Tailored Materials for Improved Internal Combustion Engine Efficiency (Agreement ID:23725)

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Overview

Timeline

- Start: late FY2011
- Project end date: Sept 2014
- Percent complete: 30%

Budget

- Total project funding
  - DOE - $1025k
  - GM - $900k (in-kind)
  - 50/50 Cost Share with GM through in-kind contribution
- DOE Funding for FY11: $200k
- DOE Funding for FY12: $350k
- DOE Funding for FY13: $300k

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

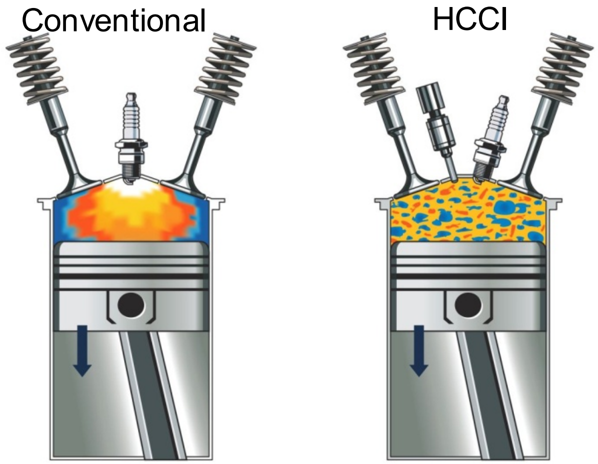
- General Motors R&D
- University of North Texas
- Project lead: PNNL

Relevance – Problem Statement

New combustion strategies (HCCI, Low Temperature Combustion, lean burn, "High Speed" diesel) can increase engine efficiency

However,

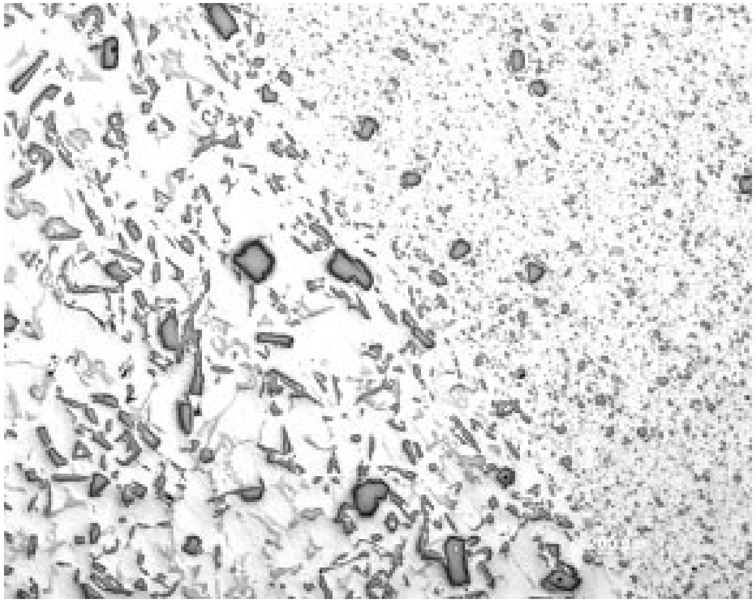
- Peak cylinder pressures can be much higher than conventional engines leading to sharp load-rise times and high loads on pistons, heads, cranks blocks, etc.(potentially requiring higher cost materials)



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

Background
Friction Stir Processing



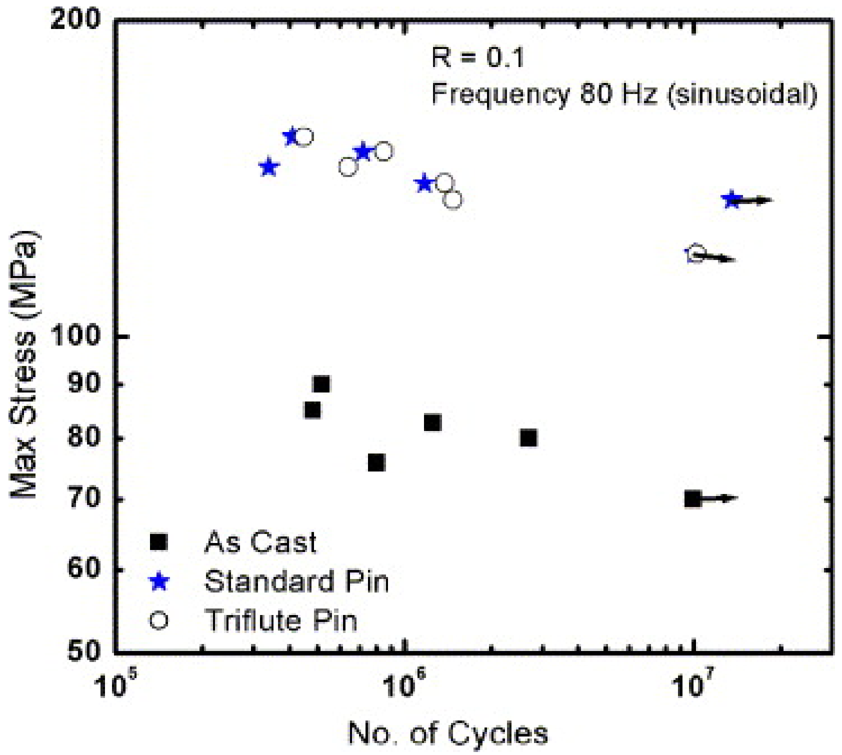
FSP can selectively modify an area of a part to produce better properties

