

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Reference herein to any social initiative (including but not limited to Diversity, Equity, and Inclusion (DEI); Community Benefits Plans (CBP); Justice 40; etc.) is made by the Author independent of any current requirement by the United States Government and does not constitute or imply endorsement, recommendation, or support by the United States Government or any agency thereof.



Final Technical Report

Federal Agency and Organization Element to Which Report is Submitted	Department of Energy – National Energy Technology Laboratory (NETL)
Federal Grant Number	DE-EE0008877
Project Title	Low-Mass and High-Efficiency Engine for Medium-Duty Truck Applications
Principal Investigator Name, Title, Contact Information	Dr. Qigui Wang GM Technical Fellow General Motors LLC 30003 Fisher Brothers Road Warren, MI 48093 Tel: (248) 762-6332 Email: qigui.wang@gm.com
Submitting Official Name, Title, Contact Information	Sean C. Campbell Government Contracts Manager General Motors LLC 29755 Louis Chevrolet Road Warren, MI 48093 Tel: (248) 296-4128 Email: sean.c.campbell@gm.com
Submission Date	8/28/2025
DUNS Number	076336064
Recipient Organization (associated with DUNS Number)	General Motors LLC 895 Joslyn Rd Pontiac, MI 48340-2920
Project /Grant Period	10/1/2019 to 09/30/2024
Reporting Period End Date	09/30/2024
Report Term or Frequency	Final

Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

1. Executive Summary

Today's transportation vehicle customers demand manufacturers to produce engines with lower weight and improved efficiency to reduce fuel consumption, emissions, and costs associated with vehicle use, while maintaining or even increasing engine performance. Developing the next generation of high-efficiency, very-low-emission internal-combustion engines requires a combination of new combustion strategies, advanced materials, and new materials-processing techniques to further increase engine efficiency and reduce weight. The expected national economic, environmental, and energy-security benefits of these next-generation engines and materials would be significant because most vehicles sold over the next two decades will still include an internal combustion engine. The availability of advanced light-weight engine designs will provide a significant positive impact on the fuel efficiency, environmental impact, and competitiveness of the U.S. auto industry [1].

This collaborative multi-year advanced engine technology project summarized in the report is to develop low mass and high efficiency medium-duty truck engine. The project was proposed as a large-scale engine design and demonstration enabled by an advanced materials and manufacturing development program, with a comprehensive plan spanning a period of four years (two phases). The project began with engine architecture design and analysis activity, advanced materials and manufacturing process development and down selection. It culminated in an engine test cell evaluation with optimal materials and manufacturing solutions supporting final vehicle simulation. The final engine tests verified engine weight reduction and performance to the project objectives. [1] Figure 1 outlines the overall project strategy and work streams.

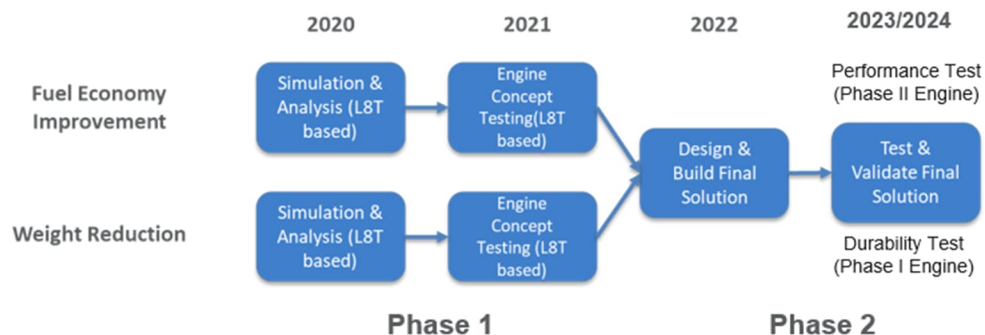


Figure 1. Low mass and high efficiency medium-duty truck engine overall development strategy and work streams. Source: GM

Several combustion concepts/technologies were investigated and down selected, including enhanced mixture motion and rapid combustion, increased compression ratio, combustion charge dilution through cooled exhaust gas recirculation (EGR), and ultra-high pressure fuel injection. High-strength and heat-resistant materials were developed and incorporated with novel metal casting and additive manufacturing (AM) processes to produce highly durable engine structures to maximize performance of the materials and systems with minimum mass and cost. The opportunity to include advanced materials and manufacturing in conjunction with

high-potential combustion system and engine technologies also created the chance to revisit the most appropriate engine specification to realize the desired efficiencies while reducing engine weight cost-effectively. A point of focus was the most cost-effective solution to promote wide market acceptance using the right materials in the right place and right process for the right parts. Single- and multi-material solutions for key engine components were investigated. Integrated computational materials engineering (ICME), [2][3] and computer-aided engineering (CAE) tools were fully utilized to accelerate both engine design and material and manufacturing solution development and optimization.

A new low-mass and high-efficiency (LMHE) medium-duty truck engine was developed in this project to address the technological and societal need by offering an unprecedented combination of lightweight and performance attributes that are superior to all known medium- and heavy-duty engines. The LMHE V8 medium-duty truck engine, Figure 2, is powered with a unique combination of several key features including 2-spark plugs per cylinder, ultra-high pressure direct injection, active charge motion control valve, high pressure-cooled exhaust gas recirculation (EGR), and split cooling with valve bridge drilling that have significantly enhanced combustion charge EGR dilution tolerance and mixture motion and rapid combustion, increased compression ratio, and improved fuel economy by 10.44% compared with the L96 baseline engine as defined in FOA (funding of announcement). [1]

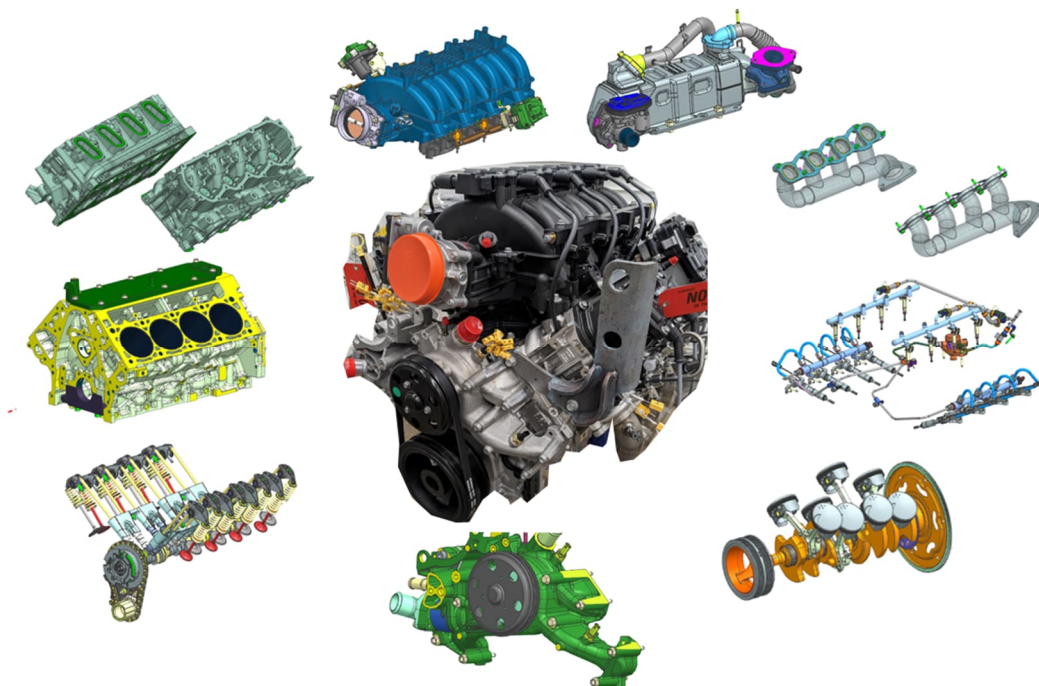


Figure 2. The newly developed LMHE medium-duty truck engine and key feature components.

Source: GM

The new LMHE engine contains several advanced material lightweight solutions, including high strength cast aluminum blocks and heads made of low-pressure precision sand cast ORNL AlCuMnZr (ACMZ) alloy and GM high-Q (AlSiMgCu) alloy, GM high strength cast steel and cast-iron crankshafts, ORNL additive manufactured high temperature AlCeNiMnZr (Alu-3D) pistons,

high strength austempered ductile iron camshafts, high value cast steel exhaust manifolds, etc. The mechanical properties of those materials solutions showed significant improvement over the baseline materials. The overall new engine weighs 200Kg, >17.7% lighter over the L96 baseline engine as defined in FOA, [1] while engine displacement is increased from 6L to 6.6L, Table 1.

Table 1. Mass comparison of key components of the new engine and baseline engines

DOE FOA Baseline Engine		Phase 2 - Validation & Demonstration
Key Parts	L96 6.0L V8 Engine	DOE New 6.6L V8 Engine
Engine Block	Cast Iron	Cast Al (saving mass by 56%)
Cylinder Head	Cast Al	Cast Al (increasing mass by 31% due to new combustion)
Crankshaft	Ductile Iron	Cast Steel (saving mass by 1%) Cast Iron (saving mass by 3%)
Camshaft:	Hollow Steel	Austempered Ductile Iron (ADI, saving mass by 9%)
Piston (Each)	Cast Al	AM Al (saving mass by 3%)
Total Engine Weight	243.1	200.0
Overall Engine Mass Reduction		
		-17.7%

The advanced materials and manufacturing solutions have not only reduced engine weight but also enhanced the engine performance and durability. The high temperature cast aluminum alloys (ORNL's ACMZ and GM's High Q) have improved the head and block high temperature properties by at least 20%. The novel casting processes along with the newly developed GM high strength high modulus cast steel and iron alloys have produced the hollow cast steel/iron crankshaft and camshaft that are equal or better than forged steel ones. In particular, the high temperature additively manufacturable ORNL's AlCeNiMnZr alloy was printed into high performance lightweight pistons which showed the fatigue limit at 300°C being improved by at least 50% as compared with the commercial high-performance cast aluminum piston alloys. With the integration of the advanced materials and manufacturing solutions, the new LMHE engine has passed the required durability tests.

2. Project Objective

The objective of this collaborative project between General Motors (GM), Oak Ridge National Lab (ORNL), The Ohio State University (OSU), Michigan Technological University (MTU), and ECK Industries Inc (ECK) is to develop a low mass and high efficiency (LMHE) medium duty truck engine equipped with advanced materials and combustion technologies capable of ≥10% fuel efficiency improvement and ≥15% engine weight reduction when compared to the 2015MY GM L96 VORTEC 6.0L V8 engine compliant with applicable EPA (Environmental Protection Agency) emission standards with performance demonstrated via simulation coupled with engine dynamometer test.

3. Project Technical Scope Summary

This collaborative project was proposed as a large-scale engine design and demonstration enabled by advanced combustion and materials technologies. The project was planned for four budget periods (two phases) separated by distinct go/no-go decision points. The proposed categories are:

PHASE 1 – Technology Research and Development

Budget Period 1: Potential engine architecture designs and initial verification coupled with advanced technologies of combustion system and materials and manufacturing concepts for weight-saving and performance improvement through simulations and development

Budget Period 2: Evaluation of proposed individual technology concepts using current equivalent architecture GM development engine(s) in conjunction with advanced materials and manufacturing process development of high value weight reduction and performance improvement strategies for components and sub-systems

PHASE 2 – Technology Validation and Demonstration

Budget Period 3: Design, procurement and manufacturing, assembly, and initial development testing of proposed medium-duty truck engine capable of meeting requirements

Budget Period 4: Demonstration of performance and weight reduction to requirements using engine test cell and vehicle simulation.

A total of three key go/no-go program decision points were dispersed throughout the four-year duration. The first decision point (end of Budget Period 1) was achieved by using simulation and evaluation of potential engine architecture and combustion and materials technology to determine the primary engine architecture, and to select potential technologies for further work. Details about the design concepts and computational simulation and evaluation are discussed in Section 4 – Overview of LMHE Engine Combustion and Materials Development Concepts and Section 5 - Advanced LMHE Engine Technology Development, respectively.

The second decision point (end of Budget Period 2) was achieved by assessing the outcome of proof-of-concept testing of individual technologies and various technology combinations in hardware with existing GM development engines. This enabled good correlation of simulation results with test data while allowing investigation of technology concept combinations that are not easily simulated. This decision point marked a key gate in determining the capability and confidence level of the identified engine architecture and advanced technologies of combustion, materials, and manufacturing solutions to meet the project objectives. The project technologies had demonstrated the capability of meeting the objectives with an appropriate confidence level. As a result, the work continued in the design, manufacture, procurement, and assembly of a new multi-cylinder engine to be built and installed in dynamometer facilities for testing. Details about the proof-of-concept testing and evaluation are discussed in Section 5 – Advanced LMHE Engine Technology Development.

The third critical go/no-go decision point (end of Budget Period 3) was achieved with the promising results of preliminary engine development testing incorporating the new materials and manufacturing process solutions and combining combustion optimization methods. These engine test results demonstrated the capability of the new concepts and technologies to meet or exceed the project targets. As a result, the engine and manufacturing processes continued to reach

successful conclusion. Details about the preliminary and final engine performance and durability tests are discussed in Section 6 - Advanced LMHE Engine Technology Validation.

4. Overview of LMHE Engine Combustion and Materials Development Concepts

In today's medium and heavy-duty truck engines, application of advanced combustion and materials technologies is lagging light duty engines. Some proven light duty engine technologies have not been combined strategically and developed to meet the cost and durability requirements of the medium duty truck market. Examples of legacy technology in medium duty truck engines that could be greatly improved include PFI (port fuel injection), OHV (overhead valve) pushrod 2 valve/cylinder combustion system, iron block, aluminum head, and VVT (variable valve timing).

This collaborative project symbiotically integrated advanced combustion technologies with innovative material and manufacturing process developments to assure that the higher thermal loads and cylinder pressures associated with efficiency gains can be practically implemented and leveraged by mass reduction. High temperature aluminum alloys and high strength cast ferrous alloys, multi-materials design, advanced metal casting, overcasting, and additive manufacturing technologies were developed and evaluated to produce highly durable engine structures to maximize performance with minimum mass and cost.

4.1 LMHE Engine Advanced Combustion Development Concepts

Several stoichiometric combustion related technology categories were selected for investigation and down-selection within the project including 1) basic combustion system specification and layout, 2) cylinder deactivation strategies, 3) advanced fuel systems, 4) advanced ignition systems, 5) advanced dilution systems, 6) advanced Atkinson or Miller cycle valve event strategies, and 7) advanced variable induction system strategies. These candidate technologies are collectively referred to as "advanced combustion technologies" in later sections.

A large displacement, normally aspirated concept, and a small displacement with boosted concepts were initially developed and evaluated. This evaluation was concluded with the selection of the engine architecture to be optimized in support of meeting the project objectives. The initial combustion system layout was driven by the performance and fuel economy requirements of the selected engine architecture. These requirements had evolved to specification of compression ratio, desired surface to volume ratio, dilution tolerance, desired charge motion, spark plug location, DI fuel injector location and proximity to spark plug, and intake port locations for advanced Port Fuel Injection (PFI) investigations. Cylinder deactivation strategies are very effective at increasing fuel economy. In this project, the benefits of specifying such a system were assessed relative to the desired medium duty truck engine high usage operating region.

Advanced direct cylinder fuel injection (DI) systems interacted with the spark plug to create turbulence and favorable mixture conditions at ignition. This project focused on “ultra” high-pressure DI gasoline fuel injectors (>750 Bar) and the capability to execute late fuel injection events creating extensive turbulence just prior to ignition. This strategy had developed the potential to increase compression ratio by mitigating knock and stochastic pre-ignition tendencies. The potential of high-pressure intake port fuel injection (PFI) was also investigated with open valve injection to reduce particulate.

Use of advanced ignition systems to increase dilution tolerance in stoichiometric combustion systems has been explored. Historically, only conventional inductive ignition systems have achieved the desired average ignition energy, but this was neither efficient nor durable. In this project, an advanced ignition system that allows the target ignition energy to be delivered with a secondary current that resolves the historical issues was selected. This system allows proper evaluation of the proposed advanced combustion technologies.

Intake charge dilution with EGR (exhaust gas recirculation) is a key enabler of improved stoichiometric combustion system performance. However, this approach can cause ignition delay and extended combustion durations which reduce efficiency and may cause poor combustion stability. As noted, advanced ignition systems have shown to resolve some of the ignitability challenges, including the presence of high charge motion. In addition, combustion performance with EGR dilution can be improved by supplying EGR from a dedicated cylinder operating with a rich air-fuel mixture. The exhaust constituents in this recirculated exhaust have shown to significantly accelerate combustion speed as demonstrated by GM in the DOE funded project “The Application of High Energy Ignition and Boosting/Mixing Technology to Increase Fuel Economy in Spark Ignition Gasoline Engines by Increasing EGR Dilution Capability” (DE-EE0005654).

Advanced Atkinson or Miller cycle valve event strategies were evaluated and applied in this project to improve extended expansion ratio and engine efficiency. Traditionally, the expansion ratio has been limited because it is geometrically linked to an engine’s knock limited compression ratio. Late and early intake valve closing (LIVC and EIVC respectively) event strategies have shown to effectively reduce the geometric compression ratio while maintaining the efficiency benefits of the high geometric expansion ratio. Advanced LIVC or EIVC valve event strategy was investigated and enhanced by the investigation of variable intake and exhaust valve lift and duration capabilities. The use of intake and exhaust cam phasing in conjunction with variable intake and exhaust valve lift and duration enables a large scale, independent variation of the effective compression and exhaust events to support optimal engine efficiency over a wide variety of engine operating points.

Advanced variable induction system strategies were applied to develop an appropriate combustion speed for best efficiency and performance while simultaneously achieving acceptable engine noise, vibration, and harshness (NVH). Often, it’s possible to achieve an acceptable combustion speed at all operating points by careful detail design of the intake port and combustion system to optimize charge motion. However, certain technology combinations

require a variable charge motion device. The induction system is also crucial to full load engine operating performance. Some of the proposed technology solutions may have a negative impact on full load performance. In this instance, using a variable induction system to alter the effective length of the intake runners might be required to meet performance objectives. An appropriate solution would be developed and implemented if such devices are required to meet objectives.

4.2 LMHE Engine Advanced Materials and Manufacturing Development Concepts

Increasing engine power and efficiency requires more aggressive thermal cycles which push cylinder pressure and temperature to the engine materials' operational limits. Reducing engine weight demands thinner wall design and lighter materials. These conflicting demands exceed the current material properties of drivetrain parts such as the cylinder head and block, pistons, and crankshaft. For cylinder heads, the more severe operating conditions require significant improvements in high temperature fatigue and creep resistance, especially in thin-walled areas. Simply improving high temperature tensile strength is not enough. Improvements in casting defect populations as well as high cycle, low cycle, and thermomechanical fatigue resistance are required. In aluminum castings, the fatigue strength can be increased 50~100% when the defect sizes are reduced below a critical size ($\sim 50\mu\text{m}$). [4-6] The size and population of multiscale defects depend upon not only alloy composition and melt quality, but also upon the casting process. Recently, there has been significant progress in developing high temperature cast aluminum alloys, however, despite improved high temperature tensile strength, the fatigue properties of the new alloys remain limited by the defects created by the traditional casting processes. [7] Therefore, one of the key objectives in this project is to develop novel casting processes to reduce and eliminate casting defects.

A significant mass reduction opportunity would be replacing the iron block with cast aluminum (-113 lbs including the use of cast iron liners, -19% for the engine and -2% for the vehicle assuming no changes to other parts). The key barriers to this are the lower stiffness of the cast aluminum, and the inferior high temperature properties of common aluminum casting alloys such as 319T7. These barriers can be overcome by local materials reinforcement strategies such as adding local chills and overcasting a cast iron insert or metal matrix composite. Another potential solution is to adapt the high temperature cast Al alloys and defect reduction strategies developed for cylinder heads to the block. Hollow crankshafts offer another opportunity to reduce mass. The crankshaft for the baseline engine was made of medium grade nodular iron. To compensate for the reduced modulus in the single Al material block, high stiffness crankshaft materials like cast steel or high-grade nodular iron can improve engine rigidity and reduce NVH (noise, vibration, and harshness).

Cast Al alloys to meet the high temperature and high strength requirements associated with the improved combustion efficiency need to be developed and applied for cylinder head, engine block and piston in this project. ORNL team recently developed a new aluminum Al-Cu alloy family with microalloying element additions of Manganese and Zirconium, termed ACMZ (AlCuMnZr) alloys through previous DOE project. ACMZ alloys were developed to address the

challenging fabrication and performance requirements of an automotive cylinder head in present and future higher efficiency engines. GM has also developed a cast aluminum Q alloy through DOE project (DE-EE0006082) for cylinder head applications. Both alloys provide a nearly 50-100°C advantage in tensile properties compared to existing cast automotive aluminum alloys. In addition, the compositions of ACMZ variants and GM Q (Al-Si-Cu-Mg) based alloys are further optimized and applied in cast aluminum engine block applications.

High strength and high modulus cast iron and steel would be evaluated for the crankshaft which is the second heaviest component in the V8 engine. A new nodular iron crankshaft with 10-15% higher Young's modulus and 30-50% increase in UTS (ultimate tensile strength) over the baseline is envisioned. These improvements would result from optimization of nodular size (type 6~7), nodular count (>200/mm²), and matrix strength (>95% pearlite). GM has developed a new cast steel alloy for the crankshaft which would be further optimized and tested in this project. [8] The outcome of the work would be an optimum engineering solution for the crankshaft based on both performance and cost.

Advanced manufacturing processes are developed and applied in the project to produce high quality key engine components such as head, block, piston, and crankshaft with minimum defects. Metal casting is one of the most cost-effective manufacturing processes for complex engine components. In this project, novel casting processes like pressure-assisted precision sand casting processes (PAPSC [9]) are implemented for producing high quality Al blocks and heads with maximized mechanical properties. Advanced additive manufacturing processes are developed to produce special high-performance parts like pistons made from aluminum or high entropy alloys. Additionally, other new manufacturing technologies are explored including 3D printing to produce intricate sand cores, overcast cylinder head valve seat. A focus is on the most cost-effective solution to promote wide market acceptance. Furthermore, integrated computational materials engineering (ICME) and advanced structural durability analysis tools are used throughout the program to accelerate both the new alloy and manufacturing process development and optimization, as well as the complete engine design and manufacturing plan. ICME unites materials, manufacturing, and system design into a holistic computational framework as shown in Figure 3, where system/product design models and materials models can be linked to manufacturing process models to predict microstructures

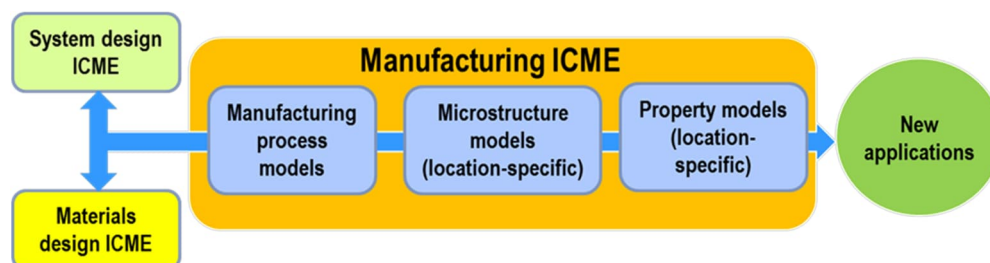


Figure 3. Integrated computational materials engineering (ICME) flow chart for new application development. [10] Source: OSU

5. Advanced LMHE Engine Technology Development

In PHASE 1 of the project, potential engine architecture designs and initial verification coupled with advanced technologies of combustion system and materials and manufacturing concepts for weight-saving and performance improvement were first studied through simulations and development. Evaluation of proposed individual technology concepts was then performed using current equivalent architecture GM development engine(s) in conjunction with advanced materials and manufacturing process development of high value weight reduction and performance improvement strategies for components and sub-systems.

5.1 LMHE Engine Advanced Combustion Technology Development

5.1.1 Layout and performance simulation of engine architectures (normally aspirated large-displacement and downsized boosted small-displacement concepts)

Work was focused on the evaluation of normally aspirated large-displacement and downsized boosted small-displacement engine concepts relative to the project objectives using simulation tools. Approximate overall engine displacement, cylinder size, and number of cylinders for peak efficiency at high fuel usage medium-duty truck engine operating points has been determined for both engine concepts. Constraints include meeting peak-power and torque targets of the model year 2015 base engine. The baseline 2015 GM medium-duty truck engine has been simulated using the PHASE 2 Greenhouse-gas Emission Model simulation tool with results transferred to a GM internal vehicle model. The simulation results identified the top 14 points representing 95% of fuel used during the test cycle, as shown in Table 2.

Table 2. Operating points weighted by fuel usage

Engine Speed (rpm)	Engine Brake Torque (Nm)	Fraction of Total Fuel (%)
2000	367.6	22.08
1750	236.3	20.51
1750	472.7	18.92
1500	315.1	7.31
2000	105.0	5.02
2500	420.2	4.70
1000	420.2	4.56
2000	577.7	4.22
2200	212.7	2.22
1300	154.9	1.76
2800	577.7	1.34
1500	52.5	1.23
2000	10.5	1.09
1000	10.5	0.66

A basic layout of concept engines in a current medium-duty truck has been accomplished to understand packaging opportunities and challenges. Both engine concepts shown in Figure 4 were successfully packaged in the target medium-duty truck.

