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Tailored Materials for Improved Internal Combustion Engine Efficiency

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GENERAL MOTORS RESEARCH AND DEVELOPMENT

JUNE 10, 2015
ARLINGTON, VA

Project ID: PM048

Overview

Timeline

- Start: late FY2011
- Project end date: Sept 2015
- Percent complete: 85%

Budget

- Total project funding
  - DOE - $1075k
  - 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
- DOE Funding for FY14: $225K
- DOE Funding for FY15: carryover

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
- Need high strength materials that are also light weight
  - The powertrain represents a significant part of the overall vehicle weight, esp. for hybrid EV
- Powertrain Cost
  - Higher peak cylinder pressure required for efficient combustion often requires higher cost engine materials. Developing new materials at cost parity is a significant challenge.

Partners

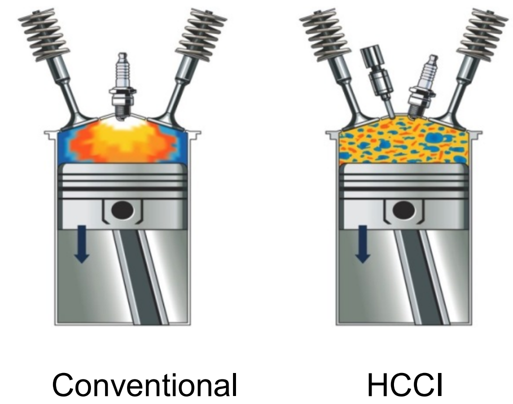
- General Motors R&D
- University of North Texas
- Project lead: PNNL

Relevance – Problem Statement

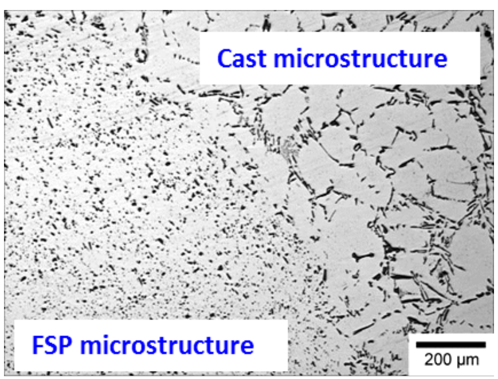
New combustion strategies (HCCI, Low Temperature Combustion, lean burn, "High Speed" diesel) can increase engine efficiency

However,

- Peak cylinder pressures can be much higher than conventional engines leading to sharp load-rise times and high fatigue or thermal-fatigue loads on pistons, heads, cranks, blocks, etc.
- This can potentially require a change to higher cost materials (Ni alloys, Ti, CGI, Nodular Fe, forged micro-alloyed steels in)



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



This project investigates a local microstructural modification tool - Friction Stir Processing (FSP)

- Ductility improvement over 5x
- Up to 80% improvement in endurance limit over as-cast alloys
- 5-15 times improvement in fatigue life over cast alloy

Relevance – Objective

Broad Objectives

- **Develop the Fundamental Science and Process of Friction Stir Processing**
  - **Produce surface modified regions on coupons made from conventional, low-cost engine materials and show the property advantages available through FSP that could address barriers related to durability at high Peak Cylinder Pressure (PCP)**
  - **Investigate the property advantages for aluminum alloys that are currently in use for heads, blocks and pistons**
  - **Investigate the property advantages for steel alloys that are currently in use for crankshafts**

- **Fabricate prototype friction stir processed components**
  - **Test prototype parts for durability and obtain performance data 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.**

2014 – 2015 Objectives

- **Elevated Temperature Fatigue Performance**
  - **In aluminum alloys we have found that FSP has the ability to produce different types of microstructure, i.e., coarse-grained or fine-grained, based on process parameters used. During 2014-2015 the objective has been to understand how these two classes of microstructure respond to fatigue loading at elevated temperature.**
- **Develop FSP for steel alloys and demonstrate fatigue property advantages are also available for alloys used in crankshaft applications**

Milestones

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Experimentally determine the thermal fatigue performance of the baseline cast microstructure and compare it to the coarse-grained and fine-grained FSP microstructures at room temperature.	→	Completed (2014)
Go/No Go Demonstrate that FSP processed aluminum head material coupons can achieve a minimum improvement of 10% over as-cast materials at elevated temperature	→	Go (2014)
Develop the FSP process, tools and control necessary to produce a defect-free FSP region in a typical micro-alloyed crankshaft steel under one FSP process condition and characterize microstructure.	→	Completed (2015)
Experimentally determine the fatigue performance of rotary beam fatigue crankshaft steel specimens that have been friction stir processed and drilled to simulate an oil passage. Compare the performance to baseline materials.	→	Completed (2015)
Go/No Go Demonstrate that FSP processed steel samples with simulated oil passage holes can show a fatigue life improvement in endurance limit or fatigue life over drilled, but unprocessed samples in excess of 5%	→	Go (2015)
Down select full sized test application that can demonstrate FSP advantage at a relevant scale. Current candidates are a cylinder head valve seat area FSP modification and an aluminum block application.	→	In Process (2015)
Demonstrate increased durability in relevant scale TBD part test. Candidate test method are a cylinder head “steam test” for thermal fatigue, a bolt retention test in an aluminum block application, and a steel shaft analog for the crankshaft application.	→	Tasked (2015)

Approach and Strategy for Deployment

Task 1 Aluminum Alloy Fatigue Life Improvement

- Produce chill-cast, Sr-modified A356 plates with optimized SDAS spacing ☑
- FSP trials to develop two different classes of microstructure ☑
- Heat treatment study: to produce two microstructures, coarse and fine ☑
- Room temperature fatigue studies on FSP coupons (miniature fatigue testing) ☑
- Elevated temperature fatigue testing FSP coupons
  - 150 C ☑, 200 C (in-process)
- Translate process to 3-d part (two applications: cylinder head and block) (in-process)
- Operating-temperature, cylinder head pressurization testing at GM and bolt retention test at PNNL (tasked)

Task 2 Crankshaft Steel Fatigue Life Improvement

- FSP trials on micro-alloyed steel alloy plate for process parameter development ☑
- Mechanical/Hardness testing of FSP nugget ☑
- Room temperature fatigue studies on FSP coupons (rotating beam fatigue)
  - Parent ☑, Parent with notch ☑, FSP ☑, FSP with notch ☑
- Demonstrate FSP microstructure is stable during induction hardening process or that property advantage still remains after PWHT (tasked 2015)
- Translate process to shaft analog and test for increased durability in fatigue (tasked 2015)

