Tailored Materials for Advanced CIDI Engines

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Project ID: PM004

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Overview

Timeline

- Start: FY2008
- Project end date: Sept 2011
- Percent complete: 90%

Budget

- Total project funding
  - DOE - $765k
  - CAT - 50/50 Cost Share with Caterpillar through in-kind contribution
- Funding for FY10: $350k
- Funding for FY11: $150k

Barriers

Identified from 2011-15 MYPP Propulsion Materials Program

- New combustion strategies necessary for increased fuel efficiency are putting higher demands on traditional engine materials.
  - Without better materials, gains can't be realized.
- Lighter Weight Propulsion Materials
  - Weight of the propulsion system must be reduced even as the combustion régimes place higher strength requirements on the engine components.
- Powertrain Cost
  - Light-duty vehicles are extremely sensitive to upfront costs and heavy-duty vehicles are extremely sensitive to lifecycle costs. Therefore any new materials technology will have to meet stringent cost targets to achieve commercial success.

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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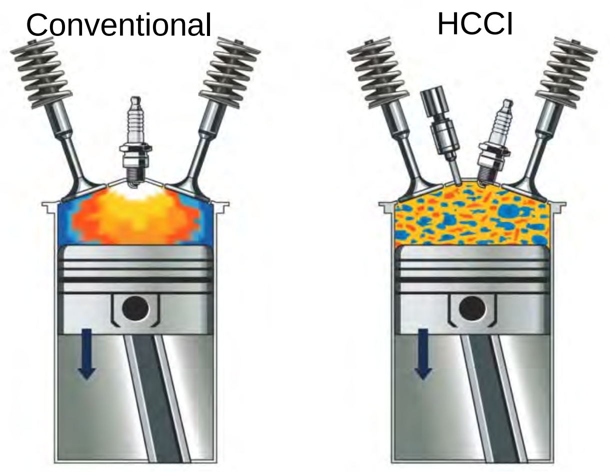
Relevance – Problem Statement

New combustion strategies (HCCI, Low Temperature Combustion, 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

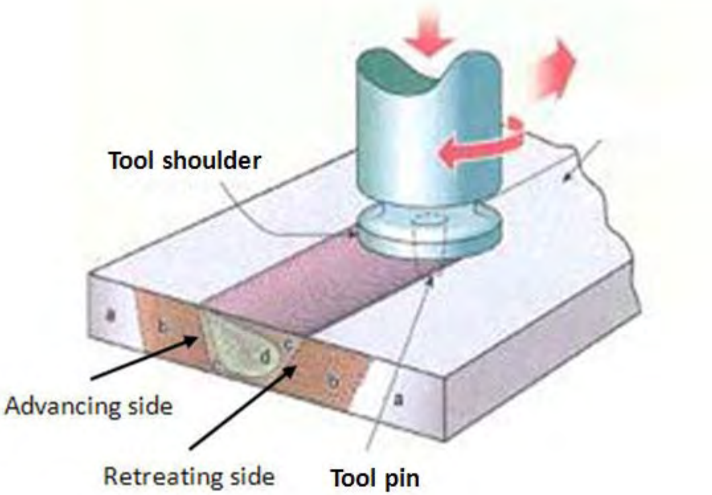
One example of a specific material barrier that prevents implementing highly efficient combustion: Bowl rim failure at high PCP

- 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.



High-load FSP machine at PNNL

FY 2011 Focus

- Experimentally develop FSP in aluminum materials that are compositional analogs to the typical piston and head alloys seen in mid-sized CIDI engines.
- Document and transfer to industry the Friction Stir process parameters, process knowledge, techniques and expected material performance so that engine designers can include this new surface engineering strategy into future designs

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Milestones

- 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)

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

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

- Milestone: Document and transfer to industry the Friction Stir process parameters, process knowledge, prototype FSP processed part sections, FSP techniques and expected material performance (on Target)

