Tailored Materials for Advanced CIDI Engines

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Project ID: PM004

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Overview

Timeline

- Start: FY2008
- Project end date: Dec. 2010
- Percent complete: 65%

Budget

- Total project funding
  - DOE - $715k
  - CAT - 50/50 Cost Share with Caterpillar through in-kind contribution
- Funding for FY09: $340k
- Funding for FY10:$350k

Barriers

In support of the Advanced Combustion Engine R&D

- Fuel Efficiency
  - New combustion strategies necessary for increased fuel efficiency are putting higher demands on traditional engine materials. Without better materials, gains can't be realized.
- Peak Brake Thermal Efficiency & Durability
  - New combustion strategies raise peak cylinder pressures beyond current material capabilities
- Powertrain Cost
  - Engineered surfaces on conventional materials could be lower cost option than replacement by 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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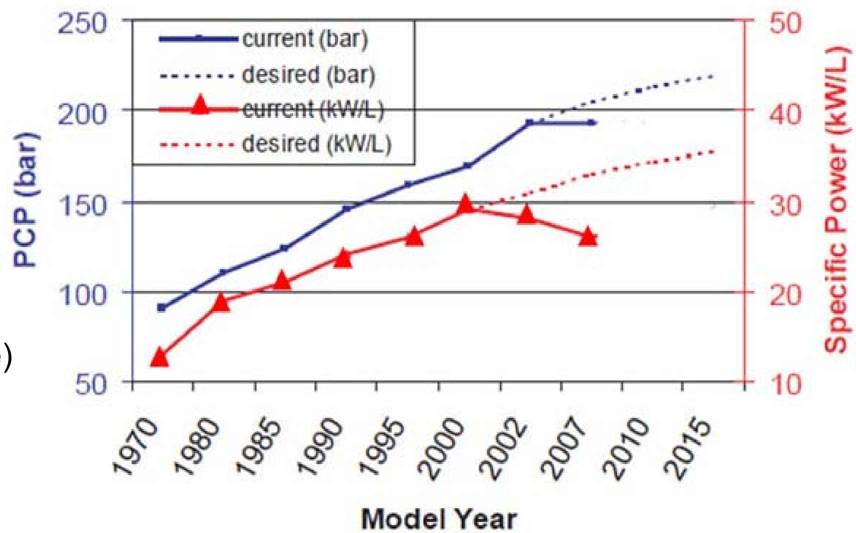
Relevance – Problem Statement



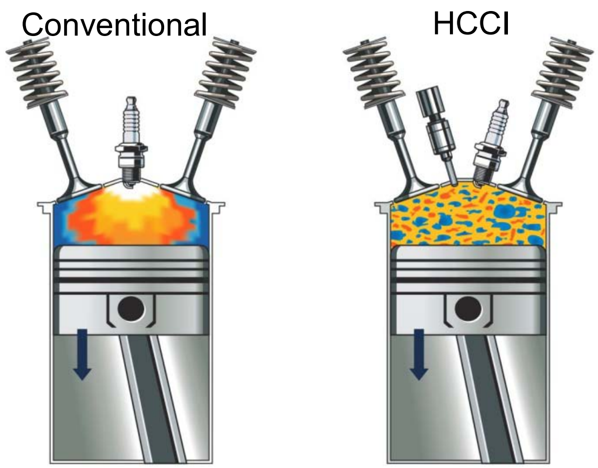
(PCP - Peak Cylinder Pressure)

Plot showing the increase in SP and PCP for Typical Heavy-duty Diesel Engines over the Last 38 Years (*Figure modified from Southwest Research Institute: http://www.swri.org/3pubs/brochure/d03/InvestHD/home.htm*)

- Specific Power is correlated with efficiency and is the combined effect of better optimization of combustion, fuels, engine materials and design, reduction in parasitic losses, and improved heat management.
- After 2001, the SP levels dropped due to emission and after-treatment devices. The drop in SP from 2001 to about 2003 would have been even greater were it not for significant advances in engine management, computer control, higher injection pressures, etc., made during this period to compensate for the power losses.
- After 2003, the restriction on the optimization of the combustion process is shown by the plateau in PCP - This is a materials issue. Conventional materials have trouble above 190 Bar.
- HCCI is 220 bar

Relevance – Problem Statement

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



However,

- Peak cylinder pressures can be much higher than conventional engines (potentially requiring higher cost materials)

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

Relevance to VT Program Goals
– Problem Statement

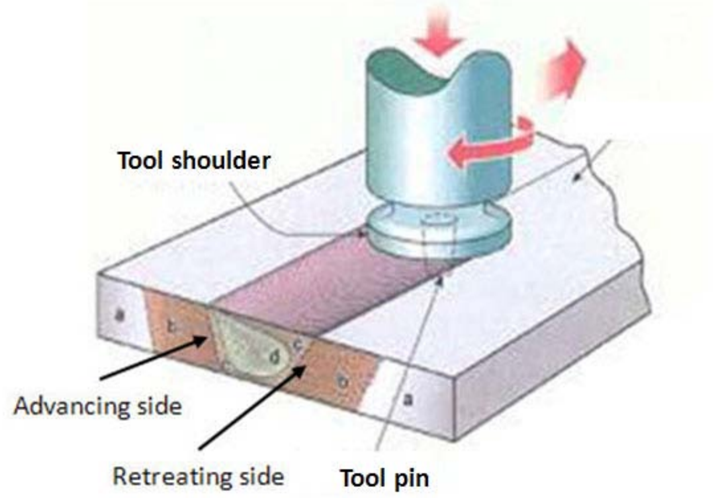
One example of a specific material barrier that prevents implementing highly efficient combustion: Bowl rim failure at high PCP

- Rather than substitute a potentially high-cost, high-temperature, monolithic material, one low-cost strategy to enable higher PCP involves using techniques to improve the thermal fatigue performance of current materials
- In the case of thermal fatigue in the bowl rim area, the technique need only be applied to the narrow area around the bowl rim itself since failures of this area drive the overall material selection.

