Development of High-Performance Cast Crankshafts

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Caterpillar Inc.

Vehicle Technologies – Annual Merit Review
June 10, 2015

Project ID: PM 065

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

MILESTONES	MEASURE	DATE	STATUS
Define prioritized crankshaft requirements	Performance, Cost	Apr '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	Mar '15	Complete
Laboratory sampling of alloy & processing concepts	~12 sample casting trials	Mar '15	Ongoing
Evaluation of laboratory sample castings (microstructure, properties, quality)	Casting quality, 850 MPa UTS, 580 MPa Yield, Initial Fatigue Assessment	Apr '15	(Go/No Go) Ongoing

- FY16 – Optimize and Characterize the High Potential Alloy and Process Concepts, Integrated Modeling to Develop New Prototype Crankshaft Design
- FY17 – Produce, Evaluate and Validate Prototype Crankshaft, and Develop Comprehensive Cost Model

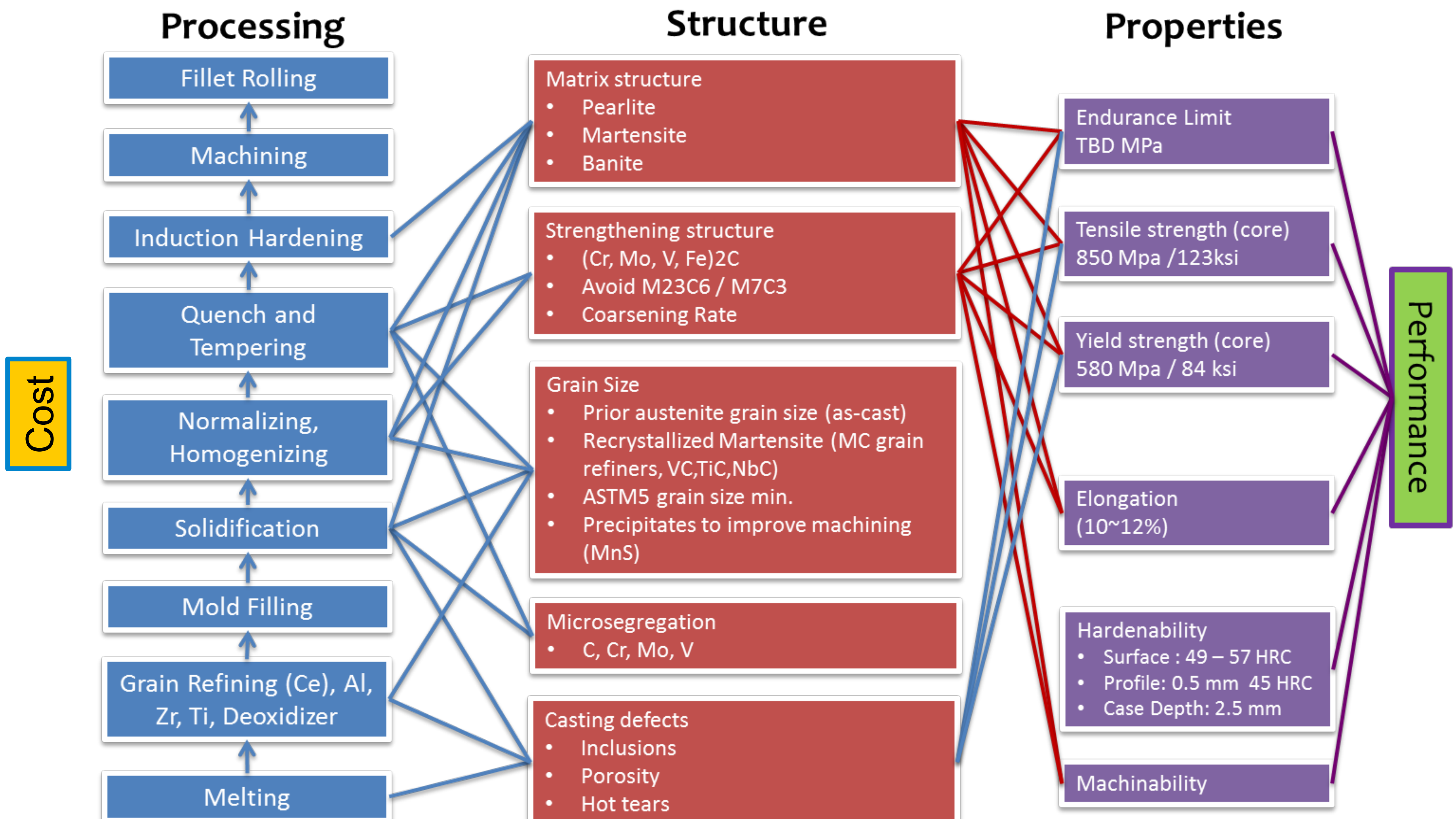
Approach

- 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.

