Development of High-Performance Cast Crankshafts

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Vehicle Technologies – Annual Merit Review
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Project ID: PM 065

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project start – March 2014
- Project end - March 2018
- Percent complete ~ 30%

Budget

- Total project funding: $3.78M
  - DOE share: $1.20M +$0.3M to ANL
  - Contractors share: $2.28M
- Expenditure of Gov't Funds:
  - FY2014: $70,219
  - FY2015: $186,237
  - FY2016: $113,342 thru Feb.

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
- Subcontractors
  - **University of Iowa**
  - **Northwestern University**
  - **Argonne National Laboratory**

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 (DOE), 850 MPa (CAT and GM)
  - Minimum 615 MPa Yield Strength (DOE), 580 MPa (CAT and GM)
- 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 (10-15%)**.
  - 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

MILESTONES	MEASURE	DATE	STATUS
Define prioritized crankshaft requirements	Performance, Cost	April '14	Complete
Define material & process requirements	Properties, Cost	May '14	Complete
Generate alloy design concepts	~4 areas of investigation, ICME complete	Dec '14	Complete
Generate process design concepts	~6 areas of investigation, ICME complete	Feb '15	Complete
Laborotatory sampling of alloy & processing concepts	~12 sample casting trials	Feb '16	Complete
Evaluation of laboratory sample castings (microstructure, properties, quality)	Casting quality, 800 MPa UTS, 615 MPa Yield, Initial Fatigue Assessment	May '16	(Go/No Go) Complete
Refine design of high potential (HP) alloy conepts	~2 HP alloy concepts, ICME optimization complete	Jul '16	Ongoing
Refine design of high potential (HP) processing conepts	~ 3 HP process concepts, ICME optimization complete	Aug '16	Ongoing
Develop initial crankshaft design concepts & FMEA based on HP alloys and processes	~3 design concepts investigated, FEA complete	Aug '16	Ongoing
Evaluate castabilty of HP alloys (fluidity & hot tear experiments)	~2 HP alloys, validate ICME models	Aug '16	
Prototype high potential alloys and processes (single crankpin scale model)	~6 casting trials	Oct '16	
Evaluate local processing effects (induction hardening, fillet rolling, etc.)	Finish processing of sample castings	Nov '16	(Go/No Go)
Evaluate casting quality & mechanical properties of sample HP castings	Casting quality, 800 MPa UTS, 615 MPa Yield, Complete Fatigue Assessment	Jan '17	(Go/No Go)

Milestones

- FY17 –Integrated Modeling to Develop New Prototype Crankshaft Design, Produce and evaluate prototype cast crankshafts
- FY18 –Validate Prototype Crankshafts and Develop Comprehensive Cost Model

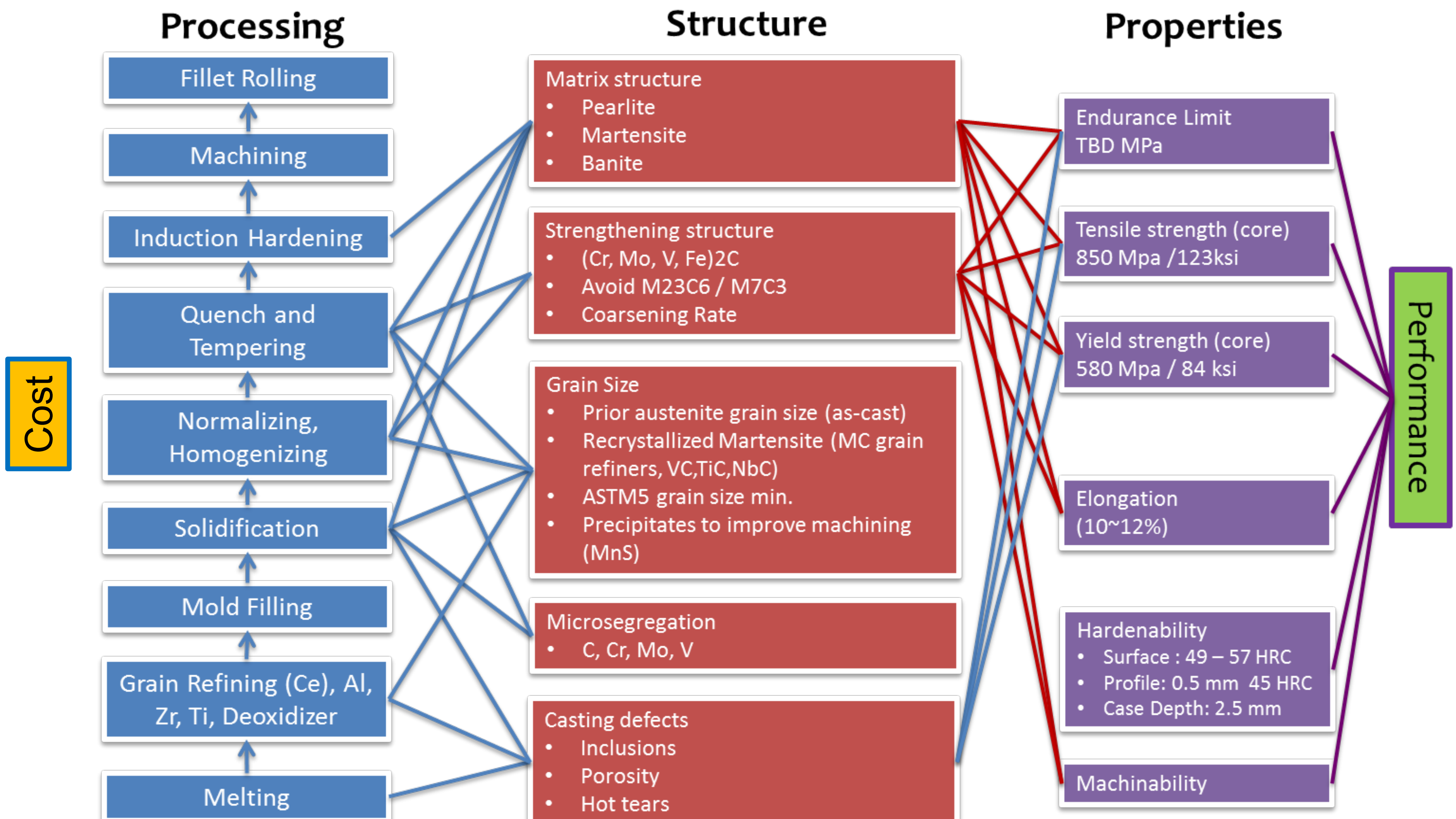
Approach

- 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 design 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.