If these failures could be prevented we could enable higher PCP and gain all the commensurate benefit for engine and fuel efficiency

Relevance - 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 this technology on traditional (low-cost) engine materials and subsystems; cast iron, alloy steels, and aluminum alloy parts
- To test and deploy friction stir processed components that can enable energy efficient combustion strategies.



FY 2010 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

High-load FSP machine at PNNL

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Milestones

- Milestone (Dec 2008): Demonstrate property improvements from FSP that can reach metrics established by project team: minimum 2 times improvement in fatigue life, significant reduction in thermal fatigue crack initiation and growth rate, 20% improvement in average failure stress level at N cycles. (Completed)

- Milestone (Sept 2009): Demonstrate consolidated FSP regions in a ferrous piston alloy, and establish process window to successfully stir particulate into the surface of steel. (Completed)

- Milestone (June 2010): Demonstrate a Friction Stir processed zone in a circular configuration appropriate to a piston bowl rim modification in an aluminum piston alloy (On target)

- Milestone (Sept 2010): Demonstrate that mechanical property metrics can be achieved (increased hardness and improved fatigue response) in a steel piston alloy modified by Friction Stir Processing (On target)

Approach

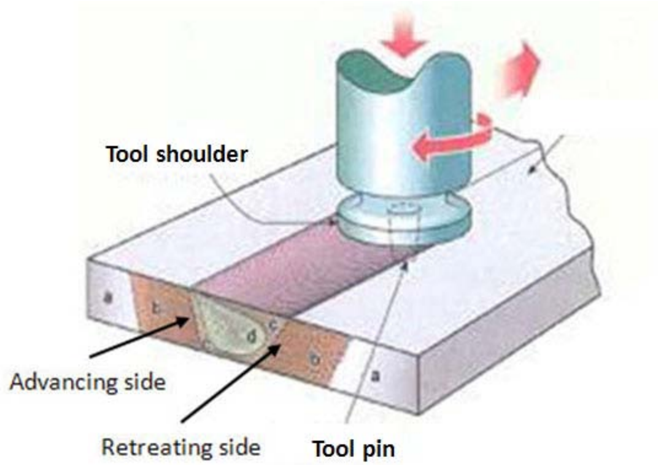
- Develop surface modification techniques, modified materials, and components. The project is a Cooperative Research and Development Agreement (CRADA) with Caterpillar, Inc., but also involves input from diesel piston suppliers.

- The project is primarily investigating FSP, a new technology that can produce functionally graded surfaces with unique and tailored properties that will allow propulsion materials to withstand higher temperatures and pressures without losing appreciable strength, hot hardness, or wear resistance, and exhibit improved resistance to thermal fatigue.

- FSP treated components will be evaluated and tested by the industry collaborators to demonstrate efficiency benefits and potential commercial applications

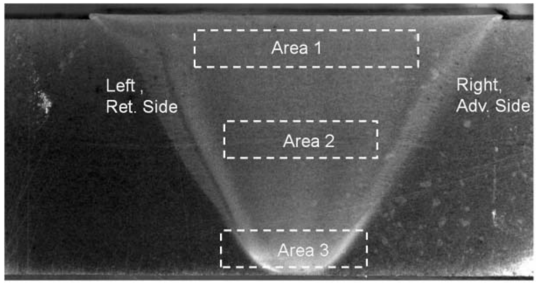
Technical Background - Friction Stir Processing