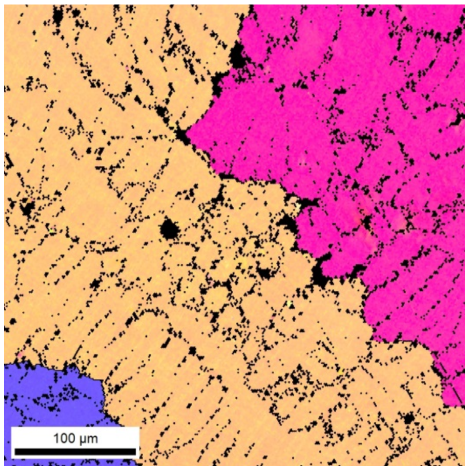
☑ Completed

Technical Accomplishments and Progress

TASK 1 Aluminum Alloy

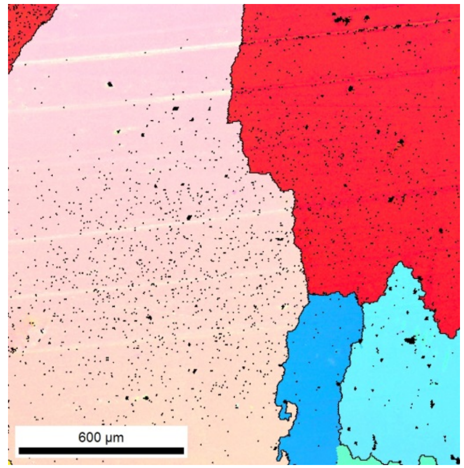
Sets of Microstructures Tested

Base metal



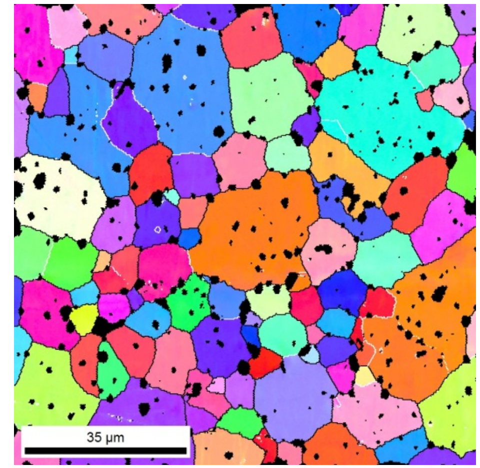
As cast +T6,
Grain size: 214 ± 115 µm

FSP Coarse grain



FSP1 + T6
Grain size: *457 ± 501* µm

FSP Fine grain



FSP2 + T6
Grain size: *9.5 ± 5* µm

2 orders of magnitude grain size difference, can be created by simply varying the FSP parameters during processing.

Two different microstructures were produced and tested. The concept was to produce different microstructures that may have different fatigue response, especially at elevated temperature.

Technical Accomplishments and Progress

TASK 1 Aluminum Alloy

S-N plot: Comparison of Microstructures vs. T

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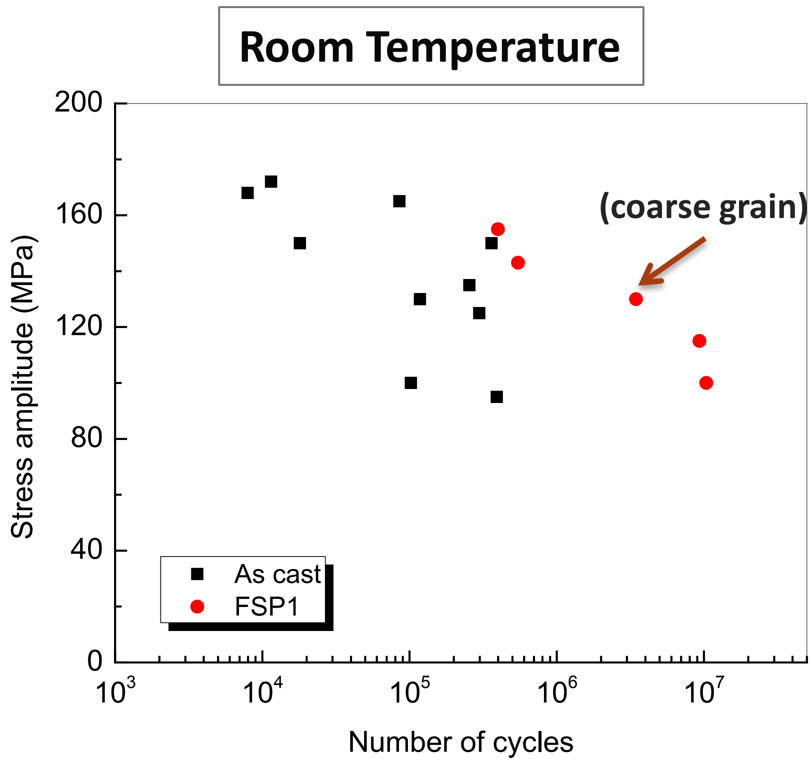

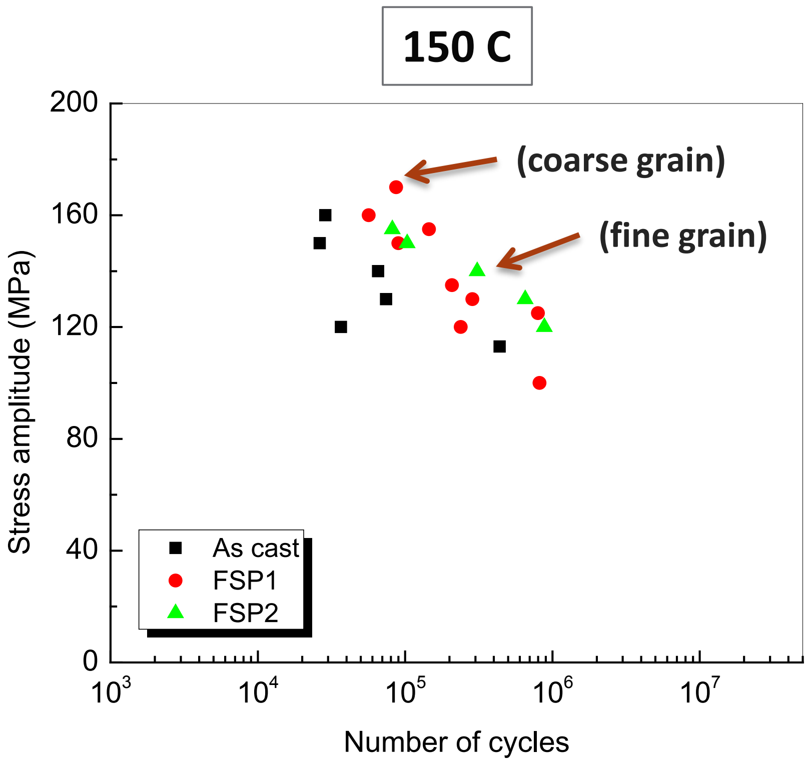

- **Effect of FSP on fatigue life enhancement is much greater at room temperature, but persists at elevated temperature as well.**
- **At 150C, both coarse-grained and fine-grained microstructures are improved over as cast, with fine-grained slightly better**