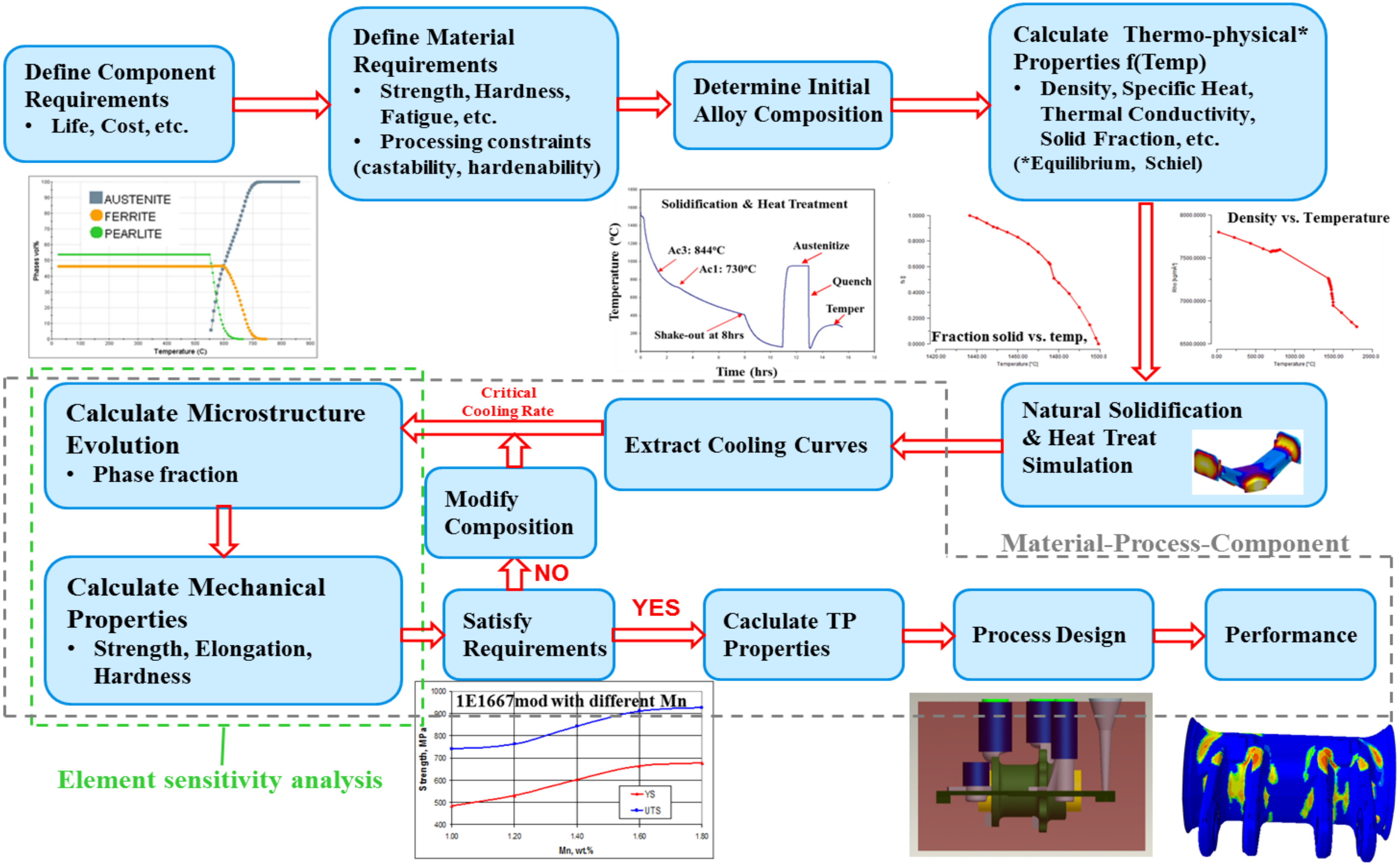
Approach

- **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



ICME - Materials Design Approach



Development of High-Performance Cast Crankshafts

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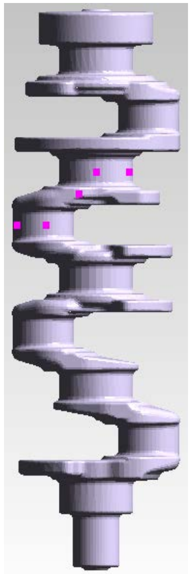
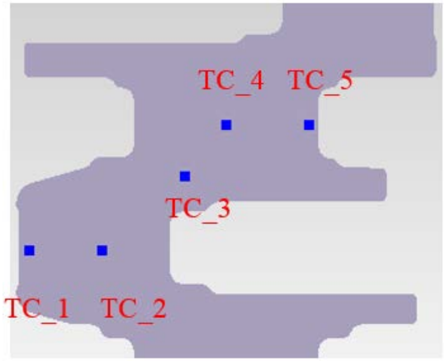
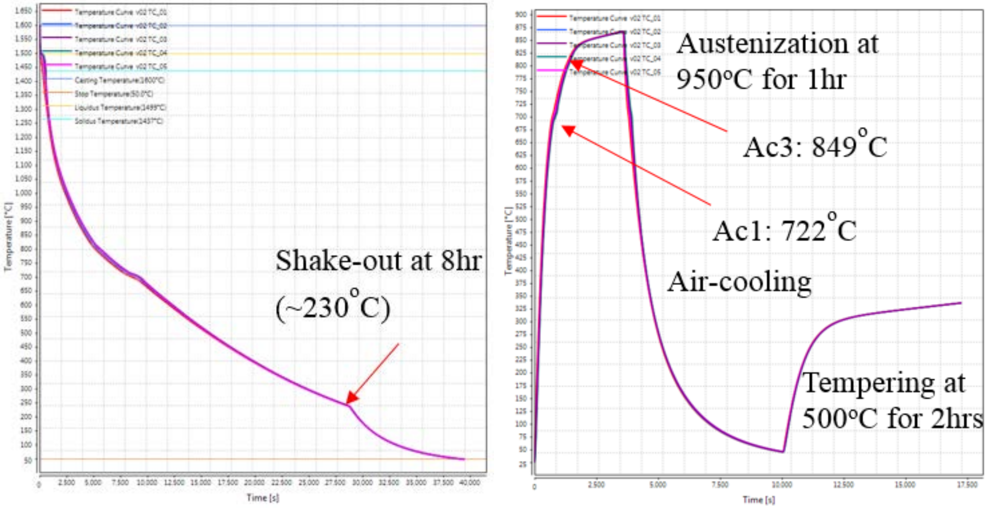
Cooling Rates in Crankshaft