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

Processed region in aluminum



Processed region in steel

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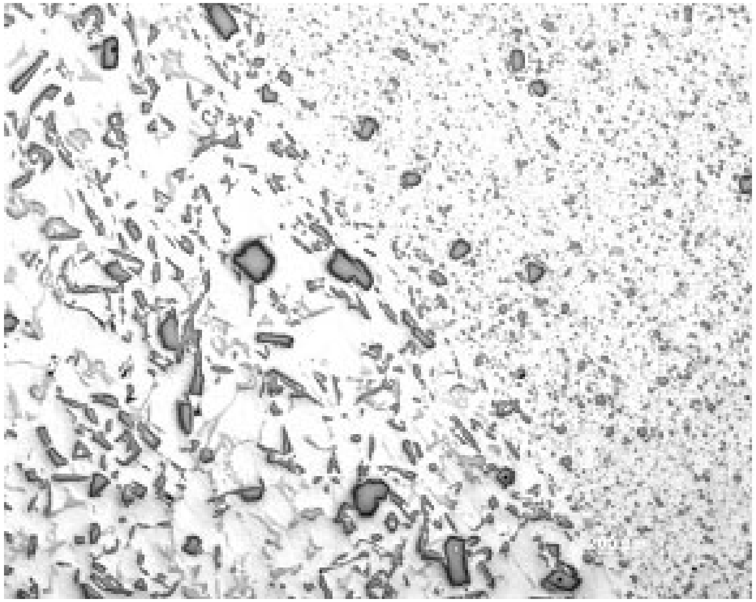
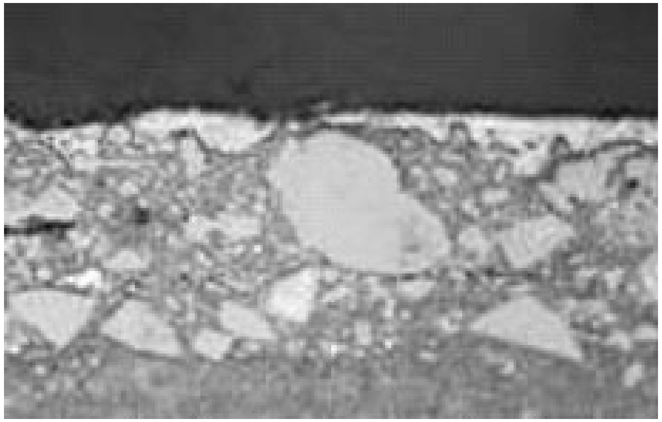
Friction Stir Processing