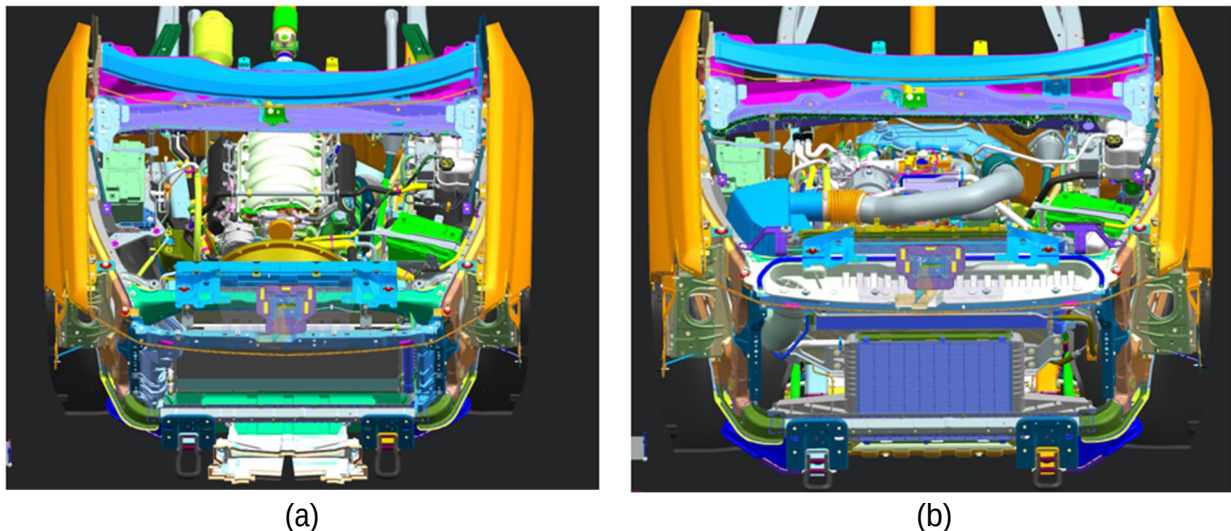


Figure 4. (a) A normally aspirated large-displacement V8 engine and (b) a downsized boosted small displacement L6 engine packaged in the target vehicle engine compartment. Source: GM

Opportunities to implement a high-value combustion system technology into both engine concept layouts were explored and design studies were completed to package this technology into both engine concept layouts. The list of high-value combustion system technologies is shown in Figure 5.

- ✓ Advanced combustion systems(s)
- ✓ Optimal cylinder deactivation
- ✓ Advanced valvetrain phasing and lift strategies
- ✓ Advanced fuel systems including “ultra” high pressure DI
- ✓ Advanced ignition systems including pre-chamber
- ✓ Advanced EGR dilution systems including E-EGR
- ✓ Atkinson or Miller cycle strategies
- ✓ Variable induction system strategies

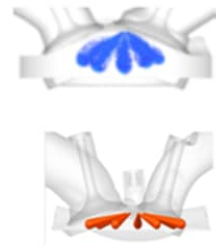
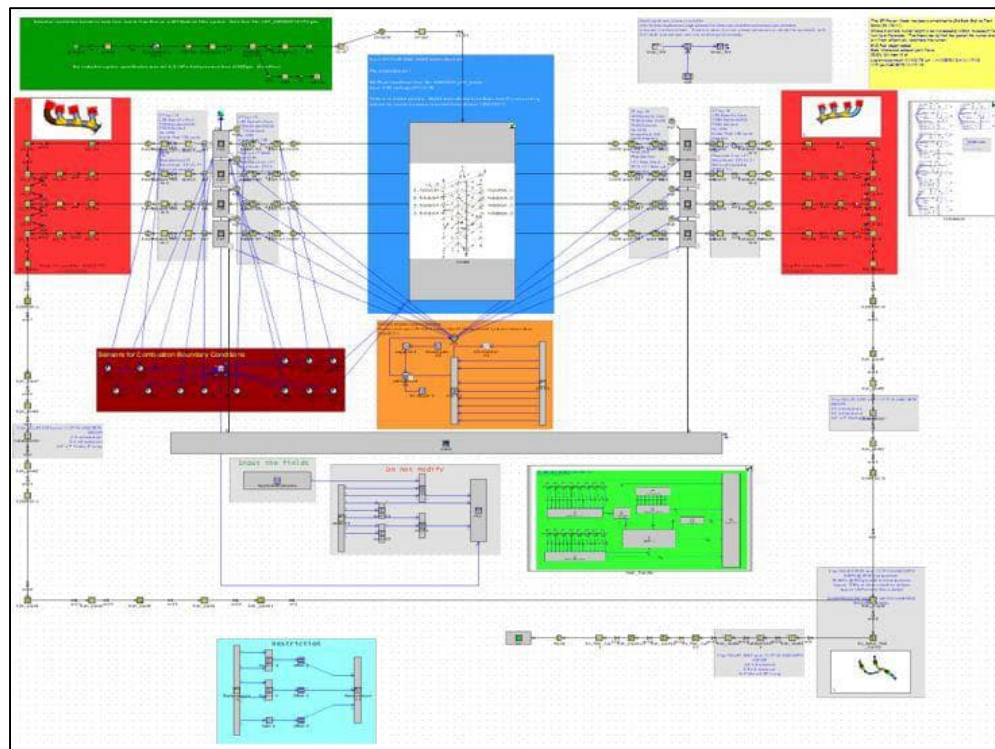
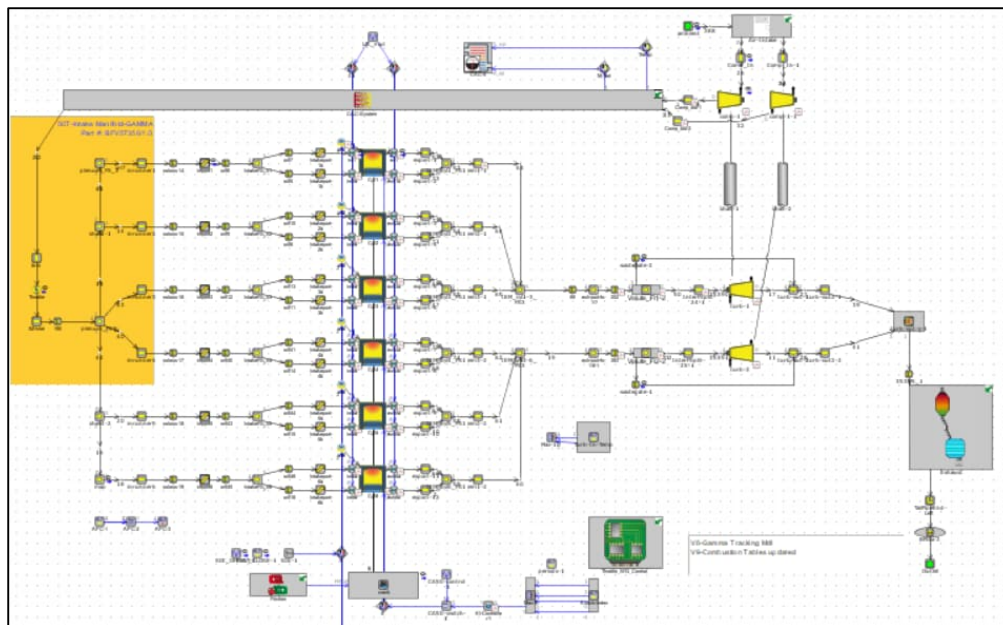


Figure 5. High-value combustion technologies. Source: GM

One-dimensional (1D) simulation models of both engine concepts were developed to establish initial performance predictions and the models were correlated using results obtained from the engine testing of similar engine configurations. Basic model representations are shown in Figure 6



(a)



(b)

Figure 6. 1D simulation model representations of (a) a normally aspirated large-displacement V8 engine and (b) a downsized boosted small displacement L6 engine. (FOR ILLUSTRATION PURPOSES ONLY) Source: GM

The correlated 1D engine concept models were used to execute the optimization of the boosting system (on the boosted concept), induction system, exhaust system, and valve events to investigate opportunities for improved performance at high-fuel-usage medium-duty truck operating points and

full load. The normally aspirated large-displacement V8 engine 1D model was used to complete an engine displacement sweep to investigate best performance and fuel consumption using engine displacements from 6.0L to 8.0L. The trend was that simulated engine fuel efficiency improved with increased engine displacement. This basic study did not account for resulting mass and size differences.

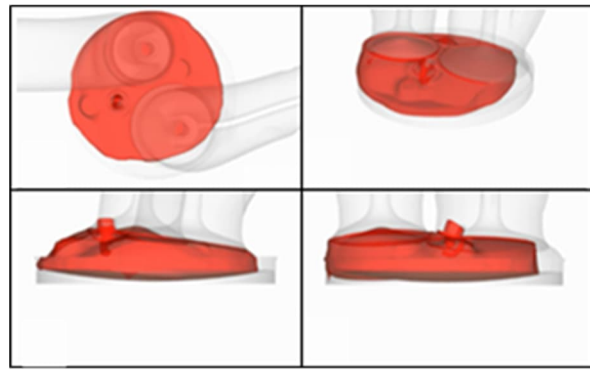
Two downsized boosted small-displacement L6 engine configurations were investigated via 1D model: 3.0L and 3.7L that is less stressed with a simplified turbocharger installation.

A 3D computational fluid dynamics (CFD) analysis was employed to create and evaluate potential combustion system design and technology enhancements that will improve net-specific fuel consumption at high fuel usage medium-duty truck operating points and/or full-load performance. Initial 3D CFD combustion models of both engine concepts were developed to establish a baseline and to assess opportunities for improvement. An example of the simulation results for flame propagation is shown in

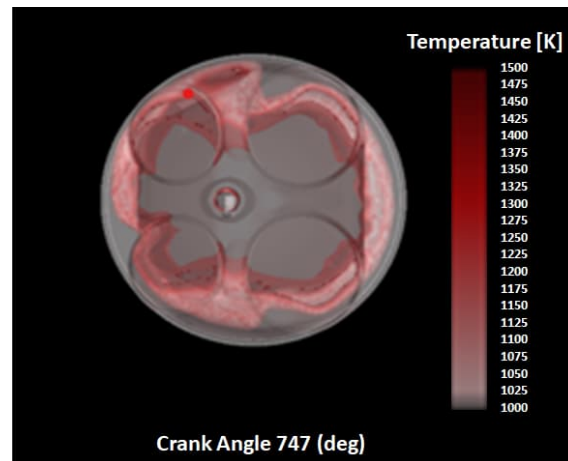
(a)

(b)

Figure 7.



(a)



(b)

Figure 7. A 3D CFD simulation of the flame propagation of (a) a normally aspirated large-displacement V8 engine and (b) a downsized boosted small displacement L6 engine. Source: GM

5.1.2 Design, build, and test cell evaluation of advanced combustion technologies using current equivalent architecture GM development engine

To physically validate the analytical work completed above, hardware was designed and acquired to evaluate the advanced combustion and advanced ignition (passive pre-chamber spark plug) systems, as shown in Figure 8. Because GM has a developed full authority cylinder deactivation system for a large displacement overhead valve V8 engine architecture, design and hardware acquisition was not required to physically evaluate optimal cylinder deactivation strategies analyzed. Instead, hardware was designed and acquired to evaluate “ultra” high pressure fuel injection using the advanced combustion system, as shown in Figure 12. The investigation of a potential radio frequency corona discharge ignition system was also conducted and hardware to implement an E-EGR system using EGR produced in dedicated cylinders was designed and acquired, as shown in Figure 13.

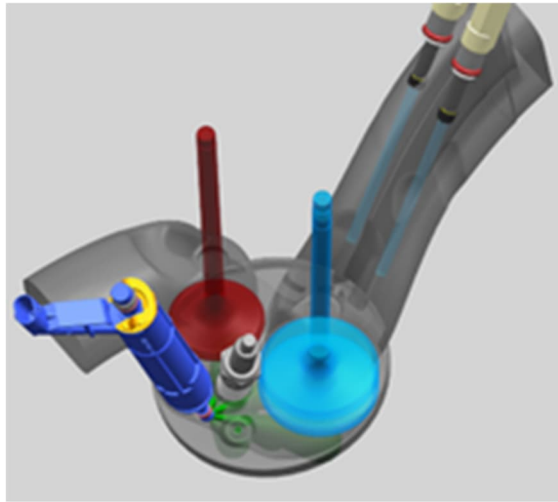


Figure 8. Proposed advanced combustion system. Source: GM

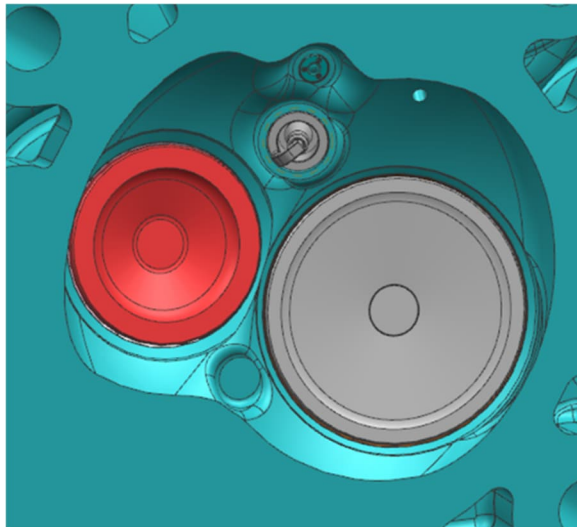


Figure 9. Proposed advanced combustion system application in hardware. Source: GM

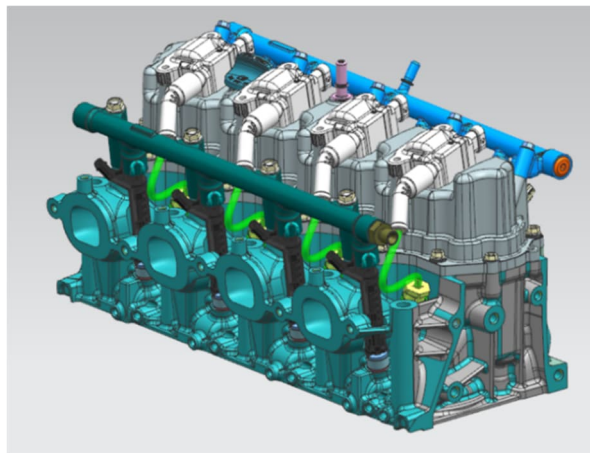


Figure 10. Proposed advanced combustion system cylinder head assembly – exhaust side view.
Source: GM

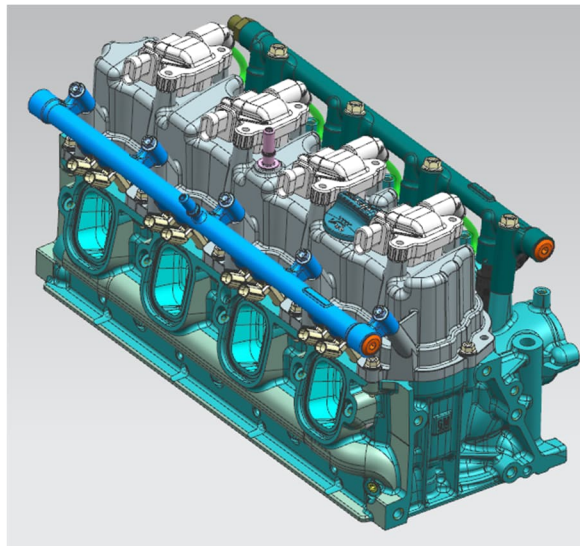


Figure 11. Proposed advanced combustion system cylinder head assembly – intake side view.
Source: GM

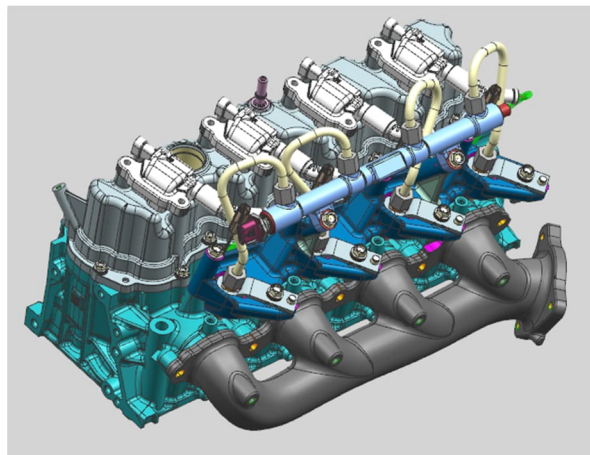


Figure 12. "Ultra" high pressure injection system adapted to proposed advanced combustion system cylinder head assembly – exhaust side view. Source: GM

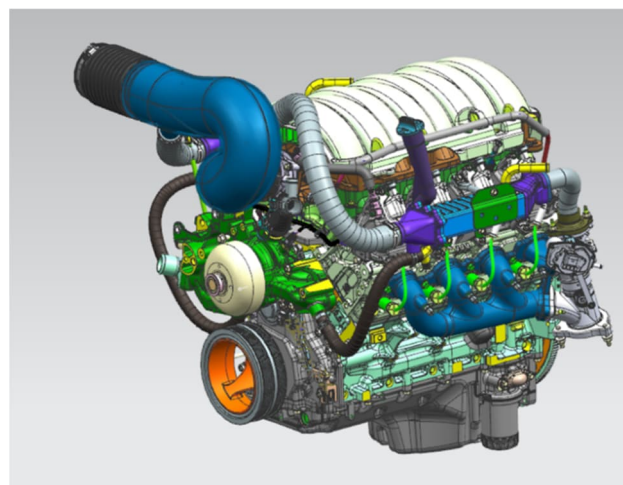


Figure 13. E-EGR system adapted to development engine. Source: GM

Hardware to evaluate advanced Atkinson or Miller cycle strategies in conjunction with advanced variable valve duration and/or lift concepts was designed and acquired. Intake valve lift profiles and camshaft phasing hardware capable of implementing an Atkinson cycle strategy were implemented into the design and acquisition of components supporting the advanced combustion development engine. A variable charge motion concept was conceived and designed to evaluate advanced variable induction system strategies. Hardware was acquired to evaluate this concept using induction system inserts to increase charge motion based on strategic port blockage, as shown in Figure 14.

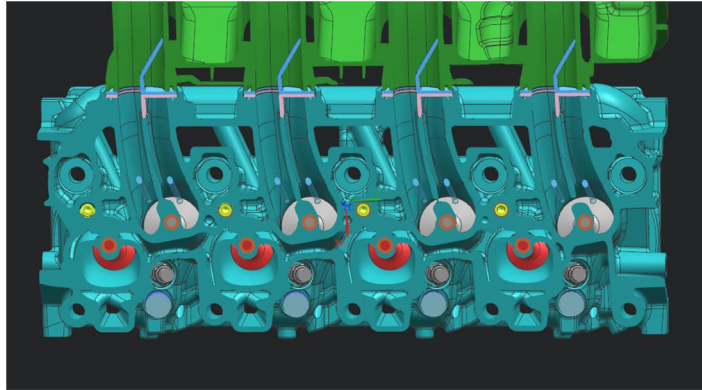


Figure 14. Variable charge motion accomplished with inserts. Source: GM

A high velocity coolant jacket has been developed including key drillings to significantly improve cooling uniformity, as shown in Figure 15.

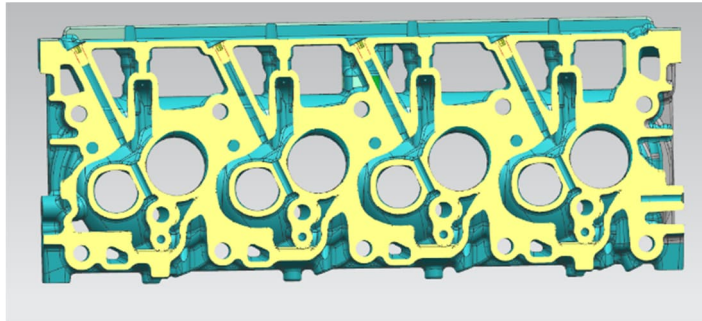


Figure 15. Cooling jacket design. Source: GM

As the team awaited physical test properties to arrive, a test cell evaluation was performed using the baseline L96 V8 engine. Projected Greenhouse Gas Emissions Model (GEM) points and evaluation status are shown in Figure 16.

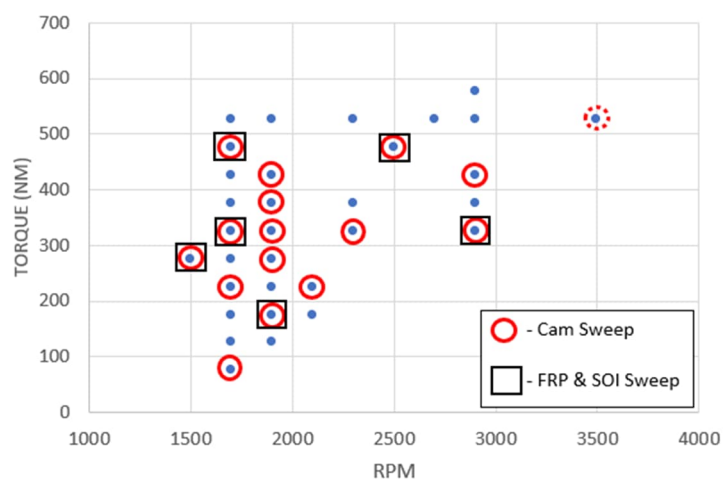


Figure 16. Projected and completed GEM cycle operating points. Source: GM

5.2 LMHE Engine Advanced Materials and Manufacturing Technology Development

In parallel to the combustion system development, significant work was performed by the materials engineering team with a dual focus on the mass-saving opportunities and manufacturing and metallurgical viability of new materials and manufacturing solutions for key engine components identified relative to the project objectives. This work was done using both simulation tools and preliminary experiments.

5.2.1 Mass-saving material and manufacturing technology opportunities

Based on mass-saving opportunities and high engine performance requirements, several key engine components were identified, including cast-aluminum engine block, cast-aluminum head, cast-steel and nodular-iron crankshaft, and piston fabricated with AM. Table 3 shows the materials and manufacturing technology solutions and Figure 17 gives the mass-saving potential opportunities for these key engine components.

Table 3. Materials and manufacturing solutions for key engine components

2015 VORTEC 6.0L VI PFI Engine (L96 Baseline) – HT3500		Mas Reduction and Performance Enhancement Opportunities	
Key Parts	Materials	Advanced Materials and Manufacturing	
		Option 1	Option 2
Engine block	Cast iron	Cast high-strength high-temperature aluminum	Multi materials
Cylinder head	Cast aluminum	Cast high-strength high-temperature aluminum	Multi materials
Crankshaft	Cast nodular iron	High-strength cast steel	High-strength high-modulus nodular iron
Piston	Hypereutectic aluminum	High-strength high-temperature aluminum for AM	High entropy alloys for AM
Exhaust manifold	Cast ductile iron	High-temperature cast steel	-----

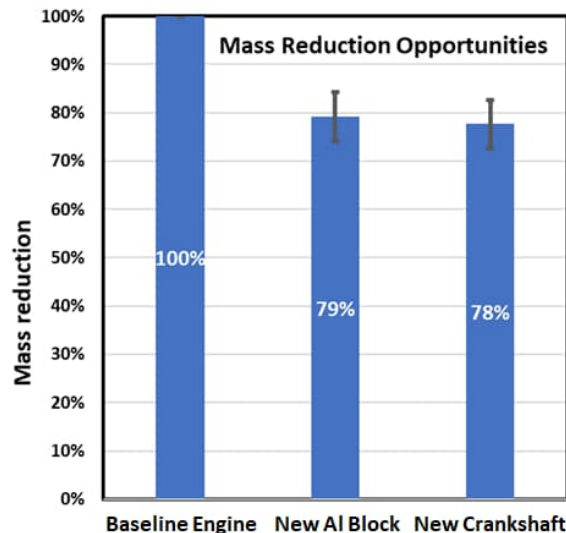


Figure 17. Mass-saving potential for the key components. Source: GM

The targeted mechanical and thermomechanical property requirements were developed for key engine components based on the required fuel-efficiency improvement (i.e., at least 10% more than the 2015 baseline engine) and CAE durability analyses. Error! Reference source not found. shows an example of the targeted properties defined for the cast-aluminum engine block.

Table 4. Baseline and targeted material properties for the cast-aluminum engine block

Component	Property	Baseline (GM L96 Engine)	Cast Lightweight Alloy Targets
Engine Block	Room Temperature Performance	@25C (cast iron)	@25C
	Ultimate Tensile Strength (MPa)	265	>280
	Yield Strength (MPa)	240	>240
	Elongation (%)	0.5	>1
	Density (g/cm ³)	7.2	<3.5
	Fatigue strength (MPa)	76	100
	Hot Tearing Resistance	Excellent	Excellent
	High Temperature Performance*	@300C	@300C
	Ultimate Tensile Strength (MPa)	222	145
	Yield Strength (MPa)	200	100
	Fatigue strength (MPa)	64	48

Cylinder Block

A study of several comparable GM cast-aluminum V8 cylinder heads was conducted. An equivalent architecture GM production head of an L8T engine—the successor to the project baseline engine 2015 L96 engine—was selected for new-alloy and novel-casting process investigation. Cast-in-place intake and exhaust valve seats were proposed to replace press-in-place valve seats to enlarge the design space for the high-performance combustion design in the cylinder head.

Single lightweight material (e.g., cast aluminum) and multi-material solutions for the engine block were extensively explored with new designs and comprehensive CAE analyses. A single-piece cast-aluminum block was iteratively designed using the state-of-the-art GM CAE durability Level 2 and Level 3 analyses, as well as a damage accumulation analysis with nodal-based materials properties from the casting process simulation, as observed in Figure 19.