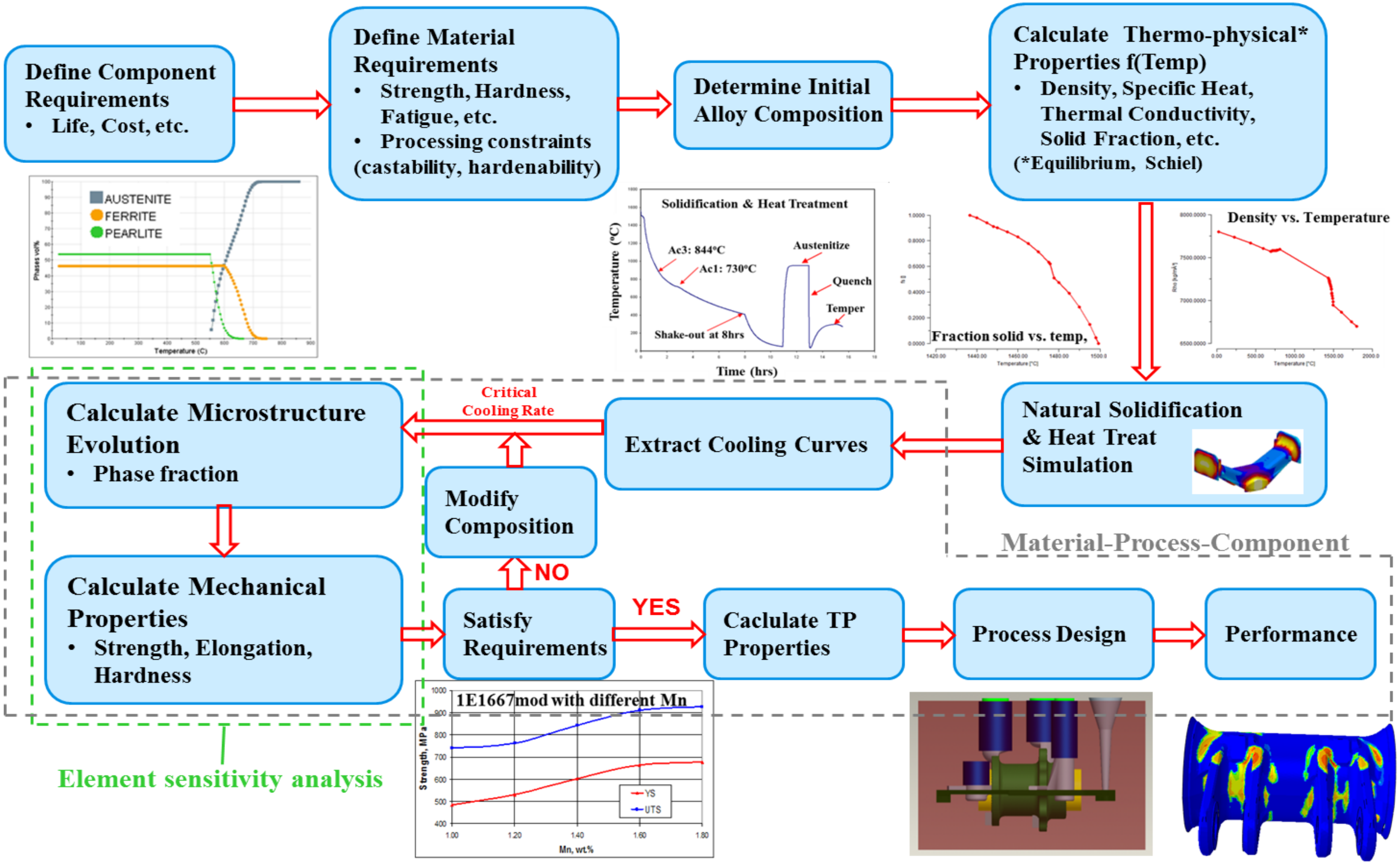
Approach

- 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.

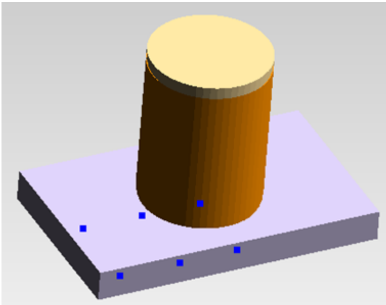
Approach – Systems Design Chart



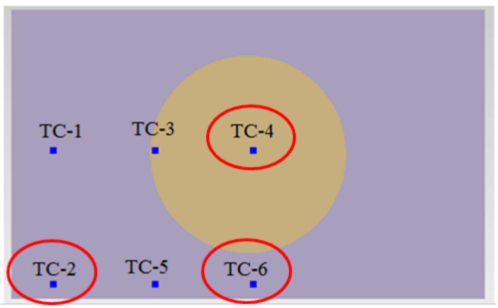
ICME - Materials Design Approach

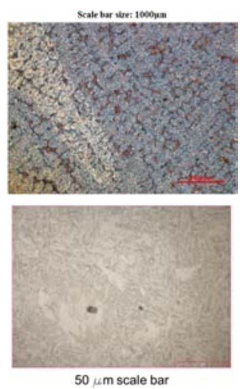


Initial Alloy Design (SAE 15V22mod) and ICME Validation



8" x 11" 1.25" Plate Casting





Bainitic Structure

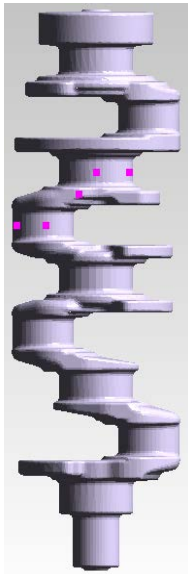
Mechanical properties of experimental weld-plate cast with SAE 15V22mod.

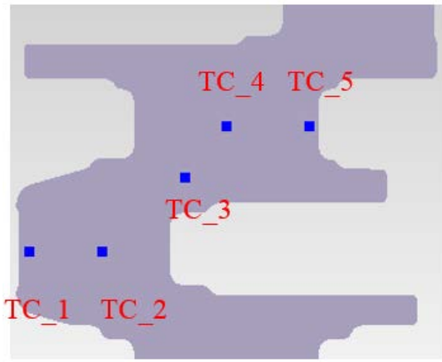
SAE15V22mod	1A	1B	1A	1B
Solution at 950°C	Normalization with air-cool	Normalization with fan-cool	2x Normalization with air-cool	2x Normalization with fan-cool
Tensile, MPa	853, 784	839, 801	833, 760	855, 800
Yield, MPa	581, 582	577, 586	575, 570	585, 591
Elongation, %	3, 2	3, 1.3	3.2, 2.1	3.1, 2.2
RA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