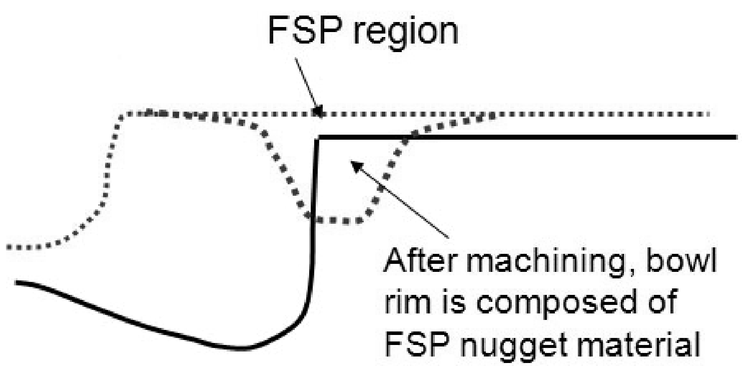
Process Advantages

- 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

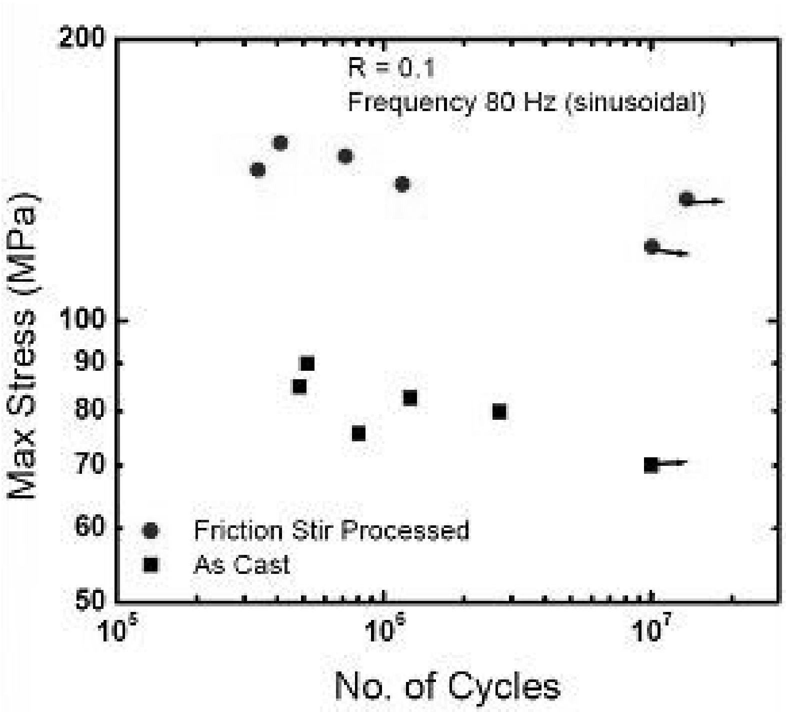
Technical Approach - Piston Concept

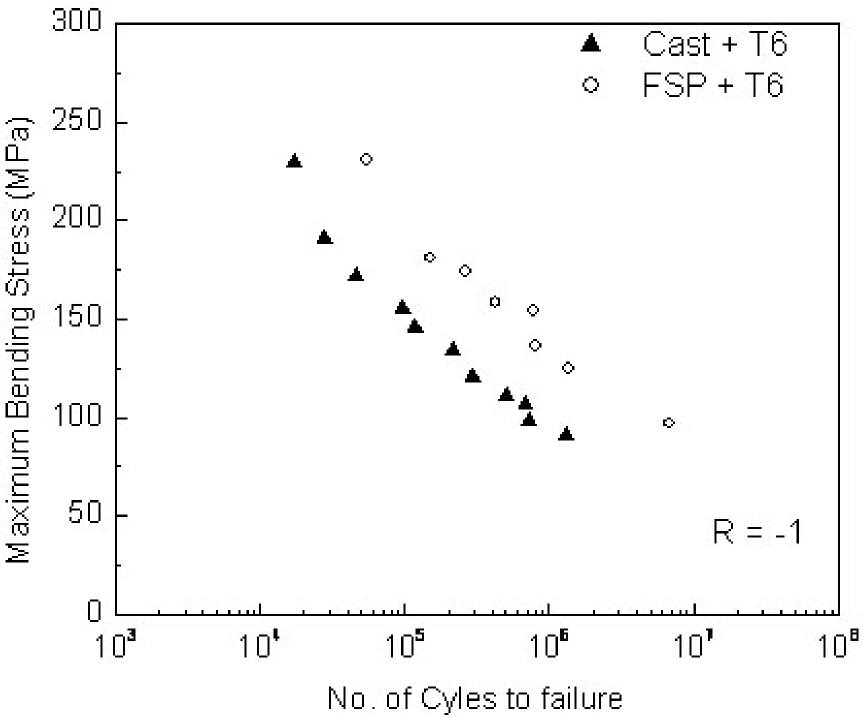


- FSP applied to the area of a piston blank (prior to final machining) that will be the bowl rim area
- During 2010 the project is focusing on FSP in aluminum materials that are compositional analogs to the typical piston and head alloys seen in small to mid-sized CIDI engines.
- Investigations are primarily :
  - 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>.
  - FSP of 6061 alloys to develop mixing parameters

Previous Results

FSP on 356 with no "new" component added



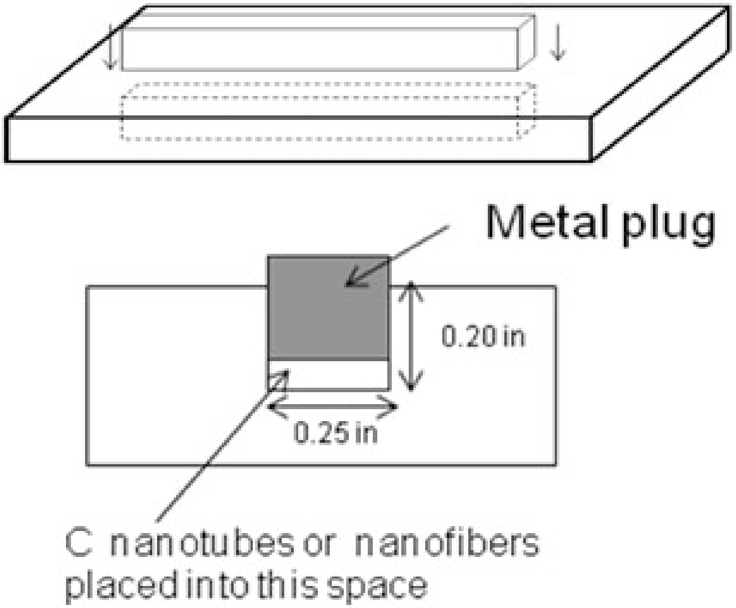


- FSP significantly refines microstructure, closes casting porosity, and reduces the aspect ratio of the Si particles in cast Al-Si alloys.
- These three features produce a dramatic improvement in fatigue life.
- A 90% improvement in maximum tensile stress at 10^7 cycles and improvements in bending fatigue lifetime up to an order of magnitude can be shown for this alloy.

Accomplishments (FY09-FY10)

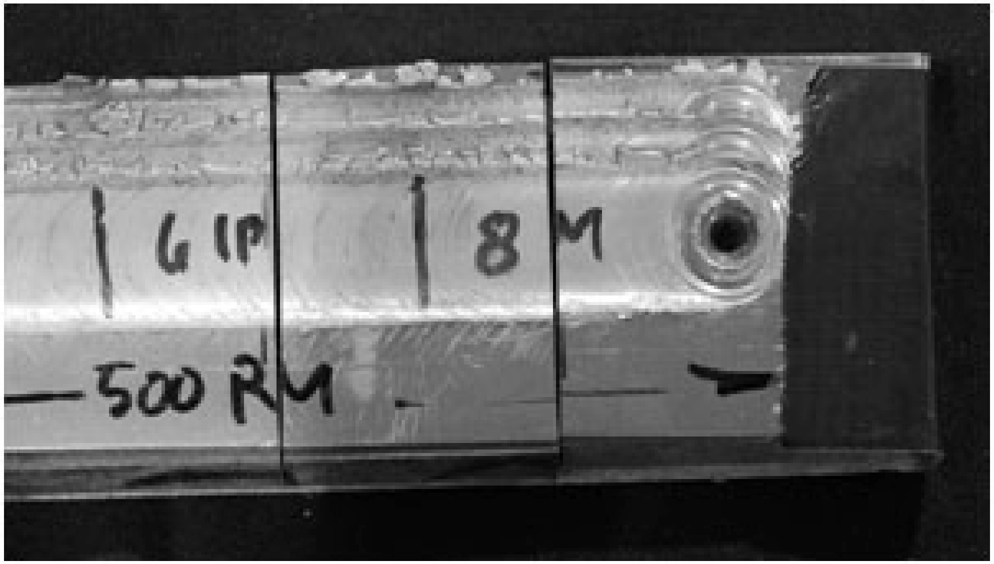
FSP—"Stirring-in" Carbon Nanotubes and Nanofibers