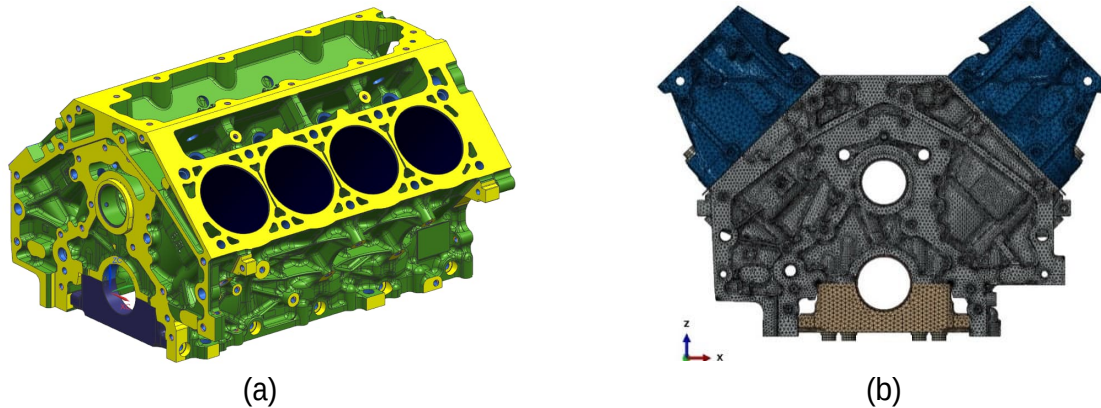


Figure 18. (a) Single-piece cast-aluminum block design and (b) meshed-assembled modes for CAE analysis. Source: GM

A study of raising the camshaft bore on durability of the cast-aluminum block was also conducted. It was found that the safety factors of the block were improved by 10%, particularly for hot-spot areas such as bulkhead breather window high-stress regions, when the camshaft bore is raised by 25 mm. This provides a design opportunity of using lightweight cast-aluminum alloys in medium-duty truck engine applications. Meanwhile, the noise, vibration, and harshness analyses were conducted with the newly designed cast-aluminum block and the results were also compared with the current cast-iron block. As expected, the cast-aluminum engine block has very marginally higher noise levels (~2 dBA) than an iron block due to its reduced mass.

Multi-material options for the L8T V8 engine block were explored to further reduce mass while maintaining the needed performance and durability. The team developed a split engine-block design where the block is split from the main crank journal centerline (Figure 19). The upper portion is cast aluminum and the lower portion is a combination of iron main-cap inserts overcast with magnesium or iron main-cap inserts molded over with polymer. A complete CAE durability and damage-accumulation analysis was used to determine the best combination of the multi-material split block.

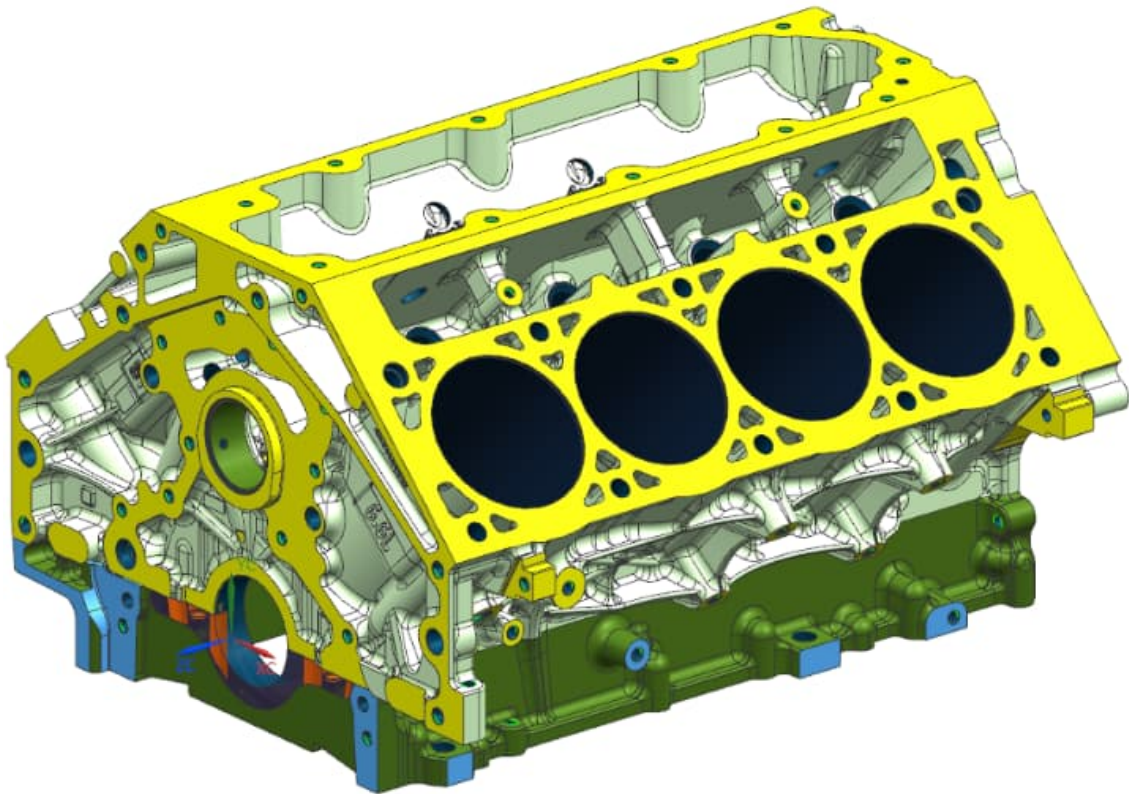


Figure 19. A new split engine block design of cast aluminum (upper portion) and a combination of iron main-cap inserts overcast with magnesium or iron main-cap inserts molded over with polymer (lower portion). Source: GM

Pistons

The additive manufacturing (AM) process was selected to make the L8T V8 engine piston in PHASE 1. Three alloys were chosen to print the piston, including the Al–Cu–Mn–Zr (ACMZ) alloy [11], the Al–Ce–Ni-based alloy [12], and the light high-entropy alloy [13]. The ORNL team developed a printable Al–Ce–Mn alloy with a thermally stable microstructure and attractive mechanical properties up to 400°C. Figure 20 shows an example of the ultimate tensile strength (UTS) of this alloy (as-printed) compared to a current automotive piston cast-aluminum alloy and the room temperature (RT) Vickers hardness pyramid number (HV) after a 200-hour thermal exposure at various temperatures as compared to ACMZ alloy.

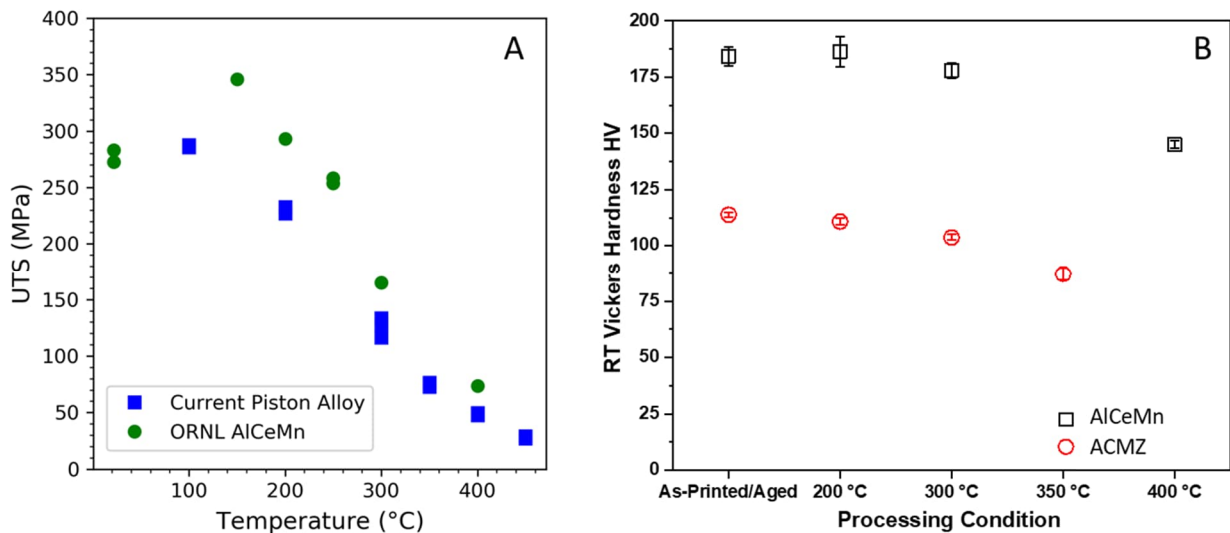
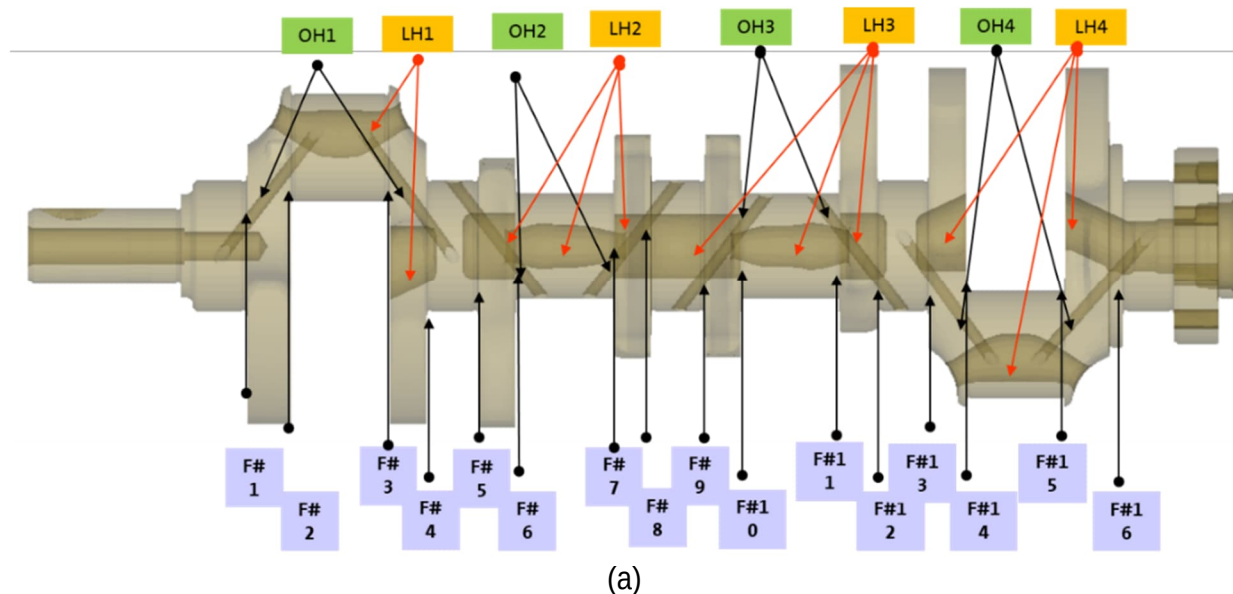


Figure 20. Mechanical properties of the ORNL AlCeMn alloy fabricated with AM compared with cast-aluminum and ACMZ alloys currently used in piston manufacture. Source: ORNL

Crankshaft

Cost-effective high-strength/high-modulus ferrous material solutions were explored for the crankshaft. Iterative design of a cast-steel hollow crankshaft with center webs, shown in Figure 21(a), and without center webs, shown in Figure 21(b) in the main journals was completed for the PHASE 1 platform L8T V8 engine. A full CAE analysis has been conducted for both designs. The calculated fatigue reserve factors on the fillets and lightening and oil holes in both designs have met the design and performance requirements. The overall fatigue reserve factors of both cast steel designs are better than those of a production V8 forged-steel crankshaft and still saves 0.15Kg in mass.



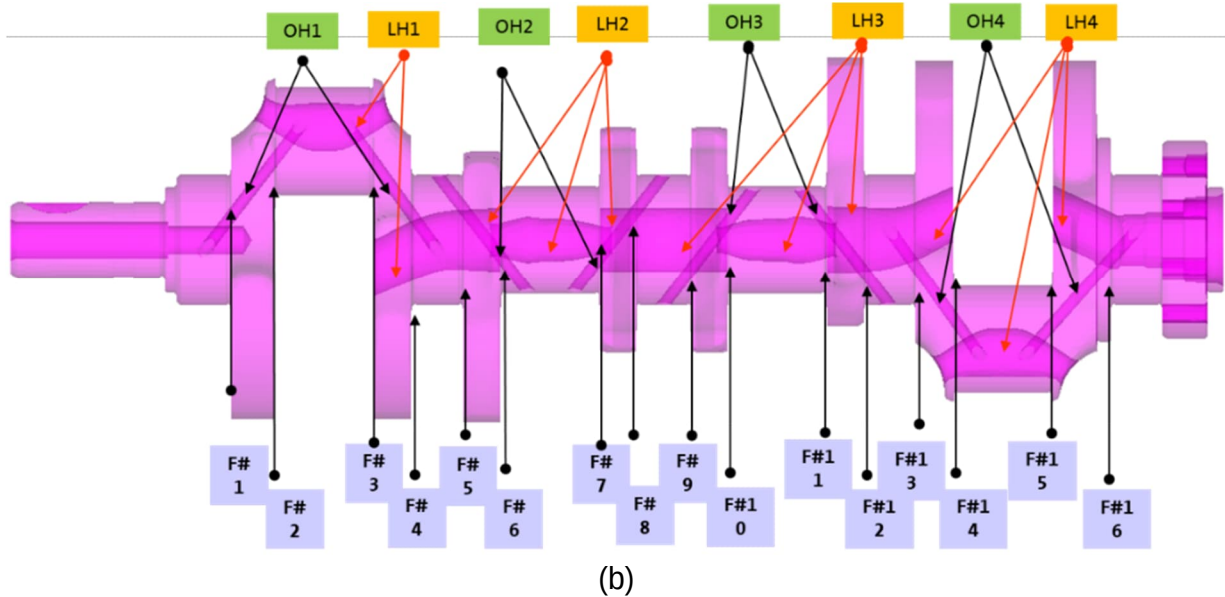


Figure 21. Cross-section of cast-steel designs together (a) with numbering of fillets (F#), lightening holes (LH) and oil holes (OH) with webs at main journals and (b) without webs at the main journals. Source: GM

The design of the nodular-iron crankshaft was explored with high-strength and high-modular, ductile iron alloy, as observed in Figure 22. Because of the design (i.e., external dimensions) constraints of the existing L8T platform engine, the new nodular-iron crank must be designed as a solid piece to be able to achieve the same performance as the forged-steel crank. Nevertheless, the newly designed nodular-iron crank is still about 0.2 kg lighter than its forged-steel counterpart.

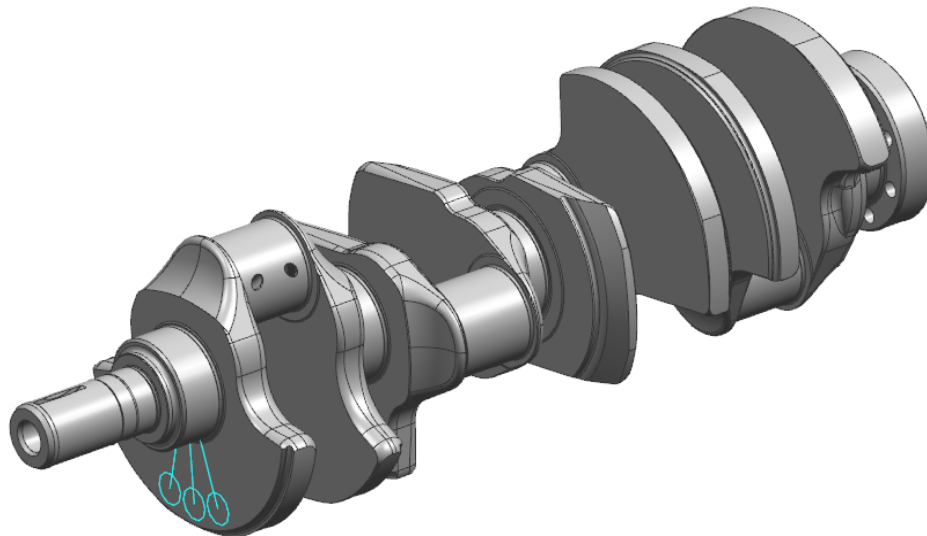


Figure 22. New nodular-iron crankshaft design. Source: GM

Other Components with Mass Reduction Potential

In addition to combustion-related components that contribute to the largest percentage of engine mass, material and manufacturing solutions for other engine components utilizing lightweight materials were also explored. As shown in .

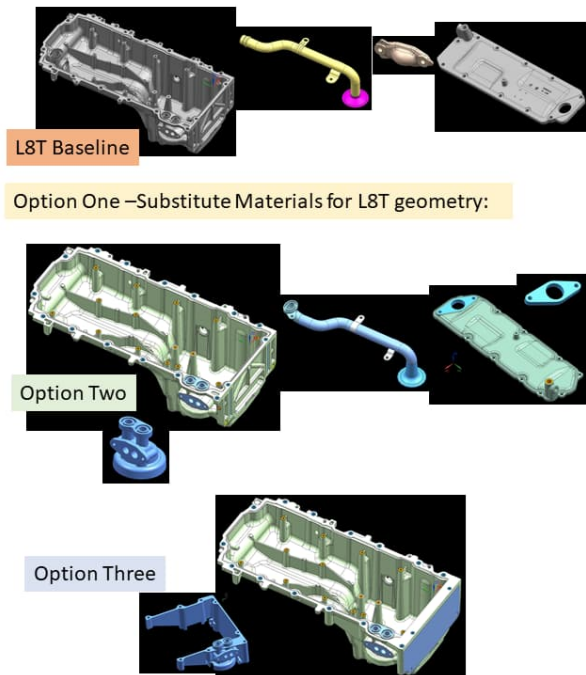
(a)

(b)

Figure 23, mass-reduction options were evaluated for the oil pan, pickup tube assembly, oil-pan cover, and engine-block valley cover. The mass savings and weight-reduction rate varied from 14% to 86%, depending upon the part geometry and material used.

Pan-Oil		Volume	Material	Density	Mass kg	Mass lbs	Weight Reduction	
L&T Baseline	12696279/002	2151648	Aluminum	2710	5.83	12.86		
Option One		2151648	PF-1110	2050	4.41	9.72	24%	
Option One		2151648	PF-6510	1700	3.66	8.06	37%	
Option Two	Pan	BGA46055	1967156	PF-6510	1700	3.34	7.37	
	Brkt-Oil Filter		127574	Aluminum	2710	0.35	0.76	
Over Mold Total					3.69	8.13	37%	
Option Three	Pan	BGA48315	1952397	PF-6510	1700	3.32	7.32	
	RearBrkt/Oil Filter		629837	Aluminum	2710	1.70	3.76	
Over Mold Total					5.02	11.08	14%	
PickUpTube-Asm		Volume	Material	Density	Mass kg	Mass lbs	Weight Reduction	
L&T Baseline	12619979/003	88820	Mix-Steel	7842	0.63	1.40		
Option One		88820	PA66	1070	0.09	0.19	86%	
Option Two		BGB46970	189445	PA66	1070	0.20	0.45	68%
Cover-Oil Pan		Volume	Material	Density	Mass kg	Mass lbs	Weight Reduction	
L&T Baseline	12630766/003	16676	Aluminum	2760	0.05	0.10		
Option One		16676	PA66	1070	0.02	0.04	61%	
Cover-Valley		Volume	Material	Density	Mass kg	Mass lbs	Weight Reduction	
L&T Baseline	12700640/002	411294	Aluminum	2620	1.08	2.38		
Option One		411294	PF-6510	1700	0.70	1.54	35%	
Option Two	Cover	BGB41214	365333	PF-6510	1700	0.62	1.37	
	FuelPumpBrkt		32469	Aluminum	2620	0.09	0.19	
Over Mold Total					0.71	1.56	34%	

(a)



(b)

Figure 23. Mass-reduction opportunities evaluated for oil pan, pickup tube assembly, oil pan cover, and engine block valley cover. Source: GM

5.2.2 LMHE engine advanced materials and manufacturing technology development

Cylinder Block and Heads

Five ACMZ alloys with copper contents of 6.0, 6.6, 7.3, 8.0, and 9.0 wt% were evaluated in terms of porosity population with two sets of end-chill sand cast plates using X-ray computed tomography (CT). Two representative sections in the plates were measured: (a) Section 1 (0-15 mm from the chill end) corresponding to the deck face in the cylinder head and the bulkhead in the engine block microstructure, and (b) Section 2 (45-60 mm from the chill end) corresponding to the head bolt boss microstructure. Porosity measurements were performed with a CT scan technique. In the second set of X-ray CT scanning, a higher resolution X-ray CT scanner was used for the samples next to the chill. Pores larger than 10 μm were detected and quantified. The total porosity of two sets of measurements in the two sections for the five evaluated alloys is summarized in Figure 24.

Following Zhu *et al.*, [14] fatigue limit was predicted with the pore size distribution and Monte Carlo technique. The predicted fatigue strength variation for two sets of CT porosity measurements is plotted in Figure 25. Based on the measured porosity distribution and fatigue strength variation predicted from the CT data on two locations of the end-chill plates, alloys with 6.6% or 9% Cu show better castability and quality than other three Cu levels. This led the team proceed with 9% Cu for the cylinder head alloy and 6.6% Cu for the engine block.

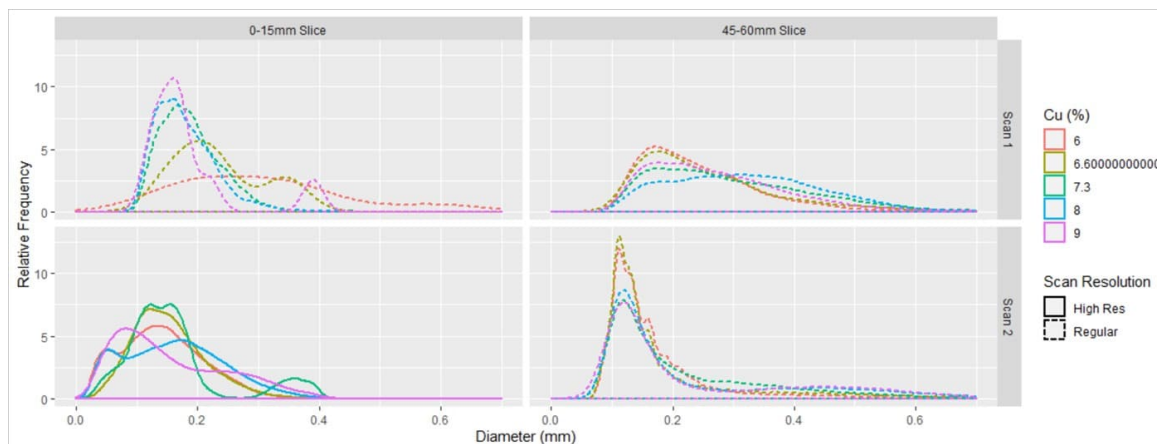


Figure 24. Two sets of CT porosity measurements of five Al-Cu-Mn-Zr alloy compositions for two representative sections of end-chill sand-cast plate castings. Source: ORNL

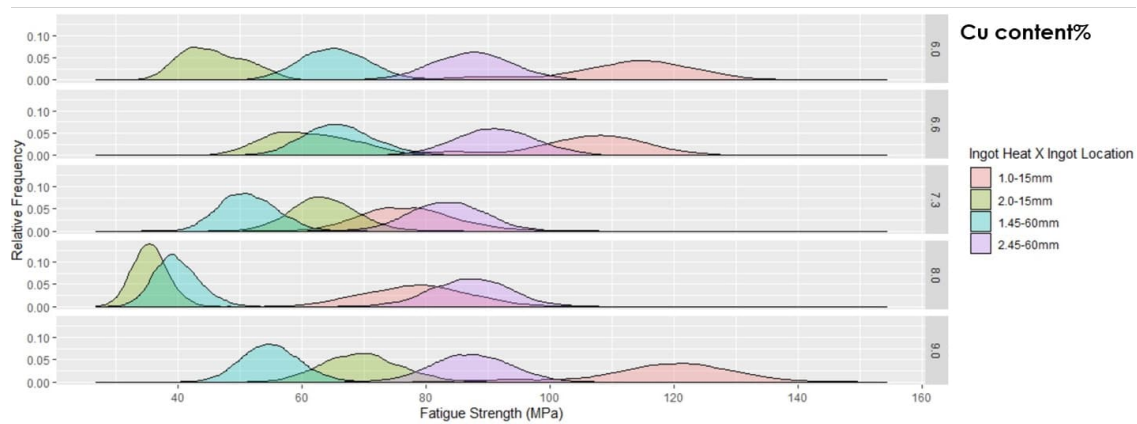


Figure 25. Predictions of fatigue strength distributions based on the porosity measurements outlined. Source: ORNL

Advanced casting process solutions for high-performance castings were explored. Alternate chilling methods were investigated with A356-T6 alloy for driving thermal gradients and solidification. An experimental ablation cell shown in Figure 26(a) was manufactured, and a standard step plate was ablated along with a control sample, as observed in Figure 26. The ablated casting shows elongation more than doubling with a roughly 10% increase in tensile strength.