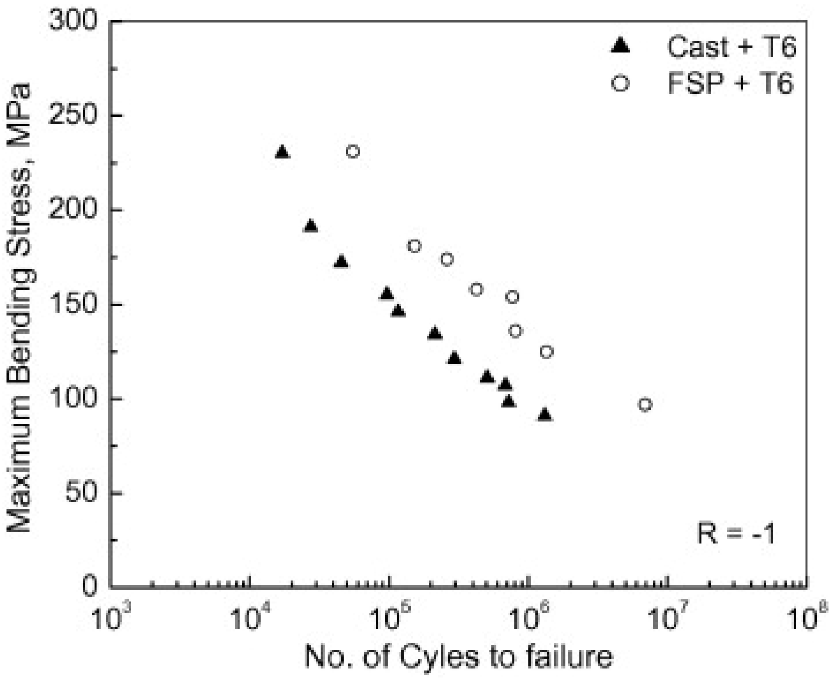
- Strength improvement by 50%
- Ductility improvement by factor of 5
- FSP-processed materials have shown up to 80% improvement in endurance limit (fatigue strength) over as-cast alloys.
- FSP-processed materials have even shown from 5 to 15 times fatigue life improvement over investment cast material.

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

Background – Previous Results Validating Concept





Enhancement of fatigue performance in a *sand cast A356 alloy* with a porosity vol. fraction ~ 0.95%. **Endurance limit improves by 80% as a result of FSP [1].**

5x enhancement in fatigue life after FSP in an *investment cast F357 alloy* [2]. This alloy had a porosity vol. fraction of only ~ 0.20%

1. Sharma et al. Scripta Materialia, vol. 51, 2004
2. Jana et al. Acta Materialia, vol. 58, 2010

Objective

Develop Friction Stir Processing to selectively produce surface modified regions on parts composed of conventional engine materials to address barriers related to durability at high PCP, without the increased raw material costs often associated with the introduction of a higher performance bulk material.

Fabricate prototype friction stir processed components that can be tested for durability and performance so that designers of the combustion process can access areas of engine control where increased specific power and low emission levels are found, but where high PCPs can create reliability problems.

Approach

- Develop the FSP manufacturing parameters, tools and techniques to produce defect-free FSP regions.
- Coupon-level testing and evaluation of the thermal and mechanical properties.
- If performance metrics are met for sample materials enhanced by FSP, demonstrate this process on 2-D and 3-D geometry part analogs.
- Fabricate prototype parts to specifications provided by project partners and relevant part testing will be completed (in-engine or other tests specified by partners).

Project Focus Areas

Thermal fatigue improvement for aluminum cylinder heads for small displacement turbocharged applications

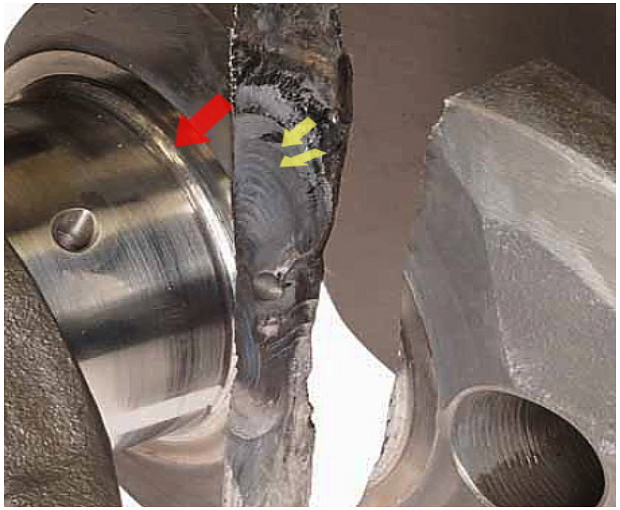
Shaft fatigue improvement on fillet and oil hole location, and on dissimilar material welded shafts (EV apps)

