Alloy Development for High-Performance Cast Crankshafts

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Vehicle Technologies – Annual Merit Review

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Overview

Timeline
- Project start March 2014
- Project end March 2017
- 5% complete

Budget
- FY14-17 = $300 K (DOE)

Barriers
- **Performance**: Meet or exceed the performance of current forged crankshafts. (as-cast UTS > 800MPa, YS > 615MPa)
- **Life**: Material and process must achieve local ultra-high cycle fatigue requirements of current baseline
- **Cost**: no more than 110% of production cast units

Project Partners
- Caterpillar, Inc. – Lead
- Argonne National Laboratory
- General Motors
- Northwestern University
- University of Iowa
**Project Team (Partners)**

- **GM**
  - Material and Process Development
  - Material Characterization
  - ICME
  - Design Optimization
  - Concept Design Cost Model

- **Caterpillar**
  - Material and Process Development
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- **The University of Iowa**
  - Casting Process Development
  - Experimental Casting Samples
  - Castability Evaluation (Fluidity, Hot Tear, Porosity)

- **Northwestern University**
  - Computational Material Design
  - Solidification Design
  - Transformation Design
  - Nano Design
  - Material Characterization

- **Argonne National Laboratory**
  - Material Evaluation using Advanced Photon Source (APS) X-Ray and MTS Testing Machine
  - In-Situ Microstructure and Damage Measurements

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[Image of a casting process and equipment]
Relevance

- Use of high strength steels can contribute to about 10% weight reduction as compared to mild steel. This can translate to about 6-7% improvement in fuel economy for a midsize sedan.

- Combining the casting process and the stiffness advantage of steel will allow the weight reduction potential to be maximized without sacrificing performance.

- Current forged crankshafts require machining post forging that adds to the cost. Cast steel crankshafts would not require additional machining costs.

- Implementing the technology developed in this project will provide US with energy security, while lowering costs and reducing impacts on the environment.
Objectives

- Overall project goal is to develop cast steel alloy(s) and processing techniques that are tailored for high performance crankshafts to achieve target as-cast properties of 800 MPa ultimate tensile strength and 615 MPa yield strength. This alloy will be a replacement for expensive forgings, without exceeding the cost target of 110% of the current production cast units.

- Effort at ANL will focus on several activities to support the project goals:
  - Utilize high-energy x-ray imaging and diffraction techniques to correlate microstructure/phases/defects in the alloy(s) with processing parameters. The results will be used to optimize design and processing of alloy compositions to achieve target properties.
  - Conduct in situ fatigue test to establish the durability requirements for high-performance gasoline and diesel engine applications which currently use forged crankshafts.
Milestones

- **FY2014 (On-going)**
  - Tomographic study of casting quality and structure
  - Design and develop high temperature apparatus for in-situ phase evolution study
  - Evaluation of laboratory sample castings (microstructure, property, and quality)

- **FY2015**
  - Optimize and characterize the high potential alloy & process concepts
  - Tomographic study of selected candidate cast alloys
  - In-situ phase evolution studies, including formation of precipitates and voids as a function of cool down temperature

- **FY2016/17**
  - In-situ tensile and fatigue behavior study on down-selected compositions/heat treatment at room and elevated temperatures
  - Investigate formation of micro-cracks during tensile loading and growth of cracks during cyclic fatigue

*Correlate microstructure to processing and mechanical properties to optimize cast alloy for crankshafts*
Approach

Advanced Photon Source – “Industrial” techniques

- **Core**
  - Macromolecular crystallography (many)
  - Powder diffraction (1-BM, 11-BM)
  - XAFS (S20)
  - Tomography (2-BM)
  - SAXS (various)
  - Strain scanning (1-ID)

- **Specialized/in development**
  - Nano-diffraction (24-ID, 34-ID)
  - Fluorescence microscopy (2-ID)
  - High-energy diffraction microscopy (1-ID)
  - Time resolved imaging (32-ID)
  - Combined techniques
    - EXAFS/SAXS/PDF
    - SAXS/WAXS (1-ID)
    - WAXS/Imaging (1-ID)
Approach

Imaging techniques for internal structure

- Absorption or phase tomography
  - Full field 2D image (mm$^2$) of direct beam
  - Absorption contrast (near) to phase contrast (far) by changing sample-detector
  - Take image and rotate M times (M images)
  - Reconstruct -> 3D volume with resolution ~ 1 µm
Example of Typical Result

Tomography study of high strength cast iron

- Internal structure of graphite phases, their network connectivity, voids and casting defects can be reconstructed in 3D
**Approach**

High Energy Diffraction Microscopy (HEDM)
- Non-destructive microstructural mapping

@1-ID, APS

**NF-HEDM**
- 3D grain map

**FF-HEDM**
- Grain-level strains vs load

**Tomography**
- Inclusion content
Example of Typical Result

In-situ HEDM study of grain rotation during annealing

- 4 deg color scale
- 2 deg boundaries
- orientation changes located at boundaries

* Information is being used to drive and test computational materials science predictions
In-situ HEDM study of copper during mechanical loading

Determine the microstructure non-destructively

“3D EBSD”

APS, Sector - 1

Near Elastic Limit

After 1% Creep Strain
Approach

X-ray micro-beam for phase and chemistry characterization

Beam size: 0.3 µm x 0.4 µm

Diffraction approach ➔ structure information
Fluorescence approach ➔ chemical information

@34-ID, APS
**Approach**

**X-ray micro-beam fluorescence analysis**

- **Sample surface**
  - Iron
  - Graphite
  - Fluorescence detector

- **Probed area**
  - Graphite
  - Ferrite
  - Pearlite

- **Fluorescence analysis**
  - provide chemical information

- **Attenuation length**
  - Graphite (~ 5 mm)
  - Iron (15 ~ 20 μm)

- **16.5 keV focused X-ray**
  - sub-micron beam size, 0.3 x 0.4 μm
**Approach**

High Energy Diffraction for phase evolution study

- **In situ** characterization of alloy solidification process
- Simultaneous WAXS/SAXS and full-field imaging
  - WAXS: lattice strain, texture, phases evolution
  - SAXS: nanoscale voids, bubbles, particles, crystal nucleation and growth
  - Imaging: microsize cracks, porosity
- 2D detector array for long sample-detector distance provide High-resolution data

@1-ID, APS
Approach

In-situ structure characterization during thermal-mechanical loading

Combining mechanical testing and strain mapping
Collaborations

- **Project Lead – Caterpillar, Inc.**

- **Caterpillar & GM**
  - ANL will characterize microstructures for structure/property correlations for optimized alloy compositions and processing variables. Validate mechanical performance of the alloy(s) by in-situ fatigue testing.

- **Northwestern Univ. & Univ. of Iowa**
  - Validate Integrated Computational Materials Engineering (ICME) modeling efforts by using high energy x-ray tools. Specifically, phase and microstructures, residual stresses based on geometry-specific casting simulations, cooling rates, etc.

- **Caterpillar/Questek/University of Alabama**
  - Working on another project related to cast iron development.

- **Air Force Research Lab**
Conclusions

- ANL role in the overall project is: (a) characterization of alloy microstructures and (b) support ICME activity.

- Several high-energy x-ray techniques have been identified for this project. Preliminary baseline experiments on some of the techniques have been initiated.

- Results of phase evolution study will be crucial in alloy development. Optimization of the controlled cooling rates to achieve desired phase/microstructures will be a key parameter.

- Microstructure interaction/evolution under thermal-mechanical loading will provide critical information for alloy composition optimizations/flaw initiation and crack growth for overall mechanical performance enhancements.