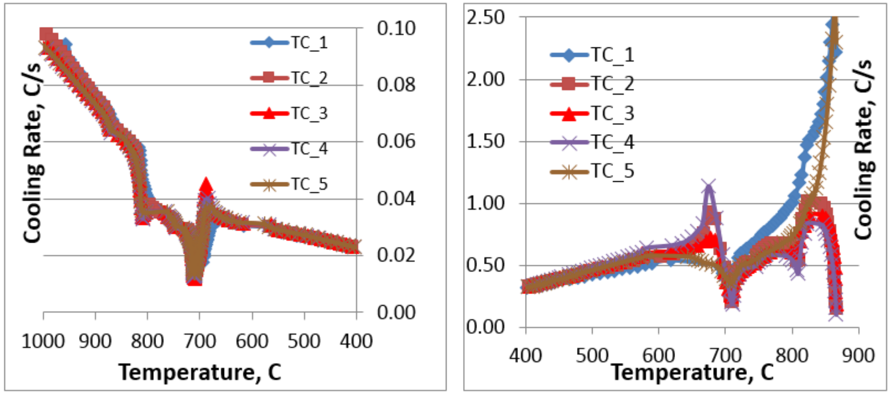


Thermocouple locations in CAT solid journal crankshaft



Temperature variation during solidification and heat treatment.

Thermo-couple	Solidification		Heat treatment	
	Temperature ºC	Cooling rate ºC/s	Temperature ºC	Cooling rate ºC/s
TC_1	704.0	0.018	702.0	0.381
TC_2	703.9	0.017	703.7	0.365
TC_3	703.8	0.019	704.7	0.310
TC_4	704.2	0.020	705.5	0.301
TC_5	704.1	0.019	704.5	0.375



Cooling rate of thermal couples during solidification and heat treatment.

Preliminary Alloy Design Concepts

ICME predictions for microstructure phases and mechanical properties.

Steel	Designation	Phases				YS	UTS	HRc
		B	F	P	M	MPa	MPa	
1	V-MA650-1	97.8	0.5	1.7	--	654	901	27.2
2	V-MA650-2	86.4	8.4	27.0	--	650	889	27
3	V-MA650-2 +GR							
4	V-MA650-3	72.6	15.0	12.4	--	662	910	27.6
5	V-MA650-3 +GR							
6	SiV-MA700	31.1	14.2	54.8	--	707	959	30
7	SiV-MA650	36.2	30.5	33.4	--	661	902	27.6
8	SiBo Steel	17.7	9.9	1.1	71.1	1364	1603	49.8
9	SiBo Steel +GR							
10	NU-Cast1000	98.8	0.01	--	1.24	1024	1283	42
11	NU-Cast700	86.2	13.8	--	--	724	977	30.8
12	4140	82.9	16.2	0.9	--	656 635*	903 972*	27.3 30*
13	GM 1538MV	--	19.2	80.8	--	531	761	19.2
14	1330							

Phases

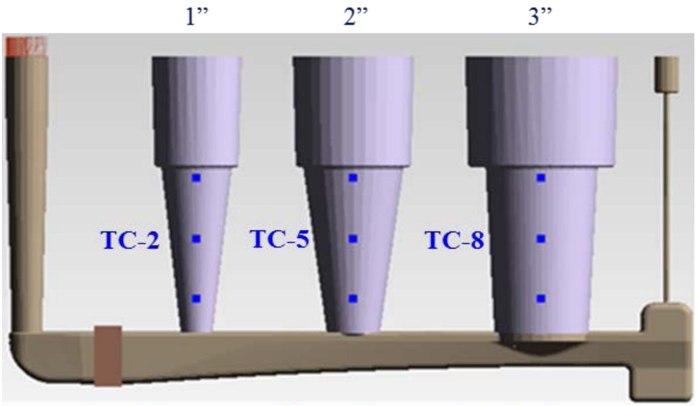
B = Bainite

F = Ferrite

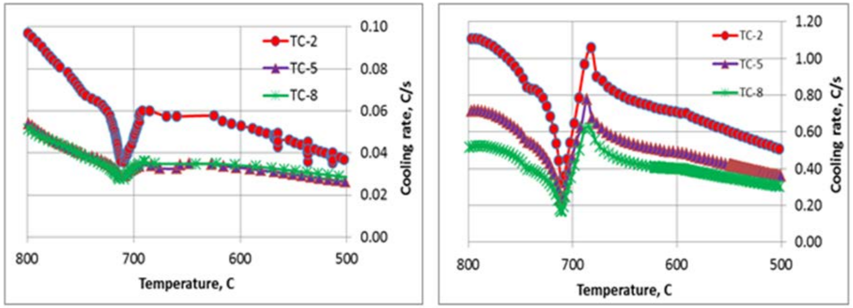
P = Pearlite

M = Martensite

Test Bar Casting Design for Alloy Sampling



Geometry of the final test casting design.