Approach   Detailed Task Breakdown

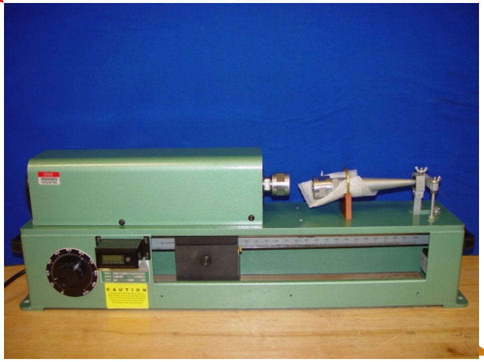
- **Task 1 <u>Cylinder Head Thermal-Fatigue, and Cylinder Head or Block "RT" Fatigue Life Improvement</u>**
  - 1a Chill Casting at GM R&D of A356 plate stock for experimental trials. (completed)
  - 1b FSP trials for Thermal aging studies (completed)
  - 1c FSP trials for stable microstructure (resistance to Abnormal Grain Growth) (completed)
  - 1d Room temperature fatigue studies on FSP coupons (miniature fatigue testing)
  - 1e Elevated temperature fatigue testing FSP coupons
  - 1f Translating process to 3-d part and producing a processed region on an actual head or head analog
  - 1g Operating-temperature, cylinder head pressurization testing at GM
    - GM uses "steam tests" and "hydraulic fatigue tests" before parts move to dyno testing. A "steam test" is accomplished by clamping the cylinder onto a fixture and blowing steam of it, then running cold coolant through it to induce a thermal shock.

Approach   Task Breakdown

- **Task 2 <u>Fillet, oil hole, or flange fatigue performance improvement on rotating shafts</u>**
  - 3a FSP trials on <u>steel</u> alloy plate for process parameter development
  - 3b Mechanical and toughness testing of FSP coupons
  - 3c Room temperature fatigue studies on FSP coupons (rotating beam fatigue on subscale specimens)
  - 3d Elevated Temperature fatigue testing FSP miniature coupons (oil bath temperature – this is not creep/fatigue, just fatigue)
  - 3e Translating process to 3-d part and producing a processed region on an actual rotating shaft assembly
  - 3f In-engine testing at GM



Fatigue failure at a fillet



RBF machines at PNNL

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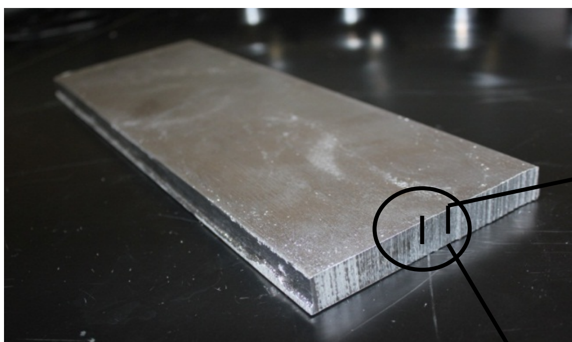
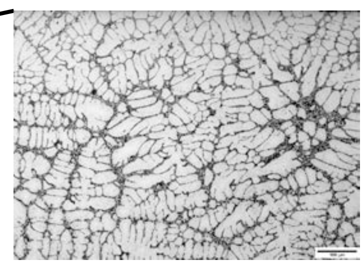
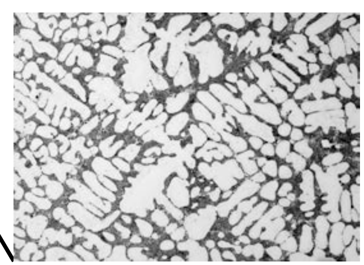
Technical Accomplishments and Progress
Chill Cast Plates (Subtask 1a)

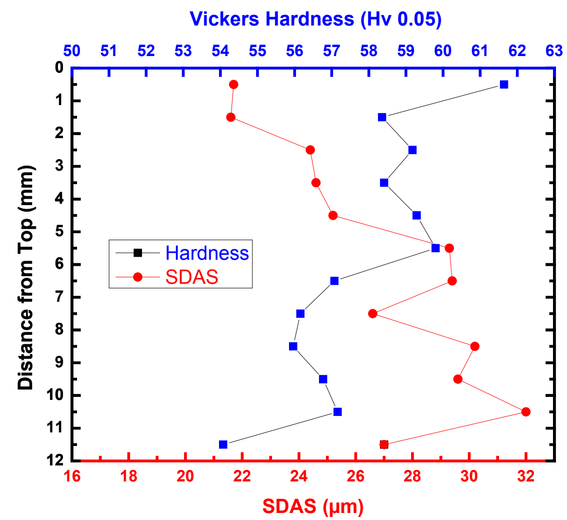
- Two general areas are being considered for selective microstructure modification:
  - Valve bridge water jacket area (higher temperature)
  - Corner tabs / bolt thread /bolt head boss locations (lower temperature)
- Specific parameter chill casting was developed at GM Research on Sr modified A356 plates. The plates were cast so that their microstructures were similar to what should be expected near the roof of the combustion chamber.
- Chill casting leads to small secondary dendrite arm spacing (SDAS), while Sr modification results in fibrous and refined morphology in the eutectic Si particles.



The average SDAS is ~ 25 µm.