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

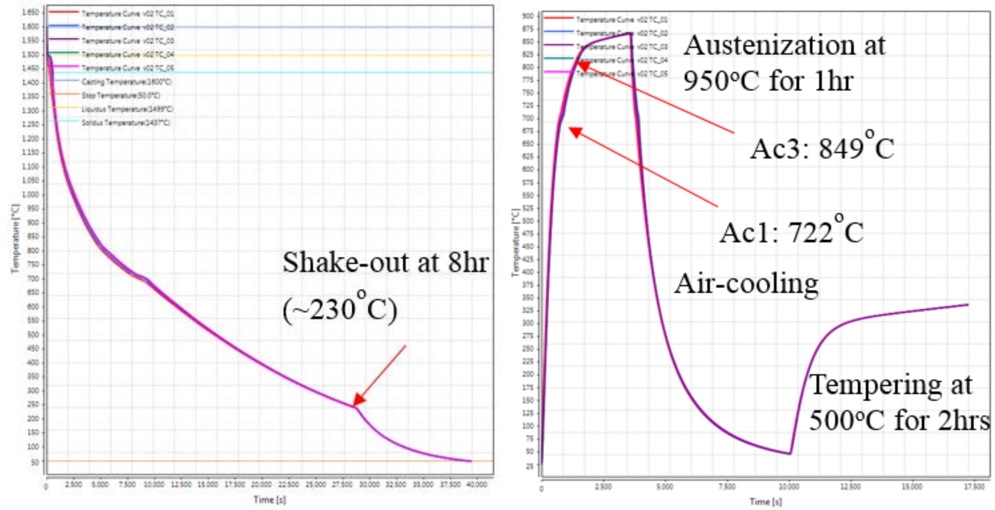
Location	Method & Cooling rate around 700°C	After normalization and tempering					
		Phases %		Properties			
		Bainite	Pearlite	YS MPa	UTS MPa	HRc/HV	El. %
TC_2 Corner	Magma 0.5°C/s	39	61	835	1098	264	8.9
	JMatPro 0.5°C/s	99	1	663	911	27.7Rc	-
TC_6 Side edge	Magma 0.4°C/s	29	71	739	1007	256	1.4
	JMatPro 0.4°C/s	98	2	654	901	27.2Rc	-
TC_4 Center	Magma 0.3°C/s	19	81	650	923	248	13.7
	JMatPro 0.3°C/s	95	4	643	888	26.5Rc	-
	Experiment 1A			581 582	853 784	26Rc 27Rc	3 2
As-cast	JMatPro 0.035°C/s	19	81	468	686	14.1Rc	-

Cooling Rates in Crankshaft



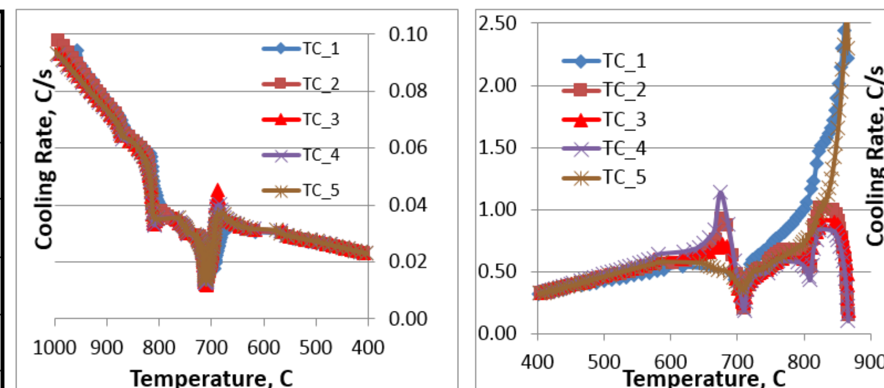


Thermocouple locations in CAT solid journal crankshaft



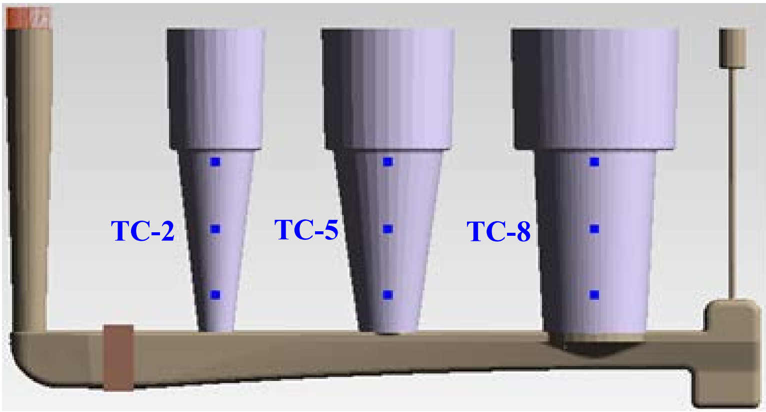
Temperature variation during solidification and heat treatment.