Approach

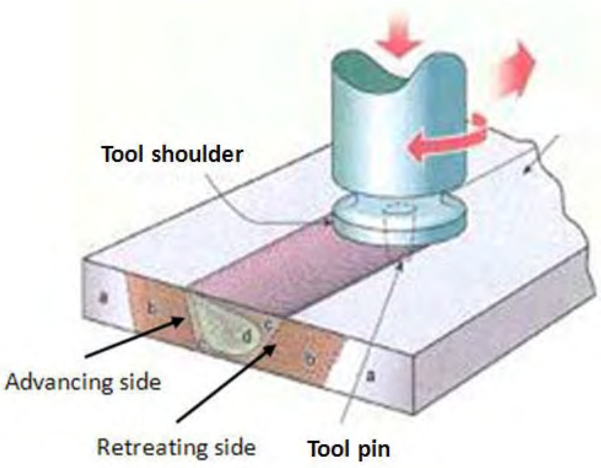
- Develop surface modification techniques, modified materials, and components. The project is a Cooperative Research and Development Agreement (CRADA) with Caterpillar, Inc., but also involves input from diesel piston suppliers.

- 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.

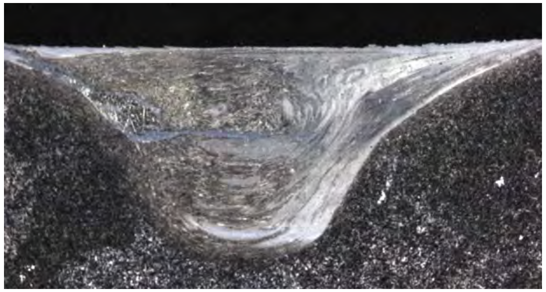
- FSP treated components will be evaluated and tested by the industry collaborators to demonstrate efficiency benefits and potential commercial applications

Technical Background - Friction Stir Processing

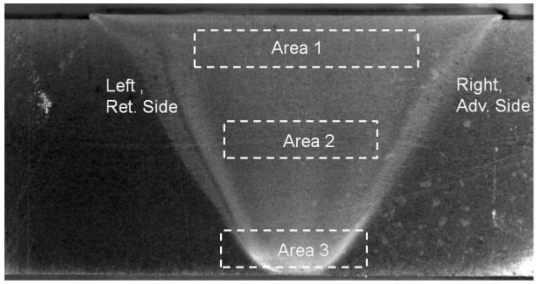
Solid-state process to create an engineered surface
(not a coating process)