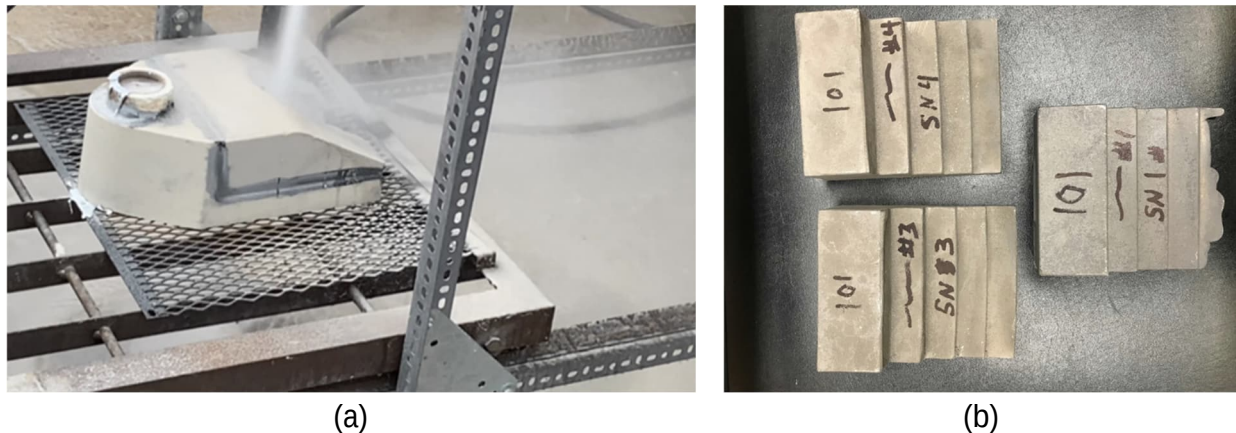
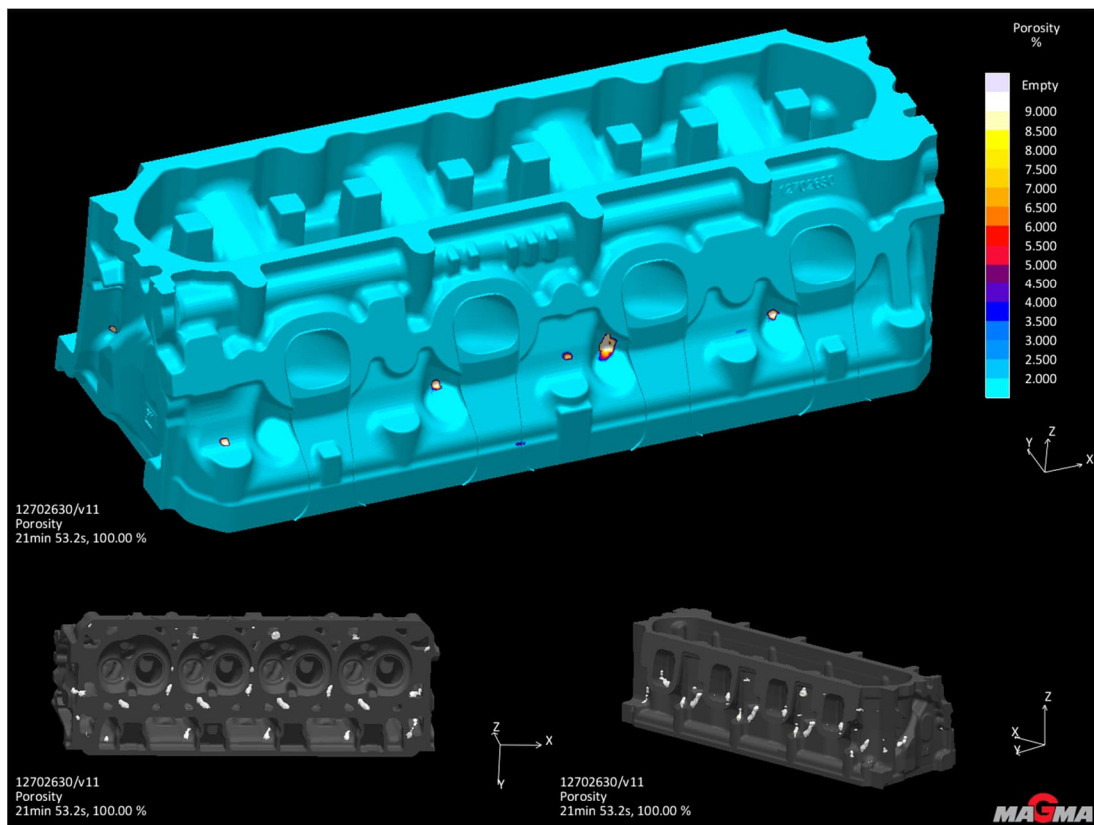


Figure 26. (a) Prototype ablation cell and (b) step plates. Source: ECK

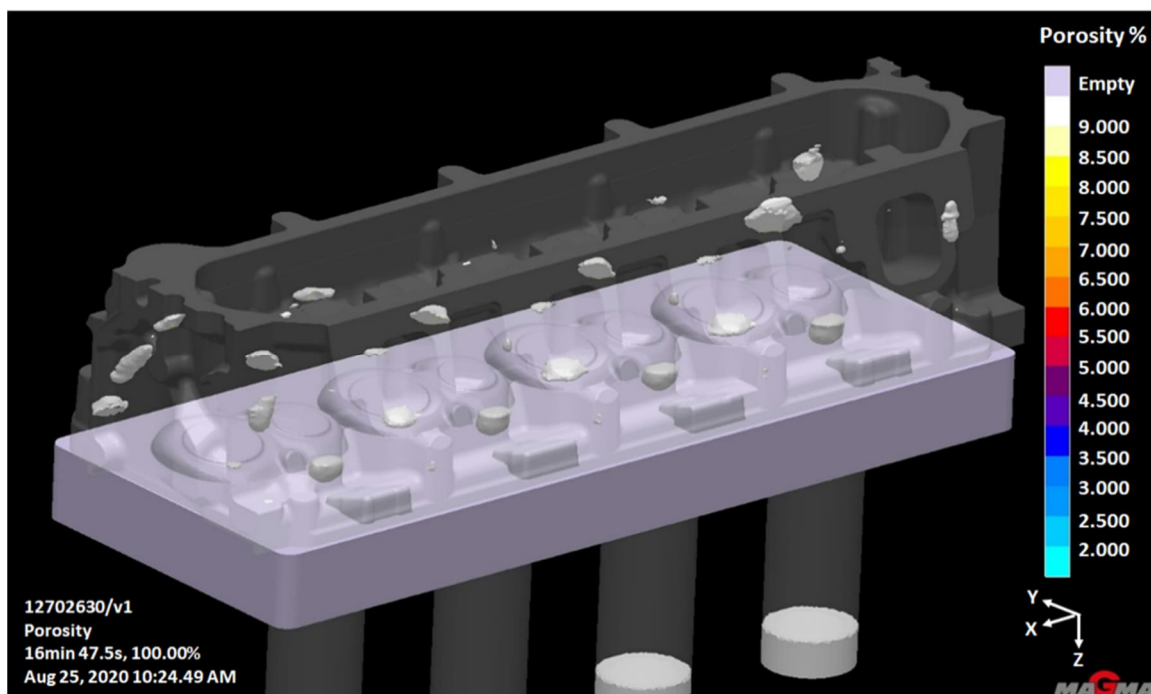
Further studies were conducted at ECK using a variety of chill types and sizes along with two pieces using nanocoated filters to understand how small amounts of nanoparticles impact strength and elongation. Mechanical-property testing and microstructure evaluation indicates that thermal conductivity and thermal capacity of the chill system plays an important role in dendrite arm spacing and mechanical properties.

Extensive casting simulations were started at ECK to determine the gating and chilling systems to produce a quality aluminum cylinder head. Initially, those simulations looked at a full-deck chill. All those scenarios showed mid-head porosity, as shown in Figure 27(a), due to the in-gates passing through the chill, resulting in reduced feeding to the midsection of the head. More simulations were then conducted with different chill and riser configurations, such as a reduced chill profile confined to the combustion chambers, shown in Figure 27(b), and added cope risers, shown in

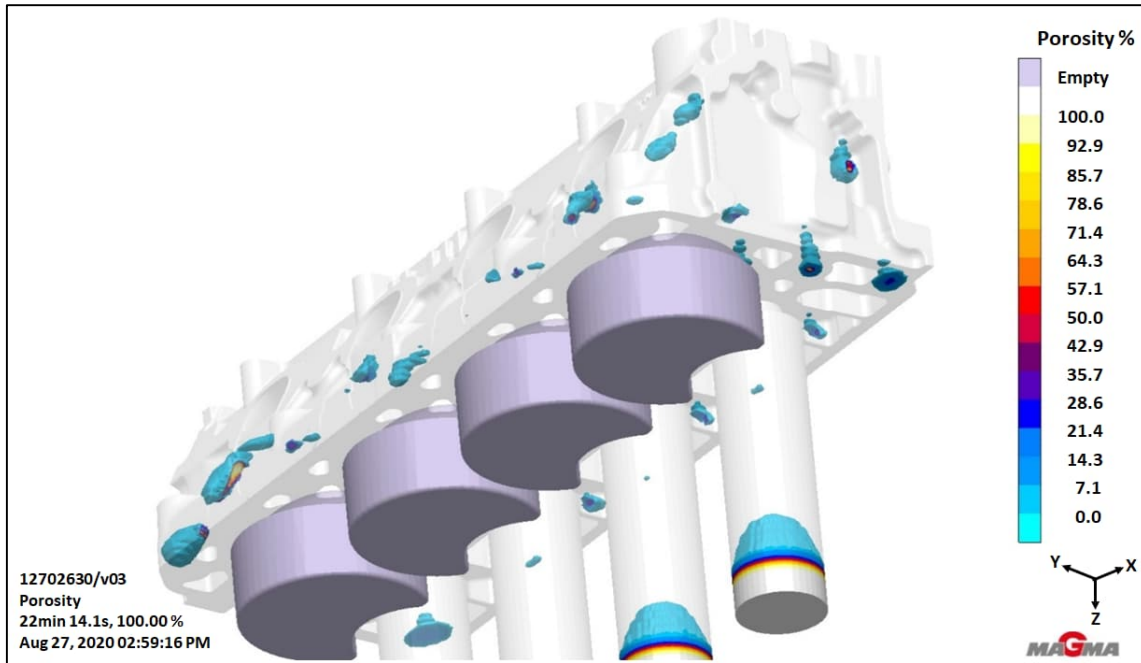


(b)

Figure 28.a). The simulation results are quite promising and removed much of the porosity, as shown in Figure 28(b).

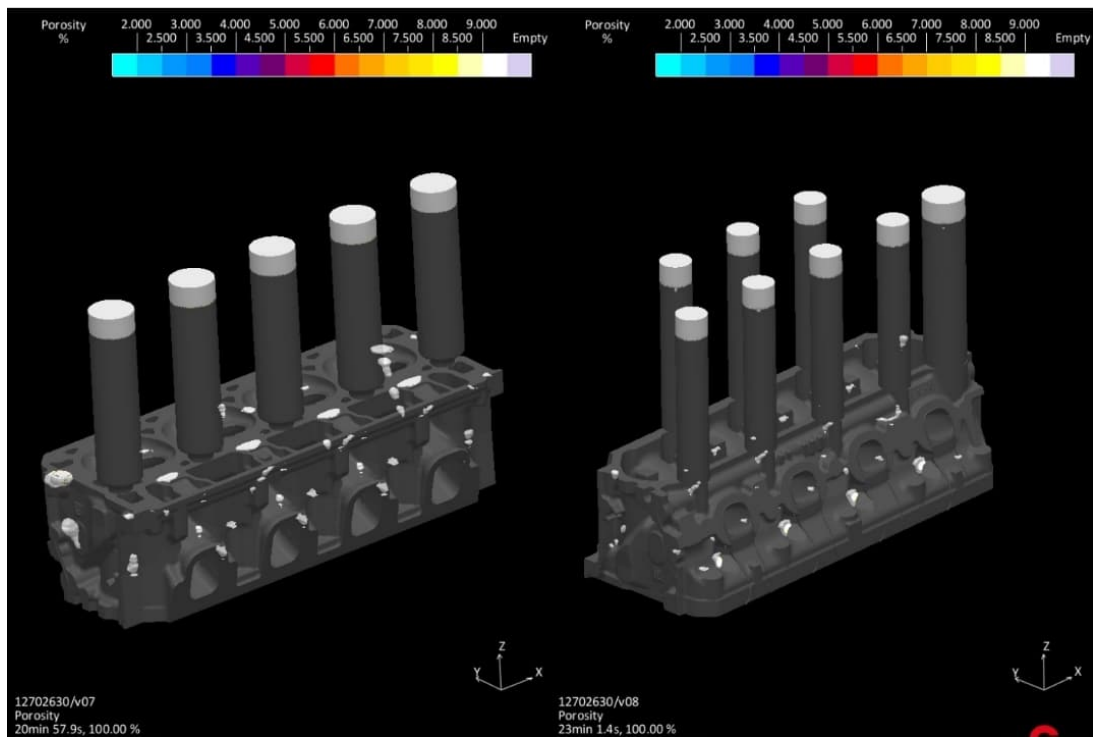


(a)

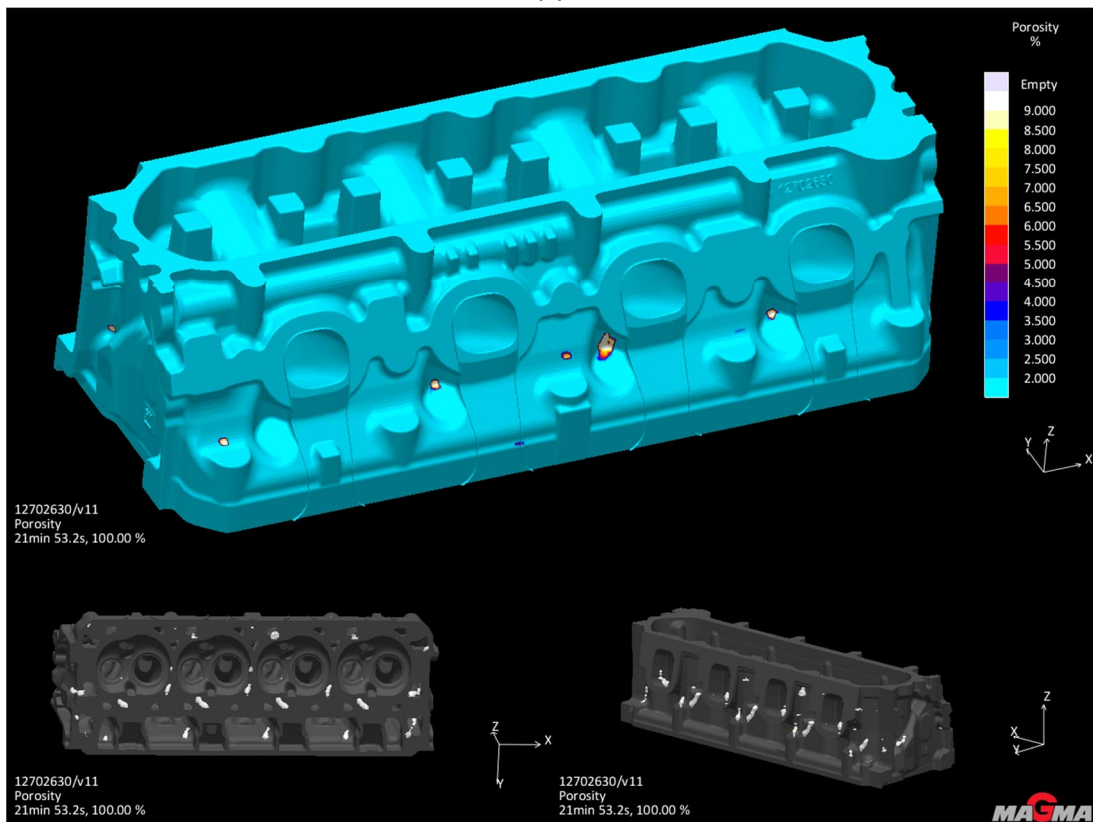


(b)

Figure 27. (a) Simulation with a large deck face chill and (b) a chill profile confined to the combustion chambers. Source: ECK



(a)



(b)

Figure 28. (a) Simulation with code risers and (b) simulation results showing reduced porosity.
Source: Source: ECK

A novel low pressure precision sand casting (LPPSC) process was proposed and investigated for cast high-quality Al cylinder head and engine block. After comprehensive casting process simulation and multiscale defect and microstructure modeling, gating, and riser system, as well as LPPSC process parameters were optimized for the cylinder head and engine block. The tooling work for the head casting was completed and the first set of cylinder heads with a baseline alloy were cast, as observed in Figure 29. X-ray CT examination of the head showed good quality in meeting the requirement.

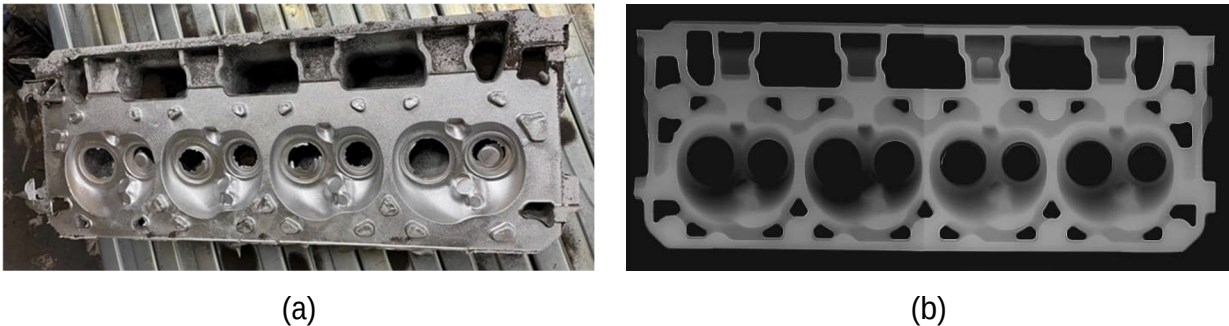


Figure 29. (a) The first cylinder head casting made by (b) the novel LPPSC process showing good quality in X-ray CT. Source: ECK.

Cast-in-place steel valve seat in cast-Al cylinder head was studied as one of the multi-material solutions for high-performance engine in this project. Figure 30 shows an assembly of the newly designed exhaust valve steel seat with an exhaust port sand core and deck face metal chill for the cylinder head.

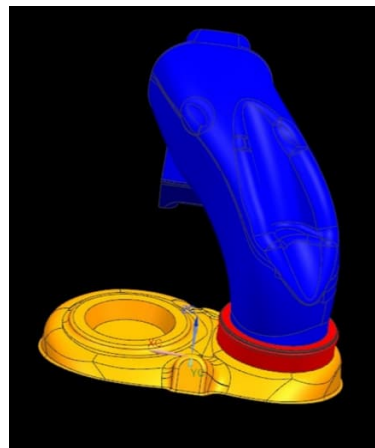


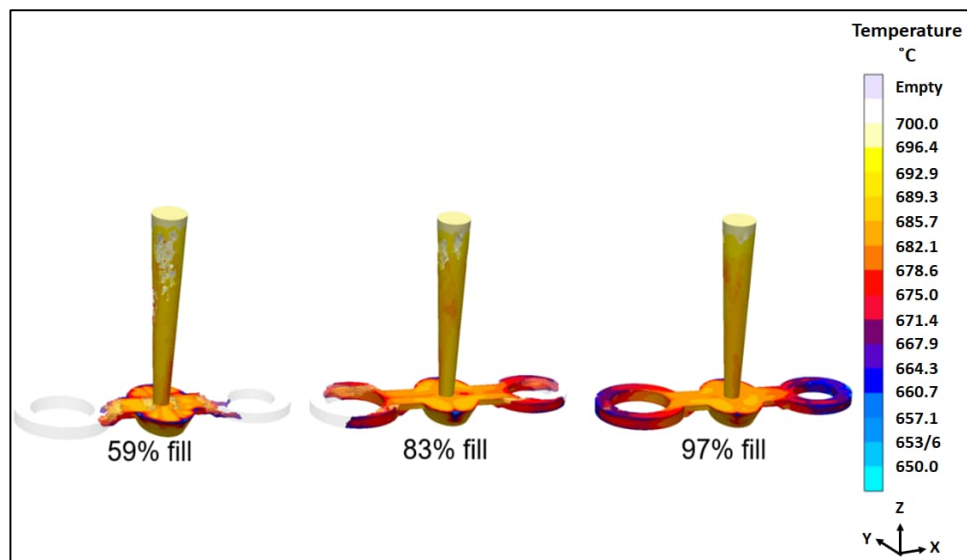
Figure 30. An assembly of exhaust valve steel seat (red) with exhaust port sand core (blue) and deck face metal chill (yellow). Source: GM

Work on overcasting cylinder valve seats was started at OSU by designing a sand-casting pattern for the overcasting experiments. Casting simulation was used in mold filling to optimize the pattern design to minimize turbulence and improve metal-front uniformity, as observed in

(a)

(b)

Figure 31(a). The finally optimized pattern was fabricated for ongoing overcasting experiments, as shown in Figure 31(b), and subsequent heat treatment was performed to evaluate the interface bonding with the production-steel-based valve seats with and without coating.



(a)



(b)

Figure 31. (a) A mold filling simulation for a 319 aluminum alloy in overcasting sand cavity simulated with sodium silicate bonded sand for three fill percentages showing the temperature distribution during filling and (b) the sand-casting pattern made of polylactic acid polymer with steel valve seats. Source: OSU

A variety of techniques were studied to achieve good metallurgical bonding between the steel and cast-Al interface including steel surface oxide removal, steel surface coating, Al-fin processing, solid diffusion, special heat treatment, etc. To evaluate the effect of mold design and filling, several iterations of mold design seen in Figure 32 were used to identify key factors affecting metallurgical bonding at the bimetallic interface.

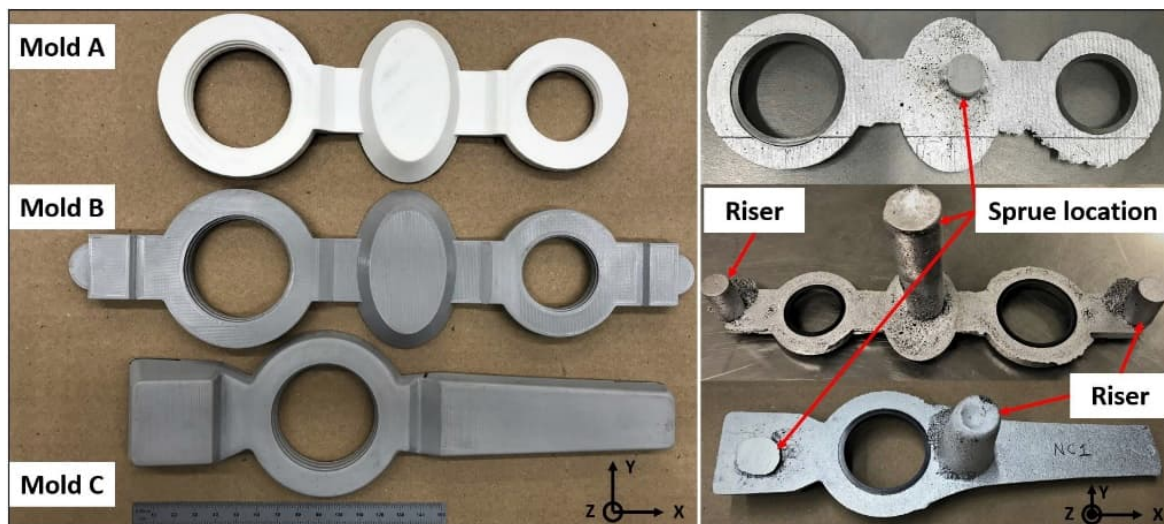


Figure 32. An assembly of exhaust valve steel seat (red) with exhaust port sand core (blue) and deck face metal chill (yellow). Source: OSU.

After valve seat sample surfaces were well prepared, good metallurgical bonding had been achieved in both Zn-plated and Al-fin processed samples. As shown in Figure 3(a) and (b), a roughly $3.5\ \mu\text{m}$ diffusion layer of Fe-Zn-Al was formed during the overcasting of the Zn plated sample. Al-fin processed samples show intermetallic bonding where $\alpha\text{-Fe}_2\text{SiAl}_8$, $\beta\text{-FeSiAl}_5$, and $\theta\text{-FeAl}_3$ phases are observed between the Al and valve seat materials, but as indicated by the star in Figure 3(c), some oxides are not broken down during the overcasting process. A sample with no coating, but well cleaned to remove the C-N-O layer, displayed a superior bonding interface. As shown in Figure 3(d) and (f), the sample with no coating displayed a large clean interface with around a $1.9\ \mu\text{m}$ Al-Fe diffusion layer.

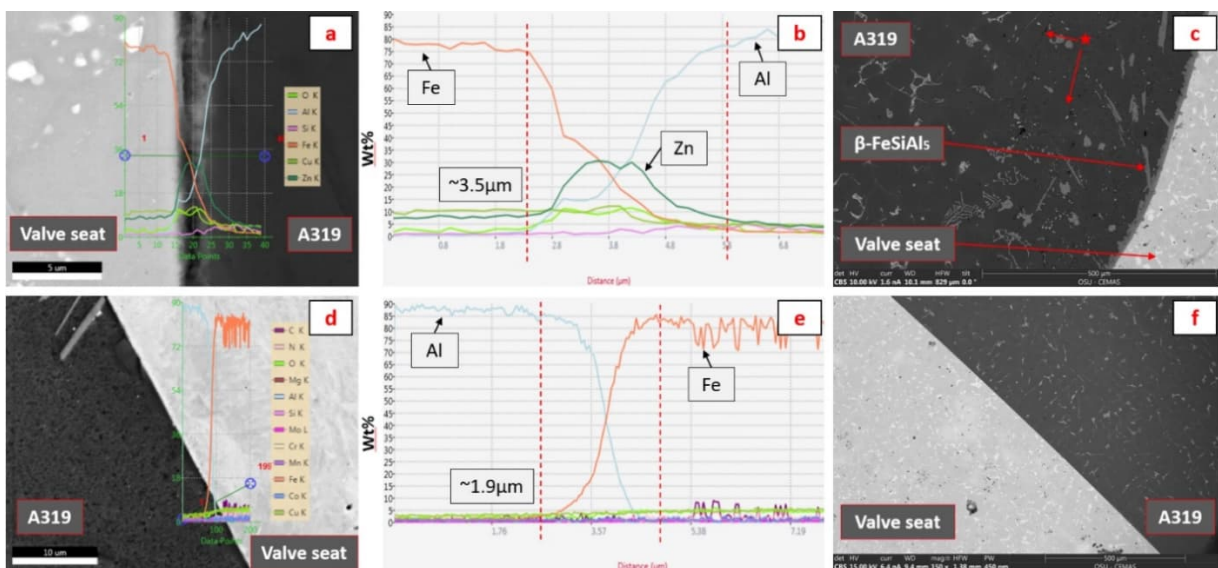


Figure 33. Overcasting sample in an as-cast state: (a, b) BSE image and EDS scan of Zn-plated sample; (c) Al-Fin processed sample; (d) SEM image; (e) EDS scan; and (f) BSE image of the sample with no coating. Source: OSU

Crankshaft

Leveraging prior DOE and GM work [15] on cast-steel crankshaft development to identify alloy-system and casting strategies, MTU started prototype crankshaft casting. Three potential alloy chemistries, shown in Table 5, were selected for coupon-level comparison of as-cast mechanical properties and shrinkage tendency to allow for final alloy selection. The GM 34CrMoV chemistry is based on a pending GM patent application. The DOE-optimized alloy represents the most-promising chemistry based on previous work completed by GM. The DOE-optimized alloy with Ce is a cerium-added variant of the DOE-optimized alloy and was included to study the potential microstructural refinement effect of cerium.

