Computational design and development of a new, lightweight cast alloy for advanced cylinder heads in high-efficiency, light-duty engines FOA 648-3a

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General Motors

6/19/2014

Project ID # **PM061**

Overview

Timeline

Start date – February 2013

End date – March 2017

Percent complete – 25%

Budget

- Total funding $5,145,073
  - DOE share $3,498,650
  - Contractor share $1,646,423
- Funding received in FY13
  - (02/13-09/13) $203,598
- Funding for FY14
  - (10/13-03/14) $247,462

Barriers and Targets

Changing ICE regimes

- Material property improvements required to accommodate increases in:
  - Peak cylinder pressure
  - Exhaust Temperature and Combustion Dome Temperature

Partners

- QuesTek Innovations LLC
- Northwestern University
- American Foundry Society
- Dr. Fred Major
- Dr. Geoffrey Sigworth (2013)
- Camanoe Associates
- MIT
- Project lead General Motors

Milestones 2013-2014

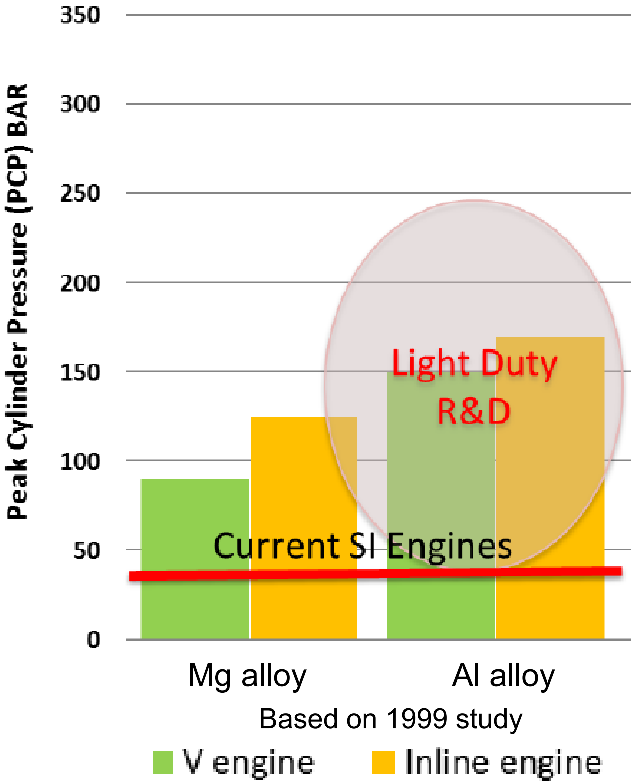
Date	Description	Status
03/27/2014	Task 2. Generate Alloy Concepts and Select Alloy Models Milestone 1: Alloy Requirement Matrix Established	Complete
03/25/2014	Task 2. Milestone 2: Alloy Concepts Generated	Complete
04/01/2014	Task 2. Milestone 3: Alloy Models Selected for Casting	Complete
04/30/2014	Task 3. Cast and Characterize Sub-scale Alloy Models Milestone 4: Sub-scale Castings Completed	Complete
07/31/2014	Task 3. Milestone 5: Sub-scale Data Development Completed	On-track
10/31/2014	Task 3. Milestone 6: Sub-scale Concepts and Models Validated	On-track
11/26/2014	Go/No Go Decision: Do models and experiments agree? Can models be used to move forward to continue to develop alloy?	

Relevance- Project Objectives

DOE FOA 648-3a Material Property Targets

Property	Cast Aluminum Baseline	Cast Non-Ferrous Alloy Targets	Key Properties
Tensile Strength (Ksi)	33 KSI	40 KSI	Key
Yield Strength (Ksi)	24 KSI	30 KSI	Key
Elongation (%)	3.5 %	3.5 %	
Shear Strength	26 KSI	30 KSI	
Endurance Limit	8.5 KSI	11 KSI	
Fluidity (Die Filling Capacity/Spiral Test)	Excellent	Excellent	Key
Hot Tearing Resistance	Excellent	Excellent	Key
High Temperature Performance	@ 250C	@ 300 C	
Tensile Strength (KSI)	7.5KSI @ 250 C	9.5 KSI @ 300 C	Key
Yield Strength (KSI)	5 KSI @ 250 C	6.5 KSI @ 300 C	Key
Elongation in 2"	20% @ 250 C	< 20% @ 300 C	

To meet energy efficiency targets, peak engine pressures and temperatures will greatly exceed current material properties and therefore needs to be improved



Based on 1999 study

Relevance – 2013 Objectives

Define and rank material properties necessary to meet project targets and optimal engine requirements

- Provide a framework for alloy development to meet objectives.