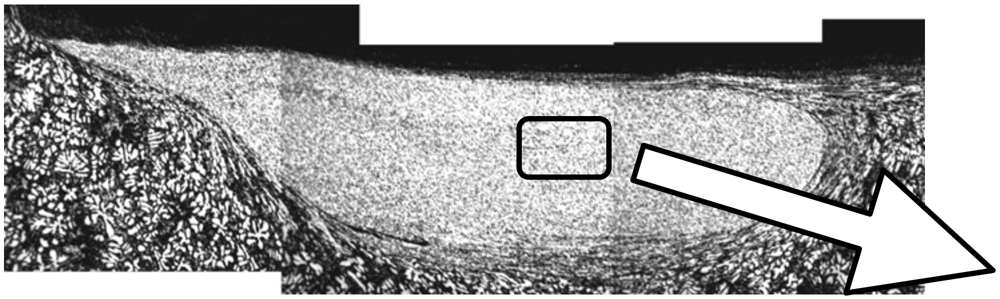




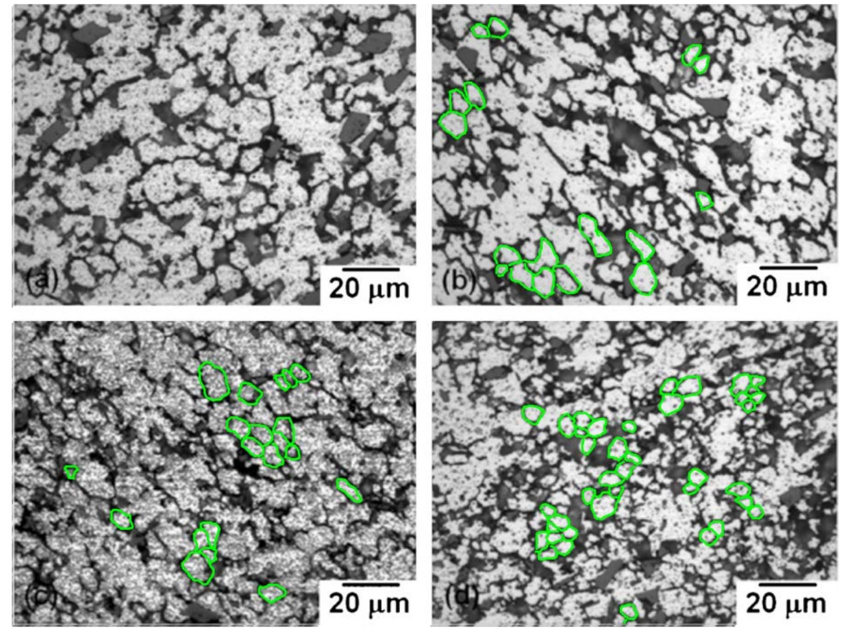
- These pates form the baseline materials that will be compared to the FSP processed coupons

SDAS and hardness variation along the thickness of the cast plate; from top to middle.

Microstructure of the As-processed Plate

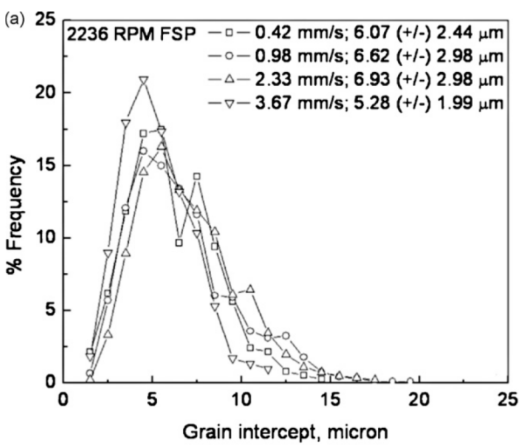


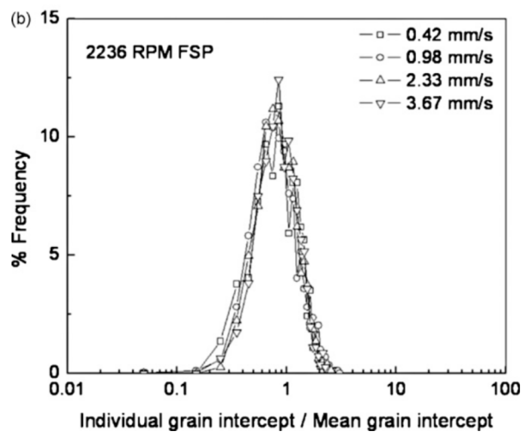
Cross-section image of the processed plate, single pass



Grain structure of the nugget zone

Tool travel speed	Tool RPM = 2236
(a) 0.42 mm/s	
(b) 0.98 mm/s	
(c) 2.33 mm/s	
(d) 3.67 mm/s	



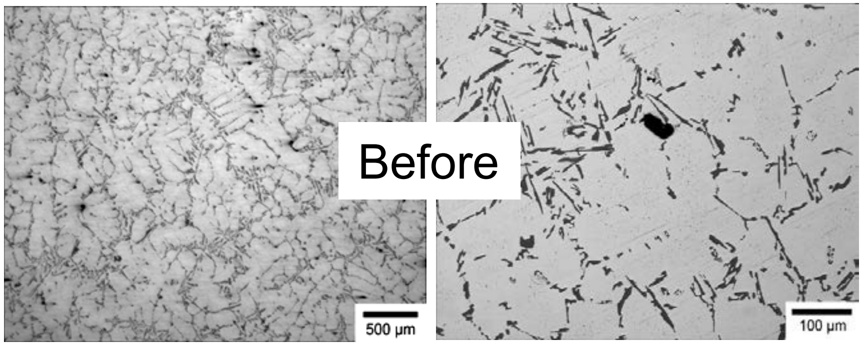


- As-processed grain size follows a log-normal distribution.
- At a constant tool RPM, the average grain size is ~ 6 µm (even for different travel speeds)