Table 5. Selected Alloy Composition for Coupon-Level Comparison

Alloy	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Ti	V	Al	Ce
GM 34CrMoV	0.38	0.4 0	0.9 0	0.03 max	0.050	1.1 0	0.25 max	0.30	0.20 max	0.03 max	0.10	0.03 0	- - -
DOE-Optimized Alloy	0.30	0.5 0	1.1 0	0.03 max	0.050	0.3 5	0.25 max	0.20	0.20 max	0.03 max	0.08	0.03 0	- - -
DOE-Optimized Alloy + Ce	0.30	0.5 0	1.1 0	0.03 max	0.050	0.3 5	0.25 max	0.20	0.20 max	0.03 max	0.08	0.03 0	0.03 0

The test coupon mold was developed using Altair Inspire casting simulation software to minimize predicted porosity and ensure good mold-filling characteristics (e.g., filling time, metal flow). The first casting trial using the initial mold design resulted in castings containing macroscopic centerline-shrinkage porosity, so insulating riser sleeves were added at the midpoint and bottom of each bar, as shown in Figure 34, to minimize shrinkage porosity in the sections between the riser sleeves from which tensile specimens are extracted.

A heat of the DOE (Design of Experiment)-optimized alloy was poured into three variants of the multiple riser sleeve mold, which are shown schematically in Figure 34, to compare the effect of varying the cooling rate. The baseline mold (standard mold) consisted of just the additional riser sleeves, while a second mold utilized steel chills with configuration of different chill thicknesses for four bars. A high-conductivity chromite facing sand was used between the riser sleeves in a third mold.

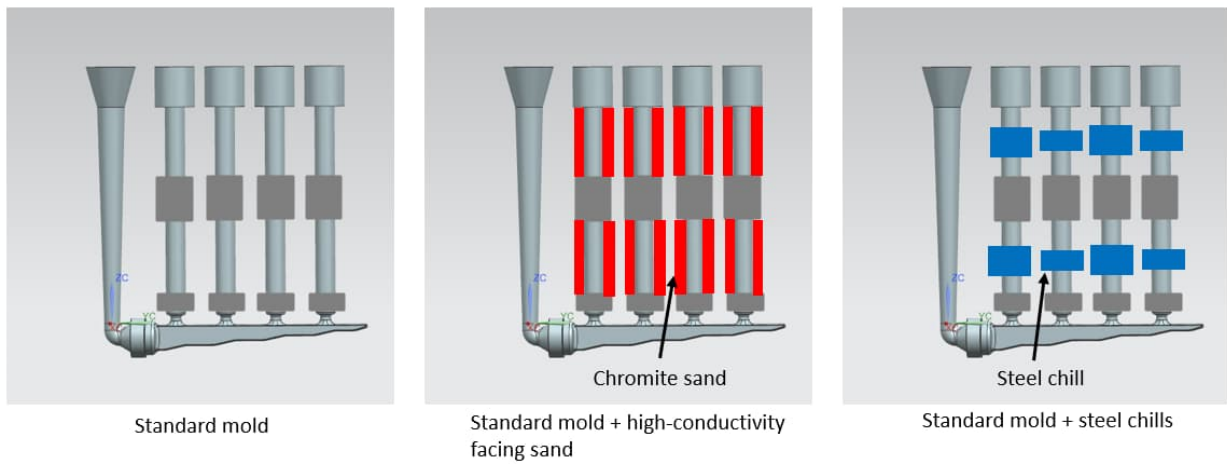


Figure 34. Schematic illustration of the three multiple riser sleeve mold variants. Source: MTU

Multiple transverse and longitudinal sections were extracted from each casting type, from within the regions between the riser sleeves, and no macroporosity was evident. The longitudinal sections were then metallographically prepared for microscopic analysis (up to 500× optical magnification), which showed little to no porosity. Tensile specimens were machined according to ASTM E8-16a Specimen 3 for each casting from the two bars closest to the sprue and tested to failure. The results are shown in

Table 6. All specimens, regardless of which casting they were extracted from, had low total elongation, which was confirmed via scanning electron microscopy fractographic analysis to be caused by shrinkage porosity. The chromite facing sand specimens were similar in strength and elongation to the standard mold, while the chilled specimens showed a higher elongation on average. Fractographic analysis of the fracture surface of two chilled specimens, 3/4-Bar 1-Upper and 3/4-Bar 1-Lower, with significantly different total elongation, showed that the specimen with lower elongation, specimen 3/4-Bar 1-Lower, exhibited significantly more shrinkage porosity on the fracture surface.

Developing a high-strength, high-modulus, castable, cost-effective quality ductile iron for a lightweight crankshaft application in a medium-duty combustion engine began at MTU. A comprehensive literature search was conducted to understand the influencing factors on the elastic modulus of ductile iron. Empirical data in the literature show that the elastic modulus decreases significantly with increasing graphite fraction and with decreasing nodularity. Therefore, one potential strategy for increasing the elastic modulus is to reduce the amount of graphite in the microstructure by reducing carbon; however, castability (i.e., fluidity/mold filling, shrinkage tendency, and hot tearing susceptibility) has been shown to degrade with decreasing carbon content. Because the matrix phase—usually pearlite, ferrite, or some combination of both—makes up much of the microstructure by volume, it is desirable to find an alloying scheme to increase the matrix elastic modulus, thereby reducing the extent to which carbon content must be reduced to achieve the target elastic modulus. The data available in the literature also indicate that cobalt is the most-promising element for increasing the elastic modulus of ferrite when practicality (e.g., cost) is considered. Silicon has been shown to significantly decrease the elastic modulus of ferrite, so, given its relatively high concentration in ductile iron, it is desirable to evaluate the viability of reducing its concentration. The available published data are for binary iron-based solid solutions, however, so the combined effect of cobalt and silicon additions on the elastic modulus of iron needs to be studied to isolate the solid solution effects from graphite effects, as well as in ductile iron alloys to understand their overall effects. To search for additional potential alloying schemes to increase the ductile-iron-matrix elastic modulus, first-principles calculations (i.e., density functional theory) was employed to simulate the combined effects of various unlike solute elements on the elastic modulus of iron.

Table 6. Selected alloy composition for coupon level comparison

Mold Type	Specimen ID*	0.2% YS (MPa)	UTS (MPa)	Total Elongation (%)	Notes
Chills	3/4-Bar-1-Upper	555	703	1.9	
	3/4-Bar-1-Lower	521	522	0.6	
	3/8-Bar-2-Upper	543	730	2.5	
	3/8-Bar-2-Lower	545	711	2.2	
	Average	541	667	1.8	
	St. Dev.	14	97	0.8	
Chromite Facing Sand	Bar-1-Upper	548	641	1.0	
	Bar-1-Lower	550	661	1.5	
	Bar-2-Upper	558	647	1.1	
	Bar-2-Lower	512	533	0.9	
	Average	542	621	1.1	
	St. Dev.	20	59	0.3	
Standard	Bar-1-Upper	538	618	1.0	Fractured outside gauge.
	Bar-1-Lower	571	596	0.7	Fractured outside gauge.
	Bar-2-Upper	541	670	1.4	Fractured outside gauge.
	Bar-2-Lower	528	559	1.0	
	Average	545	611	1.0	
	St. Dev.	19	46	0.3	
* Bar 1 is closest to the sprue; Bar 2 is the next bar away from the sprue. "Upper" indicates the region between the top two riser sleeves, while "Lower" indicates the region between the bottom two riser sleeves. The chill thickness for each chilled specimen is indicated by the fraction in the specimen ID.					

GM 34CrMoV cast-steel alloy was down-selected to optimize the lightweight hollow crankshafts. Prototype crank sand molds were printed with the optimal gating/riser system and poured with the down-selected alloy, as observed in Figure 35(a). After casting, two cranks were sectioned showing no macro porosity, as shown in Figure 35(b). The tensile properties of the cast-steel cranks exceed the targeted properties (e.g., yield strength: >800MPa, ultimate tensile stress: >900MPa, and elongation: >7%). Fatigue properties of samples taken from the cast-steel cranks are comparable with the forged steel crank samples, as seen in Figure 36. It is noted, however, that there are micro shrinkage pores on the fracture surfaces of cast-steel crank samples, which leads to further development of optimizing crank casting process and gating/riser system design.

The newly designed hollow nodular iron crank and bi-material crank can save crank mass by 791 g and 377 g, respectively, in comparison with the forged steel crank. To develop and down-select high modulus and high-strength nodular irons for the crank, laboratory-scale low-carbon equivalent nodular iron castings were successfully made with good castability and graphite nodularity using ultra-seed in-stream inoculant. An investigation on the improving iron matrix modulus with solid solution was also conducted based on density functional theory modeling and experiments.



(a)



(b)

Figure 35. Pictures showing hollow cast-steel crankshafts made (a) and longitudinal sectioning of a crank (b). Source: GM.

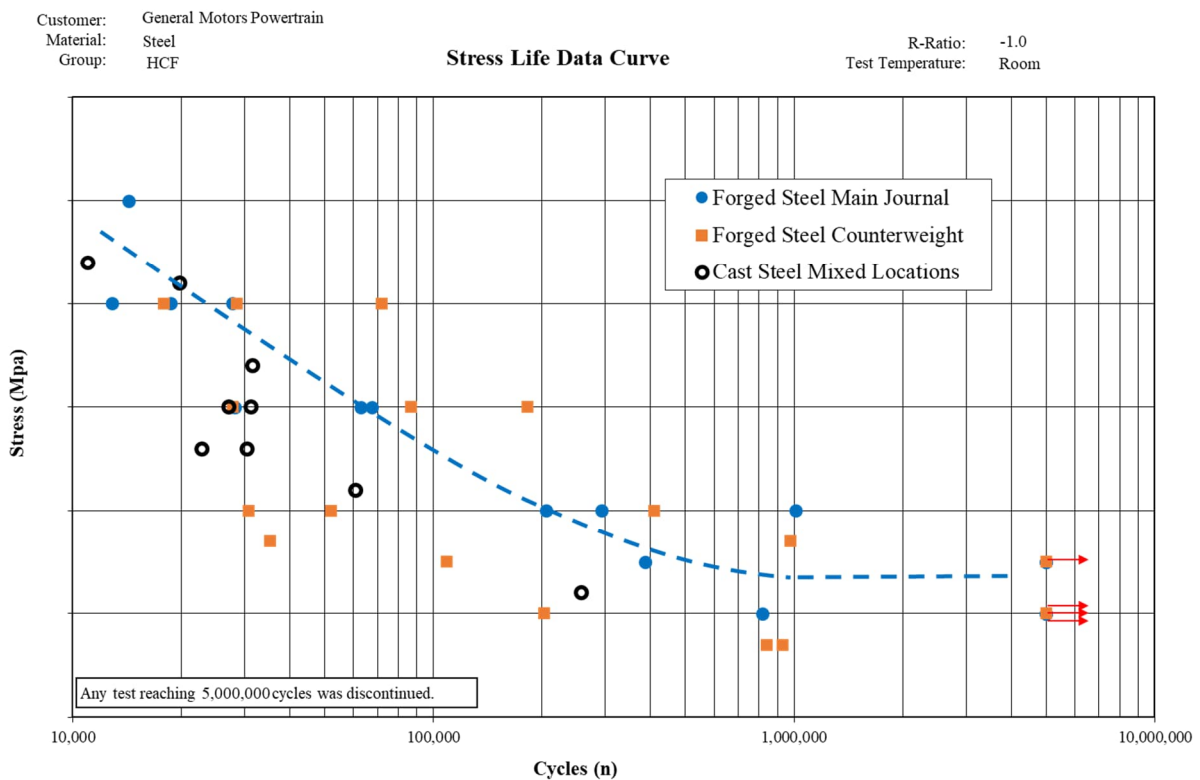


Figure 36. Fatigue S-N data comparing the fatigue properties of cast-steel crank samples with the forged steel ones. Source: GM.

Pistons

GM modified the design of the L8T V8 engine piston to account for the additive manufacturing (AM) process and material rather than the casting and machining state of the art. The first AM piston is slightly lighter (e.g., ~10 g) than a cast-Al production piston. CAE analysis indicated that the AM piston design meets the piston safety factor (PSF) requirements. Al-Ce based alloy was down-selected for printing the first set of pistons, as shown in Figure 37. Figure 38 shows the mechanical properties of as-printed Al-Ce based alloy tested.



Figure 37. Additively manufactured pistons with an AlCeNiMnZr alloy. Source: ORNL.

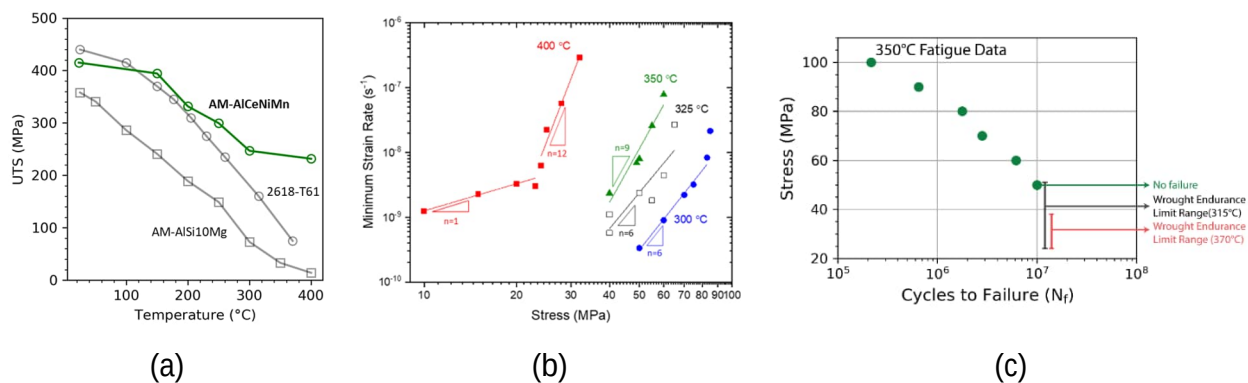


Figure 38. (a) Ultimate tensile strength, (b) creep properties, and (c) fatigue strength of Al-Ce based alloy at various temperatures. Source: ORNL.

To further optimize AM process and develop high quality AM pistons, cellular automata (CA) modeling was utilized. To more accurately model microstructure evolution during powder bed fusion AM, thermal diffusion was added to the current CA model. The thermal profile in and around the melt pool strongly influences the formation of grains during solidification. Figure 39 shows a new feature of the simulation. To simulate features less than 10 microns, the CA domain in the melt pool was subdivided into a 1-micron grid, which reflects the experimental observation.

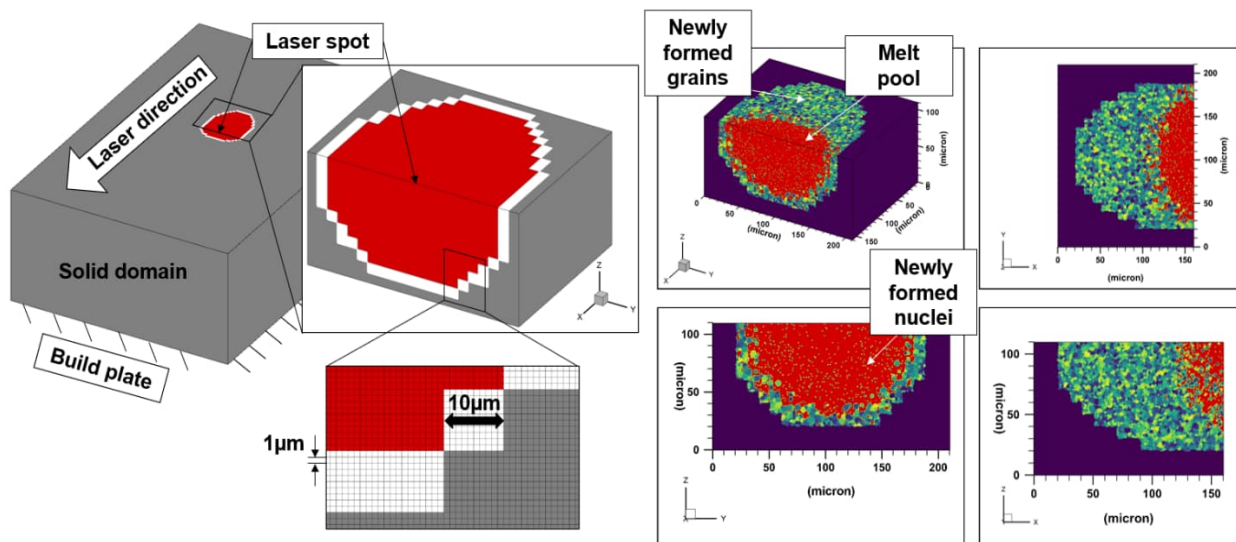


Figure 39. CA simulation of melt pool and solidified grain structure during AM with the refined grid size. Source: OSU.

Figure 40 shows CA simulated columnar to equiaxed transition (CET) microstructure of Al-8.6%Si-0.32%Mg-0.44%Fe-0.22%Mn alloy during cooling rate of 5-10K/s. Figure 41 shows an example of AM grain microstructure evolution for a vertical multi-pass build case.

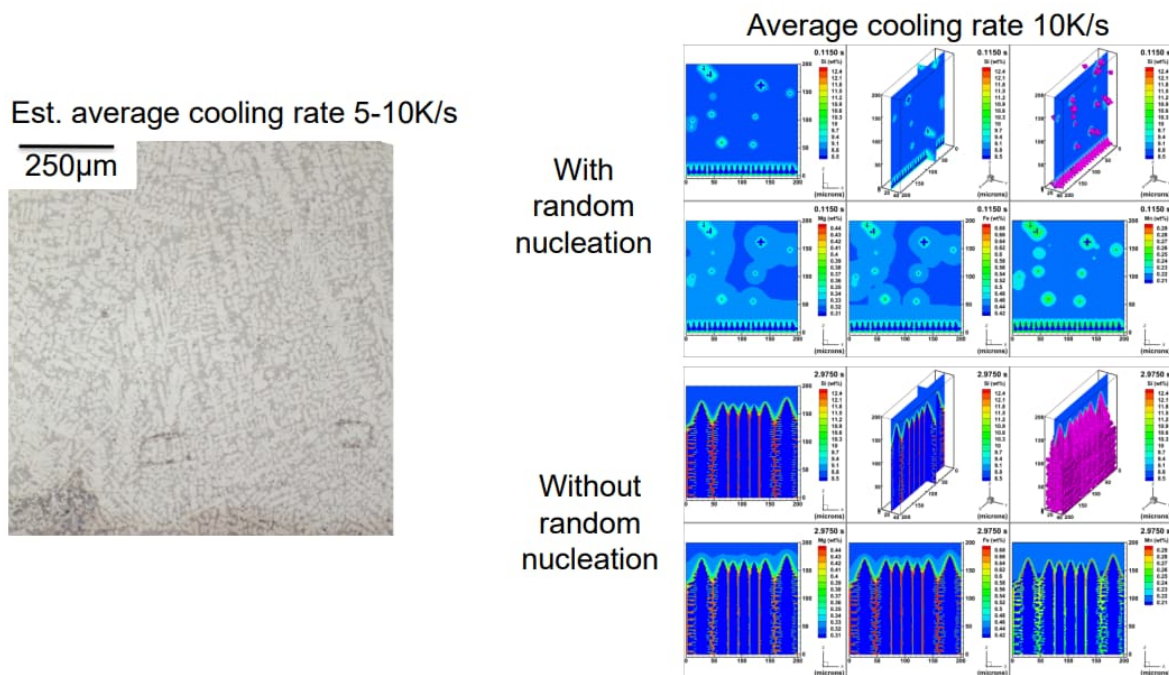


Figure 40. CET CA simulation for cast Al alloy solidified under an average cooling rate of 5-10 K/s, with or without random nucleation. Source: OSU

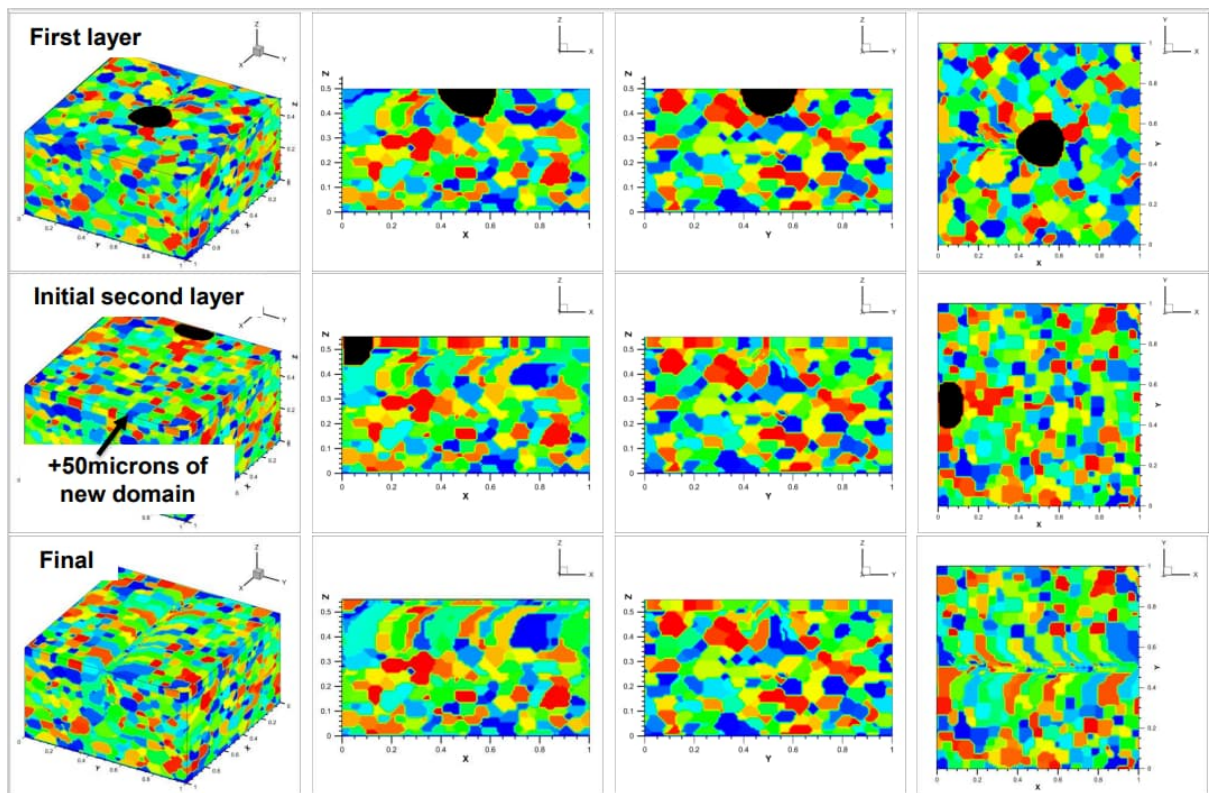


Figure 41. CET CA simulation of AM grain structure. Laser speed of 1.5M/S and thermal properties of AISi10 alloy used. Top row shows thermal profile, bottom figures show individual grains.
Source: OSU

To further improve CA model accuracy, Rappaz random nucleation model was adopted to simulate the random nucleation of grains ahead of the solidifying dendrites. Figure 42 shows a good agreement between the experimental and simulated CET microstructure after CA model enhancement.