- 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

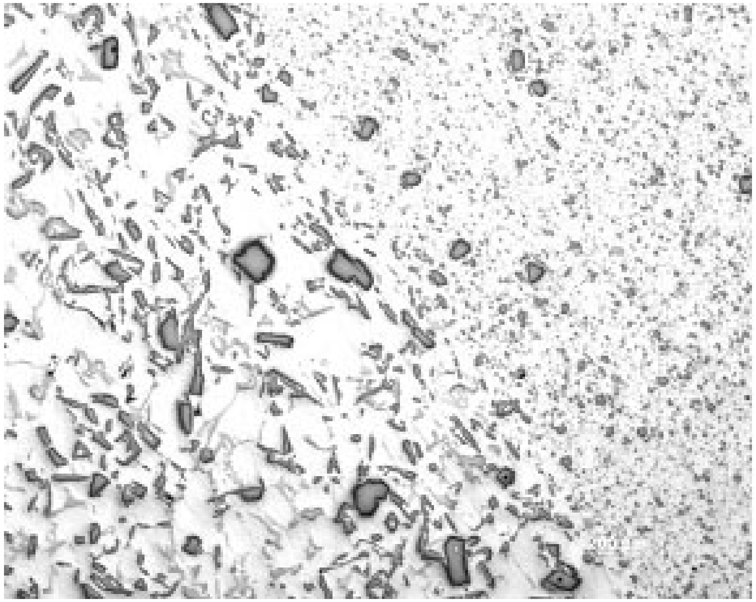


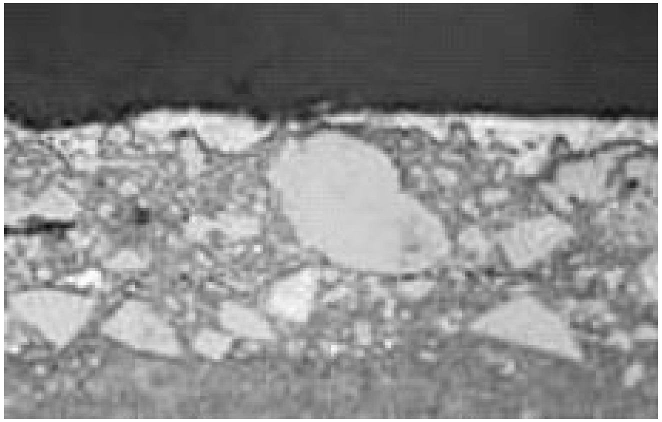
Processed region in aluminum



Processed region in steel

Friction Stir Processing





FSP can <u>selectively</u> 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

<u>Process Advantages</u>

- 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

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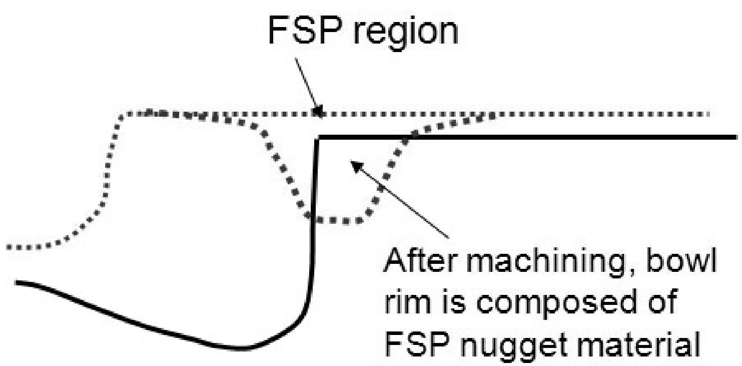
Technical Approach - Piston Concept



- FSP applied to the area of a piston blank (prior to final machining) that will be the bowl rim area
- During 2010-11 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 :
  - (2009) FSP of cast hypo-eutectic aluminum with <u>no introduction of any new component materials</u>
  - (2010-2011) FSP of eutectic Cu-Ni aluminum alloys and SI-Mg aluminum alloys by <u>physically "stirring in" various quantities of carbon nanotubes and nanofibers</u>.