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

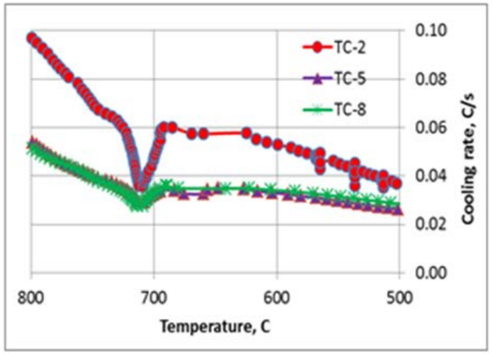


Cooling rate of thermal couples during solidification and heat treatment.

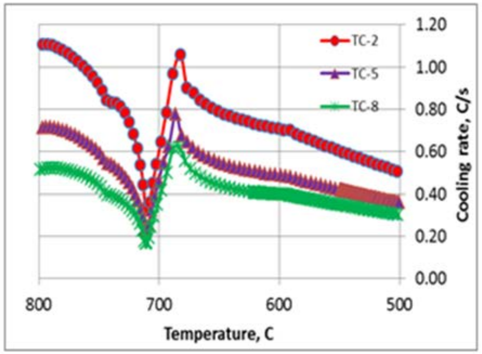
Test Bar Casting Design for Alloy Sampling



Geometry of the final test casting design.



(a). Solidification



(b). Heat treatment

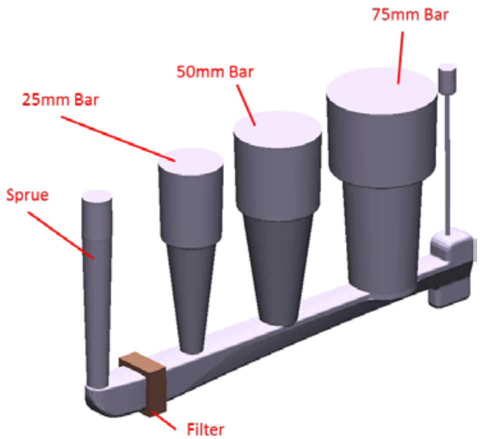
Cooling rates calculated from the temperature history during solidification and heat treatment simulations as measured by the virtual thermocouples at the center of the bars.