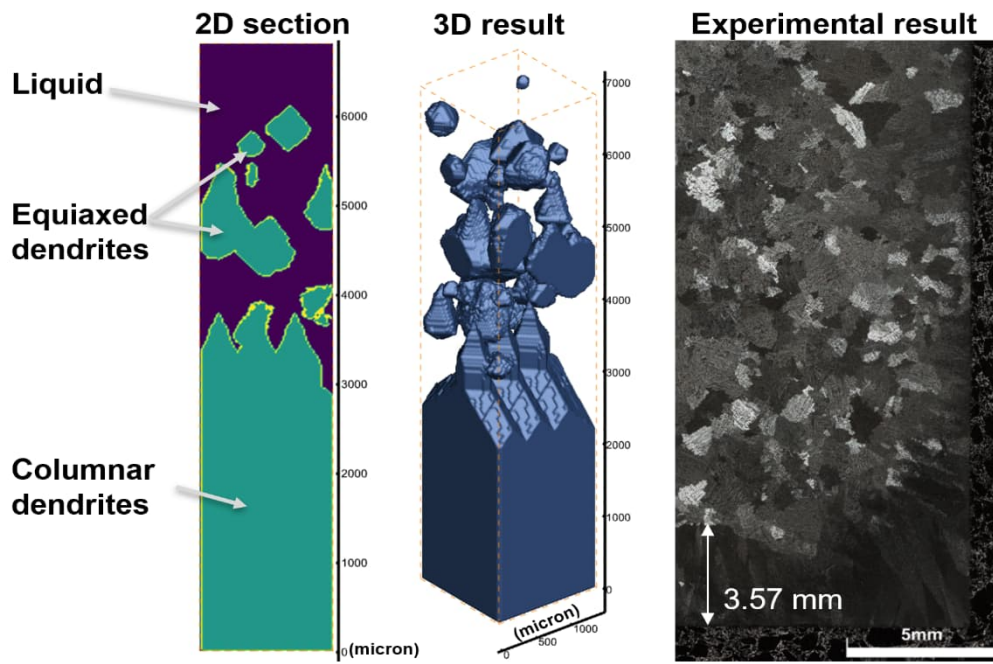


Figure 42. CA modeling of CET structure and comparison with experimental microstructure.
Source: OSU.

The CA casting model was further updated to incorporate the effect of hydrogen porosity. In the CA model, the diffusion of hydrogen in the domain (e.g., solid, liquid, solid/liquid cells) is calculated to simulate the hydrogen concentration. The nucleation and growth of hydrogen pores is also considered. Figure 43 shows a simulation example of a high-pressure die-casting process, which provides a look at the phases (top left), hydrogen concentration field (bottom left), 3D grain and pore structure (top right), and 3D pore structure (bottom right). From Figure 43, it is possible to see that the hydrogen content in the liquid decreases around the porosity as it is absorbed into the growing pore. The hydrogen porosity model was also coupled with the metal pressure during the solidification process, which impacts the pore shape. The updated casting CA model is suitable for simulating hydrogen porosity in the casting conditions ranging from sand casting to high-pressure die-casting.

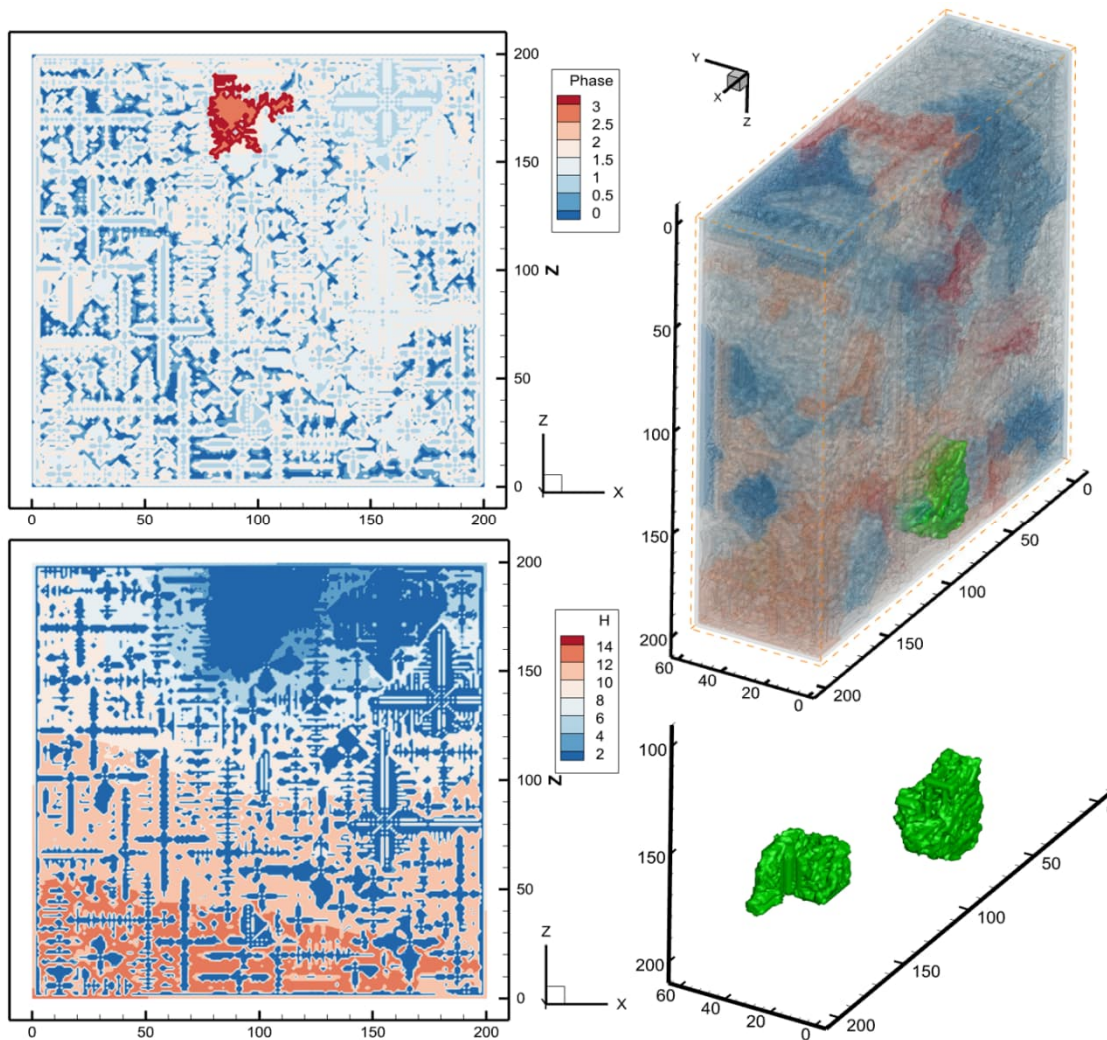


Figure 43. Casting CA simulation results for HPDC process showing simulated hydrogen porosity. Source: OSU.

The AM CA model was enhanced to include functions related to the prediction of hydrogen pores. The model adheres to Sievert's law, assuming a local equilibrium of hydrogen concentration at the hydrogen pore interface. A boundary flux is computed, and this, in turn, contributes to the net flux of the pore, which is further applied to the growth calculations. The outcomes reveal the possible presence of hydrogen pores within the AM melt pool, exhibiting a range of sizes, as seen in Figure 4.

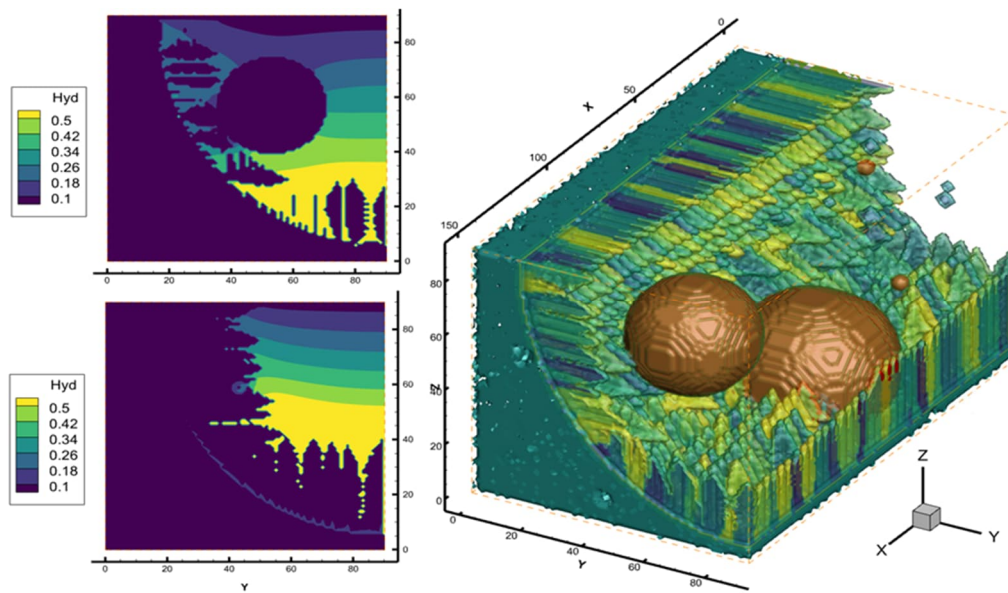


Figure 44. The AM-CA model showing a hydrogen concentration map at two YZ planes (large and small pores, left) of the solid 3D model (pores shown in brown color, right). Source: OSU.

6. Advanced LMHE Engine Technology Validation

Based on our PHASE 1 research and development initiatives, advanced combustion and materials technologies were developed and down-selected for the proposed medium-duty truck engine capable of meeting the requirements. The large displacement, normally aspirated V8 concept was selected over the smaller displacement, turbocharged options as the normally aspirated large-displacement V8 would do so much more cost effectively (estimated engine cost saving 37%).

6.1 Design and Build Engines to Facilitate Test Cell Evaluation of Proposed Medium Duty Truck Solution Incorporating Components

Although much of the engine was designed to facilitate CAE analysis and casting trials, significant design work was needed to produce an engine design that incorporates both the advanced combustion system (dual-ignition, uniform combustion cooling, and charge motion control, etc.) and the mass reduction components, particularly the aluminum block and heads, developed in PHASE 1 that could be manufactured for further development and durability testing. This engine was designated the “PHASE 2” engine. Figures 45 through 49 detail many of the critical components, culminating in the full engine assembly in Figure 50.

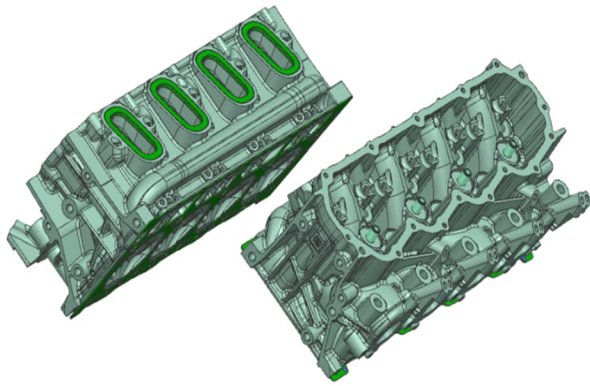


Figure 45. Cylinder head system. Source: GM

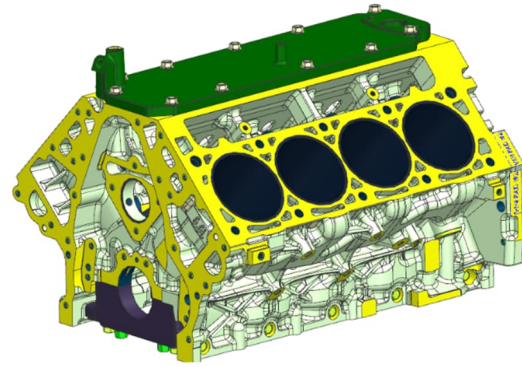


Figure 46. Engine block system. Source: GM

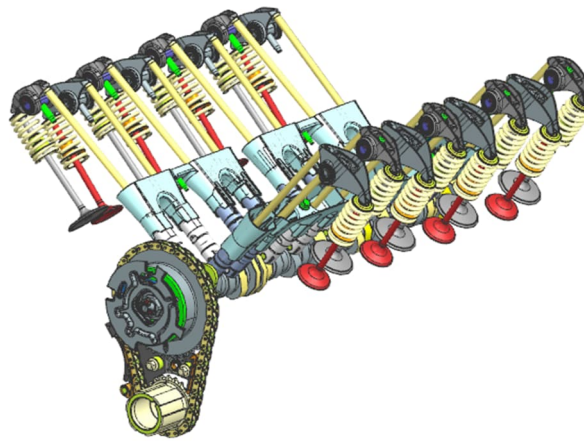
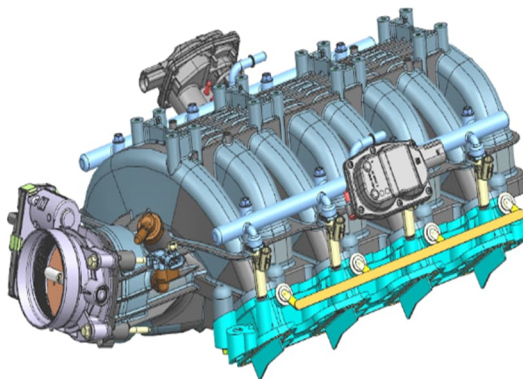
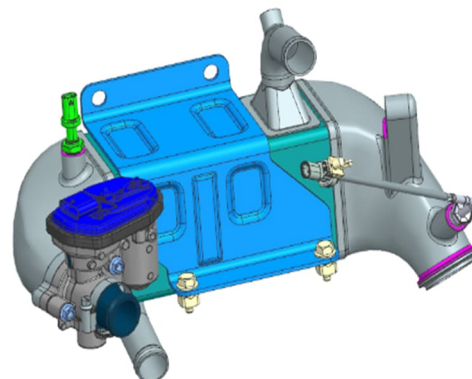


Figure 47. Valvetrain system. Source: GM



(a)



(b)

Figure 48. (a) Induction and (b) EGR systems. Source: GM

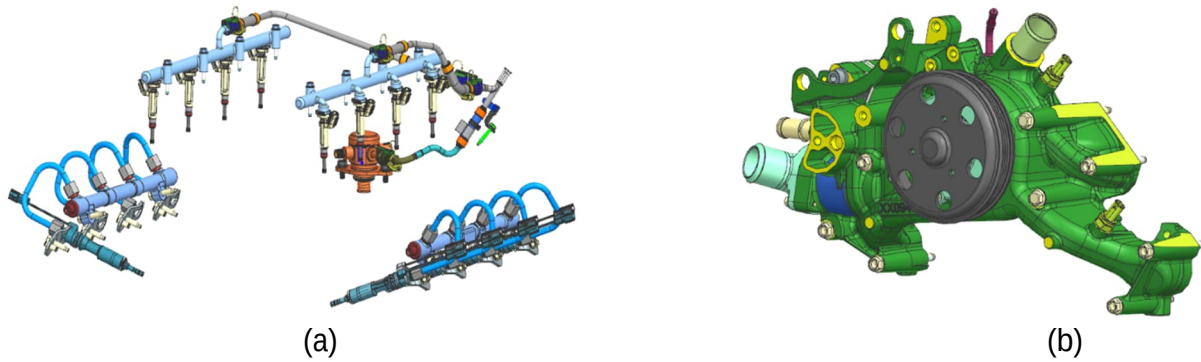


Figure 49. (a) Fuel and (b) coolant pump systems capable of 'ultra' high pressure fuel injection and advanced combustion cooling enhancement. Source: GM

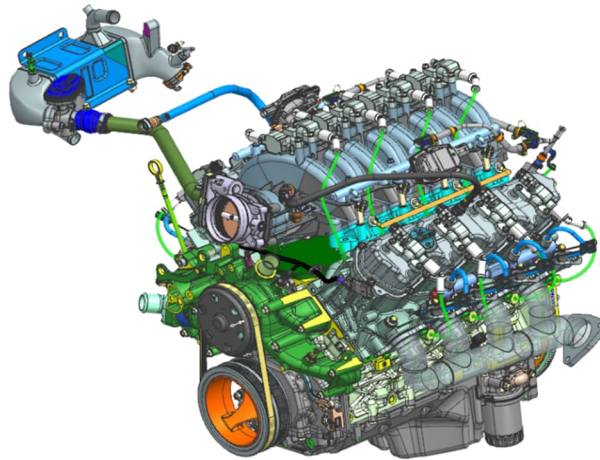


Figure 50. Complete PHASE 2 engine system. Source: GM

With the developed material solutions, the PHASE 2 engine mass is more than 15% lighter than the baseline engine, while the engine displacement increased from 6.0 L to 6.6 L. Table 7 compares the PHASE 1 engine fuel economy improvement measured from various advanced combustion technologies with the CAE model predictions. It can be noted that the reported fuel economy improvement of 9.1% is on track to meet or exceed the project target of 10% once the pre-chamber spark plug benefit is added.

Table 7. Comparison of measured and predicted new technologies to baseline L96 engine at weighted average GEM cycle operating points

Measured Weighted Fuel Economy Improvement		Predicted Weighted Fuel Economy Improvement from Simulation	
L96 Baseline		L96 Baseline	
PHASE 1	0.7%	PHASE 1	
Charge Motion Control Valve (CMCV)	2.8%	PHASE 1 + CMCV	4.4%
E-EGR	1.8%	E-EGR	4.3%
Full Authority Cylinder Deactivation	TBD	Full Authority Cylinder Deactivation	1.3%
UHP Direct Fuel Injection + PFI	2.5%	UHP Direct Fuel Injection	1.8%
Passive Pre-Chamber Ignition	TBD	Passive Pre-Chamber Ignition	2.8%
TOTAL	7.8%	TOTAL	14.6%

6.2 The Highest Payoff Materials and Manufacturing Solutions for Key Engine Components

Cylinder Block and Heads

Through-process modeling and local materials property simulation by following the ICME approach that had been continuously conducted on the PHASE 2 cast Al cylinder head and engine block, the cast steel and nodular iron cranks, as well as the cast and AM Al pistons, were all built to ensure their designs to meet the necessary performance and durability requirements. Figure 51 shows the through process modeling approach flow for the low-pressure precision sand casting (LPPSC) Al engine block. Figure 52 shows through-process modeling and durability analysis flow for the PHASE 2 cast-Al engine block development using the ICME capability at GM. After the block casting geometry and gating/riser system was optimized, the comprehensive casting process modeling was carried out to simulate the mold filling and solidification. With the modeling capabilities developed at GM for multiscale defects (e.g., porosity and oxides) and microstructure simulation, nodal-based microstructure (e.g., the secondary dendrite arm spacing) and defect population (e.g., porosity volume fraction and sizes) were predicted throughout the entire block casting. Based on the simulated defect and microstructure from casting process modeling, location-specific material properties (e.g., tensile and fatigue properties) were predicted and incorporated in the CAE performance and durability analysis of the block casting. Similarly, the through process modeling and ICME approach were applied to other castings such as cast steel crankshaft.

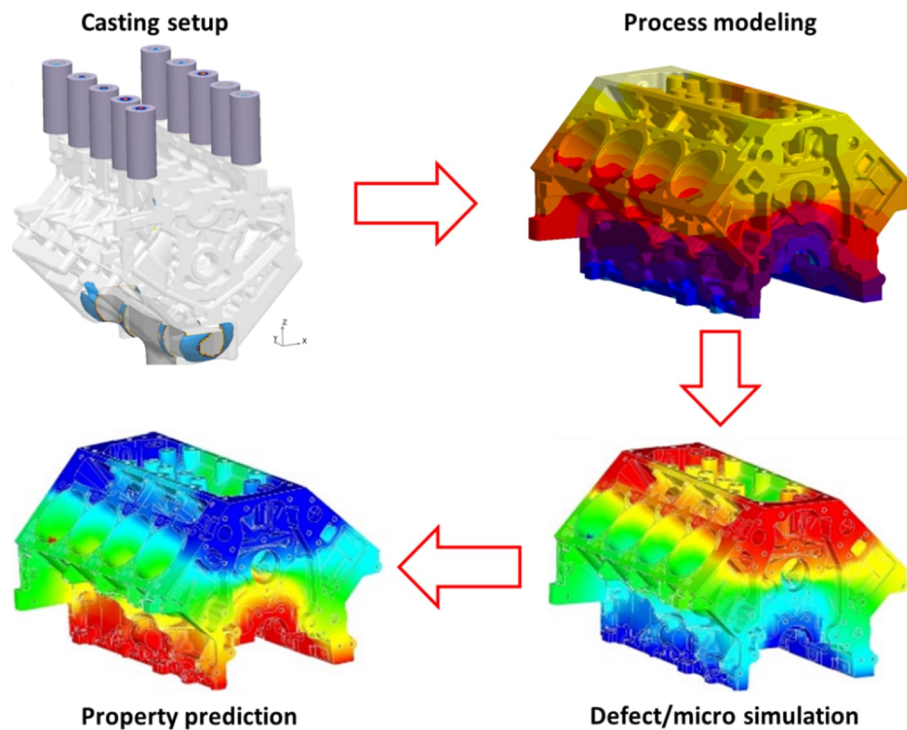


Figure 51. Through process modeling approach flow for a cast Al block. Source: GM

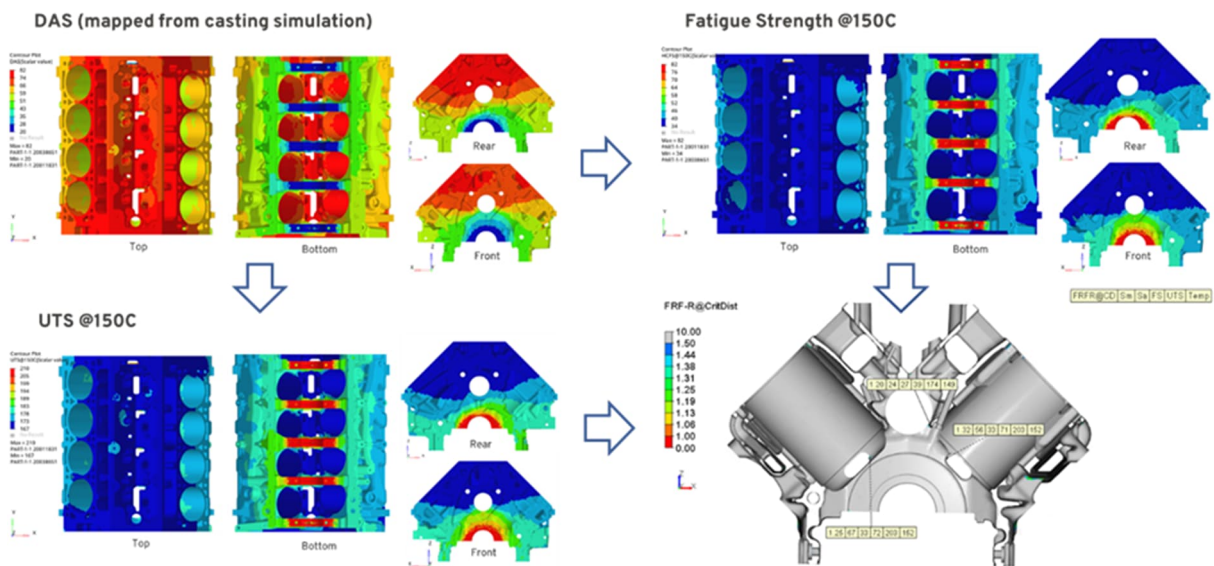


Figure 52. An example of through-process modeling and durability analysis flow for PHASE 2 cast-Al engine block development. Source: GM.

A novel low-pressure precision sand casting (LPPSC) process was developed for casting high-quality Al cylinder heads and engine blocks through a comprehensive casting process simulation and multiscale defect and microstructure modeling, gating, and riser system, as well as LPPSC process parameter optimization. The PHASE 2 cast aluminum engine blocks are shown in Figure 53(a) and the cylinder heads are shown in Figure 53(b). Both were cast using the LPPSC.



(a)



(b)

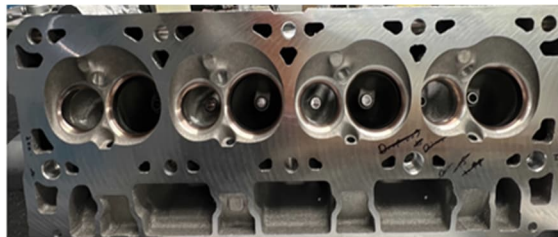


Figure 53. (a) PHASE 2 cast-Al engine blocks and (b) cylinder heads. Source: GM.

(a)

(b)

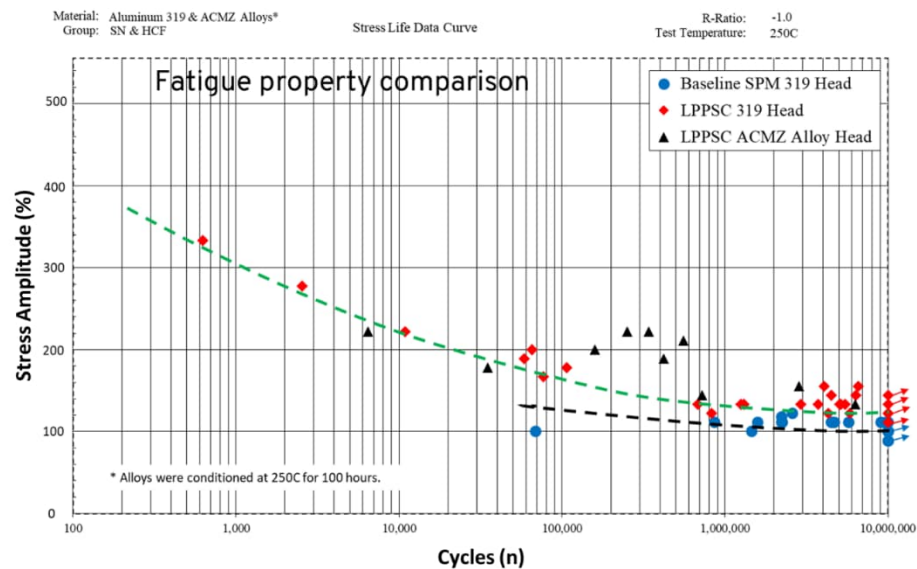
Figure 54(a) shows tensile properties of the cylinder heads made by LPPSC process with different alloys. Figure 54(b) compares the fatigue properties for the baseline and the LPPSC cylinder heads. For the same alloy (i.e., A319), the LPPSC process has improved fatigue properties of the heads by at least 20% compared with baseline heads. ORNL's aluminum-copper-magnesium-zirconium (ACMZ) alloy demonstrated very high potential of improving both tensile and fatigue properties of the cylinder heads at elevated temperatures.