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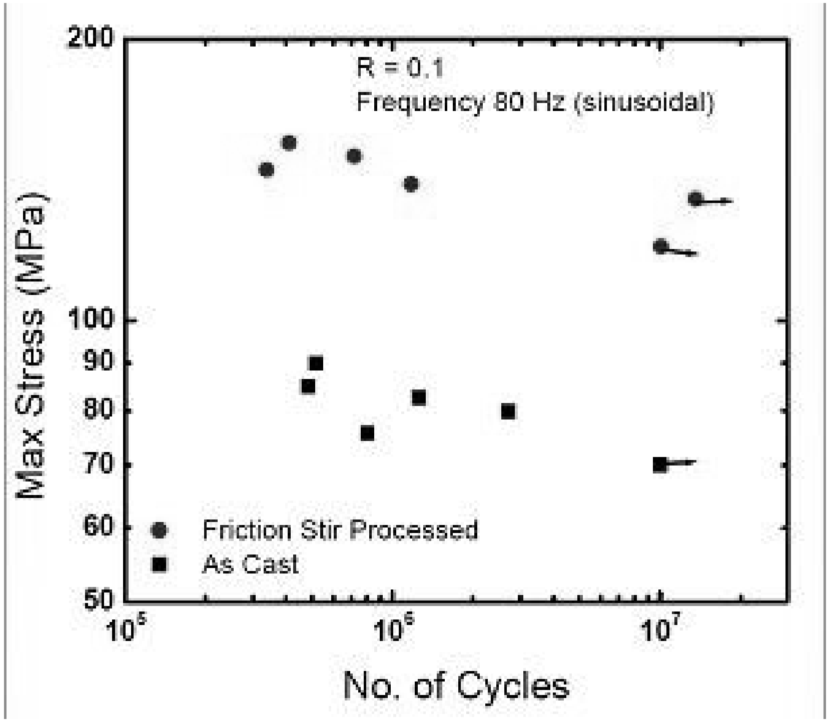
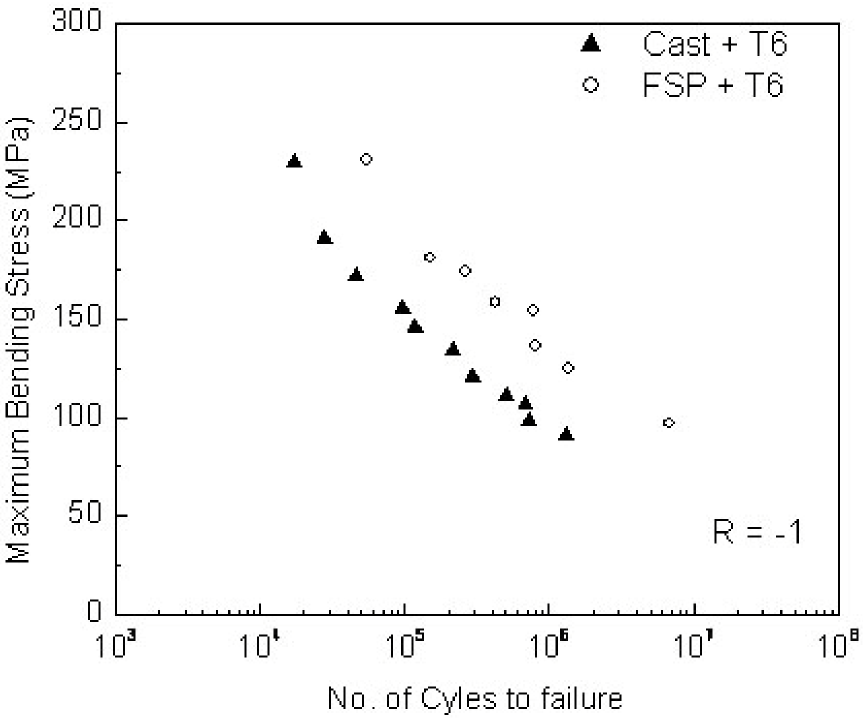
Previous Results

FSP on 356 with no "new" component added

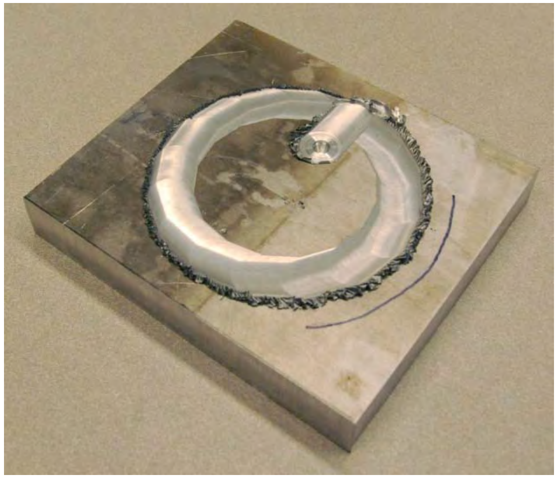




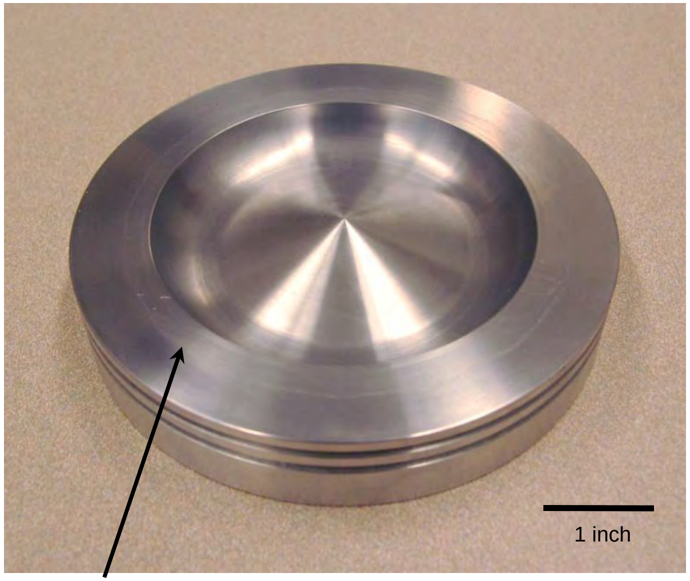
- FSP significantly refines microstructure, closes casting porosity, and reduces the aspect ratio of the Si particles in cast Al-Si alloys.
- These three features produce a dramatic improvement in fatigue life.
- A 90% improvement in maximum tensile stress at 10^7 cycles and improvements in bending fatigue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