Technical Accomplishments and Progress

TASK 1 - Aluminum Alloy

High Temperature testing of Coarse-Grained FSP

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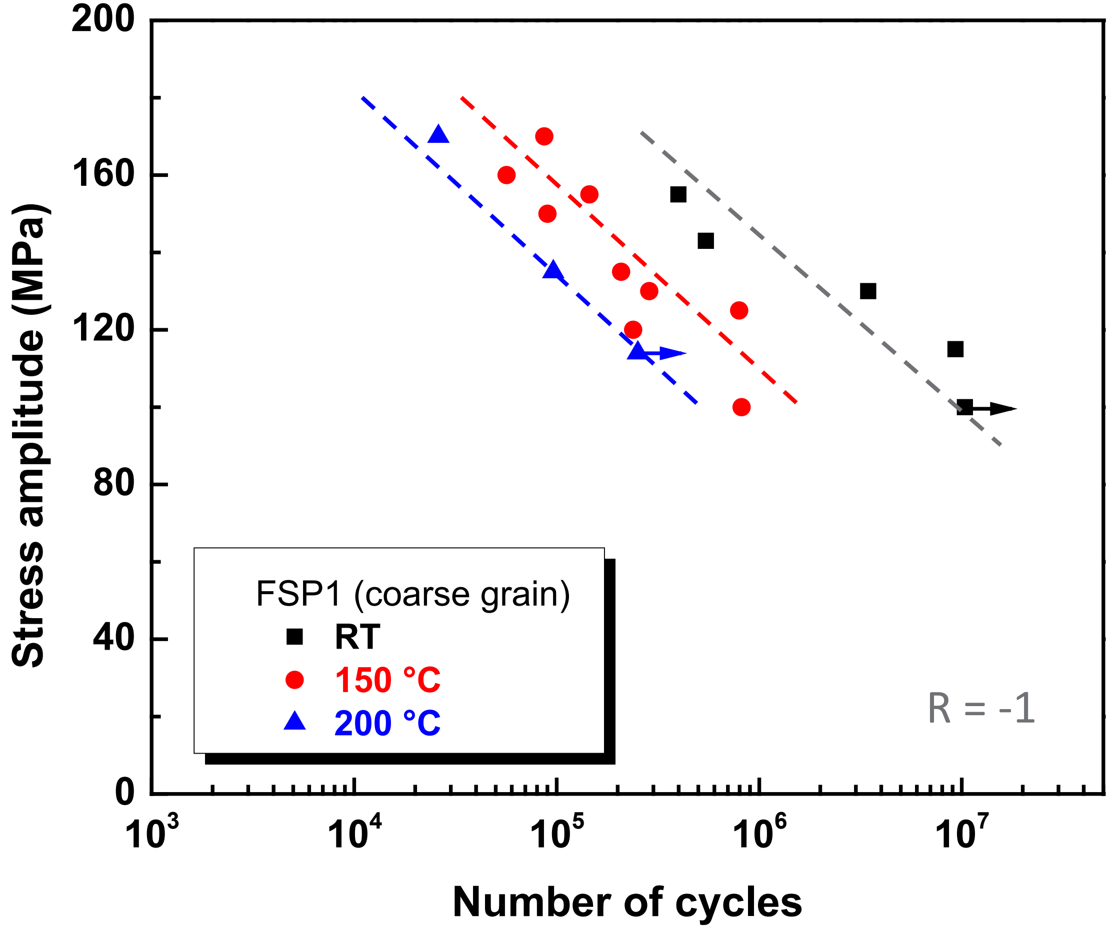
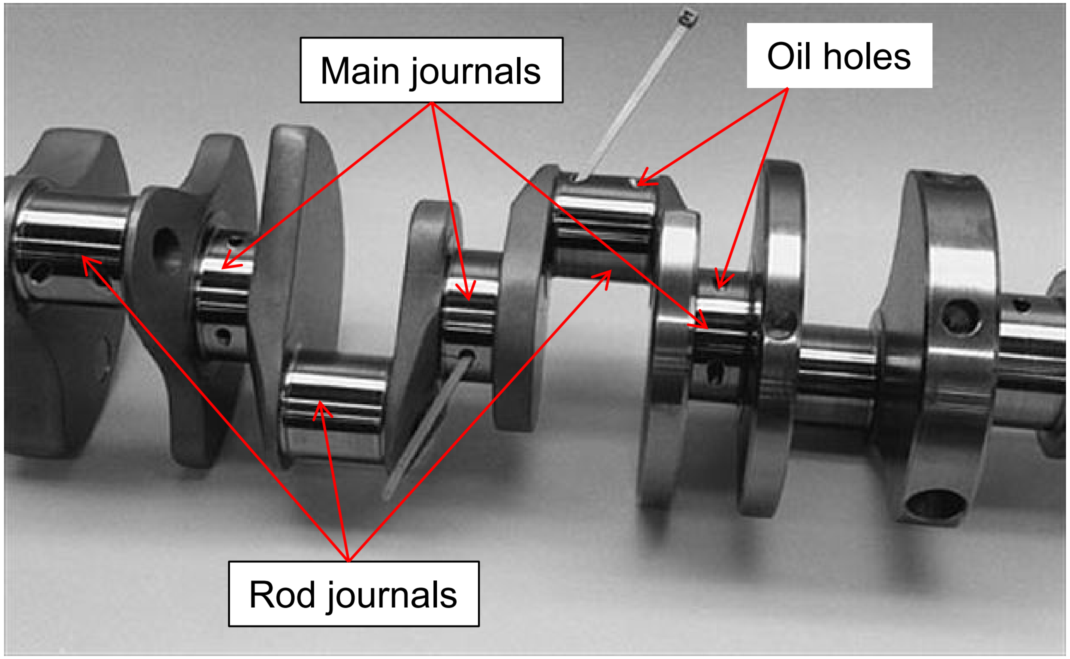


- The coarse-grained FSP processed material shows a drop in fatigue life as test temperature increases.
- This is expected due to a decrease in the number of strengthening mechanisms available at elevated temperature.
- The FSP material is still better than as-cast but the difference is not as great as at room temperature
- 200C tests of the fine-grained FSP material (not shown) has not yet been completed, but initial data suggests fine-grained may be better.

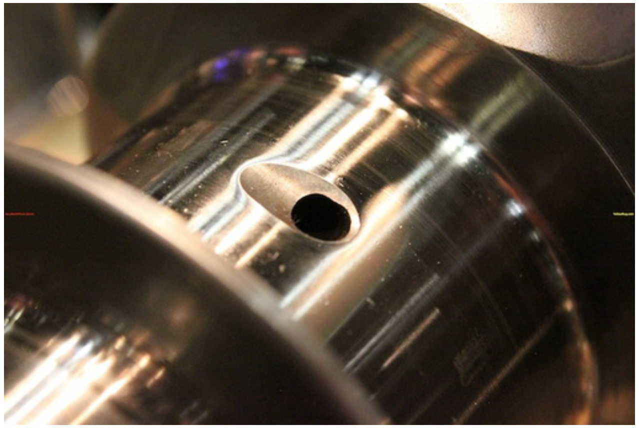
Technical Accomplishments and Progress

TASK 2 Steel Alloy FSP

Fatigue Failure of a Crankshaft



Typically, IC engine crankshaft and rod lubrication is done by pressure-feeding the rod bearings through passages drilled in the crank.



- **Oil holes can act as potential stress concentration sites.**
- **If not machined and chamfered properly, the oil hole edges can be easy fatigue crack initiation sites.**

In this work, we are creating a friction stir processed region on the pre-machined crank in the area that will be later drilled for the oil hole. FSP may be able to create a highly fatigue-resistant microstructure around the oil holes prior to drilling.

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel

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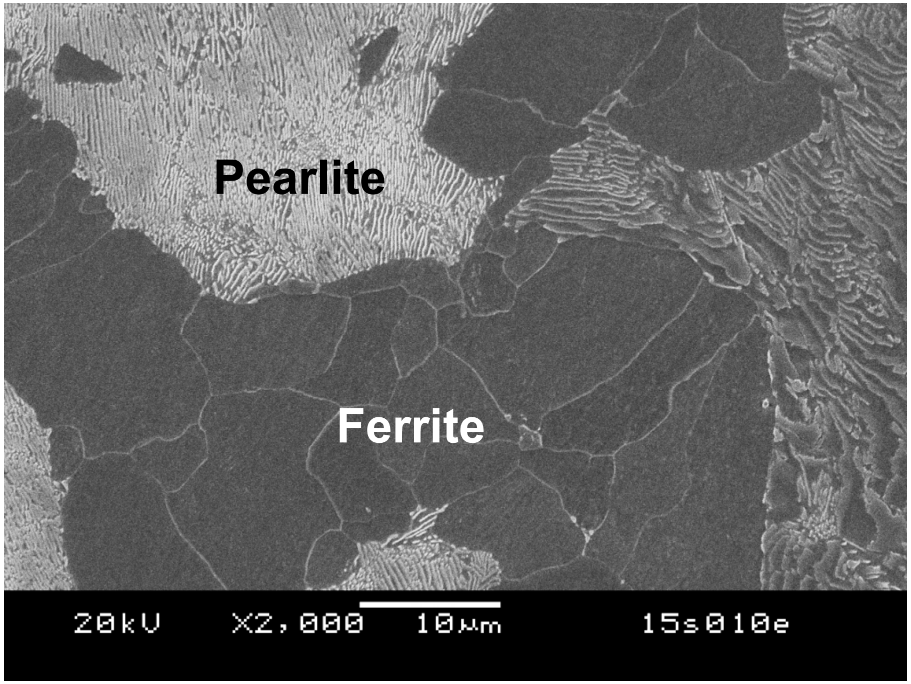
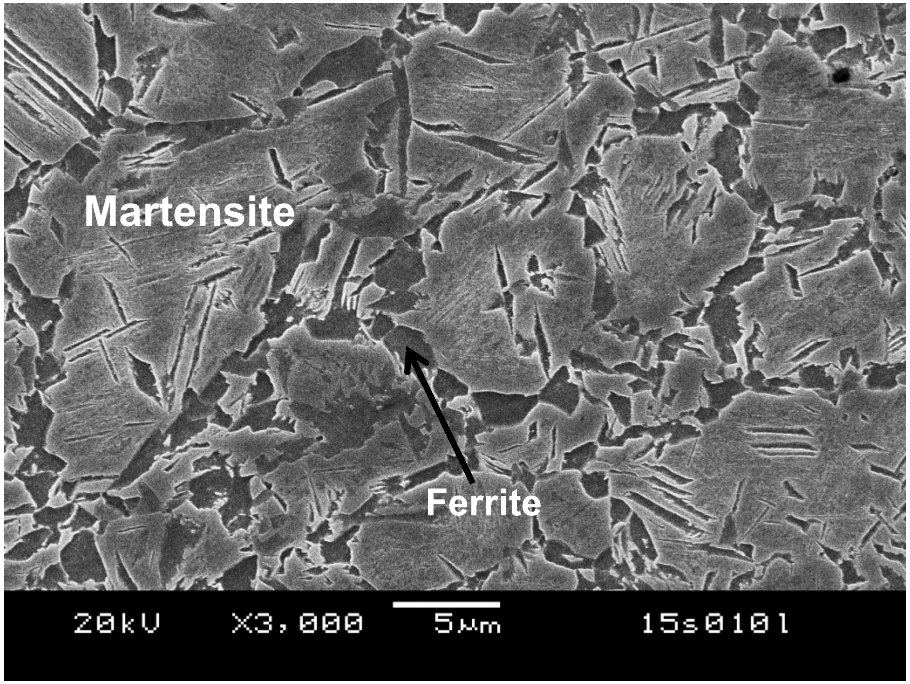
Microstructural Changes: Higher Magnification