S. Jana et. al., Mat. Sci. Eng. A 528 (2010) 189-199

Why FSP microstructure is better in fatigue

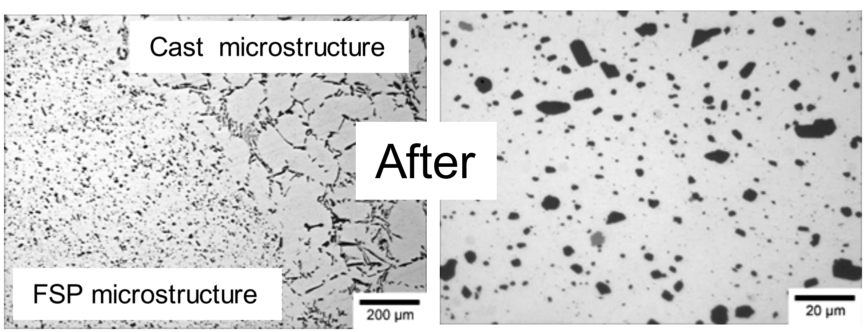
Microstructure of the cast plate



Presence of porosity.
V_f = 0.2%

Acicular Si particles in the **inter-dendritic** region

FSP

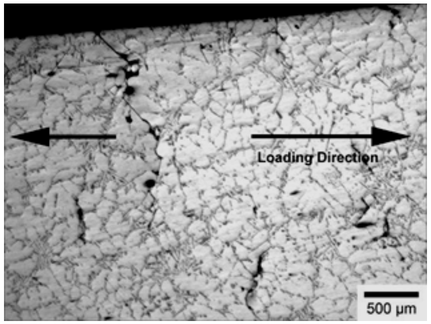


No porosity

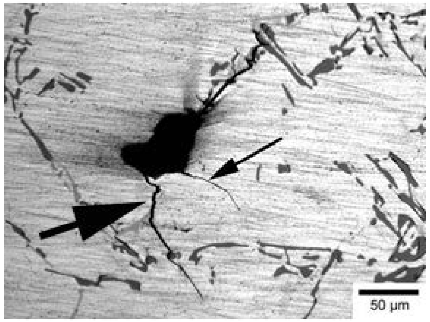
Finer & rounded Si particles distributed **uniformly**

FSP leads to over 50% reduction in Si particle size and aspect ratio, and removal of porosity

Micrograph of a failed cast specimen after fatigue testing



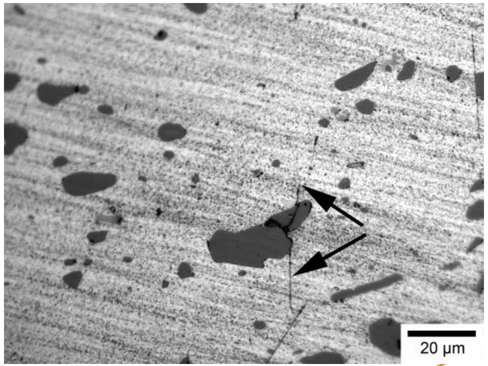
Cracks are noted to move normal to the loading direction



Porosity corners are found to be the crack initiation sites

Failed FSP specimen after fatigue testing

Si particle/Al matrix interface is found to be the crack initiation sites.



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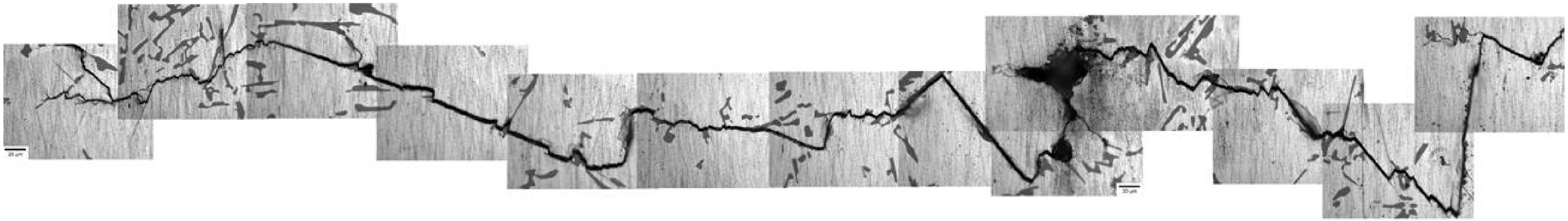
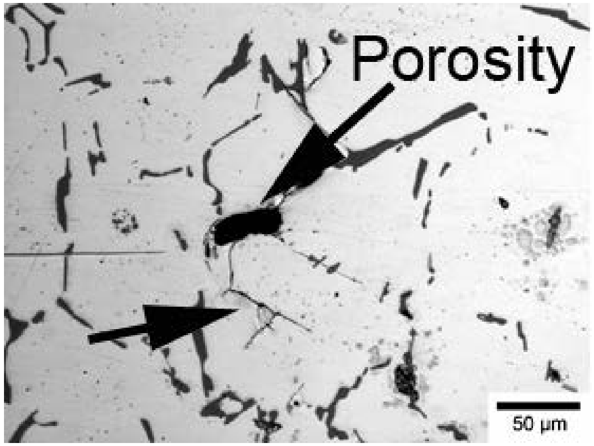
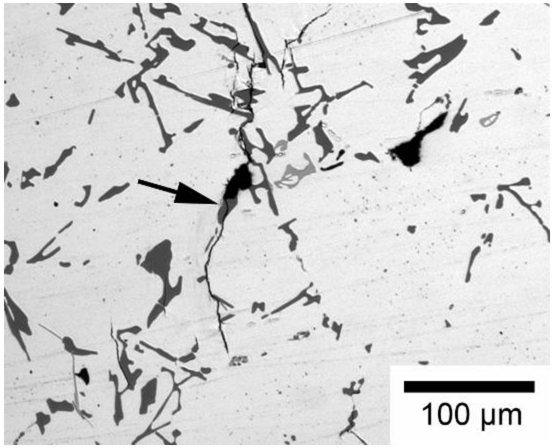
Crack Profile in a Cast microstructure