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

Test Bar Casting Design for Alloy Sampling



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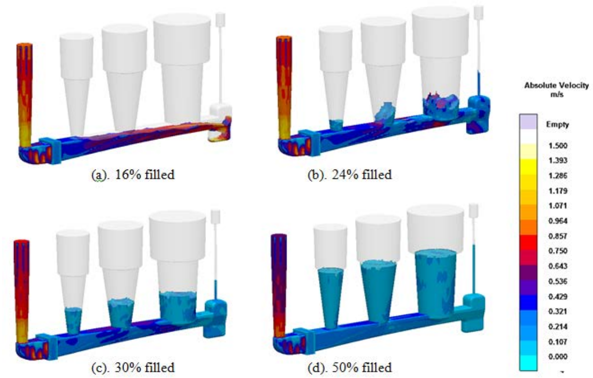
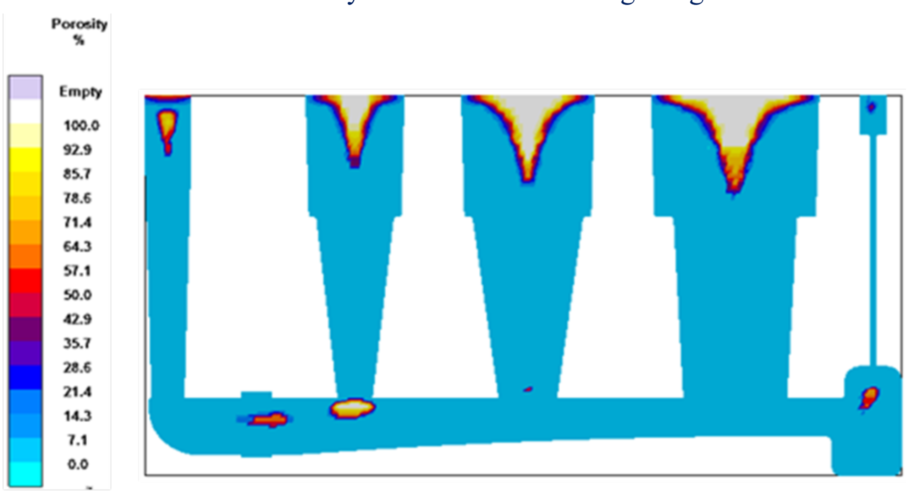
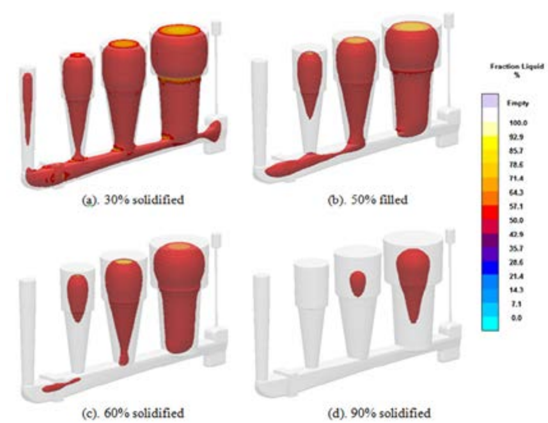


Liquid metal velocities at various stages during the filling process are shown. The filling velocities are mainly lower than the 1 m/s threshold used for optimal filling processes.



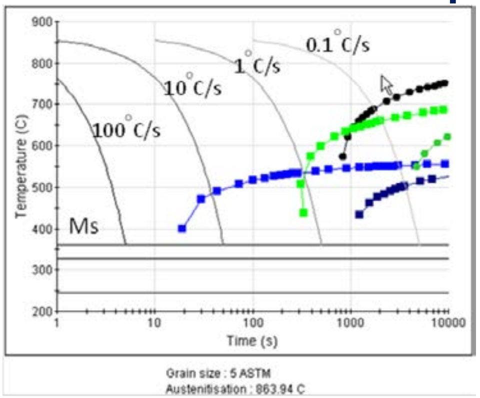
Predicted porosity in the test casting after solidification is complete. The risers pipe nicely and yield sound (porosity free) test bars.

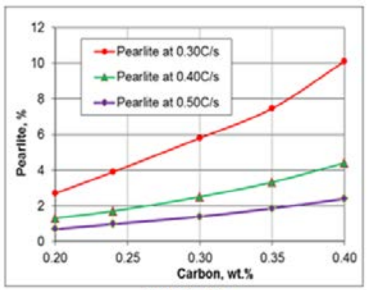


Evolution of liquid fraction (shown regions above 50%) during solidification.