Microstructure in parent metal



Microstructure in weld nugget

Effect of FSP

- ***refinement of the original ferrite phase***,
- ***replacement of pearlite phase with martensite***.
- ***reduction in ferrite volume fraction inside the nugget*** **compared to parent metal.**

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel

RBF Sample & Testing Details

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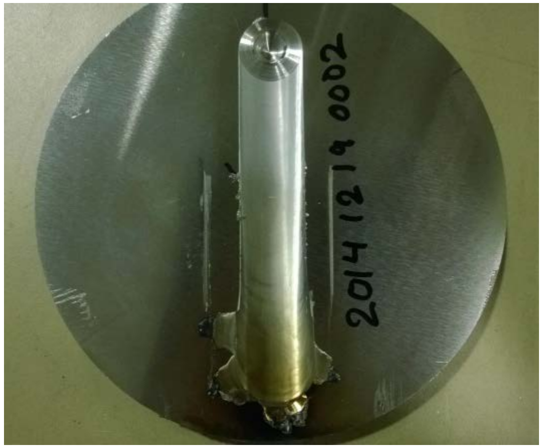
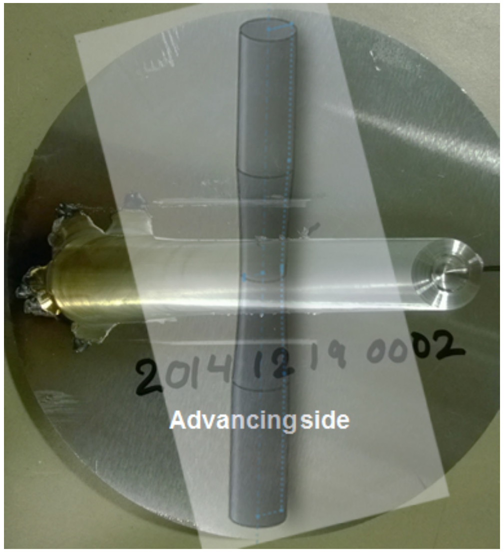
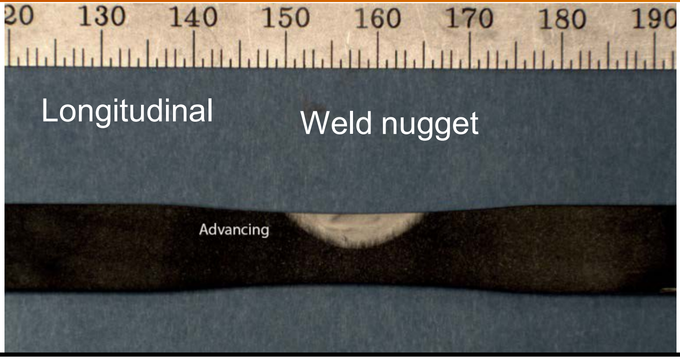


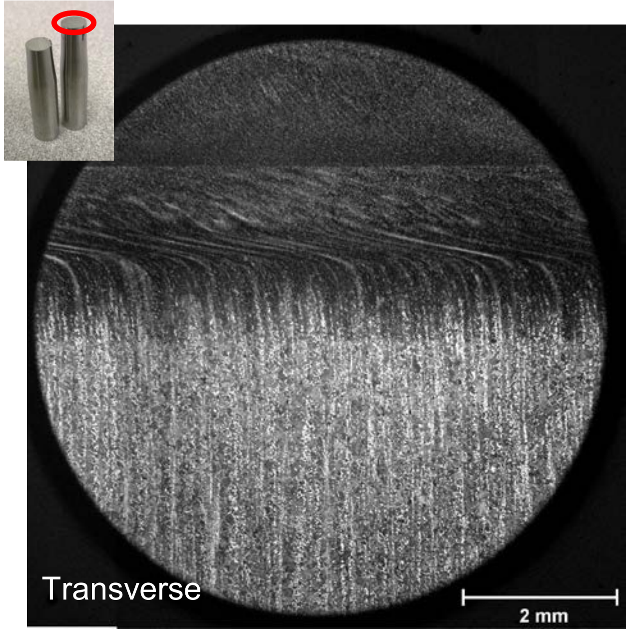
Bead on plate processed region on a plate cut from the forged billet



RBF sample orientation w.r.t. weld



Longitudinal and transverse cross-section of the RBF specimen show the weld zone on one side of the sample