Previous result – Piston top prototypes delivered

- FSP process was developed for creating a circular processed region

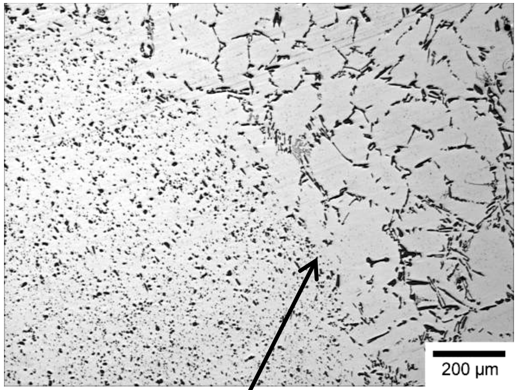


Circular process region created by “welding” in a counterclockwise direction then turning to center and exiting where piston bowl will be located



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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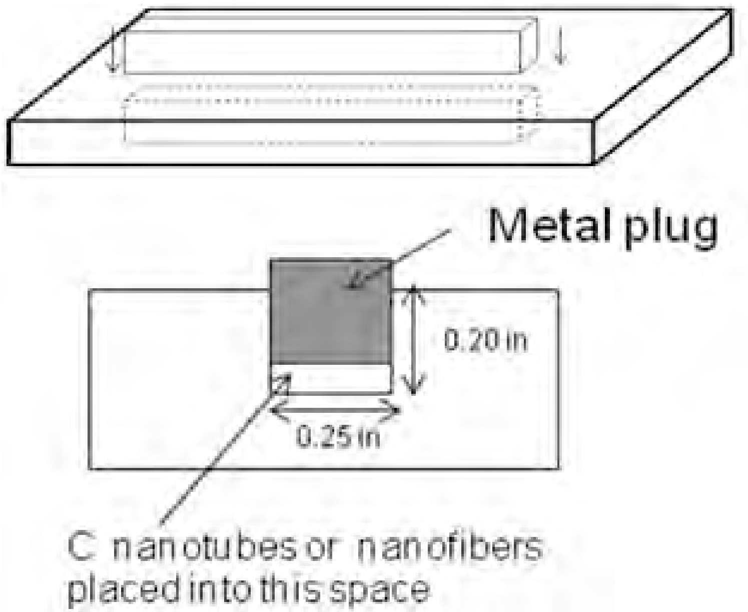
Accomplishments (FY10-FY11)

FSP—“Stirring-in” Carbon Nanotubes and Nanofibers

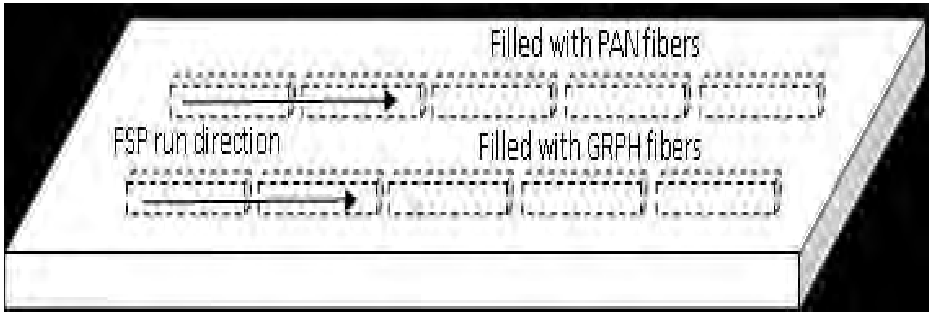
Material	Modulus	CTE	Conductivity
Aluminum	80 GPa	25 µm/m°C	180 W/m-K
SiC	410 GPa	4.4 µm/m°C	150 W/m-K
Al_2O_3	370 GPa	8.5 µm/m°C	13 W/m-K
Carbon Nanotubes	>600 GPa	Low or Can be negative !	> 1000 W/m-K