Tensile strength (UTS) comparison

Location	Test Temperature (°C)	Baseline 319 Head Tensile Strength (MPa)	LPPSC 319 Head Tensile Strength (MPa)	LPPSC ACMZ Head Tensile Strength (MPa)
Deck Face	250	98	104	184

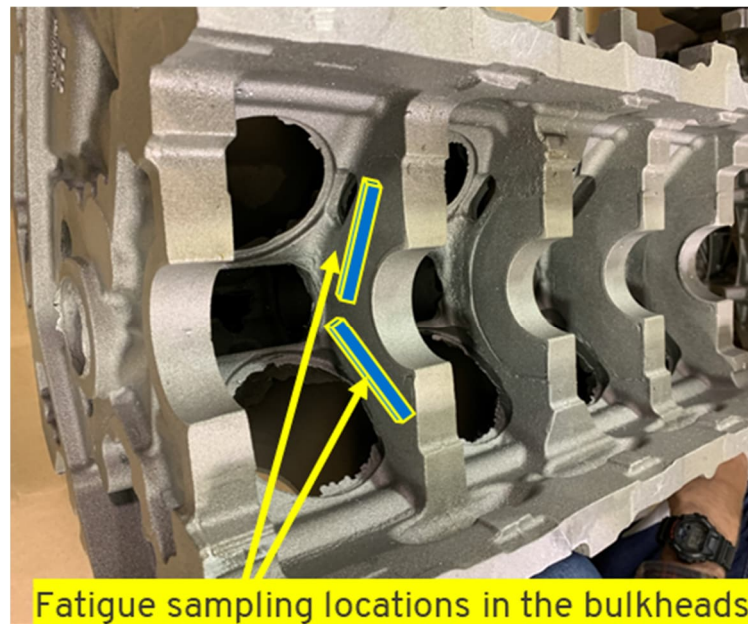
(a)



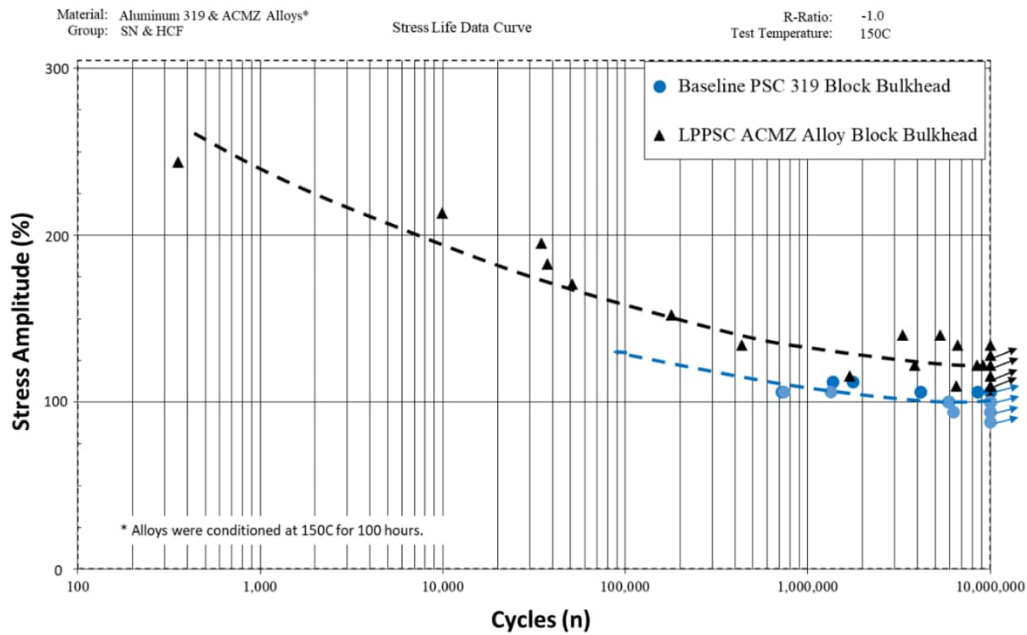
(b)

Figure 54. (a) Tensile strength comparison and (b) fatigue properties comparison of cylinder heads made by the developed LPPSC process. Source: GM.

Figure 55(a) shows the bulkhead sampling locations for fatigue testing. Fatigue properties of engine blocks made by the developed LPPSC process are shown in Error! Not a valid bookmark self-reference.(b). Similar to the findings with cylinder heads, the engine blocks made by ORNL's ACMZ alloy also demonstrated improved fatigue strength by at least 25% compared with cast-Al engine blocks made of A319 alloy.



(a)



(b)

Figure 55. (a) Fatigue sampling locations in the bulkhead and (b) properties of engine blocks made by the developed LPPSC process. Source: GM.

Piston

The PHASE 2 piston was designed and printed with ORNL's Al-Ce based DuAlumin-3D alloy, as shown in Figure 56 and Figure 57(a). The PHASE 2 AM piston is ~11g lighter than cast Al production piston. CAE durability analysis indicates that the AM piston design exceeds the piston safety factor (PSF) requirements. Figure 57(b) and Figure 58 show the tensile and fatigue properties of the AM pistons from ORNL's Al-cerium (Ce)-based DuAlumin-3D alloy together with cast-Al production pistons, confirming that the DuAlumin-3D alloy exceeds the cast alloy on every metric. At room temperature

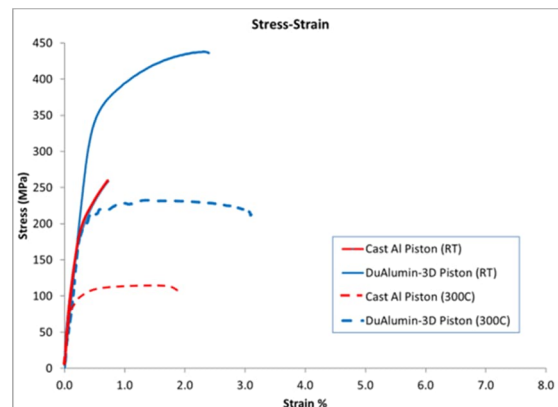
(RT), the DuAlumin-3D alloy has significantly higher tensile strength of 443 MPa, but also more than twice the ductility compared with a cast-Al piston alloy. The comparative advantages of the DuAlumin-3D alloy are even more pronounced at 300°C. Tensile strength of the DuAlumin-3D alloy is roughly twice that of the cast-Al piston alloy, with more than a 50% improvement in elongation to failure. [16] On fatigue, the DuAlumin-3D alloy AM piston samples also display a remarkably superior fatigue performance compared to the cast-Al alloy piston samples, as well as AM AlSi10Mg materials. The high cycle fatigue strength at 10^7 cycles of the DuAlumin-3D alloy AM pistons at 300°C is 105 MPa, which is a remarkable 50% improvement over the cast-Al alloy pistons of 70 MPa. The improvement of fatigue properties in low cycle fatigue region at $<100,000$ cycles for the DuAlumin-3D AM pistons is even more pronounced due to the extremely refined AM microstructure, as observed in Figure 58. As expected, the fatigue strength of AlSi10Mg AM piston samples at 300°C is much lower than that of cast-Al pistons.



Figure 56. AM printed PHASE 2 pistons. Source: ORNL



(a)



(b)

Figure 57. (a) AM DuAlumin-3D alloy piston and (b) its tensile properties compared with cast-Al pistons. Source: GM.

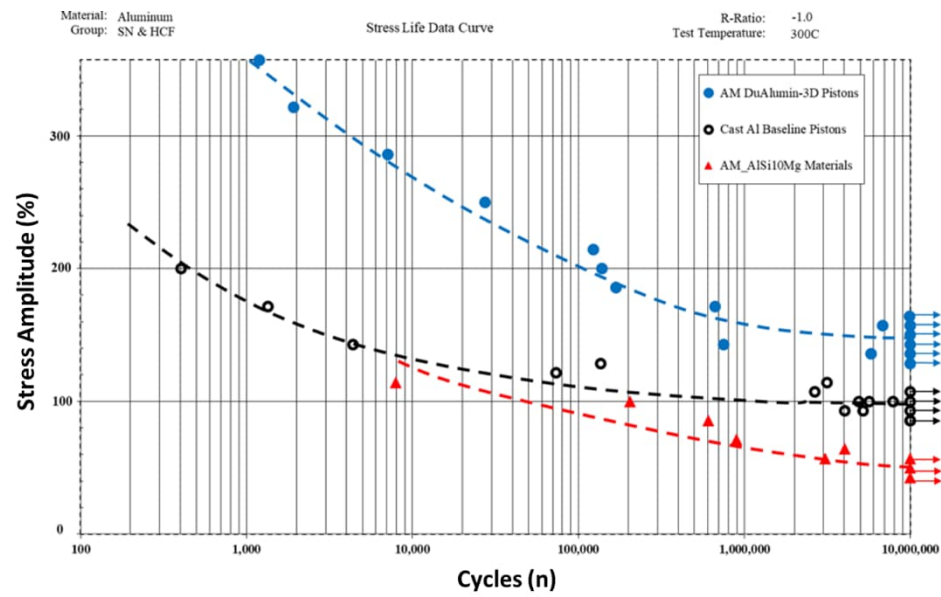


Figure 58. Fatigue properties of AM DuAlumin-3D alloy pistons, cast-Al production pistons, and AM AlSi10Mg piston sample. Source: GM.

(a)

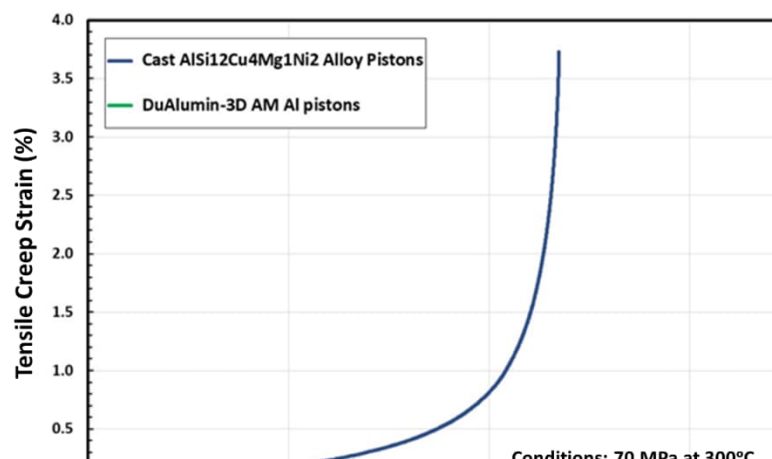
(b)

Figure 59(a) shows the creep strain as a function of exposure time for both DuAlumin-3D alloy and cast-Al piston alloy tested at 300°C and 70 MPa. At the stress and temperature tested, DuAlumin-3D alloy is clearly superior to high-performance cast-Al piston alloy, particularly with the increase in exposure time. The cast-Al piston alloy sample ruptured around 20 hours, while DuAlumin-3D had little creep even at 300 hours.

(a)

(b)

Figure 59(b) shows the Charpy impact test results of the DuAlumin-3D alloy AM pistons at both RT and 250°C. The Charpy impact energy of the DuAlumin-3D alloy piston samples at 250°C and 8.6 ft-lbs is more than three times better than their impact energy at RT (2.1 ft-lbs). In comparison with cast-Al pistons, the DuAlumin-3D AM piston samples are superior at both RT and 250°C. The Charpy impact energy of the notched cast-Al piston samples is only 0.34 ft-lbs at both RT and 250°C. The high Charpy impact energy of the DuAlumin-3D AM pistons is mainly attributed to the refined nano-scale solidification eutectic phase particles.



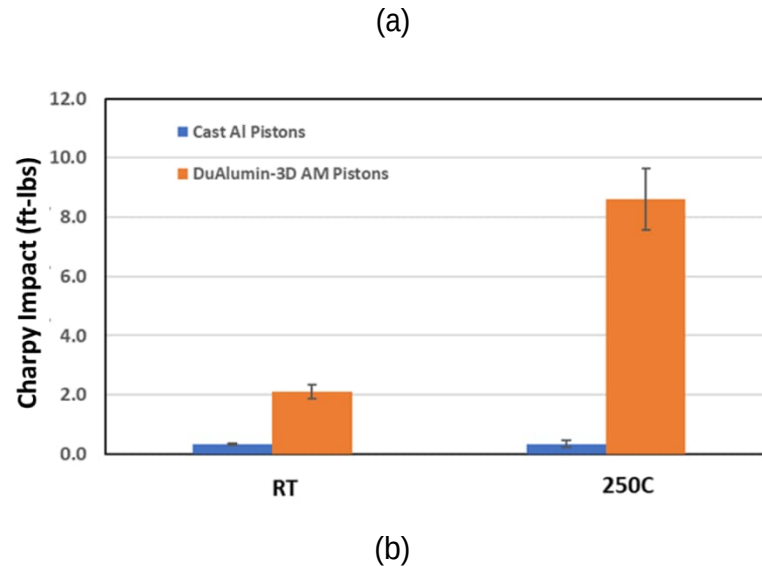


Figure 59. (a) Creep curves (ϵ -t) of the DuAlumin-3D alloy and the cast-Al piston alloy tested at 300°C and 70 MPa and (b) Comparison of Charpy impact energy of notched specimens between the DuAlumin-3D AM pistons and cast-Al alloy pistons. Source: GM.

Crank Shaft

A new design of chills, gating, and riser system as well as optimal casting process produced high-quality cast steel cranks with minimum microporosity in PHASE 2, as shown in Figure 60. Fatigue performance of the PHASE 2 cast steel cranks with the new gating system (e.g., the 2nd set cranks) is much improved in comparison with the cranks made in PHASE 1 (e.g., the 1st set cranks) particularly in the high cycle fatigue regime (e.g., > 300,000 cycles), as observed in

Figure 61. The PHASE 2 steel cranks have similar fatigue performance of the forged steel baseline cranks. After hot isostatic pressing (HIP), the PHASE 1 cranks show better fatigue performance than the forged ones. It is believed that the PHASE 2 cranks should do the same after HIP, indicating that the cast steel alloy developed in the project has inherent advantages over the baseline forged steels.

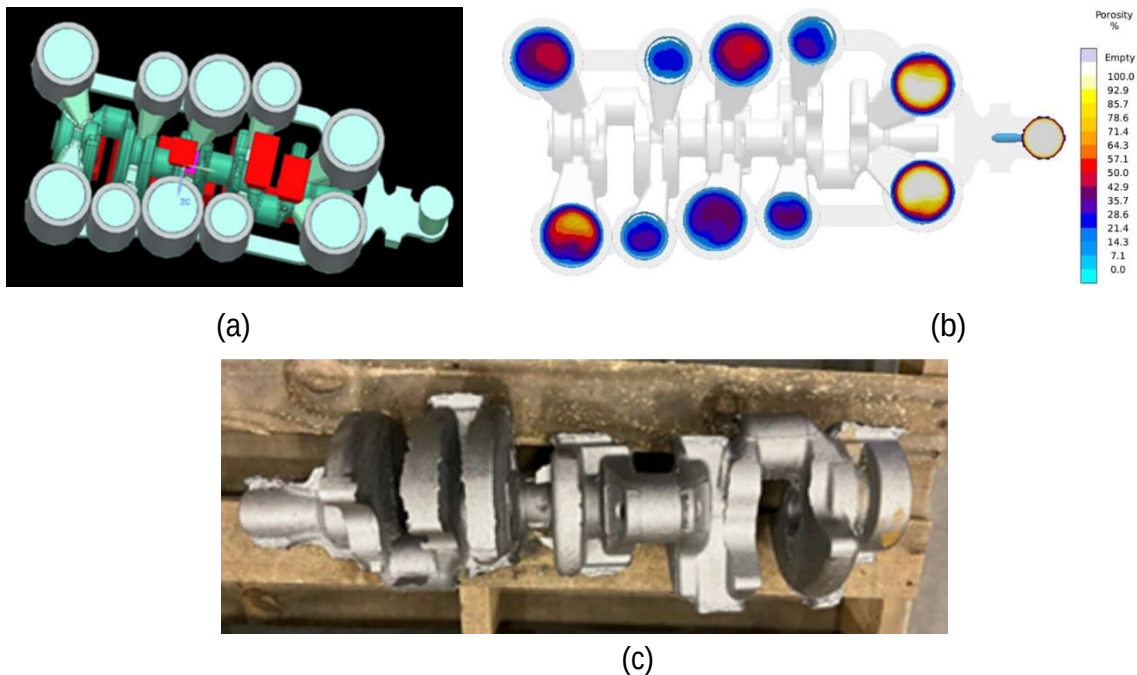


Figure 60. (a) New cast steel crank casting design, (b) casting process simulation tool used in process optimization and casting quality (e.g., porosity) prediction in cast steel crank, (c) a PHASE 2 crank made with optimal chill, gating/riser system, and casting process. Source: GM

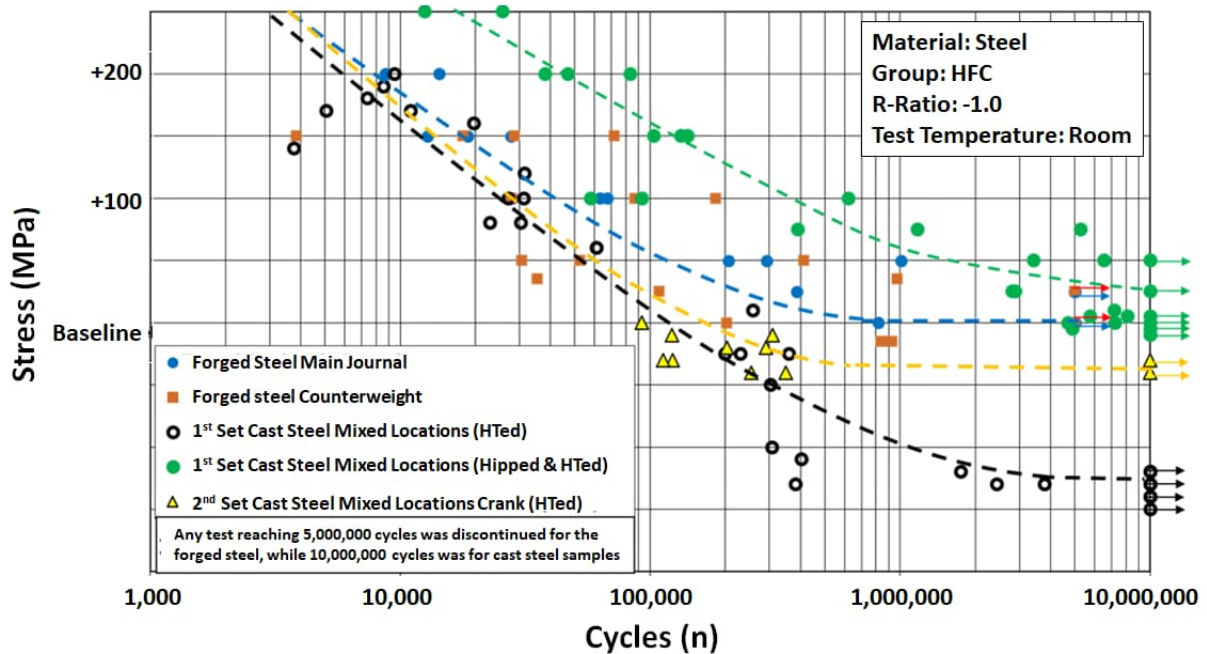
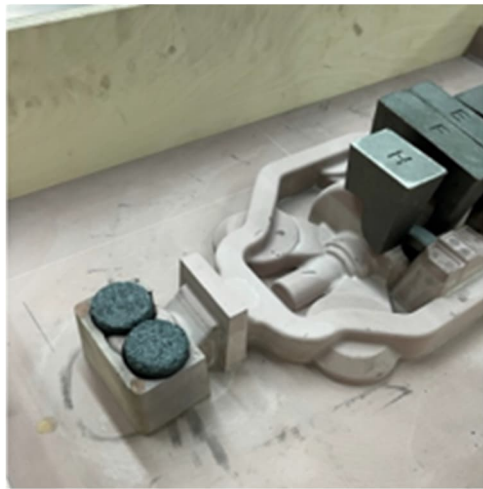
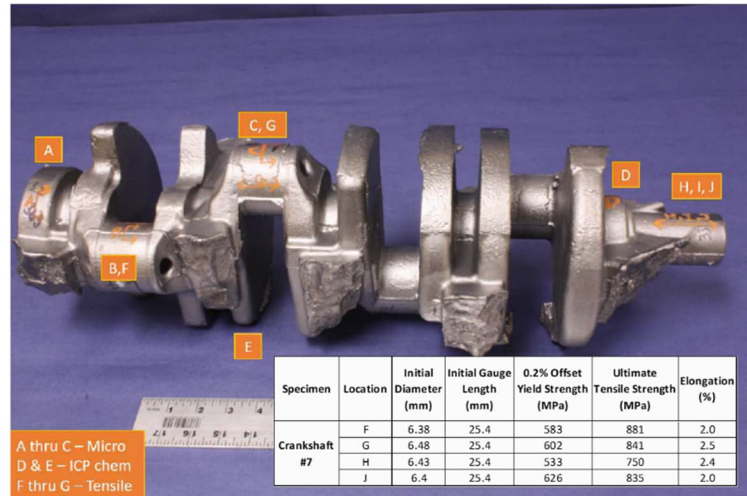


Figure 61. S-N fatigue data of cast tell cranks in various conditions compared with the forged baseline cranks. Source: GM

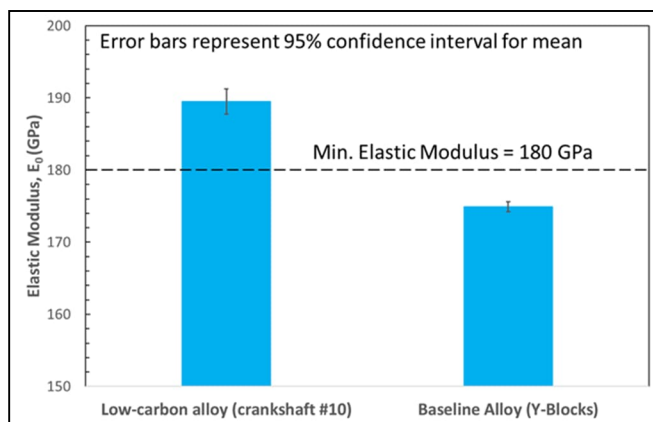
High-modulus and high-strength ductile iron cranks were developed using an innovative low-carbon alloy and two-step inoculation process, Figure 62(a) and (b). Tensile properties of the developed hollow ductile iron crank exceed the tensile property requirement and particularly the modulus of the low-carbon alloy ductile iron crank is increased by >10% because of the refined graphite nodules, increased nodularity and matrix strength, as shown in Figure 62(c). The microstructure of the low-carbon alloy crank is shown in Figure 62(d).



(a)



(b)



(c)



(d)

Figure 62. (a) In-mold inoculation for ductile iron crank; (b) nodular iron crank with tensile and micro-sampling locations and tensile properties; (c) modulus comparison of the developed low-carbon alloy crank with baseline alloy; and (d) microstructure of the low-carbon alloy crank.

Source: GM.

Camshaft

High-performance austempered ductile iron (ADI) camshafts have also been developed.

Figure shows the stress vs number of cycles fatigue data of the ADI camshafts developed in both PHASE 1 and PHASE 2. In comparison with the camshafts developed in PHASE 1, the PHASE 2 camshafts show better fatigue properties, and the high cycle (10^7 cycles) fatigue strength is increased by 10~15%. Figure compares the surface and subsurface residual stresses between the camshafts made in both phases. The camshafts made in PHASE 2 show lower subsurface tensile residual stresses in comparison with the PHASE 1 camshafts. The combination of the increased fatigue strength and the reduced subsurface tensile residual stresses shall improve the camshaft performance and durability.

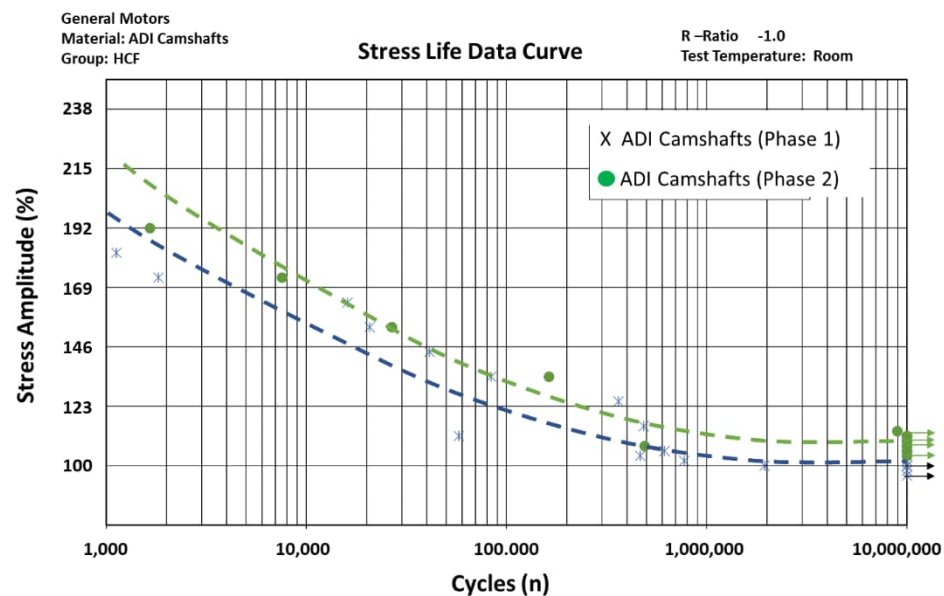


Figure 63. Stress vs number of cycles fatigue data of ADI camshafts. Source: GM.

