Development of High-Performance Cast Crankshafts

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Caterpillar Inc.

Vehicle Technologies – Annual Merit Review
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Project ID: PM 065

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Overview

Timeline
• Project start – March 2014
• Project end - September 2017
• Percent complete ~ 15%

Budget
• Total project funding: $3.78M
  – DOE share: $1.50M
  – Contractors share: $2.28M
• Expenditure of Gov’t Funds:
  • FY2014: $70,219
  • FY2015: $99,669 through Mar.

Barriers
• Power Density: achieve 10% decrease in weight over forged steel crankshaft.
• Efficiency: material and process design must achieve 800 MPa minimum tensile strength in cast crankshafts to replace forgings in high-efficiency and high-performance engines.
• Cost: no more than 110% of production cast units.

Partners
• Project lead – Caterpillar Inc.
• Partner – General Motors, LLC
• Interactions/ collaborations
  • University of Iowa
  • Northwestern University
  • Argonne National Laboratory
  • University of Northern Iowa
  • St. Louis Precision Casting Company
  • Element Materials Technology
Objectives

- Develop technologies that will enable the production of cast crankshafts that meet or exceed the performance of current state-of-the-art high performance forged crankshafts.
  - Minimum 800 MPa Tensile Strength
  - Minimum 615 MPa Yield Strength
- Cost target is to be no more than 110% of production cast units.
- Modifications to processing techniques may be included, but shall not include forging and should result in a finished product that meets all performance and cost targets.
- A current baseline shall be established, including the assembly mass, material composition, material properties, and cost.
  - Material and process must achieve local ultra-high cycle fatigue requirements of current baselines (CAT C9L, GM SGE 1.4L LV7).
Relevance

- Advanced materials that are lighter and/or stronger are essential for boosting the fuel economy and reducing emissions of modern vehicles while maintaining performance and safety.
  - Increased powertrain efficiency can be obtained by enabling engine components to withstand the high pressures and temperatures of high efficiency combustion regimes.
  - Powertrain systems often represents the highest weight systems in the vehicle.
  - Today’s high-efficiency and high-performance engines require forged steel crankshafts.
  - **Castings** increase the design flexibility over forgings, enabling material to be optimally placed for **greater light-weighting potential**.
  - Reducing the weight of the primary rotating component could reduce the structural requirements of the engine block, enabling additional light-weighting.
  - Offset weight penalties from advanced emissions-control equipment, safety devices, integrated electronic systems and power systems such as batteries and electric motors for hybrid, plug-in hybrid, or electric vehicles.
    - For example, using lighter and/or higher strength materials to achieve a 10% reduction in vehicle weight can result in a 6% – 8% fuel-economy improvement.
Milestones

- BP1- FY14 & FY15: Develop and evaluate preliminary alloy & process concepts

<table>
<thead>
<tr>
<th>MILESTONES</th>
<th>MEASURE</th>
<th>DATE</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define prioritized crankshaft requirements</td>
<td>Performance, Cost</td>
<td>Apr '14</td>
<td>Complete</td>
</tr>
<tr>
<td>Define material &amp; process requirements</td>
<td>Properties, Cost</td>
<td>May '14</td>
<td>Complete</td>
</tr>
<tr>
<td>Generate alloy design concepts</td>
<td>~4 areas of investigation, ICME complete</td>
<td>Dec '14</td>
<td>Complete</td>
</tr>
<tr>
<td>Generate process design concepts</td>
<td>~6 areas of investigation, ICME complete</td>
<td>Mar '15</td>
<td>Complete</td>
</tr>
<tr>
<td>Laboratory sampling of alloy &amp; processing concepts</td>
<td>~12 sample casting trials</td>
<td>Mar '15</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Evaluation of laboratory sample castings (microstructure, properties, quality)</td>
<td>Casting quality, 850 MPa UTS, 580 MPa Yield, Initial Fatigue Assessment</td>
<td>Apr '15</td>
<td>(Go/No Go) Ongoing</td>
</tr>
</tbody>
</table>

- FY17 – Produce, Evaluate and Validate Prototype Crankshaft, and Develop Comprehensive Cost Model
Approach

- Utilize the proven Integrated Computational Materials Engineering (ICME) approach to accelerate alloy development time by applying mechanistic materials models within a systems-engineering framework to computationally engineer new material compositions and manufacturing processes.
- Develop lab scale sample casting and produce prototype alloys.
- Standard characterization and material testing will be done to validate the alloy performance against goals and provide feedback to ICME models.
- Utilize the Advanced Photon Source (APS) at Argonne National Labs to conduct innovative in-situ measurements of phase evolutions and damage during heating and cooling under various loading conditions.
- Multi-disciplinary effort will integrate finite element analyses by crankshaft designers and geometry-specific process simulations with existing materials models to optimize crankshaft cost and performance.
- ICME tools and Accelerated Insertion of Materials (AIM) methodology will be used to forecast design allowables for the developed alloy.
Approach