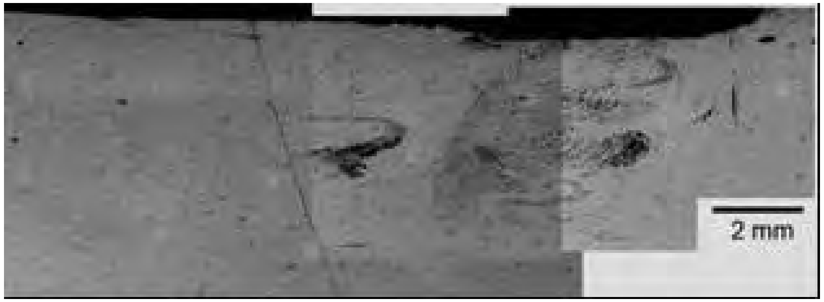


- Use FSP to improve the microstructural and mechanical properties that most influence thermal fatigue (i.e., CTE, conductivity, and, to a lesser extent, high temperature strength)
- Goal is to find the best methods of stirring in particulate into the aluminum substrate while producing the most homogeneous and highest particulate loading possible
- Last year we presented results of stirring in multiwall carbon nanotubes that showed hardness increases in nanotube rich areas

2010-11 Technical Accomplishments

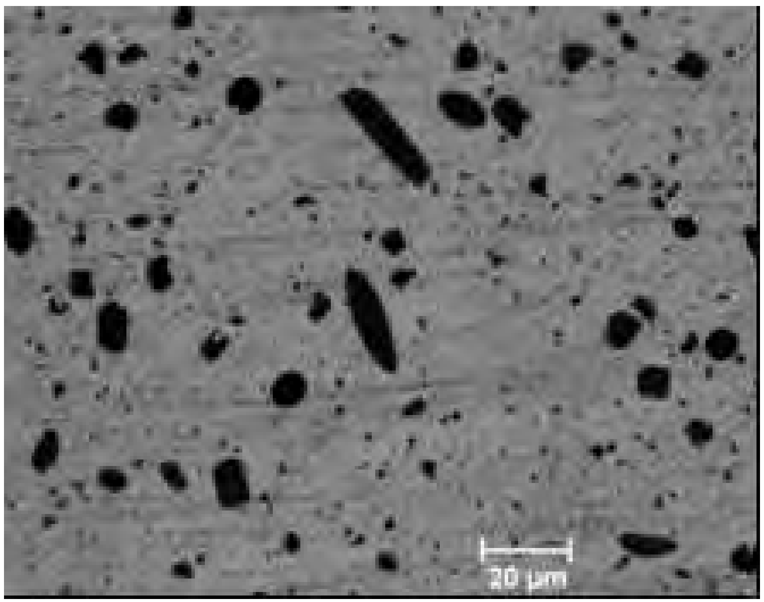
- FSP carbon fiber work
  - Efforts to stir in carbon fiber to address cost and other issues around the use of nanotubes
  - Stirred in long fibers (1 inch long ¼ inch wide flexible flat ribbon fiber braids)
  - Graphite fiber and PAN fiber tests