A typical crack profile in a failed cast specimen



Crack moving through α-Al dendrite

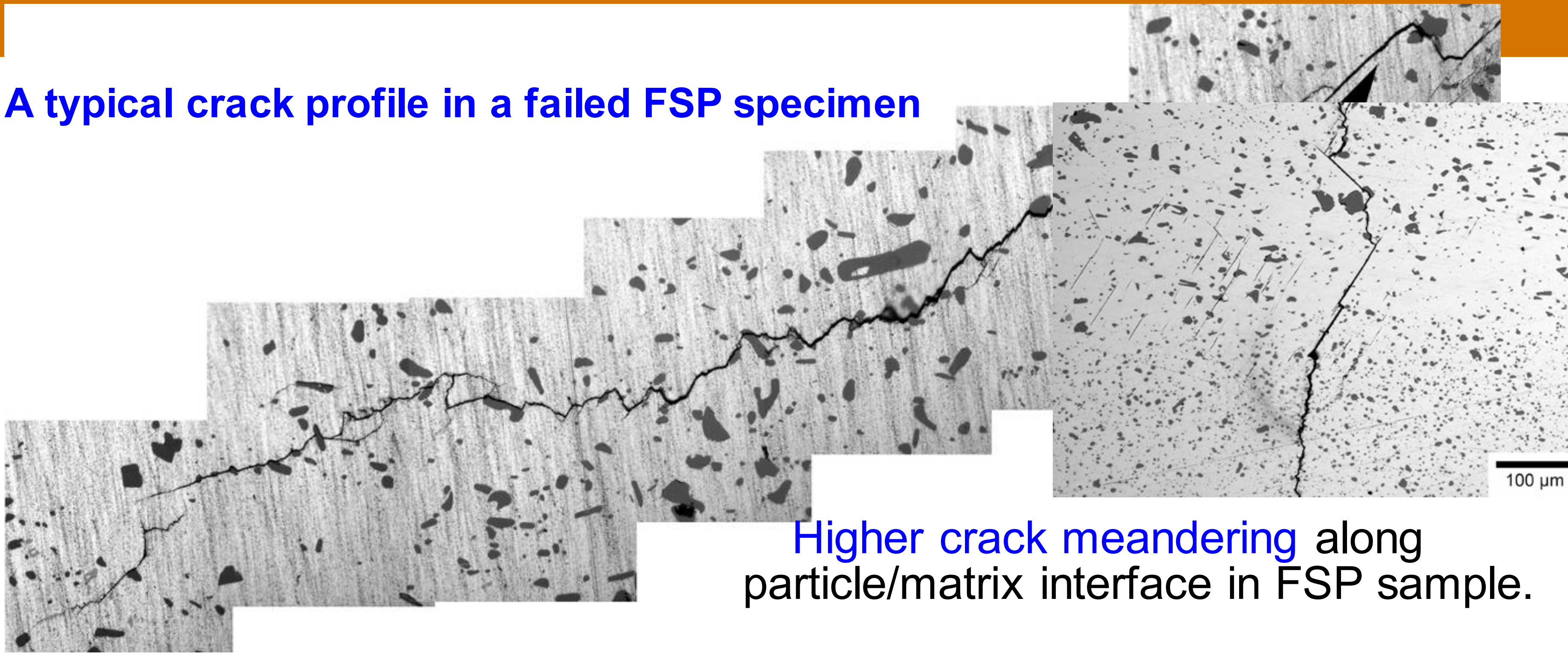


Si particles fracture as the crack interacts

Post mortem analysis reveals the linear fashion of crack growth in cast samples (fast)

Crack Profile in a FSP microstructure

A typical crack profile in a failed FSP specimen



Higher crack meandering along particle/matrix interface in FSP sample.

FSP

High density of Fine Si particles → **Interfacial instead of transgranular failure (slower)**

Uniform distribution → **Increased crack meandering**

This, and the lack of porosity, leads to both lower crack initiation and lower crack growth

Technical Accomplishments and Progress
Thermal Aging and Stable Microstructure (Subtask 1b, 1c)

FSP has been shown to dramatically improve fatigue performance, but will these improvements be realized at the high operating temperatures experienced by parts such as pistons and heads?

- At elevated temperatures some of the metallurgical properties that define fatigue crack mechanisms do not operate. Elevated temperature conditions may produce durability concerns related more to creep-fatigue mechanisms than fatigue alone.
- In addition, the stability of a FSP produced microstructure at elevated temperature can also be a concern. FSP leads to significant microstructural refinement (eutectic Si particle, grain size etc.), together with removal of casting porosity and breakdown of dendritic structure.
- Some FSP microstructures can undergo excessive grain coarsening when exposed to elevated temperatures. This is termed abnormal grain growth (AGG).