(a). Solidification (b). Heat treatment

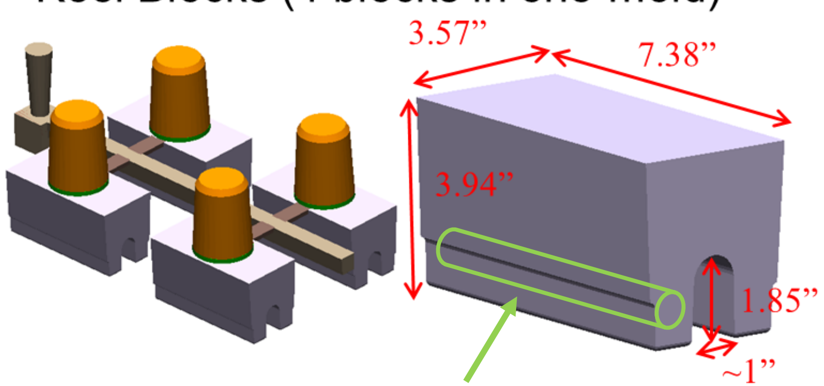
Cooling rates calculated from the temperature history during solidification and heat treatment simulations as measured by the virtual thermocouples at the center of the bars.

Thermo-couple	Solidification		Heat treatment	
	Temp. °C	Cooling rate °C/s	Temp. °C	Cooling rate °C/s
TC-2	704.12	0.042	705.23	0.452
TC-5	705.15	0.031	703.53	0.390
TC-8	704.65	0.031	703.96	0.294

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

Keel Blocks (4 blocks in one-mold)