- Produce prototype cast steel crankshafts for Caterpillar and GM concept designs.
- Validation will be performed using standard bench tests at Caterpillar and GM in order to define the crankshaft’s median fatigue strength for bending and torsion loads.
- A full engine test is planned for the prototypes to ensure the crankshaft and con-rod bearing system will withstand the same severe overspeed conditions as the current baseline forging.
- A cost model will be developed which compares costs relative to the baseline assembly, and provides a pathway to meet incremental cost targets.
  - Cost models to include materials production, component fabrication, finishing, and heat treatment costs for annual production runs up to 100,000 units, in increments of 25,000 units.
Approach – Systems Design Chart

**Processing**
- Fillet Rolling
- Machining
- Induction Hardening
- Quench and Tempering
- Normalizing, Homogenizing
- Solidification
- Mold Filling
- Grain Refining (Ce), Al, Zr, Ti, Deoxidizer
- Melting

**Structure**
- Matrix structure
  - Pearlite
  - Martensite
  - Banite
- Strengthening structure
  - $(\text{Cr, Mo, V, Fe})_2\text{C}$
  - Avoid $\text{M23C6} / \text{M7C3}$
  - Coarsening Rate
- Grain Size
  - Prior austenite grain size (as-cast)
  - Recrystallized Martensite (MC grain refiners, VC,TIC,NbC)
  - ASTM5 grain size min.
  - Precipitates to improve machining (MnS)
- Microsegregation
  - C, Cr, Mo, V
- Casting defects
  - Inclusions
  - Porosity
  - Hot tears

**Properties**
- Endurance Limit
  - TBD MPa
- Tensile strength (core)
  - 850 Mpa / 123ksi
- Yield strength (core)
  - 580 Mpa / 84 ksi
- Elongation
  - (10~12%)
- Hardenability
  - Surface: 49 – 57 HRC
  - Profile: 0.5 mm 45 HRC
  - Case Depth: 2.5 mm
- Machinability

**Cost**

**Performance**
ICME - Materials Design Approach

Define Component Requirements
- Life, Cost, etc.

Define Material Requirements
- Strength, Hardness, Fatigue, etc.
- Processing constraints (castability, hardenability)

Determine Initial Alloy Composition

Calculate Thermo-physical Properties f(Temp)
- Density, Specific Heat, Thermal Conductivity, Solid Fraction, etc.
  (*Equilibrium, Schiel)

Calculate Microstructure Evolution
- Phase fraction

Extract Cooling Curves

Modify Composition

Critical Cooling Rate

Calculate Mechanical Properties
- Strength, Elongation, Hardness

Satisfy Requirements

Natural Solidification & Heat Treat Simulation

Material-Process-Component

Caculate TP Properties

Process Design

Performance

Element sensitivity analysis
Initial Alloy Design (SAE 15V22mod) and ICME Validation

Mechanical properties of experimental weld-plate cast with SAE 15V22mod.

<table>
<thead>
<tr>
<th>SAE15V22mod</th>
<th>1A</th>
<th>1B</th>
<th>1A</th>
<th>1B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution at 950°C</td>
<td>Normalization with air-cool</td>
<td>Normalization with fan-cool</td>
<td>2x Normalization with air-cool</td>
<td>2x Normalization with fan-cool</td>
</tr>
<tr>
<td>Tensile, MPa</td>
<td>853, 784</td>
<td>839, 801</td>
<td>833, 760</td>
<td>855, 800</td>
</tr>
<tr>
<td>Yield, MPa</td>
<td>581, 582</td>
<td>577, 586</td>
<td>575, 570</td>
<td>585, 591</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>3, 2</td>
<td>3, 1.3</td>
<td>3.2, 2.1</td>
<td>3.1, 2.2</td>
</tr>
<tr>
<td>RA</td>
<td>5, 5</td>
<td>5, 4</td>
<td>6, 4</td>
<td>4, 4</td>
</tr>
<tr>
<td>Charpy-V at room temp</td>
<td>11.8, 10.9, 10.9</td>
<td>11.5, 10.6, 11.8</td>
<td>15.1, 12.9, 16.4</td>
<td>13.7, 13.6, 12.6</td>
</tr>
<tr>
<td>HRC surface</td>
<td>26, 27, 27</td>
<td>27.5, 28, 27.5</td>
<td>26.5, 26.5, 26.5</td>
<td>28, 27.5, 27.5</td>
</tr>
</tbody>
</table>

Comparison of different predictions with experiments of mechanical properties of weld-plate cast with SAE 15V22mod.