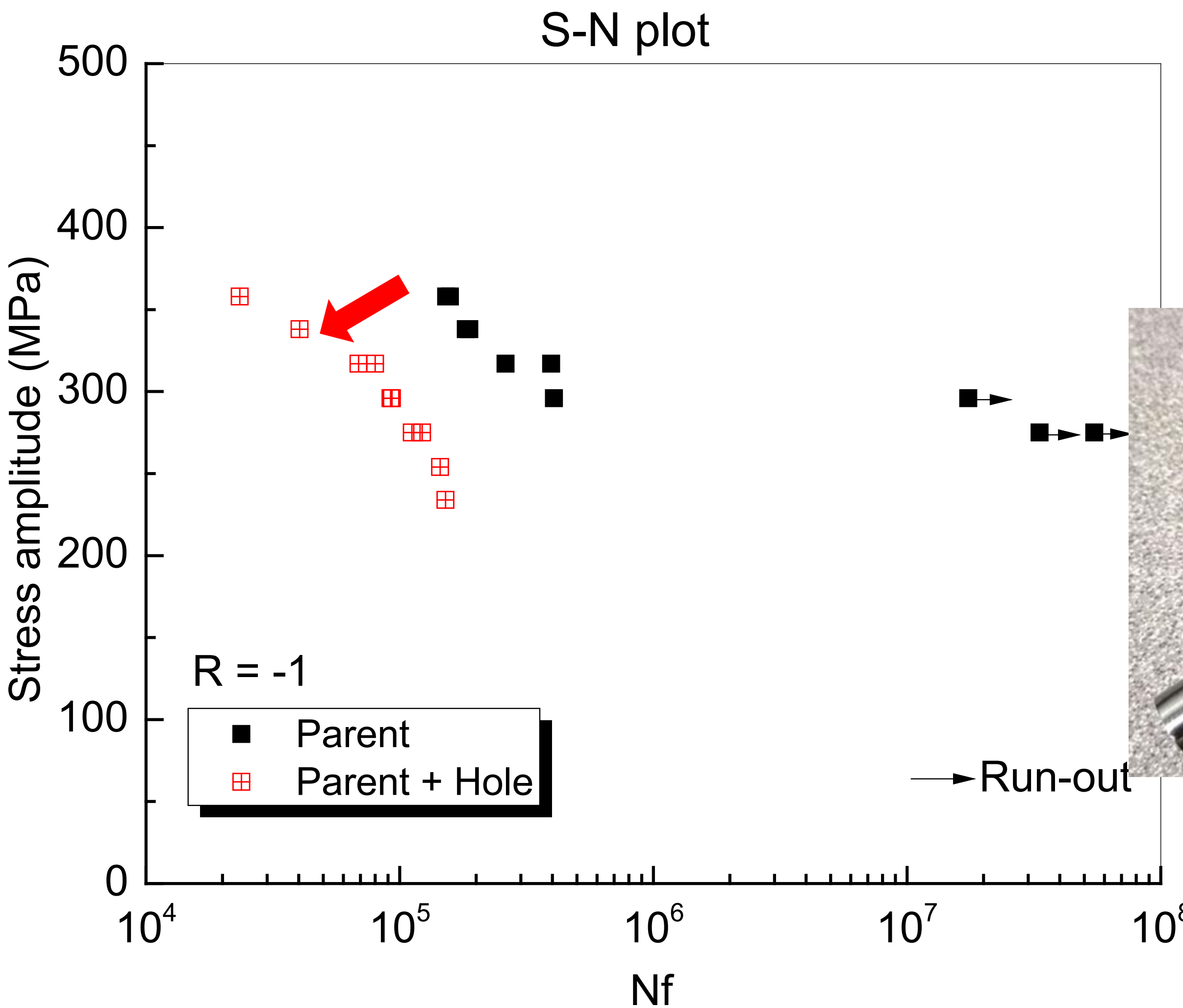


Rotary Beam Fatigue testing machine creates simple completely reversed stress cycle R=-1. Tests conducted at 10,000 RPM

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel (Oil Hole Analog)

Results: Base metal vs. base metal with a drilled hole



3mm dia., 1 mm deep hole drilled on the side of the RBF specimen

- <u>Base</u> metal samples with a drilled blind hole on one side show lower fatigue life **by ~4x** (<u>Notch effect</u>)

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel

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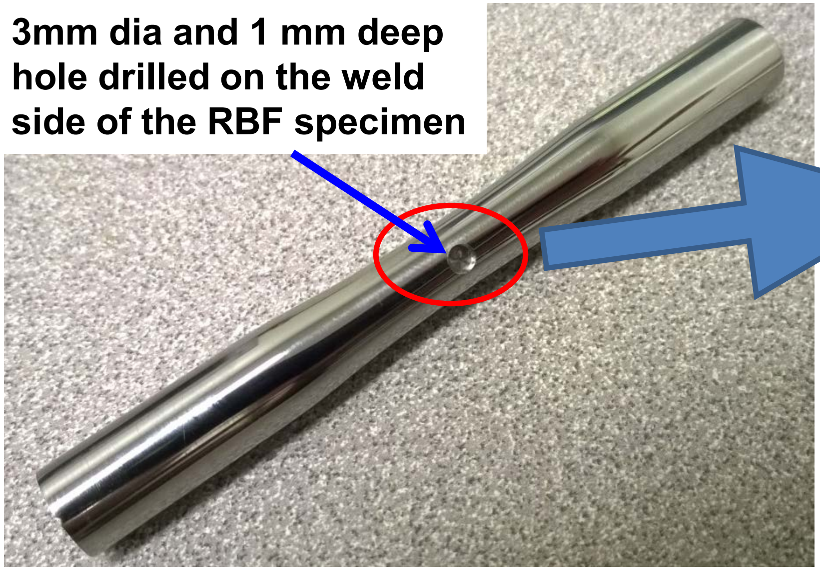
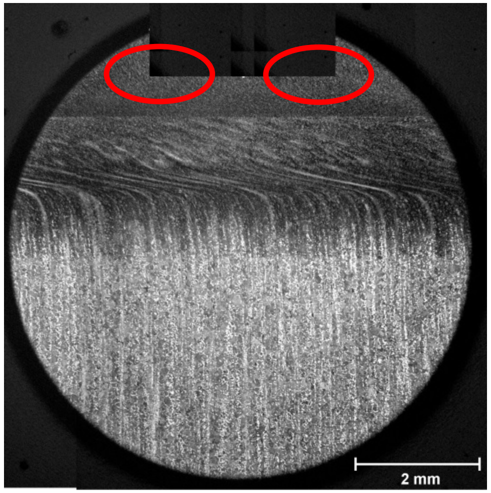
Hole drilled in the FSP region

3mm dia and 1 mm deep hole drilled on the weld side of the RBF specimen





(RBF specimens with Drilled Holes)

Transverse cross-section view of the sample with hole. The sharp corners present at the bottom of the hole creates high stress concentration.

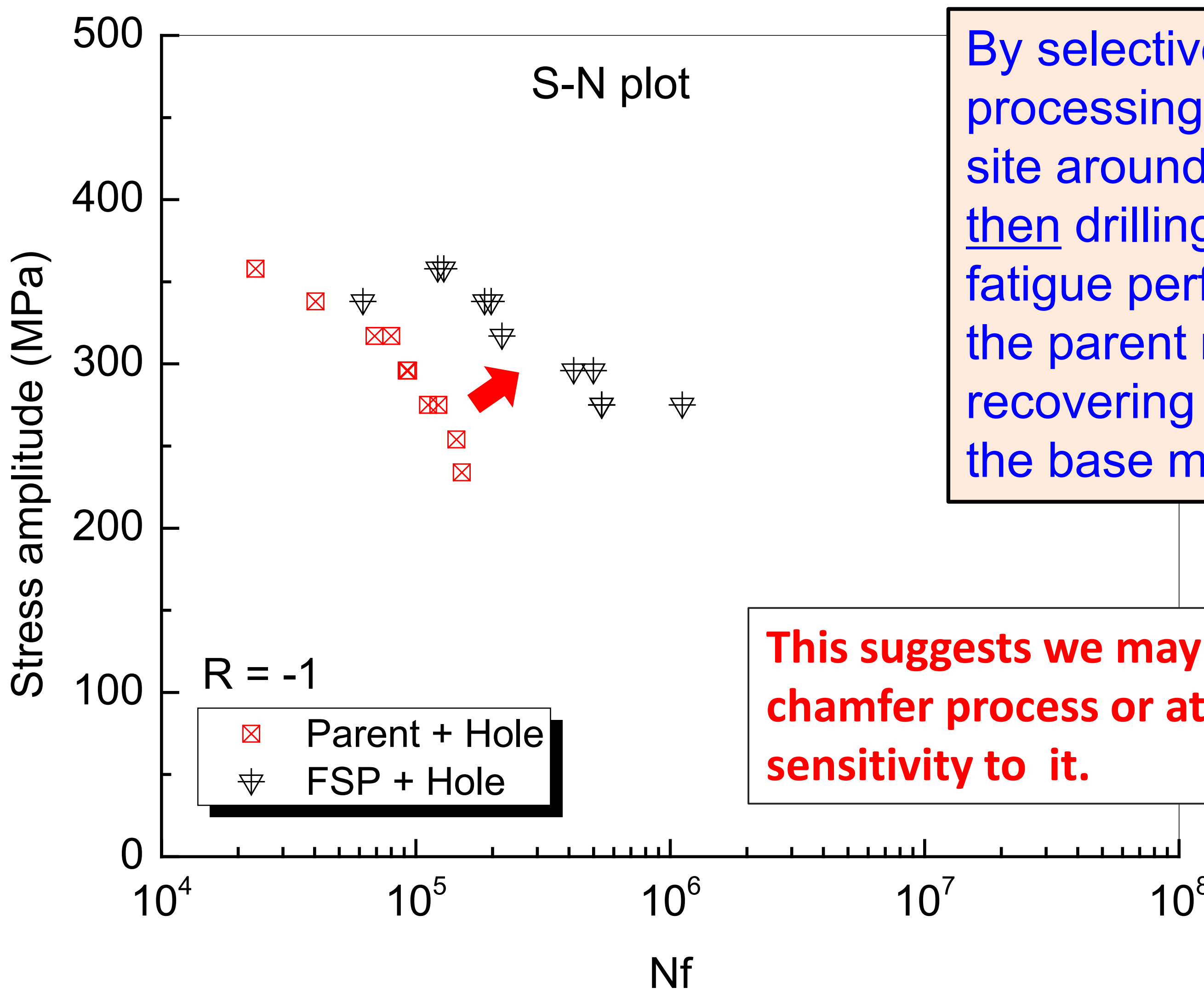
Fatigue properties were compared between base metal with a drilled hole and FS processed samples with holes drilled in the FSP zone