- ✓ Shorter feeding distance

Alloy Casting Trials

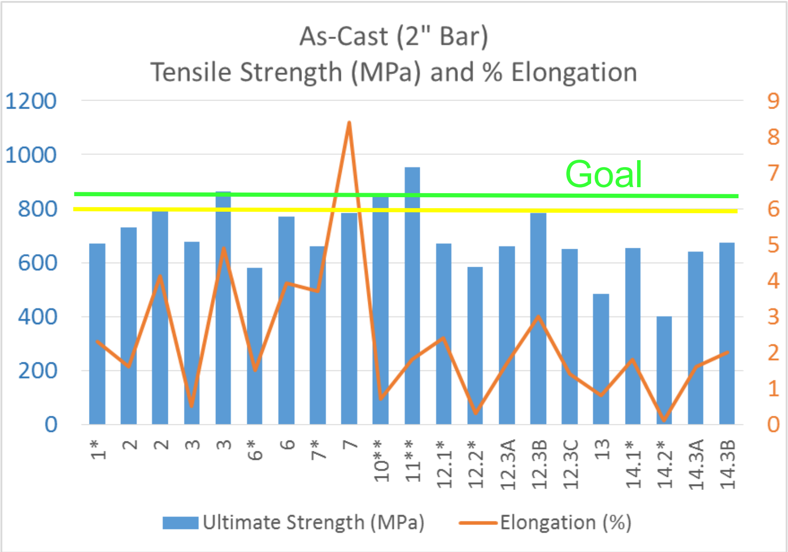


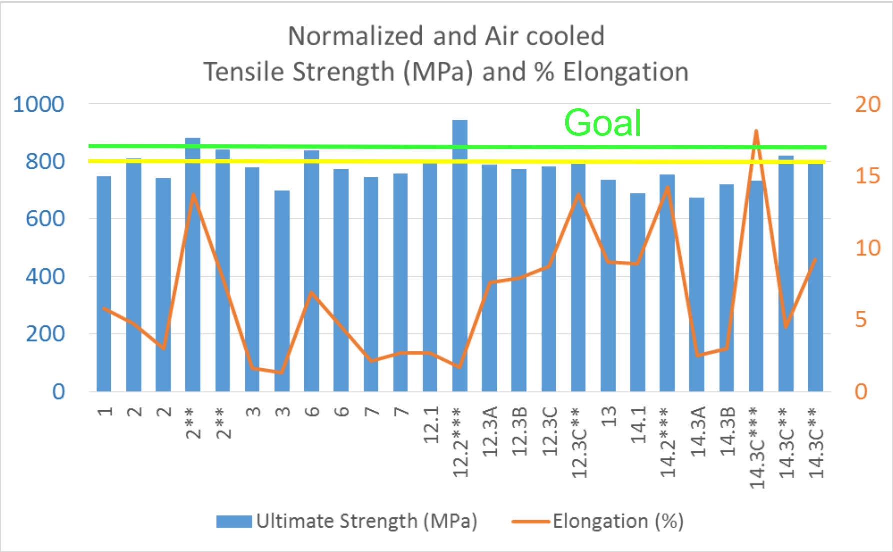

St. Louis Precision Casting Company

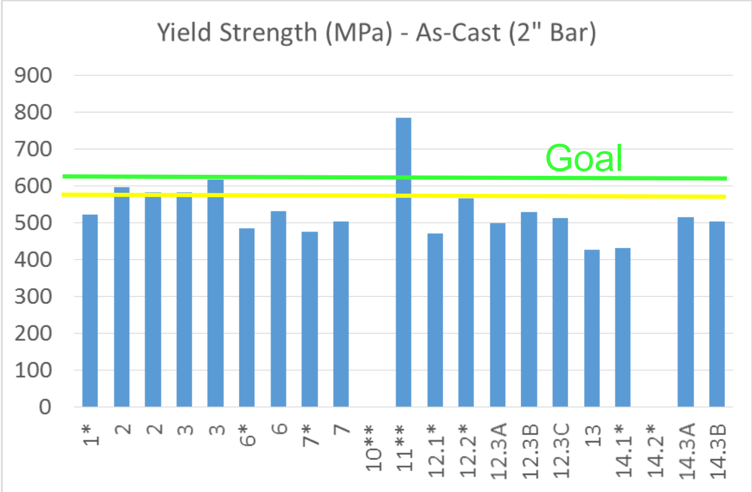


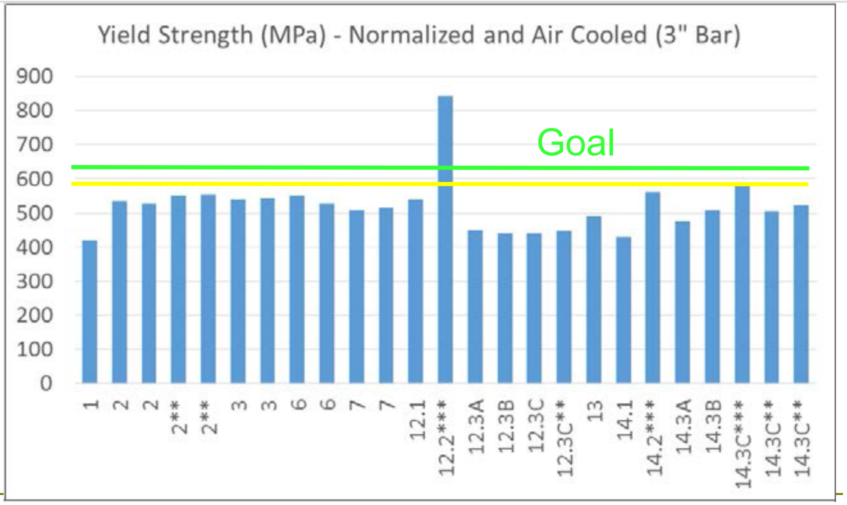
Southern Cast Products

Structure-Property Characterization



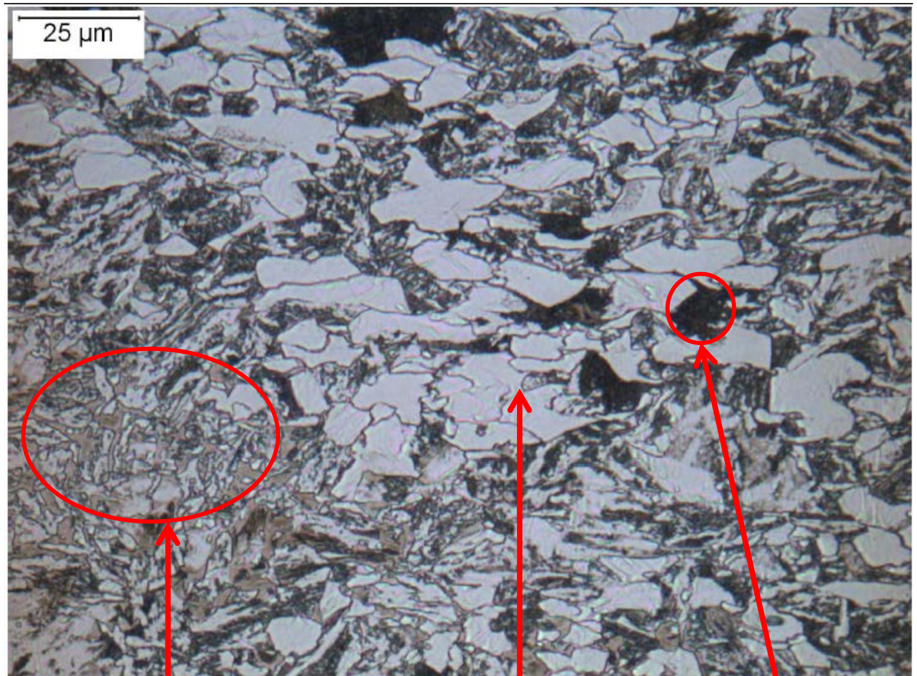






Structure-Property Characterization

As-cast of alloy-2 keel block. 500x 2% Nital



Mixture of martensite, bainite and ferrite

White area: ferrite

Pearlite

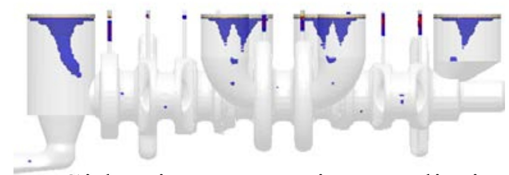
Air-cool after normalizing at 900^{o}C for 3hr for alloy-2 keel block. 500x 2% Nital

Process Development

Prototype Cast Steel Crankshaft

- Finalized rigging design for a gravity cast horizontally oriented steel crankshaft.
- Printed two sand molds at University of Northern Iowa, using the crankshaft rigging geometry from the simulation software.
- Poured two steel crankshafts using the two printed molds at St. Louis Precision Foundry.
- The crankshafts were sent to Element for material and property inspection and compared to ICME predictions.

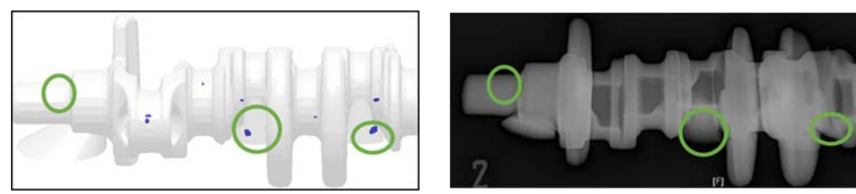

Top view: Porosity Prediction


Side view: Porosity Prediction


Crankshaft after shot blasting


Cope and drag of the printed sand molds

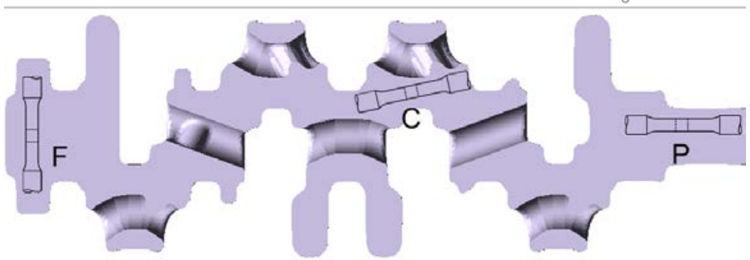

Crankshaft mold post-filling


Many of the indicated porosity locations on the x-rays were predicted by MAGMAsoft.