Research current alloys systems and develop concept models

Create castings to test stability of alloy concepts and validate model systems

Generate experimental data for input into concept models

Approach

Identify and rank most critical properties to meet high performance engine head requirements

– Milestone 1 Alloy Requirement Matrix

Use models and expert knowledge to identify and create alloy concepts that can contribute to the overall high temperature strength and fatigue requirements.

– Milestone 2, 3 Alloy Concept Generation and Selection

Produce castings for data generation, testing, and validation of models

– Milestone 4, 5 Subscale casting and data development

Validate alloy concepts by microstructural analysis, hardness testing and mechanical property testing

– Milestone 6 Subscale concept and model validation

Approach continued (2014-2017)

Develop Parametric Designs of New Alloys

- Develop alloy combinations from alloy concepts, introduce elements for increased high temperature stability, ductility, fatigue strength and castability.
- Milestones 7-9 Parametric alloy generation, casting, testing and model validation.

Create Final Embodiment of New alloy

- Milestone 10-14 Computational design, lab scale castings and component casting trial, recyclability analysis, final alloy testing and model validation

Develop alloy and component production cost models

- Milestone 15 Final cost models.

Approach: Material Requirement Matrix (Milestone 1)

Phase I Physical Properties

Control Factors:
- Coefficient Thermal Expansion
- Thermal Conductivity
- Young's Modulus
- Specific Heat
- Density

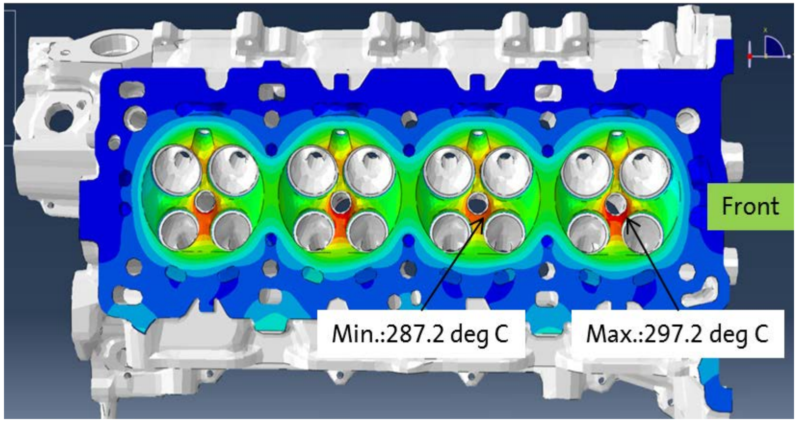
System

Cylinder Head
GETC FEA

Noise Factors:
- Coolant Temperature
- Peak Cylinder Pressure
- Combustion Temperature
- Architecture

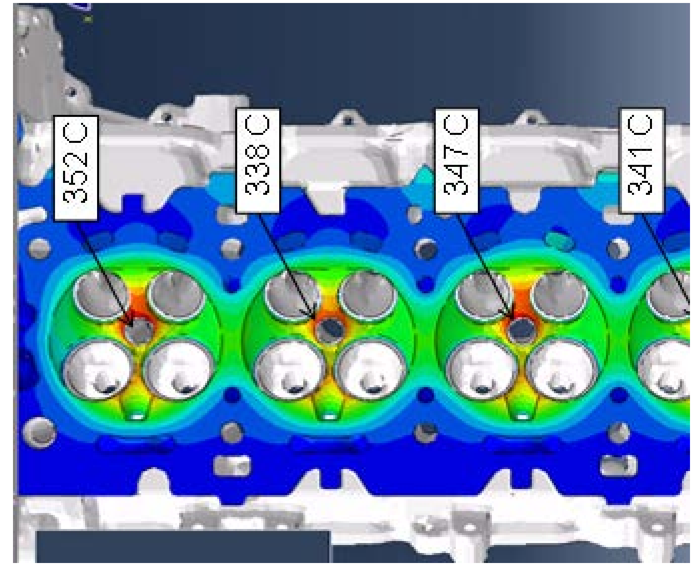
Output
- Flatness
- Mean Stress
- Alternating Stress
- Temperature Distribution (from GED)