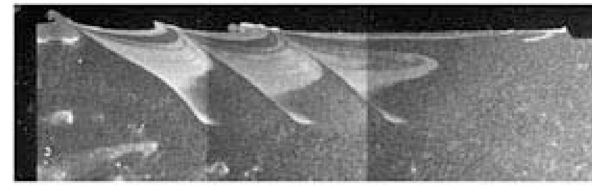
Material	Modulus	CTE	Conductivity
Aluminum	80 GPa	25 μm/m°C	180 W/m-K
SiC	410 GPa	4.4 μm/m°C	150 W/m-K
Al_2O_3	370 GPa	8.5 μm/m°C	13 W/m-K
Carbon Nanotubes	>600 GPa	Low or Can be negative !	> 1000 W/m-K

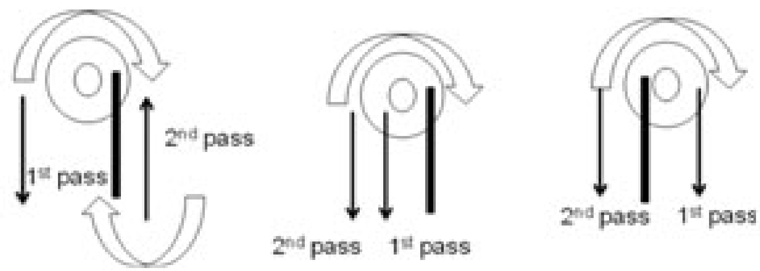


- Use FSP to improve the microstructural and mechanical properties that most influence thermal fatigue (i.e., CTE, conductivity, and, to a lesser extent, high temperature strength)
- Goal is to find the best methods of stirring in particulate into the aluminum substrate while producing the most homogeneous and highest particulate loading possible

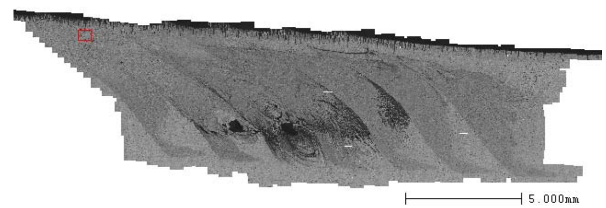
Accomplishments - The FSP Mixing Process



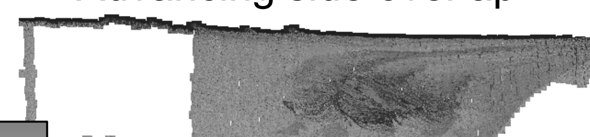




- Metal plug and groove then was processed by multiple overlapping passes of a friction stir tool at a wide range of different parameters and conditions.
- Variables investigated included RPM, travel speed, normal load, tool design, number of passes, and order of passes with respect to the advancing and retreating side of the tool.



Advancing side overlap

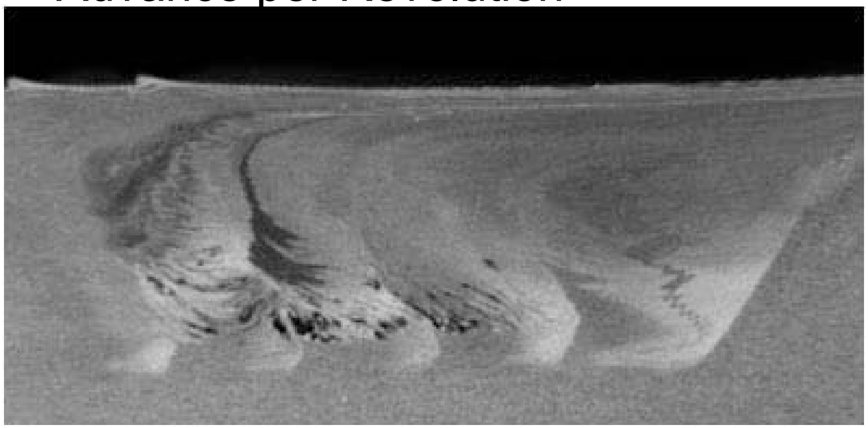


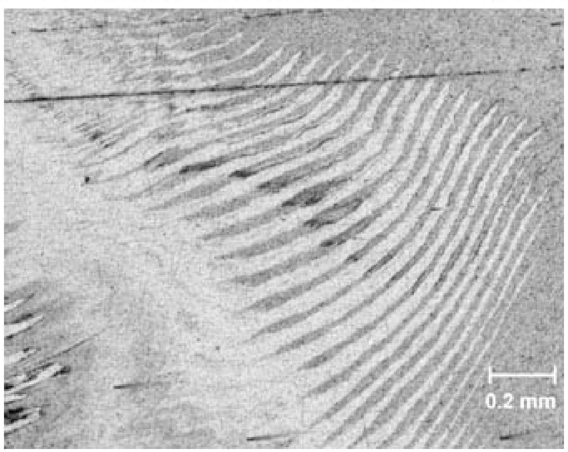
Retreating side overlap

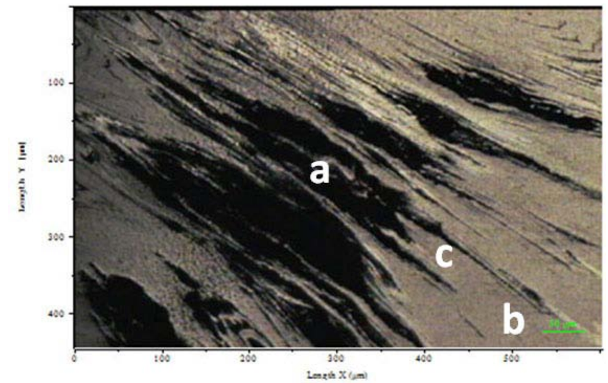
Fundamental investigation into mixing parameters resulted in specific parameters and techniques that improve homogeneity