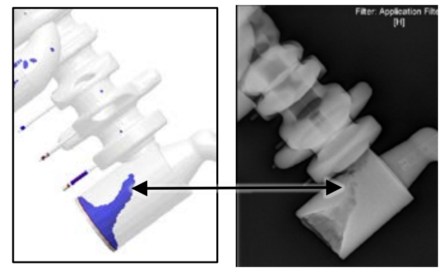
Process Development

Porosity Comparisons

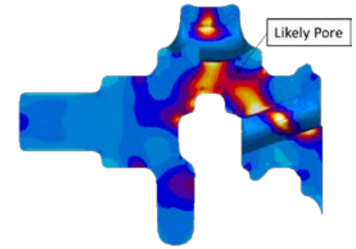
- Crankshafts were X-rayed to identify defects and compare with ICME predictions.
- A crankshaft was cut horizontally, midway through and sectioned to perform dye-tests and photomicrography.
- Tensile bars extracted from 3 locations to measure properties within the crankshaft.

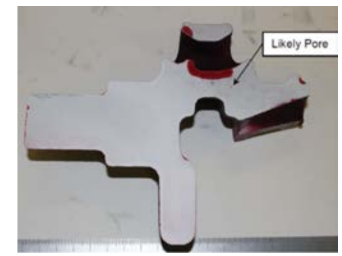


Mechanical Test Results							
Sample ID	Diameter (mm)	Gauge Length (mm)	UTS (MPa)	YS (0.2% Offset) (MPa)	Plastic Elongation (%)	Modulus (GPa)	Porosity (%)
F	**4.1**	**16.3**	**915**	**582**	**17.2**	**185.7**	**0.013**
C	4.1	16.3	894	570	14.1	201.8	<0.01
P	4.1	16.3	916	598	16.3	198.5	<0.01

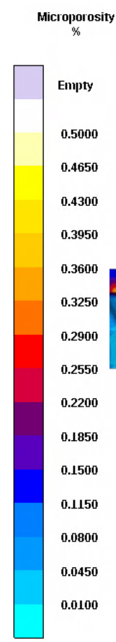


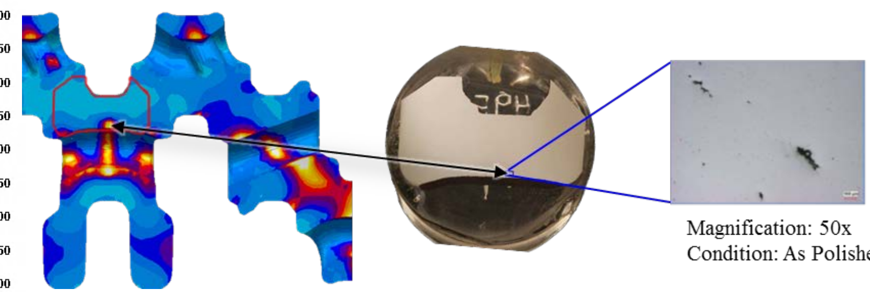
Predicted pipe in riser, is nearly identical to the cast crankshaft's





Dye-penetrant results mostly indicated locations where higher levels of porosity were predicted.



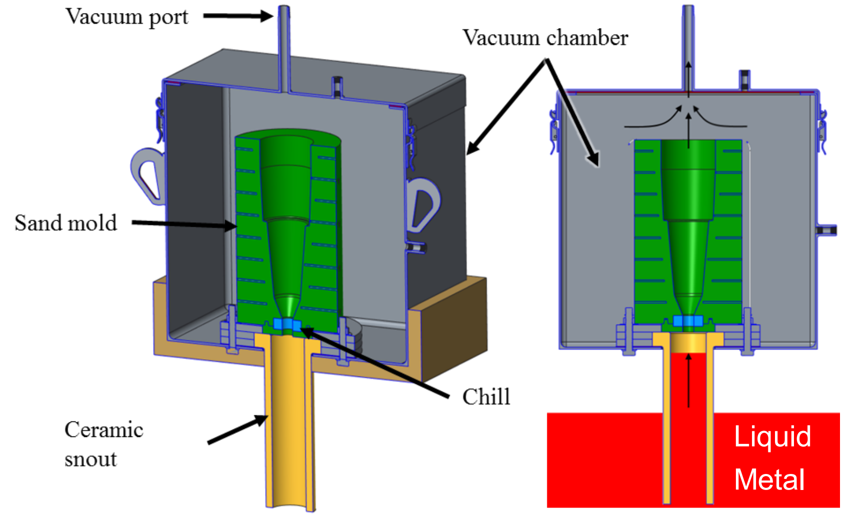


Crankshaft sample's location of maximum porosity agreed with predictions.

Process Development

Counter-gravity Filling

- Counter-gravity filling of castings has the advantages of a quicker, more quiescent fill than a traditional gravity poured process.
- Using vacuum pressure, liquid steel is drawn directly from the furnace into a sand mold in a highly controlled manner.
- A steel chill was utilized to freeze of the steel near the inlet, allowing the vacuum to be released sooner.
- A preliminary trial of the system successfully produced a steel casting.
- Next steps: Pressurize the vessel up to 5 bar to increase the feeding distance of the riser.



CAD model of counter-gravity system

Sand mold and casting produced by counter-gravity system.

Counter-gravity system assembled

Materials and Post-Process Design

Thermo-Calk and ICME software developed at Northwestern is adopted as the simulation tool to design post-processing for the casting alloys in order to achieve the optimal microstructure.

Post-processing on small-size samples are carried out at Northwestern in order to understand microstructure evolution.