Symptoms:
- Temperature increase in aluminum



Apply Design for Six Sigma (DFSS) methodology to establish the most critical material properties to meet engine requirements

Approach: Material Requirement Matrix (Milestone 1)



Phase II Mechanical Properties and Thermal Conductivity

Control Factors:
- Ultimate Tensile Strength
- Cyclic Strength Coefficient
- Cyclic Strain Hardening Exponent
- Low Cycle Fatigue Strength
- High Cycle Fatigue Strength
- Thermal Conductivity

System

Cylinder Head
FEA, GED and GETC

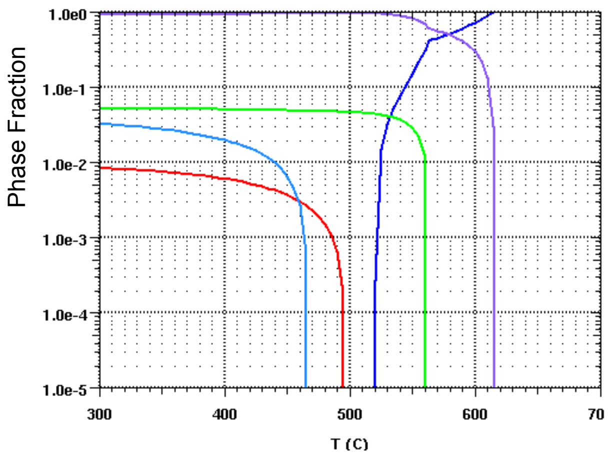
Output
- Temperature Distribution
- Mean Stress
- Alternating Stress
- Safety Factor

Noise Factors:
- Coolant Temperature
- Peak Cylinder Pressure
- Combustion Temperature

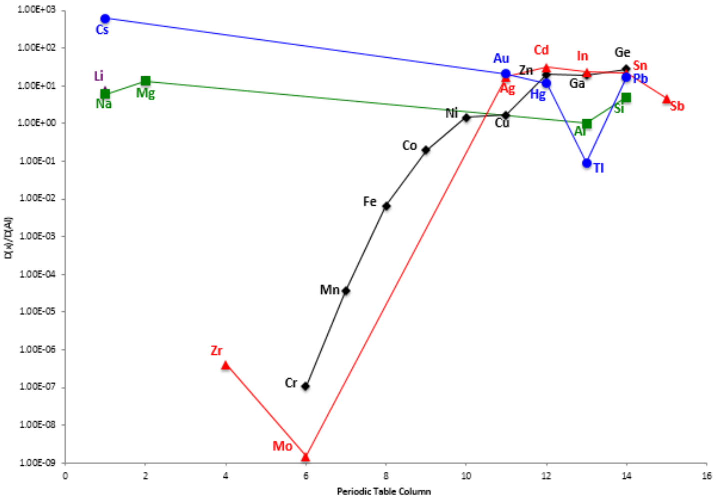
Symptoms:
- Temperature increase in aluminum

Approach: Alloy Concepts
Milestones 2-6

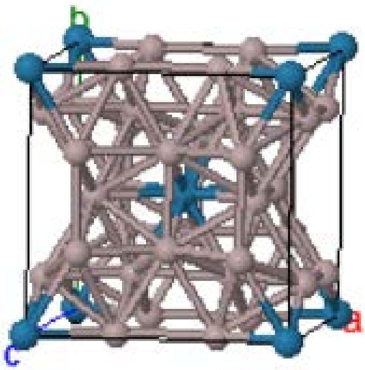
Scheil simulation of concept alloy solidification