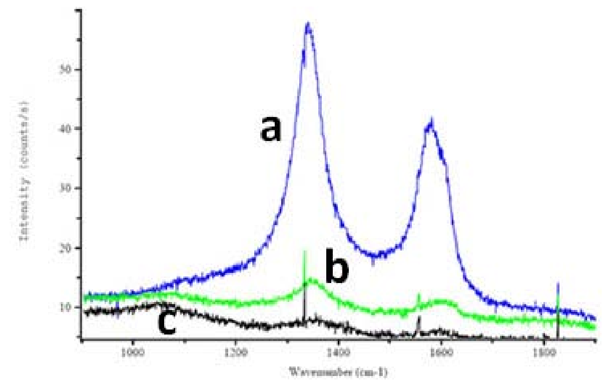
Key process parameter for homogeneous distribution - Rotation and travel speed of the tool

"Advance per Revolution"









Raman spectroscopy is used to determine nanotube distribution

- High Advance per Revolution produces poor mixing

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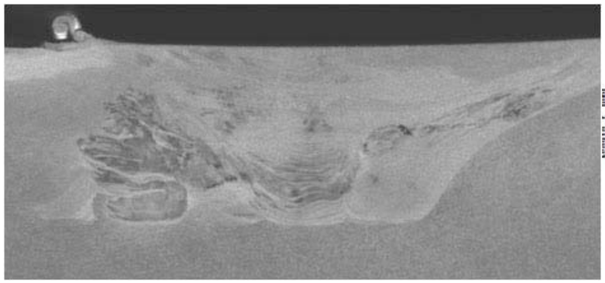
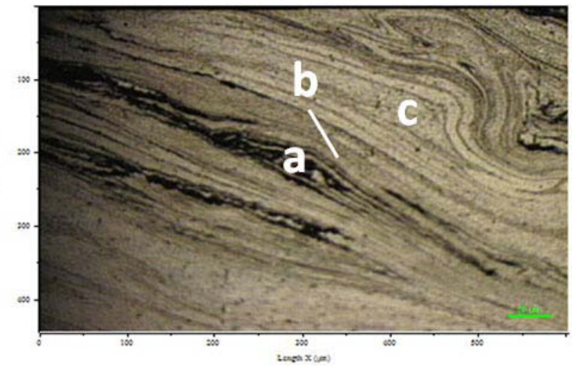
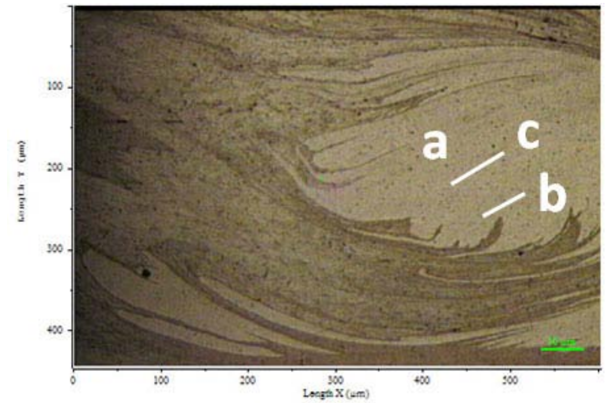
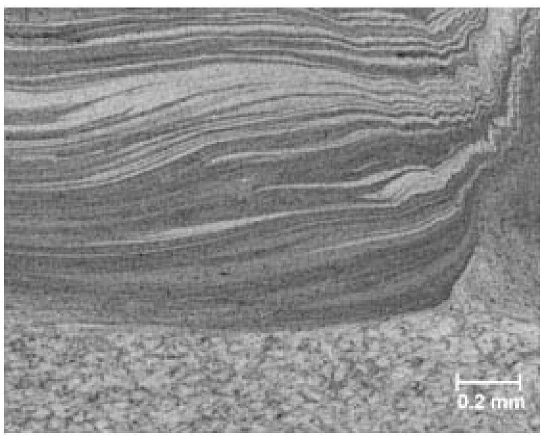
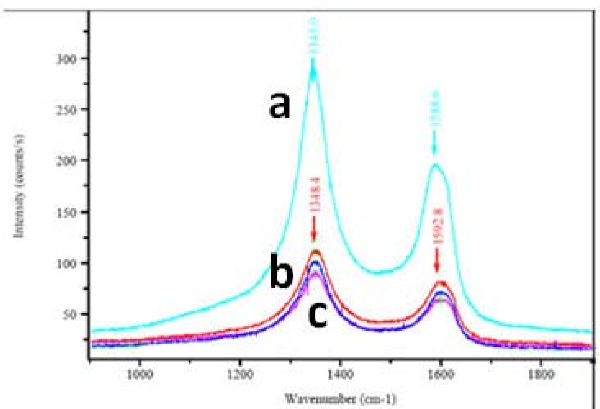
Low APR enhances mixing and homogeneous distribution of nanotubes