Mechanical Property

SEM/EDX

Metallography

Dilatometry

ICP for Composition Analysis

Microstructure Analysis (Phase & Casting Defects)

Microstructure Design

ICME software
Thermo-Calc
DICTRA

Phase diagram
Ms temperature
Bs temperature

Processing Optimization

Materials and Post-Process Design

#6

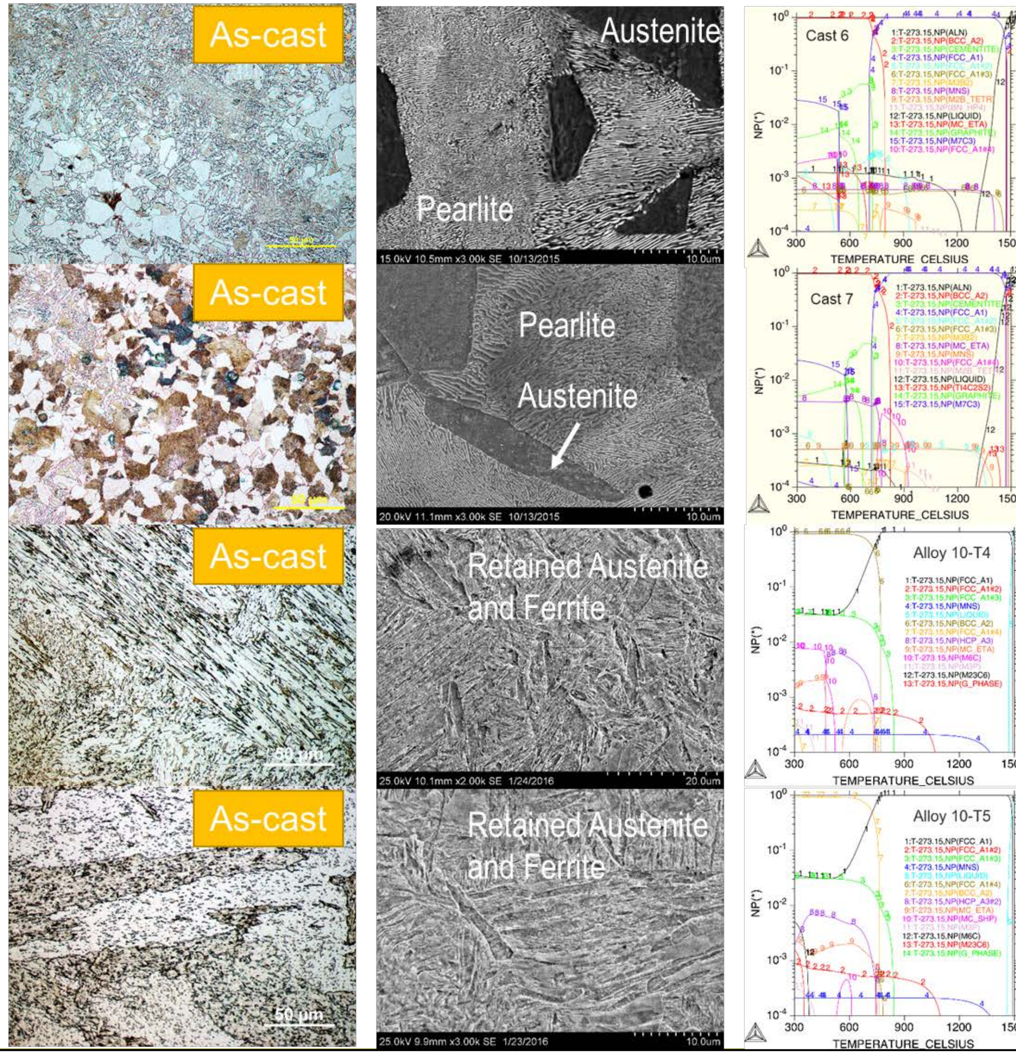
Further Design to promote lower Bainite

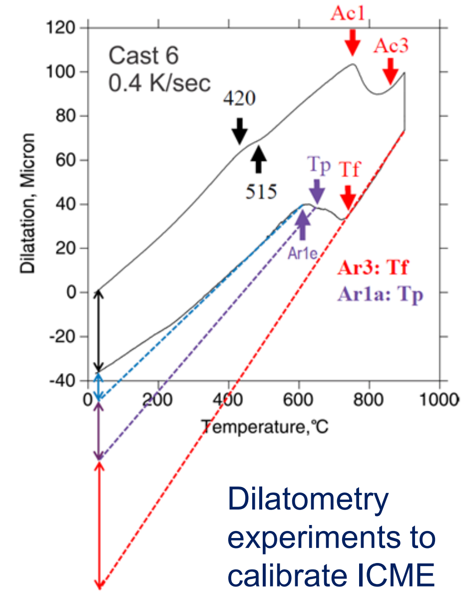
#7

#10

Further Design to promote precipitation strengthening

#11





Dilatometry experiments to calibrate ICME models and optimize phases in high potential alloy concepts

CATERPILLAR® GM NORTHWESTERN UNIVERSITY THE UNIVERSITY OF IOWA Argonne NATIONAL LABORATORY

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Response to Reviewers Comments

C1. The approach appeared sound to the reviewer, who thought, however, that it would have been preferable to see a commercial foundry involved from the beginning as a cost-share partner, along with the university, for an effort as challenging as steel casting. Nevertheless, the reviewer said, it appeared that progress was being made in identifying potential foundries.

R1. Both GM and Caterpillar have production foundries, and GM currently produces cast iron crankshafts in-house. Several current production foundries were identified for producing prototype crankshaft, however with significant process development expected it would be difficult to identify a commercial foundry to lock into at the early stages of the project.

C2. In the presentation, the reviewer said, the design approach was clear, showing that the model predictions showed some discrepancy with the data. Are there any plan to understand this gap, the reviewer wondered.

R2. Dilatometry experiments in process for high potential alloy concepts to investigate discrepancies with model predictions (Ms and Bs temperatures). Conducting detailed phase identification to quantify microstructures. Using results from various casting geometries to better quantify the effects of microporosity on the mechanical properties.