<table>
<thead>
<tr>
<th>Location</th>
<th>Method &amp; Cooling rate around 700°C</th>
<th>After normalization and tempering</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC_2 Corner</td>
<td>Magma 0.5°C/s JMatPro 0.5°C/s</td>
<td>Phases % Bainite Pearlite YS MPa UTS MPa HRc HV % EI %</td>
</tr>
<tr>
<td>TC_6 Side edge</td>
<td>Magma 0.4°C/s JMatPro 0.4°C/s</td>
<td>39 61 835 1098 264 8.9</td>
</tr>
<tr>
<td>TC_4 Center</td>
<td>Magma 0.3°C/s JMatPro 0.3°C/s</td>
<td>29 71 739 1007 256 1.4</td>
</tr>
<tr>
<td>Experiment 1A</td>
<td>JMatPro 0.035°C/s</td>
<td>19 81 650 923 248 13.7</td>
</tr>
<tr>
<td>As-cast</td>
<td>JMatPro 0.035°C/s</td>
<td>19 81 468 868 14.1Rc -</td>
</tr>
</tbody>
</table>
Cooling Rates in Crankshaft

Thermocouple locations in CAT solid journal crankshaft

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Solidification</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature ˚C</td>
<td>Cooling rate ˚C/s</td>
</tr>
<tr>
<td>TC_1</td>
<td>704.0</td>
<td>0.018</td>
</tr>
<tr>
<td>TC_2</td>
<td>703.9</td>
<td>0.017</td>
</tr>
<tr>
<td>TC_3</td>
<td>703.8</td>
<td>0.019</td>
</tr>
<tr>
<td>TC_4</td>
<td>704.2</td>
<td>0.020</td>
</tr>
<tr>
<td>TC_5</td>
<td>704.1</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Temperature variation during solidification and heat treatment.

Cooling rate of thermal couples during solidification and heat treatment.
Test Bar Casting Design for Alloy Sampling

Geometry of the final test casting design.

Simulation results:

- **Cooling rates calculated from the temperature history during solidification and heat treatment simulations as measured by the virtual thermocouples at the center of the bars.**

<table>
<thead>
<tr>
<th>Thermo-couple</th>
<th>Solidification</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>Cooling rate °C/s</td>
</tr>
<tr>
<td>TC-2</td>
<td>704.12</td>
<td>0.042</td>
</tr>
<tr>
<td>TC-5</td>
<td>705.15</td>
<td>0.031</td>
</tr>
<tr>
<td>TC-8</td>
<td>704.65</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Simulated cooling rates at the center of the test bars at about 704°C during solidification and heat treatment.

- **Cooling rates during air quenching from normalization temperature match those in crankshaft**
  - 0.3 – 0.4 °C/s
Test Bar Casting Design for Alloy Sampling

Geometry of the final test casting design.

Liquid metal velocities at various stages during the filling process are shown. The filling velocities are mainly lower than the 1 m/s threshold used for optimal filling processes.

Evolution of liquid fraction (shown regions above 50%) during solidification.

Predicted porosity in the test casting after solidification is complete. The risers pipe nicely and yield sound (porosity free) test bars.
Alloy Design

- Optimize Austenite Decomposition
- Precipitation Strengthening, Grain Refining
- Optimize Solidification Freezing Range

Strengthening phase fraction:
- Red-curve: Cu
- Cyan-curve: (Mo,V)₂C

Curve 1 – BCC_A2#1: Ferrite
Curve 2 – FCC_A1#1: Cu (if coherent, will be bcc Cu)
Curve 3 – FCC_A2#2: NbC
Curve 4 - FCC_A1#4: Austenite
Curve 5 – HCP#2: (Mo,V)₂C
Curve 6 – FCC_A1#3: VC
ICME predictions for microstructure phases and mechanical properties.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Designation</th>
<th>Phases</th>
<th>YS</th>
<th>UTS</th>
<th>HRc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>F</td>
<td>P</td>
<td>M</td>
</tr>
<tr>
<td>1</td>
<td>V-MA650-1</td>
<td>97.8</td>
<td>0.5</td>
<td>1.7</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>V-MA650-2</td>
<td>86.4</td>
<td>8.4</td>
<td>27.0</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>V-MA650-2 +GR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>V-MA650-3</td>
<td>72.6</td>
<td>15.0</td>
<td>12.4</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>V-MA650-3 +GR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>SiV-MA700</td>
<td>31.1</td>
<td>14.2</td>
<td>54.8</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>SiV-MA650</td>
<td>36.2</td>
<td>30.5</td>
<td>33.4</td>
<td>--</td>
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<tr>
<td>8</td>
<td>SiBo Steel</td>
<td>17.7</td>
<td>9.9</td>
<td>1.1</td>
<td>71.1</td>
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<tr>
<td>9</td>
<td>SiBo Steel +GR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>NW-Cast1000</td>
<td>98.8</td>
<td>0.01</td>
<td>--</td>
<td>1.24</td>
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<tr>
<td>11</td>
<td>NW-Cast700</td>
<td>86.2</td>
<td>13.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>GM 1536MV</td>
<td>--</td>
<td>19.2</td>
<td>80.8</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>4140</td>
<td>82.9</td>
<td>16.2</td>
<td>0.9</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>3130</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Casting Trials