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel

Results: It works

Base metal *with a hole* vs *FSP with hole*



By selectively friction stir processing the crack initiation site around the hole (notch), then drilling, we have improved fatigue performance by 4x over the parent material with a hole, recovering the full fatigue life of the base metal

This suggests we may be able to eliminate chamfer process or at least eliminate the sensitivity to it.

Response to Previous Year Reviewers' Comments

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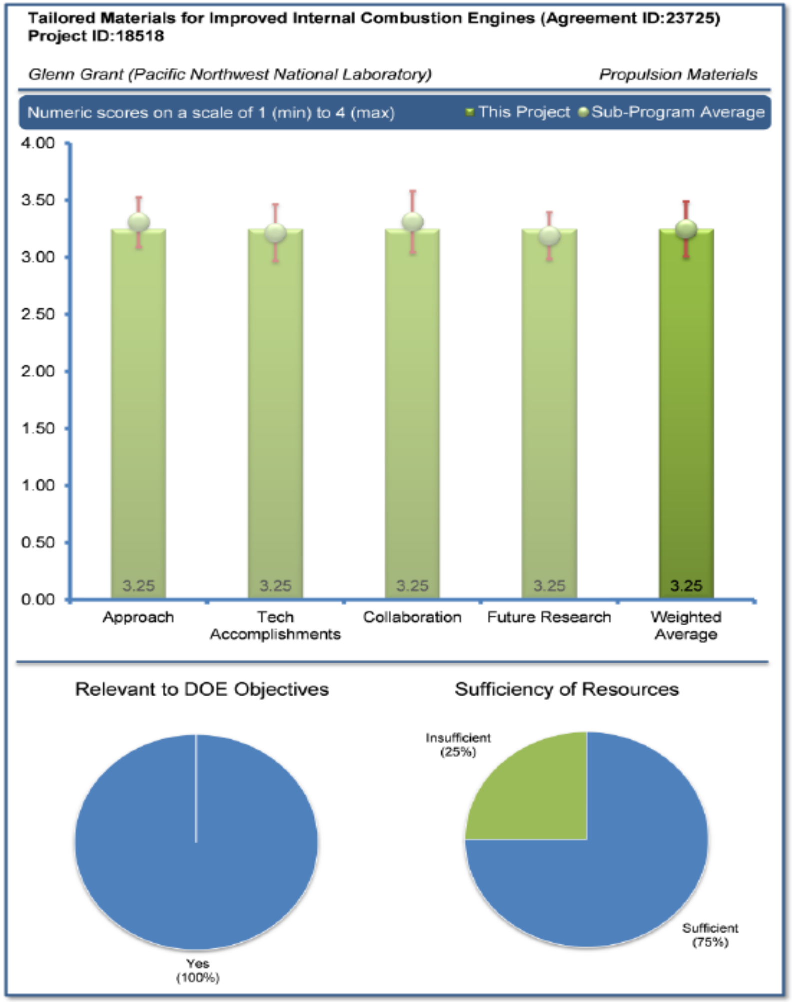
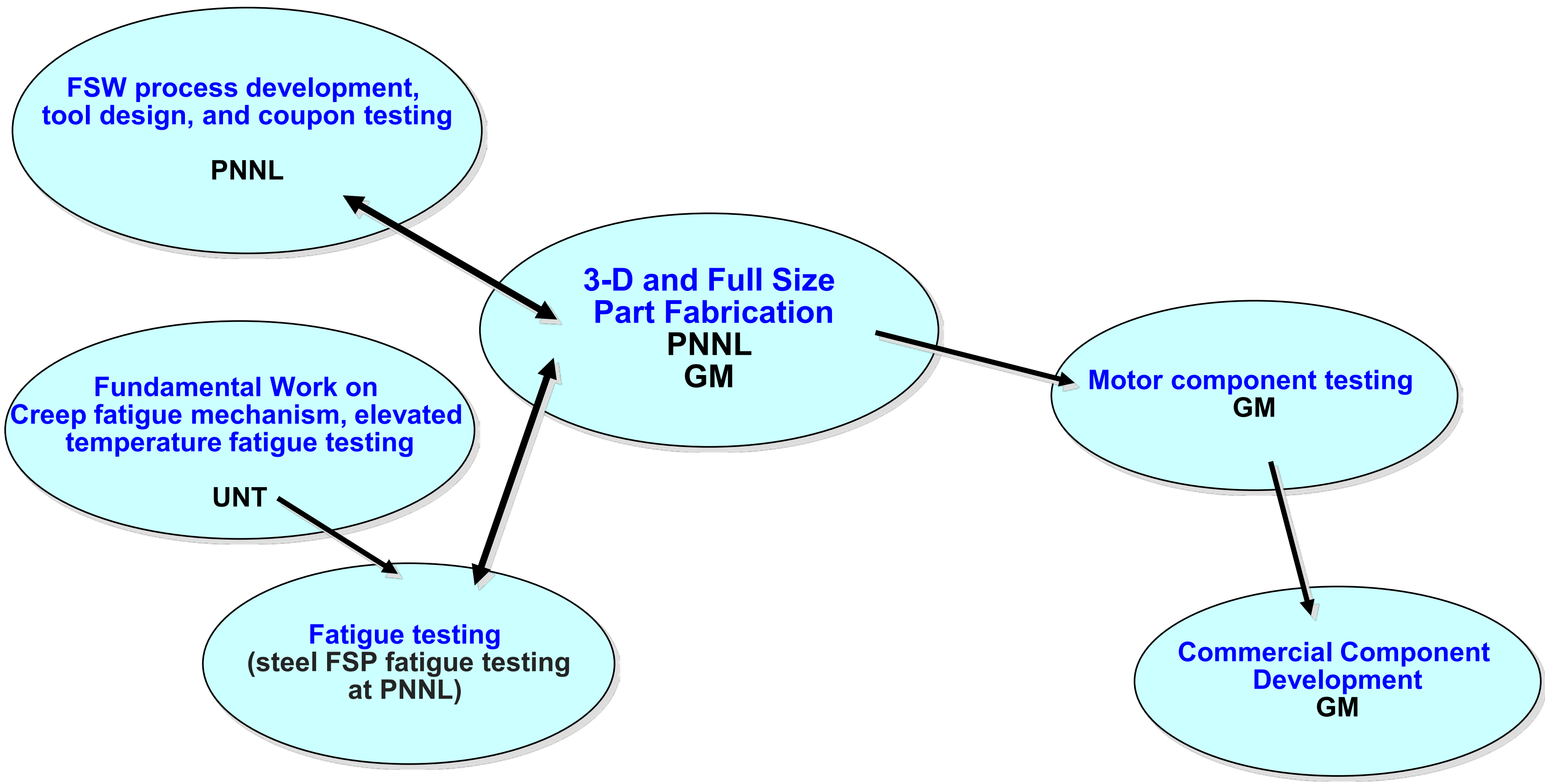
- *Any technical hurdles anticipated in attempting the process on complex shapes ? …crankshafts have high stress regions that are difficult to reach*
  - Response: Yes. A crankshaft will likely be processed with a stationary head FSP machine, where the crank is rotated under the tool. The challenge is reaching between the counterweights with a long tool that also has enough strength to survive the processing loads.
  - An application like a valve seat area in an aluminum head is envisioned to be accomplished with a multi-axis robotic FSW machine because loads are low in this application, and the weld path may be 3d.