C3. This is a good project team, the reviewer said, the combination of Caterpillar and GM crankshaft requirements and objectives strengthening the project. The reviewer asked if the cost targets will be assessed for each company, or for just one.

R3. It is expected the cost targets will be performed as a function of production volumes, considering the difference between CAT and GM. Also, the size ranges of crankshafts needs to be considered.

C4. Though praising a good team set-up, the reviewer found it difficult to understand from the presentation who in the team did what.

R4. See the details on the “Collaboration-Project Team” Slide.

Response to Reviewers Comments

C5. Steel cleanliness will be a major challenge for such a fatigue-driven component, the reviewer predicted. It would be better, the reviewer continued, if next year's review includes a strategy for increasing the cleanliness and quality of the casting process. Likewise, the reviewer expressed a desire to see work proposed on characterizing casting defects as a function of alloy composition, pouring conditions and local cooling rates.

R5. This year the presentation included process development work focused on clean steel casting counter-gravity process. Also, demonstrated efforts to quantify effects of microporosity on the property variations.

C6. Yes, the reviewer said, but the weight saving target is not well motivated and can be questioned.

R6. A forged crankshaft represents the heaviest component within a reciprocating engine. Current cast crankshafts represent a significant performance barrier in more fuel-efficient engines.

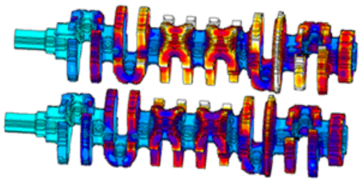
C7. The benefit of this project to improving engine efficiency was unclear to the reviewer. The underlying goal seemed to the reviewer to be reducing the cost of higher-performance crankshafts. This clearly benefits the partner engine companies, the reviewer acknowledged, because success would allow them to replace forged crank with lower-cost cast cranks. If this cost reduction results in turn in greater penetration of higher peak cylinder pressure and higher- efficiency engines, this project will contribute to the DOE objective, the reviewer concluded.

R7. Current higher peak cylinder pressure engines and higher efficiency engines require forged crankshafts, which are both heavier and more costly than the targeted cast crankshafts. Lower cost may benefit the producer companies, but also accelerates adoption by the broader public.

C8. It appeared to this reviewer that both the three-year project duration and funding resources are less than ideal for developing a highly fatigue-resistant, cast steel crankshaft, because both materials and processing development are required.

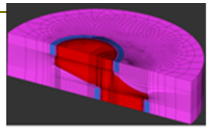
R8. Agree! However it is expected that this project could achieve a TRL-3 level demonstration and identify a path to implementation.

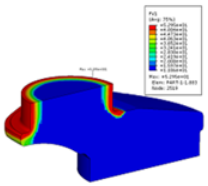
Collaboration – Project Team



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

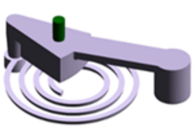




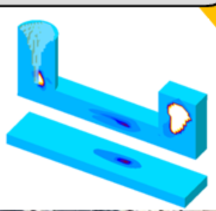
Hardness

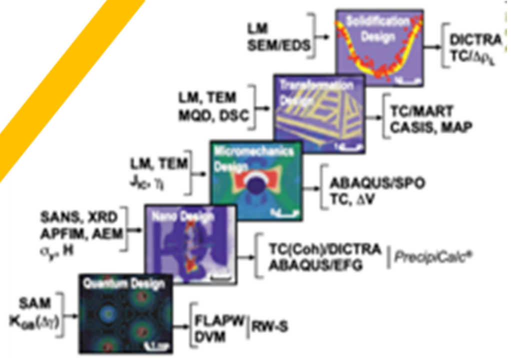
The University of Iowa
- Casting Process Development
- Experimental Casting Samples
- Castability Evaluation (Fluidity, Hot Tear, Porosity)

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



Fluidity Spiral Test Casting





Additional Collaborations
University of Northern Iowa
St. Louis Precision Casting Co.
Southern Cast Products
Element Materials Technology

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

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 being explored which maximize casting yield and minimize the contact area of the feeders.
  - Need to minimize post-processing steps requires to achieve required properties.
- Challenge to scale-up processing concepts for full-size prototyping within existing foundry base.
- Calibration of existing ICME models necessitates and iterative approach to optimize alloy design and casting processes.
- Limits of ICME tools for predicting critical material characteristics such as toughness.

Future Steps

- BP2 (FY'16): Optimize and Characterize the High Potential Alloy and Process Concepts, and apply an Integrated Modeling approach to Develop New Cast Crankshaft Design 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
  - Develop test casting pattern based on section of cast crankshaft design concepts
  - Optimize final alloy and process design concepts using new test casting and identify post-processing requirements to achieve local property requirements in critical locations of the crankshaft
- BP3 (FY'17): Produce, Evaluate and Validate Prototype Crankshaft, and Develop Comprehensive Cost Model
  - Optimize prototype crankshaft designs for new material and process
  - Create pattern and produce prototype crankshafts for CAT and GM designs
  - GM has initiated development of a cost model for cast steel crankshafts

Summary

- System Design chart established for the process-structure-property relationships to be investigated for meeting established critical customer requirements.
- Procured patterns for test bar and keel block test castings to support alloy development.
- Several alloy concepts designed using ICME approach.
- Sample castings produced for all alloy concepts and characterization complete for most alloys.
- High-potential alloy concepts capable of meeting core properties identified. Further optimization needed to achieve yield strength target.
- Several casting approaches explored using casting process simulation. Produced prototype crankshaft castings using horizontal gravity casting design. Achieved tensile strength and elongation requirements with a yield strength near the target.
- Vacuum Assisted Counter Gravity (VACG) system developed and initial trials were successfully completed. Ongoing experiments to quantify steel cleanliness and property improvements for VACG process.
- Additional new technologies being explored to optimize solidification and feeding.
- Work ongoing to calibrate ICME models and optimize alloy and process designs.
- Cast crankshaft design concepts being developed to incorporate into new test casting.