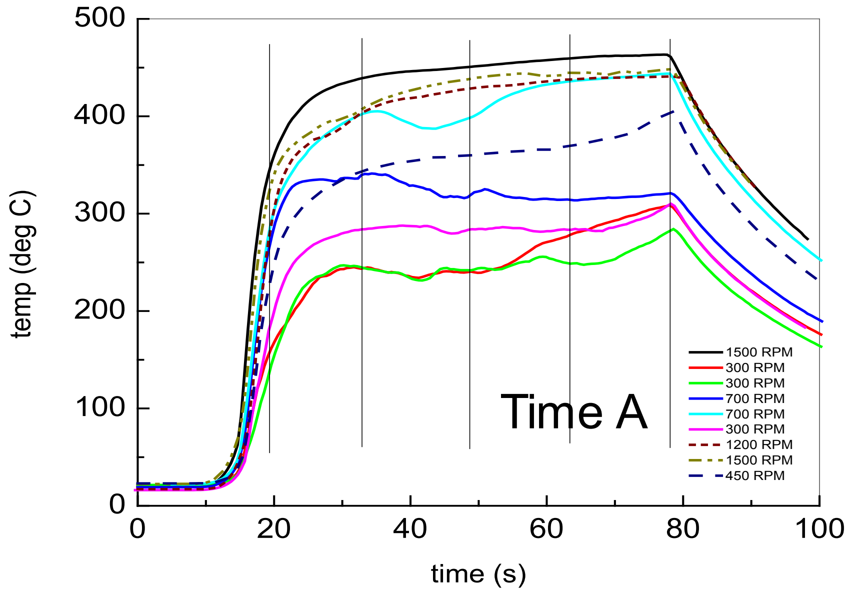
Subtasks 1b and 1c are experimental tasks to create widely differing FSP microstructures to test the effects of thermal aging and AGG on fatigue and creep fatigue properties.

Technical Accomplishments and Progress

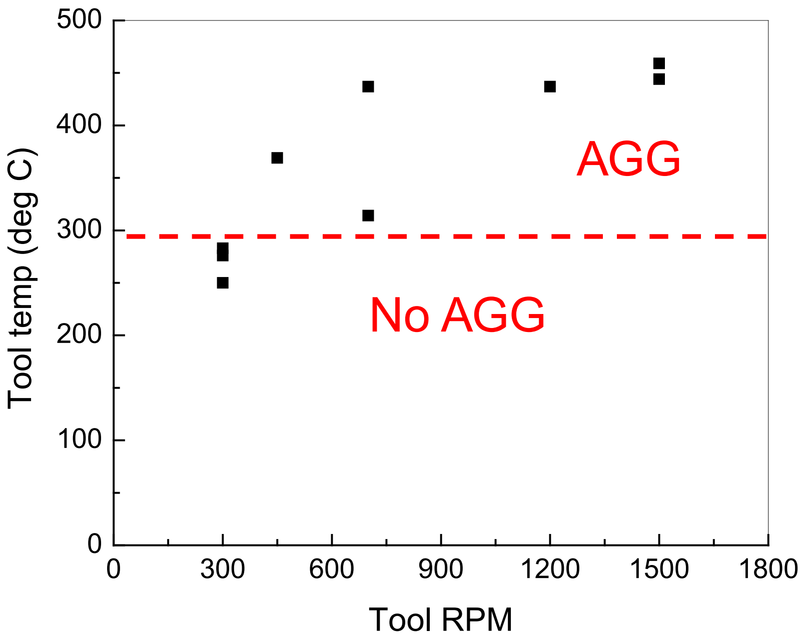
Thermal Aging and Stable Microstructure (Subtask 1b, 1c)

Experimental trials to generate AGG

- In these trials we fix travel speed and vary RPM to produce different power level processed regions
- A concave shoulder tool with a stepped spiral pin was used. Tool temperature has been recorded by placing a thermocouple in the tool, behind the tool shoulder.
- The nugget microstructure was subjected to PWHT (**535°C for 2.5 hrs**) to check the grain growth behavior.
- **AGG developed in welds made over 300 C**



Tool Temperature after 3" of weld, Time A



Technical Accomplishments and Progress

Thermal Aging and Stable Microstructure (Subtask 1b, 1c)

- So it is possible in this alloy to make either a fine grained processed region, a medium grained process region (if we run the process hot, but don't heat treat after FSP), and a very coarse grained processed region if AGG occurs with heat treat.

What do we want for the best properties?

It depends on the anticipated application and failure mechanism.