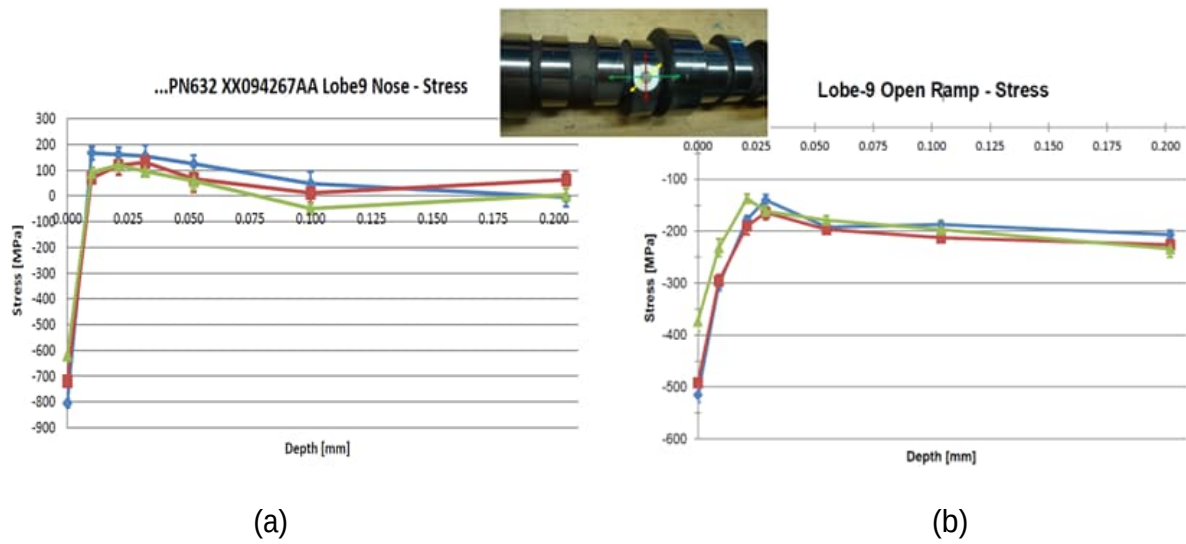


Figure 64. Residual stress comparison between PHASE 1 and PHASE 2 ADI camshafts. Source: GM.

7. LMHE Engine Technology Demonstration

7.1 Test Cell Fuel Performance Evaluation of Proposed Medium Duty Truck Solution

The combustion and materials teams worked in parallel to build PHASE 2 engines that could evaluate the fuel economy improvement performance and the durability performance of the mass reduction activities. These were referred to internally as the “Fuel Economy” (FE) engine, built and tested by the combustion team, and the “Durability” (DE) engine, built and tested by the materials engineering team; FE and DE respectively. This allowed each team to focus their test plans on their specific aspect of the project deliverables, and not lose program timing troubleshooting test cell or part performance issues that directly relate to their deliverables. The PHASE 2 engine shown in Figure 65 was designed and built to demonstrate fuel economy performance. The PHASE 2 FE engine contains the following key features: (1) two spark plugs/cylinder with supporting ignition system; (2) ultra-high-pressure direct inject fuel system design integrated with cylinder head; (3) active charge motion control valve integrated into intake assembly; (4) high-pressure exhaust gas recirculation system; (5) cast aluminum (Al) block; (6) fabricated tubular exhaust manifolds; (7) plastic rocker covers and valley tray; and (8) split cooling with valve bridge drilling, see Figure 66. The PHASE 2 FE performance engine was tested with the procedure like PHASE 1 process.

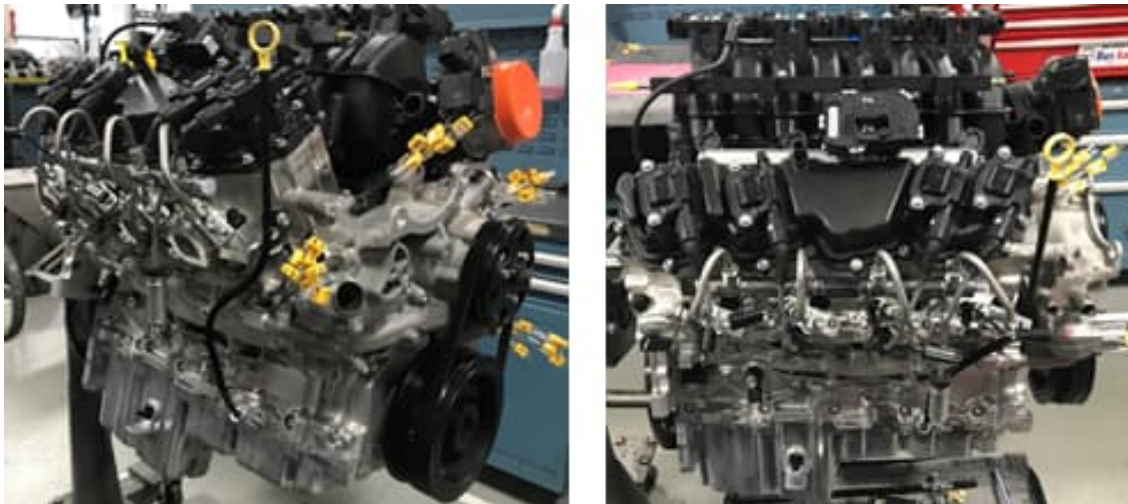
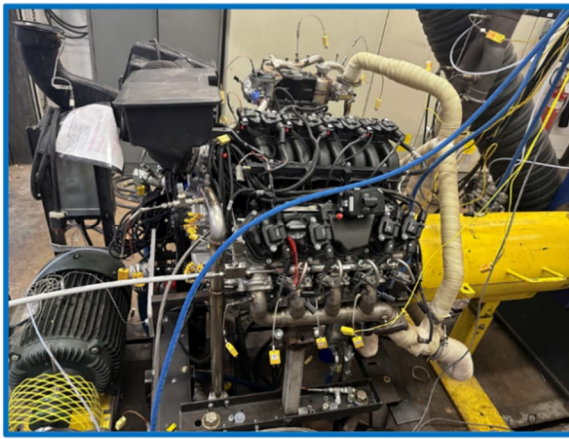


Figure 65. Completed PHASE 2 fuel economy test engine build (front and side views). Source: GM.



Key Features

- Phase 2 combustion system with 2 spark plugs/cyl and supporting ignition system
- UHP DI fuel system design integrated with cylinder head
- Active charge motion control valve integrated into intake asm
- High Pressure (HP)-Cooled EGR system
- Aluminum Block
- Fabricated tubular exhaust manifolds
- Plastic rocker covers and valley tray
- Split cooling with valve bridge drilling

Predicted Weighted Fuel Economy Improvement from L96 Baseline

• PHASE 2 Comb. Sys. + Charge Motion Control Valve	4.4%
• HP-Cooled EGR	4.3%
• Ultra High Press. (UHP) Direct Fuel Injection (+1 CR)	1.8%
TOTAL:	10.5%

Figure 66. PHASE 2 FE performance engine and its key features and the selected fuel efficiency technologies. Source: GM

The PHASE 2 engine fuel economy performance was tested at fully develop optimal part load engine operation and verified at key test points for final vehicle fuel economy simulation, as shown in Figure 67. The PHASE 2 engine was able to achieve min brake specific fuel consumption (BSFC) 215.7 g/kW-Hr; and an optimum combustion phasing over a wide range of gas emissions model (GEM) operating points.

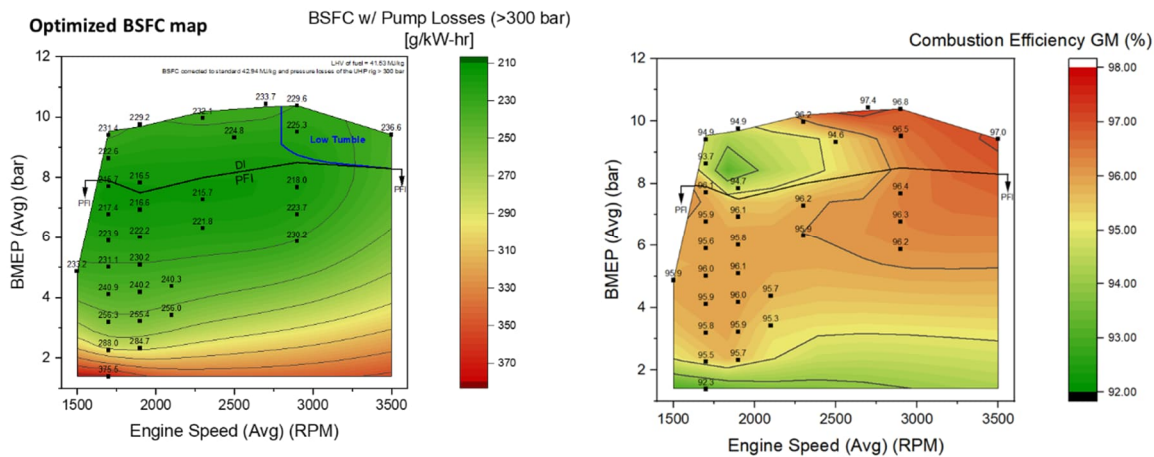


Figure 67. PHASE 2 medium duty solution FE engine optimized BSFC map. Source: GM

The PHASE 2 FE engine shows the improved combustion performance over PHASE 1 variants. It has the faster burn rates and an increased exhaust gas recirculation (EGR) tolerance and efficiency. The PHASE 2 engine has also demonstrated abilities: 1) to maintain combustion stability targets at all points with optimum calibration; 2) to achieve full load targets with optimum calibration, as shown in Figure 68.

Full Load Results:

- Peak Torque = 606 Nm (446 lb-ft) @ 4000 RPM
- Peak Power = 280kW (375 hp) @ 5000 RPM

Full Load Targets/L96 Baseline:

- Peak Torque = 518 Nm (382 lb-ft)
- Peak Power = 262 kW (352 hp)

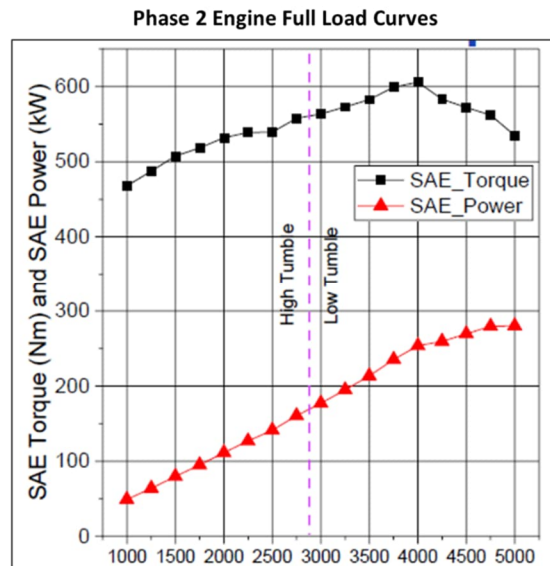


Figure 68. PHASE 2 medium duty solution FE engine full load performance. Source: GM

The PHASE 2 FE engine improves CA50 with premium fuel to tolerate a higher compression ratio from 11.8 to 12.8:1 to further improve fuel economy. Figure 69 shows the GEM points. The 12.8:1 compression ratio coupled with premium fuel and key combustion technologies achieved 10.44% total GEM cycle BSFC improvement from 7.81% under 11.8:1 compression ratio, Table 8.

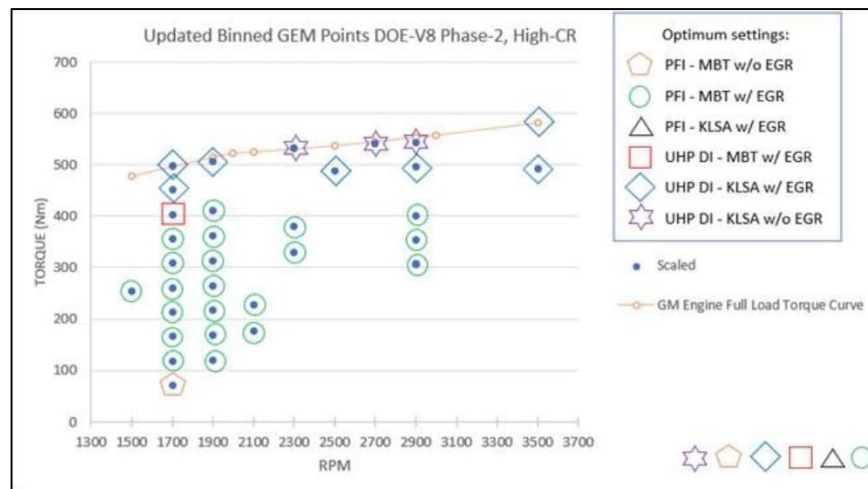


Figure 69. GEM points of PHASE 2 engine tested under high compression ratio (12.8:1). Source: GM

Table 8. PHASE 2 medium duty solution FE engine full load performance

No.	RPM /BMEP	L96 BSFC g/kWh	Phase 2 11.8 CR	Phase 2 12.8 CR	11.8 vs Base	12.8 vs Base
1	1500/5.2	238.4	233.44	225.60	2.14%	5.68%
2	1700/1.4	402.4	375.83	354.80	7.06%	13.41%
3	1700/2.4	309.7	288.24	277.70	7.46%	11.53%
4	1700/3.3	269.4	256.47	252.50	5.06%	6.71%
5	1700/4.3	250.1	241.06	237.90	3.76%	5.14%
6	1700/5.2	239.1	231.25	223.10	3.40%	7.18%
7	1700/6.2	230.9	224.05	217.80	3.07%	6.03%
8	1700/7.1	224.4	217.57	211.10	3.15%	6.32%
9	1700/8.1	221.0	215.84	210.10	2.39%	5.18%
10	1700/9.0	219.8	222.79	217.50	-1.33%	1.06%
11	1700/10.0	230.7	231.61	223.70	-0.40%	3.12%
12	1900/2.4	306.7	284.97	274.10	7.62%	11.89%
13	1900/3.3	269.7	255.64	247.70	5.48%	8.86%
14	1900/4.3	250.7	240.42	233.00	4.28%	7.60%
15	1900/5.2	239.5	230.41	223.70	3.93%	7.05%
16	1900/6.2	232.2	222.34	217.50	4.42%	6.74%
17	1900/7.1	224.4	216.81	210.16	3.52%	6.80%
18	1900/8.1	220.5	216.71	208.70	1.76%	5.67%
19	1900/10.0	226.5	229.37	222.40	-1.24%	1.85%
20	2100/3.3	269.7	256.20	246.46	5.27%	9.42%
21	2100/4.3	250.8	240.50	231.75	4.29%	8.23%
22	2300/6.2	232.8	221.99	214.24	4.86%	8.66%
23	2300/7.1	226.5	215.84	209.40	4.92%	8.15%
24	2300/10.0	226.9	232.29	223.60	-2.33%	1.46%
25	2500/9.0	226.8	224.99	220.00	0.81%	3.10%
26	2700/10.0	227.4	233.91	228.50	-2.80%	-0.50%
27	2900/6.2	242.0	230.34	223.38	5.07%	8.34%
28	2900/7.1	233.0	223.92	217.60	4.04%	7.06%
29	2900/8.1	227.6	218.14	216.20	4.36%	5.29%
30	2900/10.0	230.4	225.53	219.80	2.15%	4.81%
31	2900/10.9	231.2	229.75	224.30	0.62%	3.06%
32	3500/10.0	240.8	236.79	233.50	1.71%	3.14%
		251.0	231.40	224.8		
		baseline	-7.81%	-10.44%		

7.2 Test Cell Global Engine Durability (GED) Evaluation of Proposed Medium Duty Truck Solution with Advanced Materials Solutions

The overall PHASE 2 durability engine weighs 200Kg, >17.7% lighter over the L96 baseline engine as defined in FOA, while engine displacement is increased from 6L to 6.6L, as shown in Table 9.

One PHASE 2 durability engine was built for global engine durability (GED) dyno test, as shown in Figure 70. The GED engine contains advanced material lightweight solutions, Table 9, including high strength cast aluminum GM high Q alloy block and ORNL ACMZ heads made from low-pressure precision sand cast (LPPSC) process, high strength cast steel crankshaft, high strength austempered ductile iron camshaft, and high value cast steel exhaust manifolds, etc. The mechanical properties of those materials solutions showed significant improvement over the baseline materials, reported in Section 6.



Figure 70. The PHASE 2 durability engine built for lightweight material solution. Source: GM

Table 9. Advanced materials solutions in the PHASE 2 GED durability engine

Key Parts	Engine Block			Cylinder Head		Crankshaft		Camshaft	Exhaust manifold
New Materials and Manufacturing Solutions	Cast Iron L8T Production Block	LPPSC ORNL ACMZ Alloy	LPPSC GM HighQ Alloy	LPPSC ORNL ACMZ Alloy	LPPSC GM HighQ Alloy	High Strength Cast Steel (hollow)	High Strength Cast Iron (solid)	ADI	Ferritic stainless-steel casting
GED (Global Engine Durability) Test			✓	✓		✓		✓	✓

The GED engine passed the required 590 cycles durability dyno test for medium-duty truck applications. Post-test evaluation indicates that the advanced materials and manufacturing solutions demonstrated in the GED engine all achieved the objective of the project.

8. Project Products Developed Under the Award

8.1 Publications

- [1] Shane Anderson, Paul Sanders (MTU), Qigui Wang, John Yang, Strategy for developing a castable, high-strength ductile iron alloy with improved stiffness for a lightweight crankshaft application, Proceedings of 2023 7th Keith Mills Symposium on Ductile Iron, Oct. 16-20, Atlanta, USA
- [2] Qigui Wang, Andy Wang, Rich Ricchi, Ronald Petrus, Daniel Wilson, Alex Plotkowski, Amit Shyam, Allen Haynes, Mechanical Properties of Additively Manufactured DuAlumin-3D Alloy Pistons, Proceedings of PowderMet2023 and AMPM2023, June 18-21, Las Vegas, USA
- [3] Qigui Wang, Andy Wang, Abby Park, John Yang, Daniel Wilson, Dale Gerard, Microstructure and Mechanical Properties of Cast Aluminum Pistons, AFS Transaction 2023
- [4] Michael P. Moodispaw, Buwei Chen, Alan A. Luo, Qigui Wang, Achieving Metallurgical Bonding in Aluminum/Steel Bimetallic Castings, International Journal of Metalcasting, published online on Jan 17, 2024
- [5] Richard A. Michi¹, Joseph J. Simpson, Sumit Bahl, Quinn Campbell, Alex Plotkowski, Ryan R. Dehoff, J. A. Haynes, Qigui Wang, and Amit Shyam, Elevated-temperature fatigue limit for an additively manufactured Al-Ce-Ni-Mn alloy, Additive Manufacturing, 66 (2023) 103477
- [6] Michael P. Moodispaw, B. Chen, A.A. Luo, Q. Wang, "Achieving Metallurgical Bonding in Aluminum/Steel Bimetallic Castings", American Foundry Society Transactions, 2022, Paper 22-040. Presented at CastExpo and Metalcasting Congress, Columbus, OH, April 23-26, 2022.
- [7] Michael P. Moodispaw, C. Gu, A.A. Luo, Q. G. Wang, "Cellular Automaton Simulation of Three-dimensional Microstructure Evolution during Powder Bed Fusion Additive Manufacturing", Materials Science and Technology Conference (MS&T21), October 17-20, 2021

8.2 Patents

- [1] Liang Wang, Qigui Wang, Jianghuai Yang, Kiran Mistry, Oliver Patrick Jordan, System and method of making an enhanced cast iron crankshaft, US Patent 11,759,849 (Sept 19, 2023)
- [2] Ronald John Petrus, Jared Matthew Satkowiak, Hsiao F Wong, Kenneth E Schroeder, Qigui Wang, Rich Ricchi, Piston for Use in Internal Combustion Engines and Method of Making the Piston, US Patent 11,994,085 (May 28, 2024)
- [3] Liang Wang, Qigui Wang, Jianghuai Yang, Kiran Mistry, Oliver Patrick Jordan, System and Method of Making A Cast Steel Alloy Crankshaft Having Low Porosity, US Patent 11,890,668 (Feb 6, 2024)
- [4] Liang Wang, Qigui Wang, Dale A Gerard, Steven L. Burkholder, Ronald Daul, Method to Increase Local Cooling Rate and Improve Material Properties in a Low-Pressure Sand-Casting Heads, US Patent 11,986,879 (May 21, 2024)

- [5] Ronald J Petrus, Richard M Nichols III, Brian C Leuenhagen, William A Berry, Qigui Wang, James T Singer, Cylinder Block Casting Slab Core Cast Geometry for Sawcut Entrance Enhancement, US Patent 11,655,776 (May 23, 2023)
- [6] David C Klemstine, Guirong Cao, Jianghuai Yang, William A Berry, Qigui Wang, System and Method of Making a Crankshaft with Alternate Materials, US Patent 11619255 (April 4, 2023)
- [7] David Klemstine, Grace Cao, John Yang, William Berry, Qigui Wang, Lightweight Nodular Iron Crankshaft for Heavy Duty Engine, US Patent 12,044,270 (July 23, 2024)
- [8] Jianghuai Yang, Qigui Wang, Dale Gerard, High Modulus, High Strength Low Alloy Gray Cast Iron for Cylinder Liner and Auto Applications, US Patent 11,879,168 (Jan 23, 2024)
- [9] Ron Petrus, Richard Nichols, Qigui Wang, Brian Leuenhagen, A Novel Hybrid Cam Bore Sand Coe with Metal Chills for Cast AI Engine Block, US Patent 11,554,413 (Jan 17, 2023)

9. References

- [1] DOE-EERE, 2019, "Fiscal Year 2019 advanced vehicle technologies research funding opportunity announcement," DE-FOA-0002014, Washington, D.C., USA. Available at: <https://eere-exchange.energy.gov/FileContent.aspx?FileID=25f7a4dd-9874-4aee-9606-2ab52fe9cc18>. Accessed 9 December 2020.
- [2] Pollock, T. M., J. E. Allison, D. G. Backman, M. C. Boyce, M. Gersh, E. A. Holm, R. LeSar, M. Long, A. C. Powell IV, J. J. Schirra, D. D. Whitis, and C. Woodward, 2008, "ICME: A transformational discipline for improved competitiveness and national security," The National Academies Press, Washington, D.C., USA.
- [3] Wang, Q. G., P. Jones, Y. Wang, and D. Gerard, 2011, "Advances in computational tools for virtual casting of aluminum components," in: Allison, J. E., P. M. Collins, and G. Spanos (eds.), Proceedings of the 1st World Congress on Integrated Computational Materials Engineering (ICME), TMS 2011, pp. 217–222.
- [4] Wang, Q. G., D. Apelian, and D.A. Lados, J. of Light Metals, vol. 1, No. 1 (2001), 73-97.
- [5] Major, J.F., AFS Transactions, vol. 105 (1998), 901-906.
- [6] Wang, Q.G., P.E. Jones, and M. Osborne, in: Advances in Aluminum Casting Technology II, eds: M. Tiryakioglu and J. Campbell, ASM International, Materials Park, OH, 2002, pp. 75-84
- [7] Wang, Qigui, Mike Walker, Herb Doty, Devin Hess, SAE technical presentation, April 2019
- [8] Yang, J., Q. Wang, D. Wilson, J. Cremonesi, High-Strength Bainitic Steel, US Patent Application Publication number: 20190161838
- [9] Cogan, C., Q. Wang, M. Meyer, Method of Manuf. Metal Castings, US Patent Publication number: 20180016666
- [10] Luo, A.A., CALPHAD, 2015, 50, 6-22.
- [11] ORNL, 2018, "ORNL-developed alloy promises better fuel economy," Available at: <https://www.ornl.gov/blog/eesd-review/ornl-developed-alloy-promises-better-fuel-economy>. Accessed 9 December 2020.
- [12] Plotkowski, A., O. Rios, N. Sridharan, Z. Sims, K. Unocic, R. T. Ott, R. R. Dehoff, and S. S. Babu, 2017, "Evaluation of an Al-Ce alloy for laser additive manufacturing," Acta Mater., Vol. 126, pp. 507–519.
- [13] Luo, A. A., W. Sun, and X. Huang, 2018, "High-entropy AlCrTiV Alloys", U.S. Patent Application, US 2018/0119255.
- [14] Zhu, X., J. Z. Yi, J. W. Jones, and J. E. Allison, 2007, "A probabilistic model of fatigue strength controlled by porosity population in a 319-type cast-aluminum alloy: Part I. Model development," Metall Mater Trans A Phys Metall Mater Sci 38(5), 1111–1122.
- [15] Huff, R. K., 2016, "Development of high-performance cast crankshafts," DOE-EERE Vehicle Technologies – Annual Merit Review, 9 June 2016, Project ID: PM 065. Available at: https://www.energy.gov/sites/prod/files/2016/06/f33/pm065_huff_2016_o_web.pdf. Accessed 9 December 2020.
- [16] Wang, Q., A. Wang, R. Ricchi, R. Petrus, D. Wilson, A. Plotkowski, A. Shyam, and A. Haynes, 2023, "Mechanical properties of additively manufactured DuAlumin-3D alloy pistons," Proceedings of the PowderMet2023 and AMPM2023, 18–21 June 2023, Las Vegas, NV, USA.

10. Acknowledgement and Disclaimer

Acknowledgment: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Vehicle Technologies Office Award Number DE-EE0008877.

The project team would like to thank DOE project managers and directors Ken Howden (retired), Gurpreet Singh, Jerry Gibbs (retired), Siddiq Khan, Ralph Nine, and Michael Ursic for their great support to the project. The team also like to thank Sean Campbell (contract manager at GM), Edward Keating (Co-PI, retired), Ron Petrus (Co-PI), Jason Coryell, Dan Wilson (retired), Dale Gerard (retired), Michelle Wood, Manuel Gonzalez Delgado, Rodney Baker, Ian MacEwen, Aida Rodrigues, Chuck Gough (retired), Jeff Jocsak, Jordan lee, and David Young at GM for their support and advice to the project.