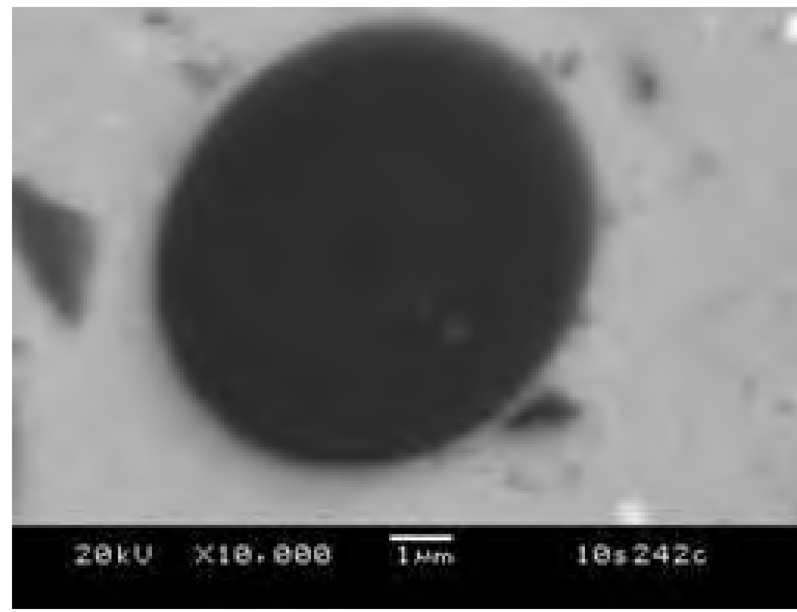




Technical Accomplishments

- Long fibers were completely fragmented and segmented and moderately well distributed within the process zone
- SEM revealed good bonding was achieved between the aluminum and the carbon fiber fragments with no reaction zones (aluminum carbide) present





- However some particle agglomeration did occur with both Graphitic fibers and PAN fibers

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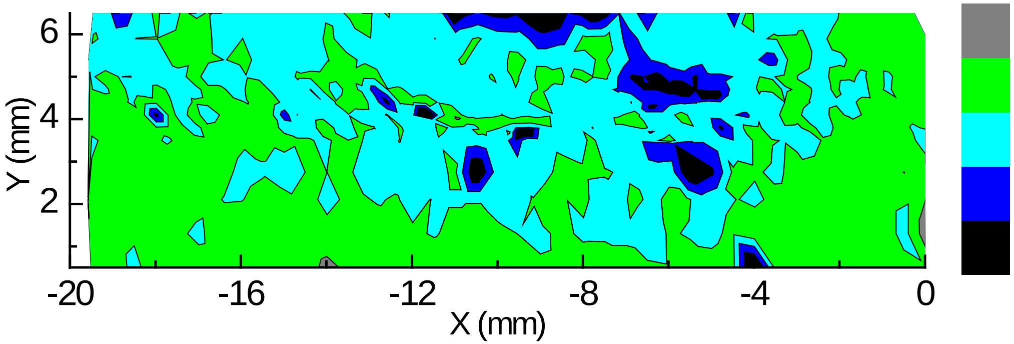
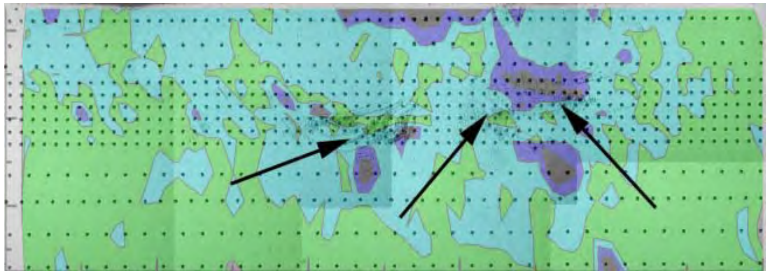
Technical Accomplishments

- Hardness profiles revealed softening in the agglomerated region. We believe due to porosity from incomplete solid state mixing