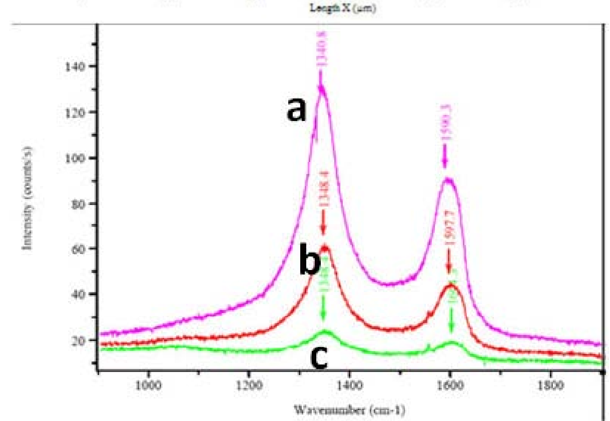








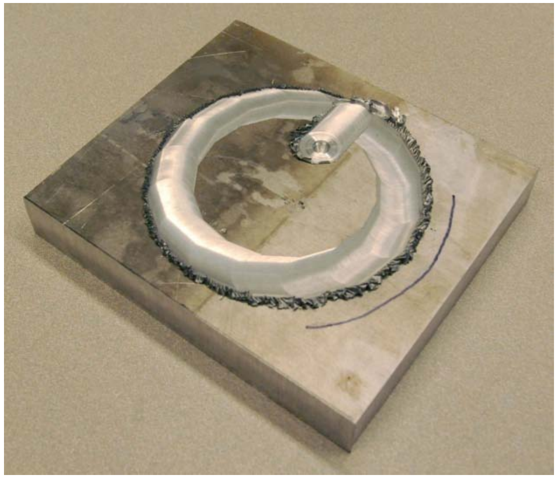




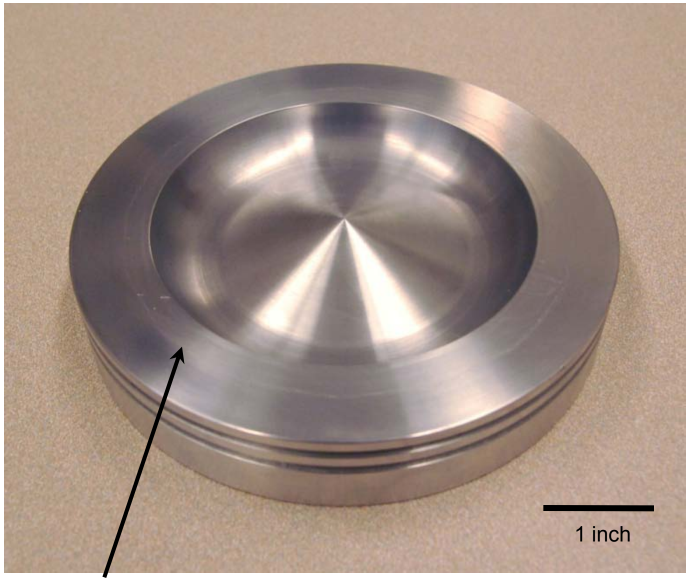
- Raman shows nanotubes even in areas with little optical signature
- Bottom line: process parameters that allow small advances in tool position relative to each rotation of the tool produce much better nano-particle distribution

Technical Accomplishments - Piston Prototype

- FSP process was developed for creating a circular processed region

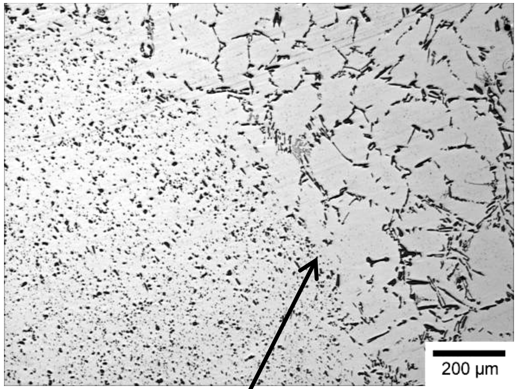


Circular process region created by "welding" in a counterclockwise direction then turning to center and exiting where piston bowl will be located



Faint line demarking edge of FSP processed zone on bowl rim after machining

Plate is then machined to a piston top configuration so that FSP region is located on bowl rim



Edge of processed region

Processed region is fully consolidated and composed of material with a highly refined microstructure to resist thermal fatigue cracking