- GM procured wood pattern for test bar mold.
- University of Northern Iowa produced air-set sand molds and produced first sample castings.
- University of Iowa sectioned the castings and performed die-penetrant testing to check for macro and micro porosity
  - Excellent soundness achieved
- Several delays have been encountered in casting the preliminary alloy concepts at UNI
  - Equipment issues (spectrometer, furnace), alloy materials
- Secondary source brought on-line for producing test bar castings
Preliminary Casting Process Exploration

Mold Filling

- Filling the crankshaft vertically leads to a much smoother flow.
- Gating the casting through the risers allows them to better feed the casting.

Horizontal -gated through one side

Vertical counter-gravity vacuum filled

Solidification

- Various feeding systems were simulated to find a rigging that yields a sound crankshaft. Yield maximized and riser contacts minimized.
- Focused on gravity casting in a bonded sand mold for quick initial casting trials.
- Chills, sleeves, hot topping, and changes to the core geometry and material were investigated.

Development of High-Performance Cast Crankshafts
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Response to Reviewers Comments

- Program not reviewed last year.
Collaboration – Project Team

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

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

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

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

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

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Remaining Challenges and Barriers

- Biggest challenge for the success of this project is to consistently produce clean steel crankshaft castings within the cost targets.
  - Crankshafts must endure ultra-high cycles without failure.
  - Mold filling process is critical to produce clean steel castings. Gravity pouring methods common for steel castings may lack sufficient quality control.
  - Complex geometry is difficult to efficiently feed during solidification.
    - Technologies need to be employed which maximize casting yield and minimize the contact area of the feeders.
  - Combination of grain refining and alloy additions to produce required structure with normalizing heat treatment only
- Challenge to scale-up processing concepts for full-size prototyping within existing foundry base.
  - GM has led efforts to assess foundry capabilities (2 facility visits, 10 e-mail surveys)
- Calibration of ICME models necessary to optimize alloy design and casting processes.
- Limits of ICME tools for predicting critical material characteristics such as toughness.
Future Steps

- **BP1: Develop and Evaluate Preliminary Alloy and Process Concepts**
  - Cast test bar samples for each of the preliminary alloy concepts
  - Conduct metallurgical and mechanical property evaluations in the as-cast and normalized conditions for each alloy concept
    - GM has established contract Element Material Technology materials characterization work
  - Continue developing casting process concepts using ICME
  - Use 3D printing technologies for molds/cores to prototype casting process concepts

  - Use alloy and process casting trials to calibrate ICME tools and develop models to optimize high potential concepts
  - Utilize integrated modeling approach to develop crankshaft design concepts optimized for casting process

- **BP3 (FY’17): Produce, Evaluate and Validate Prototype Crankshaft, and Develop Comprehensive Cost Model**
  - GM has already initiated development of a cost model for cast steel crankshafts
Summary

- Critical customer requirements defined and target material specifications established.
- System Design chart established for the process-structure-property relationships to be investigated for meeting established customer requirements.
- Designed a test bar casting with a range of cooling rates during casting and heat treatment that are similar to ICME calculated cooling rates for typical crankshafts.
- Procured wood pattern for producing test bar casting molds.
- Several alloy concepts designed using ICME approach.
  - Predicted to meet the target material strength requirements.
  - Including a couple standard industry grades and a current GM forging alloy, a matrix of 14 alloys will be cast.
- First alloy concept was cast using a weld plate test casting.
  - ICME predictions for strength and hardness were in reasonable agreement with measurements from the plate casting, which were at or very close to requirements.
  - Elongation and Charpy values were below requirements. ICME tools for predicting these properties are not mature.
- Several casting approaches explored using casting process simulation. At least two designs developed which could produce a cast steel crankshaft with acceptable porosity levels.