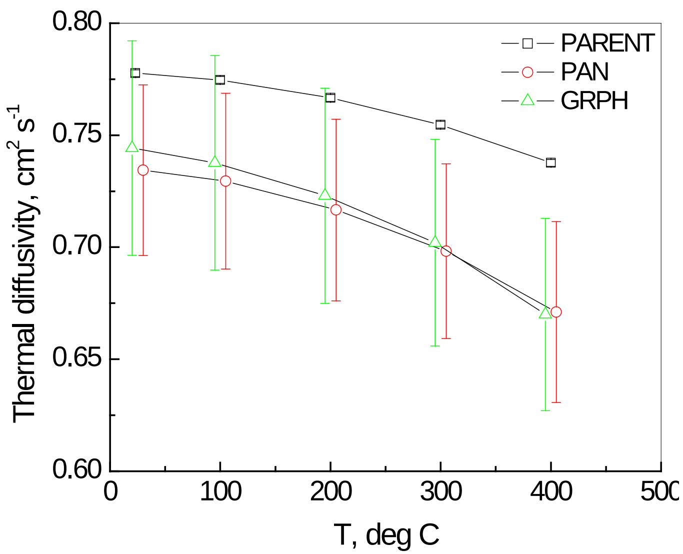


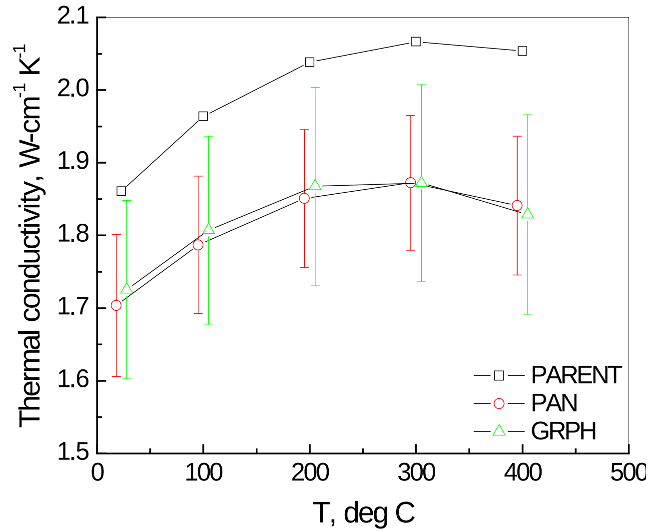
- Density measurements in the processed region also revealed a slight loss of bulk density we feel is due to very fine porosity around small fiber fragments in agglomerated regions

Parent Aluminum		PAN-Filled Samples		GRPH-Filled Samples	
2.69	0.003	2.60	0.008	2.61	0.026

Thermo-mechanical testing

- Thermal diffusivity was measured from room temperature to 400°C using a laser flash technique (ASTM E1461).
- Bulk density of the samples was then determined from the sample's geometry and mass.
- Specific heat, C_p, was measured using differential scanning calorimetry.
- Thermal conductivity values were calculated as a product of these quantities (i.e. Conductivity = Diffusivity × C_p × density).





- Thermal diffusivity of the processed region was lower than the parent due perhaps to a large amount of very fine porosity
- Thermal conductivity was also lower (from lower density numbers used in calculation of conductivity)
- Summary – Aluminum - Carbon nanotube/fiber composites can be made with FSP that show unique properties, but better mixing to avoid porosity is probably necessary before thermal property gains can be realized

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Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations

FSP process development, fatigue testing
Missouri Univ.S&T

FSP process development, tool design, and coupon testing
PNNL

3-D and Full size part geometries and FSP property testing
PNNL
CAT

Future work
Engine Dynamometer and Full scale testing
Caterpillar

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

Tech Transfer

- FSP process reports to Caterpillar
- 4 peer reviewed papers
- Several conference proceedings papers
- Over 10 technical conference presentations were given
- Two graduate students were funded by this project

Summary

- The goal of this project is to develop the new surface engineering technique of Friction Stir Processing, increase its technical readiness level, and provide industry with the tools and performance information that allows them to consider implementation into their products.
- The FSP process has been demonstrated in this project to significantly improve fatigue performance of current low-cost, engine materials, potentially allowing them to operate under highly aggressive combustion regimes anticipated in the next generation of energy efficient engines, especially combustion regimes that will require higher Peak combustion pressures like HCCI.
  - 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
  - In addition techniques were developed to apply the process to 2 and 3-d shapes necessary for real part modification
- Experimental work on aluminum alloys has shown significant increases in fatigue lifetime and stress-level performance using friction processing alone, and has shown the potential to create mechanically mixed alloys of aluminum and carbon nanotubes or fibers that may provide unique properties to specific areas of engine components.
- 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
- Future work includes project reporting and data transfer to industrial partners