- *..Project spending appears to be 80% of budget. Most of the testing has been on flat plate, where processing and testing would be much more expensive at the component level*
  - Response: We anticipate that component level tests will be done by project partners, with PNNL providing FSP processed subscale or prototypic geometries. In the case of the aluminum application we have selected two applications that should have relatively low cost test methods (a head steam test and a bolt retention test). For the steel FSP application, we will continue RBF testing, but will probably not do a full sized crank.



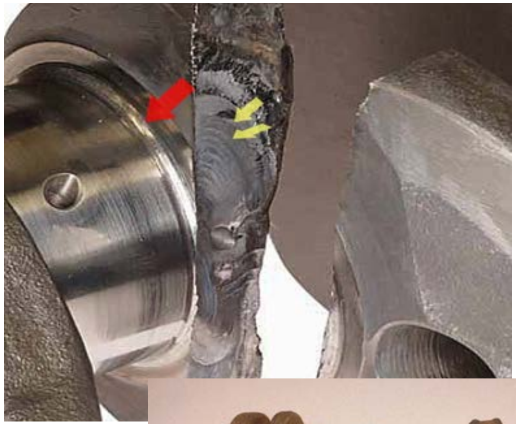
Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations



Remaining Challenges and Barriers

- Fillet fatigue is the number 1 killer of rotating shafts
  - Can we reach a fillet with FSP? Counterweights leave room for only narrow tools.
  - Is there an effect similar to the advantages seen on the oil hole analog?
- Bearing journals are often induction hardened.
  - How will the FSP region respond to another austenite cycle? Will it transform on cooling to a different microstructure because of FSP processing? Better ? Worse?
- FSP processed regions on the prototype cylinder head will need to be done in a 3-d configuration on a robotic platform.
  - We have had some delays getting our ABB IRB 7600 robot functioning for this job. We believe we now have sufficient funds in place to do the 3d work, but if more delays are encountered, we will contract the job out to a FSW robot provider.



Proposed Future Work

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Task 1: FSP of Aluminum casting

- FSP processed regions on the prototype cylinder head will need to be done in a 3-d configuration. Work during the remainder of FY15 will sort out current issues with the ABB IRB 7600 robot and complete the planned 3d welds.
- With GM input, down select full sized test application that can demonstrate FSP advantage at a relevant scale. Current candidates are a cylinder head valve seat area FSP modification and an aluminum block application
- Demonstrate increased durability in relevant scale TBD part test. Candidate test method are a cylinder head "steam test" for thermal fatigue and a bolt retention test in the block application.

Task 2: FSP of crankshaft steel

- Test the response of the FSP region to induction hardening heat cycle. Are the advantages still present after another austenite cycle?
- FSP below Ac1 to produce a fine grained acicular ferrite or ferrite-perlite with no MnS stingers. This may improve fatigue even further.

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.

Task 1 Aluminum alloys

- FSP has been demonstrated to produce significant improvement in room temperature fatigue and durability in even high quality castings (small SDAS, small eutectic particle size) . Selective applications in block, or in cooler locations on the head, and certainly all steel applications are expected to benefit from FSP under normal fatigue failure mechanisms.

- Friction stir processed material, especially if processed to produce a coarse grained microstructure, has shown an order-of-magnitude improvement in RT fatigue life, and a 3-5 times improvement at 150 C, far exceeding the project milestones.

- Some areas of the cylinder head (e.g., the valve bridge area or near the combustion chamber) are at a significantly high temperature. At high temperature the failure mechanisms are a mix of classical fatigue and creep. At present 200C testing is revealing that FSP material is still better than as-cast , and strangely, fine grained microstructures are behaving slightly better than coarse grained.

Summary (con't)

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.

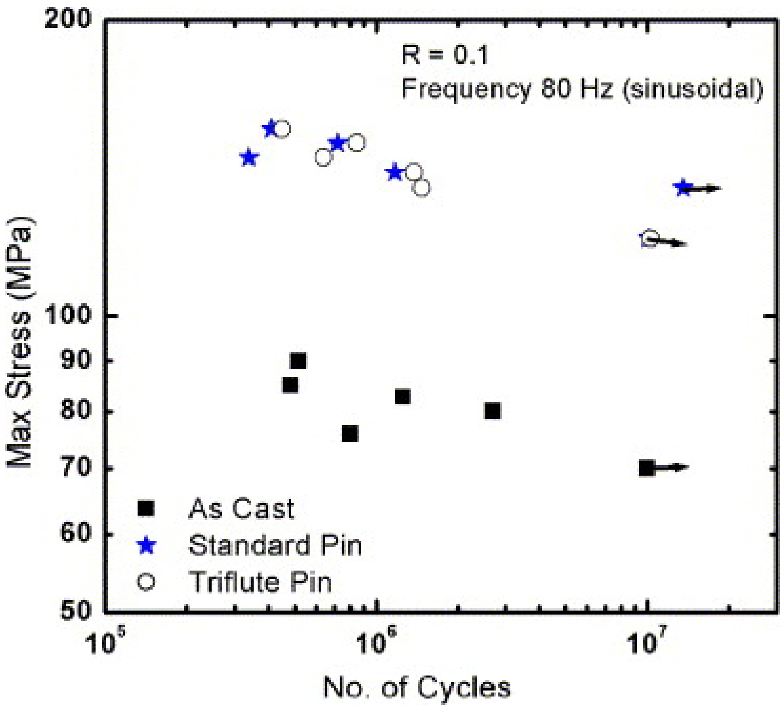
Task 2 Steel Alloys

- The steel FSP work has shown a 4X better fatigue performance when an oil hole analog is drilled in a FSP microstructure vs. the same hole drilled in an as-received micro-alloyed forged steel.
- It is possible that this improvement may be enough to justify eliminating the chamfer step in the manufacturing sequence, eliminating a source of variable performance.
- The base materials in this study are wrought products, not castings. It is expected that if this process were applied to lower cost cast products, the improvements may be even more pronounced since FSP has known benefits to closing porosity and improving cast microstructure.
- It could be speculated that a cast crank, with FSP applied to selective areas, may be able to reach the durability properties of much more expensive forged products, thereby potentially enabling a new, more aggressive combustion strategy at a lower cost.

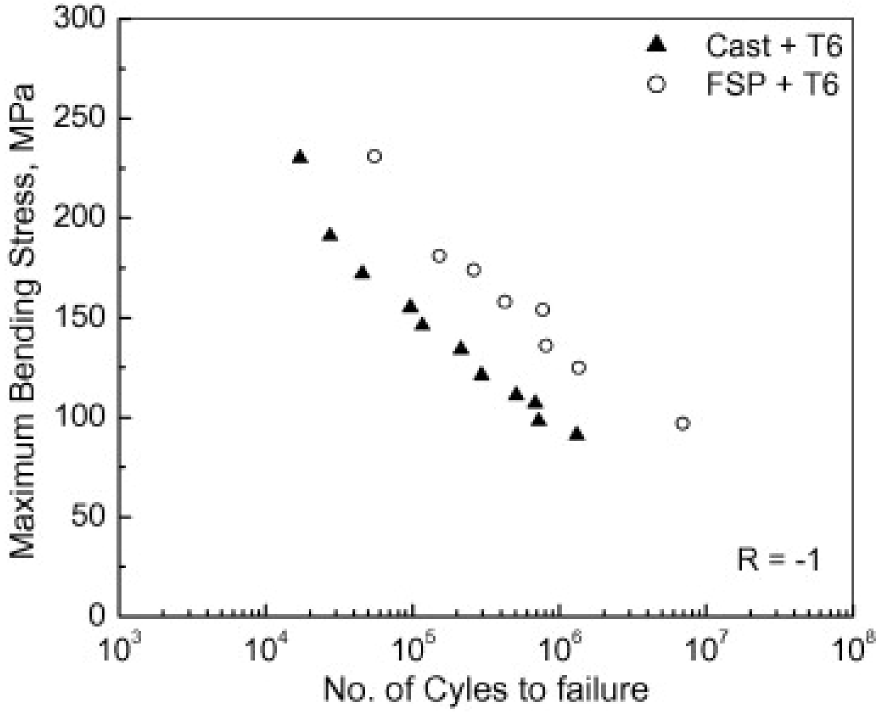
Technical Backup Slides

Relevance

Previous results show improved fatigue performance at room temperature for a cast microstructure



Enhancement of fatigue performance in a <u>*sand cast A356 alloy*</u> with a porosity vol. fraction ~ 0.95%. **Endurance limit improves by 80% as a result of FSP**



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

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?