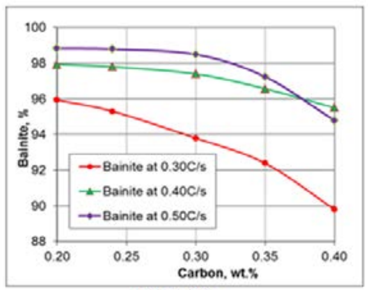
Alloy Design

➢ Optimize Austenite Decomposition

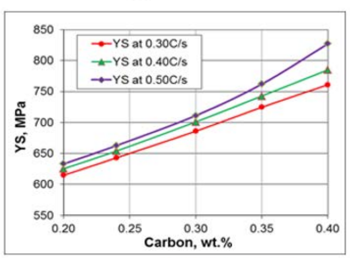




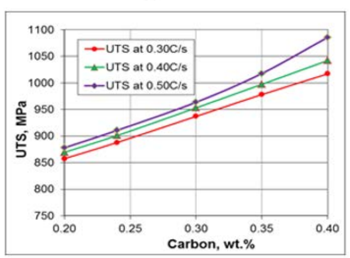
(a). Pearlite



(b). Bainite

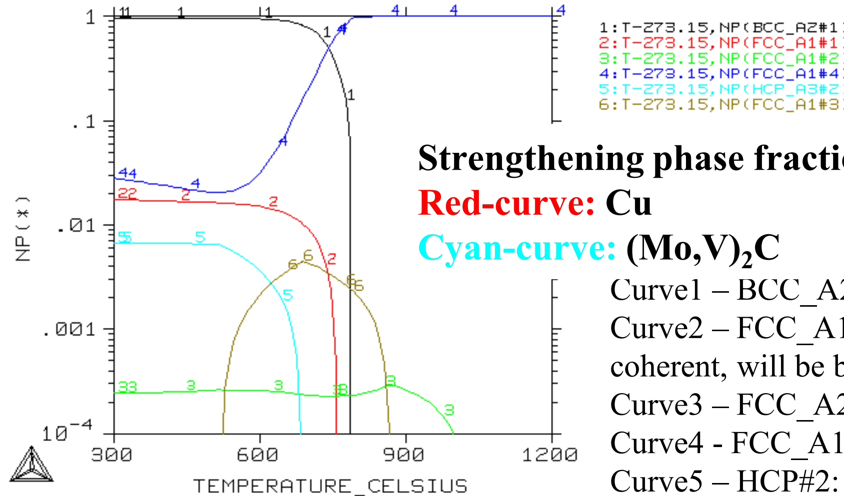


(a). Yield strength



(b). Tensile strength

➢ Precipitation Strengthening, Grain Refining



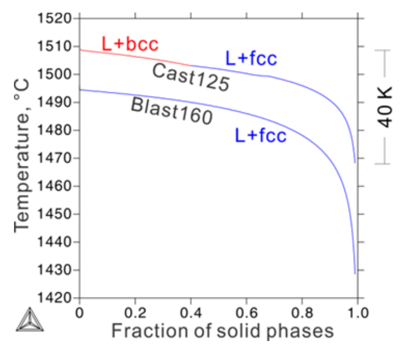
Strengthening phase fraction:

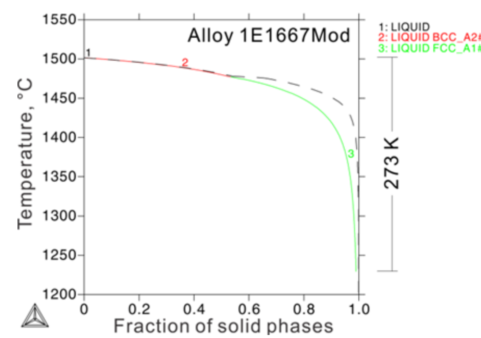
Red-curve: Cu

Cyan-curve: $(Mo,V)_2C$

Curve1 – BCC_A2#1: Ferrite
Curve2 – FCC_A1#1: Cu (if coherent, will be bcc Cu)
Curve3 – FCC_A2#2: NbC
Curve4 - FCC_A1#4: Austenite
Curve5 – HCP#2: (Mo,V)2C
Curve6 – FCC_A1#3: VC

➢ Optimize Solidification Freezing Range





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Preliminary Alloy Design Concepts

ICME predictions for microstructure phases and mechanical properties.

Steel	Designation	Phases B	Phases F	Phases P	Phases M	YS MPa	UTS MPa	HRc
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	NW-Cast1000	98.8	0.01	--	1.24	1024	1283	42.0--
11	NW-Cast700	86.2	13.8	--	--	724	977	30.8
12	GM 1536MV	--	19.2	80.8	--	531	761	19.2
13	4140	82.9	16.2	0.9	--	656 635*	903 972*	27.3 30*
14	3130							