Calculate diffusivity of Elements



Identify Alloy structures by Density Functional Theory



Technical Accomplishments
Material Requirement Matrix

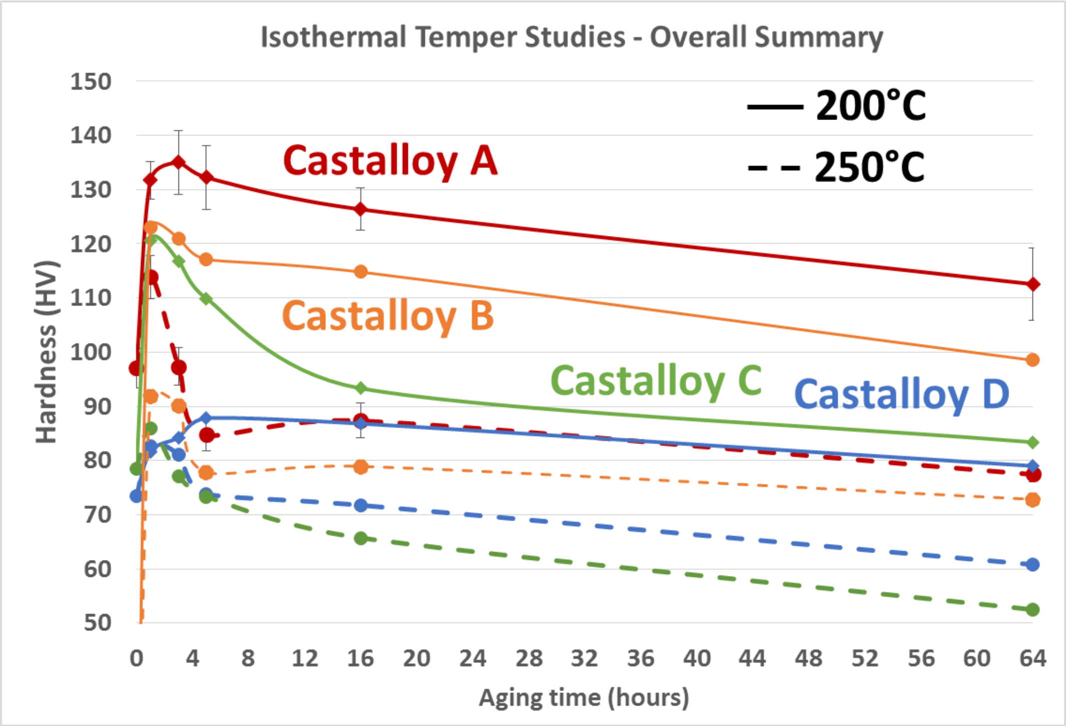
Property	Temperature	Targets		
		DOE Cast Lightweight Alloy	High Temp Alloy Requirements	Rank
Tensile Strength (MPa)	25 C	275.8	300	19
	150 C	N/A	280	15
	250 C	N/A	100	17
	300 C	65.5	65.5	21
Yield Strength (MPa)	25 C	206.8	210	13
	150 C	N/A	200	14
	250 C	N/A	75	12
	300 C	44.8	45	20
Plastic Elongation (%)	25 C	3.5	≥ 3.5	11
	300 C	< 20	N/A	22
Fatigue Strength at 10^7 cycles (MPa)	25 C	75.8	N/A	23
	150 C	N/A	70	7
	250 C	N/A	50	9
Fatigue Strength at 10^4 cycles (MPa)	150 C	N/A	140	8
	250 C	N/A	60	10
Density (g/cm^3)	25 C	< 6.4	< 3.0	5
Shear Strength	25 C	206.8	206.8	24
Thermal Conductivity (mw / mm-C)	150 C	N/A	202	6
Coefficient of Thermal Expansion (mm / mm-C)	150 C	N/A	2.20E-05	16
Fluidity (Die Filling Capacity / Spiral Test)		Excellent	≥ 319	3
Hot Tearing Resistance		Excellent	≥ 319	4
Manufacturing cost including alloy and processing		< 110% Baseline	< 110% Baseline	2
Corrosion resistance			GMW15272 for Underhood Vehicle Requirements	18
Recyclability			Must comply with GMW3059 GMW3116 Recyclability / Recoverability	1