Failure feature	Formation mechanism
Crack nucleation	Creep governed
	Fatigue governed
Crack growth	Inter-granular
	Trans-granular

- High Temperature
- Low Temperature
- Fine Grained
- Coarse grained

The FSP process can be tailored to produce the microstructure needed

Milestones

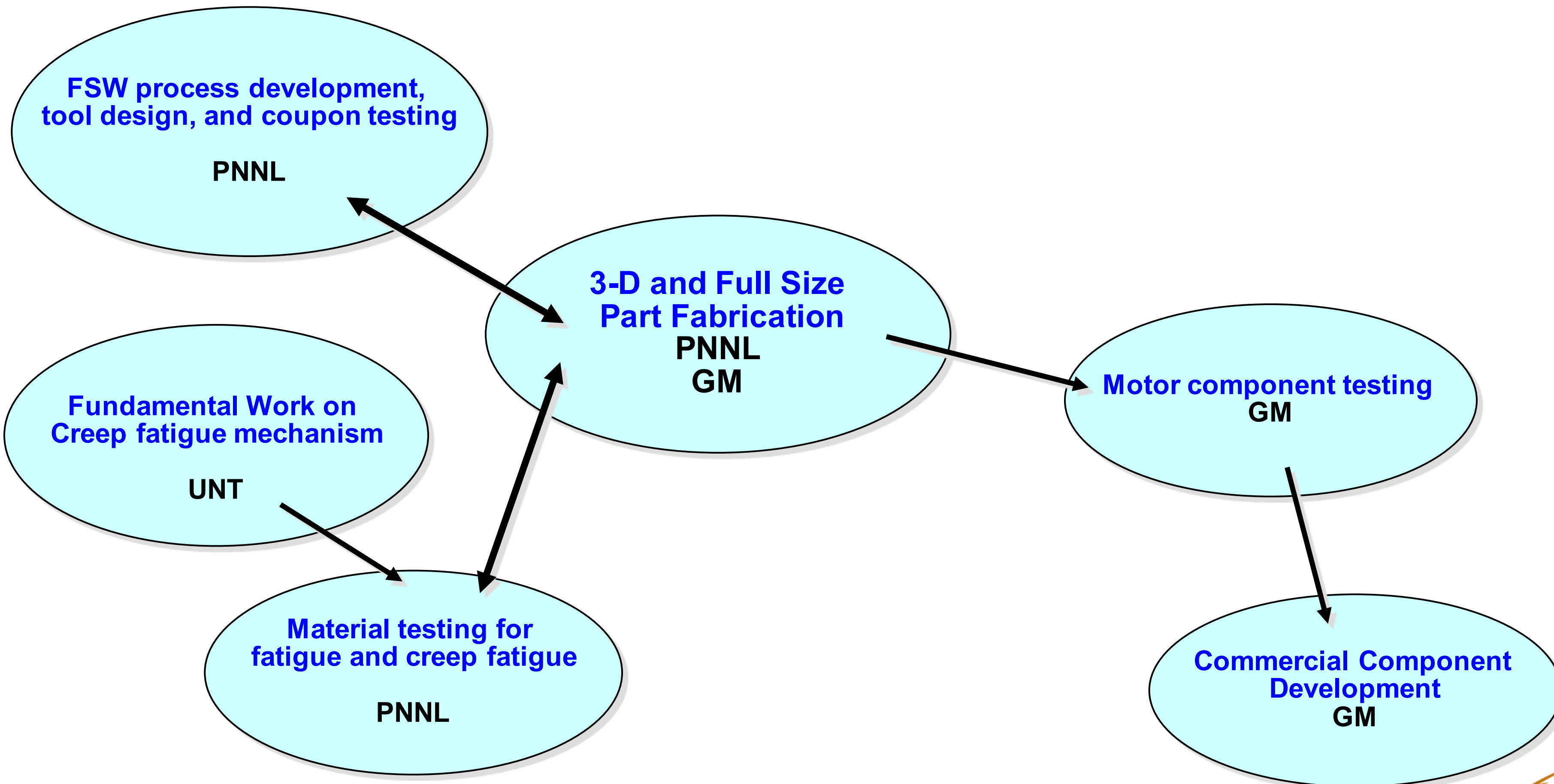
- Demonstrate fully consolidated and microstructually stable friction processed regions on specialized head alloy plates provided by GM. Test these processed regions at the coupon scale for microstructural stability at elevated temperature by subjecting them to heat treatment and examination for deleterious grain growth effects. (Completed)

- Demonstrate that room temperature fatigue performance in the FSP processed coupons can achieve a minimum 10% improvement over baseline alloys (Task 1 materials) (On schedule)

- Investigate fundamental aspects of elevated temperature creep-fatigue mechanisms as they apply to friction processing and describe through reporting the correlation between FSP process parameters and creep fatigue performance (Sept 2013)

Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations



Future Work

- Both room temperature and elevated temperature fatigue testing will begin in the second half of FY13 on Task 1 A356 FSP
- Tests for mixed mechanism (creep-fatigue) have not been finalized, but are expected to be oil bath, load and hold type tests on a miniature tensile frame at UNT
- Task 2 FSP steel process development will begin by the end of the FY. We have received crankshaft alloy steel plate from GM and are ordering tool materials
- FSP processed regions on the prototype cylinder head will need to be done in a 3-d configuration, so late FY13 early FY14 we will begin programing our ABB IRB 7600 robot that has a FSW head as an end effector.

Summary

- Increasing the durability of engine components can increase the operational envelopes of the engine, allowing designers of the combustion process to access areas of engine control where increased specific power and low emission levels are found, but where high PCPs can create reliability problems.
- FSP has been demonstrated at the coupon scale to produce significant improvement in room temperature fatigue and durability in aluminum alloys. Applications in block or in cooler locations on the head, and certainly all steel applications are expected to show normal fatigue failure mechanisms.
- The advantages of the FSP process in elevated temperature applications that are mixed mechanism (creep-fatigue) are not yet demonstrated
- However, the highly tailorable nature of FSP allows for a wide range of microstructures, opening the opportunity to customize the microstructure to the failure mechanism.