Relevance
What is different at Elevated Temperature?

- Most strengthening mechanism that affect fatigue crack growth rate, including solid solution strengthening, precipitate hardening, and grain size (dislocation-grain boundary interactions) are not as important at high temperature. However, other mechanisms like dispersion strengthening or 2nd phase particle interaction may still be active.

- At very high temperature conditions, other mechanisms like creep-fatigue may produce durability concerns that are not seen at low temperature.

- Strain concentration from defects (porosity) or other notch geometries are still important for fatigue crack initiation regardless of temperature.

- FSP gives us a knob to turn to adjust the microstructure to the best performance, it closes porosity and defects, it homogenizes 2nd phase particles and dendrites, and it can produce dispersions, it can produce coarse grain size through secondary recrystallization, all beneficial for elevated temperature fatigue resistance.

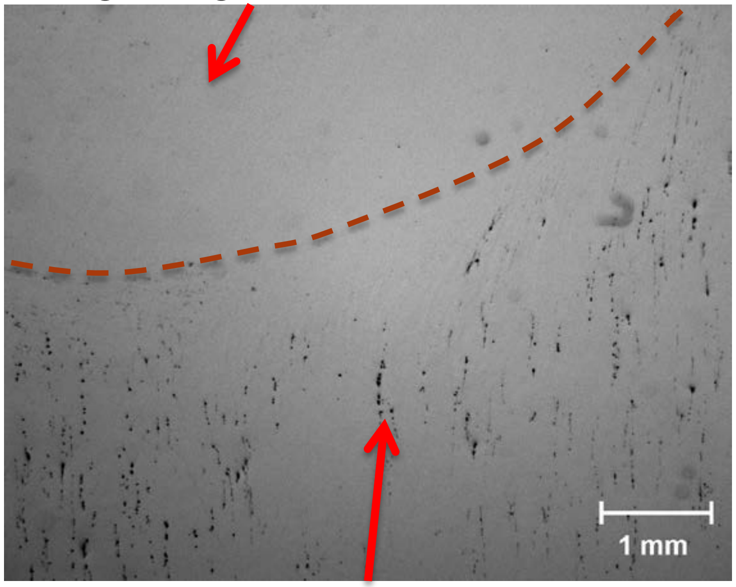
This project is developing the methods to use FSP to produce these various microstructures.
The question we are trying to answer in Task 1 is how do these different microstructures respond in fatigue at high temperature?

Task 2 - Friction Stir Processing of Steel

How FSP may contribute to increased crankshaft durability

- **If the crank is cast, all the issues of castings will be the same as seen in aluminum castings (porosity, coarse cast structures, etc.)**
- **But, even if forged, there may still be benefit:**
  - Mn, a common alloying element in steel, forms MnS inclusions. These inclusions, based on their shape, can act as potential metallurgical “notches” under fatigue loading. FSP, will refine and distribute these inclusions uniformly inside the nugget.
  - Also, based on the FSP process parameters used, various types of transformed microstructure can also be created inside the nugget giving us flexibility to choose the right one for highest fatigue resistance. (<A1, A1-Ac3,>Ac3)

FSP nugget: MnS inclusions refined, Long stringers absent



MnS inclusions in the form of long stringers in the base metal

Custom local microstructure

Technical Accomplishments and Progress

TASK 2 Micro-alloyed Steel

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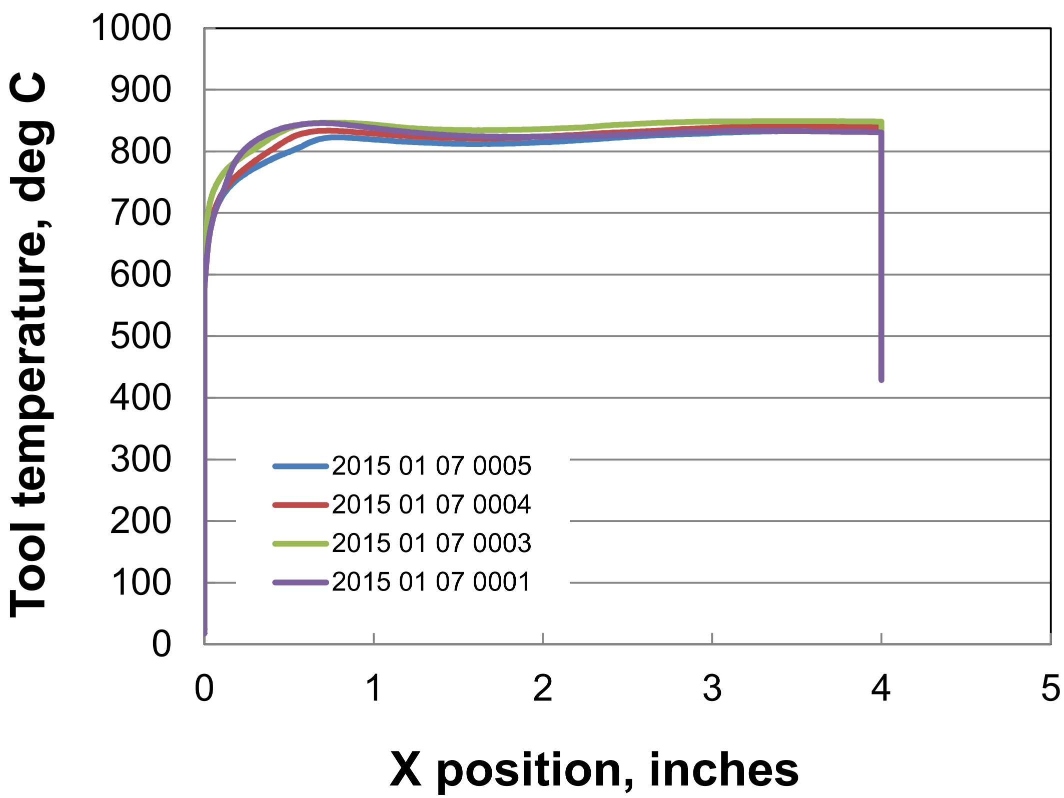
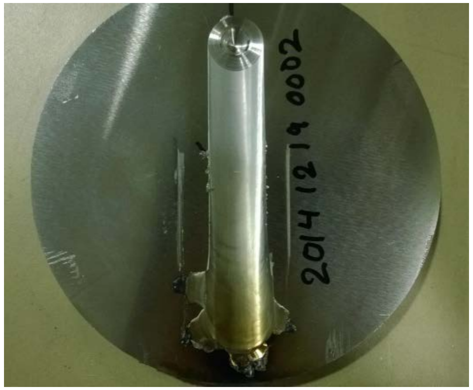
FSP of SAE 1538 MV Steel : Process Details



Typical weld temperature: 825-840° C



BoP processed region on plate cut from forged billet

- Bead on Plate welds
- Megastir Q60 tool used
- Tool RPM = 350
- Travel speed = 2.5 in/min
- Position control weld
- Process zone depth 0.22”

Full austenitization of the nugget is therefore expected.