GM

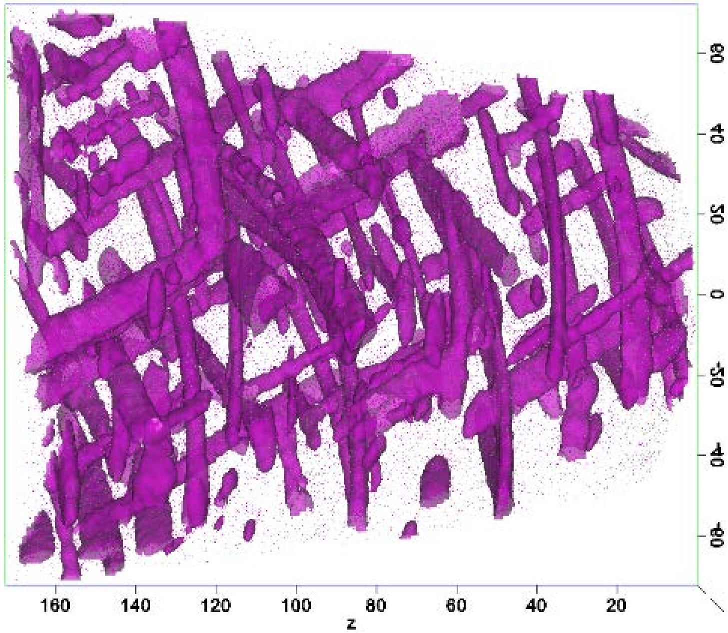
Technical Accomplishments
Alloy Concepts

- Seven alloy concepts have been created.
  - Four alloy concepts have been modelled in a thermodynamic framework, and heat treatment processing conditions identified.
  - Three alloy concepts have been identified by Density Functional Theory.
- Metallurgical buttons have been cast for each of the alloy concepts.
- Hardness studies at 200 C and 250 C give indications of the high temperature stability of the concepts.
- Microstructural analysis including local electron atom probe (LEAP) identify structures and can measure the coarsening kinetics of phases.

Technical Accomplishments



Hardness measurements on chemical buttons test temperature stability of four alloy concept models



Local electron atom probe (LEAP) analysis of phase precipitation

Collaboration and Coordination

General Motors – Principle Investigator

- Project administration, casting simulation, casting experiments, mechanical properties, microstructural evaluation

QuesTek Innovations LLC – Industrial sub-partner

- Industrial Sub-partner
- ICME calculations – thermodynamics, kinetics, DFT alloy generation, alloy concept generation, parametric and final alloy designs, heat treatment process recommendations

Northwestern University – University sub-partner

- DFT alloy generation, Phase Field modelling of microstructure, experimental validation - Optical, SEM,TEM, LEAP

Fred Major, Tom Prucha (AFS), Geoffrey Sigworth (2013 only) – Industrial sub-partners

- Technical advisors

Camanoe Associates – Industrial sub-partner

- Process Based Cost Modelling

MIT – University sub-partner

- Recyclability Analysis

Remaining Challenges and Barriers

Find chemical combinations that are able to hold properties up to 300 C.

Maintain castability requirements such as resistance to hot tearing, fluidity, and good shrinkage characteristics.

Develop complete alloy systems that are capable of meeting project targets for high temperature cylinder applications with excellent castability and low cost.

Future work in 2014

Validate alloy concept models through microstructural analysis and mechanical tests

Develop parametric alloy systems from the validated alloy concepts.

Introduce alternate chemical species to further improve high temperature stability, ductility, fatigue properties and castability.

Begin casting and test parametric alloys.

Summary

Objective: Develop a non ferrous alloy capable of withstanding the temperature and pressures associated with advanced combustion engines

Approach: (1)Determine key material properties required for engine designs. (2) Identify alloy sub-structures potentially capable of meeting requirements - through computational simulation, experimental analysis, and mechanical testing; and (3) validate and utilize ICME models to rapidly design and optimize alloy(s) to meet all requirements.

Accomplishments: Material Design Matrix and 7 alloy concepts have been created, modeled, cast, and are being tested.

Collaborations: GM, QuesTek Innovations, Northwestern University, Fred Major, AFS, MIT, and Camanoe Associates

Future Work: Model validation, parametric alloy design development, casting, microstructural analysis and thermo-mechanical testing.