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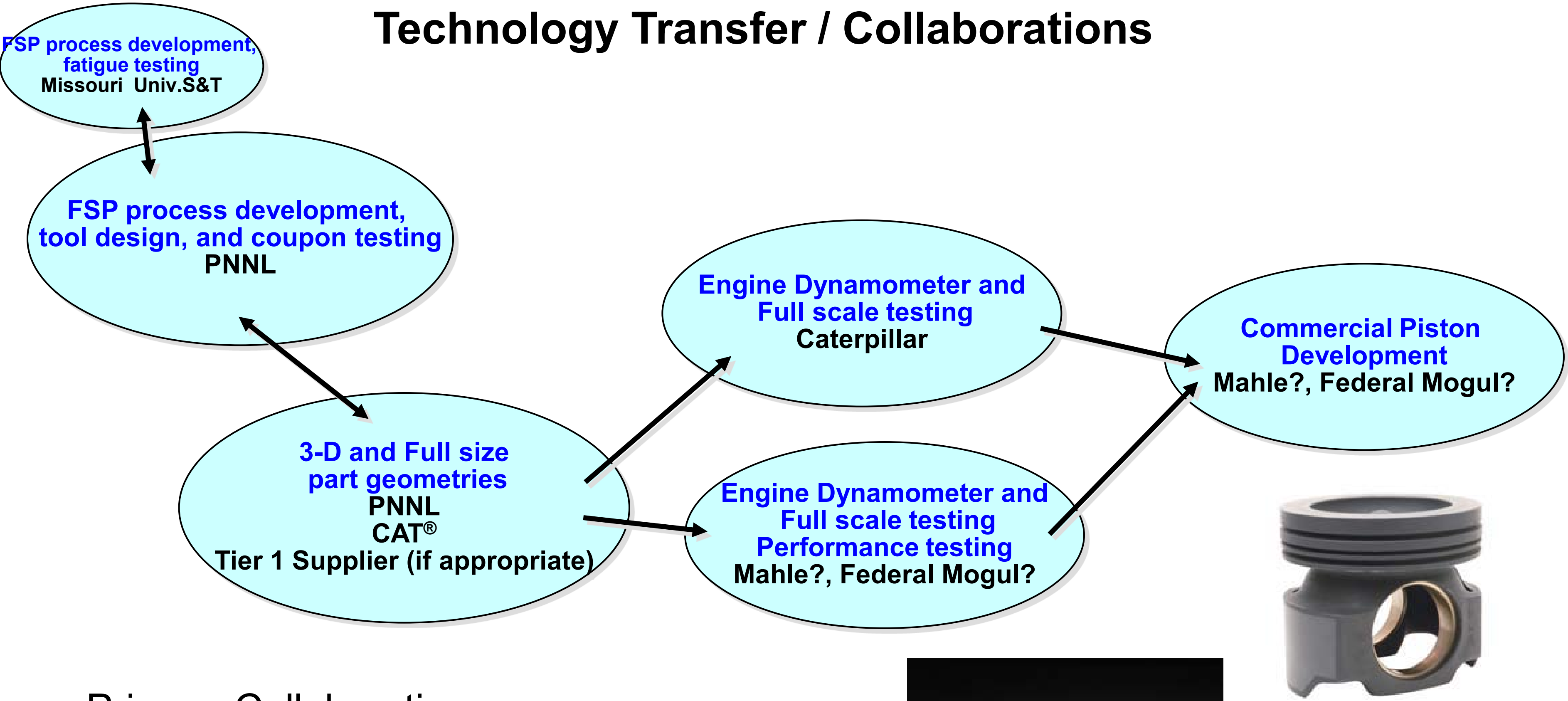
Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations



Primary Collaborations

- This project is a CRADA with Caterpillar
  - Missouri Institute of Science and Technology (Academic): Collaborated on fatigue work early in program
  - BYU (Academic): Collaborated on FSP process parameters for steel FSP

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Future Work

- Thermal and mechanical testing of Carbon Nanotube mixed piston alloys
  - RT and elevated temperature thermal fatigue testing and mechanical characterization of processed materials
  - Thermal property testing (conductivity, CTE)
- FSP trials for thermal property control
  - 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
  - Demonstrated consolidated FSP regions in a ferrous piston alloy, and established a process window to successfully stir particulate into the surface of steel. Future work needs to quantify the fatigue performance advantages.

Summary -- Milestones, Metrics and Accomplishments

- Milestone: Demonstrate property improvements from FSP that can reach metrics established by project team: minimum 2 times improvement in fatigue life, significant reduction in thermal fatigue crack initiation and growth rate, 20% improvement in average failure stress level at N cycles. (Completed)
  - FSP was found to produce significant improvement in fatigue performance when compared to as-cast aluminum alloy 356. Depending on stress ratio and stress level, the FSP-processed materials showed from 5 to 15 times fatigue life improvement over as-cast material. In addition, FSP-processed materials showed up to 80% improvement in fatigue strength across a wide range of maximum stress levels.

- FSP was used to physically “stir-in” multi-wall carbon nanotubes and several different carbon nanofiber compositions into aluminum surfaces to a depth of 5.8 mm.

- Milestone (Sept 2009): Demonstrate consolidated FSP regions in a ferrous piston alloy analog. (Completed)
  - The tooling and process parameter space for accomplishing thick section (up to 13 mm thick) FSP of steel materials was investigated. Fully consolidated process zones were demonstrated, but tool survivability must be improved.

- Milestone (June 2010) Demonstrate a Friction Stir processed zone in a circular configuration appropriate to a piston bowl rim modification in an aluminum piston alloy (Completed 3 months ahead of schedule)

Summary

- The goal of this project is to deploy friction stir processed components that can enable energy-efficient combustion strategies, especially strategies that will require higher PCP or higher temperature operation.

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

- 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

- Experimental work on aluminum alloys has shown significant increases in fatigue lifetime and stress-level performance using friction processing alone, and ongoing work has shown the potential to create mechanically mixed alloys of aluminum and carbon nanotubes that may provide unique thermal fatigue-resistant surface regions to CIDI engine components.

- Future work includes quantifying property improvements and fabrication of prototype parts for engine durability testing.