Phases

B = Bainite

F = Ferrite

P = Pearlite

M = Martensite

Casting Trials

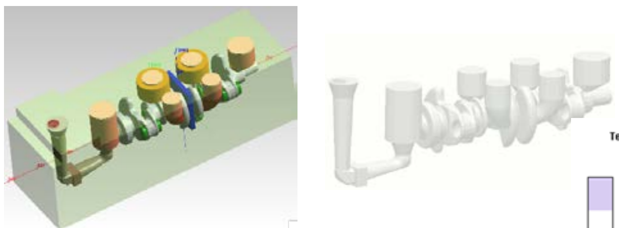
- GM procured wood pattern for test bar mold.
- University of Northern Iowa produced air-set sand molds and produced first sample castings.
- University of Iowa sectioned the castings and performed die-penetrant testing to check for macro and micro porosity
  - ✓ Excellent soundness achieved

- 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

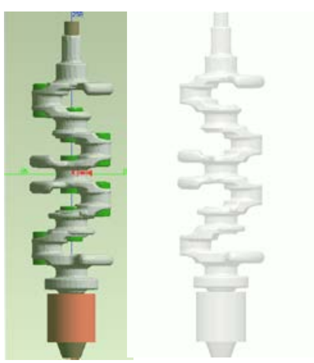
Preliminary Casting Process Exploration

Mold Filling

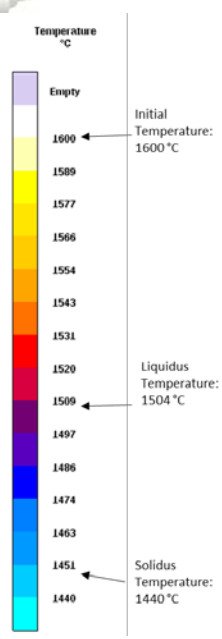
- Filling the crankshaft vertically leads to a much smoother flow.
- Gating the casting through the risers allows them to better feed the casting.



Horizontal -gated through one side

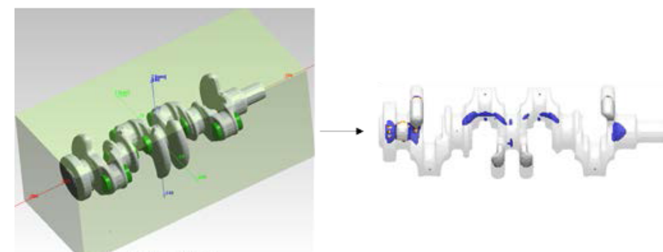


Vertical counter-gravity vacuum filled



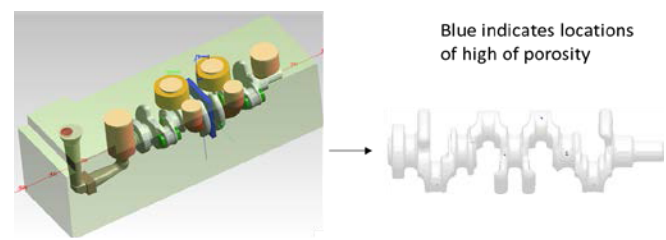
Solidification

- 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.



Geometry Porosity Prediction

Natural Solidification



Blue indicates locations of high of porosity

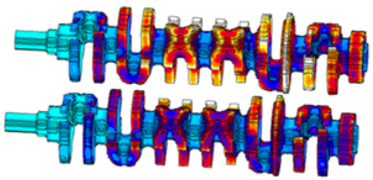
Geometry Porosity Prediction

Horizontally Cast General Motor's SGE Crankshaft

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®
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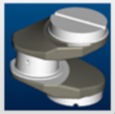
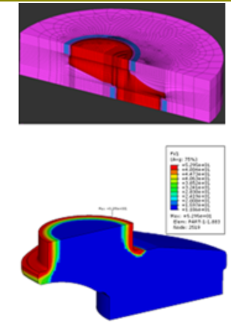
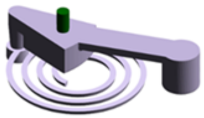




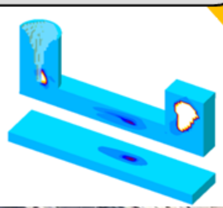
Hardness

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



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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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
- BP2 (FY'16): Optimize and Characterize the High Potential Alloy and Process Concepts, and Integrate Modeling to Develop New Prototype Crankshaft Design
  - 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.