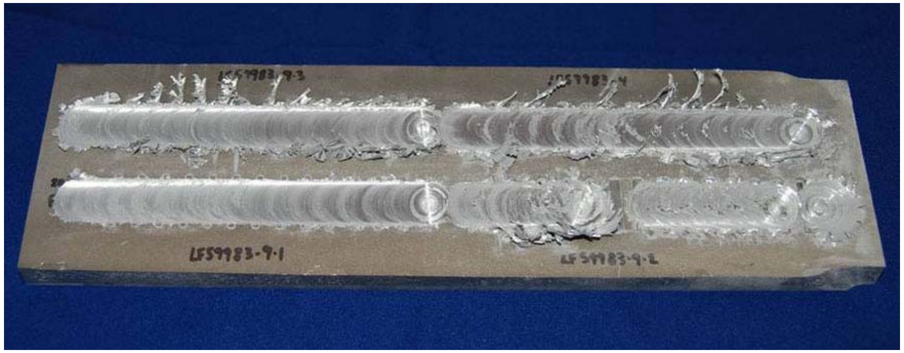
Important for thermal fatigue





3/16 and 1/8 diameter 3013 aluminum tubes packed with Carbon nanotube / fiber plus aluminum powder mixes

We were successful at stirring-in multiwall carbon nanotubes and nanofibers into the substrate



Goals for Carbon nanotube FSP:
- Low CTE
- High thermal conductivity
- May get high strength too

Technical Accomplishments / Results

Using FSP to “stir in” new components for improved bowl rim thermal fatigue

Carbon nanotubes

Stir tool used to incorporate new phases into the surface

Cross section of Stir Zone

- Carbon Nanotube filled tubes are completely consumed by the stir tool
- No volumetric defect – no holes
- Nanotubes are mixed into aluminum matrix

<u>Next steps</u>

- Evaluate these regions for thermal and mechanical performance

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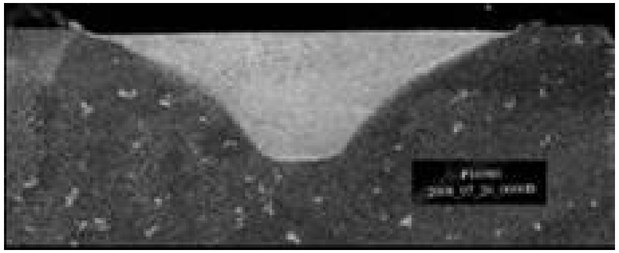
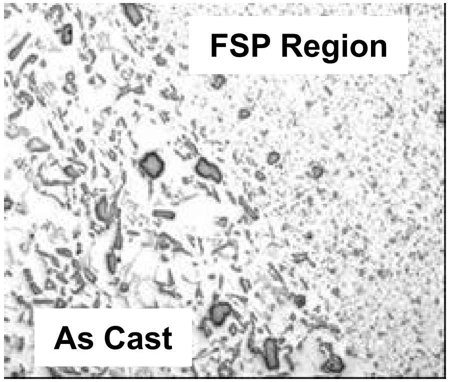
Technical Accomplishments / Results Summary

Aluminum

- Demonstrated significant fatigue improvement with FSP as applied to alloys used commonly in cylinder heads
- Developed process parameters necessary to product defect free processed zones in aluminum piston alloys, and successfully incorporated nanofibers and multiwall nanotubes into the surface of cast plates





Steel

- Began development of necessary tools and parameters to FSP steels
- Developed FSP machine mounted induction heating equipment to enable FSP in steels and cast iron materials, and to allow for study of in-situ heat treatment and microstructure control for improved high temp. properties

High-load FSP machine at PNNL

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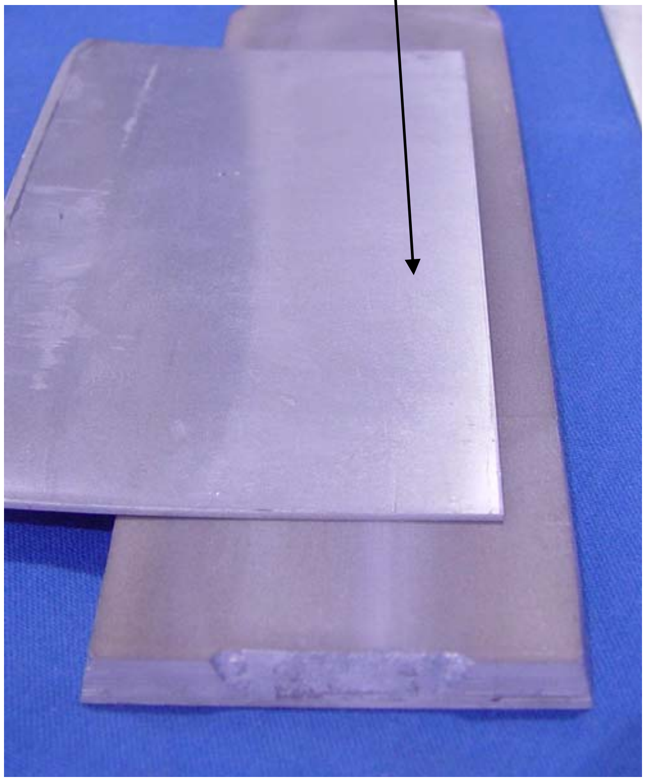
Future Work

- Thermal and mechanical testing of Carbon Nanotube mixed piston alloys
  - RT, isothermal, thermal cycling mechanical characterization of processed materials
  - Thermal property testing (conductivity, CTE)
- FSP trials for thermal property control
  - Develop strategies to change the thermal conductivity or CTE by incorporation of insoluble ceramic phases
  - May have additional benefit in wear applications (piston skirt)
  - Initial trials stirring in MMC sheet materials were successful
- Complete trials in steels necessary to achieve the Sept 09 milestone:
  - *Demonstrate consolidated FSP regions in a ferrous piston alloy, and establish process window to successfully stir particulate into the surface of steel.*

- 1 mm and 2 mm plates of hot rolled Al_2O_3/6061/20p and SiC/359/20p stirred into plate



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Summary

- Friction Stir Processing (FSP) is a new surface engineering technology that has the opportunity to produce tailored, high performance surfaces <u>on low-cost, conventional engine materials</u>

- Opportunities exist for using the process to enable new combustion processes, (HCCI and others) that can significantly increase the fuel efficiency of conventional gas and CIDI engines

- The project will systematically characterize the effects of FSP on materials to increase high temperature strength, increase durability of engine components (pistons, liners, cylinder heads), and potentially modify the thermal conductivity to increase thermal efficiency

- The project is a cost-shared collaboration between DOE/PNNL and Caterpillar, Inc., providing immediate opportunity to deploy new technology in a company that is a market leader in engine manufacturing

- Project work began in FY08 with investigations into aluminum alloy FSP with the specific target of increased mechanical and thermal properties of materials anticipated in mid-size CIDI engines

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